International Journal of GEOMATE, April 2019, Vol.16, Issue 56, pp. 153 - 158
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2019.56.4742
Special Issue on Science, Engineering & Environment

ESTIMATION OF GROUNDWATER RECHARGE AND SALINIZATION IN A COASTAL ALLUVIAL PLAIN AND OSAKA MEGACITY, JAPAN, USING $\delta^{18}O$, δD, AND Cl^-

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*Corresponding Author, Received: 25 Nov. 2018, Revised: 15 Dec. 2018, Accepted: 31 Dec. 2018

ABSTRACT: Seawater intrusion and salinization are the most common problems of water pollution in coastal groundwater. To clarify the process of groundwater salinization in a coastal alluvial plain, we estimated the groundwater recharge and salinization process in Osaka coastal groundwater using $\delta^{18}O$, δD, and Cl^-. Water samples were collected at 14 boreholes of 9 plots with depth of −5 to −60 m amsl in March 2015. The $\delta^{18}O$ values and Cl^- concentrations of the groundwater varied spatially from −6.4 ‰ to −4.7 ‰ and 17 mg/L to 5193 mg/L, respectively. Based on Cl^- concentrations, the maximum mixing ratio of seawater with the concentration of 1800 mg/L into groundwater was estimated to be 29% about 3 km inland from the shoreline at the depth of about −40 m. The relationship between $\delta^{18}O$ and Cl^- of groundwater and seawater indicated three types of end members: seawater with high Cl^- and $\delta^{18}O$, a groundwater source with lower Cl^- and lower $\delta^{18}O$ (−5.6 ‰), and a groundwater source with lower Cl^- and the lowest $\delta^{18}O$ (−7.2 ‰). According to the relationship between the altitude of groundwater recharge and $\delta^{18}O$ established by previous research, two types of groundwater recharge and source areas were estimated to be coastal lowland and upland with altitudes <10 m amsl and surrounding hill 18 km inland from the shoreline with altitudes of 100 m amsl.

Keywords: Coastal groundwater, Stable isotope, Chloride, Seawater intrusion

1. INTRODUCTION

The resource value of groundwater has been recognized again in recent years and considered widely, such as for water use in an emergency and heat for renewable energy. Within the Big Movement in Japan, the "Basic Law on the Water Cycle" was established in March 2014. It requires efforts to understand water circulation throughout the basins of Japan, including the groundwater recharge zone.

For the use of groundwater as a sustainable water resource, water quality is important from the viewpoint of safety, and it is necessary to maintain and manage water quality [1-3].

Seawater intrusion is the most common water quality problem for coastal groundwater. The main factors of seawater intrusion are a disturbance of the water balance in an aquifer caused by excess pumping (a human factor) and influences such as topography, geology, sediment, etc. (natural factors). It is important to understand the degree of influence of each of these factors to manage seawater intrusion.

Since 1940, the ground settlement has been a problem in the Osaka Plain because seawater intrusion has occurred correspondingly. However, groundwater intake restrictions have been strengthened to recover the groundwater level, so the level has been almost stable in recent years. Although several studies concerning water quality [4-11] have been conducted, this research was not sufficient to

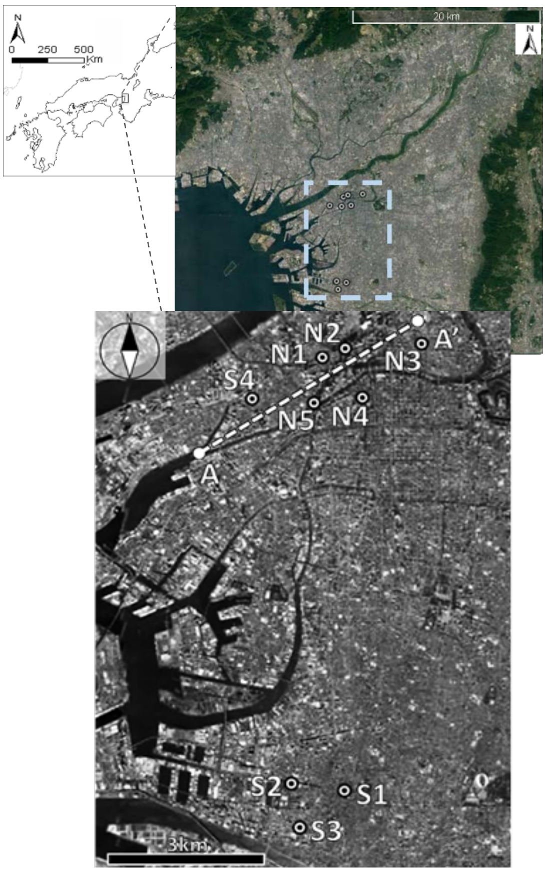

Fig. 1 Study area

elucidate in detail

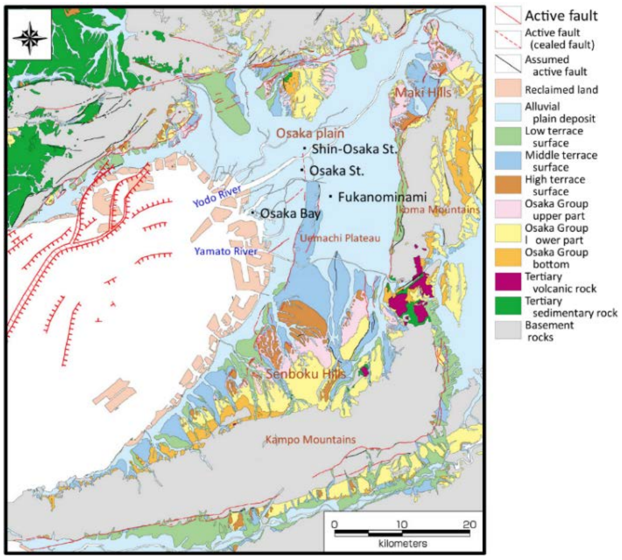

Fig. 2 Topography / Geology
(Modified after KG-NET, Kansai Area Ground Work Meeting (2007) [13])

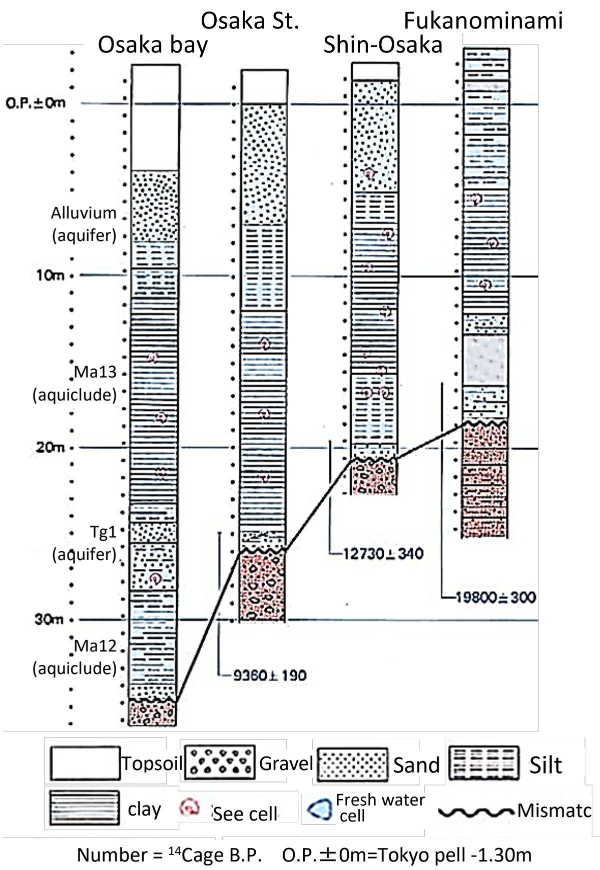

Fig. 3 Geologic columnar section
(modified after Ichihara et al. [12])

the groundwater recharge/flow in the entire Osaka Plain. Therefore, the aims of this study were to confirm the situation of seawater intrusion into the coastal groundwater and estimate the recharge process of the water by measuring the concentrations of chloride ion (Cl^-) and stable hydrogen and oxygen isotopes as well as analyzing the isotopic ratios ($\delta^{18}O$, δD) and comparing them with the existing values in the literature.

2. STUDY AREA AND METHOD

The research was conducted in the Osaka Plain. The locations of observation wells are shown in Fig. 1, and the geological features of the region are shown in Fig. 2 and Fig. 3 [12][13].

The flat area is covered with alluvial deposits. The geological column from soil surface can be summarized as (example from Osaka Bay) top soil (a), sand (b), silt (c), clay (d), sand and mixed silt (e), silt (f), sand (g), and gravel (h). Aquifers are assumed to be located in sand layer (b), gravel layer (h), alluvium, the 1st Hongan laminated gravel layer (Tg1), and the 2nd volcanic gravel layer (Tg2) near the deeper G.L-60m aquiclude (Ma13–Ma11), which is located between each aquifer [9][14].

Nine observation wells on the coast of Osaka Bay were the target of our research. Five observation wells (N1 to N5) were under the jurisdiction of the Research Council of Groundwater Environment. Two observation wells (S3 and S4) were under the jurisdiction of the Ministry of Land, Infrastructure and Transport, and the other two wells (S1 and S2) were under the authority of Osaka Prefecture (Fig. 1).

The assumed aquifer and depth (G.L-m) of each observation well follow:

- Alluvium: S1/6.70 m, S3/10.50 m, S4/10.20 m, N3-AS/22.00 m.
- The 1st Diluvial gravel layer (Tg1): S2/25.00 m, N1-Tg1/37.50 m, N2-Tg1/31.60 m, N3-Tg1/40.50 m, N4-Tg1/40.20 m, N5-Tg1/ 39.30 m.
- The 2nd Diluvial gravel layer (Tg2): N1-Tg2/56.25 m, N2-Tg2/56.80 m, N4-Tg2/61.70 m, N5-Tg2/59.75 m

The strainer length of N1 to N5 is 4.0 m, and those of S1 to S4 are 3.7 m, 3.0 m, 7.6 m, and 8.0 m, respectively. The groundwater level measurement and sample collection were carried out in March 2015. The observation wells were drained before sampling. The electrical conductivity, pH, and dissolved oxygen concentration of the sample water were measured on site. Cl^- concentration and stable hydrogen and oxygen isotopes were analyzed in the laboratory. The Cl^- concentration was analyzed by ion chromatography (Shimadzu Corporation, CL-VP),

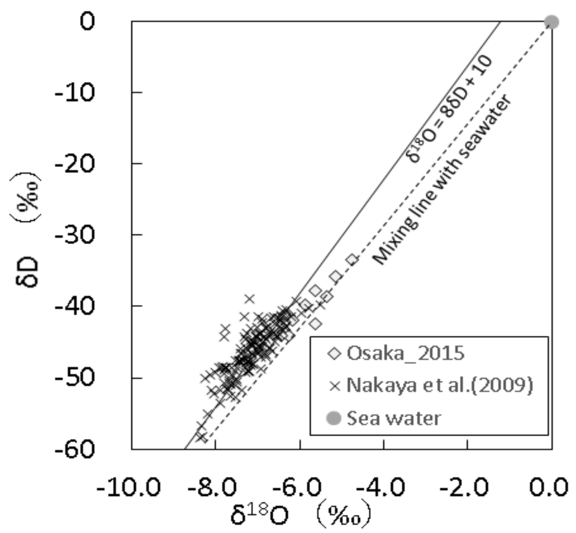

Fig. 4 δ diagram
(× refers to analysis values by Nakaya et al. [14], the same below)

and the stable isotope ratios (δD, δ^{18}O) were calculated with the WS-CRDS method (Picarro Company, L2120-i).

3. SITUATION OF SEAWATER INTRUSION

Fig. 4 shows a δ diagram with data of the groundwater and the meteoric water line ($\delta D = 8\delta^{18}O + 10$) around the Osaka Plain by Nakaya et al. [14] for comparison. The data plotted along the meteoric water line with a slope of roughly 8, indicating that the water was derived from rainwater. Some data plotted near the mixing line of modern seawater (δD: 0‰, δ^{18}O: 0.0‰) and the lower limit of groundwater. It is suggested that the mixing of groundwater and seawater shifted isotopic values to heavier ones.

Fig. 5 and Fig. 6 show the correlation between δ^{18}O and Cl^-. The concentrations of Cl^- at N5-Tg1 and N4-Tg1 were 5193 mg/L and 4813 mg/L, respectively. These concentrations were particularly high, indicating saltification. Given the values of modern seawater of δ^{18}O: 0.0 ‰, Cl^-: 18000 mg/L, seawater intrusion occurs when the mixing ratio of seawater is 0.1 to 28.9 %. At the other points, Cl^- concentration was 500 to 1000 mg/L, which confirmed the occurrence of seawater intrusion. The intrusion of seawater is stronger in the Yodo River Basin (N1–N5, S4) than in the Yamato River Basin (S1–S3). The intersection of the vertical line with the high mixing line and the low mixing line was −7.2 to −5.6 ‰ (Fig. 5). These values were included in the freshwater side data. We assume that groundwater and modern seawater are mixed in the aquifer.

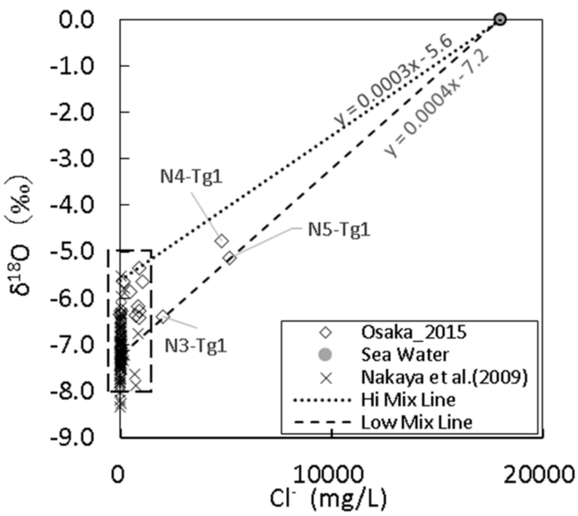

Fig. 5 δ^{18}O – Cl^-

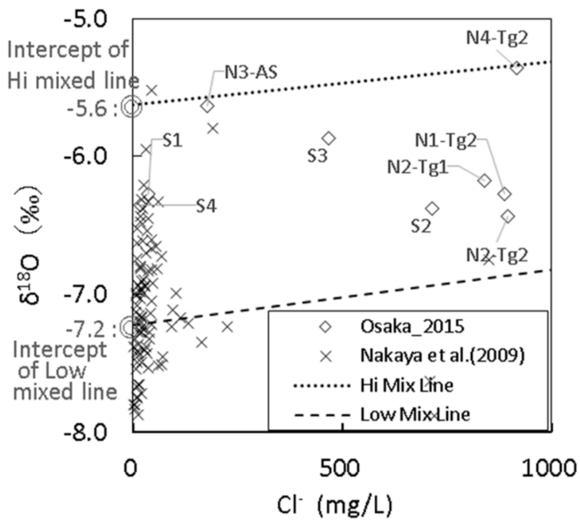

Fig. 6 δ^{18}O – Cl^-
(Inside the dotted rectangle in Fig. 5)

4. δ^{18}O AND Cl^- DISTRIBUTION CHARACTERISTICS IN CROSS SECTION A -A'

Fig. 7 shows the distribution of (a) Cl^- and (b) δ^{18}O at cross section AA'. N5-Tg1 and N4-Tg1 occur in the vicinity of about −40 m at the center in the figure and have especially high seawater intrusion.

The cross-sectional distribution of Cl^- shows that N4-Tg1 and N5-Tg1 have high concentrations of Cl^-. Wells N4 and N5 have low groundwater level, and groundwater samples were collected from the surroundings. We assume that seawater intrusion had already occurred at the sampling period. The Tg2 layer has moderate depth compared to the Tg1 layer.

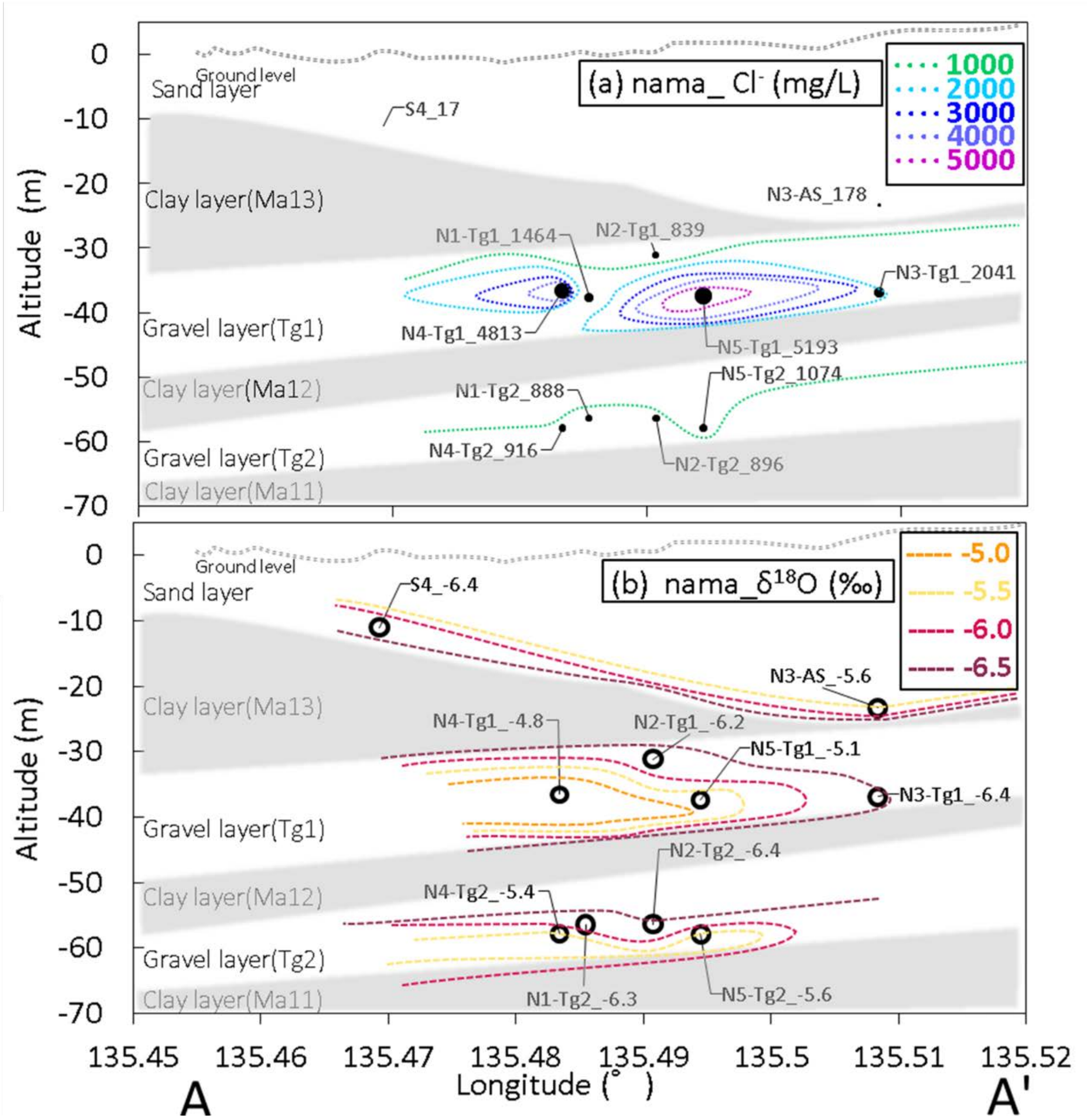

Fig. 7 Distribution of (a) Cl^- and (b) $\delta^{18}O$ in cross section A–A' in Fig. 1

The upper layers of S4 and N3-AS show a contrasting condition with N5-Tg1 and N4-Tg1. The Cl^- concentrations are low and there is fresh water on top of salt water.

The distributions of $\delta^{18}O$ show heavy values (−4.8 ‰, −5.1 ‰) at the points where Cl^- concentrations are high (N4-Tg1, N5-Tg1). Other points have values ranging from −5.4 ‰ to −6.4 ‰ and show an ambiguous distribution feature. Therefore, each value is considered to be a value generated by mixing with modern seawater.

Freshwater $\delta^{18}O$ before mixing corresponds to the intersection of the mixing line (the line connecting the plot of each value and the plot of the value of modern seawater) in Figs. 5 and 6 with the ordinate. Also, the mixing ratio of seawater was calculated with the Cl^- concentration of modern seawater as 100%. As a result, the $\delta^{18}O$ of fresh water before mixing with the heaviest point (N5-Tg1) was −7.2 ‰, and the saltwater mixing ratio was 29%.

In addition, the rough altitude of the study of Nakaya et al. [14] was obtained from the $\delta^{18}O$ results of surface water in the recharge zone of the Osaka Plain groundwater. The altitude effect characteristic is a decrease in the $\delta^{18}O$ of precipitation from low-altitude areas to high-altitude areas. This feature can be used to obtain the groundwater recharge elevation. In the Osaka Plain, a $\delta^{18}O$ of water value of −7.2 ‰ corresponds to water recharged at 100 m altitudes. The light water is considered to be recharged in the mountainous area, while the heavy water is presumed to be recharged on the hill/plateau area at less than 100 m elevations.

The calculation result for $\delta^{18}O$ at N5-Tg1 and N3-Tg1 was −7.2 ‰. These points are located in the 1st volcanic gravel layer. This location can be inferred as

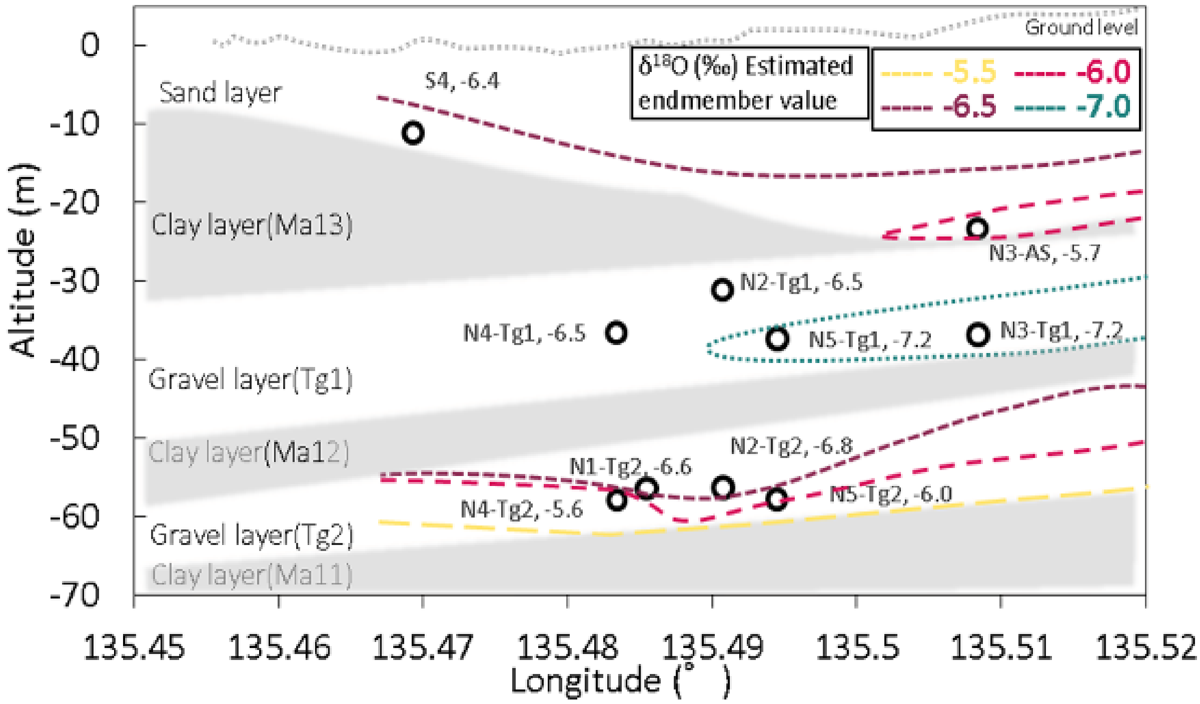

Fig. 8 Distribution of freshwater $\delta^{18}O$ before mixing in cross section A–A' in Fig. 1

representing water recharged in the mountainous areas. Shallow groundwater on the sea side of point N5 cannot reach light water from the mountains and is considered to be heavy water ($\delta^{18}O$: −7.1 ‰ or more) recharged on the plateaus and flat ground.

Particularly, there was some heavy water at N3-AS (−5.7 ‰) and N4-Tg2 (−5.6 ‰). These locations have a different type of aquifer. The water recharged at the 0 m altitude area estimated from the altitude effect is $\delta^{18}O$: −6.9 ‰. Thus, these heavy waters cannot be explained by the altitude effect. One possible reason for the heavy water is that precipitation accumulates in reservoirs, rice fields, waterways, etc., evaporates, and isotopic fractionation occurs. Other unknown factors such as contamination of sewer water into groundwater, influences from underground structures, and some others are also conceivable. However, data explaining these waters are currently lacking.

Discussion of the constant altitude effect used in this case is necessary. For example, $\delta^{18}O$ of precipitation is known to change seasonally [15], and there is the possibility that one-time sampling is not sufficient.

Even if heavy water factors are revealed, the process of heavy water invading each aquifer is still difficult to explain. Therefore, various approaches using other tracers are considered necessary.

5. CONCLUSIONS

In this study, Cl^- concentration was measured to trace seawater intrusion, and $\delta^{18}O$ and δD were measured to estimate the water recharge process.

The results showed that seawater intrusion with a maximum mixing rate of seawater of 29 % was confirmed in groundwater collected in 2015. The groundwater is considered to be derived from precipitation.

We suggested that the groundwater is formed from three sources: (i) recharge in mountainous areas with altitudes of 100 m or more, (ii) recharge in hilly areas and plateaus with altitudes less than 100, and (iii) modern seawater.

However, some heavy water cannot be explained by the altitude effect. Therefore, it is necessary to clarify the factors causing the generation of this water. The restoration process from seawater intrusion may be captured in the future by sampling water regularly.

6. ACKNOWLEDGMENTS

This research was partially supported by the Research Council on the Groundwater Ground Environment FY2008. We thank the Kinki Regional Development Bureau, Ministry of Land, Infrastructure and Transport, Osaka Prefectural Environmental Agriculture, Forestry and Fisheries Department, and Osaka City Environment Bureau for their cooperation during this investigation. We also thank our colleagues Ms. Hiroko Ito and Mr. Yutaka Maruyama (former graduate student of Hiroshima University) from the Geo-Research Institute for their great help in collecting the samples.

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