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Analysis of the Interaction between Surface Water and Groundwater Using Radon-222

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Abstract

It is essential to analyze the interaction between surface water and groundwater in order to use water effectively and predict water quality. The conventional method of analysis, however, measures only the flow of a stream and can not determine groundwater seepage accurately. Since the concentration of Radon-222 (^{222}Rn) in groundwater is much higher than in surface water, the use of ^{222}Rn was examined as an indicator for the analysis of the interaction between surface water and groundwater. Measurement of the ^{222}Rn concentration in surface water was conducted to detect groundwater seepage into a stream. Furthermore, the simultaneous movement of water both into and out of a stream from the underlying strata was quantified by solving the ^{222}Rn and water balance equations.

Discipline: Irrigation, drainage and reclamation
Additional key words: ^{222}Rn balance, water balance

Introduction

It is essential to analyze the interaction between surface water and groundwater in order to use water effectively and predict the water quality. The conventional method of analysis, however, measures only the volume of flow in a river. As a result, only the difference between groundwater seepage from the river's bed into the river and river water percolation into the underlying strata can be determined, and it is impossible to quantify both if they occur simultaneously. Therefore, since the concentration of ^{222}Rn in groundwater is much higher than in surface water, ^{222}Rn was used to develop a new method of quantifying both groundwater effluent and river water influent, even when they occurred at the same time.

Methodology

1) *Characteristics of ^{222}Rn*

^{222}Rn is a radioactive gas generated by the decay of ^{226}Ra in strata, with a half life of about 1,600 years. When water infiltrates the strata, ^{222}Rn concentration in water increases along with the increase of radioactivity. After 2~3 weeks, an equilibrium is reached between the supply, from the decay of ^{226}Ra, and loss, through the decay of ^{222}Rn, which has a half life of 3.8 days. Thus, the concentration levels off. When water leaves the strata as seepage or from a spring, ^{222}Rn concentration begins to decrease, since the supply of ^{222}Rn has ceased. Thus, the concentration in the groundwater is much higher than in the surface water. It is possible to determine where groundwater seeps into a river based on the distribution of ^{222}Rn in water. Furthermore, the solution of the ^{222}Rn and water balance equations enables to analyze quantitatively groundwater effluent and river water influent.

^{222}Rn in river water is supplied both by groundwater seepage and directly from the sediments of the river bed. Since the latter is negligible, groundwater seepage, therefore, can be treated as the only source of ^{222}Rn in river water.

^{222}Rn is lost through river water infiltration, dispersion to the atmosphere and radioactive decay of ^{222}Rn. River water infiltration affects the total amount of ^{222}Rn but not the concentration. The amount of dispersion of ^{222}Rn to the atmosphere is evaluated by assuming that there is a stagnant film which is the boundary layer between water and air (Fig. 1)[1].

The decrease in the ^{222}Rn concentration in river water by dispersion to the atmosphere and

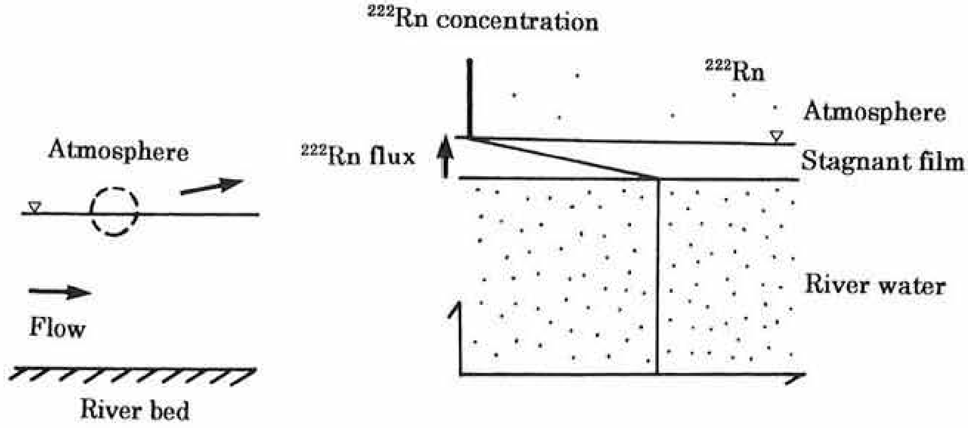

Fig. 1. Stagnant film

by radioactive decay is expressed as follows:

$$C_2 = C_1 \exp(-aL) \quad \text{............(1)}$$
$$a = (D/zhv) + \lambda/v \quad \text{............(2)}$$

where

C_1 = ^{222}Rn concentration at an upstream station (Bq/m^3);
C_2 = ^{222}Rn concentration at a downstream station (Bq/m^3);
D = molecular diffusivity of ^{222}Rn (1.2×10^{-9} m^2/s at 20°C);
z = thickness of a stagnant film (m);
h = average depth of a stream (m);
v = average velocity of a stream (m/s);
λ = decay constant of ^{222}Rn (2.08×10^{-6} s^{-1});
L = distance between stations (m).

It has been reported that the thickness of a stagnant film is about 20 μm when the distance between stations is several kilometers[2,3]. It is, therefore, possible to calculate the ^{222}Rn loss in a stream after measuring the average depth and velocity:

The amount of ^{222}Rn supplied by groundwater is expressed by the following equation, assuming that groundwater flows into a river uniformly:

$$m = qC_g\{1-\exp(-aL)\}/a \quad \text{............(3)}$$

where

m = ^{222}Rn amount supplied by groundwater (Bq/s);
q = groundwater flux (m^2/s);
C_g = ^{222}Rn concentration in groundwater (Bq/m^3).

Using these equations, the ^{222}Rn balance equation for a stream can be derived.

2) Measurement of ^{222}Rn

The ^{222}Rn concentration in water was measured using a liquid scintillation counter after extraction with toluene[5]. This method utilizes the greater solubility of ^{222}Rn in toluene than in water.

In a field, sample water was poured carefully into a vessel and toluene containing scintillators (PPO 4 g/L and POPOP 0.1 g/L) was added. The closed vessel was shaken, and toluene was collected into a vial. The vials were then sent to the laboratory, and the radioactivity was counted for 50 min using a liquid scintillation counter (Packard 2,250 CA for groundwater and Aloka LB-II for surface water). On the basis of the count rate, the ^{222}Rn concentration in groundwater was calculated after 4 corrections, i.e. background, counting efficiency, extraction rate and decay.

In the case of groundwater, 40 mL of toluene was added to 500 mL of water and toluene was collected into a 20-mL glass vial. Since the ^{222}Rn concentration in river water is lower than in groundwater, a large amount of water was necessary. In this investigation, 150 mL of toluene was mixed with 10,000 mL of river water and toluene was collected into a 100-mL Teflon vial. The detection limits were 0.04 Bq/L for groundwater and 0.004 Bq/L for river water.

3) Field investigation

The investigation undertaken to determine where groundwater seeped into a stream using the distribution of ^{222}Rn concentrations was carried out along a stream in Kyonan City, Chiba Prefecture in an area that had been subjected to a landslide. Downstream in this study area, it was inferred that groundwater flowed into the stream[4]. The ^{222}Rn concentration in the stream water and the volume of flow were measured at intervals of 20 m.

The investigation undertaken to quantify the groundwater effluent and river water influent was conducted in the Omoi River basin, Tochigi

Prefecture. Since this area is an alluvial fan where many paddy fields are located, active exchange between river water and groundwater was expected. The ^{222}Rn concentration in river water and groundwater, flow, water temperature and the groundwater level were measured. The investigation was carried out in June, a period coinciding with irrigation in Japan.

Results and discussion

1) Detection of groundwater seepage into a stream

The results of the investigation in the down stream landslide area are shown in Fig. 2. Since the ^{222}Rn concentration increased markedly in section 14–15, it was obvious that groundwater seeped into the stream in this section. Although the seepage increased the volume of flow in the stream, measurement of only the flow volume may be misleading. For example, in section 15–16, even though the flow volume increased, the ^{222}Rn concentration decreased exponentially. No groundwater seepage at all was detected downstream from observation point 15. Thus, measurement of the ^{222}Rn concentration in surface water enables to detect groundwater seepage more accu-

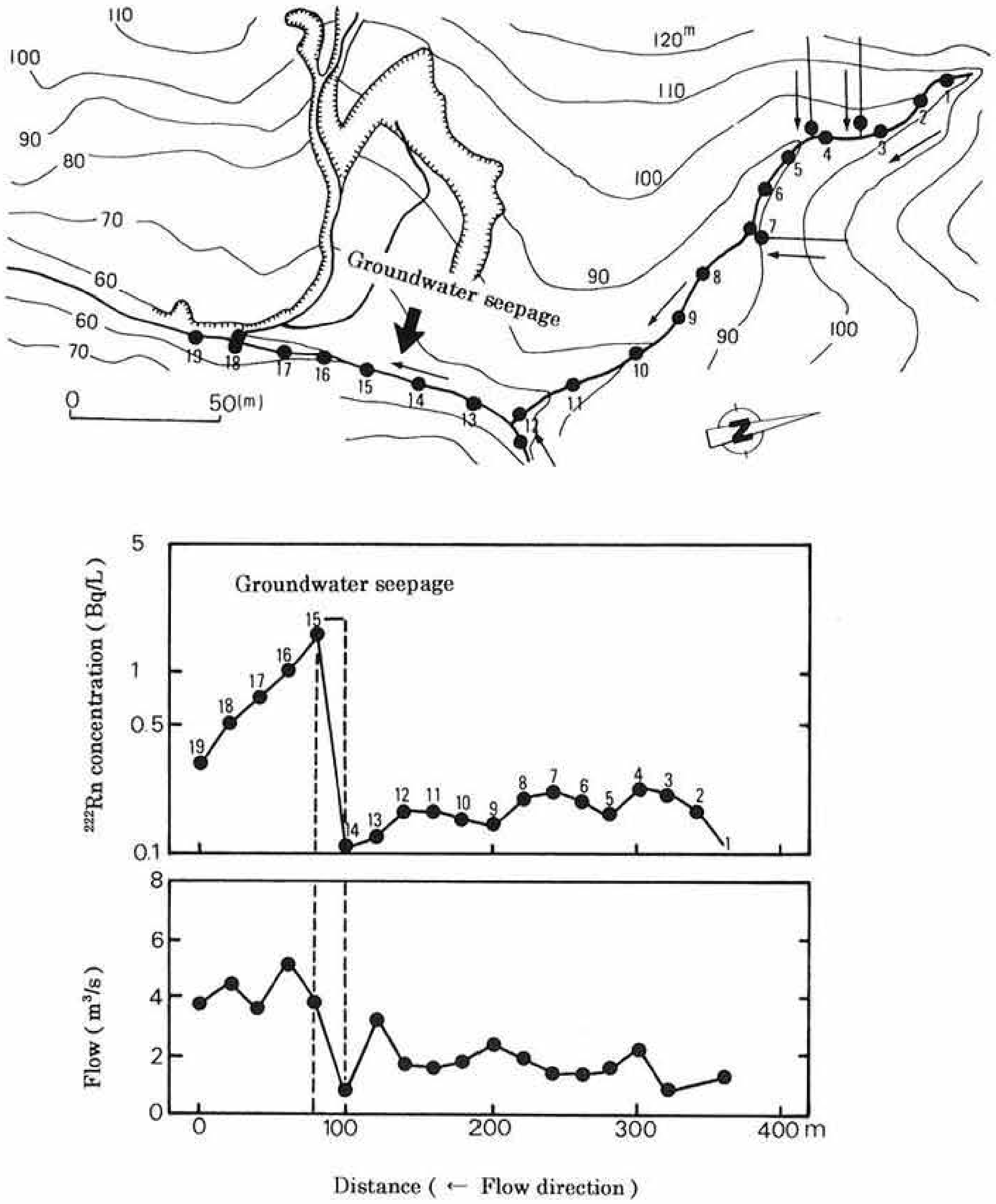

Fig. 2. Results of investigation in the downstream landslide area

rately than by measuring only the flow volume.

2) Quantitative analysis of the exchange between river water and groundwater

Fig. 3 shows the observation points and the analytical model for the exchange between river water and groundwater. It was assumed that influent and effluent seepage was uniform since there was no change in the geology. Substituting $h = 0.48$ m, $v = 0.36$ m/s and $D = 1.1 \times 10^{-9}$ m^2/s into the Equation (2), "a" was calculated to be 0.3 km^{-1}.

The water balance is;

$$Q_2 = Q_1 + Q_g - Q_r \qquad \text{............(4)}$$

where

Q_1 = flow at the upstream station (m^3/s);
Q_2 = flow at the downstream station (m^3/s);
Q_g = groundwater effluent (m^3/s);
Q_r = river water influent (m^3/s).

The ^{222}Rn balance is expressed as follows:

$$C_2Q_2 = [C_1Q_1\exp(-aL) + C_gQ_g\{1-\exp(-aL)\}/aL](1-P) \qquad \text{............(5)}$$

$$P = Q_r/(Q_1 + Q_g) \qquad \text{............(6)}$$

where

C_1 = ^{222}Rn concentration in river water at the upstream station (Bq/m^3);
C_2 = ^{222}Rn concentration in river water at the downstream station (Bq/m^3);
C_g = ^{222}Rn concentration in groundwater (Bq/m^3);
L = distance between the stations (9 km).

The term (1-P) refers to river water infiltration.

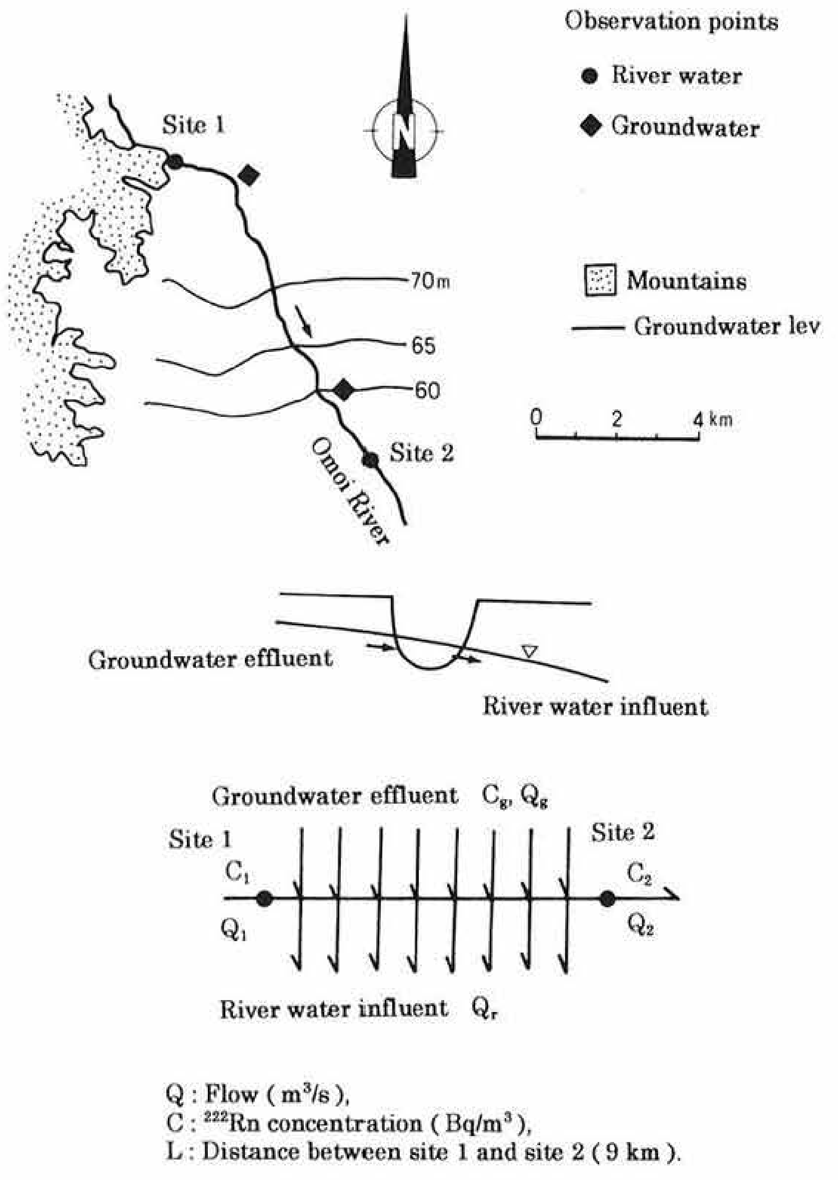

Fig. 3. Observation points and analytical model

Table 1. Results of analysis of the exchange between river water and groundwater

Site 1	C_1	0.80×10^3
	Q_1	8.2
Site 2	C_2	1.2×10^3
	Q_2	5.4
Groundwater	C_g	24×10^3
	Q_g	1.3*
River water	Q_r	4.1*

C: ^{222}Rn concentration (Bq/m^3).
Q: Flow (m^3/s).
* Calculated value using Eqns. (4), (5) and (6).

Table 1 shows the results of the investigation. ^{222}Rn concentration in groundwater is an average value. Groundwater effluent was calculated to be 1.3 m^3/s and river water influent to be 4.1 m^3/s.

Using only the water balance, the amount of groundwater effluent can be considered to be zero and river water influent to be 2.8 m^3/s. It was shown, however, that groundwater seeped into the river, because the ^{222}Rn concentration at the downstream station was higher than at the upstream station. Therefore, the proposed method gave more accurate results than the conventional method, in which only the water balance was calculated.

Conclusion

^{222}Rn was used as an indicator for analyzing the interaction between surface water and groundwater. Since the ^{222}Rn concentration in groundwater was much higher than in surface water, it was possible to detect groundwater seepage into a stream by measuring the ^{222}Rn concentration in surface water. Furthermore, by solving the ^{222}Rn and water balance equations, the amounts of groundwater effluent and river water influent occurring simultaneously were quantified along a section of a river flowing among paddy fields. The results obtained were more accurate than when the conventional method was used, in which only the water balance was calculated. Thus, the method using the ^{222}Rn concentration in water as an indicator is suitable for the analysis of the interaction between groundwater and surface water.

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