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Application of FAO-56 for evaluating evapotranspiration in simulation of pollutant runoff from paddy rice field in Japan

Son Hong Vu [a], Hirozumi Watanabe [a,*], Kazuhiro Takagi [b]

[a] *Tokyo University of Agriculture and Technology 3-5-8, Saiwaicho, Fuchu, Tokyo 183-8509, Japan*

[b] *National Institute of Agro-Environmental Science 3-1-1, Kannondai, Tsukuba, Ibaraki 305-8604, Japan*

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Abstract

Applicability of FAO-56 method in estimation of evapotranspiration for the simulation of pollutant runoff from rice paddy field in Japan was investigated. Crop evapotranspiration and crop coefficient recommended by FAO-56 method relative to those values obtained in the field monitoring for three Japanese rice varieties, namely, Nihonbare, Mangetsumochi and Koganemochi during first three growing stages were compared. Also, the pesticide fate model, PCPF-1, which incorporates the FAO-56 method was evaluated for the applicability of the FAO-56 method towards the accurate prediction of herbicide concentration in paddy water. The estimation of cumulative ET_c in paddy rice by FAO-56 method using the recommended K_c value resulted in estimation error of up to 17% from the observed values. The recommended values of $K_{c\text{-ini}}$ in FAO-56 method are appropriate if reliable atmospheric data are available. However, the $K_{c\text{-mid}}$ was found to be a sensitive parameter affecting ET_c estimation and the careful calibration according to the regional conditions and varieties seemed to be required for the accurate prediction. Considering the effect of random errors, FAO-56 method is more reliable when calculating cumulative ET_c longer than 7 days of period. Despite the relatively large error in cumulative ET_c resulted from the FAO-56 method with the recommended K_c value, the maximum error expected to have on the prediction of the herbicide concentration in paddy field is 5.6%, and that of

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* Corresponding author. Tel.: +81 42 367 5889; fax: +81 42 367 5889.
E-mail address: pochi@cc.tuat.ac.jp (H. Watanabe).

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herbicide runoff loss can be 3.2%. Therefore, it can be concluded that application of FAO-56 method with the recommended K_c value is acceptable in the simulation of pesticide fate and transport.

Keywords: Paddy rice; Evapotranspiration; Crop coefficient; Simulation model; Pollutant runoff

1. Introduction

Paddy rice is the major crop in Japan with 2.62 million ha corresponding to over 50% of total agricultural land (Sato, 2001). Since the paddy system is susceptible to surface water pollution by agro-chemicals, a number of studies of pollution runoff from rice paddy fields have been carried out to investigate the effects of paddy rice system on aquatic environment (Watanabe and Takagi, 2000a; Inao et al., 2001; Nakasone et al., 2000; Chung et al., 2003). In these studies, daily water balance in rice fields is a key factor for evaluating processes of pollutant fate and transport. Crop evapotranspiration, ET_c, is known as a main component of the water consumption in rice fields, therefore estimating accurate value of ET_c is important especially in studies of evaluating pollutant runoff from paddy fields that require a considerable accuracy. Since it is time consuming and expensive to obtain accurate measurements directly from field observations, ET_c is commonly estimated from weather data (Lage et al., 2003; Lecina et al., 2003; Shab and Edling, 2000; Tyagi et al., 2000).

So far, FAO Penman-Monteith method has been recognized as the sole standard method for the computation of reference crop evapotranspiration, ET_o, from meteorological data. The method was published in No. 56 of the FAO Irrigation and Drainage Series (Smith et al., 1991), so called FAO-56 method. The FAO-56 method refers to calculation of reference crop evapotranspiration, ET_o, by Penman-Monteith equation, which is affected by meteorological conditions, and crop coefficient, K_c, which is affected by physiological and structural factors of the crop. The FAO-56 method has been widely applied for estimation of evapotranspiration and for evaluation of crop coefficient for rice fields (Bethune et al., 2001; Lecina et al., 2003; Lage et al., 2003; Shab and Edling, 2000; Tyagi et al., 2000). Although crop coefficient values for a number of crops under different climatic condition have been suggested by the FAO-56, Allen et al. (1998) recommended that evaluation of crop coefficient values in local climatic condition by observed data using lysimeter is necessary.

In Japan, a number of studies on evapotranspiration in rice fields have been documented (Sakuratani and Horie, 1985; Adachi et al., 1995; Research group of evapotranspiration, 1967) and application of Penman equation to calculate potential evapotraspiration also has been studied (Muira and Okuno, 1993a,b; Adachi et al., 1995). However, the studies on ET_c for paddy rice field using FAO-56 method were limited. Furthermore, applicability and performance of FAO-56 method in simulation of pollutant runoff from paddy rice fields (Watanabe and Takagi, 2000a; Inao et al., 2001; Nakasone et al., 2000) need to be assessed for the models users. Therefore, objectives of this study are: (1) to compare the crop evapotranspiration and the crop coefficient obtained by FAO-56 method and lysimeter monitoring to evaluate the performance of the FAO-56 method for Japanese rice production with three varieties of Nihonbare, Mangetsumochi and Koganemochi and (2) to evaluate applicability of FAO-56 in a simulation model (PCPF-1) of pollutant runoff from paddy rice fields.

2. Materials and methods

2.1. The FAO-56 procedures for paddy rice field

The crop evapotranspiration under standard conditions, ET_c, refers to evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under given climatic conditions (Allen et al., 1998). The crop evapotranspiration is calculated by multiplying the reference crop evapotranspiration (ET_o) by a crop coefficient (K_c) as follows:

$$ET_c = K_c ET_o \tag{1}$$

where ET_c is the crop evapotranspiration (mm d^{-1}); K_c the crop coefficient; and ET_o the reference crop evapotranspiration (mm d^{-1}).

2.2. Reference crop evapotranspiration ET_o

The reference crop evapotranspiration, ET_o, was calculated according to the FAO Penman-Monteith equation. ET_o is the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 12 cm, a fixed canopy resistance of 70 sm^{-1} and an albedo of 0.23, closely resembling the ET from an extensive surface of green grass coverage that is in uniform height, actively growing, completely shading the ground and with adequate water supply (Allen et al., 1998). The FAO Penman-Monteith equation for calculating daily ET_o (mm day^{-1}) using daily average data is shown as following equation (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/T + 273)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{2}$$

where R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G the soil heat flux density (MJ m^{-2} day^{-1}); T the mean daily air temperature at 2 m height (°C); U_2 the wind speed at 2 m height (m s^{-1}); e_s the saturation vapor pressure (kPa); e_a the actual vapor pressure (kPa); $(e_s - e_a)$ the saturation vapor pressure deficit (kPa); Δ the slope of vapor pressure curve (kPa $°C^{-1}$); and γ the psychrometric constant (kPa $°C^{-1}$).

The FAO Penman-Monteith equation requires solar radiation, maximum, minimum and mean air temperatures, air humidity and wind speed data. Standardized equations for computing all parameters in Eq. (2) are given in Smith et al. (1991).

2.3. Crop coefficient

Since actual rice field production is generally well managed, K_c under standard conditions was considered. Factors determining the K_c for paddy rice consist of climate conditions and crop growth stages. As the crop develops, the ground coverage, crop height and leaf area changes. Due to differences in evapotranspiration during various growth stages, the K_c for a given crop varies over the growing period. The growing period can be divided into four distinct growing stages: initial, crop development, mid-season and late

Table 1
Length of growing stages (days) of paddy rice

Initial	Crop development	Mid-season	Late season	Total	Planting date	Region
30	30	60	30	150	December and May	Tropics, Mediterranean
30	30	80	40	180	May	Tropics

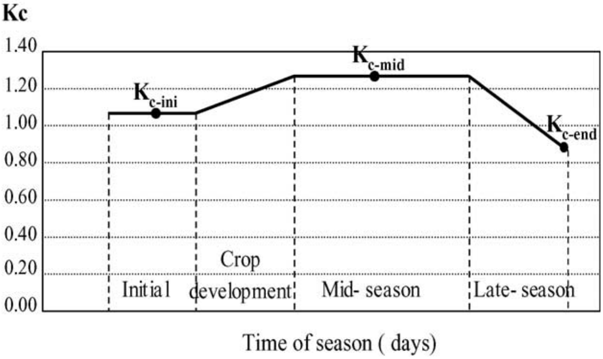

Fig. 1. Crop coefficient curve.

season. The length of growing stages of paddy rice with respect to climatic region is given in Table 1 (Allen et al., 1998).

To generate the K_c curve (Fig. 1), three typical values of K_c are required, including those during the initial stage, $K_{\text{c-ini}}$, the mid-season stage, $K_{\text{c-mid}}$, and at the end of the late season stage, $K_{\text{c-end}}$. The values of crop coefficient during growth season stages are estimated based on K_c curve and the typical values of $K_{\text{c-ini}}$, $K_{\text{c-mid}}$, and $K_{\text{c-end}}$ as shown in Fig. 1. Period during crop development and late season stage, crop coefficient K_c was linearly interpolated between two typical values of K_c. According to recommendations of FAO-56 method, under a standard climatic condition, which is defined as a sub-humid climate with average daytime minimum relative humidity (RH_{min}) of 45% and having calm to moderate wind speeds averaging 2 m s^{-1}, the typical values of K_c for rice crop, $K^*_{\text{c-ini}}$, $K^*_{\text{c-mid}}$ and $K^*_{\text{c-end}}$ are 1.05, 1.2 and 0.9, respectively (Allen et al., 1998).

The ET_c during initial stage mainly consists of evaporation. Therefore, adjustment of K_c for this stage mainly depends on climatic factors. The suggested typical value of $K_{\text{c-ini}}$ for the various climate conditions varies from 1.0 to 1.2 as shown in Table 2 (Allen et al., 1998). For the mid-season stage and late season stage, transpiration through the rice leaf

Table 2
$K_{\text{c-ini}}$ for various climatic conditions

Humidity	Wind speed		
	Light	Moderate	Strong
Arid-semi-arid	1.10	1.15	1.20
Sub-humid -humid	1.05	1.10	1.15
Very humid	1.00	1.05	1.10

and stem should be considered. As per FAO-56 method, the height of crop is one of the terms affecting crop coefficient. The typical values of K_c during mid-season stage and late season stage, $K_{\text{c-mid}}$ and $K_{\text{c-end}}$, are adjusted with climatic condition and height of crop by Eqs. (3) and (4):

$$K_{\text{c-mid}} = K^*_{\text{c-mid}} + [0.04(U_2 - 2) - 0.004(\text{RH}_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{3}$$

$$K_{\text{c-end}} = K^*_{\text{c-end}} + [0.04(U_2 - 2) - 0.004(\text{RH}_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{4}$$

where $K^*_{\text{c-mid}}$ and $K^*_{\text{c-end}}$ are the typical crop coefficient during mid-season stage and at the end of late season stage under standard climatic condition as indicated above, U_2 the average value for daily wind speed at 2 m height over grass during the growth stage (m s^{-1}), $\text{RH}_{\min}$ the average value for daily minimum relative humidity during the growth stage (%), h the average plant height during the growth stage (m).

Approaching to apply FAO-56 method for estimation of ET_c in simulation models for pollutant runoff from rice fields, this study focuses on three first stages of growing season, which are initial, crop development and mid-season. These are periods of high potential of pollutant concentration in paddy water (Watanabe and Takagi, 2000a; Inao and Kitamura, 1999). Concerning these three stages, two typical values of K_c were examined, that are the initial, $K_{\text{c-ini}}$, and the mid-season, $K_{\text{c-mid}}$.

2.4. Lysimeter monitoring

Four sets of monitoring experiments for rice evapotranspiration using lysimeter were carried out at the experimental paddy rice field at National Institute of Agro-Environmental Science (NIAES) in 1998 and 1999, in Tsukuba, and at Tokyo University of Agriculture and Technology (TUAT) experimental farm in 2002 and 2003, in Tokyo. The monitoring scenarios are shown in Table 3. Three rice varieties, Nihonbare, Mangetsumochi and Koganemochi were monitored. Nihonbare, which is non-waxy rice monitored in NIAES, has short-medium culm length of 80–85 cm (Siga Prefecture, 2004). Mangetsumochi and Koganemochi, waxy rice monitored in TUAT have long culm length (MAFF-Niigata, 2004).

Table 3
Scenarios for monitoring

Number	Location	Year	Variety	Planting date	Moitoring period	Location			Climate
						Elevation	Latitude	Longitude	
1	NIAES	1998	Nihonbare	7th May	13/5–7/8 (57 days)	20 m	36°10′N	139°56′E	Sub-humid
2	NIAES	1999	Nihonbare	6th May	13/5–7/8 (57 days)	20 m	36°10′N	139°56′E	Sub-humid
3	TUAT	2002	Mangestumochi	4th May	5/5–16/6 (41 days)	59 m	36°41′N	139°29′E	Sub-humid
4	TUAT	2003	Koganemochi	12th May	13/5–23/6 (43 days)	59 m	36°41′N	139°29′E	Sub-humid

Size of the lysimeter having closed bottom was 0.5 m long, 0.35 m wide and 0.3 m high. The conditions of rice cultivation, fertilization and water scheme inside lysimeters were set up similarly to those in the field. Fifteen centimeters of soil inside the lysimeter was taken from the corresponding paddy plot. The lysimeters were setup within the corresponding plots and the soil surface in the lysimeters was adjusted almost the same with that in the fields. Four rice hills were planted within lysimeter corresponding to density of 22.8 hills m^{-2}, which was the same with actual density in the field. Water depth inside lysimeters was kept about 5 cm, similar to that in the field. Daily change in water level in lysimeters was measured and observed daily evapotranspiration was obtained with daily rainfall data.

Also, during the monitoring period, the meteorological data were collected for maximum, average and minimum air temperatures, daily average wind velocity, daily average humidity and daily solar radiation. In NIAES, the data were provided from weather data acquisition system. In TUAT, the data were collected at weather station located at the experimental farm. The meteorological data and information presented in Table 3 were used for estimation of evapotranspiration using FAO-56 method.

2.5. Evaluation FAO-56 method

For the convenience in calculation, a simple computer program was developed to estimate ET_c using FAO-56 method. The program was coded by Visual Basic Application in Microsoft Excel. For the crop coefficient suggested by FAO-56 method, the typical value of $K_{c\text{-ini}}$ was obtained from Table 2 with actual climate condition. The typical values of K_c for mid-season stage, $K_{c\text{-mid}}$, were calculated by Eq. (3) with actual climatic data and estimated average crop height corresponding the monitoring period.

Since data for average crop height during growing season of these varieties were not available, the values of average height of rice during mid-season stage in the Eq. (3) were estimated from our observation to be 0.45, 0.55 and 0.55 m, respectively, for Nihonbare, Mangetsumochi and Koganemochi. Actual crop height may also vary depending on the environmental condition, such as temperature, day-length, light intensity, and soil condition (Matsuo and Hoshikawa, 1995), however, sensitivity analysis indicated that the effect of crop height to ET_c is very small as discussed later in Table 5.

Total growing period of three rice varieties was about 155 days, including about 30 days of rice seedling development before transplanting. FAO-56 suggested lengths of rice growing stages were 30, 30, 60, 30 days for initial, crop development, mid-season and late season stages, respectively, for Mediterranean region. Since the lack of observed data, such as leaf area index, the rice growing stages after transplanting obtained by Tyagi et al. (2000) was applied to be 21, 35, 42 and 27 days for initial, crop development, mid-season and late season stages, respectively. Duration of growing stage obtained by Tyagi et al. (2000) might not completely fit to Japanese rice varieties. However, sensitively analysis indicated that effect of duration of growing stages to ET_c was very small as discussed later in Table 5.

In order to evaluate the model performance and improve the prediction error, the values of K_c were adjusted to achieve the best fit to the observed cumulative ET_c curves. Since the bias, which is the difference between mean of prediction and observation, is the measure of systematic error in the forecast (Lettenmaier and Wood, 1992), the best-fit value of K_c was obtained corresponding to the minimum value of the bias between prediction and observation. The values of K_c were adjusted by try and error procedure to obtain the minimum value of the bias between the estimated and the observed cumulative ET_c curves. Difference between estimated and observed ET_c data was statistically evaluated for the forecast error (Lettenmaier and Wood, 1992).

Also, in order to evaluate the model response on significant parameters used in FAO-56 method under actual scenarios for climatic conditions and crop heights, sensitivity analysis was performed. Parameters used for the estimation of $K_{c\text{-mid}}$, as presented in Eq. (3), including; average crop height during the mid-season stage, h; average value for daily minimum relative humidity during the mid-season stage, RH_{min}; average value for daily wind speed at 2 m height over grass during the mid-season stage, U_2; typical crop coefficient during mid-season stage, $K^*_{c\text{-mid}}$, and typical crop coefficient during initial stage, $K_{c\text{-ini}}$, were the objects for sensitivity analysis. Duration of initial and crop-development stages was also examined. The sensitivity analysis was performed by changing the original values by ±10%. The original values were set as FAO recommended K_c values for those simulations of NIAES and TUAT experiments.

2.6. Application FAO-56 method in simulation model of pollutant runoff

Applicability of FAO-56 in estimation of evapotranspiration for the model simulation of pollutant runoff from rice paddy fields was evaluated. The coded program of FAO-56 method was used along with previously developed pesticide fate and transport model for paddy field, PCPF-1 model (Watanabe and Takagi, 2000a,b). PCPF-1 model has been validated and evaluated for commonly used herbicides in Japanese paddy rice production (Watanabe and Takagi, 2000a,b,c). For simulating pesticide concentration in paddy water using PCPF-1, water balance scenario used for the simulation was taken from field monitoring at the experimental plot of 0.137 ha (28 m × 49 m) at TUAT in 2003, for 42 days as the same period with lysimeter monitoring explained above (Watanabe et al., 2003). Target compound selected for the model evaluation was mefenacet, which was commonly used herbicides in Japan (Watanabe and Takagi, 2000c). The model parameters of pesticide dissipation in paddy water were obtained from the published results of experiments conducted in NIAES in 1998 (Watanabe and Takagi, 2000c). The mefenacet concentrations in paddy water were simulated using ET_c data that observed in lysimeter monitoring, estimated using FAO-56 with recommended K_c (case 1) and that estimated using FAO-56 with adjusted K_c (case 2). The mean relative differences in herbicide concentrations and the differences in cumulative pesticide runoff between simulated results using the observed and above two cases of ET_c data were analyzed and evaluated for the performance of the model application.

3. Results and discussion

3.1. Crop coefficient and crop evapotranspiration obtained by FAO-56 method

Table 4 shows the calculated results with K_c suggested by FAO-56 method. The mean wind speed, average minimum humidity and mean temperature in both study sites during

Table 4
Calculated results with K_c suggested by FAO-56

	NIAES-1998	NIAES-1999	TUAT-2002	TUAT-2003
Variety	Nihonbare	Nihonbare	Mangestumochi	Koganemochi
Typical value for initial stage, $K_{c\text{-ini}}$	1.10	1.10	1.10	1.10
Typical value for mid-season stage, $K_{c\text{-mid}}$	1.16	1.16	1.17	1.13
Monitoring—cumulative ET (mm)	178	199	153	155
FAO-56—cumulative ET (mm)	176	216	131	129
Relative difference of cumulative ET_c (%)	1.4	8.2	14.1	16.8
Cumulative solar radiation (MJ m^{-2})	742	955	658	564

monitoring period were about 1.6–1.72 m s^{-1}, 58–63%, and 16–20 °C, respectively, which corresponded to climate of moderate wind speed for sub-humid condition (Smith et al., 1991). Therefore, the typical values of K_c for initial stage were set to be 1.1 for all varieties from Table 2. Corresponding values for mid-season stage calculated by Eq. (3) were from 1.13 to 1.17.

The results of estimated ET_c with K_c suggested by FAO-56 method were compared with data monitored by the lysimeters as shown in Fig. 2 and Table 4. During the monitoring period, observed cumulative ET_c linearly increased with time for all of four cases. Except for Nihonbare-1998, deviation from observed cumulative ET_c became significant towards later period corresponding to mid stage. Comparing the first 40 days of observed cumulative ET_c, Mangetsumochi and Koganemochi having comparably taller plant height and body mass (MAFF-Niigata, 2004), had 27% and 21% greater cumulative ET_c than that of Nihonbare (as average of two years) although average cumulative solar radiation for Nihonbare monitoring was greater than that of Mangetsumochi and Koganemochi. For the

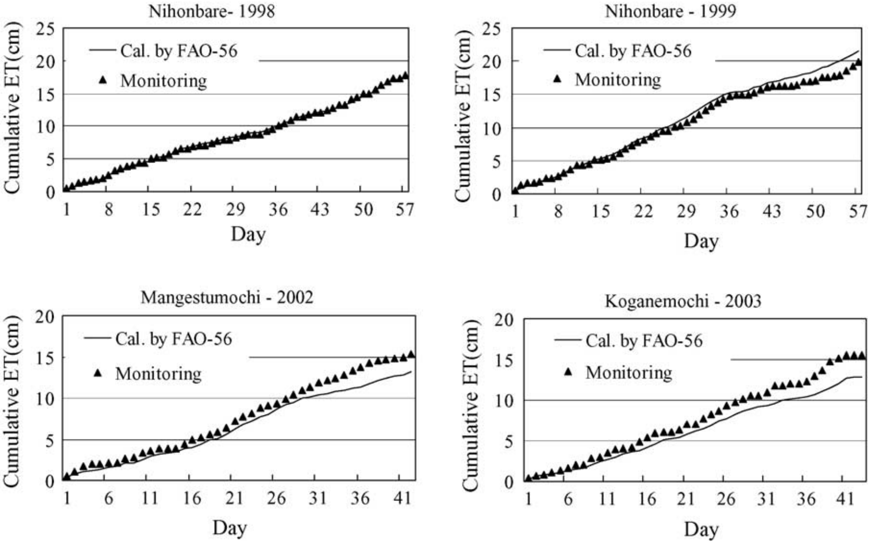

Fig. 2. Cumulative observed and estimated ET_c during monitoring period with K_c suggested by FAO-56.

monitoring in TUAT, although the cumulative observed solar radiation in 2003 was smaller than that from 2002, by about 14%, the cumulative ET_c of Koganemochi in 2003 was greater than that of Mangetsumochi from 2002, by about 1.5%. Above results suggest that ET_c may exhibit considerable variability between rice varieties. Plant factors affecting transpiration are the crop size, shape, surface characteristics (hair) as well as stomata aperture of leaf, leaf density and spatial structure (Hirasawa, 1995). Sakuratani and Horie (1985) also indicated that there are some differences in transpiration between Japanese (Nihonbare) and foreign varieties.

For the same variety (in case of Nihonbare), annual differences in cumulative observed ET_c in our observation may be the result of difference in atmospheric conditions in 1998 and 1999. Hirasawa (1995) also described that transpiration is affected by environmental factors influencing evaporation of water at the leaf–air interface, such as atmospheric vapor pressure, solar radiation, air temperature, wind speed, etc. For monitoring in NIAES, the greater the solar radiation, the greater the cumulative observed ET_c values (Table 4). The cumulative observed solar radiation and ET_c for Nihonbare in the second year monitoring (1999) was about 22% and 10% greater than those of the first year monitoring (1998), respectively.

For the model prediction of ET_c for Nihonbare, FAO-56 method overestimated the observed cumulative ET_c by about 1% to 8%. In contrast for Mangetsumochi and Koganemochi, FAO-56 method underestimated the observed cumulative ET_c by about 14–17% (Table 4). Also for the calculated ET_c in the same variety, it can be said that the larger the cumulative solar radiation the larger is the cumulative ET_c. It was observed that rice plants have a close correlation between transpiration and solar radiation although it depends on the leaf temperature (Hirasawa, 1995).

3.2. Adjustment of crop coefficient and performance of FAO-56 method

The relation of K_c and absolute bias responding to initial and crop-development stage for all scenarios obtained by try and error procedure was shown in Fig. 3. The best-fit value of K_c corresponding at the bottom of K_c-bias curve varied from 1.0 to 1.5. Absolute bias responded linearly with similar slope to the K_c value for both $K_{c\text{-ini}}$ and $K_{c\text{-mid}}$. Only in Nihonbare-1999, $K_{c\text{-mid}}$ was smaller than $K_{c\text{-ini}}$. In 1999, observed cumulative ET_c had slower increment in later period as shown in Fig. 2, and it was distinctive from other observations. The best-fit value of $K_{c\text{-ini}}$ were 1.10, 1.09, 1.23, and 1.28, respectively, Nihonbare-1998, Nihonbare-1999, Mangetsumochi-2002 and Koganemochi-2003, and they were about 0%, −1%, 12% and 16% different from those of FAO-56 recommendation, respectively. The corresponding values for $K_{c\text{-mid}}$ were 1.20, 1.02, 1.46 and 1.39, and they were about 3%, −12%, 25% and 23% different from those of FAO-56 recommendation, respectively, for the same order as above.

Adjusted $K_{c\text{-ini}}$ values were about 1.1 to 1.3, however, $K_{c\text{-mid}}$ seemed vary more as compared with $K_{c\text{-ini}}$. For the earlier period after rice transplanting, the contribution of transpiration on ET_c was less and evaporation from ponding water surface was probably the dominant process. As the crop develops and covers the surface water towards the mid-season and later period, evaporation becomes more restricted and transpiration gradually becomes the major process over the evapotranspiration in a paddy field. From observation

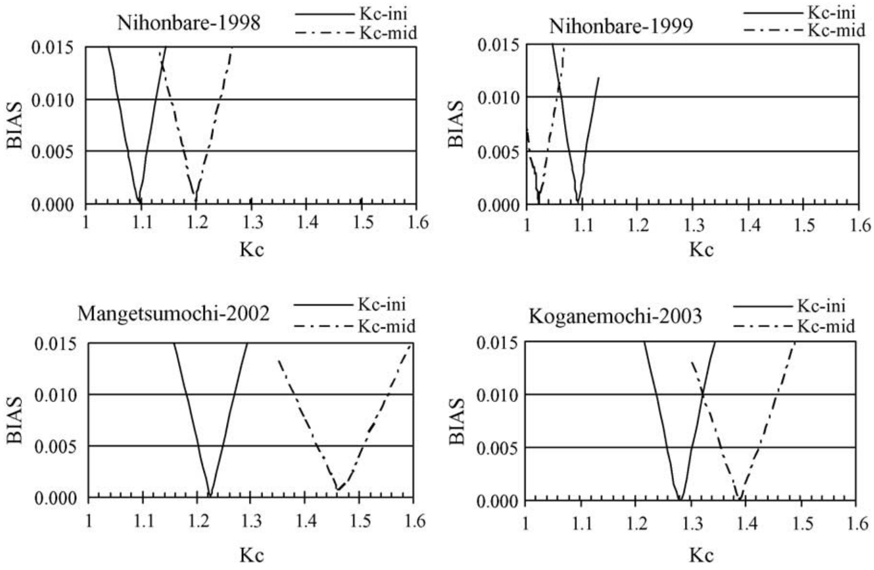

Fig. 3. Relation K_c–bias of observed and estimated ET_c by FAO-56.

in NIAES in 1998 and 1999, the rate of increase in observed cumulative evaporation below rice canopy decreased as compared to the observed cumulative evapotranspiration towards later part of monitoring period as shown in Fig. 4. During earlier period after rice transplanting, the observed values of evapotranspiration and transpiration were similar, especially in 1998. Toward later periods, difference between evapotranspiration and transpiration became larger (Fig. 4). Therefore, the model predictability towards mid-season or later could be more depending on setting a right value of $K_{c\text{-mid}}$.

Comparison of cumulative observed and estimated ET_c during monitoring period for all scenarios after adjustment of K_c is shown in Fig. 5. The square of correlation coefficient, R^2, between cumulative observed and estimated values (Lettenmaier and Wood, 1992) was grater than 0.99 (Fig. 5). With the best-fit parameter adjustment of K_c, the relative error of

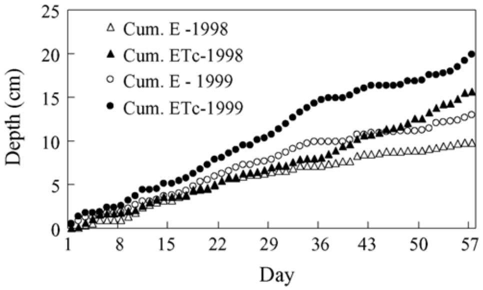

Fig. 4. Cumulative observed evaporation (E) and evapotranspiration (ET_c) in NIEAS-1998 and 1999, during monitoring period.

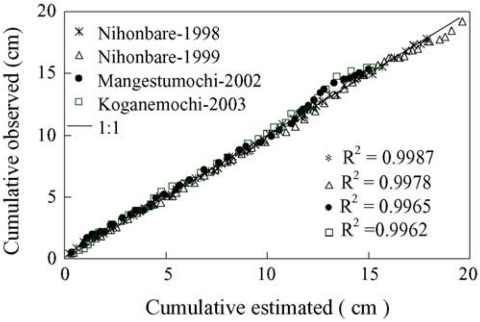

Fig. 5. Comparison of cumulative observed and estimated ET_c with adjusted K_c during monitoring period.

cumulative ET_c between observed and estimated data were decreased to be less than 1.0%. Above discussion indicated the importance of the setting appropriate parameter values especially in prediction towards mid-season period when accurate prediction is required.

3.3. Sensitivity analysis of major parameters in FAO-56 method

The result for sensitivity analysis shown in Table 5 indicated that crop height had almost no influence on estimating ET_c. The effects of RH_{min} and U_2 on ET_c as calculated through Eq. (3) were also very small with the mean of relative difference to the original values (MRDOV) ranging about 0.2% to 1%. Duration of growing stages also had very small influence to the ET_c with MRDOV ranged less than 0.5% and 1.3% for initial and crop-development stage, respectively. For the typical value of crop coefficients, $K_{c\text{-ini}}$, its MRDOV ranged less than 5%. The results implied that if one can obtain reliable atmospheric data, FAO-56 recommended $K_{c\text{-ini}}$ is acceptable for accurate prediction.

However, for the $K^*_{c\text{-mid}}$, The MRDOV ranged about 7% to 9%. The result indicated that $K^*_{c\text{-mid}}$ is the most sensitive parameter for the calculation of ET_c. As discussed previously, transpiration during midterm is subject to physiological response, which is different among varieties. The transpiration rate is affected not only by meteorological factor but also by physiological and structural factors of the crop, which is manifested through crop coefficient (Matsuo and Hoshikawa, 1995). Among a number of physiological and structural factors of the crop affecting ET_c, the crop height is the only one presented in Eqs. (3) and (4). These equations might not completely reflect physiological processes of crop. Furthermore, determination of physiological and structural factors of the crop is difficult. Therefore, $K^*_{c\text{-mid}}$ suggested in the FAO-56 method may require careful calibration according to the specific conditions and varieties if the user seeks an accurate prediction.

Allen et al. (1998) also recommended the evaluation of crop coefficient values in local climatic condition by observed data using lysimeter when the accuracy is highly concerned. Tyagi et al. (2000) compared evapotranspiration estimated by FAO method with lysimeter monitoring and suggested that estimated values of crop coefficient, K_c, for *Oryza sativa* L. rice in India are 1.15, 1.23, and 1.14 for initial stage, mid-season stage and late season stage, respectively. Shab and Edling (2000) used the water balance equation in paddy field and Penman-Monteith equation for the calculation of ET_c and estimated the

Table 5
The results of sensitivity analysis

Parameters	Scenarios	Original value	Mean of relative difference to the original value (%)		
			10%	−10%	Average
h (m)	NIEAS-1998	0.45	0.03	0.03	0.03
	NIEAS-1999	0.45	0.07	0.08	0.08
	TUAT-2002	0.55	0.05	0.06	0.05
	TUAT-2003	0.55	0.05	0.05	0.05
RH_{min} (%)	NIEAS-1998	61	0.81	0.81	0.81
	NIEAS-1999	58	0.97	0.97	0.97
	TUAT-2002	61	0.77	0.77	0.77
	TUAT-2003	63	0.73	0.73	0.73
U_2 (m/s)	NIEAS-1998	1.75	0.29	0.29	0.29
	NIEAS-1999	1.82	0.29	0.29	0.29
	TUAT-2002	1.7	0.24	0.24	0.24
	TUAT-2003	1.6	0.22	0.22	0.22
$K_{c\text{-ini}}$	NIEAS-1998	1.1	3.83	3.83	3.83
	NIEAS-1999	1.1	3.67	3.67	3.67
	TUAT-2002	1.1	4.68	4.68	4.68
	TUAT-2003	1.1	4.85	4.85	4.85
$K^*_{c\text{-mid}}$	NIEAS-1998	1.2	8.57	8.57	8.57
	NIEAS-1999	1.2	8.83	8.83	8.83
	TUAT-2002	1.2	6.95	6.95	6.95
	TUAT-2003	1.2	6.89	6.89	6.89
Duration of initial stage (days)	NIEAS-1998	21	0.13	0.15	0.14
	NIEAS-1999	21	0.09	0.11	0.10
	TUAT-2002	21	0.36	0.42	0.39
	TUAT-2003	21	0.13	0.17	0.15
Duration of crop-development stage (days)	NIEAS-1998	35	0.31	0.45	0.38
	NIEAS-1999	35	0.25	0.32	0.28
	TUAT-2002	35	0.81	1.21	1.01
	TUAT-2003	35	0.03	0.03	0.03

values of K_c for paddy rice in Louisiana to be 1.39, 1.51, and 1.43, respectively, for initial, mid-season and late season stage, respectively. The above data also showed that value of crop coefficient for paddy rice varies from 1.0 to 1.5 depending on varieties and regional conditions.

3.4. Appropriate simulation period for the application of FAO-56 method

As shown in Fig. 5, the best-fit parameter adjustment of K_c now minimized the systematic error of the prediction associated with sensitive parameters. However, the effect of random error associated with environmental variable is unknown. Although cumulative value have accurately predicted, the daily values of predicted ET_c may contain significant random errors. The relative variance, a measure of random error (Lettenmaier and Wood, 1992), between daily prediction and observation ranged about 20% to more than 50% for above four cases of experiments. Application of Penman-Monteith equation may not be for full crop season and it could be short period for some cases, such as application to the water quality modeling. Therefore, it is important to evaluate the appropriate length of the simulation period that will not be affected by the random error.

First, effect of random errors was evaluated for different simulation periods of 1, 3, 7, 14, and 28 days. Since there are differences in the magnitude of cumulative $\mathrm{ET_c}$ values and their variances depending on the length of the simulation period, variances on different simulation periods were normalized by dividing by square of the mean of observation. We define this value as the relative variance (RV). The relative variance between observed and predicted cumulative $\mathrm{ET_c}$ for these different simulation periods were calculated according to the Eq. (5) derived from formulations proposed by Lettenmaier and Wood (1992).

$$\mathrm{RV} = \frac{(1/n)\sum_{i=1}^{n}[Q_\mathrm{e}(i) - Q_\mathrm{o}(i)]^2 - [(1/n)\sum_{i=1}^{n}Q_\mathrm{e}(i) - (1/n)\sum_{i=1}^{n}Q_\mathrm{o}(i)]^2}{((1/n)\sum_{i=1}^{n}Q_\mathrm{o}(i))^2} \tag{5}$$

where $Q_\mathrm{e}(i)$ is the estimated $\mathrm{ET_c}$ for the simulation period during i days, $i = 1,2,\ldots,n$, and $Q_\mathrm{o}(i)$ the the observed $\mathrm{ET_c}$ during the same period.

Relation between the relative variance (RV) and the simulation period (i) for four sets of experiment was showed in Fig. 6. For all scenarios, relative variances were rapidly decreased when period of cumulative calculation increased from 1 day (daily data) to 7 days. At 7 days period, relative variance became less than 0.05 (Fig. 6). This analysis indicated that daily estimation of $\mathrm{ET_c}$ in paddy rice by FAO-56 method is subject to random errors. It is suggested that FAO-56 method is more reliable when calculating cumulative $\mathrm{ET_c}$ longer than 7 days of period.

3.5. Applicability of FAO-56 method in simulation model of pollutant runoff

Considering water balance equation in the field when new $\mathrm{ET_c}$ data (case 1 or case 2) was reset, differences between new and current data of $\mathrm{ET_c}$ should be balanced by adjusting one of the water balance components among irrigation, drainage, and

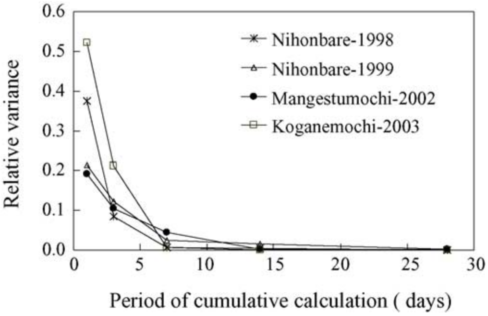

Fig. 6. Relation between relative variance and cumulative period for calculation.

percolation. The effect of different ET_c values on pesticide concentration was the greatest in the case of adjusting the drainage among the three components because the pesticide runoff was the most significant contributor for the pesticide mass balance. Actual water balance component monitored in the field plot during 42 days were 65.2, 25.6, 21, 57.7 and 15.5 cm for precipitation, irrigation, drainage, infiltration and evapotranspiration, respectively. Total evapotranspiration during the 42-day period estimated by FAO-56 method was 12.9 cm for case 1 with the recommended K_c and 15.2 cm for case 2 with adjusted K_c and they were 16.8% and 2% lower than the observed value, respectively, for the cases 1 and 2. For case 1, the mean of relative differences in herbicide concentrations to those calculated with observed ET_c were up to 5.6%. Corresponding value in case 2 was reduced to be 3%. The results showed that adjustment of K_c improved the model perdition, however, not proportionally improved on cumulative ET_c. There was probably still some error caused by the random effect in ET_c estimation. Similarly, cumulative pesticide loss by runoff as percentage of the applied mass during 41 days of monitoring were 18.6%, 19.2% and 18.7%, respectively, for the case using observed ET_c, case 1, and case 2. The corresponding relative differences to the case using observed ET_c were 3.2% and 0.05%, respectively, for the cases 1 and 2. In addition, in case of adjusting with irrigation and percolation, effect of ET_c on pesticide concentration was very small.

Even though the FAO-56 method with the recommended K_c value (case 1) gave up to 17% underestimation of cumulative ET_c, the maximum error expected to have on the prediction of the mefenacet concentration in the paddy field was 5.6%, and that of mefenacet runoff loss could as 3.2%. Therefore, it can be concluded that application of FAO-56 method with the recommended K_c value is acceptable in the simulation of pesticide fate and transport. With careful calibration of K_c values, especially $K_{c\text{-mid}}$, better model performance is expected.

4. Conclusion

The estimation of cumulative ET_c in paddy rice by FAO-56 method using the recommended K_c value resulted in estimation error of up to 17% from the observed values. Also, ET_c may exhibit considerable variability between rice varieties. The recommended values of $K_{c\text{-ini}}$ in FAO-56 method are appropriate if reliable atmospheric data are available. However, the $K_{c\text{-mid}}$ was found to be the sensitive parameter affecting ET_c estimation and the careful calibration according to the regional conditions and varieties seemed to be required for the accurate prediction. Considering the effect of random errors, FAO-56 method is more reliable when calculating cumulative ET_c longer than 7 days of period.

Despite the relatively large error in cumulative ET_c resulted from the FAO-56 method with the recommended K_c value, the maximum error expected to have on the prediction of the herbicide concentration in paddy field was 5.6%, and that of herbicide runoff loss was 3.2%. Therefore, it can be concluded that application of FAO-56 method with the recommended K_c value is acceptable in the simulation of pesticide fate and transport.

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