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Estimation of Residence Time and Catchment Area for Spring Water Using Radioactive Isotope and Groundwater Flow Model

by

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Abstract

Spring water, however, is often formed in complex geological formations and therefore it is difficult to determine the catchment area contributing to the flow. The Sayanokami spring, located in western part of Fukuoka City, Japan, is such a spring and an important water resource for the local agriculture. In order to better understand the hydrological properties of infiltration and groundwater processes for the spring water, ^{222}Rn and tritium were used as tracers. Results showed that the residence time for the spring water is 10 ~ 20 years. A groundwater model confirmed these results and the travel time from the catchment border estimated to be about 25 years. Using this information the catchment border and uptake area were estimated. The method can be used to more efficiently determine catchment area and travel time for groundwater and thus to better manage the spring water.

Keywords: ^{222}Rn, Tritium, Estimation of residence time and catchment area of spring water, Groundwater flow model

1. Introduction

The Sayanokami spring is located in the new campus area of Kyushu University, western Fukuoka City, Japan. The spring water constitutes an important water resource for the local agriculture. Decreasing groundwater discharge and possible negative implications of the new campus construction have raised concern regarding the sustainable quality of the spring water. Due to this a study was launched to improve the understanding of infiltration processes and groundwater transport in the area.

In recent years, ^{222}Rn has been used as a tracer to study discharge interactions between surface and groundwater. Using this tracer, Hoehn & Gunten[1)] showed properties of river water infiltrating into the groundwater system. Hamada & Komae[2)] proposed a method of analyzing vertical flow of recharging water through the unsaturated zone using ^{222}Rn concentration in the water sampled from the saturated soil surface. Hayashi *et al.*[3)] instead used tritium concentration

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and showed that rainfall in south Japan displays seasonal variation not affected by nuclear fallout. On the other hand, Pint *et al*.[4] used particle tracking based on a calibrated steady-state groundwater flow model to flowpaths, groundwater age, and capture zones for the Allequash Basin in northern Wisconsin. They concluded that it may be difficult to obtain accurate estimates of groundwater age by chemical analyses only of groundwater due to multiple sources of water with different age characteristics.

In numerical calculations of groundwater movement, determination of the permeability coefficient often poses a problem. A method to solve this problem may be to couple the numerical simulation of groundwater movement with tracer experiments in order to determine permeability in a better way.

In this paper, the objective is to evaluate the residence time and the catchment area for spring water by combining the residence time estimated by ^{222}Rn and tritium with calculated groundwater velocity using the model of Tsutsumi *et al*.[5].

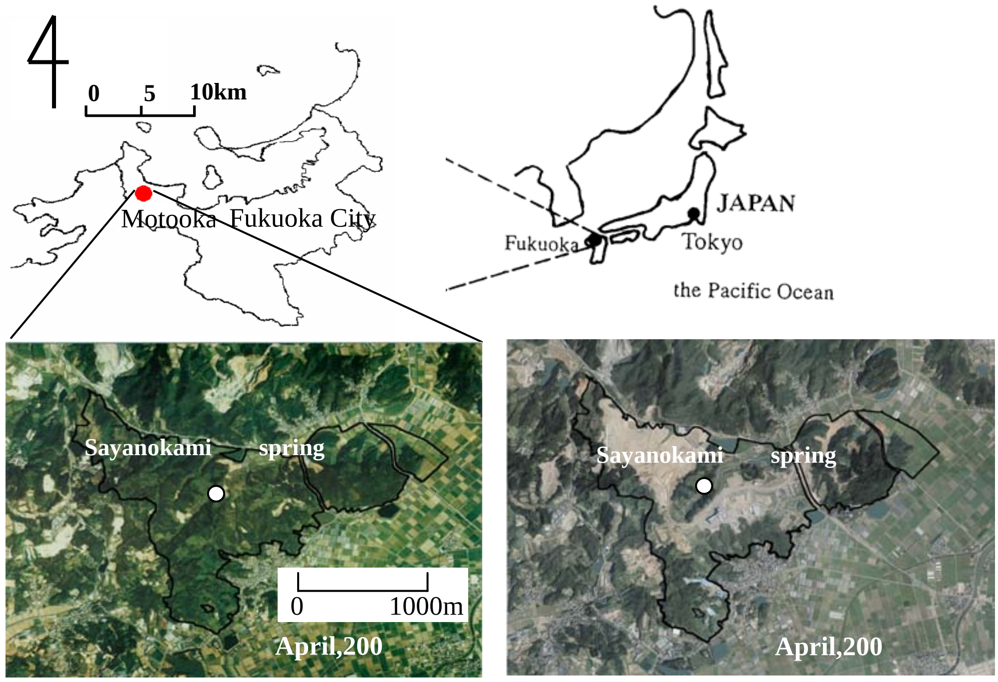


Fig. 1 The experimental area (Kyushu University new campus area).

2. Experimental Area

The experimental area is shown in **Fig. 1**. The line indicates the new campus area of Kyushu University. It comprises in total 275 ha, of which 170 ha are developed, and the remaining 105 ha serve as a “green” conservation area. The two photos in the figure show the situation at two occasions, April, 2000, and April, 2004, respectively. The rapid progress of land development can easily be recognized from the two photos. The geology of the area is characterized by granodiorite and surface soil consists of decomposed granodiorite soil. The elevation of the ground surface ranges from 0.3 m at the lowest point to about 100 m a.m.s.l. The lowland area is an alluvial plain used for agriculture such as greenhouse farming and paddy fields. The thickness of the unconfined aquifer in the lowland area is approximately 50 m. The hilly area, which is where groundwater is recharged, mainly consists of weathered granodiorite at 5-10 m depth and unweathered granodiorite below 40-50 m depth. Large cracks develop in the granodiorite at 10-40 m depth. Meteorological observational data were taken from the Maebaru Local Weather Station, which is located 5 km from the study area. Maebaru has an annual average temperature of 17 degrees C and an annual precipitation of 1600 mm.

3.Results and Discussion

3.1 Radon (^{222}Rn)

Radon (^{222}Rn) was used to investigate whether the groundwater is affected by rapid infiltration from rainfall, an often observed property of spring water. The ^{222}Rn is an inert, naturally occurring, radioactive gas with a half-life of about 3.8 days. Provided that there is no escape of ^{222}Rn in the groundwater system, the ^{222}Rn concentration increases until the rate of loss by radioactive decay in solution balances the rate of supply by radioactive decay of ^{226}Ra, primarily in the solid material of the aquifer[6)]. Under such conditions, ^{222}Rn concentration reaches an equilibrium state after about 3 weeks[7)]. The variation of ^{222}Rn concentration in groundwater can be described by:

$$C(t) = Ce\{1 - \exp(-\lambda t)\} \tag{1}$$

where *C(t)* is ^{222}Rn concentration at time *t* (*t* is assumed to be the residence time); *Ce* is ^{222}Rn concentration at equilibrium state; and λ is the radioactive decay constant (0.18 day^{-1}). If the residence time of groundwater is less than 3 weeks, the ^{222}Rn concentration of the groundwater can be assumed to be affected by only rainfall. To estimate rainfall input, samples for ^{222}Rn determination were taken at 6 occasions. Daily rainfall and sampling dates are shown in **Fig. 2**. As shown in the figure, large rainfall with more than 50 mm before a sampling date was observed on July 12, 2001, Feb. 1, 2002, and Sep. 18, 2002, respectively. The temporal variation of ^{222}Rn concentration in the spring water is shown in **Fig. 3**. The figure indicates that the rainfall input to the groundwater a month before the sampling date does not affect the groundwater concentration of ^{222}Rn. The concentration is almost constant over time.

Consequently, it is suggested that ^{222}Rn concentration of the spring water reaches an equilibrium concentration and thus the residence time of the spring water must be more than 3 weeks. Next, in order to estimate the upper limits of the residence time, tritium with a half-life of about 12.3 years was used.

3.2 Tritium

Tritium is the radioactive isotope of hydrogen (half-life equal to 12.3 years). Tritium is produced naturally in the upper atmosphere by cosmic radiation. Release of tritium into the atmosphere was done from nuclear weapon tests conducted between 1952 and 1963. Tritium in rain water infiltrates into the subsurface and then decreases in an exponential manner. Provided that there is no mixing of groundwater of different age, continuous temporal tritium concentrations in rain water and groundwater enable us to estimate the residence time of groundwater. The variation of tritium concentration in groundwater can be described as:

$$C(t) = C_0 \exp(-0.693 \cdot t / T) \tag{2}$$

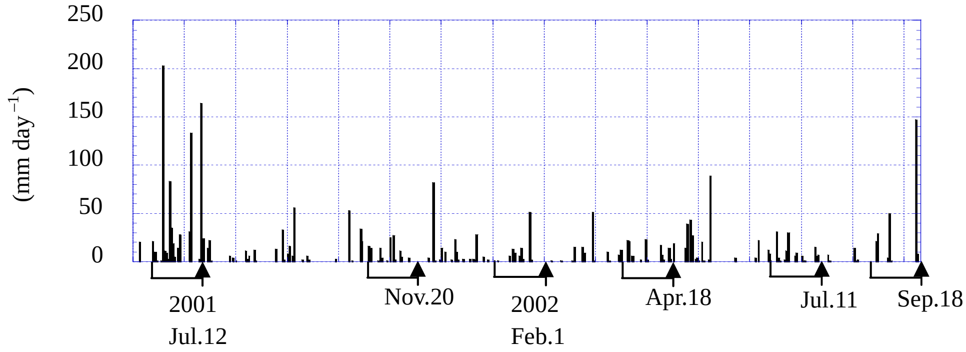


Fig. 2 Daily rainfall and sampling dates.

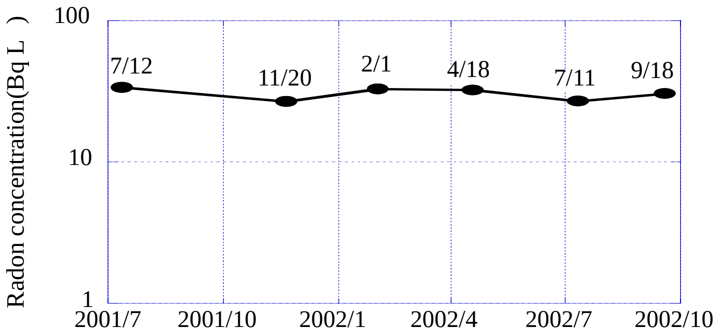


Fig. 3 ^{222}Rn concentration in the spring water.

where $C(t)$ is tritium concentration at time t; C_0 is tritium concentration in rain water; t is the residence time; and T is the half-life of tritium. As mentioned previously, when evaluating the residence time of groundwater by tritium, continuous temporal data of tritium concentration in rain water is required. Data of tritium concentration in rain water at Fukuoka, Japan, exist from 1982 to 1995 and at Chiba near Tokyo from 1974 to 2002. When comparing the data from Fukuoka the Chiba data, it is seen that they are almost identical (**Fig. 4**). Therefore, the tritium concentration at Chiba can be used to estimate the residence time of spring water at the experimental area. Sampling for tritium was performed twice, March, 1995 and June, 2004, respectively. These sampled concentrations can also be seen in **Fig. 4**. By changing the time, t (residence time of spring water), the tritium concentration C_0 in rain water at Chiba at a certain time can be substituted in Equation (2), and then give the tritium concentration $C(t)$. If the calculated concentration $C(t)$ agrees with the observed concentration, it can be assumed that the residence time, t, has been estimated. Using this procedure it was found that the residence time of the spring water is about 13 years (March, 1995) and about 23 years (June, 2004), respectively. The underlying assumption in this procedure is that groundwater flow is moving like piston flow without mixing of new and old groundwater. However, since the actual groundwater may be composed of water of different origin, the method is still approximate.

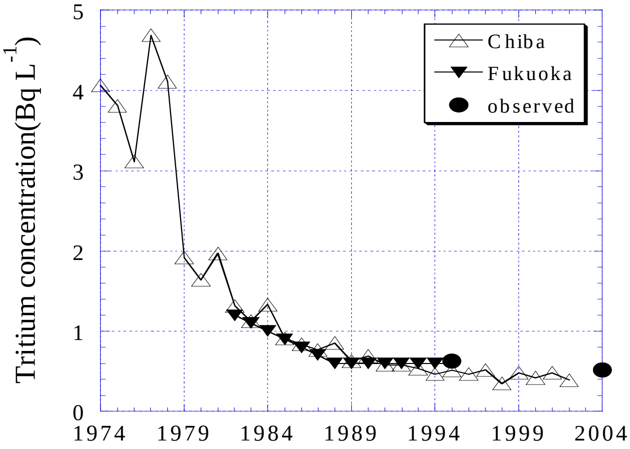


Fig.4 Tritium concentrations.

4. Estimation of Residence Time and Catchment Area Using Lagrangian Particle Tracking

A two-dimensional groundwater model involving the following equation was used

$$
\begin{aligned}
n_e \frac{\partial (h_f - b)}{\partial t} = & -\frac{\partial \{(h_f - b)\cdot u_f\}}{\partial x} - \frac{\partial \{(h_f - b)\cdot v_f\}}{\partial y} \\
& - \sum_m Q_m(x, y, t)\delta(x - x_m)\delta(y - y_m) \\
& + q_w(x, y, t) - EVT_2(x, y, t)
\end{aligned}
\tag{3}
$$

where n_e is effective porosity; h_f is height of groundwater table from base level; b is height of bedrock from base level; Q_m is the water extraction rate by pumping at location (x_m, y_m) at time t, u_f and v_f are groundwater velocity in the x and y direction, respectively; q_w is groundwater recharge rate; and ETV_2 is evaporation from groundwater. The delta functions $\delta(x\text{-}x_m)$ and $\delta(y\text{-}y_m)$ represent the location of the pumping well. The experimental area was divided in to a two-dimensional mesh (50 m x 25 m) according to **Fig. 5**.

All parameters in Equation (3) were determined by Tsutsumi *et al.*[5)] and actual velocity at every grid point was obtained from this equation. To evaluate the flow route and travel time of the groundwater, four moving Lagrangian particles were initially set at every grid point.

In **Fig. 5**, u_1~u_4 and v_1~v_4 are velocity of the x- and y-axis at every grid point, respectively. The U_p and V_p are the actual velocity of Lagrangian particles at the x- and y-coordinates, respectively. Generally, groundwater velocity at an arbitrary point (x, y) surrounded by four grid points can be described by the following equation

$$
\begin{aligned}
u &= \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 xy \\
v &= \alpha_5 + \alpha_6 x + \alpha_7 y + \alpha_8 xy
\end{aligned}
\tag{4}
$$

where α_1~α_8 are coefficients. If the origin of the coordinate system is according to the below four grid points, u_1~u_4 can be expressed by

$$\begin{cases} u_1 = \alpha_1 \\ u_2 = \alpha_1 + \alpha_2 \delta x \\ u_3 = \alpha_1 + \alpha_2 \delta x + \alpha_3 \delta y + \alpha_4 \delta x \delta y \\ u_4 = \alpha_1 + \alpha_3 \delta y \end{cases} \tag{5}$$

Solving Equation (5), α_1~α_4 are obtained as

$$\begin{cases} \alpha_1 = u_1 \\ \alpha_2 = \dfrac{u_2 - u_1}{\delta x} \\ \alpha_3 = \dfrac{u_4 - u_1}{\delta y} \\ \alpha_4 = \dfrac{(u_1 + u_3) - (u_2 + u_4)}{\delta x \delta y} \end{cases} \tag{6}$$

The Lagrangian particle velocity with respect to the x-axis can be expressed by Equation (6) using the known actual velocity from the surrounding four grid points

$$U_p = \frac{1}{\delta x \delta y}\{(\delta x \delta y - x_p \delta y - y_p \delta x + x_p y_p)u_1 \\ (x_p \delta y - x_p y_p)u_2 + (\delta x \delta y)u_3 + (y_p \delta x - x_p y_p)u_4\} \tag{7}$$

Similarly, the Lagrangian particle velocity with respect to the y-axis can be described by

$$V_p = \frac{1}{\delta x \delta y}\{(\delta x \delta y - x_p \delta y - y_p \delta x + x_p y_p)v_1 \\ (x_p \delta y - x_p y_p)v_2 + (\delta x \delta y)v_3 + (y_p \delta x - x_p y_p)v_4\} \tag{8}$$

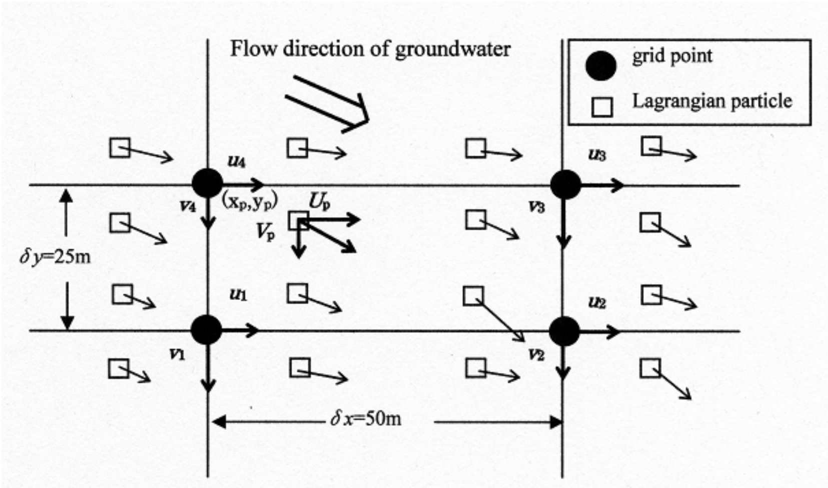
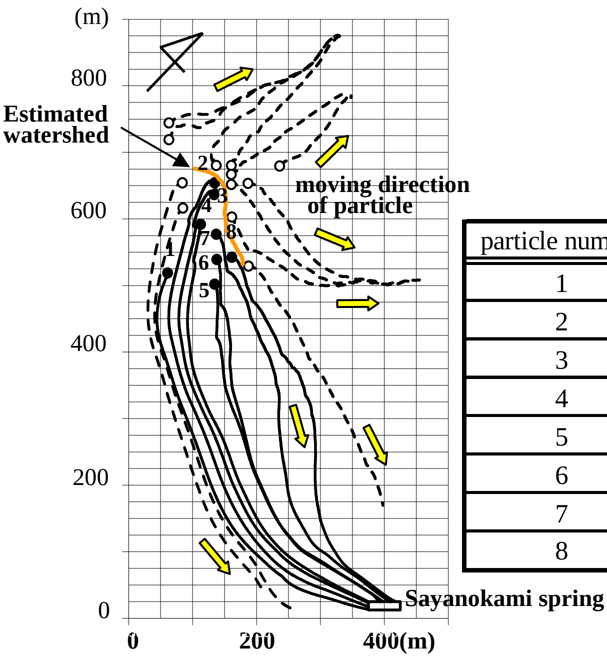


Fig.5 Initial distribution of Lagrangian particles.

Flow routes for representative particles calculated according to the above methodology are shown in **Fig. 6**. Particles that reach the spring are shown by solid lines while other particles are shown by dashed lines. The residence time for particles reaching the spring (filled circles) is also shown in the figure. Particles that do not reach the spring are shown as open circles. The flow routes for these particles indicate a travel time of about 25 years (9125 days). From **Fig. 6** it can also be seen that the boundary for the groundwater catchment is indicated. Particles set close to the boundary reach the spring after about 25 years. The residence time for water falling close to the catchment boundary is thus about 25 years.



particle number	travelling time(year)
1	4.1
2	11.6
3	14.4
4	12.7
5	9.5
6	13.2
7	20.6
8	24.1

Fig.6 Flow routes of the representative particles.

To estimate the entire catchment area, particles reaching the spring were back-tracked in time. **Figure 7** shows this for traveling times up to 25 years. In the figure, iso-age lines of 1, 2, 3, 4, 5, 10, 15, and 25 years indicate the residence time and spatial distribution of groundwater movement to the spring. From the figure it can also be seen that most of the groundwater has a residence time of about 15 years. This corroborates the residence time estimated by tritium above (about 13 years).

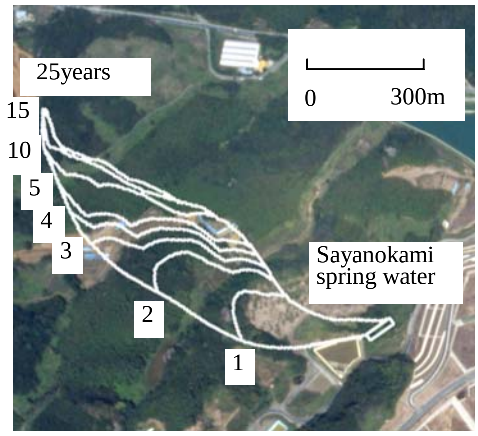


Fig.7 Contour map of the iso-age.

5. Conclusion

According to the above analysis using tracers it was estimated that the residence time of the spring water using ^{222}Rn is more than 3 weeks and not directly affected by rainfall infiltration. When using tritium, the residence time was estimated to be between about 10 to 25 years.

Using a two-dimensional simulation and Lagrangian particle tracking method, it was shown that the residence time for the studied spring water is up to 25 years. The border of the catchment area could be estimated from a back-tracking method in time.

The above methodology was seen to be useful for estimating residence time and catchment area for a previously unknown uptake area of an important spring. The gained knowledge can be used to better manage the finite water resources represented by the spring water. Both quantitative and qualitative management of water can be executed using the herein developed tools.

References

1) Hoehn, E. & von Gunten H.R. (1989) Radon in Groundwater, A Tool to Assess Infiltration from Surface Waters to Aquifers, *Water Resources Research*, **25**, 83-94.

2) Hamada, H. & Komae, T. (1998) Analysis of recharge by paddy field irrigation using ^{222}Rn concentration in groundwater as an indicator, *Journal of Hydrology*, **205**, 92-100.

3) Hayashi, Y., Momoshima, N., Maeda, Y. & Kakiuchi, H. (1999) Relation between tritium concentration and chemical composition in rain at Fukuoka, *Journal of Radioanalytical and Nuclear Chemistry*, **239**, No3,517-522.

4) Pint, C. D., Hunt, R. J., & Anderson, M. P. (2003) Flowpath Delineation and Ground Water Age, Allequash Basin, Wisconsin, *Ground Water*, **41**(7), 895-902.

5) Tsutsumi, A., Jinno, K. & Berndtsson, R. (2004) Surface and subsurface water balance estimation by the groundwater recharge model and a 3-D two-phase flow model, *Hydrological Sciences-journal-des Sciences Hydrologiques*, **49**(2), 205-226.

6) Ellins, K.K., Roman-Mas, A. & Lee, A. (1990) Using ^{222}Rn to Examine Groundwater/Surface Discharge Interaction in the Rio Grande Manati, Puerto Rico, *Journal of Hydrology*, **115**, 319-341.

7) Asikainen, M. (1981) State of disequilibrium between 238U, 234U, 226Ra and 222Rn in groundwater from bedrock, *Geochim. Cosmochim. Acta*, **45**, 201-206.