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A Simulation Model for Soil Moisture and Energy Balance of Paddy Field

[1] Satyanto Krido Saptomo, [2] Budi Indra Setiawan, [3] Kozue Yuge, [4] Ken Mori
[1] Lecturer, Department of Civil and Environmental Engineering, Bogor Agricultural University (IPB), Bogor, Indonesia
[2] Prof., Department of Civil and Environmental Engineering, Bogor Agricultural University (IPB), Bogor, Indonesia
[3] Assoc. Prof., Faculty of Agriculture, Saga University, Japan
[4] Prof. (Emmiretus) Faculty of Agriculture, Kyushu University, Japan

[1] saptomo@ipb.ac.id

ABSTRACT

The energy balance connects to water balance through the evapo transpiration term in the equation. The research utilizes soil water flow and surface energy balance models that estimates thermal environment, evapotranspiration and soil water flows. A computer program codes were developed based on the models. Energy balance model used in this study was able to calculate separately evaporation and transpiration which values were input to soil water flow. The program gives results of sensible heat energy flux, latent heat energy flux and temperatures below, at and above the canopy as well as soil water profiles. Simulation for rice field soil after irrigation is stopped shows the variation of energy fluxes and temperature, and soil water condition that still providing enough moisture for the plant even though the soil surface turns very dry.

Keywords: *Irrigation, rice field, evapotranspiration, numerical model*

1. INTRODUCTION

Water and energy balance estimation plays significant role in the prediction of water availability, consumption and the planning of irrigation water supply for food production land. The energy balance connects to water balance through the evapotranspiration term in the equation. Evapotranspiration can be approached with energy balance calculation using computer model and meteorological data of the site.

At present day, various models and computers program for soil water flow have been developed such as Hydrus (1998), VSDT (Healy and Ronan, 1996) as well as proposed by Setiawan (2007). Most models are suitable for incorporation of surface flux or evaporation at the upper boundary condition and root uptake sink in the soil column. Some of these softwares are available freely for use and modification to meet the purpose of research. This paper presents an effort to combine the two-layered resistance surface energy balance model with soil water flow model for simulating the soil, water and atmosphere system of a vegetated rice field, after the irrigation season.

2. METHODS

2.1 Atmospheric Boundary Layer

The method to model distribution of wind, humidity and temperature in the lower atmosphere, as well as soil heat transfer and surface energy balance were derived from (Nakano and Cho, 1985) and Saptomo et. al. (2004) with assumption of sufficiently wide and horizontally uniform surface as commonly adopted in micrometeorological calculation. Wind velocity u, potential temperature □$_a$ and specific humidity q are assumed only change in vertical direction z. The equations are simply arranged as follows.

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z}\left(K_m \frac{\partial u}{\partial z}\right) \qquad (1)$$

$$\frac{\partial \theta_a}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial \theta_a}{\partial z}\right) \qquad (2)$$

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z}\left(K_v \frac{\partial q}{\partial z}\right) \qquad (3)$$

K_m, K_h, K_v are momentum, thermal and vapor turbulent eddy diffusivities, in which $K_m = K_h = K_v = K_d$ (z) obtained using

K_d (z)=□□ (z-d)u*/□ (z/L) (4)

Here, □ is von Karman constant, d is displacement height, u* is friction velocity, □ is air stability function. Monin-Obkov length L is the atmosphere stability function's index.

2.2 Soil Heat Transport

Assuming the uniform heat properties of soil, vertical 1 dimensional distribution of temperature in the soil is governed with the following equation

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_s \frac{\partial T}{\partial z}\right) \qquad (5)$$

with T as temperature, and K_s as soil thermal conductivity.

2.3 Energy Balance

The basic energy balance equation is written as:

Rn=G+H+LE (6)

Where: Rn: net radiation (W m^{-2}); G: ground heat (W m^{-2}); H: sensible heat (W m^{-2}); L: latent heat (J

Kg^{-1}); E: water vapor (Kg m^{-2}s^{-1}). A detailed model that imitate electrical current and resistance (Fig. 1) was used for calculation of energy balance in paddy vegetated land which also incorporates atmospheric processes and soil heat transport (Saptomo et. al, 2004; Nakano and Cho, 1985) following the multi layer resistance model of soil, plant and atmosphere energy fluxes transfer which was presented by Waggoner and Reifsnyder (1968). The outputs of this model are sensible and latent heat fluxes for each of the layer. The latent heat fluxes can be converted to evaporation and transpiration and then to be can be feed as input to soil water flow model as upper boundary and root uptake sink, as well as to groundwater model as evapotranspiration as a whole.

Since the simulation is intended for simulating water and energy balance during after the irrigation was stopped on non poinding field, the calculation of heat energy and temperature of the ponding water body was not taken into account.

2.4 Soil Water Flow

Soil water flow simulation used the model based on Darcy-Richards equation in one dimension. The governing equations are as follows

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(K\left(\frac{\partial h}{\partial z}+1\right)\right)+S \tag{7}$$

Volumetric water content was approached with van Genuchten Model (1980)

$$m=1-\frac{1}{n};\ n\geq 1 \tag{8}$$

and the unsaturated hydraulic conductivity follows Mualem Model (1976):

$$K(S)=K_s\cdot S_e^{\lambda}\cdot\left(1-\left[1-S_e^{\frac{1}{m}}\right]^m\right)^2 \tag{9}$$

where S is degree of saturation:

$$S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{10}$$

2.5 Soil Water Flow – Energy Balance Integration

The Soil water flow – energy balance (SWF-EB) integration is enabled by applying two sinks for the soil which is evaporation and water extraction by root. Evaporation is simply applied as upward flux from the soil upper boundary or the uppermost point of the flux at the 0th node or the soil upper boundary in the SWF model. Water extraction by root is termed sink (-S) in the SWF model and occurs in the lower column within the rooting zone.

The two values obtained from the two layer resistances models which are the amount of latent heat fluxes separately for canopy and soil surface layers. These are equal to the actual transpiration and evaporation, and used to calculate the amount of evaporative flux and sink in the same unit as in the SWF, which is cm/sec.

Unlike evaporation, transpiration T_p needs further calculation procedure before can be used as sink. The simplest approach in governing the root water uptake is by assuming the equal distribution of root length density over a rooting depth L_r. Since the transpiration and evaporation are considered as actual value resulted from the simulation, water stress response function is

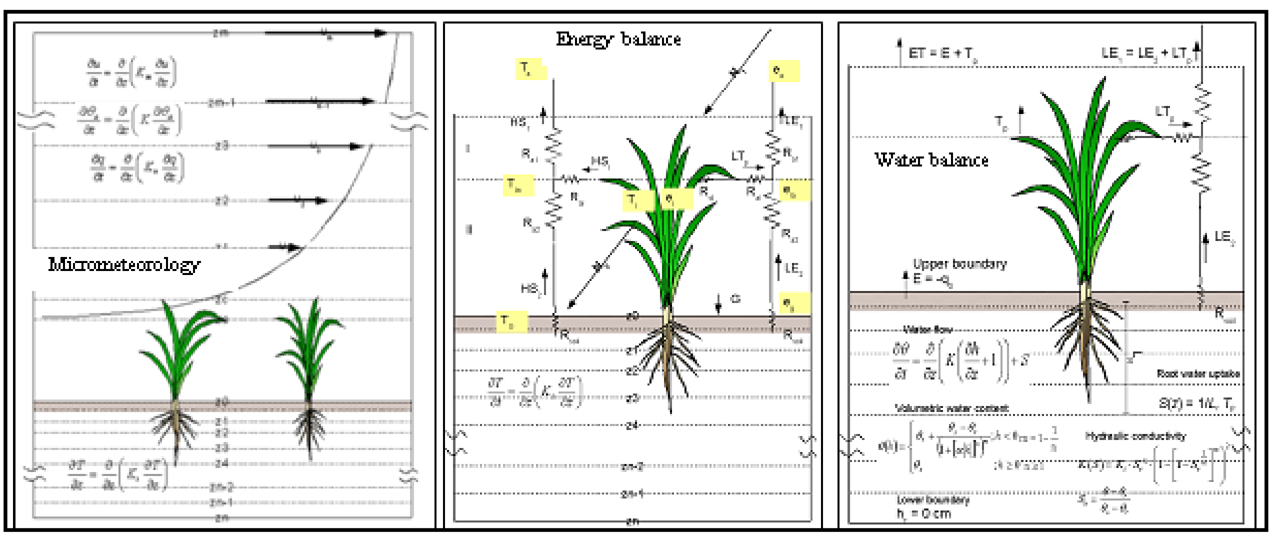

Fig 1: The scheme of the combined soil water flow and surface energy balance model

$$\theta(h)=\begin{cases}\theta_r+\dfrac{\theta_s-\theta_r}{\left(1+\left[\alpha|h|\right]^n\right)^m} & ;h<0\\ \theta_s & ;h\geq 0\end{cases}$$

assumed to a constant value 1 which notes that water stress is already considered in EB simulation. This of course is not without cautions that occasionally the EB simulation might went undesirable and resulted values that do not confirm with the SWF, which can be observed from simulation data. The governing of soil root uptake thus is as follows

$$S = \alpha (h) S_p \qquad (11)$$

$$S_p = 1/L_r T_p \qquad (12)$$

and the root water uptake for each node in depth z in the SWF model is

$$S (z) = 1/L_r T_p \qquad (13)$$

This combined program was developed based on soil water flow model and the energy balance model program which was described in the previous sub-section. The schematic description of the SWF-EB combined model is shown in the following figure.

2.6 Numerical Programming

The partial differential equations of atmospheric processes, soil heat transfer and water flow are numerically solved with finite difference approach. The numerical solution used in this paper follows the works that can be found in Saptomo et. al. (2004) and Setiawan (2007). Since one of the interest is to develop a model that ease the transfer of knowledge in the field, easiness to read and to modify as well as to use and to present results in readable form has become one of criteria in choosing the tools and the programming language. Therefore, instead of using the more powerful language as C or Fortran that are commonly used in numerical computation the program was coded in a spreadsheet with Basic macro language, with the cost of significant decrease of computation speed. The program is run by Basic interpreter, while spreadsheet tables and chart role as pre- and post- processors.

2.7 Data Collection

Soil properties were obtained with laboratory experiment to samples taken from the field. The samples were tested for determining hydraulic conductivities, water content, water retention curve and other standard properties. Observation regarding the micrometeorology was also conducted, which includes rainfall, radiation, temperature and humidity. For this study, samples and data from a paddy field in Cidanau Watershed, Banten, Indonesia was used.

2.8 Simulation Setting

Combined simulation using SWF-EB was conducted with the uniform soil properties, for simplification reason, having saturated conductivity 10^{-5} cm/s, which is within the range of hydraulic conductivities of the analyzed soil samples, which was also reported by Torise et al (2002) for other samples from the same field. The soil was assumed to have 80 depth of water table, which was also used as the lower boundary condition. On the top of the soil column, evaporation taken from energy balance calculation was applied and transpiration was used to determine root water uptake sink in the soil. The transpiration obtained from the amount of latent heat energy from the canopy. The energy balance model assumed the paddy has leaf area index of 4.2 (m^2/m^2) at 70 cm height, and the roughness length and wind displacement height was estimated based on it at 9 and 44 cm. The field was assumed to have no water ponding after irrigation is stopped, however initially the soil was water saturated. Other meteorological data from the location such as radiation were used as input for this simulation.

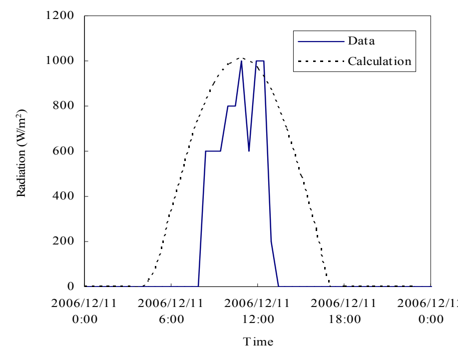

Fig 2: Measured and estimated solar radiation

3. RESULTS AND DISCUSSIONS

The simulation of energy balance used the solar radiation that was measured on a clear day at the study location as well as other data for initial value and based on this data, radiation value for the simulation was generated from global radiation estimate shown in Fig. 2 The sun radiation was intercepted by clouds at the day of measurement and the amount of radiation could not be recorded for some hours in the daytime. Therefore using estimation with extraterrestrial radiation, which formula is mentioned in Allen et. al. (1998), solar radiation that arrives above vegetation canopy was generated in order to obtain smoother radiation data for simulation in a fine day.

Figure 3 shows energy fluxes of net radiation, sensible heat, latent heat of paddy field at the canopy level and soil surface during the first day of simulation, where the soil column was initially water saturated. Most of the available energy is used for evapotranspiration process or dissipates into latent heat, and at the canopy level due to the dense canopy of the paddy.

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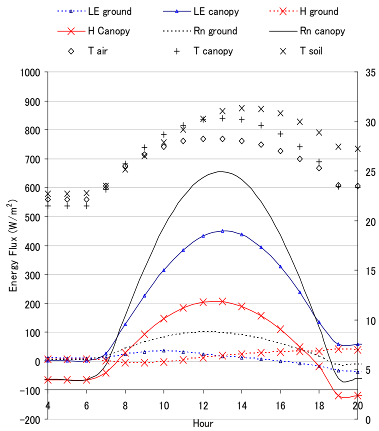

Fig 3: Temperatures, net radiation and heat fluxes on the first day of simulation.

The separation of net radiation, sensible and latent heat fluxes during 6 days of simulation can are shown in Fig. 4. The paddy field soil turns very dry with the absent of surface irrigation, as shown in soil water flow simulation results explained later in this paper. When the soil becomes drier the composition of heat fluxes will change with lower latent heat and more sensible heat energy at the ground surface. At the canopy, latent heat energy increases and sensible heat decreases.

The source of moisture to be transpired with is the root uptake in the rooting zone soil. The amount of moisture extracted from the soil at the root zone calculated by the root uptake is to be equal to the amount of transpiration

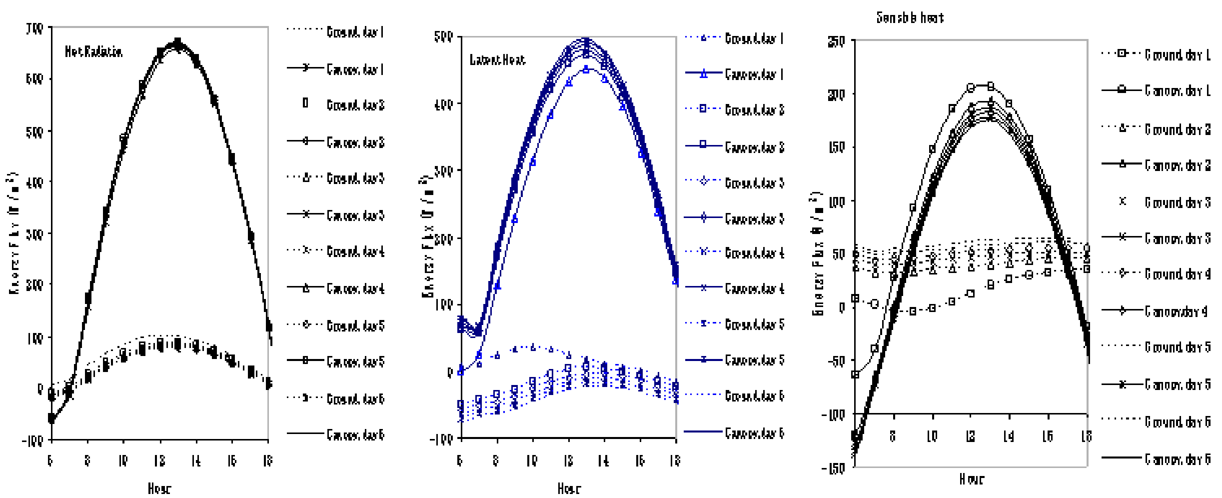

Fig 4: Net radiation, sensible heat and latent heat fluxes separation in 6 days of simulation

indicated by latent heat energy at the canopy. Following the changes of energy dissipation, temperature of soil surface, air and canopy are also changes as shown in Fig. 5.

The soil water profile in pressure/suction and volumetric water content are shown in Fig.6 and 7. Soil water content profile in the 6th day for some extent agrees with the data from soil sample analysis. This is especially in the middle layer, but significantly different at the upper and the lower layer. As mentioned previously that the water saturated soil conductivity that is used in the model are close to the value of saturated conductivity of the middle layer of the soil sample, which might be the reason. Anyhow, the soil water profile shows that the soil, supplied by capillary rise from shallow water table can provide enough water for the rice plant, even though the soil surface is dried to pF 4 or more. This is also shown by the amount of transpiration, represented by the latent heat energy flux at the canopy.

Combining two models however is not a simple matter with complicated loop and iteration, and the error that resulted from the iterative solution-finding process. This is also happened with the combined SWF-EB, which lead to very limited time range of simulation result per cycle of simulation. Fortunately this can be overcome by re-run the simulation cycle with providing new initial values resulted from the previous cycle that were saved in the file. This is with the cost of time in simulation run that increase the required time for completing simulation. Thus the developed program is not suitable for running long time simulations, for example in weeks or longer.

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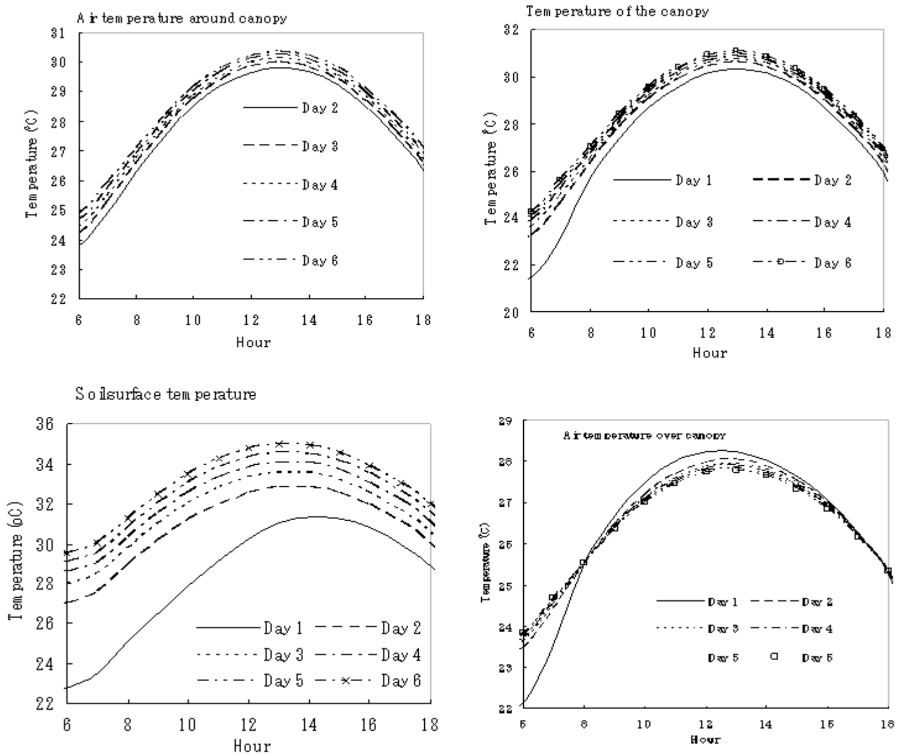

Fig 5: Temperatures over paddy rice during 6 days of simulation.

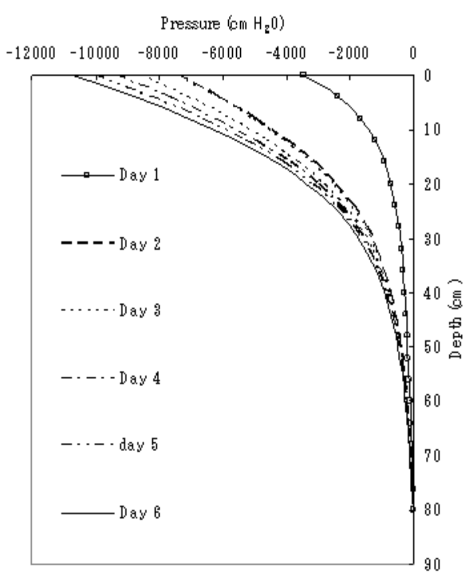

Fig 6: Soil pressure profile

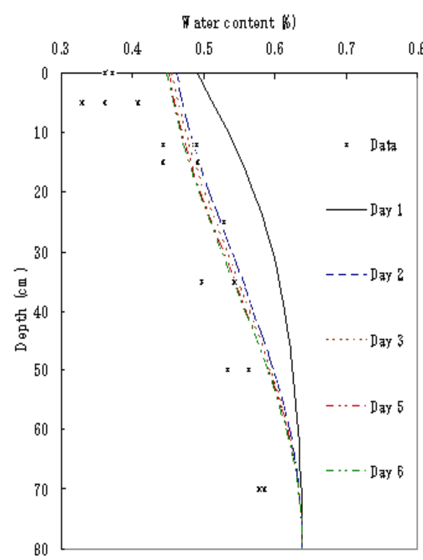

Fig 7: Soil water content profile

4. CONCLUSION

Study of energy balance and soil water flow of paddy field has been conducted using models and computer program as well as field observations. The combination model of soil water flow and surface energy balance was developed and successfully used for simulation with exceptions of limitation of the length of simulation time.

The simulation of paddy energy balance and water flow shows the mechanism of soil water extraction, energy balance changes and temperature changes, and also the soil water content profile that confirm the field data to some extent. By using the two layer resistance model, both evaporation and transpiration can be calculated and applied dynamically to the soil water flow calculation.

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AUTHOR PROFILES

Satyanto Krido Saptomo is a Lecturer, Dept. of Civil and Environmental Engineering, Bogor Agricultural University (IPB). He got his PhD degree from Kyushu University, Japan in 2004.

Budi Indra Setiawan is a Professor, Dept. of Civil and Environmental Engineering, Bogor Agricultural University (IPB). He got his PhD degree from Tokyo University, Japan in 1993.

Kozue Yuge is an Assoc. Professor, Faculty of Agriculture, Saga University, Japan. She got her PhD degree from Kyushu University, Japan in 2003

Ken Mori is an Emeritus Professor, Faculty of Agriculture, Kyushu University, Japan.