RADIOISOTOPES, **53**, 469-475 (2004)

Article

Influence of Inundation of Ground Surface on ^{222}Rn Concentrations in Shallow Groundwater

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Received April 16, 2004

Radon-222 (^{222}Rn) is a good indicator for analyzing the speed at which surface water infiltrates the ground and reaches groundwater. Preferential flow, which is very fast, is expected to occur when the ground surface is inundated. Piston flow, which is very slow, is expected to occur when the ground surface is not inundated but is only sprinkled with water such as during a light rainfall. We hypothesized that preferential flow would reduce the ^{222}Rn concentration in groundwater but that piston flow would not ; our study verified this hypothesis experimentally. We then measured ^{222}Rn concentrations in groundwater for one year in lowland and upland locations. ^{222}Rn concentrations in groundwater decreased at the lowland site, where the ground surface was inundated by irrigation and heavy rainfall, while ^{222}Rn concentrations in groundwater did not decrease at the upland site, where the ground surface was not inundated.

Key Words : Radon-222, groundwater, preferential flow, piston flow

1. Introduction

Radon-222 (^{222}Rn) is a radioactive gas with a half-life of 3.8 days that is generated by the decay of Radium-226 (^{226}Ra) in strata. Because ^{222}Rn concentrations in infiltrated water increase according to the radioactive growth curve, it is a good indicator for analyzing the speed at which surface water infiltrates the ground and reaches groundwater[1)-6)].

There are two types of water infiltration, depending on whether ground surface is inundated or not. Preferential flow through macropores is expected to occur when the ground surface is inundated, and its rate of infiltration is faster than that estimated from hydraulic conductivity of soil. We hypothesized that with preferential flow, the ^{222}Rn concentration would decrease markedly in shallow groundwater. Piston flow, however, occurs when the ground surface is not inundated but is only sprinkled with water (such as during a light rainfall) ; the infiltrated water pushes down retained soil water. Because the rate of piston flow is slow, 1 to 2 m a year[7),8)], we hypothesized that the extent of decrease of ^{222}Rn concentration in groundwater is very small.

Our study verified the effects of preferential flow and piston flow on ^{222}Rn concentration in shallow groundwater experimentally. We then measured ^{222}Rn concentrations in groundwater once a week for one year at two sites, a lowland

Table 1 Soil characteristics of the study site

Soil layer (cm)	Color	Bulk density (g/cm^3)	Specific gravity	Porosity	Saturated hydraulic conductivity (cm/hour)*)
0–40	7.5YR3/3	0.80	2.67	0.65	1.16
40–90	7.5YR4/4	0.57	2.74	0.72	0.25
90–120	7.5YR2/1	0.55	2.49	0.68	4.01

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

site with paddy fields and an upland without paddy fields, to identify the effect of preferential flow or piston flow on ^{222}Rn concentration in shallow groundwater.

2. Materials and Methods

2·1 Elucidation of the effect of inundation on ^{222}Rn concentrations in shallow groundwater

We selected the experimental field of the National Institute for Rural Engineering, Ibaraki Prefecture, Japan, where the soil is a volcanic ash soil (Andisol), as the study site. To facilitate measuring water levels and collecting groundwater samples, we installed a piezometer to a depth of 2.5 m below the ground surface. The groundwater level is about 2 m deep. Table 1 shows the physical properties of the soil profile to 1.2 m depth. The soil was subdivided into layers on the basis of the standard soil color chart. The bulk densities were quite low, 0.55 to 0.80 g cm^{-3}. The saturated hydraulic conductivity of the top soil was 1.16 cm h^{-1} with the common conductivity range of a field in Japan[9].

We constructed a pond 6.3 m by 6.3 m by 0.4 m deep and filled it with water (Fig. 1). One hour after we began to fill the pond with water, a tracer of about 600 g of Bromide (Br^-) was injected into the pond to track the infiltration of surface water to the groundwater table. Bromide, an anion belonging to the halogen family, has been used for tracing water movement in a vadose zone[10)–14)]. During the experiment, the depth of the pond water was maintained between 10 cm and 40 cm, and the infiltration rate was 10 to 15 cm h^{-1}. We measured the groundwater level using a portable level gauge and the concentrations of Br^- and ^{222}Rn in sampled groundwater using a small pump every hour until 8 hours had elapsed; thereafter, we took these measurements every 2 hours. The natural level of Br^- concentration in the groundwater was about 0.05 mg L^{-1}. We measured Br^- concentrations using an ion-chromatograph (Dionex, LC25, IC20). To measure ^{222}Rn concentrations, we used the toluene extraction method[15]. This method takes advantage of the

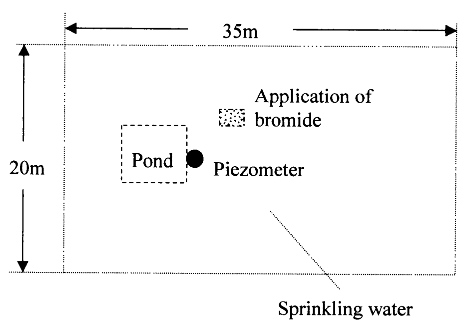

Fig. 1 Locations of the pond, piezometer and application of bromide.

fact that ^{222}Rn dissolves more readily in toluene than in water. An aliquot of 500 mL of sample water was carefully poured into an extraction vessel, and 40 mL of toluene with scintillators (4.0 g L^{-1} of PPO and 0.1 g L^{-1} of POPOP) was added. After the closed vessel was shaken for 1 to 2 min, the toluene fraction was collected into a 20-mL glass vial. The radioactivity was counted with a liquid scintillation counter (Packard 1050) for 50 min. The detection limit of this method is about 0.04 Bq L^{-1}.

After the inundation experiment, we sprinkled water at the study site (Fig. 1). The area of sprinkling was 20 m by 35 m, and the sprinkling intensity was 7 mm h^{-1}, less than the hydraulic conductivity of the top soil (11.6 mm h^{-1}). The ground surface was not inundated with water. Before the sprinkling test, 50 g L^{-1} of Br^- was applied as 1 L of potassium bromide solution to an area of 30 cm by 30 cm within the sprinkling area. During the experiment, we measured the water level in the piezometer and collected samples for the ^{222}Rn measurement; 6 days after the experiment, we collected soil samples using 100-mL cores. Four cores were collected at every 10 cm depth from the surface to 100 cm maximum depth. There was no rainfall during this period. Extraction of water from the soil cores was conducted in the laboratory using a centrifuge at a force of about 5 000 rpm, corresponding to about pF 3.5. After extraction, we measured Br^- concentrations in the extracted soil water.

2・2 Application to a field

We selected a small basin in Kasama City, Ibaraki Prefecture as the site for the measurement of ^{222}Rn concentration in shallow groundwater (Fig. 2). The area comprises upland and lowland topography. The geological structure of the upland is comprised of surface soil of about 1 m thickness, which is underlain by volcanic soil of 1 to 2 m thickness and weathered granite several meters thick. In the lowland, an alluvium layer several meters thick overlies weathered granite[5]. We selected two wells, one in the lowland and the other in the upland. The wells were about 5 m deep and screened between 3 and 5 m deep. In the lowland, there were many paddy fields, which were expected to be inundated with water in the irrigation period. Because the upland had no paddy fields, and the ground surface inclines slightly, inundation was not expected. We measured ^{222}Rn concentrations, water levels and water temperatures in the shallow groundwater weekly for a year to identify the influence of preferential flow in the lowland and piston flow in the upland on ^{222}Rn concentrations in groundwater. For the measurement of ^{222}Rn concentration, groundwater was collected carefully from a tap connected to a pump at each observation well.

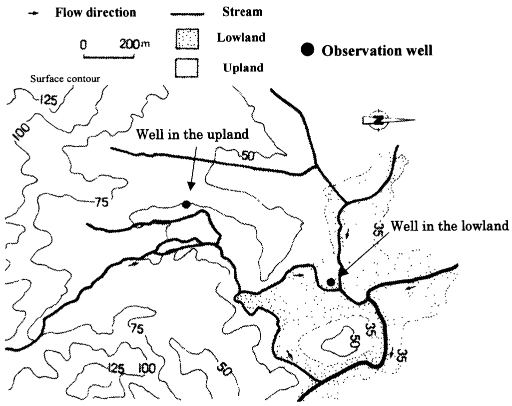

Fig. 2 Study site of the long-term measurements.

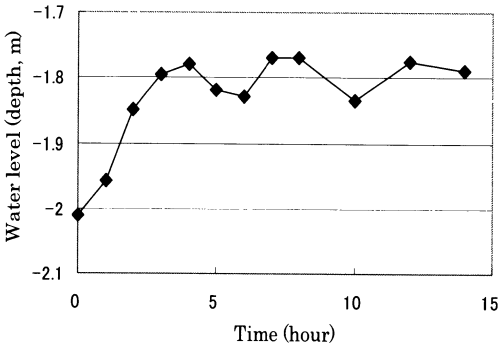

Fig. 3 Groundwater levels during the inundation experiment.

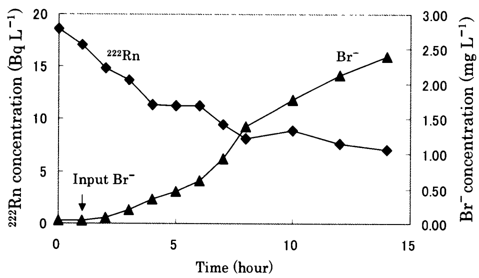

Fig. 4 Br$^-$ and ^{222}Rn concentrations in groundwater. The counting error of ^{222}Rn concentration was below 1%.

3. Results and Discussion

3・1 Variations of ^{222}Rn concentrations under condition of inundation

Figure 3 shows the variations of groundwater levels during the inundation experiment. Before water was supplied to the pond, the groundwater level was about 2 m deep. After water was supplied, the groundwater level rose and reached its highest level of about 1.8 m deep after 3 hours. The Br$^-$ tracer was deduced to reach the water table at the depth of about 1.8 m 2 hours after injection (Fig. 4). The rate of Br$^-$ infiltration was calculated to be about 90 cm h^{-1}. This rate was very rapid compared with the estimated value from the infiltration rate (10 – 15 cm h^{-1}) and porosity (0.65 – 0.72). This result suggests that the infiltration from the pond occurred as preferential flow with water moving downward through the macropores. ^{222}Rn concentrations in the groundwater continued to decrease, and reached almost a constant value, about 8 Bq L^{-1}, after 8 hours. These results indicate that when the ground surface is inundated, the preferential flow occurs and ^{222}Rn concentrations in groundwater decrease significantly.

3・2 Variations in ^{222}Rn concentrations under conditions of sprinkling water

Figure 5 shows changes in the groundwater level over time under conditions of sprinkling water. The water level under these conditions did not rise until 10 hours had elapsed, and then rose gradually. Figure 6 shows ^{222}Rn concentrations in groundwater under sprinkling conditions. The ^{222}Rn concentrations did not decrease significantly (15 to 20 Bq L^{-1}), suggesting that surface water did not arrive at the water table immediately.

Figure 7 shows the vertical distribution of Br$^-$ concentrations in soil water, and Table 2 presents distribution data for three phase dis-

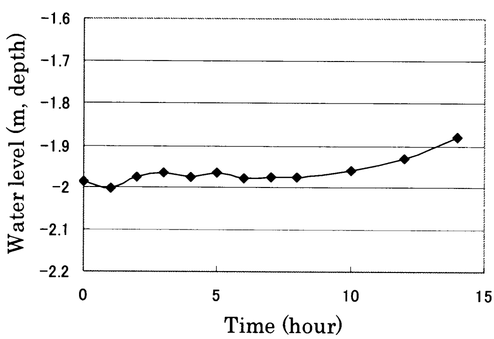

Fig. 5 Groundwater levels under sprinkling conditions.

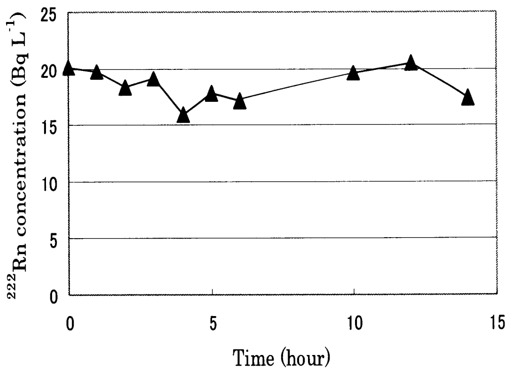

Fig. 6 ^{222}Rn concentrations in groundwater under sprinkling conditions.
The counting error of ^{222}Rn concentration was below 1%.

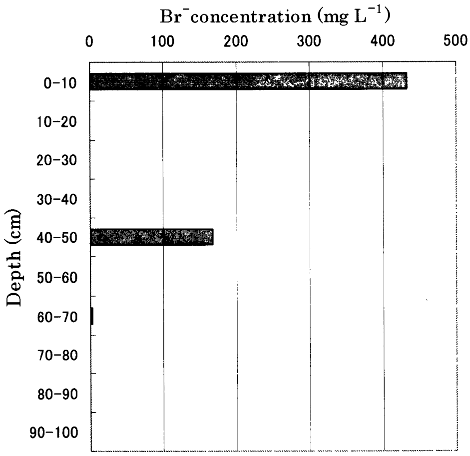

Fig. 7 Vertical distribution of Br^- concentrations in soil water.

tribution of the soil in collecting soil samples. The range of the gas phase of the soil was 20% to 33%, indicating that soil was unsaturated. The soil depths at which Br^- was detected were 0 cm to 10 cm, 40 cm to 50 cm and 60 cm to 70 cm. We deduced from the result that the Br^- applied in the study site did not reach the water table; this deduction was consistent with the ^{222}Rn concentrations measured in the groundwater.

Table 2 Three phases distribution of the soil 6 days after sprinkling experiment

Depth (cm)	Solid(%)	Liquid(%)	Gas(%)
0-10	27.7	39.7	32.7
10-20	28.2	44.0	27.9
20-30	30.4	49.7	20.0
30-40	28.0	48.3	23.8
40-50	24.3	55.8	20.0
50-60	21.7	58.1	20.3
60-70	21.0	58.5	20.6
70-80	22.7	52.3	25.1
80-90	23.0	49.4	27.7
90-100	22.2	49.1	28.8

Our results suggest that when ground surface is not inundated under sprinkling conditions, surface water does not reach groundwater immediately and that ^{222}Rn concentration in groundwater does not decrease significantly.

3·3 Long-term measurement of ^{222}Rn concentrations in shallow groundwater

Figure 8 shows the results of the long-term measurement of ^{222}Rn concentrations, groundwater level, temperature and rainfall at the lowland and upland sites. In samples collected from the lowland well, ^{222}Rn concentrations in the groundwater decreased with the start of the irrigation in May, and then increased with the end of the irrigation in September. During the irrigation period, the groundwater level was high. In the non-irrigation period, a large amount of rainfall reduced ^{222}Rn concentrations in groundwater from 20 to 30 Bq L^{-1} to about 5 Bq L^{-1}, suggesting that surface water reached groundwater immediately. These results suggest that when paddy fields are inundated with water by irrigation or rainfall, preferential flow

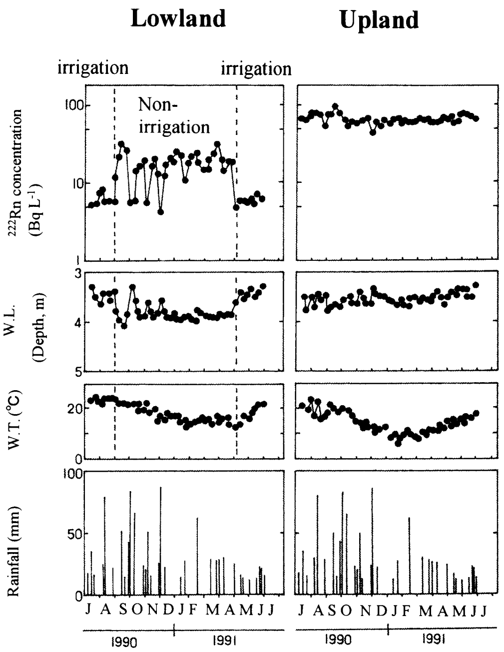

Fig. 8 Long-term measurements in groundwater. W.T. is water temperature. W.L. is water level. The counting error of ^{222}Rn concentration was below 1%.

occurs and ^{222}Rn concentrations in the groundwater decrease significantly. In the groundwater samples collected from the upland well, ^{222}Rn concentrations were almost constant and were evidently not influenced by rainfall, indicating that infiltration in the upland was slow and that surface water did not reach groundwater immediately. The ^{222}Rn concentrations in groundwater did not change significantly in the upland.

4. Conclusion

We studied the influence of the ground surface conditions, inundated or not, on ^{222}Rn concentrations in shallow groundwater. Under inundation conditions, surface water infiltrated with preferential flow and reached groundwater rapidly. ^{222}Rn concentrations in the groundwater also decreased significantly. Under sprinkling (non-inundation) conditions, surface water infiltrated slowly and ^{222}Rn concentrations in the groundwater did not decrease significantly.

Acknowledgments

We would like to thank Mr Ikuo Yoshinaga, of the National institute for Rural Engineering, for the measurement of Br^- concentrations. We also acknowledge the assistance of Ms Asuka Ochiai, a student at Iwate University, for her help with the experiment.

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要　旨

浅層地下水の ^{222}Rn 濃度に対する表面湛水の影響

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ラドンは浸透水の速度や地表水の地下水面への到達を解析するのに良い指標である。地表面が湛水している時浸透速度の速い選択流が発生し，湛水していない時は浸透速度の遅いピストン流が発生することが想定される。本研究では選択流の発生は地下水のラドン濃度を低下させ，ピストン流は低下させないという仮説をたて，実験によって確認した。現地での実証試験として，低地と台地で浅層地下水のラドン濃度を1年間測定した。低地では，灌漑や降水により地表面が湛水しラドン濃度が低下する現象が見られたが，台地ではその現象が見られなかった。