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Quantitative Analysis of Groundwater Effluent and Reservoir-Water Influent in a Small Pond Using ^{222}Rn- and Water-Balance Equations

Hiromasa HAMADA[1]* and Satoru KISHI[2]

[1] Crop Production and Environment Division, Japan International Research Center for Agricultural Sciences (JIRCAS) (Tsukuba, Ibaraki 305–8686, Japan)
[2] Planning Department, Hokuriku Regional Agricultural Administration Office (Kanazawa, Ishikawa 920–8566, Japan)

Abstract

Percolation of water from a pond may cause a landslide in a hilled rural area. Before measures to prevent such landslides can be planned, it is essential to identify reservoir-water influent from the pond. We describe an analytical method that uses ^{222}Rn- and water-balance equations to quantify groundwater effluent and reservoir-water influent simultaneously, which is impossible using the conventional method that measures only surface-water inflow and outflow. We selected F pond, Nagano Prefecture, as the study site. We estimated the rate of ^{222}Rn dispersion to the atmosphere by assuming a stagnant film between water and air with thickness inversely proportional to the rate of dispersion. By a laboratory experiment, we estimated the film to be about 830 μm thick and found that the film thickness was not influenced by wind velocities less than 1.5 m s^{-1}. A preliminary investigation suggested that reservoir-water was mixed very well. The groundwater effluent and the reservoir-water influent during the investigation were calculated to be 0.67×10^{-3} m^3 s^{-1} and 0.41×10^{-3} m^3 s^{-1} respectively, by making ^{222}Rn- and water-balance equations and solving them. This analytical method is expected to be useful for not only prevention of a landslide but also for effective use of water and prediction of water quality.

Discipline: Agricultural engineering
Additional key words: stagnant film, dispersion

Introduction

Percolation of water from a pond may cause a landslide in a hilled rural area. Before measures to prevent such landslides can be planned, it is necessary to quantify groundwater effluent and reservoir-water influent. When the conventional method for quantifying flow is used, only surface-water inflow and outflow are measured. This method allows the difference between groundwater effluent and reservoir-water influent to be calculated, but the two values cannot be quantified simultaneously. Previously, effluent and influent flows of a river were analyzed quantitatively using ^{222}Rn- and water-balance equations[2,4]. In this study, the same analytical method was applied to a small pond, and groundwater inflow and reservoir-water percolation were analyzed quantitatively.

Principle

^{222}Rn is a radioactive gas generated by the decay of ^{226}Ra in geological strata. It dissolves in water, while it decays with a half-life of 3.8 days. Since the number of decaying atoms is proportional to that of existing ones, the ^{222}Rn concentration in groundwater achieves secular equilibrium in which the number of supplying atoms is equal to that of decaying ones.

Fig. 1 is a schematic diagram of ^{222}Rn balance in a pond. The sources of ^{222}Rn in the reservoir-water are groundwater effluent, surface-water inflow, and the underlying sediments. Among these, the amount of ^{222}Rn from sediments is negligible. ^{222}Rn is lost from reservoir-water by radioactive decay, dispersion of ^{222}Rn to the atmosphere, reservoir-water outflow and influent. The rate of ^{222}Rn loss of reservoir-water outflow and influent are calculated by multiplying the ^{222}Rn concentration by the flow rate.

*Corresponding author: fax +81–29–838–6651; e-mail hamadah@jircas.affrc.go.jp
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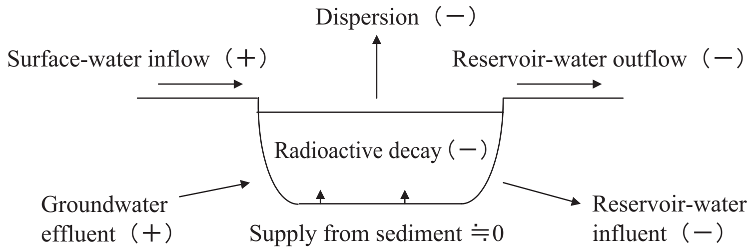

Fig. 1. Schematic diagram of the ^{222}Rn balance in a small pond

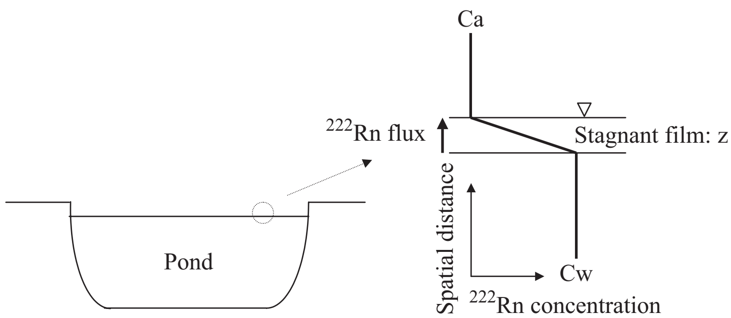

Fig. 2. Mechanism of ^{222}Rn dispersion to the atmosphere

The rate of radioactive decay is expressed as follows:

$$Rd = -\lambda\ (Cw\ Vw) \quad (1)$$

where Rd is the rate of radioactive decay (Bq s^{-1}), λ is decay constant (2.08×10^{-6} s^{-1}), Cw is ^{222}Rn concentration in the reservoir-water (Bq m^{-3}) and Vw is the volume of reservoir-water (m^3).

The rate of ^{222}Rn dispersion to the atmosphere is calculated assuming that there is a stagnant film between water and air (Fig. 2)[3]:

$$Rf = A\ D\ (Ca - Cw) / z \quad (2)$$

where Rf is the rate of ^{222}Rn dispersion (Bq s^{-1}), A is the area of a pond (m^2), D is molecular diffusivity of ^{222}Rn in water (m^2 s^{-1}), Ca is ^{222}Rn concentration in the air (Bq m^{-3}) and z is the thickness of a stagnant film (m). Ca is very low and regarded as zero. D is calculated as follows[6]:

$$-\log D = (980 / T) + 1.59 \quad (3)$$

where D is molecular diffusivity (cm^2 s^{-1}) and T is the absolute temperature of water (K). The rate of ^{222}Rn dispersion can be calculated if the thickness of the stagnant film is known. Various studies have reported the thickness of the stagnant film for oceans and rivers[1–4], but not for a pond. For this study, we experimentally determined the thickness of a stagnant film on static water such as a pond.

When the water level of a pond is constant, water balance of a pond can be expressed as follows for periods without precipitation:

$$F_{in} + G_{in} = F_{out} + G_{out} + E \quad (4)$$

where F_{in} is surface-water inflow (m^3 s^{-1}), G_{in} is groundwater effluent (m^3 s^{-1}), F_{out} is reservoir-water outflow (m^3 s^{-1}), G_{out} is reservoir-water influent (m^3 s^{-1}), and E is evaporation (m^3 s^{-1}).

It is possible to quantify groundwater effluent and reservoir-water influent in a pond by making ^{222}Rn- and water-balance equations and solving them.

Methodology

1. Determining stagnant film thickness

It is necessary to identify the thickness of a stagnant film in order to calculate the rate of ^{222}Rn dispersion. We estimated the thickness experimentally in a laboratory by measuring the rate of dispersion under controlled conditions. The experiment was conducted in a 20ºC constant-temperature room.

^{222}Rn concentration decreases with time as follows[3]:

$$Ct = Ci \exp\{-(D/zh + \lambda)\ t\} \quad (5)$$

where Ci is the initial ^{222}Rn concentration (Bq m^{-3}), Ct is the ^{222}Rn concentration after t seconds (Bq m^{-3}), h is the water depth (m) and t is time (s). Because ^{222}Rn concentration in water decreases exponentially with time, it is possible to calculate the thickness of a stagnant film from the rate of decrease using Eq. (5).

In our experiment, we poured groundwater, in which the ^{222}Rn concentration is constant, into a 40-L container (0.42 m long × 0.32 m wide × 0.30 m deep) and measured the ^{222}Rn concentration after several tens of hours. We also experimentally estimate the relationship between the thickness of the film and wind velocity to clarify the stability of the film thickness. Winds with various velocities of 0, 0.7, 1.5, 2.0 and 3.0 m s^{-1} were produced by a fan, and ^{222}Rn concentration in the water was measured. The wind velocities were measured with a wind-gauge (CISTOM CW-10) 50 cm above the center of the container.

The ^{222}Rn concentration in water was measured using a toluene extraction method[5]. This method utilizes the characteristic that ^{222}Rn dissolves more in toluene than in water. For groundwater, 500 mL of sample water was carefully poured into an extraction vessel, and 40 mL of toluene containing scintillators (4.0 g $L^{-1}$of PPO and 0.01 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 2250CA) for 50 min. The detection limit of this method is about 0.04 Bq L^{-1}.

2. Field investigation

The field investigation was conducted in F pond, Nagano Prefecture on August 19, 1999. F pond is located on a gradual slope and is underlain by alluvial sediments. The surface area of the pond was 1,550 m^2 and its average depth was 2.8 m.

In advance of the field investigation, we examined the degree of mixing of reservoir-water. Because a boat could not be brought to F pond, the examination was carried out at O pond, which is near F pond. The surface area of O pond is about 17,000 m^2, much larger than that of F pond. We sampled reservoir-waters from the bottom of the center of O pond and from near the bank, and measured the ^{222}Rn concentration in the samples by the toluene-extraction method[5]. Because the ^{222}Rn concentration is very low in surface-water, 10 L of sample water and 150 mL of toluene with scitillators were mixed in the closed vessel for 5 min, and 100 mL of the toluene fraction was collected into a 100-mL Teflon vial. The radioactivity was counted with a liquid scintillation counter (Aloka LB-II) for 50 min. The detection limit is lowered to about 0.004 Bq L^{-1} with this operation.

The ^{222}Rn concentrations in the samples of O pond water were 0.14 ± 0.01 Bq L^{-1} and 0.14 ± 0.01 Bq L^{-1} respectively, and about the same, which confirmed that the water in the pond was mixed very well. It was inferred, therefore, that the reservoir-water of F pond was mixed because F pond is located in the same area as the O pond and smaller in size.

Water flowed into F pond at two points, a spring and a stream, and flowed out at a single point. During the field investigation, we measured the rate of inflow and outflow using a measuring cup. We collected reservoir-water samples for measurement of ^{222}Rn concentration at three points near the shore (Fig. 3), a surface-water sample from the stream, and a groundwater sample from the spring. During the investigation, the water depth of the pond was in a steady state, 2.8 m (Fig. 4), and the wind velocity was 0 m s^{-1}. The temperature of the reservoir-water was 24ºC. The rate of evaporation was regarded as 5 mm day^{-1}, which is the usual value in August in the Kanto District[7], because the water temperature and the wind velocity were in the usual condition of August in the Kanto District.

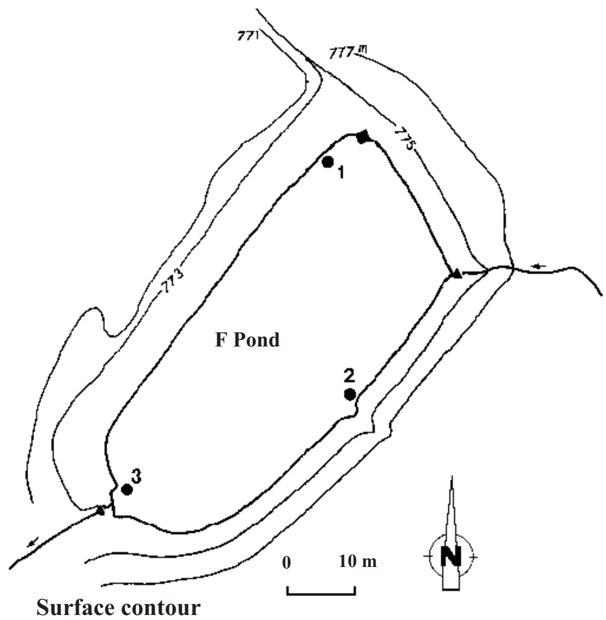

Fig. 3. Map of F pond showing sampling
Observation points: ●, reservoir-water; ◆, spring; ▲, surface-water.

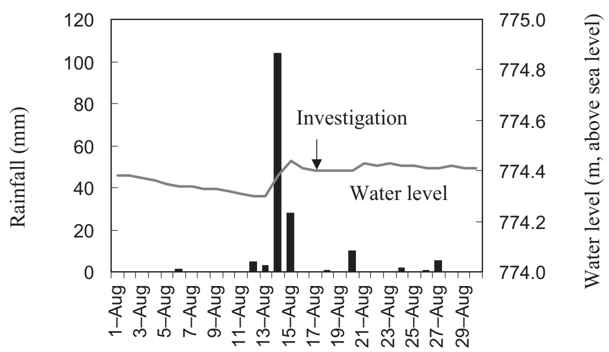

Fig. 4. Reservoir-water level and rainfall

Results and Discussion

1. Thickness of a stagnant film

The results of the laboratory experiment investigating the thickness of the stagnant film are shown in Fig. 5. The ^{222}Rn concentration decreases exponentially with time. The slopes of the straight lines on the semilog plot give values for – (D/zh + λ) in Eq. (5). The thickness of the stagnant film was calculated by substituting D = 1.1 × 10^{-9} (m^2 s^{-1}), h = 0.3 (m) and λ = 2.08 × 10^{-6} (s^{-1}) into Eq. (5). The thickness of the film at wind velocities less than 1.5 m s^{-1} ranged from 750 to 920 μm (average: 830 μm), suggesting that it was not influenced by low wind velocities (Table 1). Above that velocity, the thickness decreased as wind velocity increased (Fig. 6). From these result, we adopted 830 μm as the thickness of the stagnant film for our ^{222}Rn balance calculations for F pond. This value is higher than 5 to 50 μm for rivers and 20 to 130 μm for the oceans[1–4,6]. The condition of our experiment was for static water, while that of the other reports was for flowing water such as rivers and oceans, which indicates that the dispersion rate of ^{222}Rn from static water is smaller than that from flowing water.

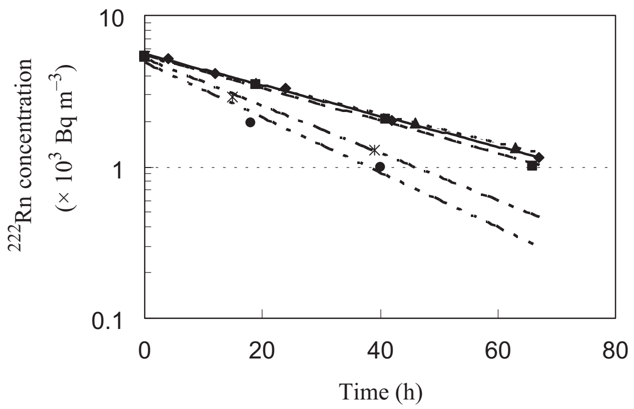

Fig. 5. Variation of ^{222}Rn concentration with time at various wind velocities
–◆– : 0 m s^{-1}, –■– : 0.7 m s^{-1}, –▲– : 1.5 m s^{-1}, –✻– : 2.0 m s^{-1}, –●– : 3.0 m s^{-1}.
The counting error was below 1.5%.
The coefficient of correlation at 3.0 m s^{-1} was 0.97, and the others were above 0.99.

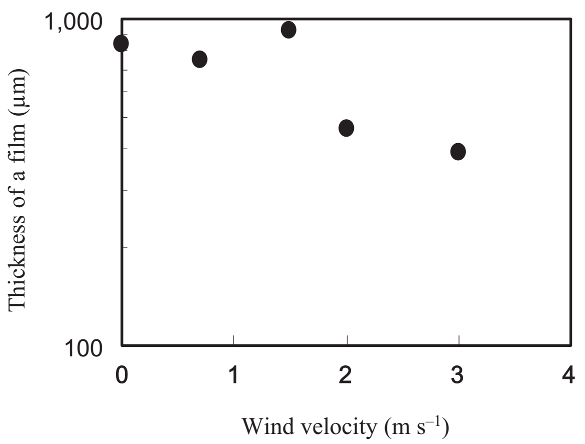

Fig. 6. Relationship between the thickness of a stagnant film and wind velocity

2. Groundwater effluent and reservoir-water influent in F pond

Table 2 shows the surface-water inflow and outflow rates and the ^{222}Rn concentrations at the five sampled points. ^{222}Rn concentrations of the reservoir-water were 0.43 Bq L^{-1}, 0.47 Bq L^{-1} and 0.33 Bq L^{-1}, respectively. ^{222}Rn concentration in groundwater is 10 to 100 times as much as that of surface-water. The range of the measured value was 0.33 Bq L^{-1} to 0.47 Bq L^{-1} and was much smaller than the difference of ^{222}Rn concentrations between groundwater and surface-water. We judged that the reservoir-water and groundwater mixed well and used the average ^{222}Rn concentration in reservoir-water, 0.41 ×

Table 1. Decreasing rate of ^{222}Rn concentration and the thickness of a stagnant film

Wind velocity (m/s)	λ + D/zh (h^{-1})	Thickness of a film (μm)
0.0	–0.0234	830
0.7	–0.0252	750
1.5	–0.0219	930
2.0	–0.0360	460
3.0	–0.0417	390

Table 2. Results of the investigation

	Discharge (m^3 s^{-1}) ×10^{-3}	^{222}Rn conc. (Bq m^{-3}) ×10^3
Spring	0.11	6.54
Surface-water inflow	0.15	0.00
Reservoir-water 1		0.43
Reservoir-water 2		0.47
Reservoir-water 3		0.33
	Average	0.41
Reservoir-water outflow	0.43	

The counting errors of ^{222}Rn concentrations are below 1%.

Table 3. ^{222}Rn balance in the F pond

		($Bq\ s^{-1}$)
^{222}Rn supply	Spring	0.72
	Surface-water inflow	0.00
	Groundwater effluent	$6.54x \times 10^3$
^{222}Rn loss	Radioactive decay	3.74
	Dispersion to the atmosphere	1.00
	Reservoir-water outflow	0.18
	Reservoir-water influent	$0.41y \times 10^3$

x: The rate of groundwater effluent ($m^3\ s^{-1}$).
y: The rate of reservoir-water influent ($m^3\ s^{-1}$).

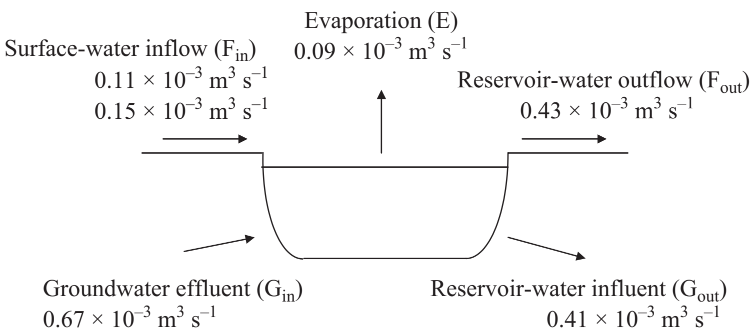

Fig. 7. Summary of water balance in F pond

$10^3\ Bq\ m^{-3}$ for subsequent calculations. This value is high for surface-water, suggesting that groundwater seeped into the pond.

The rate of ^{222}Rn supplied by the spring was calculated to be 0.72 $Bq\ s^{-1}$ by multiplying ^{222}Rn concentration by the rate of flow. Because the ^{222}Rn concentration in the stream was very low, the amount of ^{222}Rn supplied to the pond by the stream was negligible.

^{222}Rn concentration in groundwater effluent was assumed to be the same as that of the spring, 6.54×10^3 $Bq\ m^{-3}$, because the sediments are the same from the surface to about 20 m deep. Thus, if x $m^3\ s^{-1}$ is the effluent flow rate, then the quantity of ^{222}Rn supplied by groundwater effluent was $6.54x \times 10^3\ Bq\ s^{-1}$.

The rate of ^{222}Rn loss by radioactive decay was calculated to be 3.74 $Bq\ s^{-1}$, substituting $Cw = 0.41 \times 10^3$ ($Bq\ m^{-3}$) and $Vw = 1{,}550 \times 2.8$ (m^3) into Eq (1). The dispersion of ^{222}Rn to the atmosphere was calculated to be 1.00 $Bq\ s^{-1}$, by substituting $A = 1{,}550$ (m^2), $Cw = 0.41 \times 10^3$ ($Bq\ m^{-3}$), $D = 1.3 \times 10^{-9}$ ($m^2\ s^{-1}$ at 24ºC) and $z = 8.3 \times 10^{-4}$ (m) into Eq. (2).

^{222}Rn loss by reservoir-water outflow was determined to be 0.18 $Bq\ s^{-1}$ by multiplying ^{222}Rn concentration of the reservoir-water by the discharge rate. The rate of ^{222}Rn loss by reservoir-water influent was $0.41y \times 10^3$ $Bq\ s^{-1}$, where y $m^3\ s^{-1}$ is the influent flow rate.

These results are summarized in Table 3. In the analysis, we assumed that the ^{222}Rn amount in the reservoir-water during the investigation was constant, because we didn't obtain long-term data of the ^{222}Rn concentrations. The following ^{222}Rn-balance equation is obtained:

$$\Delta R = (0.72 + 6.54x \times 10^3) - (3.74 + 1.00 + 0.18 + 0.41y \times 10^3) \quad (6)$$

where ΔR is the change of ^{222}Rn amount in the reservoir-water ($Bq\ s^{-1}$).

The water-balance equation is:

$$\Delta W = (0.11 \times 10^{-3} + 0.15 \times 10^{-3} + x) - (0.43 \times 10^{-3} + 0.09 \times 10^{-3} + y) \quad (7)$$

where ΔW is the change of reservoir-water volume (0 $m^3\ s^{-1}$) and 0.09×10^{-3} ($m^3\ s^{-1}$) is the rate of evaporation from F pond (5 mm $day^{-1} \times 1{,}550\ m^2$). Since the water level of the pond was constant (Fig. 4), we considered the water balance in the pond as a stable condition during the investigation.

By solving Eq. (6) and Eq. (7), groundwater effluent (x) is quantified to be 0.67×10^{-3} ($m^3\ s^{-1}$) and reservoir-water influent (y) to be 0.41×10^{-3} ($m^3\ s^{-1}$). Fig. 7 summarizes the water balance in F pond.

Conclusion

In this study, an analytical method for quantifying groundwater effluent and reservoir-water influent using ^{222}Rn- and water-balance equations was applied to a small pond in which the reservoir-water was mixed well. The dispersion rate of ^{222}Rn was calculated by assuming a stagnant film between water and air. The thickness of a stagnant film was estimated experimentally. With this method, groundwater effluent and reservoir-water influent were determined simultaneously, which is impossible using the conventional method that measures only surface-water inflow and outflow. After that, it is now necessary to study the stability of ^{222}Rn concentration in water for making this method more accurate.

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