The Modification of Numerical Evapotranspiration Model by Using Remotely Sensed Surface Temperature Data

Satyanto K. Saptomo1  Yoshisuke Nakano2  Tomokazu Haraguchi3 Kozue Yuge4 Masaharu Kuroda5

Abstract

ET for large area with different land covers were estimated by evaluating energy balance components for each land use, using numerical model of energy balance which includes differential equations of wind velocity, specific air humidity, potential air temperature, soil temperature and soil moisture. Remotely observed surface temperatures were used to modify the parameters used within the model. The inputs for this model are direct and diffused solar radiation, solar elevation, long wave radiation, surface temperature, ground moisture, crop transpiration resistance, leaf area index, crop canopy architecture, wind velocity, air temperature and relative humidity at surface and at boundary height. The extinction of solar radiation intensity as it passes the land cover canopy is estimated by treating the plant canopy as a single ‘big leaf’. As for the upper boundary of this system, constant values of wind velocity, potential air temperature, and specific humidity were used at the height of 100 m above ground surface. The lower boundary was taken at 0.5 m depth under ground surface. This technique is applied for conducting numerical experiment to estimate ET temporal and spatial distribution over different land uses at the area of Cidanau watershed, Banten, Indonesia. Land utilizations at the study location are artificial surface, paddy field, bare soil and forest. In this study, evapotranspiration estimated in artificial surface, bare soil, paddy field and forest are 0, 4.5, 5 and 6 mm/day respectively.

Introduction

Remotely sensed data at the present time has been widely used to determine processes such as evapotranspiration at the ground surface. This method reduces the difficulty of observing parameters required to estimate the evapotranspiration and leads to more accurate result especially in large area. But the remotely sensed data is not always available, and could not provide continuous data. Therefore, mathematical models are required for estimating evapotranspiration on for example hourly basis variation.

1 Laboratory of Irrigation and Water Utilization. Kyushu University. Fukuoka 812-8581 Japan. saptomo@bpes.kyushu-u.ac.jp
2 Laboratory of Irrigation and Water Utilization. Kyushu University. Fukuoka 812-8581 Japan. ynakano@agr.kyushu-u.ac.jp
3 Laboratory of Bioproduction and Environment Information Sciences. Kyushu University. Fukuoka 812-8581 Japan thara@brs.kyushu-u.ac.jp
4 Regional Environment System Engineering. Kyushu-Kyoritsu University. Kitakyushu 807-8585. Japan. yuge@kyukyo-u.ac.jp
5 Regional Environment System Engineering. Kyushu-Kyoritsu University. Kitakyushu 807-8585. Japan. mkuroda@kyukyo-u.ac.jp
Evapotranspiration can be estimated by analyzing the surface energy balance. Some models had been presented by Myrup (1969), Denmead (1969) and Gutman and Torrance (1975). Furthermore, energy balance analysis for a surface which is covered with plant canopy by using resistance model had been proposed by many researchers such as Waggoner (1968), and Lhomme (1988). Combining the data observed by remote sensing and the model, more informative results of the estimation can be expected.

Parameterization of the models is very important before the model is applied. The ET value of every specific land surface condition (paddy, forest, bare and artificial in this paper) will be estimated by the simulation using the parameterized model. The ET resulted from the simulation should be verified using any available data of ET of the same location.

After the estimated ET of each land surface condition is obtained, the ET of the whole area can be calculated. This will need a land surface condition or land use map of the area. This map was obtained from Landsat image interpretation. Combining the digital map of the area and ET resulted from simulation using model of each surface condition, ET distribution map can be made. Also, the total ET of the whole area, i.e. watershed can be estimated by accumulating the ET of each area with the certain land surface condition.

The objective of this study is to set the parameters in numerical model of energy balance using remotely sensed surface temperature data, and use the models to estimate hourly evapotranspiration of different land use.

**Simulation Model**

1. **Numerical Model**

The estimation of evapotranspiration was done by analyzing surface energy balance. For this purpose, a two-layer resistance model following Nakano and Cho (1985), were used. This model is a simplified model of multi-layer resistance model proposed by Waggoner et.al.(1969). The model considers solar radiation interception by plant canopy, which affects the energy balance, and also has an electrical analogy of resistance properties occur in the flow of sensible heat flux and latent heat flux, on each layer. The extinction of solar radiation intensity as it passes the land cover canopy is estimated by treating the plant canopy as a single ‘big leaf’. There are many parameters interact in this model such as leaf area index ($LAI$), resistances and soil surface water potential. A simple surface energy balance model, on the other hand, was used for estimating surface energy budget over artificial surface. More information regarding the two layers model is presented in Appendix A.

The inputs for this model are direct and diffused solar radiation, solar elevation, sky long wave radiation, surface temperature, ground moisture, crop transpiration resistance, leaf area index, crop canopy architecture, wind velocity, air temperature and relative humidity at ground surface and boundary height. Wind velocity $u$, potential temperature $\theta$ and specific humidity $q$ were assumed to be uniform in horizontal direction and only change in vertical direction, neglecting the convection part; the equations are simply arranged as follow (Nakano and Cho, 1985)
\[
\frac{\partial u}{\partial t} = \frac{\partial}{\partial z} \left( K_m \frac{\partial u}{\partial z} \right) \tag{1}
\]
\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( K_h \frac{\partial \theta}{\partial z} \right) \tag{2}
\]
\[
\frac{\partial q}{\partial t} = \frac{\partial}{\partial z} \left( K_v \frac{\partial q}{\partial z} \right) \tag{3}
\]

Here \( K_m, K_h, K_v \) are turbulent diffusivity for momentum, thermal and vapor, in which \( K_m = K_h = K_v = K \). \( K \) can be obtained from the following equation.

\[
K = \kappa (z-d) u^* / \phi (z/L) \tag{4}
\]

Where, \( \kappa \) is Karman constant, \( d \) is zero-plane displacement height, \( u^* \) is friction velocity, \( \phi \) is the air stability function. Monin-Obukhov length \( L \) is the atmosphere stability function’s index and given as

\[
L = \rho_a c_p (T_a + 273.16) u^3 / g \kappa Q \tag{5}
\]

where \( T_a \) is air temperature (°C), \( Q \) is sensible heat flux, \( \rho_a \) is air density, \( g \) is the gravitational acceleration and \( c_p \) is the specific heat of air at constant pressure. The value of \( L \) indicates unstable condition (\( L<0 \)) and stable condition (\( L>0 \)).

The calculation of vertical changes of atmospheric parameters in a boundary layer were then conducted by using finite different schemes of Equation 1, 2 and 3. The height of this layer is 100 meter from the plant canopy’s top. This layer was divided into unequal 16 compartments.

The change of ground temperature is expressed

\[
\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K_s \frac{\partial T}{\partial z} \right) \tag{6}
\]

where \( T \) is temperature, and \( K_s \) is soil thermal diffusivity. The depth of sub-surface boundary layer was assumed 0.5 m and divided into 16 compartments.

2. Modification of the model

In order to obtain surface temperature resulted from simulation that agrees with those obtained by observation, parameters in the model were modified or tuned. One of the important parameters to be modified is stomatal resistance. In the process of water exchange between soil, plant and atmosphere, stomatal resistance to the evapotranspiration occurs as response to the...
changes of moisture condition. Hence, in estimating latent heat flux transfer, additionally stomatal resistance of the plant should be taken into account, instead of the sole boundary resistance or aerodynamic resistance as in the sensible heat flux transfer. Stomatal resistance in Penman-Monteith model is included in the bulk surface resistance. In multi-layered resistance model, stomatal resistance is calculated for each layer, except the bottom layer which is the soil surface layer. Since our model only consists two layers, it was only considered in the first layer.

Stomatal resistance \( r_s \) were calculated using the Equation 7 taking into account the minimum stomatal resistance \( r_{min} \).

\[
r_s = r_{min} + \frac{b}{I + \frac{b}{(r_c - r_{min})}}
\]

\( (7) \)

![Figure 1. The effect of changing \( r_{min} \) to the plant surface temperature](image)

Where, \( r_c \) is cuticle resistance, \( b \) is a constant and \( I \) is the amount of solar shortwave radiation absorbed by plant. Since latent heat flux density changes depending on \( r_{min} \), the sensible heat flux density will also be affected. When \( r_{min} \) changes corresponding to soil moisture, sensible heat flux density will also change and affect surface temperature. The effects of changing the value of \( r_{min} \) is shown in simulation result of surface temperature, using meteorological data of a fine day in August 2001, depicted in Fig. 1. The plant surface temperature is increasing when higher \( r_{min} \) occurs.

**Observation and Data Collection.**

The observation was conducted using instruments such as solarimeter and electronic temperature data logger. Surface temperature was observed hourly under clear sky condition in the daytime, remotely measured with an infrared thermometer from a hill near the location where the whole area was visible. Surface air temperature and humidity, surface temperature, solar shortwave radiation and wind velocity were observed. Local meteorological data and
Landsat surface temperature data were also obtained.

Fig. 2 is the satellite image of the surface temperature of the study location (dashed rectangular), of Cidanau Watershed Indonesia. The temperature of the location in this image ranges from about 20° to 26.8° C. More information regarding the remote sensing image is presented in Appendix B.

![Fig 2. Landsat image of surface temperature of Cidanau Watershed (August 7, 2001)](image)

Fig. 3 is an example of field observation data in the study location (S 6°11’49”, E 105°54’25”). The area is mainly a wide paddy field surrounding by trees, forest and hilly topography. The location is near to a swamp forest belongs to a natural reserve known as ‘Rawa Dano’ in Cidanau Watershed. From this picture the difference in surface temperature of different land

![Fig. 3. Example of temperature distribution observed at location (August 25, 2002 11:00AM).](image)
condition is noticeable.

The parameters used in the simulation are enlisted in Table 1. These parameters were cited from references (Nakano and Kuroda, 1989; Oke, 2001), meteorological data from local climate station, field measurement and assumption.

As for the boundary conditions, the height of 100 m was taken for the upper boundary and the depth of 0.5 m below the soil surface for the lower boundary. The diurnal variation of temperature decreases rapidly with depth in the soil, and can be approached by assuming it as sinusoidal variation such as explained in Campbell and Norman (1998). The upper boundary parameters also have diurnal variations. However, due to the unavailability of sufficient data to develop a model or to imitate the variation of boundary parameters, the boundary condition of air temperature, air humidity, and wind velocity and soil temperature were kept constant during the simulation at 30.7°C, 0.017g/g, 3.3 m/s and 31.7°C.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Forest</th>
<th>Bare soil</th>
<th>Paddy field</th>
<th>Artificial (road/asphalt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum resistance $r_{min}$ (s/m)</td>
<td>100</td>
<td>300</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Leaf Area Index $LAI$</td>
<td>8</td>
<td>0.5</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Thermal diffusivities of soil ($m^2s^{-1} x10^{-6}$)</td>
<td>0.2</td>
<td>0.4</td>
<td>0.27</td>
<td>0.38</td>
</tr>
<tr>
<td>Volumetric heat capacity of soil ($Jm^{-1}K^{-1} x10^{6}$)</td>
<td>0.6</td>
<td>0.55</td>
<td>0.65</td>
<td>0.47</td>
</tr>
<tr>
<td>Soil water potential (bar)</td>
<td>-1</td>
<td>-1000</td>
<td>0</td>
<td>-10 (20%)</td>
</tr>
<tr>
<td>Albedo (%)</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Roughness length (m)</td>
<td>1.04</td>
<td>0.02</td>
<td>0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>Obstacle height (m)</td>
<td>8</td>
<td>0.2</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>Zero-plane displacement height (m)</td>
<td>5.04</td>
<td>0.13</td>
<td>0.44</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Results and discussion

1. Surface temperature.

The estimated surface temperature of 4 different land use types are shown in Fig. 4a, 4b, 4c and 4d. Due to lack of observation data, the surface temperature resulted from simulation can only be compared with the data, which are available from 10 am to 4 pm. The temperature data was not continuously measured. Remote observation using an infrared thermometer was done on hourly basis, depended on the weather condition. The observation was conducted in the month of August year 2002. The simulation was done for a fine day in the month of August.
The simulated temperature fluctuates within the range of the measured temperature data of 28°C to 32°C (forest), 28°C to 34°C (paddy field), 31°C to 34°C (bare soil) and 38°C to 60°C (asphalt). In the noontime, the simulation results seem to agree with the observation data, especially for paddy fields, forests and bare soils. But in the afternoon, the surface temperatures were underestimated.

Fig. 4. Simulated and observed surface temperature of (a) paddy field, (b) bare soil, (c) forest (d) artificial surface (asphalt road).
The hourly variation of estimated surface temperature of four different land use types shows the effect of surface condition to its thermal environment. Under the same condition of meteorology, temperature of artificial surface (asphalt) reaches more than 50 °C, while the highest forest temperature only about 30 °C, following paddy field and bare soil. This variation presented in Fig. 5. Here, the effect of plant and vegetation existence to the thermal environment is obvious.

2. Sensible and Ground heat flux

The net radiation absorbed by the earth surface is composed by the incoming and outgoing shortwave and long wave radiation. The energy is dissipated into sensible heat flux, ground heat flux and latent heat flux. Sensible heat flux, when released, will cause the temperature of the environment above ground surface to increase. Ground heat flux in the other hand will be used for heating the soil.

Fig. 6.a and 6.b show the hourly fluctuation of sensible heat flux and ground heat flux. Fig. 6.a shows the variation of sensible heat flux of each land use. The sensible heat flux released by artificial surface is very high compared to the other. In forest area, the sensible heat flux is negative, which indicates the forest temperature is lower than its environment and the forest has the role as the sink of heat energy. In Fig. 6.b characteristic of artificial surface, in this case asphalt road, which has high ground flux, is clearly noticed.

The heat fluxes of forest area are unusual compared to the energy balance of pine and fir forests (Oke, 2001). The different is especially shown by the variation of daytime sensible heat flux, which is always negative. Although this could be explained as the heat sink role of the forest, this extreme behavior should be a consideration to re-evaluate the parameterization of the forest model.
3. Evapotranspiration

The component of energy balance used for evapotranspiration process is the latent heat flux. Each land use type has different condition of latent heat flux variation (Fig. 7). The latent heat flux of the artificial surface is zero, which means no evaporation occurs, and the whole of surface energy was used to increase the environmental temperature and the ground temperature. The evapotranspiration of bare soil is lower than paddy field. Paddy field usually has a shallow water surface above the soil surface and it contributes to the evapotranspiration. Fig. 7 shows that evaporation occurs in four different land uses are, in order from the largest, forest, paddy field, bare soil and artificial field.

The total daily latent heat of every land use (Fig. 8) are 12.5 MJ.m\(^{-2}\).d\(^{-1}\) (Paddy field), 11.2 MJ.m\(^{-2}\).d\(^{-1}\) (Bare soil) and 15 MJ.m\(^{-2}\).d\(^{-1}\) (Forest). These values are equal to 5, 4.5 and 6 mm of water. This is an estimation for evapotranspiration during daytime with fine weather, in the month of August.

Fig 6. (a) Hourly variation of simulated sensible heat flux of four different land uses. (b) Hourly variation of simulated ground heat flux of four different land uses.
There were difficulties in the validation of this result, since either data from experiment or observation, especially the surface energy fluxes, of this location are not yet available. The model parameterization in this method was done using the comparison of surface temperature, which is an intermediate result in the simulation. Continuous energy fluxes data, such as can be provided by using Eddy Correlation Methods, are required to evaluate the accuracy of the simulation results. However, conducting a more field observation of these parameters in Cidanau watershed was troublesome. In consequence there are works to do before this model can be succesfully applied to estimate the ET in the area.

**Conclusion**

In this paper, a parameterization of a numerical model for ET estimation using surface
temperature has been proposed.

Surface temperature data can be used for parameterization of the numerical model to evaluate evapotranspiration. The modification can be done by changing the value of crop’s stomatal resistance. In this study, simulations using the modified model give surface temperature in the range of observed surface temperature of different land condition at noon.

Using the modified model, evapotranspiration on four different land use types in Cidanau Watershed, were estimated. The daily evapotranspiration resulted from the simulation for artificial surface, bare soil; paddy field and forest are 0, 4.5, 5 and 6 mm/day respectively.

Observation of surface fluxes data is required for verification of the simulation. Further modification of the model is needed in order to obtain better results. The modification can be attempted to the value of various parameters in the model as well as the use of parameterization algorithms instead of trial and error solely.

### Appendix A. Two Layer Resistance Model

Energy fluxes on vegetated surface was calculated using two layers resistance model (Nakano and Cho, 1985). This model treats plant canopy as a single big leaf with a certain height. This model is depicted in Fig.3.

![Fig. A-1. Two layers resistance model.](image)

The sensible and latent heat transfer is arranged imitating electrical resistance model, and described by the following equations.

\[
T_l - T_a = \frac{R_1(h_1 + h_2) + r_a h_1}{c_p \rho} \quad \text{(A-1)}
\]

\[
T_g - T_l = \frac{R_2 h_2 + r_a h_1}{c_p \rho} \quad \text{(A-2)}
\]

\[
T_l - T_a + \frac{[e_s(T_a) - e_a]}{\Delta} = \frac{[R_1(v_1 + v_2) + r_v v_1]}{c_p \rho \Delta} \quad \text{(A-3)}
\]
\[ T_g - T_l = \frac{[e_s(T_a) - e_g]}{\Delta} = \frac{[R_2 v_2 + r_v v_1]}{c_p \rho \Delta} \]  
(A-4)

\[ N_l = h_1 + v_1 \]  
(A-5)

\[ N_g = h_2 + v_2 + G \]  
(A-6)

Here, \( T_a, T_l \) and \( T_g \) are air, leaf and soil surface temperature; \( e_s(T_a) \) and \( e_s(T_g) \) are saturation vapor pressure at \( T_a \) and \( T_g \); \( e_s \) and \( e_g \) are the vapor pressure above the canopy and at the soil surface; \( h_1, h_2, v_1 \) and \( v_2 \) are sensible and latent heat transmitted from leaf surface and soil surface; \( R_1 \) and \( R_2 \) are resistances of the canopy’s layers, \( r_1 \) is leaf resistance, \( r_v \) is latent heat transfer resistance, \( \gamma \) is humidity constant, \( c_p \) and \( \rho \) are the air specific heat capacity and density, and \( \Delta \) is the gradient of saturation vapor pressure’s curve. The value of \( T_l, G, h_1, h_2, v_1 \) and \( v_2 \) have to be determined. The air temperature within the canopy layer \( T_{la} \) is simply determined by using the following equation.

\[ T_{la} = T_l - h_1 r_1 / c_p \rho \]  
(A-7)

The acquired air temperature is the air temperature of the model that possesses the resembled functions in the actual heat exchange occur in a canopy.

Leaf surface boundary resistance \( r_a \) is determined using the next equation, involving leaf effective width \( W \) and average wind velocity \( u_{av} \).

\[ r_a = 1.8 \frac{W}{u_{av}} \]  
(A-8)

The resistance occurs in latent heat transfer is obtained with taking into account the evaporation resistance \( r_s \), known as stomata resistance, and \( r_v = r_a + r_s \). Stomatal resistance \( r_s \) is influenced by environmental condition, especially it is strongly affected by solar radiation and soil moisture.

The distribution of wind velocity inside plant canopy can be determined by using momentum exchange equation and in general is expressed by a simple exponential equation.

\[ u(z) = u_H \exp[-\alpha (1 - z / H)] \]  
(A-9)

In this equation, \( u_H \) is wind speed at the height the leaf of \( H \), \( \alpha \) is attenuation coefficient which is settled by leaf size, slope and gap density.

The diffusion coefficient \( K \) is expressed,

\[ K(z) = K_H \exp[-\alpha (1 - z / H)] \]  
(A-10)

where \( K_H \) is the diffusion occurs above plant cover surface. The transfer resistance between two compartments of heights of \( z_l \) and \( z_l - H \), are:

\[ R_1 = \frac{-H[1 - \exp[-\alpha(z_l / H - 1)]]}{K_H \alpha} \]  
(A-11)
Near the soil surface below the canopy, molecules are diffusing properly to the viscosity at the bottom layer. Following Linacre (1972), this layer resistance $R_s$ is presented as,

$$R_s = \frac{-H \left[\exp(\alpha \frac{z_s}{H}) - 1\right]}{K\mu \alpha}$$  \hspace{1cm} (A-12)

with $\delta_s$ is the average height of soil grain, $\nu$ is the viscosity coefficient, $u_s$ is the wind velocity at soil surface ($=u_H \exp(-\alpha)$), $D_a$ is the transport coefficient of air molecule. Equation 13 then is included in Eq. 12 and the new equation is termed as $R_2$.

**Appendix B. Landsat Data**

1. Surface Temperature

The Landsat 7/ETM+ band 6 data used for surface temperature estimation was acquired in August 7, 2001 at day time (scene center time : 2001:219:02:55:17.4884194). This image can be viewed online at:

http://glovis.usgs.gov/ImgViewer/ImgViewer.html?lat=-6&lon=105.7&sensor=ETM

The Landsat image was interpreted to obtain estimated surface temperature using high gain and low gain mode. The small size of the high gain image before and after interpretation are shown below.

![Fig. B.1. Landsat 7ETM+ Band 6 high gain image (left) and the estimated surface temperature (right) (Processed by S. Tsuyuki (Tokyo University) and L.B. Prasetyo (Bogor Agricultural University))](image)

---

6 Graduate School of Agricultural and Life Sciences, Tokyo University, Japan, tsuyuki@fr.a.u-tokyo.ac.jp

7 Faculty of Forestry, Bogor Agricultural University, Indonesia, lbprast@indo.net.id
2. Land Cover Analysis.

The following land cover analysis map or land surface condition map were processed from Landsat image. This map was also obtained from Tokyo University. In this map 7 different land conditions are shown.

Combining this analysis with field observation data and interview with the locale residents, there are some rough descriptions regarding the land conditions classified in this map. The areas classified as Water and Bare, in the rainy season are mostly used as paddy field. Unfortunately, the residential area and road pavement surface are not clear in this map. This caused more inaccuracy in the calculation of area utilized for paddy field. The composition of paddy field and bare field always changes. Therefore the most updated and detail land use map is needed to make an up-to-date estimation.

![Land Cover Analysis of Cidanau watershed](image)

**Fig. B.2. Land Cover Analysis of Cidanau watershed. (Source: Landsat TM, 1998/5/19; processed by S. Tsuyuki, Tokyo University)**

Most of the areas classified Abandoned and Grass are inside the natural reserves area of ‘Rawa Dano’. In the dry season this area is also used for paddy cultivation, and in the rainy season most of this area is covered with water. Most of area classified as Forest1 also lays inside this natural reserves area, which is a swamp forest. The model presented in this paper does not comply to area with these classification.

Using the land classification map of the watershed, and simulation model of each land condition, a good ET estimation result of this area is expected, not only daily but also hourly. However, more parameterization of the model to suit more specific land condition and accurate calculation of area of each land condition are required.

Saptomo, Nakano, Haraguchi, Yuge, and Kuroda, 2003

ICID Workshop on Remote Sensing of ET for Large Regions, 17 Sept. 2003
Acknowledgments:

This research is a part of JSPS-DGHE Core University Program in Applied Biosciences ‘Toward Harmonization between Development and Environmental Conservation in Biological Production’.

Authors are grateful to Prof. Satoshi Tsuyuki from Tokyo University, and Dr Lilik Budi Prasetyo from Bogor Agricultural University for valuable help in acquiring and processing Landsat Image of surface temperature.

References


