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An Improvement on the BBH Model of Soil Hydrology Made to Incorporate Bioprocesses

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The bucket with a bottom hole (BBH) model of soil hydrology was improved to incorporate bioprocesses such as interception and macropore flow into it by adding three model parameters, which is called the BBH–B model. This model was applied to the estimation of evapotranspiration (*ET*) from a cornfield in the upper Yellow River basin, China, with the results as follows: Estimates of the cumulative *ET* for periods of about one month were made using the BBH–B model with fair accuracy, if the three additional parameters were determined appropriately. It was also found that *ET* had a large spatial variation within the cornfield.

KEY WORD: BBH model, Cornfield, Evapotranspiration, Water balance, Yellow River

INTRODUCTION

Persons who tried first to measure the evaporation in the field may be irrigators. To determine irrigation requirements and to design irrigation systems, they have to know the evaporation loss from the field. The more accurately they could measure *ET*, the more efficiently they could use water. The lack of water has recently become public concern, especially in arid and semiarid regions, and therefore, it is important to develop a method for measuring *ET* easily with fair accuracy in irrigated fields.

The measurement of *ET* is a very difficult and time–consuming task, and is practiced by various approaches. The bucket with a bottom hole (BBH) model of soil hydrology was applied to estimate water balance terms including *ET* for a grass–covered flat area under humid conditions, and showed that the accuracy of estimating monthly *ET* with the BBH model was ± 10% (Wang *et al.*, 2004). And the water balance on a grass–covered slope under humid conditions were investigated using the BBH model, and shown that yearly *ET* was estimated with fair accuracy, though it was somewhat underestimated (Teshima *et al.*, 2006). The BBH model was extended to the two–layer model, which is the single layer BBH model underlain by another bucket with a bottom hole (Iwanaga *et al.*, 2005). They applied it to evaluation of irrigation requirement at a cornfield in

the upper Yellow River basin. This paper describes an improvement on the BBH model made for incorporating bioprocesses in order to estimate *ET* at the cornfield with fair accuracy, and also discusses the performance of the improved model.

AN IMPROVEMENT ON THE BBH MODEL

Figure 1 shows the schematic diagram of the two–layer BBH model (Iwanaga *et al.*, 2005). It is supposed that water balance equations, on which the two–layer BBH model is based, can be rearranged as follows.

The upper bucket or the first layer (porosity: p_1, thickness: D_1):

$$W_1(t\ 1) - W_1(t)\ \ Pr(t) - E_1(t) - Gd_1(t) - Rs(t)$$
$$(1-\ )Pr(t) - E_1(t) - [Gd_1(t) - (1-\ )\ \ Pr(t)] - [Rs(t)$$
$$-\ \ Pr(t)] \tag{1}$$

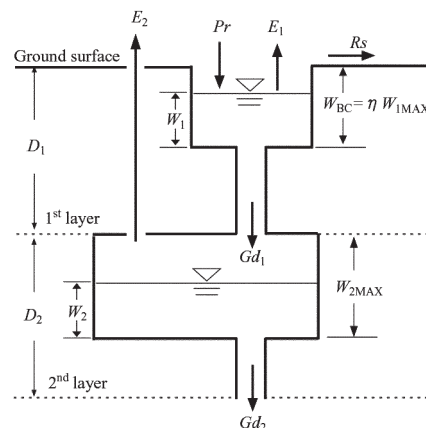The lower bucket or the second layer (porosity: p_2, thickness: D_2):

Fig. 1. Schematic diagram of the two–layer BBH model of soil hydrology.

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$$W_2(t+1)-W_2(t) = Gd_1(t)-E_2(t)-Gd_2(t)$$
$$= [Gd_1(t)-(1-\alpha)\beta Pr(t)]-[E_2(t)-\gamma(1-\alpha)\beta Pr(t)]$$
$$-[Gd_2(t)-(1-\gamma)(1-\alpha)\beta Pr(t)] \quad (2)$$

where t indicates the day, W_i ($i=1,2$) is daily mean amount of soil water contained in the ith layer, Pr daily precipitation, E_i daily water depletion by evaporation from the ith layer, Gd_i daily internal flux expressing gravity drainage plus capillary rise across the bottom surface of the ith layer and Rs daily surface runoff. All the terms appeared on the right sides of Eqs. (1) and (2) are expressed in mm day^{-1}.

The parameterizations for estimating water balance terms (Iwanaga *et al.*, 2005) are

$$E_i(t) = M_i Ep(t), \quad M_i = \frac{W_1}{\delta_i W_{iMAX}} \quad (i=1,2) \quad (3)$$

where Ep is daily potential evaporation and $W_{iMAX} = p_i D_i$ (mm). Daily potential evaporation was calculated using the FAO version of Penman–Monteith equation in this study.

$$Gd_i(t) = I \exp\left(\frac{W_i(t)-a_i}{b_i}\right) - c_i \quad (i=1,2) \quad (4)$$

where $I = 1$ mm day^{-1}, while a_i (mm), b_i (mm) and c_i (mm day^{-1}) are model parameters.

$$Rs(t) = \max[Pr(t)-(W_{BC}-W_1(t))-E_1(t)-Gd_1(t), 0] \quad (5)$$

where $W_{BC} = W_{1MAX}$ is the capacity of the first layer.

In Eq. (1), it is regarded that αPr ($\alpha < 1$) is the part of the precipitation that does not contribute to the change in W_1, βPr ($\beta < 1$) is the amount of overestimation for Rs, which is verified to be the interception loss in this analysis, and $(1-\alpha)\beta Pr$ is the amount of overestimation for Gd_1, which is supposed to be the amount of macropore flow into the second layer. Both terms have no influence on the change in W_1. Therefore, daily evaporation from the surface (E_S) plus daily water uptake by plant roots in the first layer (R_{U1}) equals $E_1 + \alpha Pr$.

It is assumed that the macropore flow of $(1-\alpha)\beta Pr$ has no influence on W_2 as well, and hence, only $Gd_1-(1-\alpha)\beta Pr$ contributes to the change in W_2. As a result, E_2 is overestimated by $\gamma(1-\alpha)\beta Pr$ ($\gamma < 1$), and Gd_2 by $(1-\gamma)(1-\alpha)\beta Pr$. Hence, daily water uptake by plant roots in the second layer is expressed as

$$R_{U2} = E_2 - \gamma(1-\alpha)\beta Pr \quad (6)$$

Consequently, evapotranspiration (ET) can be estimated from the formulation

$$ET = E_S + R_{U1} = E_1 + \alpha Pr \quad (7)$$

if the single layer model is used, and

$$ET = E_S + R_{U1} + R_{U2} = E_1 + E_2 - \{\alpha - (1-\alpha)\gamma\}\beta Pr \quad (8)$$

if the two–layer model is used. The model in which bioprocesses are incorporated by adding three parameters α, β and γ will be called the BBH–B model of soil hydrology.

EXAMPLE APPLICATION

Observations

Japan Science and Technology Agency (JST) and Institute of Agro–Environmental and Sustainable Development, CAAS, China, established an experimental cornfield at Togtoh, Inner Mongolia, China, in order to investigate salinity–controlled, water–saving irrigation techniques (Iwanaga *et al.*, 2005; Wang *et al.*, 2006). The cornfield, 55× 73 m area, is located in the alluvial valley of the upper Yellow River, and basin irrigation is applied with the water diverted from the Yellow River two or three times a year.
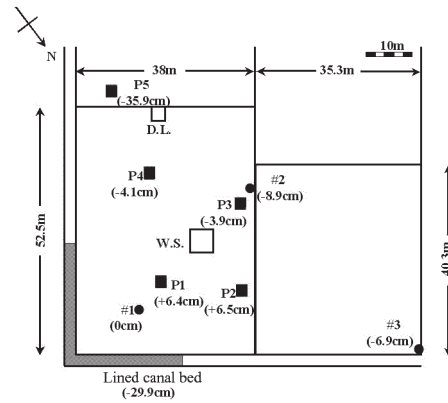

Fig. 2. Plane figure of Togtoh experimental field.

Soil water content was measured with TDR probes at five depths (10, 20, 40, 60 and 100 cm) of three points (P1, P2, P4), and meteorological observations were made with a weather station system in the clear, 5× 5 m area, at the center of the field. Actual ET was measured by the Bowen ratio method using the data obtained with the weather station system. The data taken in the growing period of 2004 were used in this analysis.

Identification of model parameters except for the additional ones

The thicknesses of the first and second layers were determined to be 40 cm and 60 cm, respectively, by taking the growth of roots into account. The single layer model was used for May because the root zone was confined in the upper 40 cm, while the two–layer model was used in the other seasons. Since the porosity averaged over the soil profile was 0.5, W_{1MAX} and W_{2MAX} were equal to 200 mm and 300 mm, respectively. Other nine parameters were determined so that

$$RMS_i = \sqrt{\frac{1}{N}\sum_{j=1}^{N} dW_{ij}^2} \quad (i=1,2) \quad (9)$$

where dW_{ij} is the difference in the measured and predicted values of W_i ($i=1,2$) on the jth day and N is the sample size, took a minimum value (Iwanaga *et al.*, 2005).

Table 1. Water balance terms for sub-periods measured in the field and estimated using the BBH–B model (mm). See text for the definition of each term

Sub–period	Pr	Ep	Ea	P1				P4			
				E_1	E_2	R_{v2}	ET	E_1	E_2	R_{v2}	ET
1–31May	69.6	130.2	78.5	48.2	–	–	93.4	30.5	–	–	75.7
1–30Jun	21.3	127.5	82.9	81.4	41.9	14.2	109.5	66.7	32.1	4.4	84.9
1–15Jul.	5.3	76.8	55.5	51.1	24.6	17.7	72.3	40.2	20.5	13.6	57.3
16–17Jul.	–	8.9	7.6	–	–	–	–	–	–	–	–
18Jul.–31Aug.	170.4	168.1	156.8	174.1	41.9	–	–	97.9	61.9	–	–
1–30Sep.	27.7	91.6	67.6	53.4	43.1	7.5	78.5	30.8	56.5	20.5	69.3
Total	294.6	638.0	468.1	–	–	–	–	–	–	–	–

Identification of the additional parameters and characteristics of ET in the cornfield

Table 1 shows the seasonal changes in water balance terms measured in the field and those estimated with the BBH–B model at P1 and P4. They are expressed by cumulative values for sub–periods in mm. As a result of the first irrigation applied on 15 Jul. 2004, the second layer was submerged in the aquifer or in the capillary fringe of the water table for a long time. Therefore, the period 16 Jul. through 31 Aug. was excluded from this analysis.

The estimates of ET shown in Table 1 were made using Eqs. (7) and (8), when the additional parameters were determined as follows. We assumed the actual ET measured by the Bowen ratio method (Ea) to be the true value of ET in this field. For May, when the field was almost free of vegetation, the single layer BBH–B was used. The ET calculated using Eq. (7) agrees well with Ea if   is set equal to 0.43 for P1 and 0.69 for P4, respectively. However, for convenience, the values calculated using 0.65 for   are shown in the Table. This means that soil surfaces almost free of vegetation intercept 40–70% of precipitation. In this season, a visibly dry crust forms on the soil. Furthermore, soil wetness was measured at depths of more than or equal to 10 cm. So it seems reasonable to regard this interception to be performed by dry soil surface layers.

For the other seasons when the two–layer BBH–B model was used, E_1 E_2 were larger than Ea for all the sub–periods at the two locations. This suggests that 0 $\{$ $–$ $(1$ $)\}$ 1.
At P4, if $\{$ $–$ $(1$ $)\}$ is set equal to 0.65, ET agrees well with Ea for all the sub–periods.

Since $(1-$ $)$ $\{$ $–$ $(1$ $)\}$, Eq. (6) can be written for P4 as

$$R_{v2}   E_2 –   (1–   )   Pr   E_2 – (0.65   )Pr   (10)$$

If we assume that   0.65 for convenience, the seasonal change in R_{v2} can be estimated as shown in Table 1. It is evident that the major zone of water use by corn moved downward through the soil as the growing season progressed.

At P1, however, $\{$ $–$ $(1$ $)\}$ has to be larger than one if ET would fit with Ea, which suggests that assuming Ea to be the true value of ET in this field is not appropriate. The estimates of ET and R_{v2} at P1 shown in Table 1 were made using the same parameters as used at P4. The estimates of ET at P1 were much larger than the measurements of Ea for all the sub–periods. Although these estimates cannot be verified because we have no reliable data to compare with, it may be concluded that ET had a large spatial variation within this small cornfield.

CONCLUDING REMARKS

The BBH–B model, which incorporate bioprocesses such as interception and macropore flow, was applied to the estimation of ET from a cornfield in the upper Yellow River basin, and it was shown that the estimates of cumulative ET for periods of about one month were made with fair accuracy if the model parameters were determined appropriately. It was also shown that ET had a large spatial variation within the cornfield. Furthermore, the BBH–B model described the phenomenon that the major zone of water use by corn moved downward through the soil as the growing season progressed. However, it needs a method of identifying the additional parameters in a rational manner to describe such a phenomenon quantitatively with this model.

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