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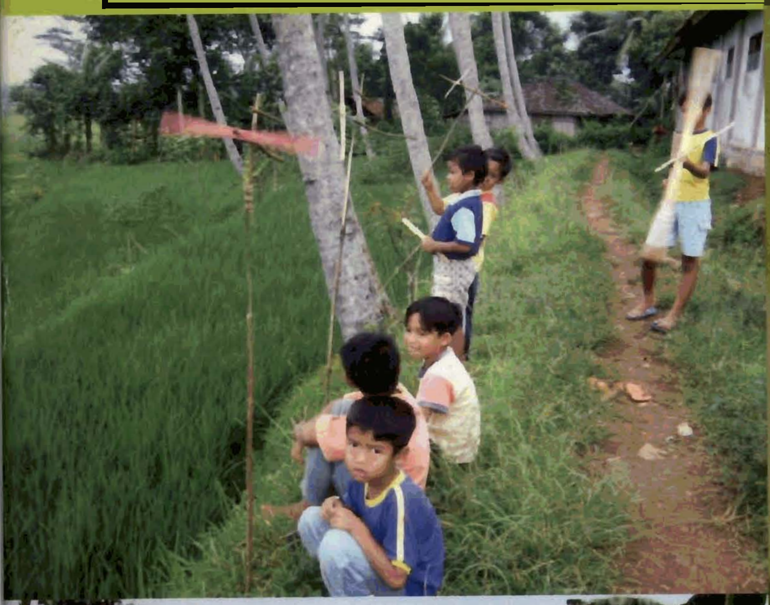

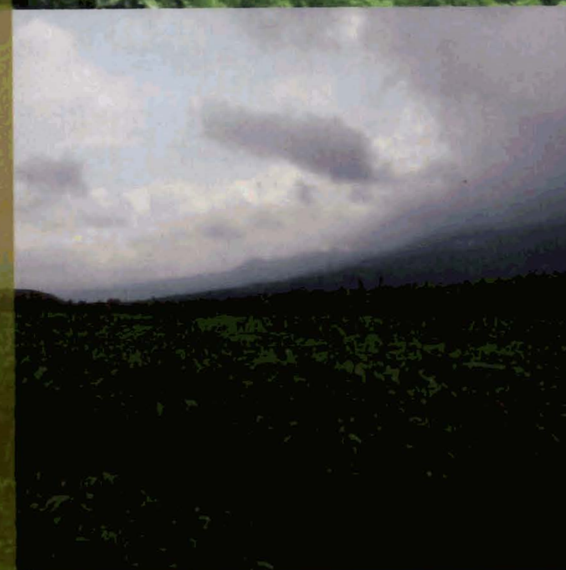

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Graduate School of Agricultural and Life Sciences
The University of Tokyo, Japan

The Study of Water and Energy Balance on a Paddy Field

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Abstract

Water and energy balance estimation plays significant role in the prediction of water availability, consumption and the planning of water supply for food production land. The energy balance connects to water balance through the evapotranspiration term in the equation. The research utilizes models and programs that estimates thermal environment, evapotranspiration, ground and soil water flows. New computer program codes were developed based on the models for some case, and using available scientific softwares for other case. Energy balance model used in this study was able to calculate separately evaporation and transpiration which values were input to soil water flow and groundwater flow model. The shallow groundwater was relatively stable and provided moisture for upper layer soil. The paddy soil surface turned to be very dry in the absent of irrigation and rainfall, but keep sufficient moisture in the deeper layer around the rooting zone.
Keywords : Cidanau watershed, groundwater, soil water, evapotranspiration, numerical model

Introduction

Water and energy balance estimation plays significant role in the prediction of water availability, consumption and the planning of water supply for food production land. The energy balance connects to water balance through the evapotranspiration term in the equation. Evapotranspiration of Cidanau paddy field was approached with energy balance calculation using computer model and meteorological data of the site. The energy balance model was intended to estimate the heat balance of the caldera of Cidanau with various surface conditions (Saptomo, 2004) and even for prediction of its historical thermal environment changes (Saptomo et. al, 2005a). With the difficulties to conduct complete micrometeorological field observations, the study was narrowed and focused on a smaller paddy field site.

The study area is a paddy field in Sadatani area, Cidanau watershed of Banten Province (was part of West Java Province), Indonesia. In this area, unstable mountain stream is taken and used repeatedly by plot-to-plot irrigation and dual-purpose canals, and thus water management of this area is high-efficient. The results of research in this area were reported by Fukuda et. al. (2003) and Torise et. al (2002). The field is dominated by heavy clay soil having small hydraulic conductivity and most of the water flows on the surface of paddy field and the percolation to the underground is very little.

The model of groundwater for the caldera area in Cidanau watershed had been developed taking into account the effects of different surface conditions (Saptomo et. al. 2004a). It is obvious that surface conditions affect groundwater level. The model is proposed for further study of groundwater in the area although there are many improvements still have to be made for the model, such as observation of soil and rivers, hydrological and geological properties of the area.

Later, groundwater modeling was getting very complicated and facing difficulties in fulfilling the needs of accurate physical parameters, boundaries and other data such as soil properties and geological data of the whole caldera. Therefore the groundwater study was focused on a small paddy field site (Saptomo et. al, 2006), along with the soil water flow and evapotranspiration. With limitation and difficulties in conducting thorough field research, the study concentrated on simulation which relied on computer as the tools and limited observation data. This paper presents the latest progress and outcome of the study of water and energy balance in paddy field of Cidanau watershed.

Methods

Most part of the study was conducted using computer simulation as the tools. The simulations were done using self-developed program as well as ready to used softwares. The program are based to mathematical models of the subjects in the research which are groundwater, soil water flow, heat transport in soil and air, changes in atmospheric boundary layer (wind, humidity, temperature), radiation and surface energy balance. Field observation and other data collection were also conducted to obtain real information of the study location.

Groundwater flow model (MODFLOW)

The ground water simulation in this study was performed using USGS Modflow model, a three dimensional groundwater flow modular model McDonald and Haughes (1988), which governing equation is as follows.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (ms^{-1}); h is the potentiometric head (m); W is a volumetric flux per unit volume and represents sources and/or sinks of water (s^{-1}); S_s, is the specific storage of the porous material (m^{-1}); and t is time (s).

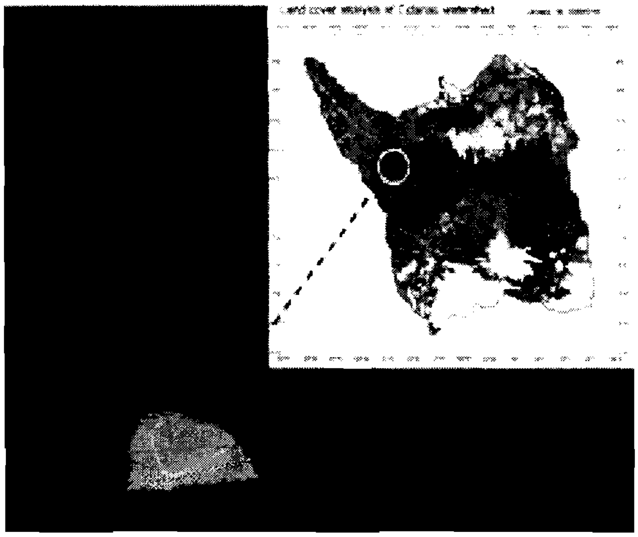

Fig. 1. The study location

The model was generated for the whole Cidanau watershed using digital elevation data of the location (Saptomo et. al., 2005), but the simulation was limited only to the studied paddy field. The groundwater estimation is important to determine the fluctuation of the shallow groundwater flow in the field as well as for the water balance. Groundwater level was used for lower boundary in soil water flow simulation.

Energy balance (EB)

The basic energy balance equation is written as :

$$Rn=G+H+LE \qquad (2)$$

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. 2) was used for calculation of energy balance in paddy vegetated land which also incorporates atmospheric processes and soil heat transport (Saptomo et. al, 2004b; 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.

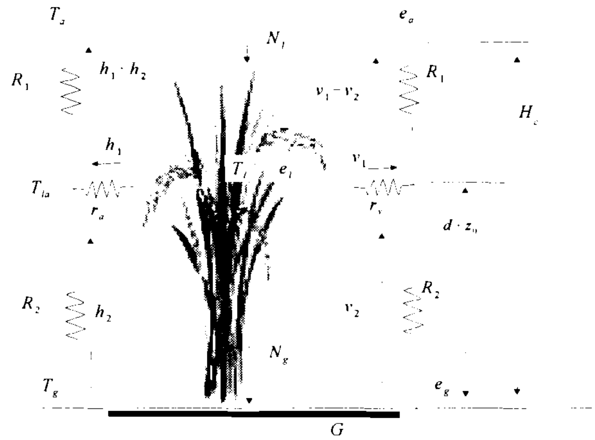

Fig. 2. Resistance model for heat balance estimation (Saptomo *et. al.*, 2004b)

Soil water flow (SWF)

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

$$\frac{\partial \theta}{\partial t}=\frac{\partial}{\partial z}\left(K\left(\frac{\partial h}{\partial z}+1\right)\right)+S \qquad (3)$$

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

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left(1 + \left[\alpha |h|\right]^n\right)^m} & ; h < 0 \\ \theta_s & ; h \geq 0 \end{cases} \qquad m = 1 - \frac{1}{n};\ n \geq 1 \qquad (4)$$

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

$$K(S) = K_s \cdot S_e^{\lambda} \cdot \left(1 - \left[1 - S_e^{\frac{1}{m}}\right]^m\right)^2 \qquad (5)$$

where S is degree of saturation:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (6)$$

Hydrus 1D software (Simunek et. al. 1998) was used for simulation for a complex soil structures having multiple layers and soil properties which resembles the real condition of the field, using the data obtained from soil sample tests. The simulation was run in longer periods. The Macro Basic self-coded spreadsheet was used for the combined soil water flow – energy balance simulation, which was not yet accommodated by Hydrus. This simulation was only run for simplified soil structure with uniform properties and in a short period due to difficulties in handling complex iteration.

SWF – EB Interface

The 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 q at the 0^{th} 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 resistance model 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 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

$S = \alpha(h)\, S_p$ (7)

$S_p = 1/L_r\, T_p$ (8)

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

$S(z) = 1/L_r\, T_p$ (9)

This combined program was developed based on soil water flow model (Setiawan et. al. 2007; Setiawan, 1993) and the energy balance model program which was described in the previous sub-section. The program was coded in a spreadsheet with Basic macro language.

Data collection

Three observation wells were prepared to observe the shallow groundwater level fluctuation. Monitoring was conducted with automatic water level sensor at one checkpoint, and later it was done manually since the water level seemed to be stable in a long period. Field surveying was also conducted in order to obtain the altitude difference between the canal and the wells.

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.

Results and Discussions

Energy balance

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. The simulation assumed no water stress condition occurs in the field. Figure 3 shows energy fluxes of net radiation, sensible, latent and ground heat fluxes on the paddy field. Most of the available energy is used for evapotranspiration process or dissipates into latent heat which means the paddy field tends to evaporate rather than to heat up. This simulation also results the fluctuation of temperature and humidity of the field but not presented in this paper.

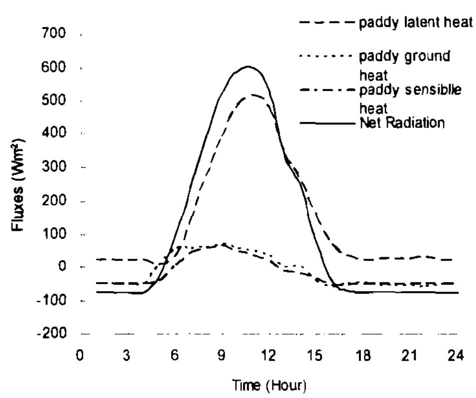

Fig. 3. Heat budget of the paddy

The latent heat flux shown in the figure is the summation of latent heat fluxes of the canopy layer and below the canopy layer resulted in this simulation is. The two can be drawn separately as shown in Fig. 4 which also depicted the equal transpiration and evaporation in cm/hour unit. Total transpiration compared to evaporation is about 1:4 or about 0.1 cm/day and 0.4 cm/day which sum 0.5 cm/day evapotranspiration.

The paddy field soil can actually turn very dry when bared, as shown in soil water flow simulation results explained later in this paper. When it is become very dry the composition of heat fluxes will change with lower latent heat and more sensible and ground heat which will cause the increase of the temperature.

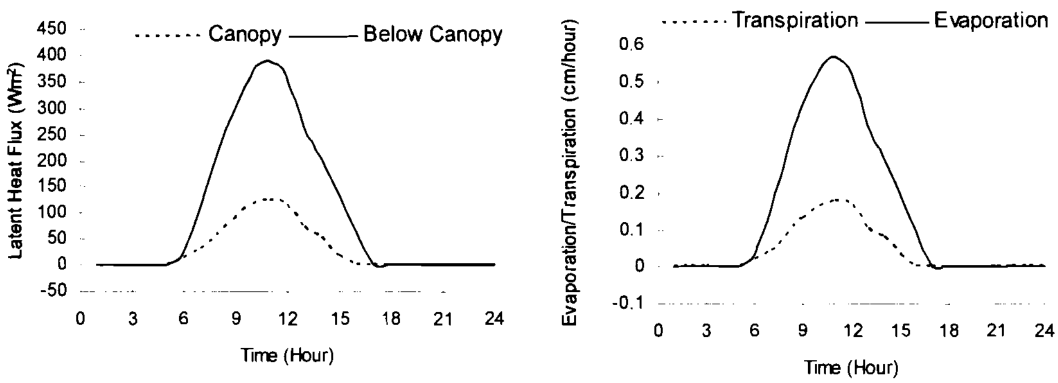

Fig. 4. Separated latent heat fluxes, evaporation and transpiration

Groundwater

Figure 5 shows the schematic of groundwater flow model area and its boundaries. In the model, the area is surrounded by boundaries of channels and constant head. The constant head however was interpolated from data of the two observation well (1 and 2) which actually slightly fluctuated. The profiles of the channels were measured in a survey. Hydraulic properties that were used in the simulation are enlisted in Table 1.

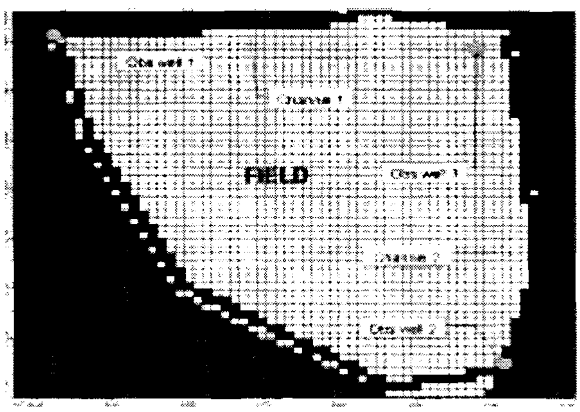

Fig. 5. Groundwater model

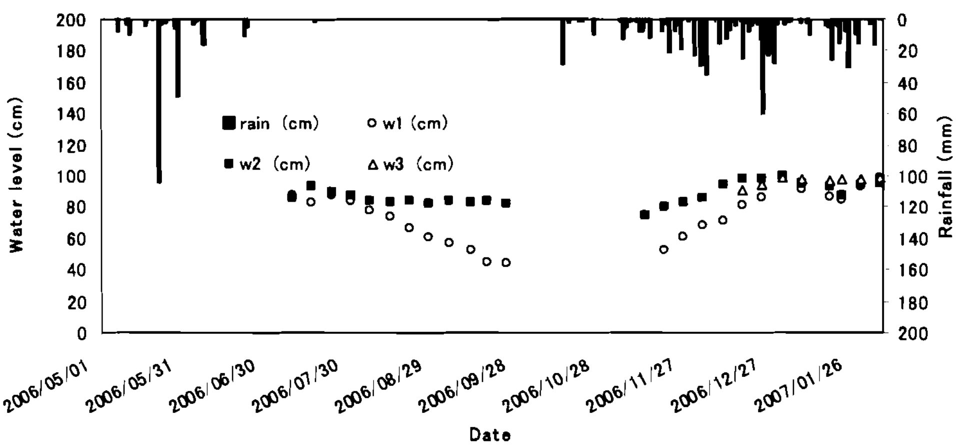

Fig. 6. Rainfall and groundwater observation well water fluctuation

Figure 6 shows the rainfall and fluctuation of observation well 1, 2 and 3. Water levels fluctuate in a narrow range, and only the 1st well had the water level decreased down to about 50 cm. The water level slightly increased as the rainy season come, but relatively stable. With small soil hydraulic conductivity which would lead to small infiltration and most water flows as surface run off that was also reported by the previous reports, it seems that rainfall does not have direct high impact to the groundwater. The stable groundwater level is also shown in the simulation. Figure 7 shows the equipotential contour of the groundwater during simulation on 1 day, 50 days, 100 days and 135 days.

Table 1. Parameters used for groundwater simulation

Parameter	Unit	Value
Hydraulic conductivity :		
K_{xx}	cm sec^{-1}	10^{-6}
K_{yy}		10^{-6}
K_{zz}		10^{-6}
Specific Storage S_s	-	0.28
Specific yield S_y	-	0.28
Porosity	-	0.7
Effective Porosity	-	0.28

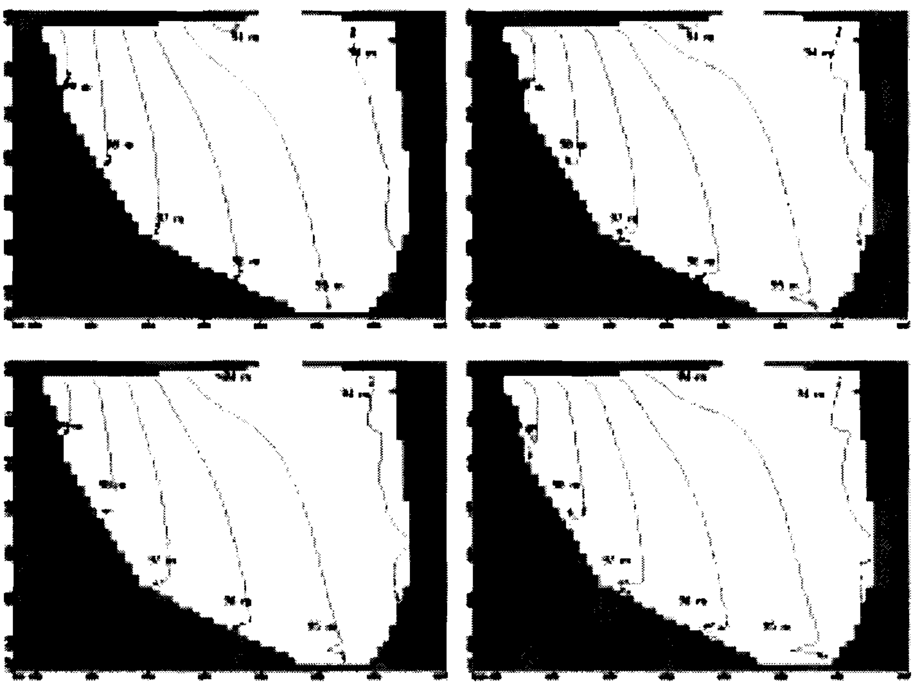

Fig. 7. Simulated groundwater level

The stable groundwater level might be because of the fact that the area was formerly a lake. The lake was drained to provide land for food production, and the remaining part formed the swamp that has high surface water level which affects the shallow groundwater of the paddy field and anywhere else inside the caldera. It is an interesting subject if water level fluctuation on any surface water and wells can be observed continuously and the real condition of the groundwater can analyzed in more detail.

Soil water flow

Simulation using Hydrus software for 100 days was conducted using the acquired data from soil samples taken from the field. The simulation assumed nearly saturated condition for most layers as initial condition. The soil column has depth of 80 cm which is about the equal depth of the shallow groundwater table in on of the field check point and assumed constant throughout the simulation. Constant saturated soil as representation of the present of the shallow groundwater table is assumed at lower boundary. Constant flux for upper boundary at 0.4 cm/day and root water uptake model for sink factor was implemented. Root water uptake was calculated from 0.1 cm/day transpiration. The root was assumed to extent down to 30 cm depth. Figure 8 shows the hydraulic properties of the soil, approached with van Genuchten and Mualem model.

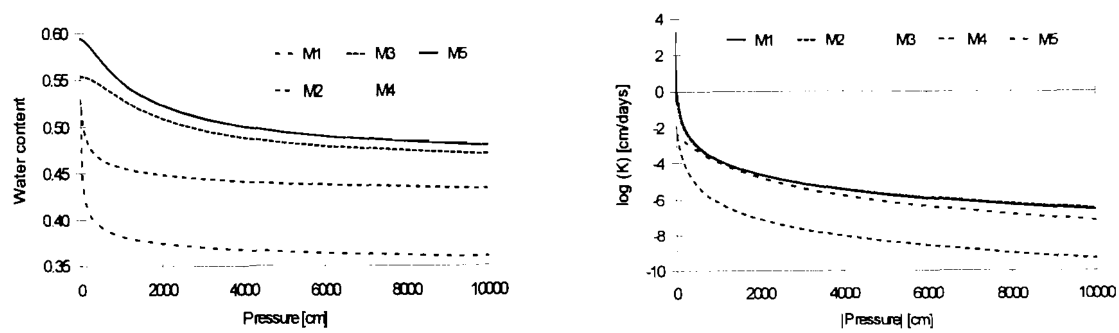

Fig. 8. Hydraulic properties of the paddy fields soil

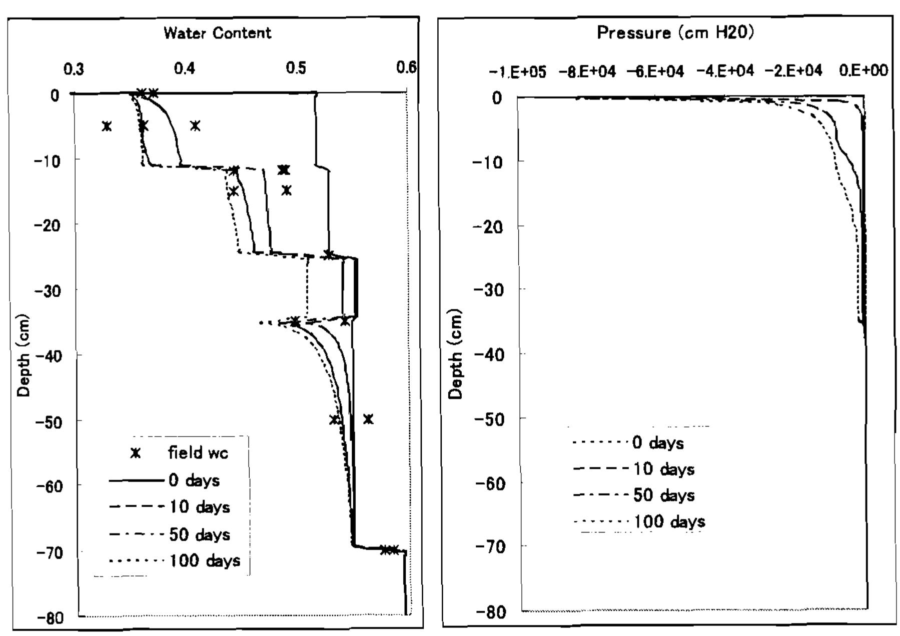

Fig. 9. Soil water content and pressure profiles

Figure 9 shows the profiles of soil water content and pressure resulted from simulation. In this figure, even though the soil is very dry at the surface in deeper layer soil water content is near enough to field capacity, as shown by the data and simulation result. This means the soil reserves moisture below the surface and that is probably enough for plants to extract water even with the absent of surface irrigation and rainfall. The shallow water table is somewhat functioning as subsurface irrigation for the plants.

SWF-EB

Combined simulation of soil water flow and energy balance (SWF-EB) was conducted with the uniform soil structures having saturated conductivity 10^{-5} cm/s. The soil data was obtained from the report by Torise et.al. 2002. 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 as for the root water uptake sink in the soil, the transpiration was used to determine it. The energy balance model assumed the paddy has leaf area index of 4.2 (m^2/m^2) and was at 70 cm height, thus 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, however initially the soil was water saturated. Other meteorological data from the location such as radiation were used as input for this simulation.

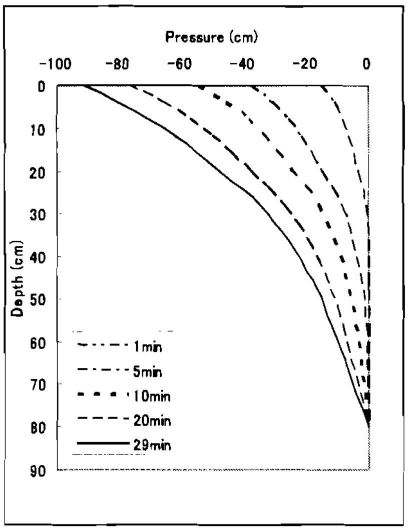

Fig. 10. Pressure profile from SWF-EB

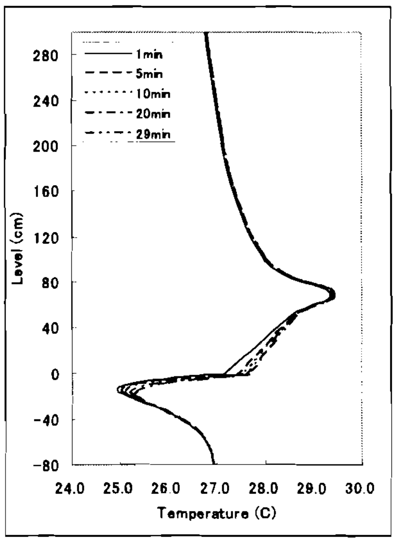

Fig. 11. Temperature profile from SWF-EB

The combined program was able to simulate the interaction of soil, water and atmosphere as can be seen in Fig. 10, 11 and 12 which depicted the profile of soil water potential, temperatures and air humidity. Similar to the previous simulation with Hydrus model, the surface tends to loose moisture and the water table supplies water to the upper layer. The temperature, as commonly known has its peak on about after the midday and has the highest at the canopy surface. Figure 13 shows energy fluxes composition during this simulation.

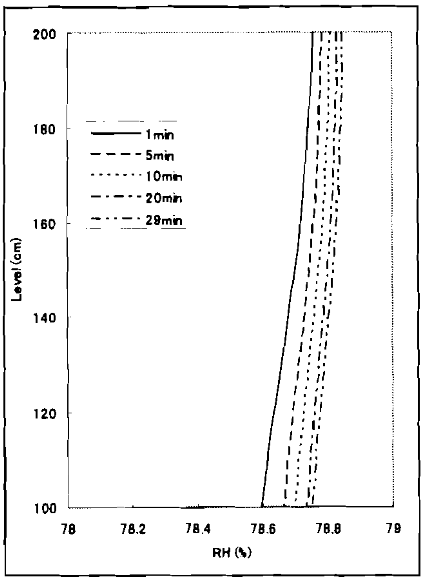

Fig. 12. Air humidity profile from SWF-EB simulation

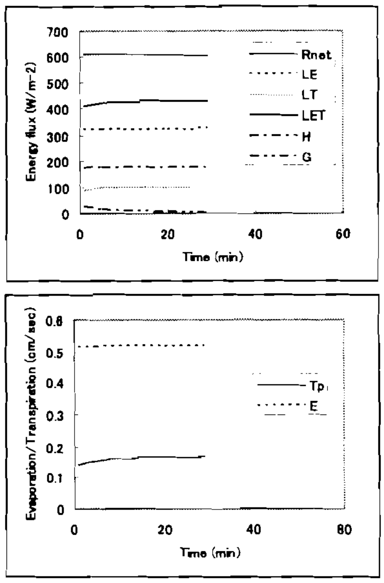

Fig. 13. Energy fluxes, evaporation and transpiration rates from SWF-EB simulation

Combining the two models however is not a simple matter when the complicated loop and iteration, and the error that resulted from the iterative solution-finding process. This was also happened with the combined SWF-EB, which lead to very limited time range of simulation result can be presented in this paper. The calculation over 30 minutes had lead to execution error. Although some problems had been identified, to fix the problem significant change might need to be done. This will be managed along with the improvement of the model for research continuation in the near future.

Conclusion

Study of energy balance, evapotranspiration, groundwater and soil water flow of paddy field has been conducted using models and computer program as well as field observations. The study touched several aspects of the bio-environment of the specific location and resulted in information and tools that can be used for further research. But also it faced many difficulties that limiting the study area and deepening the research have turned out to be solution.

The groundwater of the paddy field is stable and has function to provide water in the soil below the surface enough for water extraction by root. The soil surface can has very dry in the dry season but below the surface water seems to be available. The combination model of soil water flow and surface energy balance was developed. Although the program can provide some information of the soil, plant and atmosphere conditions, it is not yet capable for running simulations in a long period of time because of the increasing of instability with time.

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References

Fukuda, T., M. Kuroda,Y. Nakano and S. Takeuchi. 2003. Water System Management and Irrigation Practices of Traditional Paddy Farming - Utilization of Small Stream Runoff for Irrigation, *Sustainable Agriculture in Rural Indonesia*, Gadjah Mada Univ. Press, pp. 57-63.

McDonald, M.G. and A.W. Harbaugh (1988). *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model.* U.S. Geological Survey.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.* **12**, pp. 513–522

Nakano, Y. and T. Cho 1985 A Numerical Study to Evaluate the Effect of a Plant Canopy on the modification of Thermal Environment (*in Japanese with English abstract*). *Trans.JSIDRE*,115:1-7.

Saptomo, S.K., B. I. Setiawan,Y. Nakano, M. Kuroda, and Rudiyanto. 2006. The Use of Shallow Groundwater as Irrigation for Rice Cultivation. *Proceeding of The 4th PAWEES International Conference on Management of Paddy and Water Environment for Sustainable Rice Production (II)*, Utsunomiya, August 10 -11.

Saptomo, S.K., B. I. Setiawan,Y. Nakano, M. Kuroda, T. Fukuda and S. Takeuchi. 2005a. Regional Water and Heat Balance in Sedatani Paddy Field Cidanau Watershed. *Proceeding PAWEES International Conference*, Kyoto, September 7^{th}-8^{th}, pp. 65-70.

Saptomo, S.K., Y. Nakano, T. Haraguchi and K. Yuge. 2005b. Historical Changes of Land-use and Thermal Environment of Cidanau Watershed. *J. Agric. Meteorol.* 60(50):701-704.

Saptomo, S.K., B.I. Setiawan, Y. Nakano, M. Kuroda and K. Yuge. 2004a. Development of Model for Simulation Study of Groundwater under Affection of Various Surface condition in Cidanau Watershed. JSPS-DGHE International Seminar *Toward Harmonization between Development and Environmental Conservation in Biological Production*, pp. O1-1:1-10. Banten, 3-5 December

Saptomo, S.K., Y. Nakano, K. Yuge and T. Haraguchi. 2004b. Observation and Simulation of Thermal Environment in a Paddy Field. *Paddy and Water Environment,* 2004(2):73-82

Saptomo, S.K. 2004. *Simulation study of regional thermal environment, evaporation and groundwater under various surface conditions.* Dissertation. Division of Regional Environment, Graduate School of Bioresource and bioenvironmental Sciences, Kyushu University, Japan.

Setiawan, B.I. 1992. *Studies on infiltration in soil having macropore*. Dissertation. Division of Agricultural Engineering, Faculty of Agriculture, The University of Tokyo, Japan.

Setiawan, B.I. 2007. *Numerical Solution to The Water Flow Equations in Unsaturated Soils (Explicit and Implicit Schemes of Finite Different Method-Dirichlet, Neumann and Cauchy Boundary Conditions-Microsoft Excel and Visual Basic Editor)* - Unpublished. Umea, Swedish.

Simunek, J., M. Sejna, and M. Th. van Genuchten. 1998. *The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, Version 2.0.* IGWMC - TPS - 70, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado, 162pp.

Torise, K., T. Fukuda, Y. Nakano, M. Kuroda and S. Takeuchi. 2002. Water Management of Paddy Area in Cidanau Watershed, Indonesia (*in Japanese*). *Sci. Bull. Fac. Agr., Kyushu Univ*, 57(1), pp. 143-152.

van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc.* Am. J., 44, 892-898.

Waggoner, P.E and W.E. Reifsnyder. 1968. Simulation of the temperature, humidity and evapotranspiration profiles. *J.Appl.Met.*, 7:400-409.