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Agricultural Water Management 82 (2006) 433–451
Agricultural water management
www.elsevier.com/locate/agwat

Estimation irrigation water requirements with derived crop coefficients for upland and paddy crops in ChiaNan Irrigation Association, Taiwan

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Accepted 21 August 2005
Available online 10 October 2005

Abstract

Field experiments were performed at the HsuehChia Experimental Station from 1993 to 2001 to calculate the reference and actual crop evapotranspiration, derived the crop coefficient, and collected requirements input data for the CROPWAT irrigation management model to estimate the irrigation water requirements of paddy and upland crops at the ChiaNan Irrigation Association, Taiwan. For corn, the estimated crop coefficients were 0.40, 0.78, 0.89 and 0.71 in the initial, crop development, mid-season and late-season stages, respectively. Meanwhile, the estimated crop coefficients for sorghum were 0.44, 0.71, 0.87 and 0.62 in the four stages, respectively. Finally, for soybean, the estimated crop coefficients were 0.45, 0.89, 0.92 and 0.58 in the four stages, respectively. With implementation of REF-ET model and FAO 56 Penman–Monteith method, the annual reference evapotranspiration was 1268 mm for ChiaNan Irrigation Association.

In the paddy fields, the irrigation water requirements and deep percolation are 962 and 295 mm, respectively, for the first rice crop, and 1114 and 296 mm for the second rice crop. Regarding the upland crops, the irrigation water requirements for spring and autumn corn are 358 and 273 mm, respectively, compared to 332 and 366 mm for sorghum, and 350 and 264 mm for soybean. For the irrigated scheme with single and double rice cropping patterns in the ChiaNan Irrigation Association,

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doi:10.1016/j.agwat.2005.08.002

the CROPWAT model simulated results indicate that the annual crop water demands are 507 and 1019 mm, respectively, and the monthly water requirements peaked in October at 126 mm and in January at 192 mm, respectively.

Keywords: Irrigation water requirements; Crop coefficient; Evapotranspiration; Cropping pattern; CROPWAT model; REF-ET model

1. Introduction

The amount of water available for agricultural use in Taiwan has recently become critical. Average annual rainfall in Taiwan is approximately 2500 mm. However, this rainfall is distributed unevenly both temporally and spatially, and the distribution is not optimal for the growing seasons of various crops. Therefore, water shortages are frequent, especially during the dry seasons. Additionally, competition with irrigators for water has intensified owing to rapidly accelerated population growth, industrialization and urbanization. To effectively and efficiently use the available water sources to meet the possible variation of cropping pattern, studies of crop water requirements for upland and paddy crops based on derived crop coefficient are crucial. To improve management practice, experimental data based the irrigation management model can be applied for estimating crop water requirements and upgrading irrigation management capability for the 17 Irrigation Associations (IA) in Taiwan.

Crop coefficients have been used to estimate evapotranspiration for specific crops by measuring potential or reference evapotranspiration. Crop coefficients must be derived empirically for each crop based on local climatic conditions (Doorenbos and Pruitt, 1984). Vories and Tacker (2002) used the Arkansas Irrigation Scheduler and executed field experiments using a subsurface drip irrigation system to confirm the crop coefficient functions for corn and cotton in Arkansas. Allen et al. (2005) based on FAO56 to calculate the crop coefficient and potential evapotranspiration, and included calculation of evaporation from precipitation and irrigation events for the Imperial Irrigation District in the Western United States.

Corn, sorghum and soybean are important upland crops in Taiwan, and are planted in numerous agricultural zones. Experiments have been performed involving these crops over many years to develop ways of using water resources economically. Shih and Chang (1995) performed experiments in three sites such as common field, drainage lysimeter, and rainshelter lysimeter since 1989–1992. Crop coefficients can be obtained by the ratio of evapotranspiration and Penman potential evapotranspiration model results, and crop evapotranspiration are obtained by measuring water balance results. The results show that the evapotranspiration required about 200–300 mm, and the grain yield of spring sorghum is about 7000–8000 kg/ha. Lin and Hung (1995) used the evaporation pan to estimate the transpiration potential of crops, and the potential evapotranspiration was estimated by Penman equation. The results demonstrates that ratio between potential evapotranspiration and pan evaporation is 0.692; furthermore, the designed simple evaporation pan could be used for timing the irrigations in fields for different crops as long as the crop coefficient values were provided. Shih and Ho (1997) conducted field experiment at the HsuehChia Experimental Station to estimate the crop coefficient and actual evapotranspiration for soybean. The relationships between the mean crop coefficient against the days after crop planting and the fraction of the growing season have been analyzed. Chen (1997) used Penman–Monteith method and meteorological data of Taipei, Hsinchu, and Kaohsiung from 1951 to 1990 to estimate the values of reference evapotranspiration in every 10 days for different recurrent periods in different areas of Taiwan. Furthermore, the result was used to analyze the differences of the 10-day irrigation absolute water consumptions in paddy fields in different areas under various recurrent periods.

Pleban and Israeli (1989) advocated on-farm water balance as the normal method for deciding how much water to apply per irrigation. Cavero et al. (2000) applied CROPWAT model to simulate maize grain yield reduction caused by water stress under semiarid conditions. Arora and Gajiri (2000) combined a crop growth simulator (SUCROS) with a water balance model (WBM) to forecast maize growth and yield in a subtropical environment. Moreover, Lascano (2000) conducted a field experiment using a surface drip irrigation system together with an ENWATABL model to calculate daily crop water use. Finally, Anadranistakis et al. (2000) used an SM model to estimate crops grown in Greece and validated using meteorological and crop data from experimental fields run by the Agricultural University of Athens.

Field experiments provide the basic data required for irrigation management. The HsuehChia Experimental Station of the ChiaNan Irrigation Association in Taiwan performed field experiments to obtain the crop coefficients for corn, sorghum and soybean, respectively, from 1993 to 2001. Furthermore, the irrigation management model of CROPWAT, designed by Smith (1991) of the Food Agricultural Organization (FAO), was used in this investigation to assess the crop water requirements in the ChiaNan irrigation district using field experiment data from the HsuehChia Experimental Station.

2. Materials and methods

2.1. Site description

The ChiaNan Irrigation Association (IA) is the biggest IA among the 17 IAs in Taiwan and with a total irrigated area of 78,422 ha. The area has an average annual temperature of 21–24 °C, and annual rainfall of 2500 mm, of which 80% is concentrated in the wet season from May to September. The area of similar meteorological condition above in Taiwan totals about 595 415 ha, representing approximately 68.6% of Taiwan's agricultural land. Consequently, numerous experiments for upland and paddy crops water requirements were performed at this station, and the results can be applied to much of the agricultural land in Taiwan, and also to land in other sub-tropical zones. The irrigation requirements for upland crops are significantly less than for paddy rice, and the water saved from upland crop irrigation can be diverted to irrigate paddy rice; consequently, the upland crops and paddy rice cropping pattern is used in this district.

Table 1
Soil texture and soil physical characteristics at the HsuehChia Experimental Station

Parameters	Soil depth from ground surface (cm)					Average
	0–10	10–20	20–30	30–40	40–60	
Soil texture	Silty loam	Silty loam	Silty loam	Silty loam	Loam	–
Saturation content (% of dry weight)	31.4	31.9	33.05	32.80	31.70	32.17
Field capacity (% of dry weight)	24.80	20.20	20.40	21.90	19.50	21.40
Wilting point (% of dry weight)	5.98	6.31	6.37	5.90	5.84	6.08
Bulk density (g/cm^3)	1.37	1.54	1.60	1.56	1.52	1.52

2.2. Field experiment

The experimental site was the HsuehChia Experimental Station of the ChiaNan Irrigation Association in Taiwan, located at 23°13′N, 120°11′E and 4 m above MSL. The monthly mean temperature at the station varies from 18.2 °C in February to 28.5 °C in June. Moreover, the monthly mean relative humidity ranges from 76.9% in February to 75.7% in June, and the monthly mean solar radiation varies from 221.2 cal cm^{-2} day^{-1} in February to 283.1 cal cm^{-2} day^{-1} in June. A weather station was established at the experimental site, and regularly recorded air temperature, relative humidity, sunshine hours, solar radiation, and wind speed and direction. The above data were collected for this work.

Crop evapotranspiration was measured using a drainage lysimeter during the crop growth season. The lysimeters were constructed using a concrete foundation, and were 3 m × 5 m × 2.9 m in size and had filters at the bottom and provision for collecting drainage water. The texture of the packed soil was silty loam and loam. Table 1 lists the soil texture and soil moisture constants at different soil layers. The complete block design of the lysimeters was replicated twice. Fig. 1 illustrates that the overall system comprises 12 lysimeter blocks, irrigation pipes for water supply; 12 runoff and percolation collectors were also provided.

All of the lysimeter blocks were irrigated using the corrugation method. Irrigation water was applied to maintain the soil moisture at 50% of maximum available soil moisture during the crop growth season. Furthermore, the gravimetric method was employed to determine the soil moisture content. A spiral-shaped bit made from a standard wood-anger bit used in carpentry, about 3 cm in diameter and 110 cm in length, was used to take the soil samples. Soil samples of around 60 g were stored in the soil cans, and had diameter of 5 cm and depth of 4 cm. Soil moisture was measured by weighing the soil sample before and after oven drying with 24 h was necessary for drying in the laboratory. Soil samples were taken weekly, before and following each irrigation. Soil samples were taken at 10 cm intervals until to a depth of 60 cm.

2.3. Calculate reference and actual evapotranspiration to derive crop coefficient

Many methods are available for estimating reference evapotranspiration (ET$_o$). The methods proposed by Doorenbos and Pruitt (1984), namely the modified Penman,

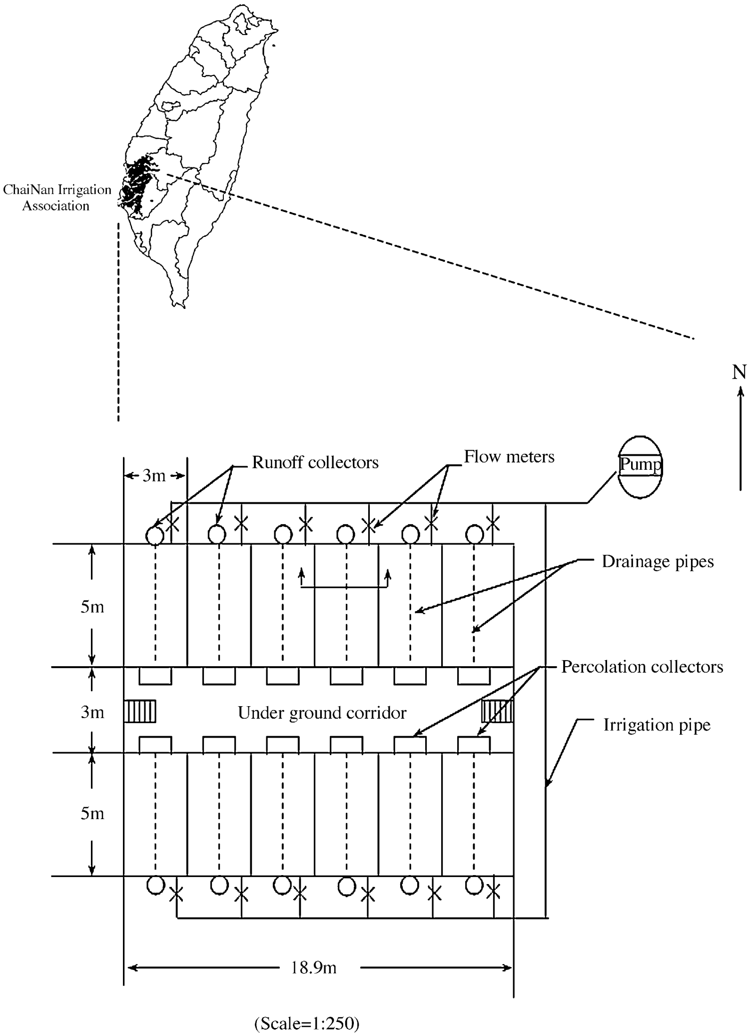

Fig. 1. The overall system comprises 12 lysimerers at the HsuehChia Experimental Station of the ChiaNan Irrigation Association, Taiwan.

Blaney–Criddle, Radiation, and Pan evaporation, have been extensively applied in different climatic conditions. Blaney and Criddle used temperature as the main variable to obtain an index for consumptive use in the arid Western United States, the Radiation method used temperature and solar radiation and the Pan evaporation method used evaporation and environmental factors to calculate the reference crop evapotranspiration (Hansen et al., 1980). FAO 56 (Allen et al., 1998) mentioned that Penman equation derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed. The climatic conditions of the original Penman equation are the same as the local climatic conditions in this work; additionally, the daily weather data could be gathered from the weather station. Therefore, the Penman–Monteith method recommended by FAO 56 was used in this investigation to estimate $\mathrm{ET_o}$ as expressed by Eq. (1); furthermore, the REF-ET version 2.0 that developed by Allen (2000) was implemented in this study to compare the different types of equation with FAO56 Penman–Monteith method to calculate the $\mathrm{ET_o}$.

$$\mathrm{ET_o} = \frac{0.408\Delta(R_\mathrm{n} - G) + \gamma \frac{900}{T+273} u_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where $\mathrm{ET_o}$ denotes the crop reference evapotranspiration (mm $\mathrm{day^{-1}}$); R_n the net radiation at crop surface (MJ $\mathrm{m^{-2}}$ $\mathrm{day^{-1}}$); G the soil heat flux density (MJ $\mathrm{m^{-2}}$ $\mathrm{day^{-1}}$); T the mean daily air temperature at 2 m height (°C); u_2 the wind speed at 2 m height ($\mathrm{ms^{-1}}$); e_s the saturation vapour pressure (kPa); e_a the actual vapor pressure (kPa); $e_\mathrm{s} - e_\mathrm{a}$ the saturation vapor pressure deficit (kPa); Δ the slope vapor pressure curve (kPa $^\circ\mathrm{C}^{-1}$); γ the psychometric constant (kPa $^\circ\mathrm{C}^{-1}$).

Actual evapotranspiration ($\mathrm{ET_c}$) was calculated for each crop via a water balance method, as in Eq. (2).

$$\mathrm{ET_c} = I + P - D - R \pm \Delta S \tag{2}$$

where I denotes irrigation depth (mm); P, rainfall (mm); D, drainage (mm); R, runoff (mm); ΔS, the change in soil moisture (mm).

Daily values of crop coefficients were calculated for each crop using Eq. (3).

$$K_\mathrm{c} = \frac{\mathrm{ET_c}}{\mathrm{ET_o}} \tag{3}$$

where K_c is a crop coefficient; and $\mathrm{ET_c}$, $\mathrm{ET_o}$ actual and reference crop evapotranspiration, respectively.

2.4. CROPWAT model

The CROPWAT model was originally developed by the FAO in 1990 to calculate crop water requirements and for planning and managing irrigation projects. The input data of the CROPWAT model include crop, meteorology, and soil. The meteorology data include: (1) maximum and minimum temperature; (2) wind speed; (3) sunshine hours; (4) relative humidity; (5) rainfall. The Penman–Monteith explicit equation was used to determine the potential evapotranspiration (ETr).

Four common empirical methods exist for calculating effective rainfall (Smith, 1991) as follows: (1) fixed percentage of rainfall; (2) dependable rainfall; (3) empirical formula; (4) USDA Soil Conservation Service Method. The USDA Soil Conservation Service method was used in this study as Eq. (4).

$$P_\mathrm{eff} = P_\mathrm{tot} \times \frac{125 - 0.2P_\mathrm{tot}}{125}, \quad \text{for}\, P_\mathrm{tot} < 250\,\mathrm{mm}, \qquad P_\mathrm{eff} = 125 + 0.1 \times P_\mathrm{tot}, \\ \text{for}\, P_\mathrm{tot} > 250\,\mathrm{mm} \tag{4}$$

where P_{eff} denotes the effective rainfall; P_{tot} the measured (or generated) total daily rainfall.

Given the required data input, the CROPWAT model can be used to calculate crop-related data in each decade of a month, including data such as: (1) crop coefficient, (2) crop leaf index, (3) crop evapotranspiration, (4) percolation, (5) effective rainfall, and (6) crop water requirements. Additionally, the model can be applied to estimate the irrigation schedule for each crop using five different options: (1) each irrigation as defined by the irrigation manager, (2) irrigation at below or above critical soil depletion (% RAM), (3) irrigation at fixed interval per crop growth stage, (4) deficit irrigation, and (5) no irrigation. Subsequently, the CROPWAT model can simulate the on-farm crop water balance, including: (1) irrigation times, dates and depths, (2) soil moisture depletion, (3) amount of percolation, (4) actual crop evapotranspiration, and (5) crop yield.

After simulating the irrigation schedule for each crop, the CROPWAT model could be used to estimate the monthly agricultural water requirements of an irrigation scheme, based on different cropping patterns, as expressed below:

$$Q_{\mathrm{gross}} = \frac{1}{e_{\mathrm{p}}t} \times \left[0.116 \times A_{\mathrm{scheme}} \times \sum_{i=1}^{n} (\mathrm{ET}_{\mathrm{crop}} - P_{\mathrm{eff}}) \times \frac{A_{\mathrm{crop}}}{A_{\mathrm{scheme}}}\right] \tag{5}$$

where Q_{gross} denotes the monthly agricultural water requirement of an irrigation scheme (l/s); e_{p} irrigation efficiency ($\leqq 1$, dimensionless); t time operational factor ($\leqq 1$, dimensionless); i the crop index of the cropping pattern for an irrigation scheme; A_{crop} crop planted area (ha); A_{scheme} the total area of the irrigation scheme (ha); ET_{c} crop evapotranspiration (mm/day); P_{eff} effective rainfall (mm/day).

3. Results and discussion

3.1. Calculation of reference and actual evapotranspiration

The long-term meteorological data, from 1964 to 2001, recorded by agricultural weather station of HsuehChia Experimental Station was applied to REF-ET model to calculate the reference evapotranspiration. The daily meteorological data includes: (1) mean air temperature, (2) maximum and minimum temperature, (3) dewpoint temperature, (4) average relative humidity, (5) wind speed, (6) sunshine hours, and (7) solar radiation. From REF-ET model, four evapotranspiration equations include: (1) FAO 56 Penman–Monteith, (2) 1948 Penman, (3) Blandy–Criddle, and (4) 1985 Hargreaves (Hargreaves et al., 1985) was used to calculate and compare the reference evapotranspiration for ChiaNan irrigated area. Figs. 2–4 presents the comparison between FAO 56 Penman–Monteith to 1948 Penman, Blandy–Criddle, and 1985 Hargreaves, respectively. With implementation of REF-ET model for four empirical equations, FAO 56 Penman–Monteith, 1948 Penman, Blandy–Criddle, and 1985 Hargreaves, to calculate the annual reference evapotranspiration for ChiaNan Irrigation Association are 1268, 1355.5, 1301.7 and 1318 mm, respectively. The results from FAO 56 Penman–Monteith was used in this

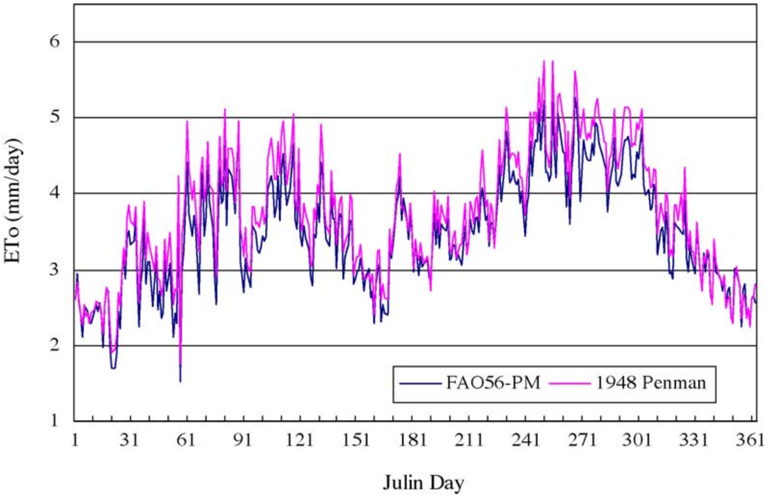

Fig. 2. FAO56 Penman–Monteith and 1948 Penman method to calculate reference evapotranspiration from REF-ET model for ChiaNan Irrigation Association.

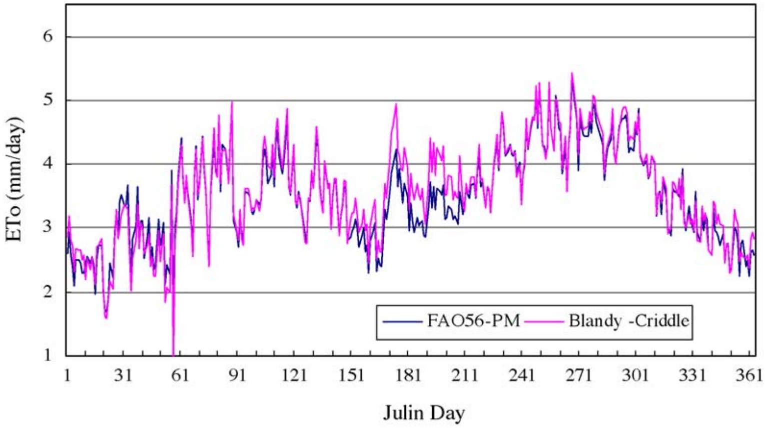

Fig. 3. FAO56 Penman–Monteith and Blandy–Criddle method to calculate reference evapotranspiration from REF-ET model for ChiaNan Irrigation Association.

investigation for further application in the CROPWAT model to calculate the upland and paddy crops water requirements in ChiaNan Irrigation Association.

Displaying information on field experiments involving corn, sorghum and soybean from 1993 to 2001 at the HsuehChia Experimental Station, Table 2 shows the agronomic management data in various growing seasons and Table 3 illustrates the length of crop growth days for corn, sorghum and soybean as recorded by the ChiaNan Irrigation

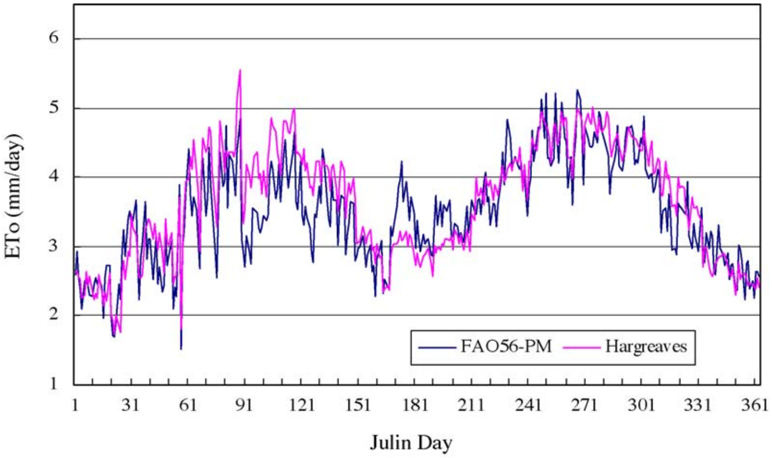

Fig. 4. FAO56 Penman–Monteith and Hargreaves method to calculate reference evapotranspiration from REF-ET model for ChiaNan Irrigation Association.

Table 2
Agronomic management data for corn, sorghum and soybean crops at the HsuehChia Experimental Station

Seasons	Crop	Variety	Planting date	Harvest date	Fertilizer (kg/ha)			Seed yields (Mg/ha)
					N	P	K	
1993	Corn	Tainan no. 351	24 February	23 June	200	35	60	6.28
1994			23 February	22 June				8.54
1995			22 February	20 June				7.67
1996	Sorghum	Taichung no. 5	13 March	26 June	145	40	75	7.77
1997			16 March	29 June				7.43
1998			25 February	10 June				7.82
1999	Soybean	Kaohsiung no. 10	8 February	24 May	20	40	60	3.4
2000			7 March	20 June				3.38
2001			20 February	5 June				3.06

Table 3
Length of crop growth days for corn, sorghum and soybean crops at the ChiaNan irrigated scheme in Taiwan

Crop	Growth days	Crop growth stages			
		Initial (I)	Development (II)	Mid season (III)	Late season (IV)
Corn	119	21	35	42	21
Sorghum	105	14	28	42	21
Soybean	105	14	28	42	21

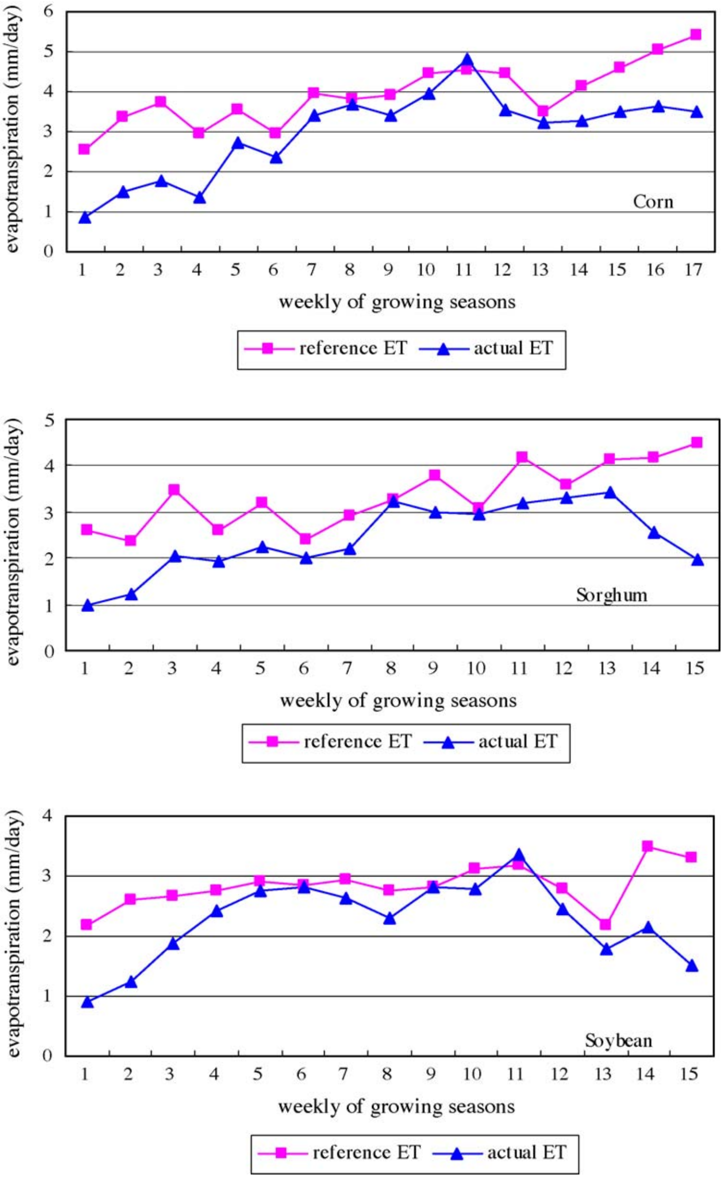

Fig. 5. Reference and measured actual evapotranspiration of corn, sorghum and soybean at the ChiaNan Irrigation Association, Taiwan.

Association. Fig. 5 presents the mean values of the weekly reference evapotranspiration from FAO 56 Penman–Monteith and the mean weekly values of measuring actual evapotranspiration for corn, sorghum, soybean during the growth period. The reference evapotranspiration values display an increasing trend with the increase in crop growth

Table 4
Actual crop coefficient for first and second paddy from the ChiaNan Irrigation Association, Taiwan

Growing days	Stage	First paddy	Second paddy	FAO
1–30	Land preparation	–	–	1.1
31–45	Transplant seedling	0.6	1.0	
46–60	Tiller initial	1.0	1.3	1.1
61–75	Tiller final	1.3	1.6	
76–90	Flower initial	1.5	1.7	1.05
91–105	Flower final	1.5	1.6	
106–120	Mature initial	1.4	1.4	
121–135	Mature medium	1.1	1.0	0.95
136–150	Mature final	0.8	0.5	

days, and are influenced by various factors such as temperature, solar radiation, and rainfall from February to June. The total reference evapotranspiration values during the growth season of corn ranged from 459.1 to 488.1 mm. Furthermore, actual seasonal evapotranspiration ranged from 300.5 to 424.8 mm; moreover, the rate of actual evapotranspiration during the four growth stages was 1.3, 2.7, 3.7 and 3.8 mm/day, respectively. The total reference evapotranspiration of sorghum ranged from 280.7 to 386.3 mm. Seasonal actual evapotranspiration ranged from 210.1 to 293.1 mm. On average, actual evapotranspiration during the four growth stages was 1.1, 2.1, 3.0 and 2.6 mm/day, respectively.

3.2. Derived crop coefficients

Crop coefficients (K_c) were determined by dividing the measured actual evapotranspiration by reference crop evapotranspiration, as calculated based on the modified Penman equation. Next, K_c values were determined at 7-day intervals during the growth season. These values changed at different periods due to natural climatic conditions. Therefore, this work designed a mean crop coefficient curve for different growth periods.

According to final report from the HusehChia Experimental Station in 1976 (ChiaNan Irrigation Association, 1976), Table 4 shows the actual crop coefficient for first and second paddy crops from ChiaNan Irrigation Association. Table 5 illustrates the average crop coefficient and actual evapotranspiration of corn, sorghum and soybean for three growing seasons. During the first and second stages, the average K_c values of corn were identical to the average K_c values as suggested by FAO (Doorenbos and Kassam, 1986). However, during the third and fourth stages the K_c values were 19.2% lower than the average K_c values suggested by FAO, respectively.

For the sorghum during the second stage, the average K_c value was the same as the average K_c values suggested by FAO during the second stage. Meanwhile, in the first stage, the average K_c value exceeded the average K_c value of FAO by 10%. During the third stage, the average K_c value was 13% lower than the average K_c values of FAO during the second stage. In the final stage, the K_c values ranged from 0.55 to 0.69; additionally, the average K_c value was 19% higher than the average K_c values of FAO.

Table 5
Actual evapotranspiration and crop coefficient for four stages of corn, sorghum and soybean from the ChiaNan Irrigation Association, Taiwan

Crop type	Seasons	Actual evapotranspiration and crop coefficient							
		Stage I		Stage II		Stage III		Stage IV	
		ET_a (mm)	K_c	ET_a (mm)	K_c	ET_a (mm)	K_c	ET_a (mm)	K_c
Corn	1993	40.4	0.58	122.6	0.94	169.5	1.02	92.2	0.75
	1994	20.6	0.27	101.0	0.85	166.1	0.89	61.0	0.65
	1995	21.4	0.36	61.1	0.54	130.7	0.77	87.3	0.74
	Average	27.5	0.40	94.9	0.78	155.4	0.89	80.2	0.71
	FAO		0.4		0.78		1.10		0.85
Sorghum	1996	20.9	0.53	74.4	0.83	137.0	0.83	60.9	0.69
	1997	8.2	0.25	37.4	0.47	145.0	0.93	71.1	0.61
	1998	17.9	0.54	61.4	0.83	93.7	0.84	34.3	0.55
	Average	15.7	0.44	57.8	0.71	125.2	0.87	55.5	0.62
	FAO		0.40		0.72		1.00		0.52
Soybean	1999	17.3	0.44	75.6	0.91	124.0	1.05	37.4	0.52
	2000	13.4	0.43	74.6	0.83	112.2	0.86	45.4	0.68
	2001	14.6	0.48	57.5	0.93	108.2	0.85	31.9	0.55
	Average	15.1	0.45	69.3	0.89	114.8	0.92	38.2	0.58
	FAO		0.35		0.75		1.10		0.45

For the soybean, the average K_c values clearly differ from the average K_c values of FAO during the first and second stages, the average K_c values were approximately 29.2% higher than the average K_c values suggested by FAO; meanwhile, during the third and fourth stages, the average K_c values was 16% lower and 29% higher, respectively, than the average K_c values obtained by FAO.

According to the results in this study, the estimated values of crop coefficients markedly differed from those suggested by FAO for the crops considered herein. For corn, marked differences arose between the estimated K_c values and the average K_c value suggested by the FAO in the third and fourth stages for sorghum and all stages for soybean. Above differences are attributed primarily to specific cultivator, the changes in local climatic conditions, and seasonal differences in crop growth patterns. Such differences obviously reflect the difficulty not only in extrapolating crop coefficients to other environments, but also in applying crop coefficients in individual year with differing crop development patterns.

3.3. Application of CROPWAT model

Based on the field experiments and water management data, the CROPWAT model simulated the on-farm water balance for the first and second paddy crops for the ChiaNan Irrigation Association. Table 6 and Fig. 6 summarize the results. Table 6 illustrates the percentage of percolation for the first paddy crop, which is 30.7% (295/962 × 100) of crop water requirements, and 26% (296/1140 × 100) for the

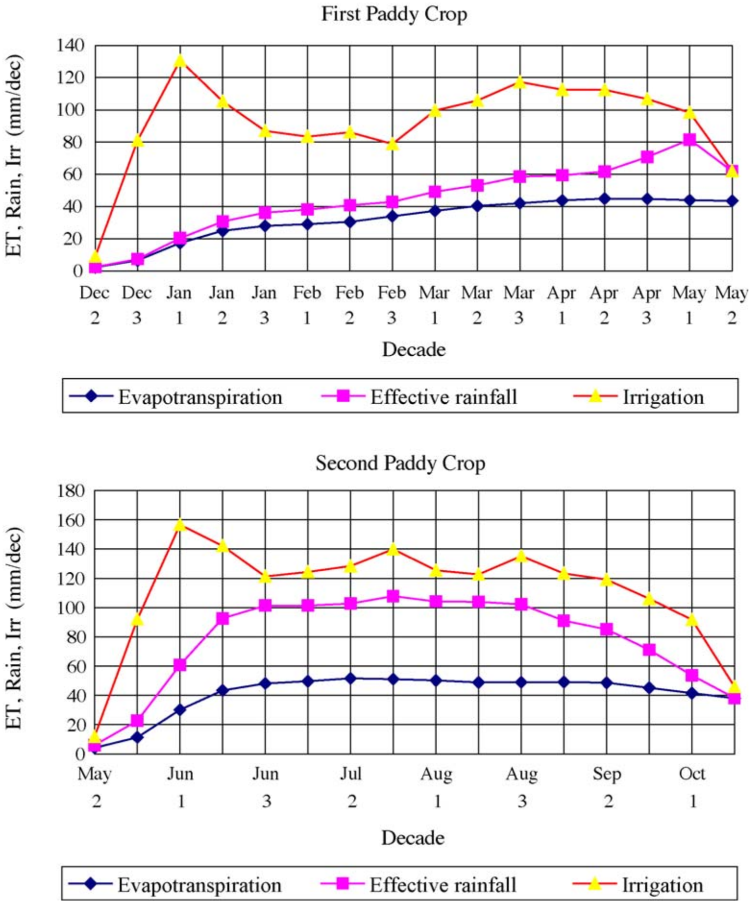

Fig. 6. On-farm water balance for the first and second paddy crops from the ChiaNan Irrigation Association, Taiwan.

Table 6
CROPWAT model simulating the on-farm water balance for paddy crop from the ChiaNan Irrigation Association in Taiwan

Items	First paddy crop (planted date: 15 January)	Second paddy crop (planted date: 15 June)
Crop evapotranspiration (mm)	488	639
Percolation (mm)	295	296
Effective rainfall (mm)	202	584
Crop water requirements (mm)	962	1140
Irrigation water requirements (mm)	760.8	541.4

Table 7
CROPWAT simulation of on-farm water balance for upland crops from the ChiaNan Irrigation Association in Taiwan

Items	Corn		Sorghum		Soybean	
	Spring	Autumn	Spring	Autumn	Spring	Autumn
Planting date	17 February	23 September	28 February	4 June	7 March	20 September
Crop ET (mm)	358.1	272.9	332.1	366.2	350	264.8
Effective rainfall (mm)	328.2	74.6	293.8	517.9	323.1	73.9
Irrigation water requirement (mm)	69.5	203.6	75.3	0	38.4	198.2

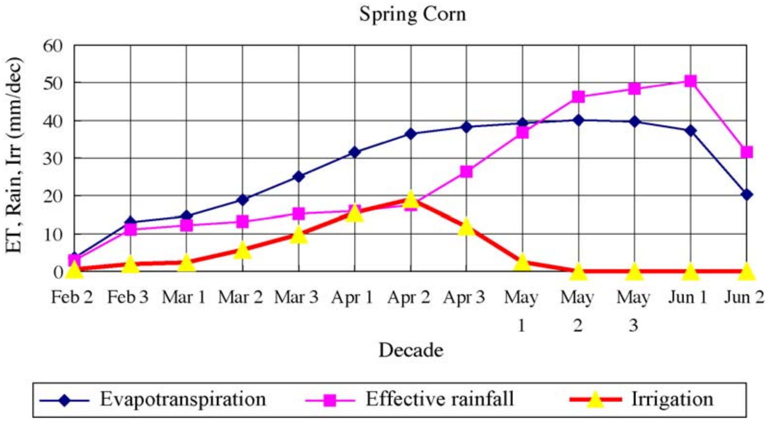

Fig. 7. On-farm water balance for the spring corn at the ChiaNan Irrigation Association, Taiwan.

second paddy crop. The average deep percolation in paddy fields is approximately 28.4% of total crop water requirements. Therefore, the paddy fields clearly function to recharge groundwater, and thus preserve the ecological environment. The CROPWAT model was also applied to simulate the upland crops, including corn, sorghum and soybean, to assess the on-farm water balance which results are as shown in Table 7 and Figs. 7–9.

For evaluating the monthly water requirements of the irrigation scheme in the HsuehChia Experimental Station of the ChiaNan IA, two types of cropping patterns were defined using the water management data listed in Table 8. Meanwhile, Table 9 and Fig. 10 show the simulated monthly water requirements obtained for the HsuehChia Experimental Station area. The simulated results obtained using the CROPWAT model demonstrates that annual agricultural water demand is 537 mm, and the peak monthly water requirement of 126 mm occurred in October. For the double rice-cropping pattern, annual agricultural water demand is 1019 mm, and the peak monthly water requirement of 192 mm happened in January.

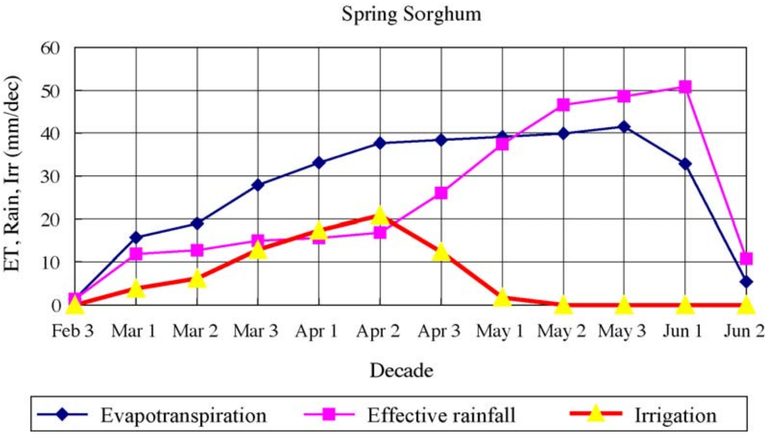

Fig. 8. On-farm water balance for the spring sorghum at the ChiaNan Irrigation Association, Taiwan.

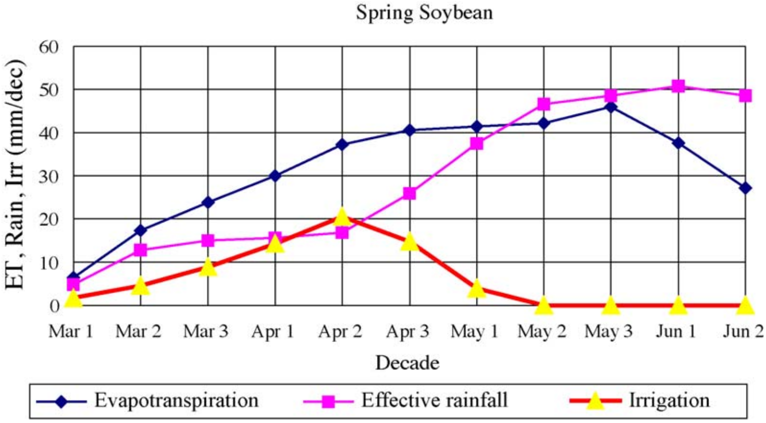

Fig. 9. On-farm water balance for the spring soybean at the ChiaNan Irrigation Associaiton, Taiwan.

Table 8
Cropping patterns for the ChiaNan Irrigation Association in Taiwan

Types	Crop name	Planting date	Harvest date	Area (%)
Single rice cropping pattern	Corn	15 February	14 June	45
	Sorghum	15 February	31 May	45
	Rice	15 July	12 November	65
	Sorghum	1 July	14 October	25
Double rice cropping pattern	Rice	15 January	15 May	90
	Rice	1 July	29 October	90

Table 9
Monthly irrigation water requirements with single and double rice cropping pattern for the ChiaNan Irrigation Association in Taiwan

Month	Monthly irrigation water requirements (mm/month)	
	Single rice cropping pattern	Double rice cropping pattern
January	0	192
February	2	89
March	28	118
April	48	100
May	2	7
June	49	177
July	121	42
August	44	36
September	79	77
October	126	109
November	38	0
December	0	72
Total	537	1019

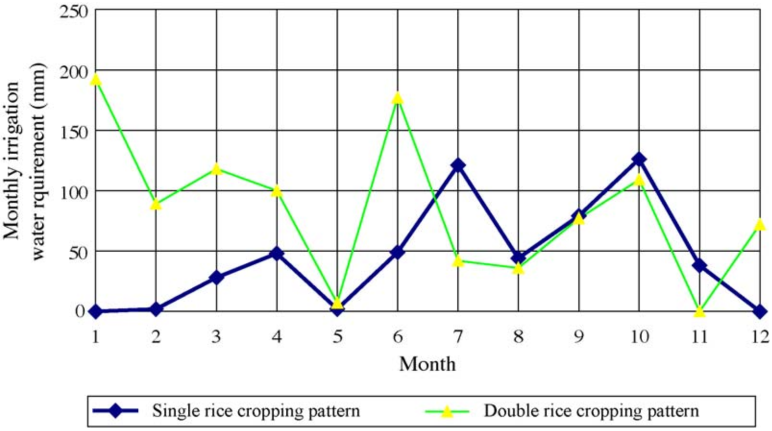

Fig. 10. Monthly irrigation water requirements of the ChiaNan Irrigation Association in Taiwan.

3.4. Discussion

Using field experiments conducted at the HsuehChia Experimental Station from 1993 to 2001, the reference crop evapotranspiration was calculated via the FAO 56 Penman–Monteith equation for the most important irrigation region in Taiwan. Crop coefficients for corn, sorghum and soybean were estimated under subtropical climatic conditions using lysimeter crop ET data. According to the results in this work, the estimated values of crop coefficients differed considerably from those suggested by FAO for the crops considered here. For corn, marked differences occurred between the estimated K_c values and the average K_c value proposed by the FAO during the third and fourth stages for sorghum and all stages for soybean. The above differences are attributed mainly to specific cultivators, local climatic changes, and seasonal differences in crop growth patterns. Such differences clearly reflect the difficulty not only in extrapolating crop coefficients to other environments, but also in applying crop coefficients to individual years with variable crop development patterns.

Lysimeters are unavailable in many countries located in subtropical zones for estimating actual crop ET. The crop coefficients models developed herein can facilitate the rapid estimation of crop coefficients under subtropical climatic conditions. Since the values proposed by FAO-24 are designed for application to any climatic conditions, these values may not be directly applied to subtropical zones with extremely arid and strictly rained conditions. Thus, the local calibration of crop coefficients would be necessary before adopting them for estimating crop requirements and supplementary irrigation scheduling.

Based on the application of the CROPWAT model, the irrigation water requirements for spring and autumn corn are 69.5 and 203.6 mm, respectively, compared to 68.4 and 198.2 mm for soybean. The significant difference in irrigation requirements between the spring and autumn crops can be explained by the different amounts of effective rainfall. For example, the autumn corn could utilize just 74 mm of effective rainfall, compared to 328 mm for the spring corn.

The CROPWAT model simulated results demonstrate that for the single rice cropping pattern area, the annual agricultural water demand totalled 537 mm, with the peak monthly water requirement of 126 mm occurring in October; meanwhile, for the double rice cropping pattern area, annual demand was 1019 mm, with the peak monthly water requirement of 192 mm happening in January. This work thus demonstrates important evidence that the CROPWAT irrigation management model could be used to estimate effectively and efficiently the agricultural water requirements for different cropping patterns. This will facilitate IAs in Taiwan in meeting possible changes in irrigation management following WTO entry.

The percentage of percolation in the single rice fields reached around 30.7% of crop water requirements, compared to 26% in the double rice area, which yielded a deep percolation of 28.4% of the total irrigation water requirements. Consequently, the paddy fields can recharge groundwater, and thus have remarkable ecological environment functions.

4. Conclusions

The study used the field experimental data at the HsuehChia Experimental Station from 1993 to 2001 to calculate the reference crop evapotranspiration via the Penman–Monteith equation for the most important irrigation region serviced by the ChiaNa IA in Taiwan.

For corn, the estimated crop coefficients were 0.40, 0.78, 0.89 and 0.71 in the initial, crop development, mid-season and late-season stages, respectively, with the peak crop coefficient value occurring at 77–78 days after planting. Meanwhile, the estimated crop coefficients for sorghum were 0.44, 0.71, 0.87 and 0.62 in the four stages, respectively, with the peak crop coefficient value appearing at 63–64 days after planting. Finally, for soybean, the estimated crop coefficients were 0.45, 0.89, 0.92 and 0.58 in the four stages, respectively, with the peak crop coefficient value appearing at 57–58 days after planting. Based on final report from HsuehChia Experimental Station, the crop coefficient for first paddy, with different stages of transplant, tiller, flower and mature, are 0.6, 1.0–1.3, 1.5 and 0.8–1.4, respectively. Regarding the second paddy, the crop coefficient for first paddy, with different stages of transplant, tiller, flower and mature, are 1.0, 1.3–1.6, 1.6–1.7 and 0.5–1.4, respectively.

With implementation of REF-ET model for four empirical equations, FAO 56 Penman–Monteith, 1948 Penman, Blandy–Criddle, and 1985 Hargreaves, to calculate the annual reference evapotranspiration for ChiaNan Irrigation Association are 1268, 1355.5, 1301.7 and 1318 mm, respectively. The results from FAO 56 Penman–Monteith was used in this investigation for further application in the CROPWAT model to calculate the upland and paddy crops water requirements in ChiaNan Irrigation Association.

The irrigation water management model of CROPWAT was also used in the study to assess the crop water requirements in the ChiaNan IA. The CROPWAT model simulated results of the annual potential evapotranspiration and effective rainfall in ChiaNan irrigation area are 144 and 897 mm, respectively. The irrigation water requirement for the upland crops of corn in spring and autumn are 358 and 273 mm, compared to 332 and 366 mm for sorghum, and 350 and 269 mm for soybean.

The irrigation water requirement and deep percolation of the first and second rice crop range from 962 to 1140 and 295 to 296 mm suggesting a considerable amount (30.7–28.4% of the total irrigation water requirement) recharges to ground water and exhibits an important function to water resource conservation.

Acknowledgement

The authors would like to thank the Council of Agriculture of the Republic of China, Taiwan for financially supporting this research under Contract no. COA 93-8.2-Forest-01.

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