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A Comparative Experiment on Evapotranspiration for Validating the Estimates Made Using the Bucket with a Bottom Hole (BBH) Model

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An experiment was conducted in a vegetation–covered experimental field in Karatsu, Saga, Japan for one year to compare the estimates of evapotranspiration (*ET*) made using the bucket with a bottom hole (BBH) model of soil hydrology with the measurements made by the Bowen ratio method. The BBH model estimates the daily *ET* as the product of the daily potential evaporation and a soil moisture availability that is a function of soil moisture in the surface layer a few tens of centimeters thick. As a result, it was shown that this model estimates the daily evaporation fairly well if the seasonal change of a model parameter σ, which specifies the resistance to evaporation, is taken into account.

KEY WORDS: BBH model, Bowen ratio method, Evapotranspiration, Soil moisture

INTRODUCTION

The bucket with a bottom hole (BBH) model is an improved version of the bucket model of soil hydrology used by Manabe (1969). The main drawback of the original bucket model is, as pointed out by Chen *et al.* (1996), overestimation of evaporation during wet periods and underestimation during dry periods. This drawback was overcome by making a hole at the bottom of the bucket, whence comes the name of this model (Kobayashi *et al.*, 2001). Five parameters were added to improve the bucket model. Three of them specify the soil moisture movement through the bottom hole of the bucket. The other two parameters account for surface evaporation including transpiration and surface runoff processes, respectively.

Soil hydrology models can be tested against observations of soil moisture, evaporation and surface runoff. It may be most desirable to verify a model based on these three kinds of outputs. However, surface runoff, in general, cannot directly be measured but estimated from river discharge data by using jointly, for example, a river routing model (Oki *et al.*, 1999). Therefore, observations and estimates of soil moisture and evaporation have generally been compared for model validation.

For the purpose of verifying the BBH model two experiments were conducted in a field in fallow and a vegetation–covered experimental field on a hill in Karatsu, Saga, Japan. One experiment was focused on the temporal variation in soil moisture and the other in evapotranspiration (*ET*). This paper describes the latter, while the former, which verified this model to be very effective to simulate soil moisture, has been presented elsewhere (Kobayashi *et al.*, 2001).

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OBSERVATIONS

Observations were made at the experimental field of Marine & Highland Bioscience Center (MHBC) of Saga University, 32×70 m area, and located in a hilly area about 3 km south of the town of Karatsu, Saga, Japan (Lat. N33° 25' 03", Lon. E129° 57' 41", Alt. 125 m). The field was used for various purposes, and one of the corners where meteorological instruments were installed was overgrown with weeds less than a few tens of centimeters high. Although part of the data used in this analysis was taken with the weather station (MEISEI) operated by Prof. A. Tanaka of Saga University, the rest was taken using instruments transported from Kyushu University, Fukuoka. The details of the instruments used are omitted in this paper. Physical properties of the soil are shown in Table 1. Observation periods were (I) Nov. 12 to Dec. 31, 1996, (Ⅱ) Jun.1 to 30 and (Ⅲ) July 16 to Aug. 22, 1997.

Table 1. Physical properties of the soil

Particle size (mm)	% by weight
<0.005	7
0.005〜0.074	23
0.074〜0.42	20
0.42〜2	29
2<	21
Particle density (gcm^{-3})	2.67
Bulk density	(gcm^{-3})(Porosity)
Depth (cm)	
0–5	1.24 (0.54)
10–15	1.22 (0.54)
20–25	1.23 (0.54)

BBH MODEL

The BBH model is a water balance model with seven parameters (Table 2). The soil profile in the BBH model consists of the active soil surface layer (*ASSL*) with depth *D* and the underlayer. The *ASSL* is defined as the soil surface layer in which water content varies greatly from day to day and often reduces to below field capacity, while in the underlayer soil moisture conditions hardly change in a short period except for an event of strong rainfall or irrigation, but may exhibit a seasonal variation. The depth *D* is determined case by case based on various conditions, such as the root distribution. In the BBH model, daily precipitation *Pr* and daily potential evaporation *Ep* are regarded as observed values, and daily evaporation including transpiration *E*, daily gravity drainage *Gd* and daily surface runoff *Rs* are estimated by the parameterization techniques shown in Table 2. In this sturdy, *Ep* was calculated using the Priestley–Taylor equation with the parameter α of 1.26. Although the detail of the equation is not described here, measurements of wind speed at 9.5 m, air temperature and humidity at 1.5 m and net radiation at 2 m were used to calculate *Ep*. The ground heat flux could be neglected except for a few days because its contribution was small as compared to the net radiation when 24–hour integrated values were used.

MODEL PARAMETRS

In this study, the depth of the *ASSL*, *D*, was fixed to be 20 cm because a preliminary study showed that the estimates of evaporation made with this model were hardly affected by the depth in the range of 20 cm to 60 cm. The model parameters other than σ used in this study were the same as determined and used in the previous study (Kobayashi *et al.*, 2001); that is, W_{MAX}= 106 mm, η=0.72, *a*=40 mm, *b*=15 mm, and *c*=1 mm day^{-1}. The value of σ will be shown below.

ACTUAL EVAPOTRANSPIRATION

Actual evapotranspiration (*ET*) at the MHBC experimental field was measured by the energy–balance Bowen ratio method. Water vapor flux E_f (kgs^{-1}m^{-2}) can be written as

$$E_f = \frac{R_N - G}{L(1+\beta)} \quad (1)$$

where R_N is the net radiation (Wm^{-2}), *G* the ground heat flux (Wm^{-2}), *L* the latent heat of vaporization (Jkg^{-1}) and β the Bowen ratio. The Bowen ratio was calculated using the air temperature and humidity measurements made at heights of 0.3 m and 3 m during the period I, and 0.3 m and 1.5 m during the periods II and III. The ground heat flux was measured at a depth of 5 cm. All values used in this calculation were 10–minute means or integrated values over 10 minutes. When the value of β for a 10–minute period was negative, the period was excluded from the integration of getting the daily evaporation; otherwise the estimate of E_f showed unstable behavior.

Daily actual *ET* that was obtained by integrating the 10–minute value of E_f over 24–hour period from midnight to midnight was converted to E_a in mm. Figure 1 (a) and (b) show the day–to–day changes in E_a during the two observation periods, II and III, respectively. The daily potential evaporation calculated using the Priestley–Taylor equation with the parameter α of 1.26 and that using the Penman equation are shown for reference, which were almost equal to one another with some exceptions. In general, actual *ET* on a rainy day was very small, though precipitation data are not shown here.

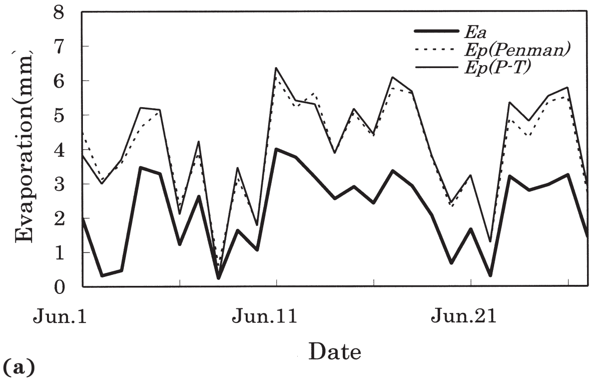
Another remarkable feature of these results is that although the level of potential evaporation was almost unchanged from the middle of June to early August, the level of actual *ET* decreased gradually with time during this period. It is conjectured that this trend is related to the plant coverage in the field; as plant grew thick, the amount of decrease in soil surface evaporation exceeded that of increase in transpiration from plant leaves.

SEASONAL VARIATION IN σ

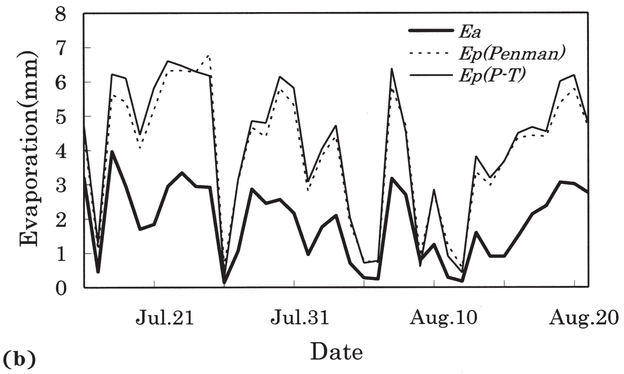
We estimated the daily evaporation including tran-

Table 2. Basic equations and parameterizations of the BBH model

Basic equation	*W*: daily mean equivalent depth of liquid water contained in the active soil surface layer (*ASSL*) (mm) $W(t+1)=W(t)+Pr(t)-E(t)-Gd(t)-Rs(t)$: water balance equation *t* : time (days) *Pr*: daily precipitation (mm day^{-1}) *E*: daily evaporation including transpiration (mm day^{-1}) *Gd*: daily gravitational drainage (positive) or capillary rise (negative) (mm day^{-1}) *Rs*: daily surface runoff including interception (mm day^{-1})
Obs.	*Pr* *Ep*: daily potential evaporation (mm day^{-1})
Parameterization	*D*: depth of the *ASSL* W_{MAX}: maximum value of *W*= [porosity]×*D* (mm) σ (–): $E=M\cdot Ep$, $M=W/\sigma W_{MAX}$ (–) η (–): bucket capacity $W_{BC}=\eta W_{MAX}$ (mm) *a* (mm), *b* (mm), *c* (mm day^{-1}): $Gd=I\exp((W-a)/b)-c$, $I=1$ mm day^{-1} $Rs=\max[Pr-(W_{BC}-W)-E-Gd, 0]$

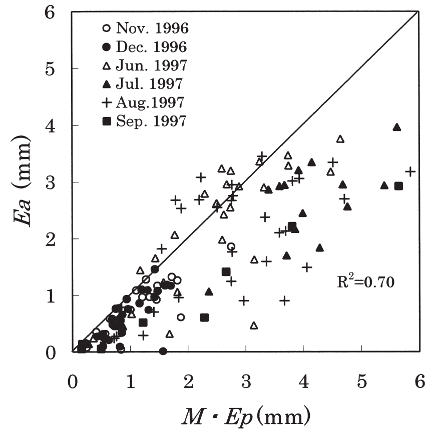


(a)

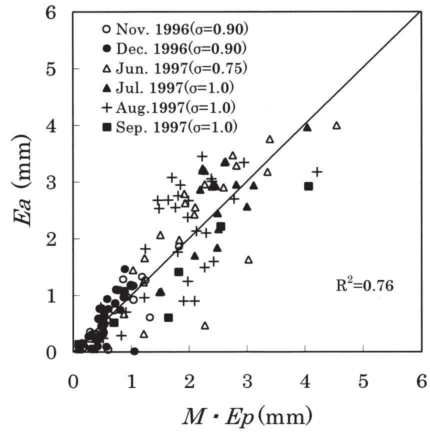


(b)

Fig. 1. Time variation in daily actual *ET*, *Ea*, and daily potential evaporation, *Ep*, during the periods (a) Ⅱ and (b) Ⅲ (1997).



(a)



(b)

Fig. 2. Relationship between *Ea* and *M*·*Ep* when σ was (a) fixed to be 0.54 and (b) the optimum values.

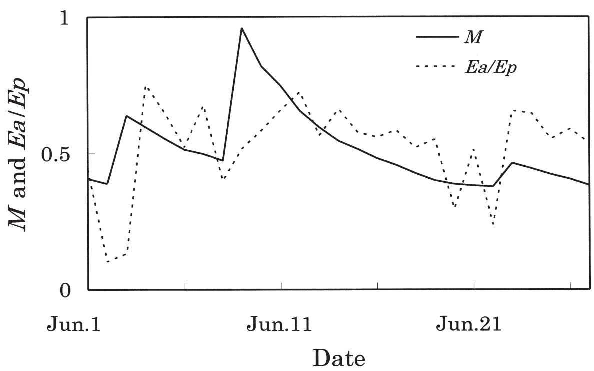


Fig. 3. Time changes in *Ea* / *Ep* and *M* (σ=0.75) during the period Ⅱ (1997).

spiration E using the daily potential evaporation calculated from the Priestley–Taylor equation and the soil moisture availability M that is a function of W and a parameter σ. The initial conditions on W for the three periods were obtained *in situ*.

As a preliminary calculation, σ was set to be 0.54 as in the previous study (Kobayashi *et al.*, 2001). Figure 2 (a) shows the relationship between daily actual *ET* measurements and the estimates made using the BBH model. As can be seen, there is a tendency for the BBH estimates $M \cdot E_p$ to be larger than the actual *ET*, E_a, especially in July, August and September in 1997. These results suggest that the value of σ should be larger than 0.54 and its optimum value changes with the season.

The optimum value of σ can be obtained by comparing $M \equiv W/\sigma W_{MAX}$ with E_a/E_p. Figure 3 shows their time changes in the period Ⅱ when σ is set to be 0.75. The optimum values of σ for the periods Ⅰ and Ⅲ were also determined by trial and error to be 0.90 and one, respectively. Wang *et al.* (2004) determined parameters a, b, c, η, and σ simultaneously so that the root mean square of the difference in W between the measurement and its BBH model estimate took a minimum value. Their procedure seems to be more rational than ours.

Figure 2 (b) shows the relationship between the daily actual *ET* and the estimate made with the BBH model using the optimum values of σ. As a result of using the optimum values of σ, correction for the overestimation was achieved and also the coefficient of determination (R^2) became larger than when a fixed value of 0.54 was used. Although we have no data for the period from January to May, the value of σ seems to be related to the degree of vegetation growth, especially in the rainy season. Wang *et al.* (2004) concluded that the error of estimating actual *ET* with the BBH model might be less than 10% on a monthly basis. The accuracy of the present results seems to be almost the same as or a little bit larger than theirs.

CONCLUDING REMARKS

One of the main drawbacks of the original bucket model is, as pointed out by Chen *et al.* (1996), overestimation of evaporation during wet periods and underestimation during dry periods. However, according to the present results, they can be eliminated in the BBH model if the optimum value of a model parameter, σ, which changes with the season, is used. Seasonal changes in the parameters of the BBH model will be discussed in more detail elsewhere (Teshima *et al.*, 2006).

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