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CONTENTS

Research Papers

- 79 **Morphological Structure and Genetic Mapping of New Leaf-Color Mutant Gene in Rice (*Oryza sativa*)** LI Yu-hong, WANG Bao-he, DAI Zheng-yuan, LI Ai-hong, LIU Guang-qing, ZUO Shi-min, ZHANG Hong-xi, PAN Xue-biao
- 86 **Active Methyl Cycle and Transfer Related Gene Expression in Response to Drought Stress in Rice Leaves** ZHANG Xiao-li, ZHOU Jian, HAN Zhuo, SHANG Qi, WANG Ze-gang, GU Xiao-hui, GE Cai-lin
- 94 **Special DNA Methylated Sites Between Haploid of Twin-Seedling and Its Hybrids in Rice (*Oryza sativa*)** WU Shao-hua, XUE Jing-jing, ZHANG Hong-yu, XU Pei-zhou, WU Xian-jun
- 100 **Altered Expression of Transcription Factor Genes in Rice Flag Leaf under Low Nitrogen Stress** ZHAO Ming-hui, ZHANG Wen-zhong, MA Dian-rong, XU Zheng-jin, WANG Jia-yu, ZHANG Li, CHEN Wen-fu
- 108 **Leaf Photosynthetic Activity and Antioxidant Defense Associated with *Sub1* QTL in Rice Subjected to Submergence and Subsequent Re-aeration** Debabrata PANDA, Ramani Kumar SARKAR
- 117 **Evaluation of Agronomic Traits in Chromosome Segment Substitution Lines of KDML105 Containing Drought Tolerance QTL under Drought Stress** Vaiphot KANJOO, Kanchana PUNYAWAEW, Jonaliza L. SIANGLIW, Suwat JEERAKONGMAN, Apichart VANAVICHIT, Theerayut TOOJINDA
- 125 **Effects of Nitrogen Application Levels on Ammonia Volatilization and Nitrogen Utilization during Rice Growing Season** LIN Zhong-cheng, DAI Qi-gen, YE Shi-chao, WU Fu-guan, JIA Yu-shu, CHEN Jing-dou, XU Lu-sheng, ZHANG Hong-cheng, HUO Zhong-yang, XU Ke, WEI Hai-yan
- 135 **Effects of Phosphorus on Grain Quality of Upland and Paddy Rice under Different Cultivation** ZHANG Ya-jie, HUA Jing-jing, LI Ya-chao, CHEN Ying-ying, YANG Jian-chang
- 143 **Estimating Crop Coefficient in Intermittent Irrigation Paddy Fields Using Excel Solver** Chusnul ARIF, Budi Indra SETIAWAN, Hanhan Ahmad SOFIYUDDIN, Lolly Martina MARTIEF, Masaru MIZOGUCHI, Ryoichi DOI
- 153 **Logistic Regression Analysis on Factors Affecting Adoption of Rice-Fish Farming in North Iran** Seyyed Ali NOORHOSSEINI-NIYAKI, Mohammad Sadegh ALLAHYARI

Mini-Review

- 161 **Involvement of Plasma Membrane $\text{Ca}^{2+}/\text{H}^{+}$ Antiporter in Cd^{2+} Tolerance** SHEN Guo-ming, DU Qi-zhen, WANG Jiang-xin

Short Communication

- 166 **Estimating Out-Crossing Rate of Bg 379-2 Using Morphological Markers and Confirmation by Molecular Markers** L. H. M. Y. K. SOMARATNE, A. S. M. T. ABAYAWICKRAMA, I. P. WICKRAMASINGHE, W. L. G. SAMARASINGHE

Estimating Crop Coefficient in Intermittent Irrigation Paddy Fields Using Excel Solver

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Abstract: The current study proposes a novel method using Excel Solver to estimate, from limited data, crop coefficient (K_c) in paddy fields under intermittent irrigation (II). The proposed method was examined in a field experiment conducted at Karang Sari Village, Bekasi, West Java, Indonesia during the first rice season of 2007/2008 (December 2007 to April 2008) in the rainy season. As the control, continuous flooding irrigation (CF) was applied to the conventional rice cultivation fields. Based on the observed water storage, Excel Solver was used to estimate crop evapotranspiration. Estimated crop evapotranspiration was used to compute K_c value, then the average K_c values at each growth stage were compared with that for the CF treatment. The estimation method was evaluated by comparing estimated crop evapotranspiration and the crop evapotranspiration derived by the well established FAO procedure. Excel Solver estimated crop evapotranspiration accurately with R^2 values higher than 0.81. Accordingly, more than 81% of the FAO crop evapotranspiration was described by the proposed method. Thus, K_c value could be well determined from those estimated crop evapotranspiration. Under the II treatment, the average K_c values were 0.70, 1.06, 1.24 and 1.22 for the initial, crop development, reproductive and late stages, respectively. These values were lower than those under the CF treatment for initial and crop development stages because of a minimal soil evaporation and intense dryness during these stages. However, average K_c values under the II treatment were higher than those under the CF treatment at the reproductive and late stages, indicating that the II treatment promoted more plant activity particularly for dry biomass production as indicated by a greater number of tillers per hill.

Key words: crop coefficient; evapotranspiration; intermittent irrigation; Excel Solver; water balance

Commonly, in Indonesia rice is cultivated under continuous flooding irrigation by maintaining the depth of water between 2 and 5 cm to control weeds, reduce the frequency of irrigation and secure against possible future shortage of water due to the unreliable water delivery system. Therefore, the quantity of irrigation water is usually greater than the actual water requirement. This weakens water saving effects, causing large amounts of surface runoff, seepage and percolation (Bouman, 2001). One strategy to promote water saving without significant yield losses is to adopt intermittent irrigation (Won et al, 2005), in which the field is kept saturated or under shallow standing water, and then the soil is kept dry for particular periods instead of continuously flooded. This was verified to save up to 28% water in Japan (Chapagain and Yamaji, 2010), 40% in Eastern Indonesia (Sato et al, 2011), 38.5% in Iraq (Hameed et al, 2011) and increased water use efficiency up to 43.9% in China (Lin et al, 2011).

Crop coefficient is important for studying plant

responses to available water particularly under non-standard irrigation practices such as intermittent irrigation. Moreover, it is needed for estimating crop evapotranspiration, which represents the main route of water loss from both plant and soil surfaces and is a main component of water consumption in paddy fields. Both crop coefficient and crop evapotranspiration data are vital for irrigation scheduling and water resource allocation, management and planning (Jensen et al, 1990). Commonly, crop coefficient is derived empirically by using a lysimeter and is computed as the ratio of crop evapotranspiration to reference evapotranspiration based on weather data. This method has been developed in Japan (Vu et al, 2005) and India (Mohan and Arumugam, 1994; Tyagi et al, 2000) under Food and Agriculture Organization (FAO) standard conditions with continuous flooding irrigation. However, this method is time consuming and expensive, especially for equipment preparation. In addition, no research has yet reported values of crop coefficient for paddy with intermittent irrigation.

The current study proposes a novel method for estimating crop coefficients in paddy fields with

intermittent irrigation by using Excel Solver. Excel Solver, which is incorporated into Microsoft Excel, is a software tool that helps users find the best way to allocate scarce resources (<http://www.solver.com/tutorial.htm>). Excel Solver works by using search algorithms. It has sufficient power to find the coefficients to fit the data in non-linear equations (Walsh and Diamond, 1995) such as chromatographic peak resolution (Dasgupta, 2008), enzyme activity values (Abdel-Fattah et al, 2009) and molar absorptivities of metal complexes and protonation constants of acids (Maleki et al, 1999). Excel Solver can solve the problem by minimizing or maximizing an objective function to find optimal decision variables up to 200 variables within one process. Accordingly, Excel Solver has the ability to estimate non-measurable variables by up to 200 data. However, Excel Solver has not yet been used in estimation of non-measurable variables.

Therefore, the aim of the current study is to examine Excel Solver in estimation of non-measurable water balance variables, including crop evapotranspiration. Then, incorporating the estimated values of the non-measurable variables, daily crop coefficient of a paddy under intermittent irrigation was computed as a ratio of estimated crop evapotranspiration to reference evapotranspiration, and their results were compared with those of the continuous flooding irrigation as the control.

MATERIALS AND METHODS

Experimental site and field water management

The field experiment was conducted at the village of Karang Sari, district of Cikarang Timur, Bekasi, West Java, Indonesia during the first rice season of 2007/2008 (December 2007 to April 2008, wet season). The field is located at $6^{\circ}14'16''$ S and $107^{\circ}12'30''$ E. Here, rice is cultivated in almost all seasons (wet-dry seasons). A rice crop had been cultivated in the season immediately

before the experiment. The soil was alluvial and had a heavy clay texture with a soil pH value of 5.8 and low organic matter content (1.7%).

The fields were watered according to intermittent irrigation (II) and continuous flooding irrigation (CF), respectively (Table 1). Each treatment had three replication plots within a $9.6\text{ m} \times 18.0\text{ m}$ rectangular shaped field. All plots were planted with a local rice variety (*Oryza sativa* L.), Sintanur, a current rice variety suitable for cultivation in Indonesia. Each plot was divided into five parts and a single hill in each part was selected to analyze plant growth performance i.e., plant height and number of tillers per hill, every 10 days starting from 15 days after transplanting (DAT).

Model development

Hydrologic characteristics of the paddy field can be explained as shown in Fig. 1. The inflow to the field

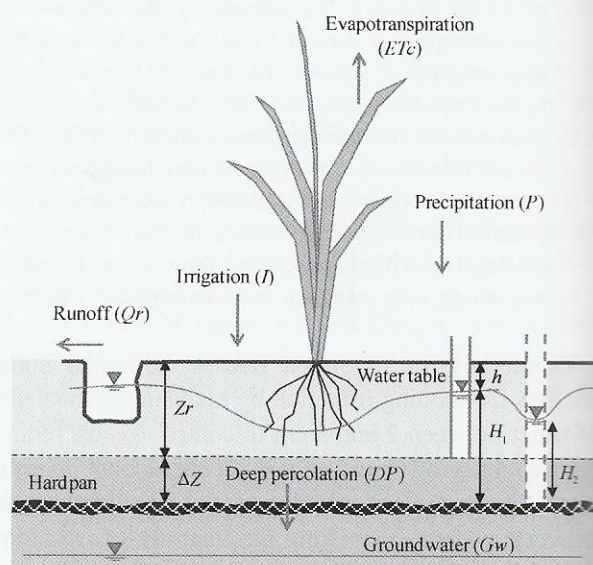


Fig. 1. Schematic diagram of paddy water and soil variables considered in this study.

Z_r , Effective soil depth layer; ΔZ , Secondary soil depth layer; H_1 , Water table at the first point; H_2 , Water table at the second point.

Table 1. Current field water management and rice cultivation.

Treatment	Water management	Rice cultivation
Intermittent Irrigation (II)	The soil was kept moist but with no standing water during the vegetative stage (initial and crop development stages), then shallow standing water with depth ranging from -5 to 2 cm was applied during the reproductive stage, and finally water was drained to maintain saturated soil until harvesting day.	Seedling: young seedlings (10 d after sowing) Transplanting: single transplanting (one seedling per hill) spaced at $30\text{ cm} \times 30\text{ cm}$ Weeding: four times with an interval of 10 d and starting from 10 d after transplanting (DAT) Fertilizer: an organic fertilizer applied at 7 t/hm^2
Continuous flooding (CF)	The field was maintained by ponding water with the interval of $2\text{--}5$ cm water depth during planting period, then at the late stage, water was drained to maintain saturated soil until harvesting day.	Seedling: old seedlings (30 d after sowing) Transplanting: $5\text{--}10$ seedlings per hill spaced at $20\text{ cm} \times 20\text{ cm}$ Weeding: every two times during early vegetative stage Fertilizer: chemical fertilizers based on the guideline of agricultural officer

consists of precipitation, irrigation water and ground-water, while the water leaves the field through runoff, deep percolation and crop evapotranspiration. Accordingly, the water balance model can be derived as the following equation:

$$S_m(t) = S_m(t-1) + \Delta S(t) \tag{1}$$
$$\Delta S(t) = P(t) + I(t) + Gw(t) - Qr(t) - DP(t) - ETc(t) \tag{2}$$

where S_m is calculated as water storage (mm), ΔS is the change of water storage (mm), P is precipitation (mm), I is irrigation water (mm), Gw is groundwater (mm), Qr is runoff water (mm), DP is deep percolation (mm), ETc is crop evapotranspiration (mm) and t is the time (day). We assumed that the soil consisted of two layers, i.e., effective soil depth layer (Zr) and secondary soil depth layer (ΔZ) as shown in Fig. 1. Then, the equations (1) and (2) were used to determine calculated water level.

Certain water balance variables such as irrigation water, crop evapotranspiration and deep percolation can not be easily measured. The typical measurement methods are often costly for specific instruments, complicated and time consuming and can be fully exploited only by well-trained research personnel. Therefore, those water balance variables were estimated by using Excel Solver. Meanwhile, other water balance variables such as observed water storage, precipitation and runoff were obtained from the field measurements except groundwater which was assumed to be zero because its rate was negligible. The observed water storage was determined based on soil moisture and observed water level, while runoff water was defined as excess water from precipitation that was removed from the field artificially to maintain desired water levels, and it was obtained by the difference between water levels before and after draining water. Table 2 summarizes both measured and non-measurable water balance variables.

Excel Solver estimation

Excel Solver works by searching algorithms in a spreadsheet environment, in which the users can follow the procedures based on its guidelines (Morrison, 2005). The maximum number of decision variables that can be estimated by Excel Solver was limited up to 200 data.

Therefore, we performed a two-step estimation process which consisted of crop evapotranspiration estimation in the first step, then estimation of deep percolation and irrigation water in the second step.

Estimation I: estimation of crop evapotranspiration

Crop evapotranspiration is mainly affected by the change of water storage (Allen et al, 1998). Therefore, we simplified equation (2) considering only the changes in water storage and crop evapotranspiration to estimate crop evapotranspiration. Thus, by introducing the dummy variables, $NetA$, we got a modified equation, as follows:

$$\Delta S = NetA(t) - ETc(t) \tag{3}$$

where:

$$NetA(t) = P(t) + I(t) - Qr(t) - DP(t) \tag{4}$$

$NetA$ and ETc , decision variables for Excel Solver in the first estimation, were estimated by minimizing the following objective function:

$$Error\ 1 = \sum_{t=7}^n |S_o(t) - S_m(t)| \tag{5}$$

subject to the constraint

$$ETc_{min} \leq ETc \leq ETc_{max} \tag{6}$$

where S_o is observed water storage (mm), S_m is calculated water storage (mm), t is time (d, starting from 7 to 86 DAT), and n is total days ($n = 79$). We determined ETc_{min} by multiplying reference evapotranspiration (ET_0) by minimum crop coefficient and ETc_{max} by multiplying ET_0 by maximum crop coefficient.

Estimation II: estimation of deep percolation and irrigation water

Deep percolation (DP) was calculated according to Darcy’s law for vertical flow (Jury and Horton, 2004). Hence, we calculated this variable based on the different water tables with different hydraulic head as the schema in Fig. 1 by following equation:

$$DP(t) = Ks \frac{H_1(t) - H_2(t)}{\Delta Z} \tag{7}$$

where Ks is saturated hydraulic conductivity (mm/d) with a constant value, H_1 is water table at the first point (mm) and H_2 is water table at the second point (mm).

Table 2. Measured, calculated and estimated water balance variables.

Variable	Measured	Calculated	Estimated	Method
Change of water storage (ΔS)		√		Based on the change of soil moisture and observed water level
Precipitation (P)	√			Rain gauge
Crop evapotranspiration (ETc)			√	Excel Solver
Irrigation water (I)			√	Excel Solver
Deep percolation (DP) ^a	√	√	√	Based on Darcy’s law
Runoff/drainage (Qr)	√			The difference between water level before and after draining water

^aFor deep percolation, water table in the first point (H_1) and saturated hydraulic conductivity (Ks) were measured; water table in the second point (H_2) and secondary soil layer (ΔZ) were estimated by Excel Solver. All of those parameters were used to calculate deep percolation with Equation (7).

However, we did not measure H_2 and it was estimated by Excel Solver as well as ΔZ .

Therefore, by combining the equations (4) and (7), a new equation was founded as follows:

$$NetA(t) = P(t) + I(t) - Qr(t) - K_s \frac{H_1(t) - H_2(t)}{\Delta Z} \quad (8)$$

I , H_2 and ΔZ , decision variables for Excel Solver in the second estimation, were estimated by minimizing the following objective function:

$$Error\ 2 = \sum_{t=7}^n |NetA_1(t) - NetA_2(t)| \quad (9)$$

subject to the constraint

$$H_2(t) \leq H_1(t) \quad (10)$$

Where $NetA_1$ and $NetA_2$ are equal to $NetA$ data from the first and second estimations, respectively. Total data for the estimated variables are shown in Table 3.

Crop coefficient

Based on the FAO recommendation (Allen et al, 1998), crop coefficient can be determined as a single crop coefficient or a dual crop coefficient. A dual crop coefficient consists of the soil evaporation coefficient and the basal crop coefficient to show the effects of soil evaporation and crop transpiration separately. Here, we used a single crop coefficient (K_c) to examine the effect of crop transpiration and soil evaporation simultaneously. K_c value was computed from the following equation:

$$K_c = \frac{ET_c}{ET_0} \quad (11)$$

where ET_0 is reference evapotranspiration which was calculated based on Penman-Monteith model (Allen et al, 1998). Here, K_c value was calculated on the daily basis and each value was filtered by using the Kalman filter equation (Kalman, 1960; Welch and Bishop, 2006) to show the trend. Average K_c value was then calculated based on each growth stage, namely, initial, crop development, reproductive and late stages (Mohan and Arumugam, 1994; Allen et al, 1998; Tyagi et al, 2000; Vu et al, 2005).

Model evaluation

The proposed method was evaluated by comparing

Table 3. Total data for the estimated variables by Excel Solver.

Estimation process	Variable	Total data
First estimation	Crop evapotranspiration (ET_c)	79
	Dummy ($NetA$)	79
	Lower water table (H_2) ^a	79
Second estimation	Secondary soil layer (ΔZ) ^a	1
	Irrigation water (I)	79

^aParameters used to calculate deep percolation with Equation (7).

observed and calculated values of water storage given by the model [equations (1) and (2)] using three statistical indicators, i.e., coefficient of determination (R^2), root mean square error ($RMSE$) and average percentage deviation (APD). The values of R^2 ranged from 0.0 to 1.0 with higher values indicating better agreement. $RMSE$ is an absolute error measure quantifying the error in terms of the unit of the variables, while APD is a fraction of deviation between the original data and the model (Stoecker, 1989). The smaller the value (close to zero) of those errors, the better the model's performance.

Then, as another supporting evidence of the estimation performance, estimated crop evapotranspiration was compared to crop evapotranspiration derived by the FAO procedure as a well established method by considering observed water storage in the field (Allen et al, 1998).

RESULTS

Plant growth under different water managements

Changes in plant height and tiller number per hill for the treatments are shown in Fig. 2. In the II treatment, with the same physiological age, the plant height was higher than that in the CF treatment. This

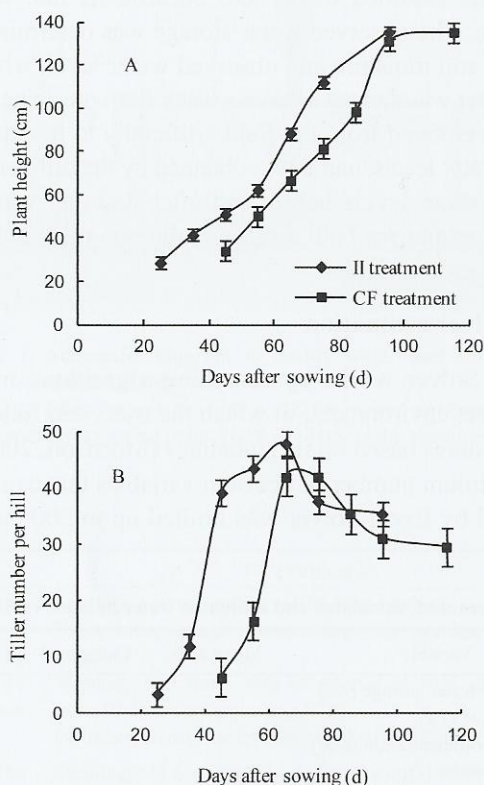


Fig. 2. Effects of water management on plant height (A) and tiller number per hill (B).

II, Intermittent irrigation; CF, Continuous flooding.

is probably due to the plant had greater growth potential of root and shoot by the application of young seedling and wider spacing (Uphoff et al, 2011). Moreover, the II treatment promoted increased plant activity in roots and shoots due to optimal water and oxygen availability under mostly aerobic soil conditions (Yang et al, 2009; Yang and Zhang, 2010). However, at the late growth stage, both the plant heights were comparable with the maximum plant height of 136 cm for both treatments.

The same trend was seen for the tiller number per hill. The tiller number in the II treatment was higher than that in the CF treatment particularly at the initial, crop development and late stages. It showed that under the II treatment with wider spacing, the ability of rice tillering could be enhanced to some extent when the plant had a wider space to grow. Rice tillering could also be enhanced by application of straw mulching under non-flooded irrigation as reported by the previous study (Wang et al, 2010). Overall, in both treatments, rice tiller number per hill gradually increased and peaked at about 65 d after sowing (Fig. 2-B). The maximum tiller number per hill was 48 and 42 for the II and CF treatments, respectively.

Model evaluation of estimation processes

Table 4 presents the model’s performance revealed by the comparison between the observed and calculated values of water storage. Excel Solver estimated non-measurable water balance variables, and resulting R^2 values of greater than 0.75, which indicated the model’s performance. Tight linear correlations between the observed water storage and those values predicted by the model described in equations (1) and (2) were observed. Thus, more than 75% of the changes in observed water level were well described by the model. The R^2 values also demonstrate how well the current method functions, given the availability of a minimum set of observed variables. In addition, $RMSE$ and APD values were low and close to zero, indicating that the model was satisfactory.

Estimated crop evapotranspiration had high degrees of correlation to crop evapotranspiration derived by the FAO procedure for both treatments (Fig. 3). R^2 values were greater than 0.81 for both treatments, indicating that the proposed method can be reliably applied for estimation of crop evapotranspiration under different water management regimes as supported by the well established FAO method.

The total water balance variables for both treatments could be referred to Fig. 4. Excel Solver has estimated reliable non-measurable deep percolation and irrigation

Table 4. Statistical indicators of the model’s performance provided by the comparison between observed and calculated values of water storage.

Water management	Statistical analysis		
	R^2	$RMSE$ (mm)	APD (%)
II treatment			
Plot 1	0.814	0.59	0.04
Plot 2	0.760	0.50	0.04
Plot 3	0.780	0.56	0.05
CF treatment			
Plot 1	0.855	0.44	0.03
Plot 2	0.858	0.73	0.05
Plot 3	0.839	0.52	0.04

$RMSE$, Root mean square error; APD , Average percentage deviation.

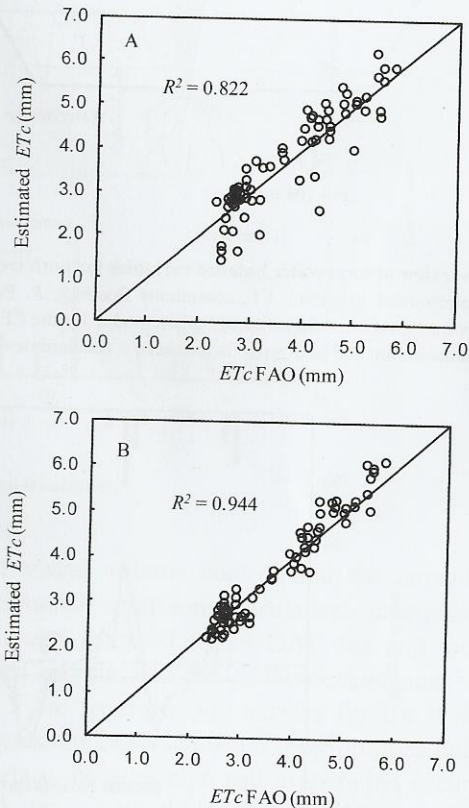


Fig. 3. Correlation between estimated and the FAO crop evapotranspiration (ET_c). A, II treatment and FAO values; B, CF treatment and FAO values.

water in addition to crop evapotranspiration during the cultivation period indicated by low differences (1 mm) between total inflow (precipitation and irrigation water) and outflow (runoff, deep percolation and crop evapotranspiration) for both treatments (Fig. 4).

Total crop evapotranspiration was comparable between the treatments, 292 and 290 mm for the II and CF treatments, respectively. In the CF treatment, crop evapotranspiration was higher than that in the II treatment during the initial and crop development stages when standing water was applied in the fields.

On the other hand, their values were lower at the reproductive and late stages when the water levels in the fields were almost the same (Figs. 5 and 6). Under

the II treatment, higher crop evapotranspiration at these stages was probably due to the enhancement of plant activities particularly transpiration process, thus the II

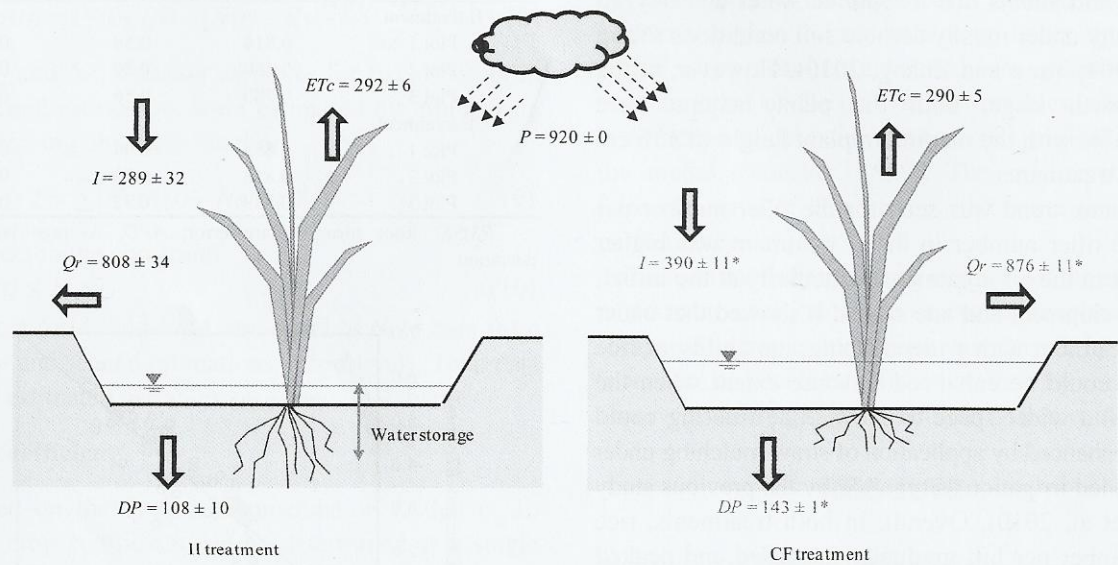


Fig. 4. Overview of total water balance variables for both treatments. II, intermittent irrigation; CF, continuous flooding; *P*, Precipitation, *I*, Irrigation water, *Qr*, Runoff water, *DP*, Deep percolation, *Etc*, Crop evapotranspiration. * Significantly greater value for the CF treatment according to the ANOVA test ($P = 0.05$). All units in mm and each value is the mean \pm standard deviation.

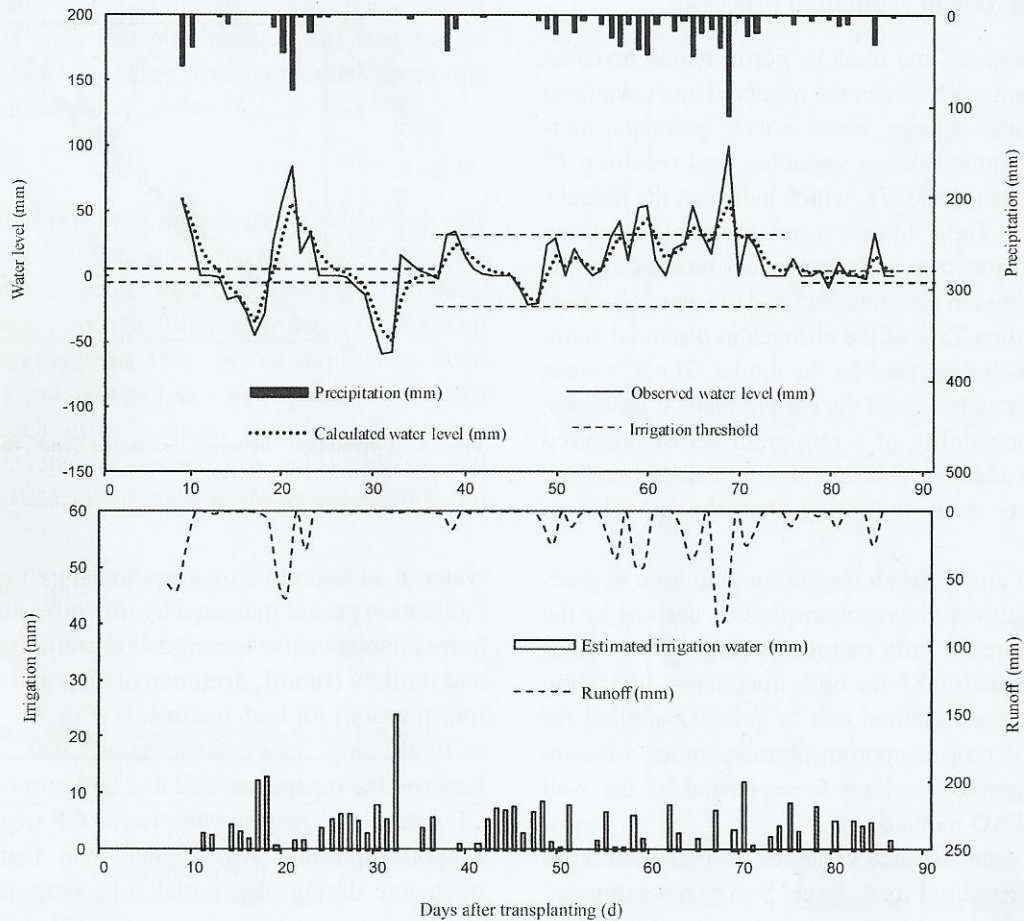


Fig. 5. Observed and estimated water balance variables for the intermittent irrigation treatment.

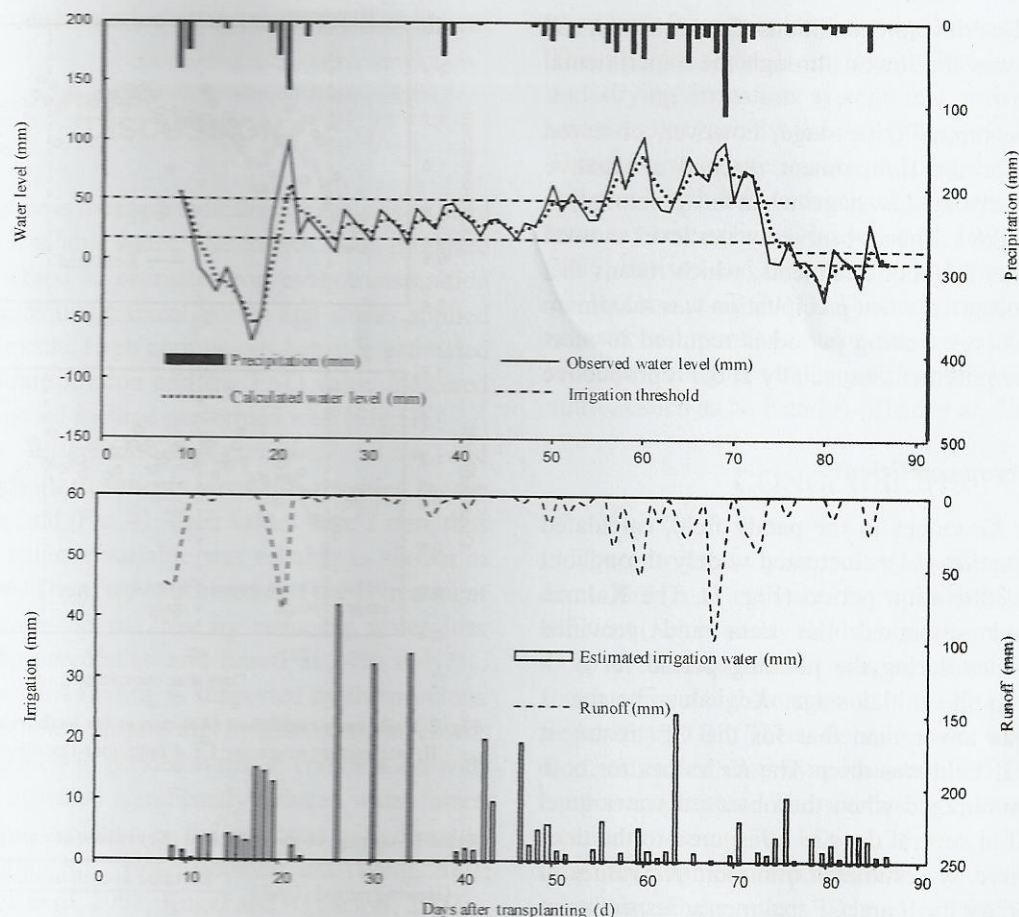


Fig. 6. Observed and estimated water balance variables for the continuous flooding treatment.

treatment would produce higher dry biomass represented by higher tiller numbers (Fig. 2-B). This assumption was supported by the previous finding which showed higher crop evapotranspiration correlated to higher dry biomass production (Shih, 1987).

The CF treatment needs more water supplied in the fields. We estimated that the total irrigation water for this treatment was 390 mm or approximately 26% greater than that for the II treatment. Consequently, in the CF treatment, the water loss increased significantly through deep percolation and runoff up to 24% and 7%, respectively (Fig. 4).

Observed water level in field

K_c value is directly affected by the change of water storage in the fields dominated by the local climate. Thus, it is important to present the observed water level contributing to daily K_c interval as well as calculated values. Although for both treatments, the water levels were planned to be between irrigation thresholds (Figs. 5 and 6), the observed water levels were little bit different. This was due to the irrigation water supplied

by the visual volume control and the unpredictable environmental conditions, particularly precipitation.

Although from 10 to 20 DAT, the soil was kept saturated and the water levels were maintained between 2 and 5 cm from the soil surface for the II and CF treatments, the observed water level dropped below the soil surface, because high soil evaporation occurred on several days particularly between 12 and 17 DAT. Commonly, soil evaporation is the dominant process at the initial stage since the plants only covered approximately 10% of the ground surface (Allen et al, 1998), therefore we were sure that the observed water level was dropped by water loss through soil evaporation.

At the first crop development stage, observed water level increased rapidly, particularly on 20 DAT, and reached approximately 10 cm above the soil surface when precipitation was high (136 mm) over 3 d. Then, the water was drained down to the irrigation thresholds. In the II treatment, water stress probably occurred during the middle and late crop development stage (20–40 DAT) as illustrated by the lowest water level in Fig. 5. At this time, water level reached its lowest level between 5 and 10 cm below the soil surface, thus

resulting in the driest soil conditions. Consequently, soil evaporation was the lowest through the experimental period.

During the reproductive stage, however, observed water level for the II treatment reached a negative value only early at this stage when no precipitation fell for some days. Then, observed water level showed positive values for both treatments, which means that soil wetting occurred when precipitation was maximum (Figs. 5 and 6). A wetting period is required to meet plant water requirement, especially at the reproductive stage.

Estimating crop coefficient

The daily K_c values in the paddy field, calculated using the equation (11), fluctuated widely throughout most of the cultivation period (Fig. 7). The Kalman filter method smoothed the data and provided continuous lines during the planting period for both treatments. At the initial stage, K_c value for the II treatment was lower than that for the CF treatment because the II field was drier. The K_c values for both treatments minimized when the observed water level was dropped in several days as a response to the drier condition. Here, we estimated minimum K_c values of 0.64 and 0.86 for the II and CF treatments, respectively.

During the crop development stage, K_c value gradually increased, and then declined rapidly. The decrease of K_c value occurred when the water level reached the minimum irrigation threshold for both treatments. At this stage, the minimum K_c values were 0.90 and 1.02 for the II and CF treatments, respectively. However, when the water level increased again to each maximum irrigation threshold, K_c values also increased gradually until the end of this stage.

The K_c value remained at high level during the reproductive stage when water level reached the maximum level after frequent precipitation over several days. At the late stage, however, when precipitation was infrequent, water was drained and the plants exhibited full senescence, K_c value declined for both treatments. This phenomenon showed how the plants response to water availability.

Table 5 records the average K_c values for both treatments compared to the typical ranges reported by the FAO for rice cultivation under the standard conditions (Doorenbos and Kassam, 1979). At the initial stage, both average K_c values for the II and CF treatments were lower than the FAO value since the actual field conditions were drier than the FAO standard conditions. In addition, the II treatment, with single planting and younger seedlings under drier soil conditions, had lower

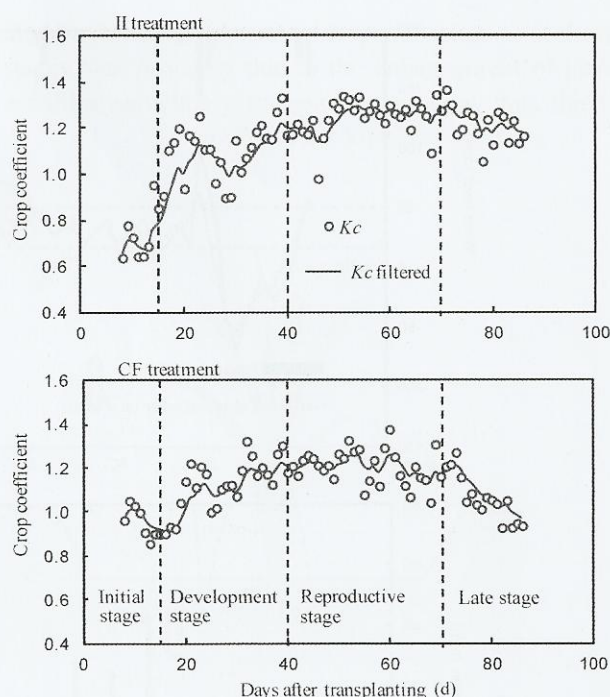


Fig. 7. Daily crop coefficient (K_c) curves for both treatments. II, Intermittent irrigation; CF, Continuous flooding.

Table 5. Average crop coefficient (K_c) values at each growth stage.

Growing period (DAT)	K_c value in each treatment		FAO K_c range
	II	CF	
Initial stage (1–15)	0.70	0.97	1.10–1.15
Development stage (16–40)	1.06	1.10	1.10–1.15
Reproductive stage (41–70)	1.24	1.21	1.10–1.30
Late stage (71–90)	1.22	1.10	0.95–1.05

II, intermittent irrigation; CF, continuous flooding.

K_c value than the CF treatment. This was likely to show the minimum levels of both evaporation and transpiration rate. The same could occur at the crop development stage when the average K_c value for the II treatment was also lower than for the CF treatment. Water stress (drying period) had affected on lower K_c value over several days (Fig. 5). During this stage, K_c value varies depending on crop type and frequency of soil wetting (Allen et al, 1998). Thus, the dry conditions during this stage also should have corresponded to the decreased K_c value.

The average K_c values during the reproductive stage for both treatments were within the FAO range due to the wet conditions in the fields as a result of the maximum water level in the field and frequent precipitation (Figs. 5 and 6). Additionally, the average K_c value for the II treatment was slightly higher than that for the CF treatment at this stage. Interestingly, during the late stage, the average K_c value for the II treatment was higher than those for the CF treatment and the FAO value. This is probably related to plant

activities producing more tillers under the II treatment (Fig. 2-B).

DISCUSSION

The K_c value is the main indicator for analysis of plant response to available water. The current study proposed a simple method to estimate crop evapotranspiration in paddy fields using Excel Solver and it was applied to two treatments. High correlations between estimated crop evapotranspiration and the FAO value indicated that the proposed method performed well (Fig. 3).

The low differences between total inflow and outflow for both treatments were also revealed by the proposed method (Fig. 4). Their values were 1 mm, thus each water balance variable was reliable as shown in Figs. 5 and 6. Then, we confirmed that the II treatment can save water up to 26% by reducing water loss through deep percolation and runoff at 24% and 7%, respectively. This finding is supported by the previous studies that noted improving irrigation management through reduction in ponded water in combination with intermittent irrigation significantly reduced water losses through deep percolation by the reduction of hydrostatic pressure (Kalita et al, 1992; Bouman and Tuong, 2001; van der Hoek et al, 2001; Kukal and Aggarwal, 2002).

We found, by this model, that the II treatment gave different effects on K_c value at each growth stage. At the initial and crop development stages, the K_c values were lower than those in the CF treatment. The lower K_c value at the initial stage was caused by the drier field condition; therefore, soil evaporation was also at its minimum level. Moreover, single transplanting with younger seedlings at the drier field condition commonly reduced crop transpiration as response of the plants. At the initial and crop development stages, water used is directly proportional to transpiration, so when the field became drier, the most effective response of the plant is to reduce the transpiration (Heinemann et al, 2011). Meanwhile, the lower K_c value at the crop development stage was probably caused by water stress suggested by the lowest water level (drying period) during several days (Fig. 5). The water stress conditions might have been critical, because the extreme dryness (soil water potential at 10–20 cm depth) is likely to have decreased yield by up to 40% (Bouman and Tuong, 2001). Consequently, soil moisture monitoring will be helpful in the II treatment when minimum water is applied during the crop development stage.

The II treatment resulted in higher K_c values at the reproductive and late stages than in the CF treatment (Fig. 7). It was likely that the II treatment promoted more

plant activity particularly for dry biomass production. This was due to the II treatment with alternate wetting and drying irrigation system that provided optimal water and oxygen availability (Yang and Zhang, 2010). Therefore, water stress accelerated higher root elongation and root length than under flooding irrigation as reported by many researchers (Nguyen et al, 1997; Zheng et al, 2006; Barison and Uphoff, 2011; Mishra and Salokhe, 2011; Zhao et al, 2011). The root length is important in water and nutrition uptakes since a greater and longer root enables higher nutrient uptake especially for macro-nutrient such as N, P and K (Zhao et al, 2011).

CONCLUSIONS

The current study proposes a novel method using Excel Solver to estimate, from limited data, crop coefficient (K_c) in paddy fields with intermittent irrigation. Crop evapotranspiration was estimated accurately as indicated by a high correlation to the FAO value with R^2 higher than 0.81. Then, K_c value was well calculated from estimated crop evapotranspiration and reference evapotranspiration. The average K_c values under II treatment were 0.70, 1.06, 1.24 and 1.22 for initial, crop development, reproductive and late stages, respectively. These values were lower than those under continuous flooding treatment for initial and crop development stages, because of a minimum soil evaporation and intense dryness during these stages, respectively. Besides, the average K_c values were higher than those under the CF treatment at the reproductive and late stages, indicating that the II treatment promoted more plant activity particularly for dry biomass production as shown by a greater number of tillers per hill.

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