

Study of rainfall distribution and groundwater flow using the Cl⁻ ion and stable isotopes on a volcanic island in Japan

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Abstract Using the stable isotope and water quality method, we investigated groundwater movement in Hachijojima Island, a volcanic island located about 290 km south of Tokyo Bay, Japan. Rain samples for analyses of oxygen-18 and Cl⁻ were collected by 20 evenly distributed precipitation collectors during a one-year period (April 1997–April 1998), with a sampling interval of 45 days. A hydrological survey was carried out, and more than 50 groundwater and surface water samples were also collected. We found: (a) Cl⁻ in springs is a suitable tracer for groundwater study in this island; however, we could not estimate recharge area using oxygen-18 because the altitude effect (of precipitation isotope) is small; (b) Cl⁻ concentration in springs and well water was more than 2 times higher than Cl⁻ concentration of precipitation; we could not calculate the recharge area, comparing Cl⁻ concentration in precipitation with that in groundwater; (c) groundwater quality is classified into several groups, which reflect the different groundwater flow processes.

INTRODUCTION

Hachijojima Island belongs to the group of Izu islands, south of Tokyo. The island consists of two Quaternary volcanoes: Higashiyama in the southeast, Nishiyama in the northeast. The plain area combines both volcanoes (Fig. 1). The hydrological characteristics of Higashiyama include many water resources such as ponds, rivers, and springs.

In a previous survey, the Ministry of Agriculture, Forestry, and Fisheries of Japan (1988) presented a hydrogeological map of the plain area from electric logging data and hydrological surveys. Shindo (1980) conducted hydrological surveys and found that groundwater flow in Higashiyama was controlled by a buried caldera. In this study, we conducted a field exploration to quantify the rainfall distribution and hydrological conditions. As part of this effort, we also evaluated the effectiveness of Cl⁻ concentration as a tracer of water movement.

GEOLOGICAL SETTING AND CLIMATE

The highest points of the Nishiyama and Higashiyama volcanoes are 854 m and 701 m, respectively. Higashiyama was formed during the Pleistocene (Isshiki, 1959);

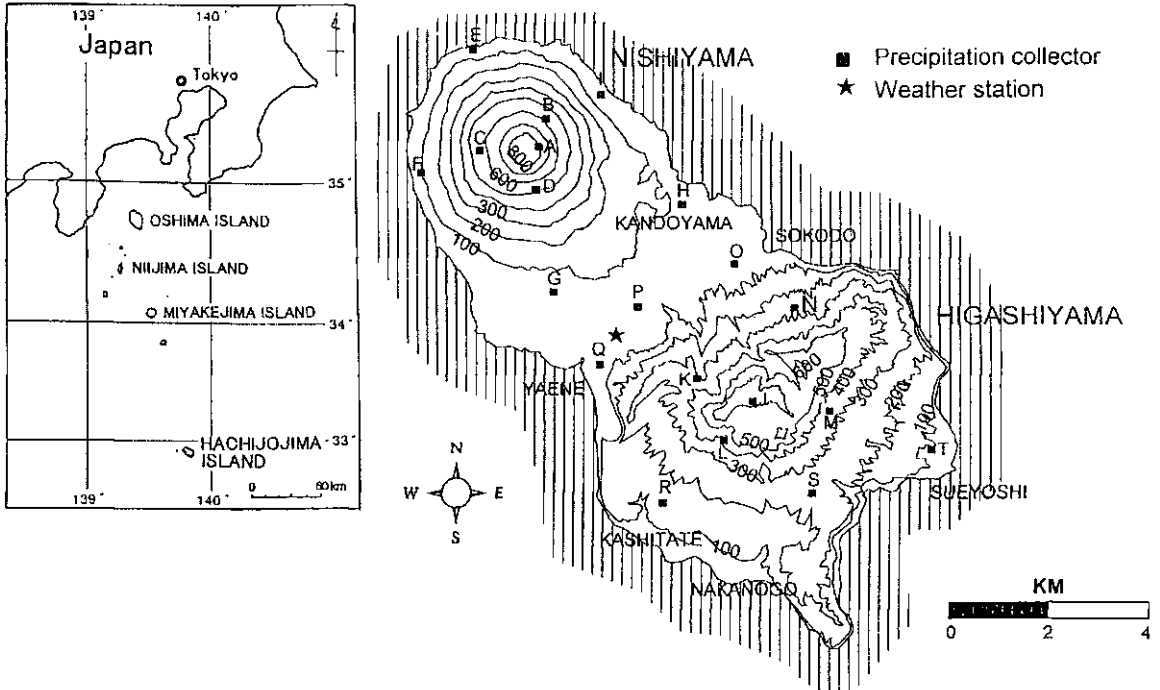


Fig. 1 Location of Hachijojima Island and precipitation sampling points(■). Weather station is indicated by ★.

While the ages of Nishiyama and the plain area are unknown, it is inferred that its volcanic activity began towards the end of Higashiyma's.

The climate of Hachijojima Island is characterized by heavy rainfall, high temperatures, and strong winds. According to weather station data during 1961–1990, (Hachijo Village Office, 1979), the annual average precipitation is approximately 3000 mm and annual average temperature is about 18.1°C. December, January, February, and August are characterized by less precipitation (less than 200 mm month⁻¹). Heavier precipitation is expected during the Baiu season (more than 300 mm month⁻¹; June) and typhoon season (more than 500 mm month⁻¹; end of September or October). West and northwest winds are predominant, and annual average wind speed is approximately 7.3 m s⁻¹.

METHODS

To confirm the effectiveness of Cl⁻ and stable isotopes as a tracer, 20 precipitation collectors were installed over the island (Fig. 1) and sampled every 45 days from April 1997 to April 1998. We used 10-l or 20-l polyethylene bucket precipitation collectors with a device to prevent the sample from evaporating (Shimada & Sanjo, 1987). The funnel is 14-cm in diameter. At the end of the collection period the volume of rainwater was measured. These samples were analysed for oxygen-18 content and Cl⁻ concentration.

Furthermore, more than 50 groundwater and surface water samples (from rivers, and ponds) were collected beginning in 1997. These were analysed for oxygen-18 and water quality (pH, EC, Na⁺, Mg²⁺, Ca²⁺, K⁺, Cl⁻, SO₄²⁻, NO₃⁻).

RESULTS AND DISCUSSION

Precipitation

Figure 2 shows the distribution of volume-weighted average oxygen-18 content in precipitation. The lightest rainfall (isotopically) was observed at 500–600 m elevation on the southwest side in the island. A gradient of about -0.1‰ per 100 m was similar to other island data (Avis-Ishidro *et al.*, 1993; Liu, 1984; Gonfiantini & Simonot, 1987; Ellins, 1992; Scholl *et al.*, 1996; Tang *et al.*, 1998), but it does not coincide with the data from other mainland areas in Japan (-0.25‰ per 100 m, Waseda & Nakai, 1983, Mizutani & Satake, 1996). We reason that the small altitude effect is controlled by:

- Earlier stage of condensation of atmospheric moisture. The altitude effect will depend on a degree of Rayleigh condensation (Scholl *et al.*, 1996). The altitude effect should increase at high elevations (mainland Japan), where condensation occurs as snow rather than rain (Smith *et al.*, 1979).
- Hachijojima Island is a small isolated island only about 700 m a.s.l.; many clouds may not only rise up the mountain, but also move laterally across the island.

Figure 3 shows that distribution of volume-weighted average Cl⁻ concentration in rainfall for April 1997–April 1998. It indicates that the Cl⁻ concentration in rainfall depends on the distance from shoreline. In the plain area, however, Cl⁻ concentration in rainfall was constant at about 14 ppm. This indicates that in a wind a particle containing a Cl⁻ ion moves more easily over flat terrain than rising up a slope.

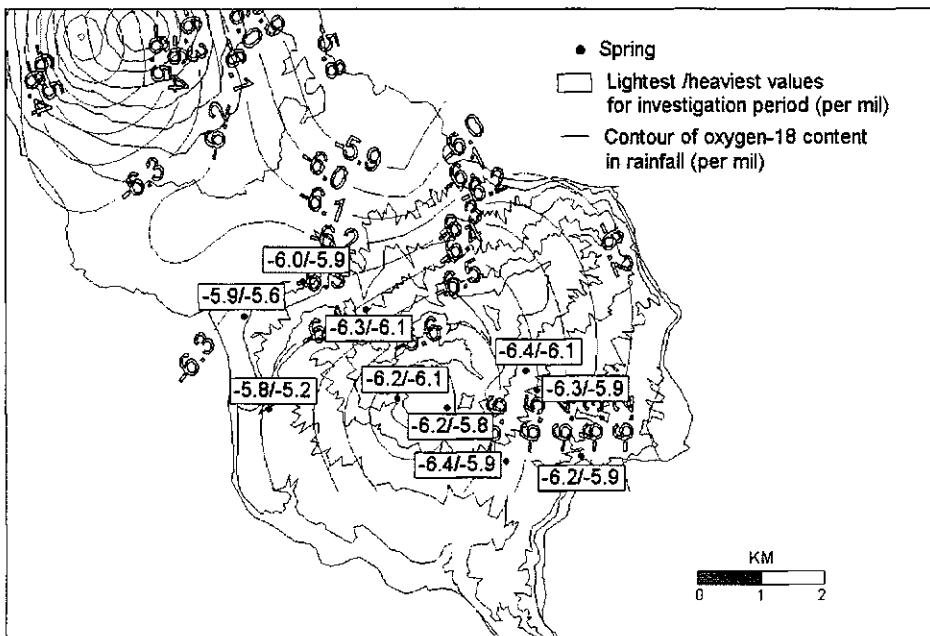


Fig. 2 Distribution of volume-weighted average oxygen-18 content in precipitation (1997–1998). Solid circles (●) show the sampling points for the springs. Figures in squares mean the lightest/heaviest values of oxygen-18 for groundwater during the investigation period (sampled 4 times).

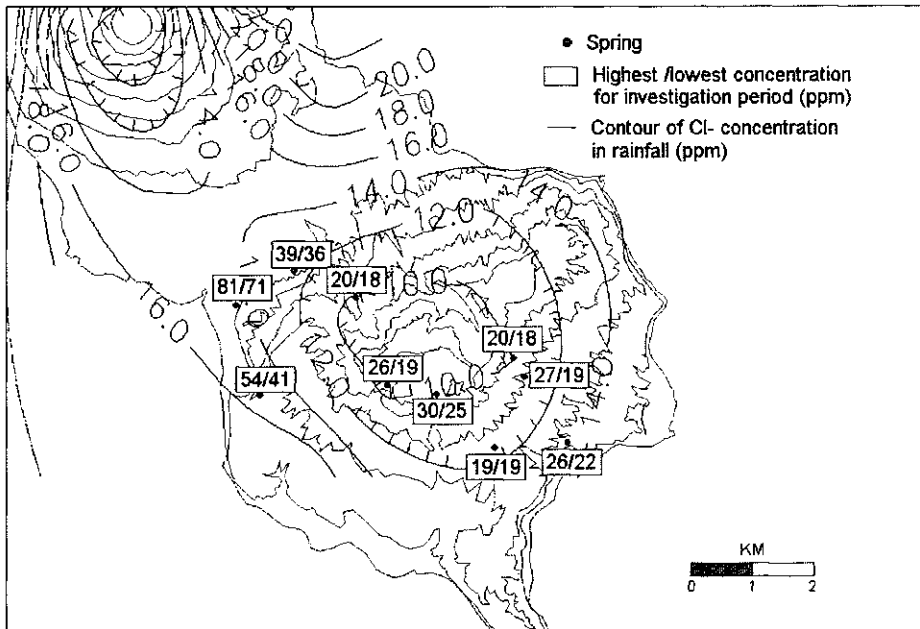


Fig. 3 Distribution of volume-weighted average Cl⁻ concentration in precipitation (1997–1998). Solid circles (●) show the sampling points of springs. Figures in squares mean the highest/lowest Cl⁻ concentration (ppm) of groundwater during the investigation period (sampled 4 times).

Groundwater

Inland springs in Higashiyama were classified into three types (Fig. 4):

- Fissure water type, defined as springs that flow out from a fissure in a stratum which is composed of volcanic ash, lava and so on. Generally, springs of this type have a large volume of flowing water.
- Stratum water type, defined as springs falling from a stratum.
- Unknown. All inland springs exist as perched water.

Figure 4 shows hexa diagrams of water quality. Despite the large-scale fissure type springs distributed in different areas, their chemical (Na⁺-Cl⁻-HCO₃⁻-Ca²⁺) trend was very similar. This fact indicated that groundwater moved in chemically similar geologic units. The water quality of well water in the plain was classified into two groups: groundwater in the southeast part of the plain (Area A) showing high HCO₃⁻-Ca²⁺ which was similar to fissure type springs; and in other parts (Area B), water quality was high in Na⁺-Cl⁻ (electrical conductivity was 300–900 μS cm⁻¹).

Most of the stratum type springs and well water in Area B had high Na⁺-Cl⁻ which implies the mixing with saline water. Well water in Area A was high in HCO₃⁻-Ca²⁺ implying the strong influence of geology or a long residence time. Although wells in Area A were located near the shoreline, there was no mixing with saline water. It is inferred that the large volume of groundwater brought to this area prevents the intrusion of saline water (Ministry of Agriculture, Forestry and Fisheries of Japan, 1988). But too much pumping from Area B for water supply will carry the risk of upconing.

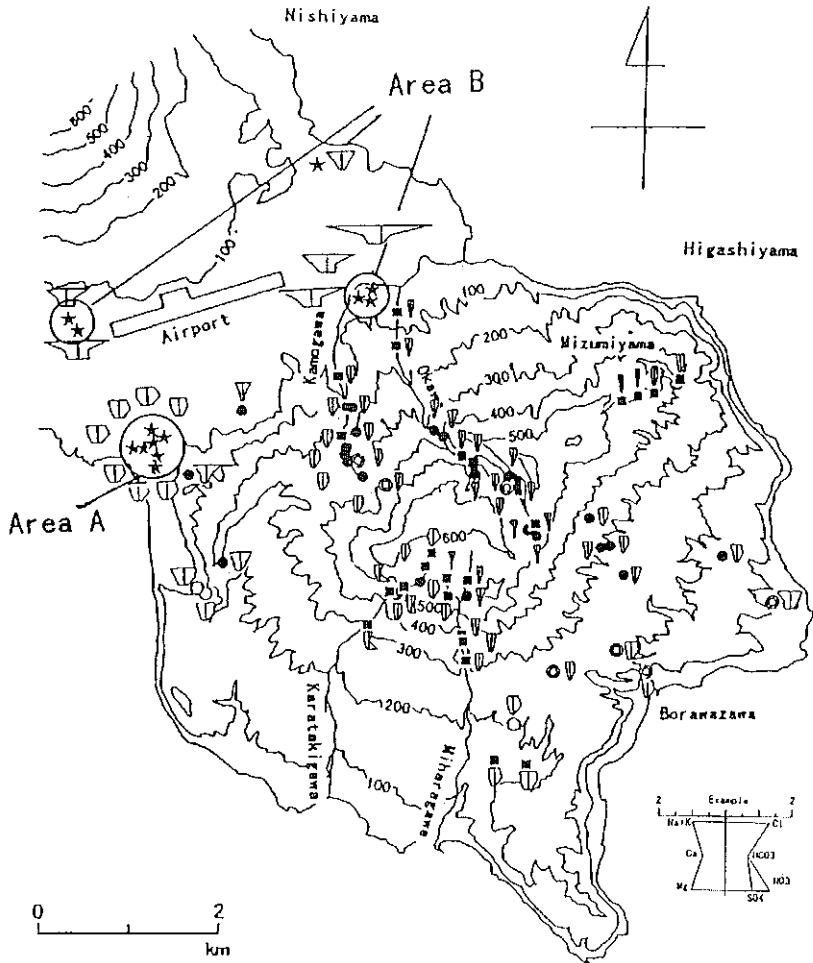


Fig. 4 Water quality and spring type. Water quality represented by hexa-diagram. Spring type: ⊙ fissure water type; ● stratum water type; ○ unknown. ■ river and pond; ★ well.

Effectiveness of Cl⁻ and δ¹⁸O as tracers on a small island

Cl⁻ and δ¹⁸O were used to estimate the recharge area of springs and wells. We hypothesize that:

- (1) the recharge area of stratum type springs are near spring points; and
- (2) Cl⁻ and oxygen-18 are not added from soil or removed from water.

Comparing the distribution of Cl⁻ concentration in rainfall with Cl⁻ concentrations in stratum springs (Fig. 3), the Cl⁻ concentration in springs is more than 2 times higher than that of rainfall in the same area. The difference in Cl⁻ concentration may be caused by dry deposition and evaporation. Thus chloride is not applicable as a tracer for rainfall. However, plotting the Cl⁻ concentration of stratum type springs as a function of the distance (Fig. 5) allows us to estimate the recharge area. For example, the main recharge area of some fissure type springs seems to extend to 1500–2000 m from the shoreline based on the regression line.

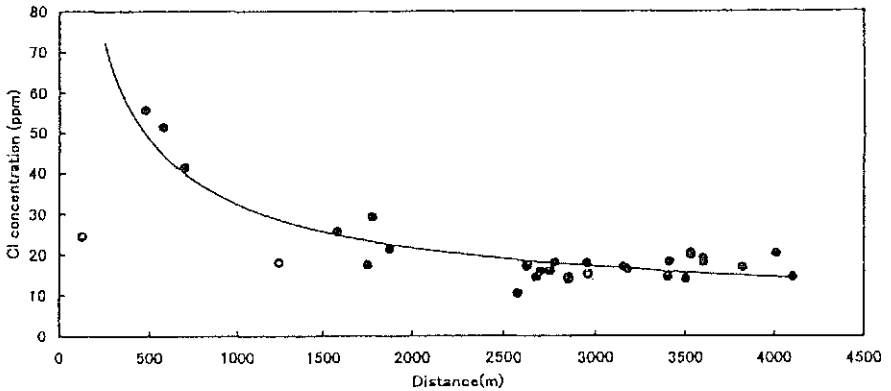


Fig. 5 Relationship between Cl⁻ concentration and the distance of springs from the shoreline.

It is difficult to determine the recharge area from only oxygen-18 data on this island, because of the relative large difference of groundwater isotope content by the effect of throughfall (i.e. Saxena, 1986) and rain events just before the sampling. The $\delta^{18}\text{O}$ content of springs was 0.2–0.8‰ higher than that of rainfall (Fig. 2) in the same area. Furthermore, the maximum difference of $\delta^{18}\text{O}$ values of each spring were 1.2‰, and the seasonal fluctuation of stratum type springs was 0.1–0.4‰.

CONCLUSION

The results of this paper are summarized as follows:

- (a) The effect of altitude on precipitation in this island is about -0.1‰ per 100 m which is the same as data from other islands, but it does not agree with data from central Japan ($0.2\text{--}0.4\text{‰}$ per 100 m). The small altitude effect will have a close relationship with the degree of Rayleigh condensation of air masses and the movement of clouds on a island.
- (b) Chloride is applicable as a tracer. Plotting the Cl⁻ concentration of stratum type springs as a function of the distance from the shoreline allowed us to estimate the groundwater path.
- (c) The recharge area of a fissure type spring is far from the spring outlets, and groundwater flows as an underground stream in a buried valley in Hachijojima Island.

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