An Experiment on the Spatial Variability of Water Balance Terms in a Small Grass-Covered Area

小規模草地内の水収支項の空間変動性に関する一実験

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By analyzing the time series of measurements of soil moisture at a point along with precipitation and potential evaporation using the bucket with a bottom hole (BBH) model, we evaluated water balance terms at the point. The estimates of those terms made at nine points on a 1.5m grid in a small grass-covered area showed their own spatial variations. The results obtained are summarized as follows.

- (a) Ranking of the spatial variability of the water balance terms involved in the BBH model was W (soil moisture) < E (evaporation) < R_s (surface runoff) < G_d (gravity drainage)
- (b) Clear patterns showing the spatial variation in surface runoff and gravity drainage in a 3×3 m patch were obtained, which suggests that subsurface water below the ASSL (30cm thick) has flow systems on spatial scales of a few meters.
- (c) The spatial variation patterns of the water balance terms obtained by the parameterization of the BBH model did not necessarily agree with that of soil moisture but showed ones peculiar to the terms. This means that the parameterization takes the effects of other factors than soil moisture such as the micro topographic relief, vegetation cover, soil texture and structure into account appropriately, because such factors should by nature exhibit spatially not random but organized variations.
- (d) Daily evaporation estimates made by the BBH model were in good agreement with the measurements taken for reference by the Bowen ratio method, though it was conducted by the expedient of disregarding an insufficiency of fetch and neglecting the heat flux into the soil.

Key words: BBH model, Evaporation, Soil moisture, Spatial variability, Water balance terms

1 地点の土壌水分測定値の時系列を、降水量やポテンシャル蒸発量と共に、底穴付きバケツ (bucket with a bottom hole, BBH) モデルを用いて解析し、その地点の水収支項を評価した。小規模草地の1.5m 格子上の9点において求められたそれら収支項の推定値は独自の分布を示した。得られた結果は次のように要約できる。

- (a) BBH モデルに組み込まれている水収支項の空間変動性の大きさは、 W (土壌水分) < E (蒸発) < R_s (表面流出) < G_d (重力排水) の順番になった。
- (b) 3×3 m の小面積内で、表面流出と重力排水ははっきりした空間変動パターンを示した。これは地中水が厚さ30cmの表土層より深い所で数メートルのスケールの流系を持っていることを示唆する。
- (c) 土壌水分の空間変動と他の水収支項が示す空間変動の分布パターンは必ずしも一致せず、各項独自の形を示した。これはBBHモデルのパラメタリゼーションが、微地形、植被、土壌組成および土壌構造など土壌水分以外の諸因子の影響を適切に反映させることを示唆する。なぜなら、それらの諸因子は本来空間的に組織化された変動を示すはずだからである。
- (d) BBH モデルを用いて推定した日蒸発量は、フェッチの不足や地中熱伝導率を無視する便宜的な条件の下ではあるが、参考のためにボーエン比法によって求めた測定結果とよく一致した。

キーワード: BBH モデル, 蒸発, 土壌水分, 空間変動性, 水収支項

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I. INTRODUCTION

We see puddles here and there after a heavy rain, which is a visualized realization of the spatial variability of soil hydrological properties. Some of the water balance terms such as infiltration, evaporation, surface runoff, and subsurface drainage may be related to this phenomenon, which terms will be influenced by the micro topographical relief, vegetation cover, soil texture and structure. Since these properties have large spatial variability, water balance terms also exhibit large spatial variations. The large spatial variability of soil hydrological properties causes various difficulties in, for example, scheduling irrigations or estimating the surface runoff from a watershed based on computer models, because water balance terms measured *in situ* are essential to validate those models or to tune the model parameters. Therefore, the spatial variability of water balance terms needs further investigation.

Although not a few field studies have been conducted to examine the spatial variability of soil mois-

ture (Bell *et al.*, 1980; Sunada *et al.*, 1995; Qiu *et al.*, 2001), only a few studies have been made on the other water balance components such as infiltration (Shaake *et al.*, 1996), subsurface drainage (Nielsen *et al.*, 1973), capillary rise and surface runoff. The main reason for this is that it is difficult or impossible to measure, for example, the capillary rise at a point in the field. Measuring the infiltration *in situ*, say it were not impossible, needs instruments such as a ring infiltrometer, which inevitably demands the artificial setting that does not occur in reality.

The objective of this study is to estimate the infiltration rate, evaporation rate, surface runoff and gravitational drainage or capillary rise at a point under natural conditions from the data on soil moisture along with rainfall and potential evaporation, and to evaluate their spatial variations in a small area where the uniformity of meteorological data is assured. Therefore, the spatial variation is supposed to be included only in the data on soil moisture. To this purpose the BBH (bucket with a bottom hole) model of soil hydrology (Kobayashi *et al.*, 2001; Nagai *et al.*,

Fig. 1 Experimental plot.

2002) is used, the performance of which is judged based on the degree of agreement between the calculated and measured values of soil moisture; that is, we pick a set of water balance terms that can interpret the change in soil moisture at a point using the parameterization of the BBH model.

II. OBSERVATIONS

Observations were made in a plot (about 10×10 m) located in the Kaizuka Experimental Farm of Kyushu University (Lat. $N33^{\circ}37.9'$, Log. $E130^{\circ}25.6'$, Alt. 11m) (Fig. 1). Although the plot was covered with grass that was clipped to be less than several centimeters in height and on the stage of dying, it was encircled with a hut, vinyl houses, a road, cultivated fields and a place overgrown with weeds a few tens of centimeters high. Rainfall excess in the plot was drained into ditches around it. The soil in the surface layer is an arkose sand (*masado*), the physical properties of which are shown in Table 1. The grass roots extended from the surface to depths of about 20cm.

The information on the instrumentation for meteorological observation is shown in Table 2. Soil moisture measurements were made at nine (3×3) points on a 1.5m grid (Fig. 1) with the TDR probes (CAMPBELL, CS610), which had the wave guides consisted of three rods 30cm long, 0.48cm in diameter and spaced 2.2cm apart. They were inserted vertically into the soil, thus the measurements were 30cm layer averages. Near the point 8 on the edge of the

Table 1 Physical properties of the soil.

Particle size (mm)	% by weight
< 0.005	15
0.005~0.07	15
0.07~0.4	37
0.4~2	33
Particle density (g cm^{-3})	2.72
Dry density (g cm^{-3})	1.38
Porosity	0.492

Table 2 Meteorological instrumentation.

Variables	Instruments	Heights (m AGL)
Temperature & humidity	HUMICAP sensor (CAMPBELL, CS500-6)	0.6, 2.7
Net radiation	N.R. sensor (CAMPBELL, Q7.1-L20)	1.6
Wind speed	Three-cup anemometer (MAKINO, AF860)	0.75, 2.3
Rainfall	R.F. sensor (CAMPBELL, CS700-L25)	—
Atmospheric pressure	B.P. sensor (CAMPBELL, CS105)	1.4

measuring grid water content at a depth of 30cm (in Fig. 1) was measured with a TDR probe of the same kind as above but inserted horizontally. The measurements were taken at intervals of 10 min and registered. The output of CS610 was transferred to the volumetric water content, ($\text{cm}^3 \text{cm}^{-3}$), using the calibration curve obtained by indoor experiment (Fig. 2)

$$= (-751 + 355K_a - 11.6K_a^2 + 0.021K_a^3) \times 10^{-4} \quad (1)$$

where K_a is the TDR permittivity.

The observation period from 27 Sep. to 27 Nov. 2002 was divided into two sub-periods, 27 Sep. ~ 31 Oct. and 1 Nov. ~ 27 Nov. There occurred several events of rainstorm heavier than 10mm depth in the first sub-period, and on the last day (31 Oct.) a rainfall of 24.1mm was recorded, while in the second sub-period there occurred only one event of rainstorm heavier than 10 mm depth on the first day (1 Nov.), that is, it rained two consecutive days in advance of the second sub-period (Fig. 3). By analyzing the data from the two sub-periods, we will compare the model parameters and the difference in the spatial variability of water balance terms between the rainy warm spell and the cold spell of little rain.

III. BBH MODEL

The BBH (bucket with a bottom hole) model of soil hydrology proposed by Kobayashi *et al.* (2001) is used in this analysis. This model is a water balance model with seven parameters (Table 3). The soil profile in the BBH model consists of the active soil surface layer (ASSL) with depth D and the underlying soil moisture reservoir. The ASSL is de-

Fig. 2 Relationship between the TDR permittivity K_a and volumetric water content θ for the soil.

Fig. 3 Time variations in the daily means of 30-cm-layer-averaged volumetric water content at points 2 and 3, daily mean volumetric water content at 30cm depth at point 10 and daily precipitation.

fined as the soil surface layer in which water content varies greatly from day to day and often reduces to below the field capacity, while in the underlying reservoir 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 observations, and daily evaporation including transpiration E , daily gravity drainage Gd and daily surface runoff Rs are estimated by the parameterization technique shown in **Table 3**. Daily potential evaporation is calculated using the Penman-Monteith equation recommended by FAO (FAO, 1998) in this study:

$$Ep = \frac{0.408 (R_N - G) + \frac{900}{T + 273} u_a (e_s - e_a)}{1 + (0.34 u_a)} \quad [\text{mm}] \quad (2)$$

where R_N : net radiation [$\text{MJ m}^{-2} \text{day}^{-1}$], G : heat flux into the soil [$\text{MJ m}^{-2} \text{day}^{-1}$], T : daily mean air temperature at 2m height (2.7m in this study) [$^{\circ}\text{C}$], u_a : wind speed at 2m height (2.3m in this study) [m s^{-1}], e_s : saturation vapor pressure [kPa], e_a : actual vapor pressure [kPa], γ : slope of saturation vapor pressure curve [$\text{kPa } ^{\circ}\text{C}^{-1}$], Δ : psychrometric constant [$\text{kPa } ^{\circ}\text{C}^{-1}$], P : atmospheric pressure [kPa]. Since G is small compared to R_N when 24 hour values are considered, the former was neglected in this calculation. The initial value of W (**Table 3**)

was the mean of 144 measurements taken every 10 min on the first day of each period.

The water balance components in this model are not expressed in mm day^{-1} but in mm, because all the terms of water balance equation are evaluated on a daily basis (**Table 3**).

IV. DETERMINATION OF MODEL PARAMETERS

The depth of the ASSL (D) was fixed to be 30cm in this study mainly because we made measurements of 30 cm surface layer mean of soil moisture with the TDR probes. However, although the soil moisture content at 30cm depth increased abruptly on the days having a rainfall larger than about 15mm, it remained nearly constant or decreased slowly on the other days (**Fig. 3**). Therefore it seems reasonable to regard the layers below 30cm depth as the underlying soil moisture reservoir of the BBH model. The value of W_{MAX} was set to be 147.6mm, the product of D and the soil porosity (**Table 1**). Of course the porosity varies spatially, and hence its ef-

Table 3 The basic equation and parameterization of the BBH model. Underlined characters in the table show the seven parameters 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) E : daily evaporation including transpiration (mm) Gd : daily gravitational drainage (positive) or capillary rise (negative) (mm) Rs : daily surface runoff (mm)
Obs.	Pr Ep : daily potential evaporation (mm)
Parameterization	<u>D</u> : depth of the ASSL (cm) <u>W_{MAX}</u> : maximum value of $W = [\text{porosity}] \times D$ (mm) $\sigma(-)$: $E = M \cdot Ep$, $M = \min[W/\sigma W_{MAX}, 1]$ (-) <u>η</u> (-): bucket capacity $W_{BC} = \eta W_{MAX}$ (mm) <u>a</u> (mm), <u>b</u> (mm), <u>c</u> (mm): $Gd = \exp((W-a)/b) - c$ $Rs = \max[Pr - (W_{BC} - W) - E - Gd, 0]$

fects on retention and detention storages of soil water may be included in the spatial variation in the other parameters such as σ and a . The five parameters σ , η , a , b and c were determined by a kind of trial-and-error procedure so that the root mean square (R.M.S.) of the difference in W between the measurement on i th day (W_i) and their BBH model outputs ($W_{B,i}$)

$$\text{R.M.S.} = \sqrt{\frac{1}{N} \sum_{i=1}^N (W_i - W_{B,i})^2} \quad (3)$$

took the minimum value. Since each parameter has its physical meaning, we can define a narrow trial range of its value when executing this procedure.

The optimum model parameters were determined for each sub-period, which are summarized in **Table 4**. Since the values of b (20mm) and c (1.5mm) were constant in time and space, they are not shown in the table. The value of a , which is a measure of the field capacity, was also constant in time, but varies widely from point to point, which suggests that a large spatial variation in the field capacity existed. The optimum values of σ and η for one sub-period differ a little bit from the other, but the difference may be insignificant. The R.M.S. in the table shows the minimum value of the root-mean-square error when these optimal model parameters were obtained. The errors were larger in the first sub-period than in the second, because it rained more often heavily in the former. **Fig. 4** shows the comparison of W_i and $W_{B,i}$ calculated using those optimum parameters at points 2 and 3.

V. RESULTS AND DISCUSSION

1. Soil moisture

Table 5 shows the means of W measured at each point for the respective periods. The total mean of the nine points over the whole period was 101.7mm and the standard deviation (S.D.) was 5.2mm, and hence the coefficient of variation (C.V.) was 0.05. Although water content at the center point 5 was small relative to the others, the spatial distribution of soil moisture in the 3×3m patch was rather uniform. The total rainfall in the first sub-period of 35 days was 100.6mm and that in the second sub-period of 27 days was 33mm. However, the mean of W for the second sub-period was larger than that for the first, provably because evaporation decreased as the season proceeded toward the winter as will be shown later.

2. Evaporation

Table 6 shows the accumulated evaporation estimated by the BBH model. The mean of daily evaporation over the first sub-period was 1.3mm, while that over the second sub-period was 1mm. The C.V. for the first rainy sub-period was a little bit larger than that for the second sub-period of little rain. As will be seen later, however, they are much smaller than the C.V. of other components, which means that the spatial variation in evaporation was relatively small among water balance terms.

Actual evaporation was measured in the experimental plot near the measuring grid by the Bowen ra-

Table 4 Optimum model parameters. Upper: first sub-period, lower: second sub-period.

M. point	1	2	3	4	5	6	7	8	9
σ	1.0	1.5	0.9	1.2	1.0	1.0	1.2	1.0	1.0
	1.2	1.3	1.0	1.0	1.0	1.0	1.2	1.1	1.2
η	0.73	0.79	0.73	0.75	0.70	0.78	0.80	0.75	0.80
	0.73	0.79	0.74	0.77	0.71	0.79	0.80	0.77	0.80
a	90	100	90	100	85	90	95	90	95
R.M.S.	2.7	2.1	2.2	1.7	2.9	2.5	2.9	2.4	2.9
(mm)	1.5	1.4	1.4	1.1	1.6	1.5	1.8	1.8	1.5

Fig. 4 Comparison of W measured with the TDR probe and estimated by the BBH model.

Table 5 The period mean of W (mm) and precipitation Pr (mm) and period length $P.L.$ (days)

Period	Measuring point									Mean	S.D.	C.V	P_r (P.L.)
	1	2	3	4	5	6	7	8	9				
First	96	109	96	105	91	100	105	98	101	100.1	5.6	0.06	100.6 (35)
Second	98	110	101	108	95	103	107	102	107	103.4	5.0	0.05	33.0 (27)
Whole	97	109	98	107	93	101	106	100	104	101.7	5.2	0.05	133.6 (62)

tio method (Fig. 1) in which actual evaporation rate E_a ($\text{kg m}^{-2} \text{s}^{-1}$) can be expressed as

$$E_a = \frac{R_N - G}{wL(1 + \gamma)} \quad (4)$$

where R_N : net radiation flux (W m^{-2}), G : heat flux into the soil (W m^{-2}), L : latent heat of evaporation (J kg^{-1}), w : density of liquid water (kg m^{-3}), γ : Bowen ratio. The value of γ was evaluated every ten minutes using measurements of air temperature and humidity at two heights (Table 2). The heat flux into the soil G was tentatively assumed to be zero in this analysis. Daily evaporation was calculated by summing up the evaporation in each ten-minute period except for the period in which net radiation was negative, because otherwise the results became ex-

remely shaky. Since negative net radiation occurred mostly at night, its influence on the estimates of daily evaporation should be small. The error resulted from these procedures including the assumption that $G=0$ may be 10% at most on a monthly basis, as one of the basis of this appraisal will be shown later.

To get the Bowen ratio in the experimental plot was rather difficult because the fetch was not long enough. Since the Bowen ratio in the surrounding area was conjectured to be, on the average, a little bit larger than in the plot (Fig. 1) the measured ratio must have been overestimated. The mean of measured Bowen ratios for the whole period was 0.78. On the other hand, when net radiation is posi-

Table 6 The accumulated evaporation (mm) estimated by the BBH model.

Period	Measuring point									Mean	S.D.	C.V.
	1	2	3	4	5	6	7	8	9			
First	47.9	36.1	52.8	43.6	45.2	49.2	43.2	49.0	50.2	46.4	5.0	0.11
Second	22.9	23.7	28.1	30.2	26.9	28.9	25.1	26.1	25.1	26.3	2.4	0.09
Whole	70.8	59.9	80.9	73.8	72.1	78.0	68.3	75.1	75.4	72.7	6.1	0.08

Fig. 5 Comparison of E measured by the Bowen ratio method and estimated by the BBH model.

tive, heat flux into the soil is in general positive too, therefore assuming G to be zero will result in the overestimation of the numerator of Eq. (4). The value of G is in general about one tenth of R_N . Thus if the true value of Bowen ratio was about 0.8 of the measurement, or $0.9 \times 0.78 - 0.1$ $0.8 \times 0.78 - 0.6$, the error made in calculating the daily evaporation using Eq. (4) should be small.

Fig. 5 shows the comparison of the daily evaporations obtained by the BBH model, which is the mean of nine estimates made at the nine points, and by the Bowen ratio method for the period 17 Oct. to 27 Nov. 2003. The accumulated value for the period obtained by the BBH model was 43.01mm, while that by the Bowen ratio method 44.68mm. Their relative differ-

ence is 4%, which is one of the basis of the above appraisal of error. The coincidence might be fortuitous, but the close agreement provides a control from which we can interpret the spatial variations in water balance terms with more confidence.

3. Gravity drainage or capillary rise

In the first sub-period the accumulated gravity drainage at a depth of 30cm estimated by the BBH model was almost zero (Table 7). At three points 1, 3 and 4 they were negative, which means that the capillary rise including the moisture uptake by grass roots was greater than the gravity drainage at the depth in this sub-period. In the second sub-period when rainfall and evaporation were small relative to

Table 7 The accumulated gravity drainage (positive) or capillary rise (negative) (mm) estimated by the BBH model.

Period	Measuring point									Mean	S.D.	C.V.
	1	2	3	4	5	6	7	8	9			
First	-0.6	3.6	-0.2	-4.8	0.0	7.9	8.0	3.8	0.2	2.0	4.2	2.1
Second	11.9	5.5	5.3	2.7	7.2	14.9	13.7	12.8	10.8	9.4	4.3	0.46
Whole	11.3	9.1	5.1	-2.1	7.2	22.8	21.7	16.6	10.9	11.4	8.0	0.70

Table 8 The accumulated surface runoff (mm) estimated by the BBH model.

Period	Measuring point									Mean	S.D.	C.V.
	1	2	3	4	5	6	7	8	9			
First	24.7	36.5	22.3	39.3	21.7	11.4	18.0	21.5	16.5	23.5	9.0	0.38
Second	12.9	15.2	12.5	13.6	13.6	10.2	12.5	9.6	12.5	12.5	1.7	0.14
Whole	37.6	51.7	34.8	53.0	35.3	21.6	30.5	31.2	29.0	36.1	10.3	0.29

the first sub-period, gravity drainage was larger than in the first.

The spatial variation in the accumulated gravity drainage for the whole period displayed a clear pattern; that is, it was large on the corner in which points 6, 7 and 8 were located (dark tone in **Table 7**), while small or negative on the opposite corner in which points 3, 4 and 5 were situated (light tone in **Table 7**) (**Fig. 1**). This suggests that subsurface water below the ASSL has horizontal flow systems on spatial scales of a few meters, which may reflect properties such as soil texture and structure. Therefore, the accumulated gravity drainage at the 30cm depth had the C.V. about an order of magnitude larger than the cases of soil moisture and evaporation shown above.

4. Surface runoff

Table 8 shows the accumulated surface runoff estimated by the BBH model. The runoff coefficient (= runoff / rainfall) for the first sub-period averaged 0.23, while 0.38 for the second sub-period, which probably reflected the soil moisture level that was higher in the second sub-period than in the first. In other words, the mean infiltration coefficient (= infiltration / rainfall) for the first sub-period was 0.77 and 0.62 for the second sub-period. The spatial varia-

tion in the accumulated surface runoff for the whole period shows a similar pattern to that of the gravity drainage; that is, surface runoff was relatively large in the half part of the plot including points 1, 2, 3, 4 and 5 (with underline in **Table 8**), whereas it was somewhat small in the other half covering points 6, 7, 8 and 9 (with double underline in **Table 8**). Both patterns are almost the reflected images of the other, which means that surface runoff has a tendency to be large at a point where gravity drainage is small. The accumulated surface runoff took an intermediate value of the C.V. for the whole period among water balance terms.

VI. CONCLUDING REMARKS

Not a few studies on the spatial variability of soil moisture have been made because many techniques for making *in situ* measurements of soil moisture have been developed. However, we have few techniques for measuring evaporation, infiltration, surface runoff and subsurface drainage at a point in the field. Therefore, in order to evaluate such components at a point, we analyzed the time series of measurements of soil moisture taken with a TDR probe inserted vertically into the soil at the point along with the data on precipitation and potential evaporation using the BBH model. Based on such analyses

at nine points on a 1.5m grid in a small grass-covered area for two months, we got the following results.

- (a) Ranking of the spatial variability of the water balance terms involved in the BBH model was W (soil moisture) $< E$ (evaporation) $< R_s$ (surface runoff) $< G_d$ (gravity drainage)
- (b) Clear patterns showing the spatial variation in surface runoff and gravity drainage in a 3×3 m patch were obtained, which suggests that subsurface water below the ASSL has flow systems on spatial scales of a few meters.
- (c) The spatial variation patterns of each water balance terms obtained by the parameterization of the BBH model did not necessarily agree with that of soil moisture but showed one peculiar to the terms. This means that the parameterization takes the effects of other factors than soil moisture such as the micro topographic relief, vegetation cover, soil texture and structure into account appropriately, because such factors should by nature exhibit spatially not random but organized variations.
- (d) Daily evaporation estimates made by the BBH model were in good agreement with the measurements taken for reference by the Bowen ratio method, though it was conducted by the expedient of disregarding an insufficiency of fetch and neglecting the heat flux into the soil.

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