

## **A bucket with a bottom hole (BBH) model of soil hydrology**

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**Abstract** An improved version of the bucket model of soil hydrology with seven parameters, which permits not only downward but also upward water movement across the bottom, is constructed. This model is validated by comparing with actual soil moisture data.

**Key words** bucket model; soil moisture; evapotranspiration; gravity drainage

### **INTRODUCTION**

It is unlikely that any model will be accepted before its effectiveness can be demonstrated. Although there are many models of soil hydrology that have been installed in land surface parameterization schemes, most of them have been verified only by inter-model comparison without actual soil moisture data. They are, in general, constructed elaborately; however, soil hydrology is a developing discipline and fundamental knowledge does not seem to suffice for constructing a complete, distributed model of soil hydrology. This paper describes a simple lumped model of soil hydrology with seven parameters, which is validated by comparing with actual soil moisture data.

### **BASIC IDEAS**

The vertical profile of soil moisture in equilibrium with groundwater can be expressed by the soil moisture characteristic curve regarding the height from the water table ( $z$ ) as the negative of the matric potential or suction head ( $-\psi$ ). The height corresponding to the field capacity ( $pF \cong 1.8$ ) is about 1 m. And hence if a water table is at about 1 m depth (Chen *et al.*, 1997), the water content in the top tens of centimetres of the soil is near the field capacity (Beljaars & Bosveld, 1997).

When the water content is around the field capacity, the values of  $\psi$  and relative humidity in soil pores change little with changing soil water content, which means that

the change of actual evapotranspiration should also be small. Therefore, it seems sufficient for analysing the surface water budget to predict the soil moisture in the upper layer in which water content often becomes much lower than the field capacity.

## BBH MODEL

The original bucket model of soil hydrology (Manabe, 1969) is a lumped model, and the present model is its improved version, but the simplest next to the original. It is called the bucket with a bottom hole (BBH) model because it permits not only downward but also upward water movement across the bottom surface (Fig. 1).

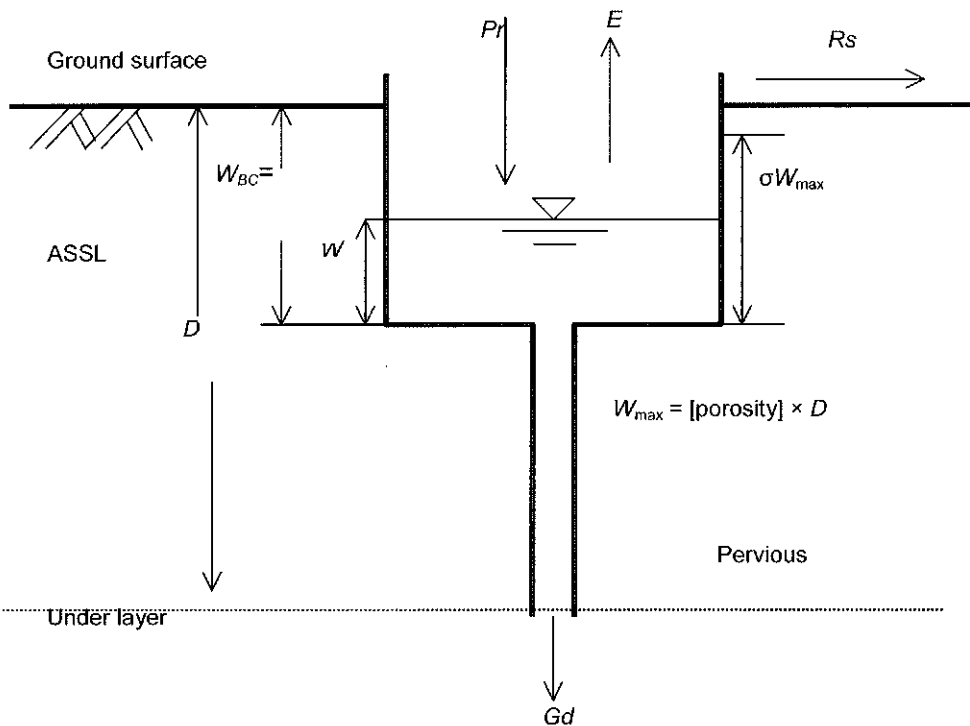


Fig. 1 Schematic representation of the BBH model. See text for the symbols.

The BBH model consists of an active surface soil layer (ASSL), some tens of centimetres thick, in which water content often reduces to below the field capacity, and an underlying soil moisture reservoir. If  $W$  (mm) stands for the equivalent depth of liquid water contained in the ASSL with depth  $D$  (cm), the change of  $W$  in a day,  $\Delta W$  (mm), can be expressed as:

$$\Delta W = W(t+1) - W(t) = P_r(t) - E(t) - G_d(t) - R_s(t) \quad (1)$$

where  $t$  is the time in days,  $P_r$  the daily precipitation (mm),  $E$  the daily evapotranspiration (mm),  $G_d$  the daily gravity drainage (positive) or capillary rising

(negative) (mm), which the bucket model takes no account of, and  $R_s$  the daily surface runoff (mm). We assume  $E$  to be expressed as:

$$E = M \cdot E_p \quad (2)$$

where  $M = \min[W/\sigma W_{\max}, 1]$ ,  $E_p$  is the daily potential evapotranspiration (mm),  $W_{\max}$  the total water-holding capacity (porosity multiplied by  $D$ ), and  $\sigma$  the parameter specifying the resistance of, for example, the ground cover to evapotranspiration.

Let us assume that  $G_d$  is expressed as:

$$G_d = \exp\left(\frac{W - a}{b}\right) - c \quad (3)$$

where  $a$  is nearly equal to or somewhat smaller than  $W_{FD}$  (field capacity) (mm),  $b$  the soil moisture recession parameter (mm), and  $c$  the daily potential capillary rising (mm).

When  $W$  reaches the bucket capacity,  $W_{BC} = \eta W_{\max}$ , and  $P_r > E + G_d$ ,

$$R_s = P_r - E - G_d \quad (4)$$

Even if  $W < W_{BC}$ , when  $P_r > E + G_d + (W_{BC} - W)$

$$R_s = P_r - E - G_d - (W_{BC} - W) \quad (5)$$

The parameter  $\eta$  ( $\leq 1$ ) specifies the moisture retaining capacity of the ASSL.

## VERIFICATION

To run this model, observations of  $P_r$  and estimates of  $E_p$  made by some methods are necessary. Therefore, meteorological observations and measurements of soil water content in the top 65 cm (0–5, 10–15, 20–25, 30–35, 40–45, 60–65 cm) were taken in a field in fallow situated on a hill for a year (Kobayashi *et al.*, to be submitted). The porosity and the field capacity of the soil were 0.53 and 0.27, respectively. The potential evapotranspiration was calculated using the Priestley-Taylor equation with the factor  $\alpha$  of 1.26.

Figure 2 shows the seasonal variations of  $W$  in the top 60 cm ( $D = 60$  cm,  $W_{\max} = 318$  mm,  $W_{FC} = 162$  mm). Estimates made by the BBH model ( $\sigma = 0.56$ ,  $\eta = 0.75$ ,  $a = 100$  mm,  $b = 35$  mm,  $c = 1.5$  mm) are shown along with those made by the bucket model ( $\sigma = 0.37$ ,  $\eta = 0.50$ ). The parameters  $a$ ,  $b$  and  $c$  were determined by a trial-and-error procedure taking their physical meanings into account. In the BBH model, the average of  $W_{FC}$  and  $W_{\max}$  was used in place of  $W_{FC}$  in the bucket model. Figure 3 shows the accumulations of  $P_r$ ,  $E$  estimated by the bucket and the BBH model, and the sum of  $G_d$  and  $M \cdot E_p$  by the BBH model. The yearly total of  $G_d$  was larger than  $E$ , the reason for which seems to be the well-drained observation field situated on a hill. As can be seen in Fig. 3, the original bucket model without a bottom hole cannot estimate  $W$  in the ASSL in rather dry seasons.

## CONCLUDING REMARKS

The original bucket model has two parameters (Manabe, 1969), and the present model added five parameters to it. Three of them,  $a$ ,  $b$  and  $c$ , were evaluated by comparing

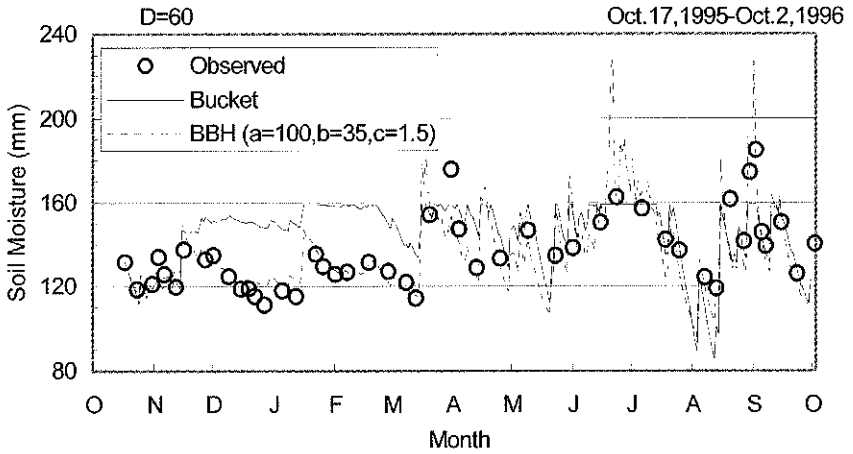


Fig. 2 Seasonal variation of the soil moisture contained in the ASL ( $W$ ).

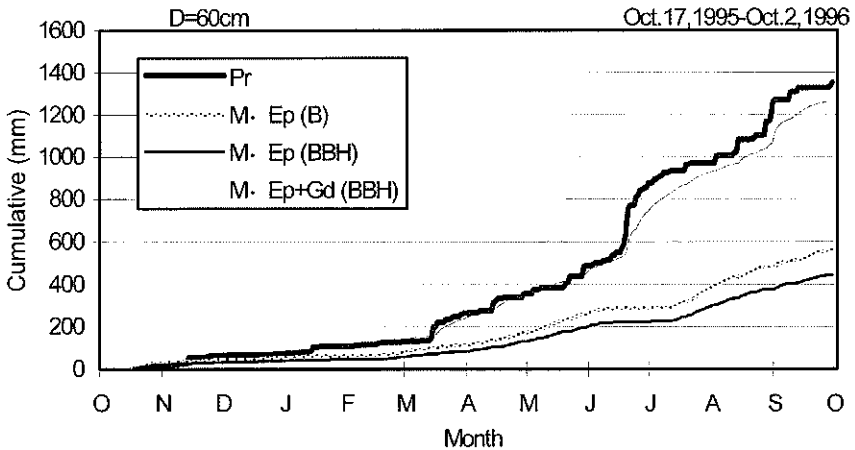


Fig. 3 Cumulative precipitation ( $Pr$ ), estimates of cumulative evapotranspiration ( $MEp$ ) by the bucket model (B) and the BBH model (BBH), and cumulative gravity drainage ( $Gd$ ) by the BBH model.

actual soil moisture data with the model estimates in this study, but  $\eta$  and  $\sigma$  were fixed according to the original model. Kobayashi *et al.* (to be submitted) estimated  $\sigma$  by comparing actual evapotranspiration data with the model estimates and showed that the value of  $\sigma$  should be larger than the original value. The parameter  $\eta$  must be determined based on the surface runoff data. Although the parameters that are directly involved in the purpose of using the BBH model should be determined by experiment (e.g.  $\sigma$  in case of estimating evapotranspiration), other parameters could be specified by an empirical approach guided by considerations of their physical meanings (Kobayashi *et al.*, to be submitted).

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