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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: \(D_1\)):

\[
W_1(t+1) - W_1(t) = Pr(t) - E_1(t) - Gd_1(t) - Rs(t)
\]

\[
= (1 - \theta)Pr(t) - E_1(t) - (Gd_1(t) - (1 - \theta)Pr(t)) - \theta Rs(t)
\]

(1)

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

\[\text{Fig. 1. Schematic diagram of the two-layer BBH model of soil hydrology.}\]
where \( t \) indicates the day, \( W_i \) (\( i = 1, 2 \)) is daily mean amount of soil water contained in the \( i \)th layer, \( Pr \) daily precipitation, \( E_i \) daily water depletion by evaporation from the \( i \)th layer, \( Gd_i \) daily internal flux expressing gravity drainage plus capillary rise across the bottom surface of the \( i \)th 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., 2006) are:

\[
E_i(t) = M_i \cdot Ep(t), \quad M_i = \frac{W_i}{W_{\text{sat}}} \quad (i = 1, 2)
\]

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

\[
Gd_i(t) = I \exp \left( \frac{W(t)-a_i}{b_i} \right) - c_i \quad (i = 1, 2)
\]

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

\[
Rs(t) = \max \{Pr(t)-(W_{\text{sat}}-W_i(t))-E_i(t)-Gd_i(t), 0\}
\]

where \( W_{\text{sat}} = \cap W_{\text{sat}} \) is the capacity of the first layer.

In Eq. (1), it is regarded that \( \cap Pr \) (\( \cap 1 \)) is the part of the precipitation that does not contribute to the change in \( W_i \), \( \cap \) \( \cap Pr \) (\( \cap 1 \)) is the amount of overestimation for \( Rs \), which is verified to be the interception loss in this analysis, and \( (1-\cap ) \cap Pr \) is the amount of overestimation for \( Gd_i \), which is supposed to be the amount of macropore flow into the second layer. Both terms have no influence on the change in \( W_i \). Therefore, daily evaporation from the surface \( (E_i) \) plus daily water uptake by plant roots in the first layer \( (R_{i1}) \) equals \( E_i + \cap \cap Pr \).

It is assumed that the macropore flow of \( (1-\cap ) \cap Pr \) has no influence on \( W_i \) as well, and hence, only \( Gd_i-(1-\cap ) \cap Pr \) contributes to the change in \( W_i \). As a result, \( E_i \) is overestimated by \( (1-\cap ) \cap Pr \) (\( \cap 1 \)), and \( Gd_i \) by \( (1-\cap ) \cap (1-\cap ) \cap Pr \). Hence, daily water uptake by plant roots in the second layer is expressed as:

\[
R_{i2} = E_i - (1-\cap ) \cap Pr
\]

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

\[
ET = E_i + R_{i1} + R_{i2} \quad (i = 1, 2)
\]

if the single layer model is used, and

\[
ET = E_i + R_{i1} + R_{i2} = E_i + E_i' - (1+\cap)Pr
\]

if the two-layer model is used. The model in which bioprocesses are incorporated by adding three parameters \( \cap \), \( \cap \) and \( \cap \) 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 \( \times \) 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.

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 \( \times \) 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, \( W_{\text{sat}} \) and \( W_{\text{sat}} \) were equal to 200 mm and 300 mm, respectively. Other nine parameters were determined so that:

\[
\text{RMS}_i = \sqrt{\frac{1}{N} \sum_{j=1}^{N} (\text{d}W_{ij}^z)} \quad (i = 1, 2)
\]

where \( \text{d}W_{ij} \) is the difference in the measured and predicted values of \( W_i \) (\( i = 1, 2 \)) on the \( j \)th day and \( N \) is the sample size, took a minimum value (Iwanaga et al., 2005).
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 estimated using 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 (\(E_a\)) 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 \(E_a\) if \(\frac{\Delta}{\Delta} \) is set equal to 0.43 for P1 and 0.69 for P4, respectively. However, for convenience, the values calculated using 0.65 for \(\frac{\Delta}{\Delta} \) 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, \(E_t + E_r\) were larger than \(E_a\) for all the sub-periods at the two locations. This suggests that \(0 < \frac{\Delta}{\Delta} \frac{\Delta}{\Delta} (1 + \frac{\Delta}{\Delta}) < 1\).

At P4, if \(\frac{\Delta}{\Delta} \frac{\Delta}{\Delta} (1 + \frac{\Delta}{\Delta})\) is set equal to 0.65, ET agrees well with \(E_a\) for all the sub-periods.

Since \(\frac{\Delta}{\Delta} (1 - \frac{\Delta}{\Delta}) \frac{\Delta}{\Delta} \frac{\Delta}{\Delta} (1 + \frac{\Delta}{\Delta}) \frac{\Delta}{\Delta}\), Eq. (6) can be written for P4 as

\[
R_{2} = E_r - (1 - \frac{\Delta}{\Delta}) \frac{\Delta}{\Delta} Pr = E_r - (0.65 + \frac{\Delta}{\Delta}) Pr
\]

If we assume that \(\frac{\Delta}{\Delta} = 0.65\) for convenience, the seasonal change in \(R_{2}\) 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, \(\frac{\Delta}{\Delta} \frac{\Delta}{\Delta} (1 + \frac{\Delta}{\Delta})\) has to be larger than one if ET would fit with \(E_a\), which suggests that assuming \(E_a\) to be the true value of ET in this field is not appropriate. The estimates of ET and \(R_{2}\) 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 \(E_a\) 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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REFERENCES