An Improvement in the BBH Model for Estimating Evapotranspiration from Cornfields in the Upper Yellow River

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Abstract

The bucket with a bottom hole (BBH) model of soil hydrology was improved to incorporate bioprocesses such as surface rainfall interception and macropore flow into it by introducing three model parameters or two composite parameters. The improved model (BBH-B model) was applied to the estimation of evapotranspiration (ET) from a cornfield in the upper Yellow River. The results obtained are summarized as follows.

- Estimates of the cumulative ET during periods of about one month were made using the BBH-B model with fair accuracy if the model parameters could be evaluated appropriately.
- ET had a large spatial variation within the cornfield.
- The major zone of water use by corn moved downward through the soil as the growing season progressed. The ratio of root water uptake in depths between 40 cm and 100 cm to ET increased from about one-fourth in June, when LAI increased quickly, to about one-half in September, when the corn matured.
- The surface conditions, such as the fraction of crop cover, exerted a large influence on the partition of rainwater at the surface of the cornfield.

Key words: BBH model, Cornfield, Evapotranspiration, Water balance, Yellow River

1. Introduction

In terms of the water quantities transported on a global basis, evaporation is the second most important component of the hydrologic cycle after precipitation (Brutsaert, 2005). However, measuring evaporation is not easy, mainly because no standard method exists to give the “true” value of evaporation at any given spot. The first persons attempting to measure evaporation in the field may have been irrigators. To determine irriga-

tion requirements and to design irrigation systems, they must have had knowledge about evaporation loss from the field (Fuchs, 1973). Evaporation from a vegetated surface is called evapotranspiration (ET). ET consists of soil surface evaporation and plant transpiration, although it is difficult to measure each separately. The more accurate the measurement of ET is, the more efficient the use of water. Water shortages have recently become a public concern, especially in arid and semiarid regions. Therefore, devising a method for measuring ET easily and with fair accuracy in the field is important.

The measurement of ET is a very difficult and

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time-consuming task, and is practiced by various approaches, including meteorological methods (e.g. Bowen ratio method, aerodynamic method, eddy correlation method) and lysimetric measurement (Burman and Pochop, 1994). However, meteorological methods, which are the most popular in the field of hydrology, are not applicable when measuring ET from a small area. On the other hand, although lysimetric measurement, which is often used by agronomists, permits the calculation of water balance for a small area, it generally eliminates percolation beyond the root zone and/or prevents the addition of water to the root zone from a water table. Therefore, results obtained with lysimeters cannot include, at the least, the effects of deep percolation and capillary rise.

Several soil water balance methods were also applied to the estimation of ET (Rouse and Wilson, 1971/1972; Teshima, 2007). However, they have almost the same problems as do lysimetric techniques. Wang *et al.* (2004) applied the bucket with a bottom hole (BBH) model of soil hydrology to the estimation of 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 $\pm 10\%$. This model is, so to speak, a numerical version of a lysimeter that permits the calculation of a water balance for a small area where soil moisture is measured continuously, by taking account of vertical water movement such as deep percolation and capillary rise. Teshima *et al.* (2006) investigated the water balance at a grass-covered slope under humid conditions using the BBH model, and showed that yearly ET was estimated with fair accuracy, though somewhat underestimated. On the other hand, Iwanaga *et al.* (2005) extended the BBH model to the two-layer model, which is the single layer BBH model underlain by another bucket with a bottom hole. They applied this two-layer model to the evaluation of irrigation requirements at a cornfield in the upper Yellow River, the root zone of which extended to a depth of 1 m or more. This paper describes an improvement on the BBH model made for estimating the ET from cornfields, which will contribute to improving the efficiency of water use in growing corn, and discusses the performance of this improved model.

2. Observations

The Japan Science and Technology Agency (JST) and the Institute of Environment and Sustainable Develop-

ment in Agriculture, CAAS, China collaborated in a study on developing water-saving and salinity-controlled irrigation techniques at an experimental cornfield. The cornfield, with an area of 55×73 m (Fig. 1), was located in the alluvial valley of the upper Yellow River (Lat. $N40^{\circ}14.8'$, Long. $E111^{\circ}11.0'$, Alt. 995m), and was divided into a few plots surrounded by borders to facilitate ponding (Fig. 1). Basin irrigation was applied two or three times a year with water diverted from the Yellow River. Climatic characteristics, including a wind rose at this field, are described elsewhere (Ikegami *et al.*, 2005). The distance from the leading

Fig. 1. Plane figure of Togtoh experimental field. Solid square: TDR measurement point, solid circle: observation well, W.S.: weather station, D.L.: data logger. Numbers in parentheses indicate the relative heights of the soil surface to that at an observation well, #1, and the shaded area of the irrigation canal indicates the section paved with concrete.

Fig. 2. Soil texture profiles at P1 and P4. Depth is expressed in cm.

Table 1. Instrumentation.

Variable	Instrument	Height & Depth (m)
Air temperature & Humidity	CAMPBELL, CS500-L6	1.16, 2.52, 3.81, 5.79
Net radiation	CAMPBELL, Q7.1-L20	3.79
Atmospheric pressure	CAMPBELL, CS105	—
Wind speed	CAMPBELL, 03101-L11	2.50, 3.90, 5.76
Wind speed & direction	CAMPBELL, 03101-L11	7.46
Precipitation	CAMPBELL, CS700-L25	—
Groundwater level	CAMPBELL, CS420-L	—
Ground heat flux	REBS, HFT-3.1	−0.05, −0.15
Soil temperature	CAMPBELL, MODEL 107	−0.1, −0.2, −0.4
Soil water content	CAMPBELL, CS615-L50	−0.1, −0.2, −0.4, −0.6, −1.0

edge is long enough to measure the latent heat flux over the canopy by meteorological methods.

Water content was measured with time domain reflectometry (TDR) probes at five depths (10, 20, 40, 60, 80 or 100 cm) of three points (P1, P2, P4 in Fig. 1). The depth to a water table was observed at two observation wells (#1, #2 in Fig. 1), and other meteorological and hydrological elements were also observed in a clear plot, a 5×5 m area, in the field (W.S. in Fig. 1). The soil profile consisted of alluvial silt loam (silt), clayey soil (clay), and mixtures of the soils (silt+clay) as shown in Fig. 2. Instruments used in this study are summarized in Table 1. Data obtained during the 2004 growing season are used mainly in this analysis.

3. Corn Growth

This field was cultivated as usual by a farmer. Corn (*Zea mays* L.) was planted at the end of April and harvested in the first half of October. Surveys on the growth of corn in this field were conducted six times

during the years 2003–2005. Leaf area index (LAI) and crop height measurements are shown in Table 2 (Iwanaga *et al.*, 2003). Seasonal change in the root distribution, which is expressed in percentage by dry weight, is listed in Table 3 (Iwanaga *et al.*, 2003; Iwanaga *et al.*, 2004). Although root activity is not directly related to root weight, it can be said that corn roots extract water from soil layers even below a depth of 1 m, at the least, during the silking stage from the end of July to the beginning of August. Russell and Danielson (1956) found evidence that corn utilized water to a depth of 5 feet (152 cm) or deeper in a deep Brunizen soil.

4. BBH Model

4.1 Two-layer BBH model

The bucket with a bottom hole (BBH) model is an improved version of the bucket model used by Manabe (1969) (Kobayashi *et al.*, 2001; Iwanaga *et al.*, 2005; Kobayashi *et al.*, 2005; Teshima *et al.*, 2006). The two-layer BBH model is the single layer BBH model

Table 2. Growth of corn in the field.

Date	7 Jun 2005	30 Jun 2004	15 Jul 2005	24 Jul 2003	22 Aug 2004	1 Oct 2003
LAI (–)	0.4	3.8	4.4	4.8	5.2	3.8
Height (m)	0.24±0.03	1.40±0.17	1.73±0.27	2.53±0.07	2.55±0.12	2.85±0.08

Table 3. Vertical distribution of roots (% by weight).

Depth (cm)	28Jun–5Jul 2004	22–30Jul 2003	20–27Aug 2004	29Sep–6Oct 2003
0–10	59.3%	55.9%	53.4%	49.8%
10–20	22.0	17.9	17.7	16.5
20–30	9.1	9.5	9.5	12.2
30–40	6.2	5.4	4.7	6.2
40–50	3.1	3.1	5.3	6.2
50–60	0.2	2.4	3.9	4.6
60–70	—	3.0	3.3	4.5
70–80	—	2.4	1.9	—
80–90	—	0.3	0.4	—
90–100	—	0.1	—	—

underlain by another bucket with a bottom hole (Fig. 3) (Iwanaga *et al.*, 2005). Water moves downward or upward through the bottom holes as the gravity force either predominates over the capillary force or does not. Plant roots extract moisture not only from the upper bucket (R_{U1}) but also from the lower bucket (R_{U2}), the stems transport the water up to the leaves, and the leaves transpire the water into the atmosphere (Tr).

Since the single layer BBH model is the same as the first layer of the two-layer BBH model, the two-layer BBH model mechanism is described in this section. This means that water movement through the bottom hole of the upper layer is controlled only by the soil moisture condition in the layer.

Water balance equations for the two buckets are written as follows.

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

$$\begin{aligned} W_1(t+1) - W_1(t) \\ = Pr(t) - E_1(t) - Gd_1(t) - Rs(t) \end{aligned} \quad (1)$$

where t indicates the day, W_1 =daily mean amount of soil water contained in the first layer (mm), Pr =daily precipitation, E_1 =daily evaporation from the first layer that comprises evaporation from the soil surface (E_{so}) and R_{u1} , Gd_1 =daily internal flux expressing gravity drainage plus capillary rise at the upper bucket bottom, and Rs =daily surface runoff.

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

Fig. 3. Schematic representation of the improved two-layer model (BBH-B model). R_s shown in the figure does not mean the term in the water balance equation (Eq. 1) but denotes surface runoff literally.

$$\begin{aligned} W_2(t+1) - W_2(t) \\ = Gd_1(t) - E_2(t) - Gd_2(t) \end{aligned} \quad (2)$$

where subscript 2 indicates that the terms are related to the second layer, and $E_2 = R_{U2}$. All of the terms appearing on the right sides of Eq. (1) and Eq. (2) are expressed in mm day^{-1} .

We assume the following parameterizations.

$$\begin{aligned} E_i(t) &= M_i \cdot Ep(t), \\ M_i &\equiv \frac{W_i}{\sigma_i W_{iMAX}} \quad (i = 1, 2) \end{aligned} \quad (3)$$

where Ep =daily potential evaporation, $W_{\text{MAX}} = p_i \cdot D_i$ (mm), and σ_i = a model parameter specifying the resistance to evapotranspiration. In this study, Ep was calculated using the FAO version of the Penman-Monteith equation (FAO, 1998).

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

$$(i = 1, 2)$$

where $I \equiv 1 \text{ mm day}^{-1}$, and a_i (mm), b_i (mm) and c_i (mm day^{-1}) are model parameters. See Iwanaga *et al.* (2005) for the physical meanings of these parameters. The flux Gd_i is determined based only on the moisture condition in the i th layer, or W_i . Therefore, it is assumed that the lower bucket is well above a water table.

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

where $W_{BC} = \eta W_{IMAX}$ is the capacity of the upper bucket, in which η is a model parameter specifying the moisture detention capacity of the first layer.

4.2 Parameter identification

The thirteen model parameters are determined as follows. See Iwanaga *et al.* (2005) and Teshima *et al.* (2006) for further details. Four parameters, p_i , D_i ($i = 1, 2$), can be determined by experiment. Five parameters for the first layer, σ_1 , η , a_1 , b_1 , c_1 , are determined empirically and/or by trial and error so that RMS defined by Eq. (6) reaches a minimum using Eqs. (1), (3), (4) and (5).

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N (W_{1,i} - W_{1B,i})^2} \quad (6)$$

where $W_{1,i}$ and $W_{IB,i}$ are the measured and predicted values of W_1 for day number i and the size of the set

of measurements used for identifying the parameters is $N+1$. The other four parameters for the second layer, σ_2 , a_2 , b_2 , c_2 , are determined in the same manner as for the first layer using Eqs. (2), (3) and (4), when the estimate of $Gd_1(t)$ is used as the inflow of water from the first layer.

Six parameters, a_i , b_i , c_i ($i=1, 2$), specify the soil's characteristics. Hence they are not expected to exhibit seasonal changes, but in fact are affected by depth to a water table and other factors, and often change with the season. The other three parameters, σ_1 , σ_2 , η , change with the season because they depend on the vegetative conditions. Therefore, identifying these parameters for sub-periods of about one month is recommended.

Although we can predict W_i ($i=1, 2$) with fair accuracy using this model, we need some information about the suitable ranges of the model parameters when a particular water balance term, such as Gd_i , is to be estimated (Iwanaga *et al.*, 2005). However, E_i can be estimated more accurately than the other terms because it is assumed to be proportional to Ep and includes only one parameter, σ_i .

4.3 BBH-B model

The BBH model must be improved if it is used for estimating the ET from cornfields, because this model disregards the effects of bioprocesses such as macropore flow and rainfall interception. Since Gd_i is estimated from W_i , which is the daily mean amount of soil water contained in the first layer, using Eq. (4), it is difficult to evaluate the amount of water flow through macropores in the layer during a heavy rain or during irrigation when the flow process is completed in a period much shorter than one day. This situation is likely to occur when the soil layer in the BBH model is shallow and its porosity is large (Teshima *et al.*, 2006).

Furthermore, the portion of rainfall that moistens the different surface elements such as vegetation and dry soil and is depleted by evaporation, which will be called surface rainfall interception, should not be included in Pr in Eq. (1).

Let IM denote the portion of rainfall that does not contribute significantly to the daily increase in W_i , such as surface rainfall interception, macropore flow and surface runoff. Then, Eq. (1) can be rewritten as

$$\begin{aligned} W_1(t+1) - W_1(t) \\ = [Pr(t) - IM(t)] \end{aligned}$$

$$\begin{aligned} - E_1(t) - [Gd_1(t) - (1-\alpha)IM(t)] \\ - [Rs(t) - \alpha IM(t)] \end{aligned} \quad (1')$$

where α , such that $0 \leq \alpha \leq 1$, is a parameter indicating the fraction of IM diverted to the surface interception loss and surface runoff. Since E_1 is strongly dependent on Ep (Eq. 3), while IM is independent of Ep , it is surmised that IM should be shared between the other terms, Gd_1 and Rs . Inevitably, αIM , or surface interception loss and surface runoff, is included in Rs , because Rs is evaluated from Eq. (5) as a residue of precipitation. On the other hand, the rest of IM, $(1-\alpha)IM$, is diverted to the macropore flow.

$(1-\alpha)IM$ is assumed to be included in Gd_1 in the present case. This assumption means that the macropore flow is expressed by Eq. (4) for the relatively dry, first layer of 40 cm thick (Fig. 5), and this is tested below based on experimental data. However, if $(1-\alpha)IM$ cannot be taken in Gd_1 for the reason mentioned above, $(1-\alpha)IM$ also is apparently included in Rs (Teshima *et al.*, 2006). Therefore, if precipitation observed in the clear plot (gross rainfall) is substituted for Pr in the water balance equation, the estimate of Rs made by Eq. (5) is approximately equal to or somewhat larger than αIM .

$$Rs \geq \alpha IM \quad (7)$$

Since the cornfield consists of plots surrounded by borders, no surface runoff occurs. Hence, αIM is approximately equal to the surface interception loss caused by dry soil (E_{IS}) plus evaporation from wetted plant surfaces (E_{IP}), or

$$\alpha IM \cong E_{IS} + E_{IP} \quad (8)$$

As a result, the sum of evaporation from the surface (E_S) and R_{U1} can be written as follows (Fig. 3).

$$\begin{aligned} E_S + R_{U1} &= E_{SO} + E_{IS} + E_{IP} + R_{U1} \\ &\cong E_1 + \alpha IM \end{aligned} \quad (9)$$

Therefore, if we write IM as

$$IM = \beta Pr \quad (0 \leq \beta \leq 1) \quad (10)$$

then

$$E_S + R_{U1} \cong E_1 + \alpha \beta Pr = E_1 + \Psi Pr \quad (11)$$

The composite parameter $\Psi \equiv \alpha \beta$ ($0 \leq \Psi \leq 1$) indicates the fraction of gross rainfall intercepted by various surface elements and depleted by evaporation.

Part of the macropore flow, $\gamma(1-\alpha)\beta Pr$ ($0 \leq \gamma \leq 1$) (Fig. 3), is assumed not to be included in Gd_2 in contrast with the case of Gd_1 , because the second layer is consistently rather wet (Fig. 5), and hence E_2 is overestimated by this amount. This assumption is also tested below based on experimental data. Therefore, root water uptake in the second layer (R_{U2}) can be written as

$$\begin{aligned} R_{U2} &= E_2 - \gamma(1-\alpha)\beta Pr \\ &= E_2 - \Phi Pr \end{aligned} \quad (12)$$

where $\Phi \equiv \gamma(1-\alpha)\beta$ ($0 \leq \Phi \leq 1$) is the coefficient of overestimation for E_2 .

The BBH model, which incorporates bioprocesses such as macropore flow and surface rainfall interception by adding three parameters α , β and γ , or two composite parameters Ψ and Φ will be called the BBH-B model.

Consequently, evapotranspiration (ET) can be estimated as

$$\begin{aligned} ET &\equiv E_s + R_{U1} \cong E_1 + \alpha\beta Pr \\ &= E_1 + \Psi Pr \end{aligned} \quad (13)$$

if the single layer BBH-B model is used, and

$$\begin{aligned} ET &\equiv E_s + R_{U1} + R_{U2} \\ &\cong E_1 + E_2 - \beta(\gamma - \alpha(1 + \gamma))Pr \\ &= E_1 + E_2 - (\Phi - \Psi)Pr \end{aligned} \quad (14)$$

if the two layer BBH-B model is used.

Identifying these parameters in a rational manner is a matter requiring further investigation. In this study, Ψ and Φ will be evaluated by fitting the model to experimental data.

5. Actual Evapotranspiration

Actual evapotranspiration (Ea) was measured by the Bowen ratio method. Water vapor flux E_f can be written as

$$E_f = \frac{R_N - G}{L(1 + Bo)} \quad (15)$$

where R_N = net radiation, G = ground heat flux, L = latent heat of vaporization, and Bo = the Bowen ratio. Since G is much smaller than R_N when they are integrated over a day, G was neglected in this study. The Bowen ratio was calculated using air temperature and humidity measurements made at two heights selected well above the corn canopy from the four heights

shown in Table 1.

All measurements used in this analysis were 10-minute means, but E_f was calculated on the hour (BST). When Bo and/or R_N were negative, the value of E_f at the time was excluded from the integration to obtain the daily actual ET; otherwise, values of E_f showed unstable behavior. However, since most such times appeared at night, the effect of the exclusion to the integrated daily actual ET seems to be negligible.

6. Results and Discussion

6.1 Model parameters

The thicknesses of the first and the second layers were determined to be 40 cm and 60 cm, respectively, by taking root growth into account (Table 3). Since the average porosity over the soil profile was 0.5 (Iwanaga *et al.*, 2005), W_{1MAX} and W_{2MAX} were equal to 200 mm and 300 mm, respectively. The values of W_1 and W_2 (mm) were calculated from the following equations using the daily mean volumetric water contents $\theta_{m,h}$ ($\text{cm}^3 \text{ cm}^{-3}$) measured at depth h (cm).

$$W_1 = 150\theta_{m,10} + 150\theta_{m,20} + 100\theta_{m,40}$$

$$W_2 = 100\theta_{m,40} + 300\theta_{m,60} + 200\theta_{m,100}$$

Following the results obtained by Wang *et al.* (2006), who analyzed the vertical water movement in this cornfield, the parameter c_1 was predetermined to be 2 mm day^{-1} in May (establishment period) when the single layer BBH model was used because the root zone was judged to be confined in the first 40 cm thick layer (Table 3). During the other seasons when the two-layer BBH model was used, c_1 and c_2 were fixed to be 3 mm day^{-1} . However, they brought large values of RMS in September and, therefore, were evaluated based on the RMS criterion to be 0.5 mm day^{-1} (Table 4). The cause of this seems to be that a water table steadily got deeper in September, which decreased the potential for upward movement of soil moisture specified by the parameter c_i (Fig. 4). The other parameters were identified using RMS as the decision criterion for several sub-periods (Table 4). Since basin irrigation was practiced on 16 July 2004, its depth being estimated to be more than 150 mm (Iwanaga *et al.*, 2005), the parameters were not identified during the period between 16 and 17 July because the lower bucket was submerged completely in the groundwater. Seasonal changes in W_1 and W_2 at P1 and P4 are shown in Fig. 5.

Table 5 shows the seasonal changes in the main

water balance terms measured, those estimated with the BBH model using the optimum parameters, and the estimates of ET made using Eqs.(13) and (14) for the two measurement points P1 and P4. They are cumulative values for the sub-periods. The situations at P2 were intermediate between P1 and P4 (Iwanaga, 2005). As a result of the first irrigation, the water table briefly rose to above a depth of 1 m, and hence the lower bucket was submerged in the groundwater for a short time, and in the capillary fringe of the water

Fig. 4. Seasonal changes in the groundwater level (#1) and daily precipitation in 2004.

table for a long time after that (Fig. 5). Therefore, the period of 16 July through 31 August was excluded from this analysis.

We estimated the composite parameter Ψ using the following approximate relation (Eq. 7, Eq. 10, and Eq.11) at P1 and P4 for each sub-period.

$$\alpha\beta \equiv \Psi \cong Rs/Pr \quad (16)$$

This estimate indicates an upper limit for the parameter. The results obtained are shown in Table 6.

Fig. 5. Seasonal changes in W_1 and W_2 at P1 and P4 in 2004.

Table 4. Optimum model parameters and RMS for P1 (2004).

Upper: first layer, Lower: second layer.

Sub-period	σ (—)	η (—)	a (mm)	b (mm)	c (mm/d)	RMS (mm)
1May-31May	1.2	0.50	95	5	2	2.02
1Jun-30Jun	0.6	0.44	65	40	3	2.26
	1.9	—	225	5	3	3.31
1Jul-15Jul	0.4	0.30	65	40	3	3.56
	1.9	—	230	40	3	7.00
18Jul-31Aug	0.5	0.54	110	10	3	5.31
	3.0	—	335*	5	3	14.04
1Sep-30Sep	0.7	0.47	115	35	0.5	1.35
	1.7	—	250	40	0.5	3.88

*These values are larger than W_{2MAX} , which suggests that the second layer was not located well above the water table.

Table 5. Main water balance terms measured and those estimated using the BBH model at P1 and P4 for sub-periods (2004). See text for the definition of each term. All terms are expressed in mm.

Sub-period	Pr	Ea	P1				P4			
			E_1	E_2	Rs	ET	E_1	E_2	Rs	ET
1-31May	69.6	91.3	48.2	—	45.1	93.3	30.5	—	65.1	95.6
1-30Jun	21.3	93.7	81.4	41.9	4.6	119.0	66.7	32.1	4.5	94.5
1-15Jul	5.3	61.1	51.1	24.6	0.0	75.7	40.2	20.5	0.0	60.7
16Jul-17Jul	0.3	8.7	—	—	—	—	—	—	—	—
18Jul-31Aug	170.7	176.2	—	—	—	—	—	—	—	—
1-30Sep	27.7	75.6	53.4	43.1	0.5	85.4	30.8	56.5	1.9	76.2
Total	294.6	497.9	—	—	—	—	—	—	—	—

This coefficient shows the fraction of gross rainfall intercepted by dry soil and vegetation (Eq. 8 and Eq. 9). However, because the coefficient decreased as crop coverage increased, the main part of the surface interception loss seems to have been caused by dry soil.

If we assume Ea to be the true value of ET in this field, E_1+E_2 is nearly equal to or larger than Ea at the two measurement points for all of the sub-periods when the two-layer BBH model was used. This result and the definition of parameters suggest that $0 \leq \beta(\gamma - \alpha(1+\gamma)) \leq 1$ from Eq. (14), but we cannot determine the appropriate values for the coefficient at P1, because $1 < \beta(\gamma - \alpha(1+\gamma))$ for two out of three sub-periods at this point. At P4, however, $\beta(\gamma - \alpha(1+\gamma))$ is smaller than 1 for every period. Since Ea was measured on the edge of a clear plot, a 5×5 m area, in the cornfield (Fig. 1), the likelihood exists that Ea was smaller than the mean value for the cornfield. Hence, $\beta(\gamma - \alpha(1+\gamma)) = \Phi - \Psi$ was tentatively determined equally for the two measurement points so that the estimate of ET at P4 was nearly equal to Ea . As a result, the composite parameter Φ was estimated as shown in Table 6. It seems natural that $\Phi = \Psi = 0$ in the sub-period of little rain (1-15 July) because surface rainfall interception and macropore flow do not occur in rainless conditions.

These results suggest that the fraction of gross rainfall diverted to surface rainfall interception, which is indicated by Ψ , decreased with increasing LAI (Table 2). This means that the interception loss of dry soil was superior to that of plants (Table 6). The estimates of Ψ made using Eq. (16), which indicates the ratio of surface interception loss to gross rainfall, were less than 0.2 for the sub-periods when the two-layer BBH-

B model was used. Furthermore, the fraction of gross rainfall diverted to macropore flow, indicated by Φ , was unexpectedly large except for the dry sub-period (1-15 July) (Fig. 4). These results suggest that the two assumptions made when Eqs. (12)-(14) were derived from the BBH-B model are realistic.

6.2 Evapotranspiration

It is a matter of course that the estimates of ET made using Eqs. (13) and (14) for P4 agree well with the measurements of Ea made by the Bowen ratio method. However, those for P1 obtained using the same parameters were much larger than Ea except for during the dry sub-period. This suggests that ET had a large spatial variation within the cornfield under humid conditions (Wang *et al.*, 2004; Teshima *et al.*, 2006). One of the major causes of this variability may be the spatial variation in the soil texture profile (Fig. 2). However, it is impossible for us to specify the mechanisms without further investigation.

R_{U2} can be evaluated from Eq.(12) using the estimates of Φ (Table 6). Table 7 shows the means of the estimates for ET and R_{U2} made at P1 and P4 and the ratios of R_{U2} to ET for the three sub-periods when the two-layer BBH-B model was used. The values of Ea also are shown for reference. It is evident that the percentage of water uptake in the second layer (40–100 cm) increased with time during the growing season and reached about a half of ET at maturity. This indicates that the major zone of water use by corn moved downward through the soil as the growing season progressed, as Russell and Danielson (1956) showed, and the BBH-B model describes the phenomenon in the root zone properly, although further investigations are necessary for obtaining reliable, quantitative results.

Table 6. Estimates of the composite parameters made at P1 and P4 (2004).

Sub-period	P1			P4		
	Ψ	Φ	$\Phi - \Psi$	Ψ	Φ	$\Phi - \Psi$
1-31May	0.65	—	—	0.94	—	—
1-30Jun	0.2	0.4	0.2	0.2	0.4	0.2
1-15Jul	0.0	0.0	0.0	0.0	0.0	0.0
1-30Sep	0.0	0.4	0.4	0.1	0.5	0.4

Table 7. Estimates of root uptake in the second layer (R_{U2}) (2004).

Each value is the mean of estimates made at P1 and P4 except for Ea .

Sub-period	Ea (mm)	ET (mm)	R_{U2} (mm)	R_{U2} / ET (%)
1-30 Jun	91.3	106.8	28.5	27
1-15 Jul	61.1	68.2	22.6	33
1-30 Sep	75.6	80.8	37.4	46

7. Concluding Remarks

Since a large part of precipitation is used to moisten the different surface elements, such as vegetation and dry soil, and another part flows down quickly through macropores during heavy rain, three model parameters, α , β , and γ , or two composite parameters Ψ and Φ that specify such effects were introduced into the BBH model.

The improved BBH model (BBH-B model) was applied to the estimation of ET from a cornfield in the upper Yellow River, when the composite parameters Ψ and Φ were evaluated by fitting the model to experimental data.

The results obtained are summarized as follows.

- (a) Estimates of the cumulative ET during periods of about one month were made using the BBH-B model with fair accuracy if the model parameters could be evaluated appropriately.
- (b) ET had a large spatial variation within the cornfield.
- (c) The major zone of water use by corn moved downward through the soil as the growing season progressed. The ratio of root water uptake in depths between 40 cm and 100 cm to ET increased from about one-fourth in June when LAI increased quickly, to about one-half in September, when the corn matured.
- (d) Surface conditions, such as fraction of crop cover, exerted a large influence on the partition of rain-water at the surface of the cornfield.

Teshima *et al.* (2006) showed that the estimates of yearly ET from a grass-covered slope under humid conditions made using the single layer BBH model, or the formulation $ET = E_1$, were somewhat small. The neglect of the term $\alpha \beta Pr = \Psi Pr$ seems to have caused the underestimation.

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