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An isotopic study of the groundwater regime of a seepage caldera lake district, southern Japan

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Abstract The 233-m deep Lake Ikeda is a seepage caldera lake with no surface outflow or inflow. During February–March 1998 water samples were taken from lakes, rivers, wells, hot springs, and springs. They were analysed for δD, $\delta^{18}O$, and Cl^- concentration to determine the contribution of lake water to river discharge and downgradient groundwater field. The results indicate that the influence of leakage from Lake Ikeda is confined to the area east-south of the lake, where a mixing of lake water, local rainwater, and sea water takes place. For certain rivers and springs, lake water contributes more than 80% of the discharge. Many of the wells and hot springs represent a 7–100% lake-water contribution. Leakage of lake water is most likely to occur through the southern caldera walls, where thick volcanic aquifers are hydraulically connected to Lake Ikeda. The study showed that leakage from Lake Ikeda was found to play a predominant role in the groundwater regime of the district.

INTRODUCTION

Early studies on Lake Ikeda (Fig. 1) indicated that, on the basis of the water balance method, there is major discharge (up to 0.82 $m^3\ s^{-1}$) of lake water to the surrounding volcanic aquifers (e.g. Satoh *et al.*, 1984). Water temperature measurements permitted the recognition of lake-water contribution to two nearby springs south and north of the caldera (Satoh *et al.*, 1984). In addition, Matsubaya *et al.* (1973) showed the possible contribution of lake water to some Ibusuki hot springs at a considerable distance from the lake. In this seepage caldera lake district, however, no comprehensive studies have been carried out on possible hydraulic connections between lake water and the downgradient groundwater field.

On the other hand, lake water which is subject to evaporation is known to become enriched in deuterium (δD) and oxygen-18 ($\delta^{18}O$) isotopes, thus providing a characteristic isotope labelling of the water. A number of studies concerning lake water–groundwater mixing have been based on this (e.g. Payne, 1970; Dinçer and Payne, 1971; Darling *et al.*, 1990; Yehdegho *et al.*, 1997). The purpose of this study is, using the same type of labelling, to trace the plume of leakage from Lake Ikeda and

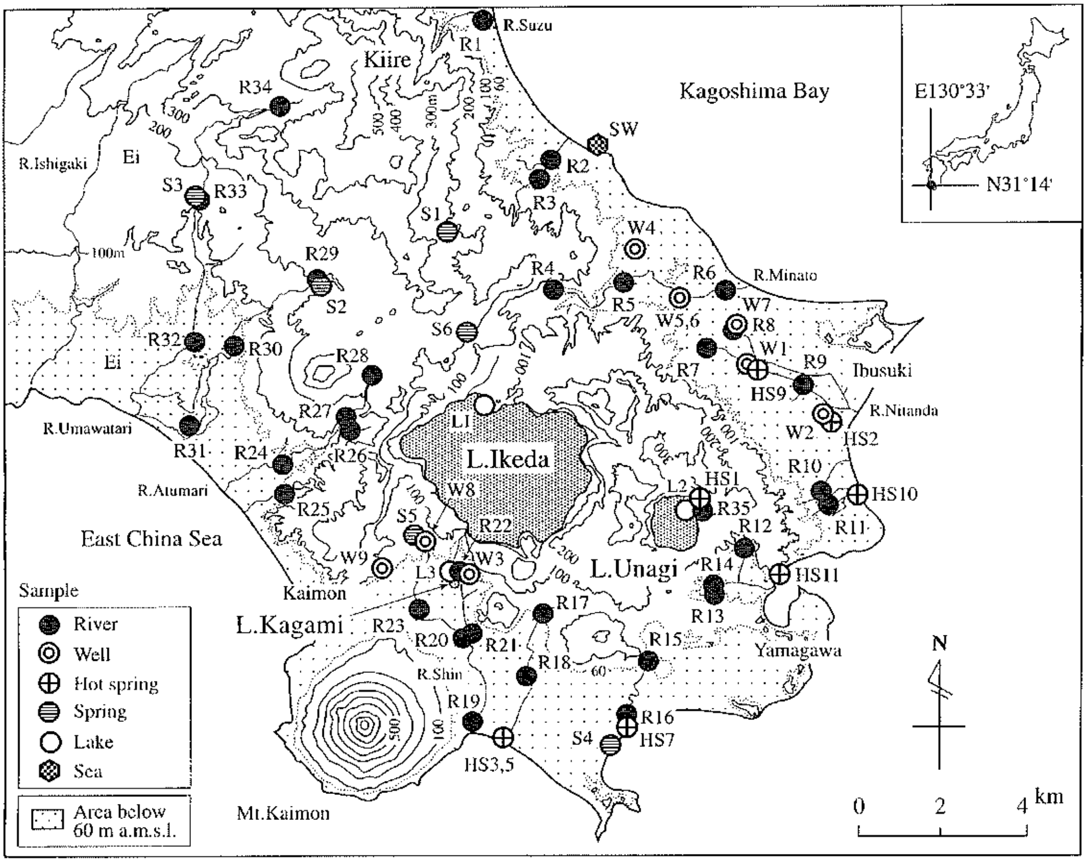

Fig. 1 Physical features of the study area, showing the relative position of the lakes and the various volcanic complexes. Sampling locations are also shown.

provide an estimate of its spatial extent. The contribution of lake water to the discharge of rivers, wells, springs, and hot springs is also isotopically estimated.

STUDY AREA

Geology

The study area (Fig. 1), including Lake Ikeda and two small crater lakes (Lakes Unagi and Kagami), is in the Ata caldera formed by a pyroclastic eruption about 90 000 years ago (Matsumoto, 1943). The eastern half of the Ata caldera underlies Kagoshima Bay and its northern–western rim is delineated by the Onkadobira fault scarp with relative height up to 250–300 m (Fig. 2). North and west of the fault, partially weathered, less permeable clayey pre Ata rocks (Tertiary sedimentary rocks and volcanic rocks) and Ata pyroclastic flow deposits (welded tuff) are present. In this context, the fault may act as a barrier to the northerly and westerly groundwater flow.

After the Ata eruption, the caldera was buried with many cones, known as the Ata central cones. Lower parts of these cones were dominated by permeable clastic

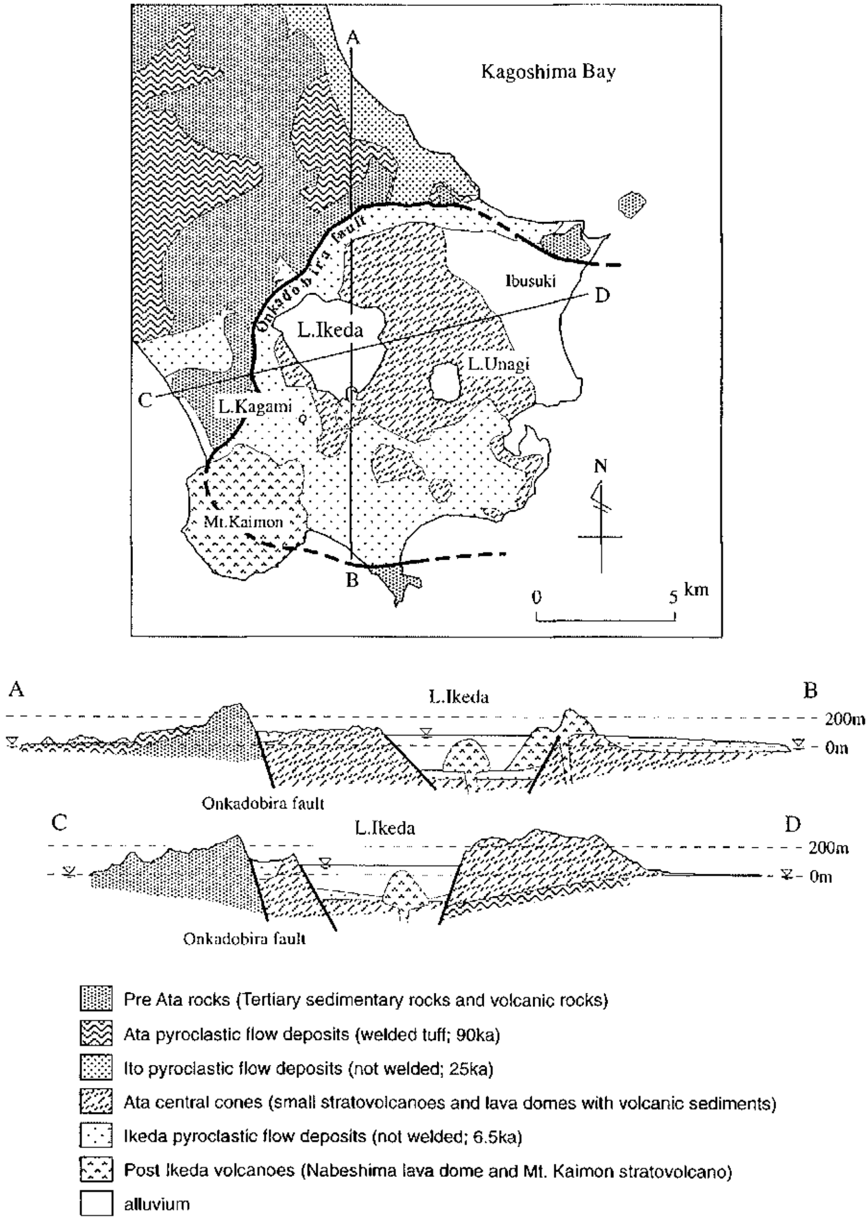

Fig. 2 Generalized geological map and cross-sections. Water level of Lake Ikeda and mean sea level are also shown in the cross-sections. ka = 1000 years ago.

sediments and upper parts by lava flows. About 6500 years ago, another eruption occurred and formed the Ikeda caldera and Lake Ikeda (Ui, 1967). The associated volcanic products, Ikeda pyroclastic flow deposits, covered large parts of the western half of the Ata caldera. Mount Kaimon stratovolcano was formed afterwards. The main aquifers in the area consist of the Ikeda pyroclastic flow deposits and the clastic sediments of the Ata central cones. However, little is known about the distribution and hydraulic properties of these aquifers.

Hydrology and climate

Lake Ikeda has a surface area of approximately 11.3 km^2, a maximum depth of 233 m and its surface elevation averages 65 m a.m.s.l. (Fig. 2). Lake Ikeda and two crater lakes are classified as closed or seepage lakes with no surface inflow or outflow. They are recharged by rainfall and groundwater inflow; and water losses from the lake consist of evaporation from the lake surface and leakage (underground outflow) through the lake walls. Lakes Unagi and Kagami have much smaller areas and shallower depths (56 m and 10 m, respectively). Both these lakes, therefore, are far smaller in volume than Lake Ikeda. From a quantitative point of view, the leakage from these lakes may be negligible, if any, and may be of little hydrological significance.

The mean annual temperature at Ibusuki is 17.8°C (Japan Meteorological Agency, 1993). At Lake Ikeda, rainfall averages 2295 mm $year^{-1}$, and the high mean annual temperature causes potential evaporation of 1018 mm $year^{-1}$ from the lake surface (Satoh *et al.*, 1984). Due to the high evaporation rate, the concentrations of the heavy isotopes ^2H and ^{18}O in the lake water are expected to be considerably higher than that of the local groundwater.

Many springs, of which spring S5 is the largest, with a discharge of about 0.20 $m^3\ s^{-1}$ (Satoh *et al.*, 1984), are located in the study area (Fig. 1). Besides the springs, many rivers originate around the Ikeda caldera and Ata central cones. Along the coast, thermal waters (hot springs) with temperatures greater than 30°C are either emergent or found by drilling to a depth of 3–150 m. Somewhat inland from the coast, wells with depths of 30–200 m are used for fish breeding and agriculture. Groundwater from some of these wells is also heated to considerable temperatures by the effect of the geothermal system.

SAMPLE COLLECTION AND ANALYSIS

Water sampling took place during the late February–early March baseflow period in 1998. Fifty-nine samples were collected from four sources: (1) rivers; (2) wells; (3) hot springs; and (4) low-temperature springs (Fig. 1). Samples were also taken from three lakes and the sea, approximately 0.5 m below the surface. All samples were stored in 30 ml air-tight glass bottles prior to analysis, which was performed at the Geological Survey of Japan on a Finnigan-mat delta S mass spectrometer following preparation by standard methods: $^{18}O/^{16}O$ by equilibration of CO_2 with an 8 ml water sample, and $^2H/^1H$ by equilibration of H_2 with an 8 ml water sample with Pt catalyst at 25°C using the method of Ohba & Hirabayashi (1996). The deuterium and oxygen-18 isotopic compositions of water samples are conventionally expressed in delta notation (δ) as a per mil deviation from SMOW. The overall precision of stable isotope determinations is less than 1.5‰ and 0.1‰ for δD and $\delta^{18}O$, respectively. Samples were also analysed for major ions at the Geological Survey of Japan on a Yokogawa Ion Chromatographic Analyser IC7000.

RESULTS AND DISCUSSION

Water chemistry

The river and spring waters are predominantly of the Ca-HCO$_3$ or Na-HCO$_3$ type with low solute concentrations, except for three rivers of the Na-Cl type (rivers R6, R9 and R16 in Fig. 1). Their proximity to the river mouths (less than 1.5 km) seems to point to possible interaction with sea water. By contrast, all but one of the hot springs are Na-Cl rich with very high solute concentrations; the Cl$^-$ concentration ranges from 11 to 242 mmol l^{-1}, indicating sea water contributes significantly to most hot spring waters. Exceptionally, hot spring HS1, 2 km from the coast and lying at some 150 m a.m.s.l. by Lake Unagi, is of the Ca-SO$_4$ type with the very low Cl$^-$ concentration of 0.3 mmol l^{-1}. Groundwater from wells W1, W2, W5, W6, and W7 near the sea also show high Na$^+$ and Cl$^-$ concentrations (Cl$^-$; 6 to 65 mmol l^{-1}), which is indicative of sea-water influence. Other wells W3, W4, W8, and W9, located at a considerable distance from the coast and relatively higher on the slope, are low in Cl$^-$ concentration (<2.0 mmol l^{-1}) and are generally of the Ca-HCO$_3$ type.

The δD-$\delta^{18}O$ diagram

Data from samples are plotted in Fig. 3 and define a local meteoric water line (MWL; slope = 8.0) with the relationship $\delta D = 8.0\delta^{18}O + 12.0$. The samples which are most depleted in stable isotopes are found in Kiire and Ei, the northern part of the study area

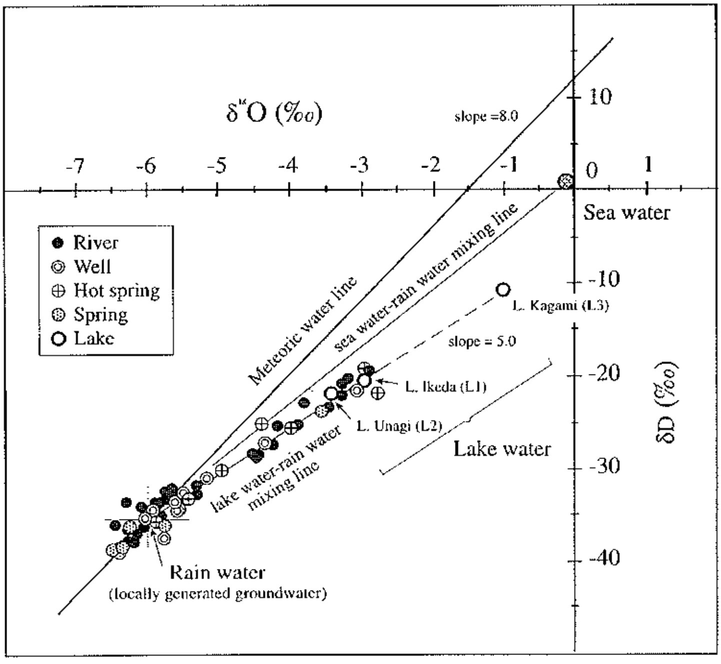

Fig. 3 Plot of δD and $\delta^{18}O$ of various waters in the study area.

(Fig. 1), with δD and $\delta^{18}O$ values as low as –39‰ and –6.5‰, respectively. The samples from Lakes Ikeda (–21‰ δD; –3.0‰ $\delta^{18}O$), Unagi (–22‰ δD; –3.4‰ $\delta^{18}O$) and Kagami (–11‰ δD; –1.0‰ $\delta^{18}O$) are markedly enriched in heavy isotopes as compared to normal meteoric waters falling on or near the MWL between $\delta^{18}O$ of –6.5‰ and –5.7‰.

In Fig. 3, three end-members of recharge to the groundwater system are isotopically distinct: (1) lake water; (2) rainwater; and (3) sea water. The isotopic compositions of samples from lakes and also from many rivers, wells, and springs are on a straight line distinctly different from the MWL. A regression carried out on these samples resulted in a line with a slope of about 5.0, which is characteristic of open-water bodies subject to evaporation. A point for the rainwater, which is a potential source of recharge to the groundwater system, is marked in Fig. 3 on the extension of the line at the intersection with the MWL. The values of –36‰ δD and –6.0‰ $\delta^{18}O$ are considered to be representative of the local rainwater (or locally generated groundwater) free from evaporative enrichment.

The isotopic compositions of data points falling on this lake water–rainwater mixing line (LRL) are between those of Lake Ikeda (–3.0‰ $\delta^{18}O$) and local rainwater (–6.0‰ $\delta^{18}O$). Evaporative enrichments are not likely to take place in the

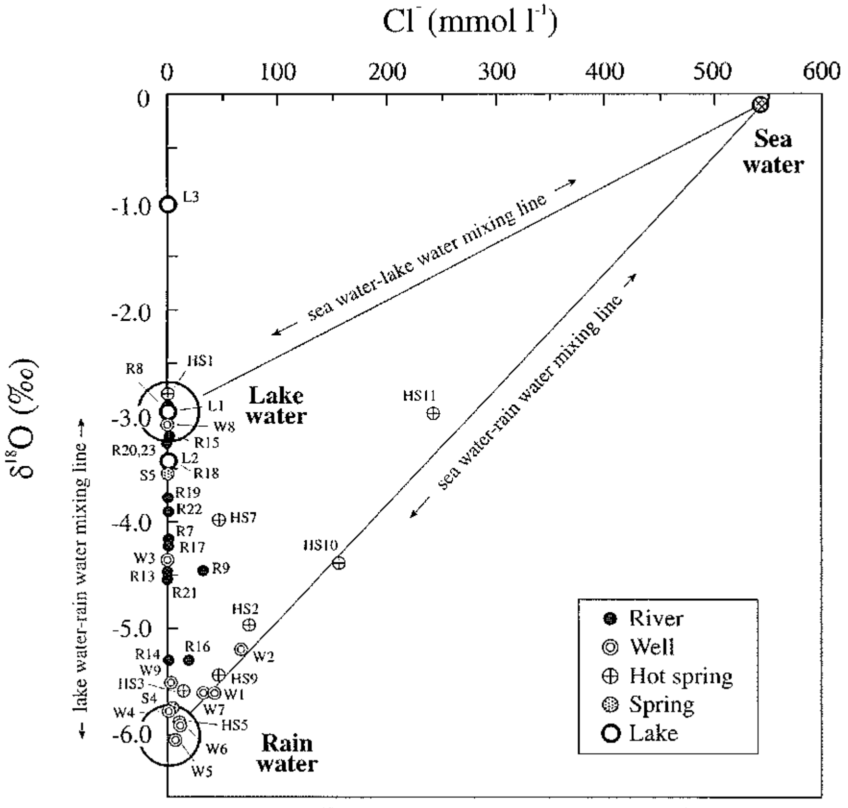

Fig. 4 Plot of $\delta^{18}O$ and Cl^- concentration (in mmol l^{-1}) of waters in the study area. Only the samples which plot on the lake water–rainwater mixing line (LRL) or are of partial sea-water origin (see Fig. 3) are plotted.

rivers and springs of the study area because of very short exposure time to the free atmosphere and large quantity of flow. The alignment may therefore be explained by simple mixing, in varying proportions, of the isotopically depleted local rainwater and enriched lake water leaking from Lake Ikeda.

On the other hand, data points for rivers, wells, and hot springs of the Na-Cl type do not align on the LRL (Fig. 3). They exhibit a positive δD shift of 2–3‰ and scatter between the LRL and the sea water–rainwater mixing line (SRL). This is indicative of contribution of sea water to the Na-Cl rich samples.

The $\delta^{18}O$-Cl^- diagram

Figure 4 illustrates the variation of $\delta^{18}O$ against the Cl^- concentration of samples which plot on the LRL or are of partial sea-water origin (Fig. 3). From this figure it is obvious again that the Cl^- concentration of samples is a result of the mixing of lake water (Lake Ikeda; –3.0‰ $\delta^{18}O$; 0.3 mmol l^{-1} Cl^-), rainwater (–6.0‰ $\delta^{18}O$; 0.2 mmol l^{-1} Cl^-), and sea water (–0.1‰ $\delta^{18}O$; 544 mmol l^{-1} Cl^-). The Cl^- concentration of rainwater was taken to be the same as the average (0.2 mmol l^{-1}) of the nine spring water samples. The mixing lines LRL, SRL, and SLL (sea water–lake water mixing line) are defined by these three end-members.

Hot spring HS1, which is of the Ca-SO_4 type, has nearly the same isotopic composition as Lake Ikeda. Data points for rivers R7, R8, R15, R17, R18, R19, R20, R22, and R23, and spring S5 are on the LRL and the isotopic composition is close to that of Lake Ikeda, suggesting a high proportion of lake water in the discharge. The Na-Cl poor groundwaters from wells W3, W4, W8, and W9 also are on the LRL, but in highly different positions. The actual position would be a function of the respective contributions of each end-member. The samples from wells and hot springs of the Na-Cl type generally plot near the SRL, demonstrating mixing between highly saline sea water and rainwater. However, the isotopic compositions of hot springs HS2, HS3, HS7, and HS11 show a positive $\delta^{18}O$ shift in the direction of lake water to a certain extent. Contribution of lake water is thought to account for the displacement of these waters from the simple SRL.

Contribution of lake water to the discharge

Based on Fig. 4, the mixing proportion of lake water was calculated by applying a three end-member mixing model (Table 1 and Fig. 5). Data points more positive than the water of Lake Ikeda (hot spring HS1 and river R8) were presumed to represent a 100% lake-water contribution. In addition, data points falling on or near the MWL (Fig. 3) were considered to be indicative of 100% rainwater.

The leakage is found to be confined to the area between Rivers Nitanda (Ibusuki) and Shin (Kaimon) east–south of Lake Ikeda, and it can still be detected on the coast some 5 km away from the lake. The lake-water contribution is especially significant in the River Shin, contributing more than 70% of the river discharge. Taking into account its large discharge of 10 000 m^3 day^{-1}, it is reasonable to conclude that the predominant direction of flow of the leaked lake water is southerly along River Shin. With the excep-

Table 1 Mixing proportion of lake water, rainwater, and sea water in hot spring waters (HS1–HS11) and groundwaters (W1–W9).

Sample	Lake water (%)	Rainwater (%)	Sea water (%)
HS1	100	0	0
HS2	7	80	13
HS3	8	89	3
HS5	0	98	2
HS7	49	42	9
HS9	0	91	9
HS10	0	72	28
HS11	13	42	45
W1	0	92	8
W2	0	88	12
W3	54	46	0
W4	6	94	0
W5	0	98	2
W6	0	99	1
W7	0	94	6
W8	95	5	0
W9	23	77	0

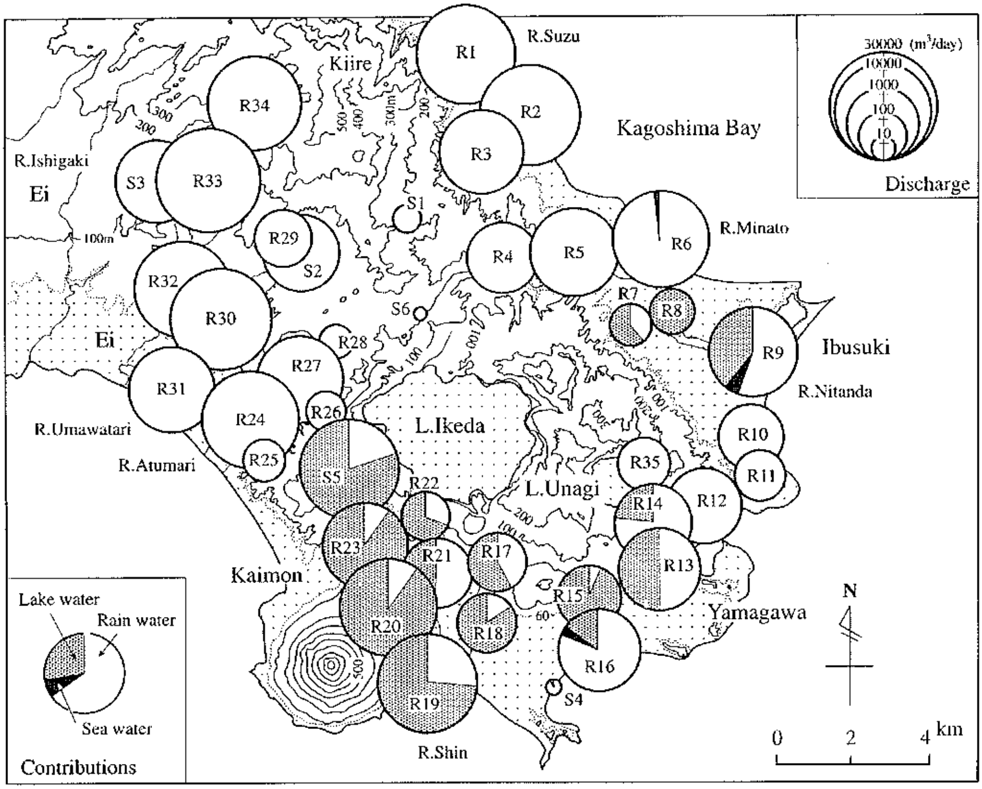

Fig. 5 Contribution of lake water, rainwater, and sea water to river and spring discharges.

tion of well W4, northwest of the Onkadobira fault (Fig. 1) and along River Minato, waters show little or no evidence of lake water. This fact would imply a much smaller amount of leakage to the north of Lake Ikeda.

Along River Nitanda, to the east of Lake Ikeda, rivers R7, R8, and R9 contain more than 40% lake water, and hot spring HS2, tapped by a 2.5 m well, also contains 7% lake water. However, deep waters from a hot spring and wells (HS9, W1, and W7 tapped by the wells more than 100 m deep) show little or no evidence of lake water, indicating that leakage from Lake Ikeda is at a depth that is of significance only for very shallow wells and rivers. To the south, by contrast, water from wells W3, W8, and W9 (about 100 m deep) and hot springs HS3 and HS7 (30–150 m deep) appears to contain substantial proportions of lake water (23–95% and 8–49% lake water, respectively). The results suggest that the southerly leakage from Lake Ikeda also takes place at depth, down to at least 150 m below the ground surface. The deeper and larger quantity of southerly leakage may be attributed to the hydraulic connection of thicker aquifers to Lake Ikeda, as shown by the cross section A–B in Fig. 2.

SUMMARY

The stable isotopic composition and chemistry of waters proved a useful tool in understanding the complex groundwater regime of the seepage from the caldera lake district. The interpretation of data suggests a groundwater regime of considerable southerly and easterly leakage from Lake Ikeda with less northerly leakage. The hydraulic connection of thicker aquifers to the lake is likely to result in the southerly leakage of especially large amounts of water. Although the estimates of mixing proportions of lake water should be considered as approximate, there is no doubt that continuous observation throughout the year will give more precise answers and will shed light upon the complex groundwater regime in the area studied.

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