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Estimation of Water Balance Variables in the SRI Paddy Field by Considering Soil Moisture

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Abstract

Water Balance analysis in the System of Rice Intensification (SRI) paddy field is essential to evaluate water management regarding its water productivity and water use efficiency. In the observed field, however, particular water balance variables are not easily measured since the methods are often costly, complicated and time consuming. The current study proposed the novel method to estimate non-measurable water balance variables by considering monitored soil moisture in the field by using Excel solver estimation. The field experiment was conducted by adopting SRI rice cultivation in the SRI experimental field in Nagrak Organics SRI Center, Sukabumi, West Java, Indonesia during the first rice season 2010/2011 (October 2010 to Februari 2011, wet season). Results of the developed model showed satisfactory result between observed and estimated soil moisture with the values of R^2 higher than 0.70 in the all growth stages. Accordingly, each estimated water balance variable has reasonable trend and value. We found that total inflows through precipitation and irrigation water were 1331.8 and 107 mm, respectively. Meanwhile, the water has leaved the field through crop evapotranspiration, runoff and percolation with their total values were 296.5, 1010.7 and 116 mm, respectively. Minimum irrigation water was needed to meet plant water requirement since no standing water and high precipitation occurred in the current wet season. Also, the total crop evapotranspiration and percolation were low according to the FAO values as the results of low reference evapotranspiration and reduction of hydrostatic pressure, respectively. On the other hand, high runoff was estimated because almost precipitation was drained directly and only retained the water in the field to meet crop evapotranspiration.

Keywords: system of rice intensification (SRI), water management, water balance, soil moisture, excel solver estimation

Introduction

Recently, the System of Rice Intensification (SRI) is well-known as a set crop management practices for raising the productivity of irrigated rice by changing the management of plants, soil, water and nutrients. Although some critics were dismissed to the SRI (Sinclair and Cassman 2004; Sheehy et al. 2004; Dobermann 2004), however, its benefits have been validated in 42 countries of Asia, Africa and Latin America (Uphoff et al. 2011).

In the SRI paddy field, water is irrigated according to intermittent irrigation with an alternate wetting and drying irrigation system instead of continuous flooding for conventional rice cultivation. By this method, SRI can save up to 28% of water in Japan (Chapagain and Yamaji 2010), 40% in Eastern Indonesia (Sato et al. 2011) and 38.5% in Iraq (Hameed et al. 2011), and can increase water use efficiency by up to 43.9% in China (Lin et al. 2011). Here, the field is kept saturated and then letting the field dry for particular period. Accordingly, water balance analysis is usually performed to evaluate water productivity and water use efficiency in field scale.

However, particular water balance variables such as crop evapotranspiration and percolation are not easily measured in the field. The typical field measurement methods are often costly, complicated and time consuming especially for equipment preparation. Crop evapotranspiration, the main route of water loss from both plant and soil surfaces, is commonly measured empirically by using a lysimeter (Vu et al. 2005; Tyagi et al. 2000; Mohan and Arumugam 1994). Meanwhile, percolation, as downward movement of excess water through the soil, is measured by using range infiltrometer and lysimeter technique and then calculated based on Darcy's law (Janssen et al. 2010).

Soil moisture represents water availability in the field and it commonly affect pattern of water balance variables such as evapotranspiration, percolation and runoff in paddy field (Kim et al. 2009; Reshmidevi et al. 2008; Li and Cui 1996). In addition, it is easier measured than those variables based on the dielectric constant of the soil by well-developed sensor. Accordingly, real time soil moisture monitoring has been developed for monitoring SRI paddy field in Japan with intermittent irrigation (Manzano et al. 2011). Therefore, the method to estimate non-measurable water balance variables based on the monitored soil moisture is vital for water productivity and water use efficiency evaluation without complicated water balance variables measurements.

The present study proposes novel method to estimate non-measurable water balance variables in SRI paddy field by considering the monitored soil moisture on daily basis. Then, the model is validated by comparing observed and estimated soil moisture during planting period.

Methods

Field Experiment

Water balance analysis was performed according to the field data on experimental SRI paddy field in the Nagrak Organics SRI Center (NOSC), Sukabumi West Java, Indonesia during the first rice season 2010/2011 (October 2010 to Februari 2011, wet season). The field is located at 06°50'43" S and 106°48'20" E, at an altitude 536 m above mean sea level (Fig. 1).

Fig. 1 Experimental field location in west java, Indonesia

The field was planted with the local variety of rice (Oryza sativa L), Sintanur, a rice variety suitable for SRI in Indonesia. Here, we used the following SRI rice cultivation: single planting of young seedlings (5 days after sowing) spaced at 30 cm × 30 cm, using an organic fertilizer at 1 kg/m2 on the land preparation and no chemical fertilizer. Moreover, weeding process was conducted regularly every 10 days, starting from 10 day after transplanting (DAT) to 40 days after together with supplying local indigenous microorganism (IMO) to enhance biological activity in the soils.

The field was kept continuous saturated and no standing water was applied during planting period as recommendation from local SRI center. Continuous soil saturation is recommended as the less water consumptive irrigation regime and its application is feasible only when the irrigation water supply is reliable (Janssen et al. 2010). Accordingly, irrigation threshold was performed to maintain water level at -5 cm to 0 cm soil depth.

Field Measurements

The field was monitored by the new developed information system, Field Network System (http://info.ga.a.u-tokyo.ac.jp/fns/Main_Page), which is comprise of meteorological and soil sensors. The meteorological data including precipitation were recorded by using Davis Vantage Pro2 Weather Station every 30 minutes. Daily average values of air temperature, wind speed and relative humidity as well as total solar radiation were used to calculate reference evapotranspiration (ETo) based on the FAO Penman-Mointeith (Allen et al. 1998). In the soil layer, soil moisture sensor (5TE: soil moisture, temperature, electrical conductivity), developed by Decagon Devices, Inc., USA, was installed at the 10-cm depths from the top of soil to measure soil parameters every 30 minutes. All of data were sent daily to the web server on the particular time, thus we called this information system as a quasi real time monitoring system.

Modeling Approach

Water balance analysis was performed according to the schema in Fig. 2. The inflow to the field consists of precipitation and irrigation water, while water leave the field through crop evapotranspiration, runoff and percolation. Here, we define runoff as lateral water movement either artificially through drainage process or naturally when water depth exceeds the height of the drainage outlet and as seepage through bunds in paddy field. Accordingly, water balance equation can be expressed as:

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

where ΔS is the change of soil moisture equivalent to water depth (mm), P is precipitation (mm), I is irrigation water (mm),Qr is runoff (mm), DP is percolation (mm) and ETc is crop evapotranspiration (mm).

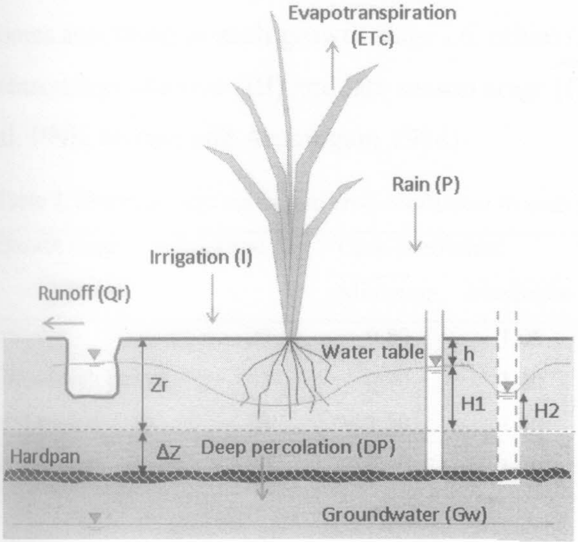

Fig. 2 Water balance in paddy field

Table 1. Review measured and estimated water balance variables of the current study

Variables	Measured	Calculated	Estimated	Method
Soil moisture	√			Soil moisture sensor
Precipitation	√			Rain gauge
Crop evapotranspiration			√	Excel Solver
Irrigation water			√	Excel Solver
Percolation		√		Based on Darcy's law and their parameter was estimated by Excel Solver
Runoff/drainage			√	Excel solver

As mentioned above, however, only soil moisture, precipitation were measured by the developed monitoring system. Therefore, others variables were estimated and calculated based on their parameters as presented in Table 1. Hence, we used Excel solver to estimate non-measurable variables since it has ability to find optimal decision variables up to 200 data within one process by minimizing or maximizing objective function. The guidelines for using Excel Solver could be referred to Morrison (2005).

Excel solver estimation

Excel solver was performed to estimate non-measurable variables according to Eq. 1. Since the number of decision variables was limited, the estimation process was carried out four times according to each growth stage i.e. initial (I), crop development (II), mid-season/reproductive (III) and late season stage (IV) (Vu et al. 2005; Tyagi et al. 2000; Allen et al. 1998; Mohan and Arumugam 1994).

Table 2. Minimum and maximum crop coefficient in each growth stage

Growth stage	Total day	Crop coefficient	
		Minimum	Maximum
Initial	27	0.80	1.05
Crop development	45	0.90	1.20
Mid-season	24	1.10	1.40
Late season	20	0.90	1.20

The decision variables consist of ETc, I, Qr and H2 by minimizing the following equation objective function:

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

subject to the constraints:

$$ETc_{min} \le ETc(t) \le ETc_{max} \qquad (3)$$

$$H2(t) \le H1(t); Qr(t) \ge 0; I(t) \ge 0 \quad (4)$$

where So(t) is observed soil moisture equivalent to water depth (mm), Sm(t) is estimated soil moisture equivalent to water depth (mm), t is time (day, starting from 1 to 116 DAT), n is total days (n = 116), ETc_{min} is minimum crop evapotranspiration, ETc_{max} is maximum crop evapotranspiration, H1 and H2 are water table at different point as parameters to determine deep percolation (mm). ETc_{min} and ETc_{max} were given by multiplying ETo to minimum and maximum crop coefficient, respectively (Table 2). Those values were determined according to the FAO recommendation value (Allen et al. 1998) and by considering current rice cultivation and soil moisture at the field as well particularly in the initial and crop development stages.

Initial Conditions

The initial condition for each decision variable should be determined properly to gain reliable estimated variables. Hence, we consider the actual field situation for each decision variable as explained below:

1. Crop evapotranspiration (ETc)

Initial condition was given according to actual crop evapotranspiration under water stress condition (Allen et al. 1998) and can be calculated using following relationship.

$$ETc(t) = Ks(t) \times Kc(t) \times ETo(t) \qquad (5)$$

where Kc is a crop coefficient that varies with the crop growth stage, Ks is water stress coefficient as the effect of soil moisture in the root zone and calculated using the relationship between actual and saturated water content (Kim et al. 2009; Li and Cui 1996):

$$Ks = 1 \qquad \text{if } Sa(t) = Ss \qquad (6)$$

$$Ks = \frac{\ln(1+100(Sa(t)/Ss)}{\ln 101} \qquad \text{if } \eta Ss \leq Sa(t) < Ss \quad (7)$$

$$Ks = \varepsilon \exp\left(\frac{Sa(t) - \eta Ss}{\eta Ss}\right) \qquad \text{if } Sa(t) < \eta Ss \qquad (8)$$

where Sa and Ss are the actual and saturated water content (m^3/m^3), respectively and η and ε are empirical coefficient for rice set equal to 0.80 and 0.95, respectively (Li and Cui 1996).

2. Percolation (DP)

Percolation (DP) was calculated according to Darcy's law for vertical flow (Jury and Horton 2004). According to Fig. 2, DP was calculated based on two different water tables by following equation:

$$DP(t) = Ks\frac{H1(t) - H2(t)}{\Delta Z} \qquad (9)$$

where Ks is saturated hydraulic conductivity (mm/day) with a constant value, ΔZ is secondary soil layer (mm), H1 is water table according to effective depth (mm) and H2 is lower water table at different points in the field (mm) which was estimated by Excel solver. Percolation loss is primary function of soil texture, and its rate is relatively low for clay soil range to 1-5 mm/d (Guerra et al. 1998) as the current location. Thus, percolation was given at the rate of 1 mm/d on determined H2 as initial condition.

3. Runoff (Qr)

In paddy field, runoff is primary function of precipitation which has positive correlation (Chen et al. 2003). Accordingly, as initial condition, runoff was occurred when precipitation occurred and its value was given by the following formula:

$$Qr(t) = 0 \qquad \text{if } P(t) < ETo_{max} \quad (10)$$

$$Qr(t) = P(t) - ETo_{max} \qquad \text{if } P(t) \geq ETo_{max} \quad (11)$$

where ETo_{max} is maximum reference evapotranspiration (mm).

4. Irrigation water (I)

Irrigation water was given when the precipitation doesn't meet to the plant water requirement through crop evapotranspiration, and also no runoff on the current day. Accordingly, initial condition was given as the following formula:

$$I(t) = 0 \qquad \text{if } Qr(t) > 0 \qquad (12)$$

$$I(t) = ETc_{ini}(t) - P(t) \qquad \text{if } Qr(t) = 0 \qquad (13)$$

where ETc_{ini} is initial crop evapotranspiration (mm).

Model Validation

The model was validated by the indicator of the coefficient of determination (R^2) to compare between observed and estimated soil moisture. The value of R^2 ranged from 0.0 to 1.0 with higher values indicating better agreement.

Results and Discussions

Evaluation of the model feasibility

The model feasibility was evaluated by comparing observed and estimated soil moisture during planting period. Estimated soil moisture was resulted based on estimated non-measurable water balance variables (Table 1). Estimated soil moisture showed good agreement with observed data pointed by high R^2 at the values of 0.71, 0.78, 0.77 and 0.83 for initial, crop development, mid-season and late season stages, respectively (Table 3). R^2 value greater than 0.6 is acceptable or satisfactory for model prediction (Kim et al. 2009). Therefore, the current method was feasible to estimate non-measurable water balance variables.

Table 3. Model validation for estimated soil moisture in the experimental field

Growth stage	Total number estimated data	R^2
Initial	108 (each variables was 27 data)	0.71
Crop development	180 (each variables was 45 data)	0.78
Mid-season	96 (each variables was 24 data)	0.77
Late season	80 (each variables was 20 data)	0.83

The highest R^2 was achieved when total estimated data were lowest number on the late season. However, when the total number estimated data more than 100, higher estimated data has higher R^2 value, and *vice versa.* Accordingly, the number estimated data were not corresponding to R^2 value, despite higher number data need more time for the estimation process. The major factor to gain high R^2 with reliable estimated data is the initial conditions. This should consider the actual field condition such as weather, soil texture and crop as considering in this study.

Estimation of water balance variables

Excel solver has estimated non-measurable water balance variables properly with reliable values and trend during planting period as shown in Fig. 3. Estimated soil moisture trend deal with those observed data in the entire planting period. However, over and underestimation occurred when observed soil moisture increased and decreased suddenly in the crop development and late season stages. The observed soil moisture values varied from 0.511 to 0.608 m^3/m^3 as the result of continuous saturated irrigation threshold at water level ranged from -5 cm to 0 cm from soil surface. Therefore, high intensity of precipitation in the current wet season was commonly drained directly as runoff. Accordingly, the runoff trend's was similar to that precipitation. High intensity of irrigation water was supplied when precipitation was limited particularly in the end of mid-season and early late season stage (Fig. 3).

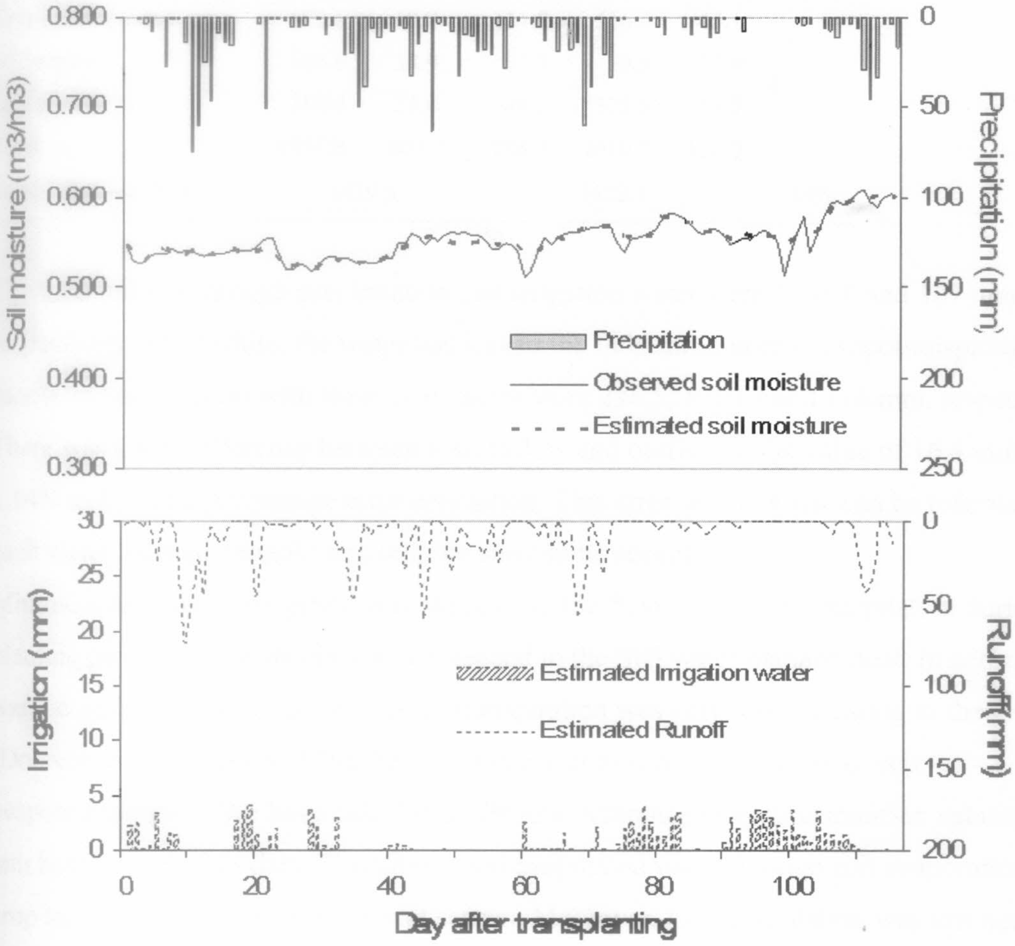

Fig. 3 Observed and estimated water balance variables during planting period.

The non-measurable water balance variables were estimated on daily basis and the total result in each growth stage is presented on Table 4. Crop development stage consumed most water through crop evapotranspiration and loss through percolation as well. Therefore, the most water inflow was should supplied through precipitation and irrigation water. The highest water consumed and water loss were caused by the longest total day in the crop development stage since SRI rice cultivation used younger seedling, therefore plant has more opportunity to remain its growth potential for roots and shoots development (Uphoff et al. 2011).

Table 4. Total water balance variables in each growth stage

Growth stage	Water balance variables					Percentage error (%)
	Inflow (mm)		Outflow (mm)			
	P	I	ETc	Qr	DP	
Initial	374.2	26.4	68.3	311.8	27.1	
Crop development	670.6	19.0	114.7	516.5	45.1	
Mid-season	106.6	38.9	65.3	59.9	23.9	
Late season	180.4	23.4	48.2	122.5	19.9	
Total	1331.8	107.7	296.5	1010.7	116.0	
Total inflow-outflow	1439.5		1423.1			1.14%

The total inflows through precipitation and irrigation water were 1331.8 and 107 mm, respectively. Meanwhile, the water has leaved the field through crop evapotranspiration, runoff and percolation with their total values were 296.5, 1010.7 and 116 mm, respectively. There was a low difference between total inflow and outflow at the value of 16.4 mm or 1.14% as the total percentage error estimation. This error was low and can be tolerated, thus each water balance variable was reliable and can be accepted.

Minimum total water irrigation was supplied to the field since high precipitation during planting period and no standing water needed in the SRI water management. In addition, total water consumption through crop evapotranspiration was very low according to the FAO value (Doorenbos and Kassam 1979), because the effect of low total reference crop evapotranspiration. We have calculated that total reference evapotranspiration value of 279 mm based on weather data. Therefore, total evaporated water through soil evaporation and crop transpiration was low in the wet season. Moreover, total percolation was low according to the FAO noted (FAO 2004) due to the soil texture and application of continuous saturated soil irrigation which can reduce water loss through that percolation by the reduction of hydrostatic pressure (Van der Hoek et al. 2001; Bouman and Tuong 2001).

Conclusions

The novel and simple method was applied to estimate non-measurable water balance variables in SRI paddy field by considering the monitored soil moisture. The proposed method has estimated those variables by using Excel solver estimation. Results of the developed model showed satisfactory result between observed and estimated soil moisture with the values of R^2 higher than 0.70 in the all growth stages. Accordingly, each estimated water balance variable has reasonable trend and value. We found that minimum irrigation water was needed to meet plant water requirement since no standing water and high precipitation occurred in the wet season. Also, the total crop evapotranspiration and percolation were low according to the FAO values as the results of low reference evapotranspiration and reduction of hydrostatic pressure, respectively.

This method can provide a valuable approach for evaluating the water productivity and water use efficiency not only for SRI rice cultivation but also others rice cultivation system with less effort and lower cost without complicated water balance variables measurements. However, those field measurements are still needed to the future research to make the method more acceptable and satisfactory.

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