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Estimation of Water Balance Components in Paddy Fields under Non-Flooded Irrigation Regimes by using Excel Solver

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Abstract: Water saving technologies such as non-flooded irrigation have been introduced in many rice production during the past decade. Water balance analysis is needed to quantify water supply, loss and consumption for maximization rice production under such irrigation. However, hydrological data are often limited because acquisition of measurements in the field is costly, complicated and time consuming, hence methods that can estimate water balance components based on the combined use of available measurement data and an appropriate model are required. This study presents the estimation method using excel solver to estimate non-measurable water balance components, i.e., irrigation water, crop evapotranspiration, percolation and runoff, in a paddy field under non-flooded irrigation. The method was examined in two cultivation periods under different weather conditions. The model validation, indicated by coefficient of determination (R^2) values, was greater than 0.86 ($p<0.01$) between observed and calculated values of soil moisture. Furthermore, when relationships among precipitation and estimated runoff was compared, the reliability of the model was shown by the significant linear correlations with correlation coefficient (R^2) higher than 0.98 ($p<0.01$). These results indicate the reliability and applicability of the proposed method for estimating non-measurable water balance components for rice production when only limited data of measurable components are available.

Key words: Paddy fields, non-flooded irrigation, soil moisture, excel solver estimation

INTRODUCTION

Water saving is the main issue in maintaining the sustainability of rice production when water resource is becoming increasingly scarce (Bouman and Toung, 2001). Rice is highly possible produced under water saving technique in which continuous submergence irrigation is not essential anymore to gain high rice yields and dry matter production as reported previous studies (Vijayakumar *et al*., 2006; Lin *et al*., 2011; Sato *et al*., 2011; Zhao *et al*., 2011). Hence, water saving technologies, such as saturated soil culture and aerobic rice systems, have been introduced in many rice production sites during the past decade (Bouman *et al*., 2007). In Indonesia, rice is commonly grown under non-flooded conditions for both irrigation regimes. In saturated soil culture, water input can be saved on average 23% when the soil is kept as close to saturation as possible (Bouman and Toung, 2001). Meanwhile, in aerobic rice systems, the roots grow in unsaturated soil where the field is allowed to dry by a certain threshold for soil water tension during growing stages (Bouman *et al*., 2005). Water inputs in aerobic rice systems were 30-50% less than in flooded irrigation as reported by previous experiments (Bouman *et al*., 2005; Yang *et al*., 2005).

Optimization of the hydrological conditions is the main challenge in adopting those water saving technologies by determining optimal amount of water supply to the fields. For this purpose, quantitative knowledge of water supply, loss and consumption is needed by performing water balance analysis. It is one of the greatest advances in understanding the response of plants in water-limited environment (Angus, 1991). Also, it is important to evaluate the difference of hydrologic parameters under different climate condition to find proper water management such as in watersheds area (Ghandhari and Moghaddam, 2011).

However, particular water balance components such as crop evapotranspiration and percolation cannot be easily measured in the field because typical measurement methods are costly, complex and time consuming, especially with respect to equipment preparation. Crop evapotranspiration, the main route of water loss from both plant and soil surfaces, is commonly measured with a lysimeter (Mohan and Arumugam, 1994; Tyagi *et al*., 2000; Vu *et al*., 2005; Najafi, 2007). Percolation, as downward movement of excess water through the soil, is typically measured using various infiltrometer and lysimeter techniques and then calculating the results based on Darcy's law

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(Kalita *et al*., 1992). Therefore, it is impractical to actually measure some or all of these water balance components.

When measurement data is limited, estimation of non-measurable water balance components is an important alternative if the available measured data and an appropriate water balance model can be combined using an appropriate method. Geographic information system and remote sensing technologies are suitable to estimate water balance components on basic scale by using distributed recharge methodology, WetSpass (Abu-Saleem *et al*., 2010). However, it is difficult to use those technologies on the field scale.

Excel solver which is incorporated into Microsoft Excel 2007, is a software tool that helps users find the best way to allocate scarce resources by searching algorithms. It has sufficient power to find the coefficients to fit the data in non-linear equations (Walsh and Diamond, 1995) such as chromium biosorption (Berekaa *et al*., 2006), 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). Moreover, it has ability to estimate up to 200 data within one process. Accordingly, it can be used to estimate non-measurable water balance components by combining measurement data and model on the field scale.

The objective of this study, therefore, was to propose the method using excel solver for estimating non-measurable water balance components, i.e., irrigation water, crop evapotranspiration, percolation and runoff in a paddy field on daily basis under non-flooded irrigation regimes.

MATERIALS AND METHODS

Field experiments: The field experiment was conducted in the experimental paddy field in the Nagrak Organics SRI Center (NOSC), Sukabumi West Java, Indonesia during two cultivation periods. The first period was started from 14 October 2010 (planting date) to 8 February 2011 (harvesting date) in wet season, while the second period from 20 August 2011 to 15 December 2011 in dry-wet season. In both cultivation periods, the field was planted with the variety of rice (*Oryza sativa* L.), Sintanur, using the following cultivation practices: single planting of young seedlings (5 days after sowing) spaced at 30×30 cm, applying an organic fertilizer from the compost at 1 kg m^{-2} in the land preparation instead of chemical fertilizer as common organic practice in the location.

Non-flooded irrigation regimes were applied for both cultivation periods. Soil moisture condition in the field was described by changes in soil suction head (i.e., pF value). In the first period, the soil moisture was kept between saturated (pF 0) and air entry (pF 1.6) conditions without standing water by maintaining water level at 0 to -5 cm water depth during the cultivation period. In the second period, aerobic soil condition was maintained to achieve soil moisture between air entry (pF 1.6) and field capacity (pF 2.54) conditions with water levels from -5 to -20 cm water depth. The relationship between soil moisture and soil suction head was represented by soil water retention curve by the van Genuchten model (Van Genuchten, 1980), as an optimal soil water retention model (El-Shehawy, 2008) in which the soil properties are presented in Table 1.

Field measurements: The observed parameters were measured every 30 min consisting of meteorological (air temperature, wind speed, relative humidity, solar radiation and precipitation) and soil moisture. Here, observed soil moisture (θ_o, cm^3 cm^{-3}) was measured by 5-TE sensors (Decagon Devices, Inc., USA), while meteorological parameters were measured by a Davis Vantage Pro2 Weather Station (Davis Instruments Corp, USA). Daily average values of air temperature, wind speed, relative humidity and total solar radiation were used to calculate reference evapotranspiration (ET$_o$) based on the FAO Penman-Monteith model (Allen *et al*., 1998) as a model for the direct calculation of evapotranspiration from any canopy and it has been validated by lysimeter observations (Persaud *et al.,* 2007).

Model development: Water balance model was prepared according to the scheme in Fig. 1. The inflow to the field consisted of precipitation and irrigation water, while the outflow consisted of crop evapotranspiration, runoff and percolation. Accordingly, water balance equation can be expressed as:

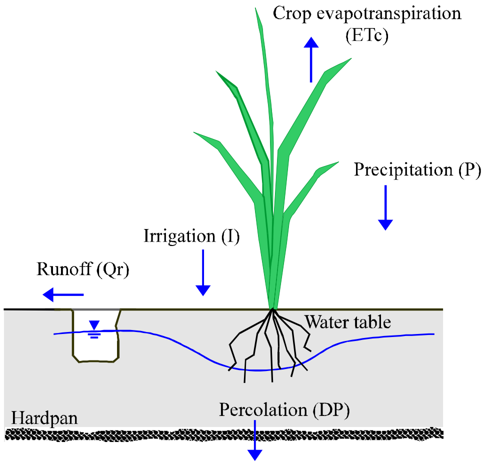

Fig. 1: Water balance scheme in paddy field

$$S_m(t) = S_m(t-1)+P(t)+I(t)-ETc(t)-Qr(t)-DP(t) \quad (1)$$

where, S_m is calculated soil water storage (mm), P is precipitation (mm), I is irrigation water (mm), ETc is crop evapotranspiration (mm), Qr is runoff (mm) and DP is percolation (mm).

In this study, observed soil moisture and meteorological data were used to estimate non-measurable water balance components consisting of irrigation water, crop evapotranspiration, runoff and percolation using Excel solver (Fig. 2). Before performing the estimation, initial values of the estimated components for each day were determined as described later. Then, calculated soil moisture (θ_m, cm^3 cm^{-3}) was determined by dividing calculated soil water storage (S_m) by the effective soil depth (Table 1).

Table 1: Soil properties of the experimental field

Parameters	Values
Soil texture	
Clay (%)	31
Silt (%)	66
Sand (%)	3
Texture name	Silty clay loam
Saturated hydraulic conductivity (Ks, mm day^{-1})	12.7
Effective soil depth (Zr, mm)	300
Saturated water content (cm^3 cm^{-3})	0.597
Residual water content (cm^3 cm^{-3})	0.250
Genuchten's shape factor	
α	63
n	1.330
m	0.248

Within one process, excel solver can estimate non-measurable components up to 200 data only. Hence, the data set through the entire cultivation period was divided into four data sets based on the growth stages, i.e., initial, crop development, mid-season and late season stages (Mohan and Arumugam, 1994; Allen *et al*., 1998; Tyagi *et al*., 2000; Vu *et al*., 2005). In each estimation process, an objective function was defined as:

$$\text{Error} = \sum_{t=1}^{n} \left| S_o(t) - S_m(t) \right| \quad (2)$$

where, S_m is calculated soil water storage (mm), S_o is observed soil water storage (mm), t is time point and n is the total number of days in the growth stage. S_o was determined by multiplying observed soil moisture (θ_o, cm^3 cm^{-3}) by the effective soil depth (Table 1). Non-measurable water balance components were estimated with the following constraints:

$$ETc_{min} \leq ETc(t) \leq ETc_{max} \quad (3)$$

$$I(t) \geq 0;\ Qr(t) \geq 0;\ DP(t) \geq 0 \quad (4)$$

where, ETc_{min} is minimum crop evapotranspiration, ETc_{max} is maximum crop evapotranspiration (mm). ETc_{min} and ETc_{max} were given by multiplying ET_o by the minimum (0.2) and maximum (1.6) values of crop coefficient for bare soil and maximum value of continuous submergence paddy field, respectively.

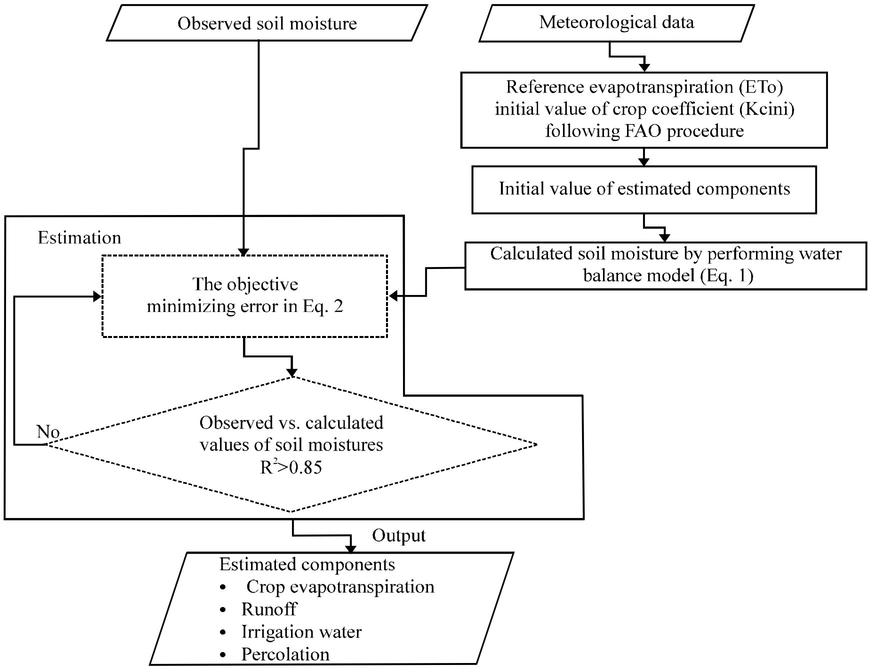

Fig. 2: Schematic diagram for the estimation of non-measurable water balance components

Initial values: The determination of initial values is a critical point in this estimation. If the initial values are too different from the true one, then, a poor convergence may be obtained, leading to a lack of fit between the actual values and estimated results (Machuca-Herrera, 1997; Comuzzi *et al*., 2003). Hence, we determined the initial values by considering the actual field conditions as explained below.

- **Crop evapotranspiration:** Initial value of crop evapotranspiration for each day was determined according to the FAO calculation procedure by considering crop coefficient (Allen *et al*., 1998)
- **Runoff:** Since runoff is a function of precipitation in which it has a positive correlation (Chen *et al*., 2003) and no standing water was in the field, initial value of runoff was given at zero level if precipitation was less than maximum reference evapotranspiration. On the other hand, it was given by reducing precipitation to maximum reference evapotranspiration
- **Irrigation water:** Since the percolation rate was thought to be low under non-flooded irrigations (Bouman *et al*., 2007), initial value of irrigation water was given by reducing crop evapotranspiration to precipitation if the runoff was zero. On the other hand, it was given at zero level
- **Percolation:** Initial values of percolation (DP_{ini}) was assumed to be 1 mm day^{-1} since the rates were between 1 and 5 mm day^{-1} in previous studies conducted in similar soil conditions and greater hydraulic pressure under flooded irrigation regimes (Guerra *et al*., 1998; Bouman *et al*., 2007)

Model validation: Coefficient of determination (R^2) was used as an indicator to compare between observed and calculated values of soil moisture given by the model (Eq. 1). The model is accepted if R^2 equal or greater than 0.85 (Luo *et al*., 2009). Then, as another supporting evidence of the estimation performance, linear correlation between precipitation and estimated runoff was analyzed using correlation coefficient (R) and degree of significance (p-value).

RESULTS AND DISCUSSION

Weather conditions: Meteorological conditions in the first and second cultivation periods are shown in Fig. 3a-c. In the first cultivation period, the meteorological parameters were characterized by low air temperature, low solar radiation and high precipitation compared to the second period. Consequently, total reference evapotranspiration was lower than its value for the second period because the reference evapotranspiration had a positive correlation to solar radiation (Fig. 3b). Total reference evapotranspiration for the first and second cultivation periods were 311 and 428 mm, respectively. The monthly average air temperature changed during in the end of 2010 and 2011, where its value was highest on November 2010 for the first cultivation period and then it occurred on December 2011 for the second period. The same situations occurred to the solar radiation and precipitation. As the result, the patterns of water balance components in both periods were different.

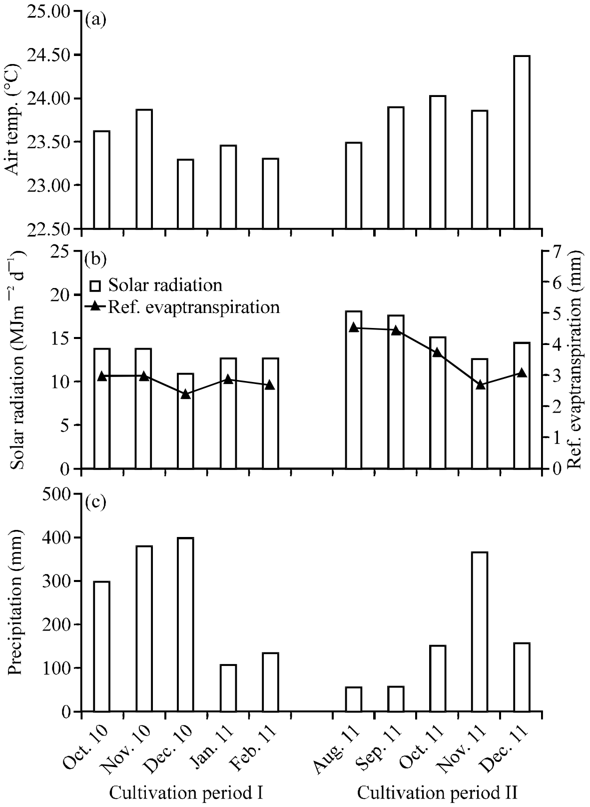

Fig. 3(a-c): Meteorological data during the cultivation periods, (a) Monthly average air temperature, (b) Monthly average solar radiation and reference evapotranspiration and (c) Monthly precipitation

Estimated water balance components: Table 2 presents values of total water balance components for both cultivation periods. Excel solver estimated non-measurable water balance components and the R^2 values of greater than 0.86 ($p<0.01$) indicate the model's performance. Tight linear correlations between observed soil moisture and the soil moisture levels predicted by the model described in Eq. 1 were observed (Fig. 4, 5). Thus,

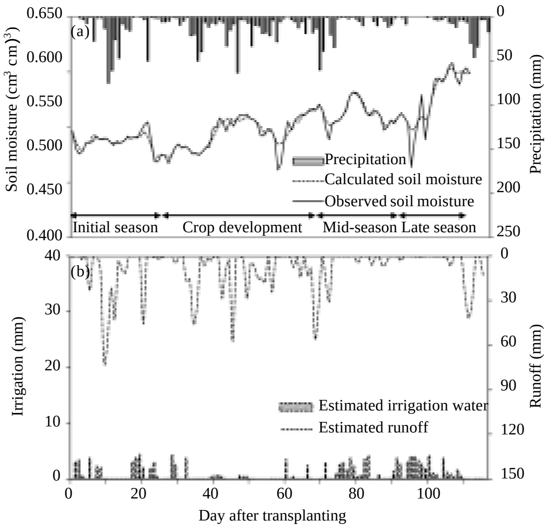

Fig. 4(a-b): Observed and estimated water balance components in the first cultivation period

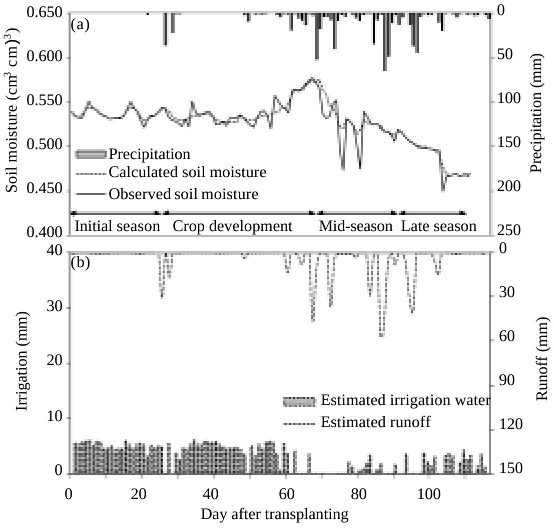

Fig. 5(a-b): Observed and estimated water balance components in the second cultivation period

Table 2: Model validation and water balance components in each cultivation period

	Cultivation period	
Parameters	First period	Second period
Model validation		
R^2-value	0.92	0.87
p-value	<0.01	<0.01
Inflow		
Precipitation (mm)	1332	626
Irrigation water (mm)	120	345
Total inflow (mm)	1452	971
Outflow		
Runoff (mm)	981	437
Crop evapotranspiration (mm)	338	451
Percolation (mm)	117	104
Total outflow (mm)	1436	992
Water storage (mm)	15.9	-21.2

more than 86% of the changes in observed soil moisture were well described by the model (Eq. 1). The R^2 values and their degrees of significance ($p<0.01$) also demonstrate how well the current method functions, given the availability of a minimum set of observed components.

The patterns of changes in the water balance components were clearly different between the cultivation periods (Fig. 4-5). In the second cultivation period, total irrigation water was higher than its total value for the first period though the soil was drier because less precipitation occurred in this period. In addition, in the second period, total water storage showed a negative value (Table 2) indicating that the total inflow was lower than the total outflow, thus soil moisture at the last stage was lower than at the initial stage (Fig. 5). For both periods, frequent irrigation water was estimated when the intensity of precipitation was low, particularly at the mid-season and early in the late stage for the first period (Fig. 4) and at initial and crop development stages for the second period (Fig. 5). Overall, during the entire period of this study, obvious contrasts between precipitation and irrigation were observed (Fig. 4, 5). On the days when amounts of precipitation were large, the amounts of irrigation were small or nil.

In the first cultivation period, runoff was the dominant outflow component, accounting for approximately 68% of the total outflow, because high precipitation occurred (Table 2). On the other hand, when less precipitation occurred, the contribution of runoff to the outflow dropped as seen in the second period. Accordingly, runoff had a high degree of correlation to precipitation with R values higher than 0.98 (Fig. 6). The unaccountable variations (2.5% of the total or less) were clearly attributed to the cultivation days with the small amounts of precipitation that still remained in the field resulting in the negative intercept values in the linear relationships shown in Fig. 6. In addition, regarding R values greater than 0.98 ($p<0.01$), precipitation-estimated runoff relationships were similar among periods (Fig. 4-5), as also reported in a previous study (Cho, 2003) which showed that runoff is mainly dominated by precipitation when the percolation rate is low (Table 2).

Total percolation was comparable among the periods and their values were low according to the FAO note which reported the minimum percolation value of 200 mm in comparable conditions but for flooded paddy regimes.

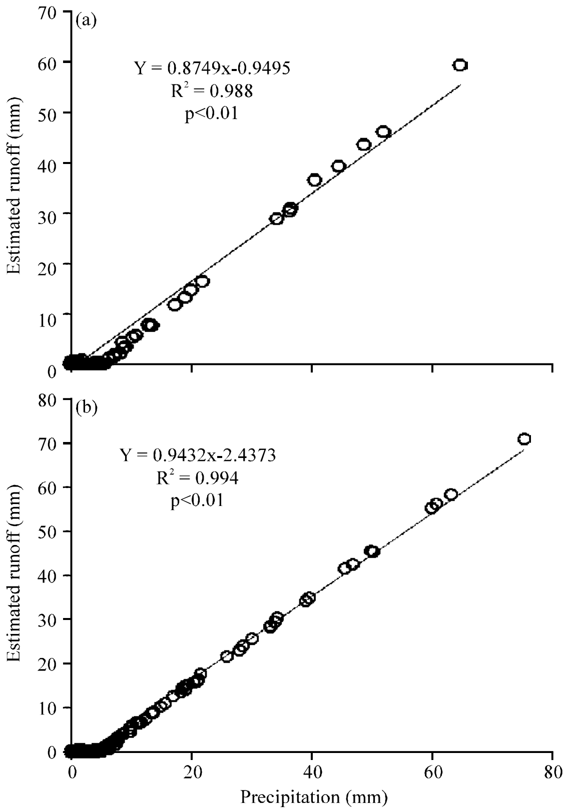

Fig. 6(a-b): Correlation between estimated runoff and precipitation in, (a) Cultivation periods II and (b) Cultivation periods I

The low percolation of the current site is thought to be due to the silty clay loam soil texture and lack of standing water that might reduce water loss through percolation by reducing hydrostatic pressure (Bouman and Toung, 2001). In the first cultivation period in which the soil moisture level was higher than in the second period, percolation rate was faster probably due to the increased hydrostatic pressure when the soil was more saturated.

Crop evapotranspiration for the second cultivation period was higher than its value for the first period because of higher contribution of reference evapotranspiration (Fig. 3b). This shows that the plant water requirement was mainly affected by weather conditions as represented by reference evapotranspiration (Allen *et al.*, 1998).

Excel solver was well implemented for estimating non-measurable water balance components for rice cultivation in paddy fields as suggested from these results. The set of estimated components are expected to elucidate the relationships between the patterns of water balance and the physiological conditions of the crop. Consequently, optimal water managements are expected to be developed that incorporate the most suitable values for components such as crop evapotranspiration and required irrigation water, components that crucially affect land and water productivity under non-flooded irrigation scenarios.

CONCLUSIONS

Excel solver was used for estimating water balance components consisted of irrigation water, crop evapotranspiration, percolation and runoff in a paddy field in two cultivation periods. The method was reliable indicated by coefficient of determination value (R^2), was greater than 0.86 ($p<0.01$) between observed and calculated values of soil moisture. Furthermore, when relationships among precipitation and estimated runoff was compared, the reliability of the model also was shown by the significant linear correlations between precipitation and estimated runoff with correlation coefficient (R) higher than 0.98 ($p<0.01$). This method is useful particularly when measurement data is limited and it can be used for further water management analysis in paddy fields without the need for complex, costly and time consuming techniques.

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