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Use of Bromide to Trace Infiltration of Rainfall through Sandy Soil in Northeast Thailand

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Abstract
Bromide (Br^-) was used to successfully trace the infiltration of rainfall through a sandy soil in northeast Thailand. A method was developed to measure the Br^- concentration in extracted water from soil samples in order to determine the vertical distribution of the Br^- concentration in soil water. Our experimental results revealed that Br^- moved downward with a piston flow and that the increase in the amount of water in the soil above the depth of the peak Br^- concentration equaled the increase in soil moisture caused by the infiltration. Using our method, we found that the largest amount of rainfall infiltration occurred during September. The amount of soil water above the peak Br^- concentration was calculated to be about 0 mm during the period between June 27, 2003 and August 7, 2003; about 100 mm during the period between June 27, 2003 and September 10, 2003; and about 80 mm during the period between June 27, 2003 and February 12, 2004.

Discipline: Agricultural engineering
Additional key words: piston flow

Introduction

Northeast Thailand, where the undulating Korat Plateau spreads, accounts for about one-third of the entire area of Thailand. The plateau consists of salt rock formed by the Maha Sarakham Formation underlain by the Mesozoic sediments, called Korat group. The area of sandy soil that is generated by weathering of the sediments above the Maha Sarakham Formation, occupies about 80% of northeast Thailand. In this region, annual rainfall, upon which agriculture depends, ranges from 1,100 to 2,200 mm. However, rainfall is erratic and the rate of evaporation is high, resulting in unstable crop yield. To help stabilize yield, it is necessary to use water resources and soil water effectively[10]. Research on soil in northeast Thailand has mainly been concerned with classifying and taking measures against salinization[5,6,11,12]. Few studies on soil moisture have been performed, and no report analyzing infiltration of rainfall has been published.

In this study, we attempted to estimate the amount of infiltration of rainfall from the vertical distribution of bromide (Br^-), which was applied to the surface of the ground as a tracer ion. Bromide anion belongs to the halogen family and is often used for tracing soil water, especially the preferential flow through macropores[1–4,7–9]. In previous research, water discharged from a column or water collected by suction was analyzed. In this study, we collected soil samples at depth intervals of 10 cm and extracted water from the samples with a centrifuge to identify the vertical distribution of Br^- concentration in soil water.

Materials and methods

1. Study site

We selected Nong Saeng village, about 40 km south of Kohn Kaen, as a study site (Fig. 1). The gently undulating hills of Nong Saeng village are typical of the topography in northeast Thailand. Annual rainfall is

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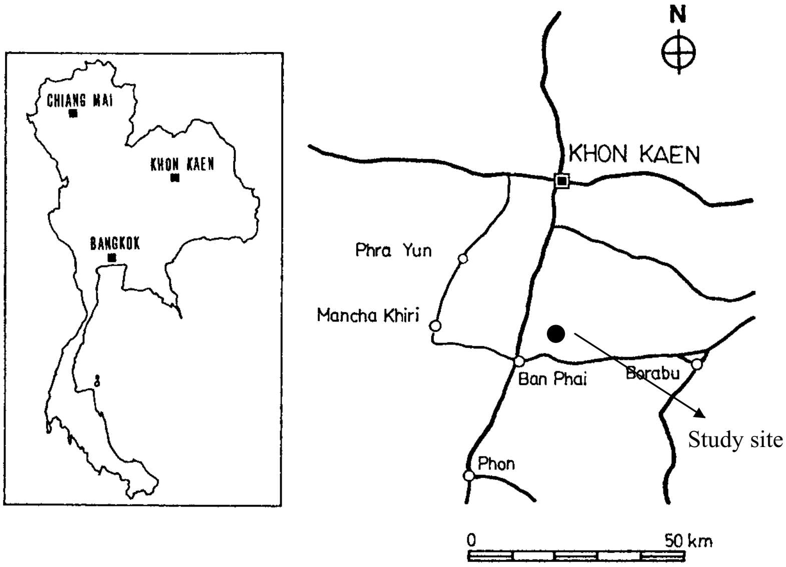

Fig. 1. Study Site

Table 1. Soil characteristics

Depth (cm)	Soil texture	Bulk density ($g\ cm^{-3}$)	Specific gravity	Porosity (%)	Saturated hydraulic conductivity ($cm\ s^{-1}$)*
0–100	SL	1.40–1.60	2.65	40–47	$(5.0–9.4) \times 10^{-4}$
100–	SCL	1.64–1.79	2.67	33–39	$(1.1–9.8) \times 10^{-6}$

* Measurement by falling head permeability test (100 mL core).

about 1,200 mm. Sugarcane and cassava are cultivated in the highland, and rice grows during the rainy season (May to October) in the lowland. The soil consists of sandy loam (SL; 0 to 1 m deep) underlain by sandy clay loam (SCL). The porosity is 40–47% in SL and 33–39% in SCL. The saturated hydraulic conductivity is on the order of 10^{-4} cm s^{-1} in SL and the order of 10^{-6} cm s^{-1} in SCL. SCL is impermeable to water, and water is retained in the SL layer (Table 1).

2. Experimental procedure

The vertical distribution of Br^- was determined as follows.

(A) 1 L solution of potassium bromide (KBr) was applied to a 30 cm × 30 cm level area of bare ground. The study area was a fallow between sugarcane and paddy fields.
(B) After a fixed time elapsed, 100-mL core samples were collected at depth intervals of 10 cm (Fig. 2).
(C) The soil samples were sent to a laboratory, and soil water was extracted with a centrifuge at a force of about 4,000 rpm, corresponding to about pF 3.5.
(D) After extraction, the Br^- concentration was determined with an ion-chromatograph (Dionex, LC25, IC20).

① Rate of collection of bromide

A 1 L solution of KBr (Br^- concentration: 0.5 g L^{-1}) was sprinkled to a 30 cm × 30 cm test area of bare ground (depth of applied solution: 11 mm). After 30 min, four 100-mL cores of the top 5 cm of soil were collected, and the Br^- concentration in the cores was determined.

✍ Confirmation of suitability of our method using bromide as a tracer

A 1 L solution of KBr (Br^- concentration: 2 g L^{-1}) was sprinkled to a 30 cm × 30 cm test area of bare ground, and the treated area was sprayed with 8 L of Br^- free water (total water depth: 100 mm). After 1 h, four 100-mL cores were collected for each depth interval of 10 cm, and the Br^- concentrations in the cores were determined.

③ Determination of infiltration of rainfall

A 1 L solution of 50 g L^{-1} KBr was applied to three

30 cm × 30 cm test areas to trace the infiltration of rainfall over a long period (Fig. 2). Br^- concentration of 50 g L^{-1} was used to ensure an experimentally measurable concentration of Br^- after dilution by rainfall and soil water. The solution was applied on June 27, 2003. The soil samples were collected on August 7, 2003, when there was little rainfall (in spite of the rainy season) and soil was dry; on September 10, 2003, when there was much rainfall and soil was wet; and on February 12, 2004, when it was dry (Fig. 3).

Results and discussion

1. Rate of collection of bromide

We expected that very little KBr solution would penetrate below 5 cm deep because the applied solution

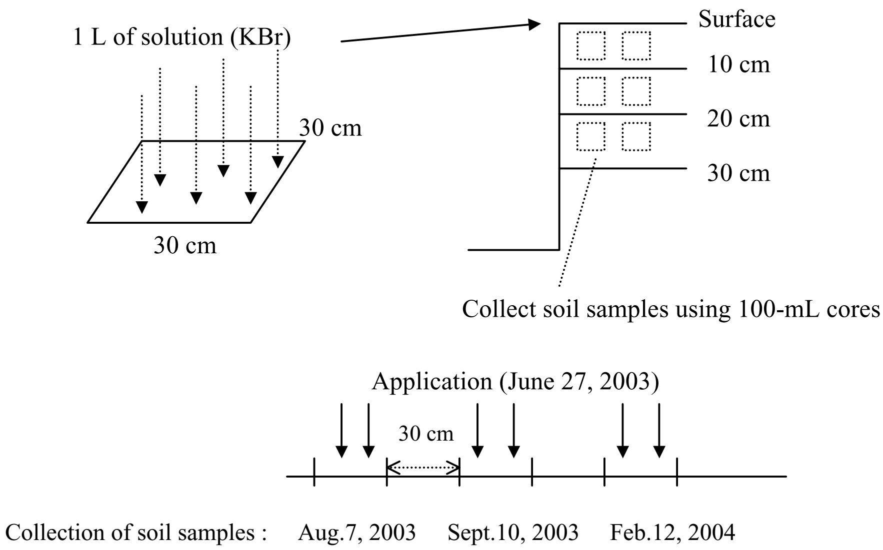

Fig. 2. Application and collection of bromide

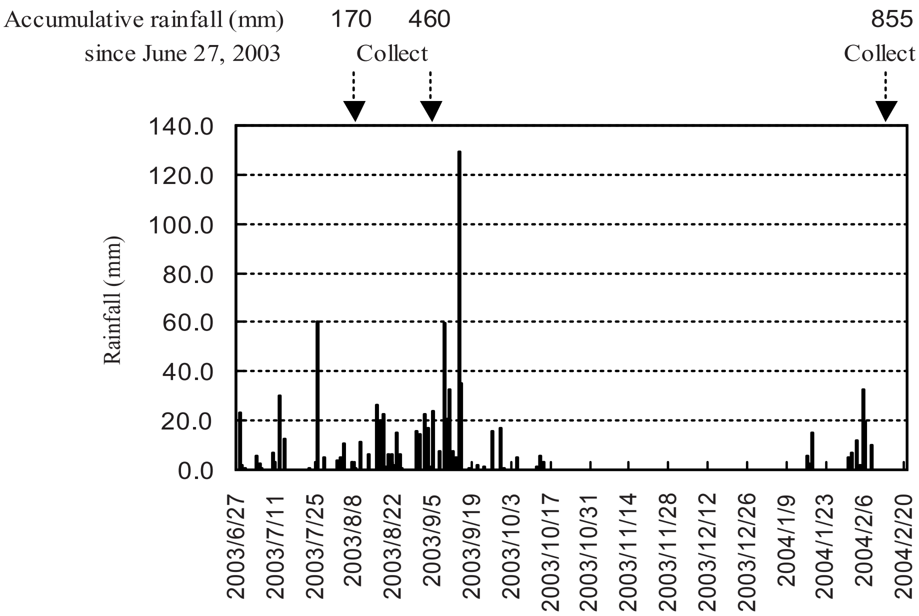

Fig. 3. Daily rainfall

depth was 11 mm, the porosity of the soil was more than 40%, and the effective porosity of sandy soil was expected to be high. We studied the top 5 cm of soil and determined that the water content of the soil was 9.2% by volume before spraying and 15.5% by volume after spraying (Table 2). The increase in water content in the spray area was calculated to be 284 mL (30 cm × 30 cm × 5 cm × (0.155 – 0.092)). From these results, we inferred that about 70% of the solution that we applied flowed out laterally from the applied area. The water content determined by extraction with a centrifuge was 9.2%, and the Br^- concentration was 133.8 mg L^{-1}. From these data, we calculated a collection rate of about 11% (Table 2). Thus, we deduced that the collection rate was quite low because Br^- solution flowed out laterally and not all soil water could be extracted by the centrifuge.

2. Suitability of our method using bromide as a tracer

Table 3 shows the vertical distribution of Br^- concentration in soil water and the variation of soil moisture before and after application of water. The difference in soil moisture before and after application of water increased above a depth of 40 cm. The increase in soil water was calculated to be about 30 mm (Table 3), suggesting that about 70% of the applied water flowed out laterally. The highest concentration of Br^- was found in the 10–20 cm deep layer. We can attribute the increase in soil moisture above 15 cm to infiltration of the sprayed water assuming the Br^- concentration peaked at a depth of 15 cm (halfway between 10 and 20 cm). The amount of soil water above 15 cm was calculated to be about 30 mm (Table 3), which agreed with the calculated increase in soil moisture above 40 cm. From these results, we surmised that the Br^- that was applied to the surface moved through the soil with a piston flow, that the infiltrating water pushed down existing soil water, and that the soil water content from the surface to the depth of the peak Br^- concentration was equal to the increase of soil moisture underground. We inferred that Br^- moved with convection by a piston flow and with dispersion due to difference in Br^- concentration because Br^- was detected in both the 0–10 cm deep layer and the 20–30 cm deep layer.

We concluded from these results that Br^- is suitable for tracing infiltration of water through soil.

3. Infiltration of rainfall

In the soil samples collected on August 7, 2003, the Br^- remained in the 0–20 cm deep layer and the soil moisture was low, about 10%, indicating that the amount of infiltration was very small (Fig. 4, Table 4). Assuming that the total rainfall, between June 27 and August 7, about 170 mm, evaporated, the average rate of evaporation during this period was about 4 mm day^{-1}.

In the soil samples collected on September 10, 2003, the peak Br^- concentration appeared in the 30–40 cm deep layer. The Br^- concentration was normally distributed around the 30–40 cm deep layer, indicating that the

Table 2. Collection rate of bromide

Depth (cm)	Soil moisture (%, Vol.)		Collected water (%, Vol.)	Br^- concentration (mg L^{-1})	Estimated collection rate (%)
	Before spraying	After spraying			
0–5	9.2	15.5	9.2	133.8	11*

*(0.1338 × 30 × 30 × 5 × 0.092 × 100) / (1,000 × 0.5).

Table 3. Variation of soil moisture and Br^- concentration

Depth (cm)	Soil moisture (%, Vol.)		Difference in soil moisture (%) (After-Before)	Br^- concentration (mg L^{-1})
	Before spraying	After spraying		
0–10	9.2	20.2	11.0	2.5
10–20	10.2	19.3	9.1	225.9
20–30	13.1	19.9	6.8	3.8
30–40	18.1	19.6	1.5	0.0
40–50	22.9	15.7	–7.2	0.0

Soil moisture (%) equals water depth (mm).
The increased soil moisture was about 30 mm (11.0 + 9.1 + 6.8 + 1.5).
The amount of the infiltration was calculated to be about 30 mm (20.2 + 19.3/2).

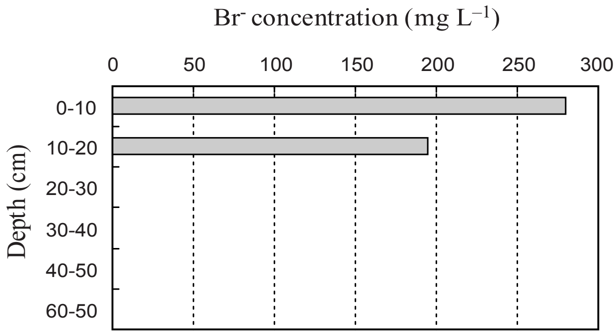

Fig. 4. Vertical distribution of bromide (August 7, 2003)
The collection rate was 0.4%.

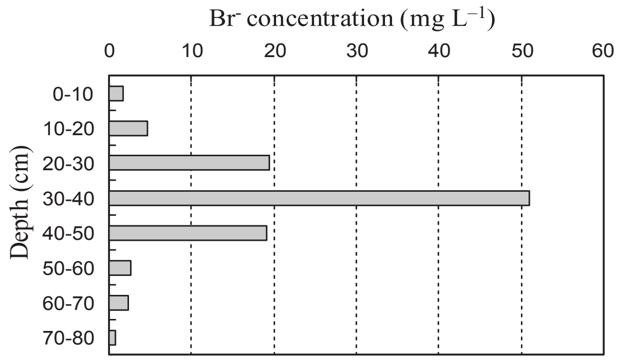

Fig. 5. Vertical distribution of bromide (September 10, 2003)
The collection rate was 0.5%.

Table 4. Three phases of soil (August 7, 2003)

Depth (cm)	Bulk density (g cm^{-3})	Solid (%)	Liquid (%)	Gas (%)
0–10	1.49	56.2	10.4	33.4
10–20	1.43	54.0	11.6	34.4
20–30	1.53	57.7	14.2	28.1
30–40	1.47	55.5	12.2	32.3
40–50	1.47	55.5	14.3	30.2
50–60	1.48	55.8	16.6	27.6

Table 5. Three phases of soil (September 10, 2003)

Depth (cm)	Bulk density (g cm^{-3})	Solid (%)	Liquid (%)	Gas (%)
0–10	1.45	54.7	21.8	23.5
10–20	1.51	57.0	33.2	9.8
20–30	1.54	58.1	33.6	8.3
30–40	1.50	56.6	33.5	9.9
40–50	1.56	58.9	31.8	9.3
50–60	1.55	58.5	33.1	8.4
60–70	1.60	60.4	30.6	9.0
70–80	1.59	60.0	31.2	8.8

The depth of the peak concentration was 35 cm deep.
The quantity of the infiltration was calculated to be about 100 mm (21.8 + 33.2 + 33.6 + 33.5/2).

Br^- moved downward with a piston flow induced by the infiltration of rainfall and with dispersion due to differences in the Br^- concentration (Fig. 5). Since Br^- was assumed to move downward with a piston flow, the amount of water in the soil above the depth of the peak Br^- concentration was equal to the amount of rainfall infiltration between August 7 and September 10. The amount of the rainfall infiltration was about 100 mm (Table 5), assuming that the Br^- concentration peaked at a depth of 35 cm. The total rainfall during this period was about 290 mm, so the amount of evaporation and surface runoff was about 190 mm (Fig. 3).

In the soil samples collected on February 12, 2004, the peak Br^- concentration appeared in the 50–60 cm deep layer, and the Br^- concentration in the 0–10 cm deep layer was 6.2 mg L^{-1}, higher than that on September 10 (Fig. 6). The Br^- concentration in the 0–10 cm deep layer was higher than that in the 10–30 cm deep layer because of the effect of evaporation. These results suggested that part of the Br^- that had infiltrated the soil returned to the

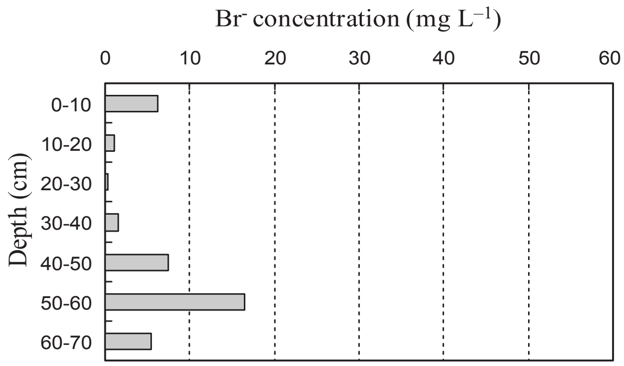

Fig. 6. Vertical distribution of bromide (February 12, 2004)
The collection rate was 0.1%.

Table 6. Three phases of soil (February 12, 2004)

Depth (cm)	Bulk density (g cm^{-3})	Solid (%)	Liquid (%)	Gas (%)
0–10	1.42	53.6	9.2	37.2
10–20	1.48	56.0	10.2	33.8
20–30	1.40	52.6	13.1	34.3
30–40	1.45	54.8	18.1	27.1
40–50	1.54	57.9	22.9	19.2
50–60	1.51	56.9	19.0	24.1
60–70	1.50	56.8	19.7	23.5

The depth of the peak concentration was 55 cm deep.
The quantity of the soil water above the peak concentration was calculated to be about 80 mm (9.2 + 10.2 + 13.1 + 18.1 + 22.9 + 19.0/2).

surface, resulting in the accumulation of salts at the surface.

Assuming the Br^- concentration peaked at a depth of 55 cm, the amount of water in soil above the peak Br^- concentration was about 80 mm (Table 6). Though the total rainfall between June 27, 2003 and February 12, 2004, was about 860 mm, this value was smaller than that on September 10, indicating that some soil water was lost by evaporation during the period between September and February. However, the peak Br^- concentration appeared at a greater depth on February 12 (50–60 cm) than on September 10 (30–40 cm), suggesting that the peak Br^- concentration was not raised by evaporation though a part of the infiltrated Br^- moved upward.

Conclusion

Br^- was used to successfully trace the infiltration of rainfall through a sandy soil in northeast Thailand. We determined that Br^- moved downward with a piston flow and that the increase in the amount of water in the soil above the depth of the peak Br^- concentration equaled the increase in soil moisture caused by infiltration. Using our method, we determined that the largest amount of rainfall infiltration occurred during September. The amount of soil water above the peak Br^- concentration was calculated to be about 0 mm during the period June 27, 2003 and August 7, 2003; about 100 mm during the period between June 27, 2003 and September 10, 2003; and about 80 mm during the period between June 27, 2003, and February 12, 2004.

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