Identification of Seasonal Water Discharge Characteristics using Stable Isotopes of Water in the Mountain Region, Japan

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Abstract. Understanding water discharge processes in mountainous areas with large amounts of precipitation and high hydraulic gradients is important for disaster prevention and water resource management. In recent years, it has become clear that mountain bodies themselves have water storage functions in addition to primary water storage as snow accumulation in winter. However, the water discharge process in an environment with large amount of precipitation throughout the year is not fully understood. This study focuses on mountain springs and rivers in the Japanese Northern Alps to clarify the characteristics of water discharge processes. Hydrological observations and analysis of oxygen and hydrogen stable isotope ratios revealed the followings. Stream water level decreased in winter when snow cover was observed, and increased in summer when heavy precipitation was frequently occurred. The stable isotope ratios of spring water and river water showed smaller fluctuations during the study period than those of precipitation. This may be because precipitation is not discharged quickly, but rather after storage and mixing. The d-excess increased to the similar value of winter precipitation in summer at the same time as the stream level rose. This suggests that a winter precipitation component with high d-excess contributes to the discharge in summer due to snowmelt. On the other hand, during winter, snow accumulation limits groundwater recharge by precipitation, and summer precipitation stored in the mountain could be discharged, resulting in lower d-excess value in springs and river.

Keywords: Mountain Region, Oxygen and hydrogen stable isotopes, Seasonal variation, Water discharge

1 Introduction

Mountainous regions are the principal water discharge area on the terrestrial hydrological cycle, and because of their large amounts of precipitation and high hydraulic gradients, understanding the mechanisms of water discharge is important for disaster prevention and water resource management. Recently, it has been shown that mountain bodies themselves have water storage functions [1]. Therefore, it is essential to understand the water cycle system in mountainous areas, including mountain bodies. The mountainous regions under the Asian monsoon climate such as Japan have different characteristics in terms of precipitation compared to Europe and the United

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States, where mountain hydrology research is more actively undertaken. For example, Mt. Norikura in the Japanese Northern Alps, the study area of [2] and [3], had a total precipitation of 1581.4 mm from June to September (summer season). This amount is comparable to the annual precipitation in Europe and the United States, indicating that mountainous areas under the Asian monsoon climate receive a large amount of precipitation, especially in summer. On the other hand, during the winter season from November to April, there is a large amount of snowfall that covers most of the ground surface with snow. This snow cover melts as the temperature rises and contributes to the water discharge downstream as snowmelt water [4]. Mountainous areas are also known to be significantly affected by climate change, for example, [5] pointed out that the timing of snowmelt changes with global warming. Therefore, it is necessary to understand the water discharge mechanisms in mountainous areas under the Asian monsoon climate, which have unique hydrological environments. However, the contribution difference of summer precipitation and snowmelt to discharge in mountainous areas associated with the seasonal variation of hydrological processes under an Asian monsoon climate is still largely unknown.

Stable isotopes of oxygen and hydrogen are useful tracers to determine the origin and dynamics of water discharge. For example, [6] quantified the groundwater recharge source at the foot of a mountain using an endmember mixing method with δ-values and Cl^- of water. The results showed that mountain groundwater was the major recharge source for groundwater resources. [7] also analyzed the isotopic composition of mountain river water flowing from the Himalayas to show its water source. They found that meltwater from glaciers accounts for the majority of the river flow, indicating a clear increase in glacier melts with global warming. As described above, isotope tracers are useful for elucidating the hydrological cycle (e.g., the lag time of discharge generation after precipitation and discharge, groundwater recharge sources) in mountainous regions. Therefore, the objective of this study is to clarify the water discharge characteristics in terms of hydrological lag time and seasonal variation of contribution sources on discharge water in mountainous areas under the Asian monsoon climate by analyzing the stable isotope ratios of oxygen and hydrogen in mountain spring water and river water.

2 Methods

The study area is the Kamikochi region belonging to the Japanese Northern Alps. Kamikochi is one of the representative mountainous areas in Japan with elevations ranging from 1490 to 3190 m above sea level. It is surrounded by steep mountains such as Mt. Okuhotakadake (3190 m) and Mt. Yarigatake (3180 m). On the other hand, the Kamikochi basin is characterized by a gentle gradient of 8% and a basin width of 600-900 m [8]. In this study, we investigated the Azusa River, which is the main river flowing through this area, and two springs (see Fig. 1). We defined the spring near the main river as the floodplain spring and the spring at the foot of Mt. Myojindake (2931 m) as the mountain-block spring. Both springs and river water were sampled once every two weeks for one year from October 2018. For precipitation samples, bottles were placed at 1530 m and precipitation was collected every month. These water samples were analyzed for oxygen and hydrogen stable isotope ratios using a water isotope analyzer (PICARRO: L2130-i).

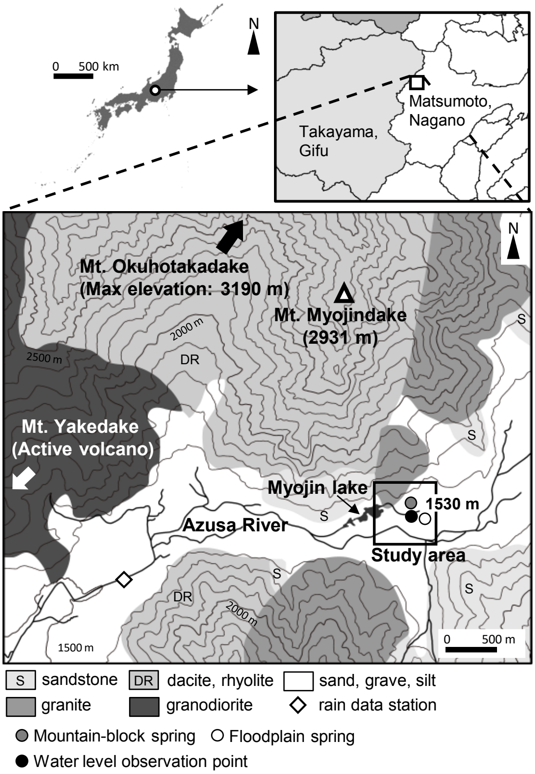

Fig. 1. Study area

The stable isotope ratio of water is described as follows:

$$\delta^{18}O \text{ or } \delta D\ (‰) = \left(R_{sample}/R_{std} - 1\right) \times 1000 \quad (1)$$

where R_{sample} and R_{std} respectively refer to the ratios of heavy to light isotopes ($^{18}O/^{16}O$ or $D/^{1}H$) in a sample and the internationally accepted standard reference water (V-SMOW: Vienna Standard Mean Ocean Water). The deuterium excess (d-excess) was calculated as follows:

$$d\text{-}excess = \delta D - 8\delta^{18}O \quad (2)$$

Stream water levels were observed at 10-minute intervals using a water level gauge (KADEC21-MIZU-C) in tributaries located in the downstream portion of springs. Precipitation amount data was obtained from the AMeDAS (Automated Meteorological

Data Acquisition System) of the Japan Meteorological Agency at the Kamikochi observatory. This station is located at an elevation of 1510 m, about 3 km from the study springs.

3 Result and Discussion

Hydrological characteristics

Temporal changes in precipitation and stream level over the year from October 2018 are shown in (see Fig. 2). The total annual precipitation was 2608.5 mm. This is clearly higher than in Europe and the United States (e.g., about 930 mm/year, [9], where mountain hydrology is widely studied. Precipitation was highest in August (533.5 mm/month) and lowest in November (35.0 mm/month). Precipitation tended to be higher during the summer months of June-August, with an average value of 372.2 mm/month. On the other hand, precipitation in winter (November-April) was less than that in summer, and most of the precipitation was in the form of solids (snowfall).

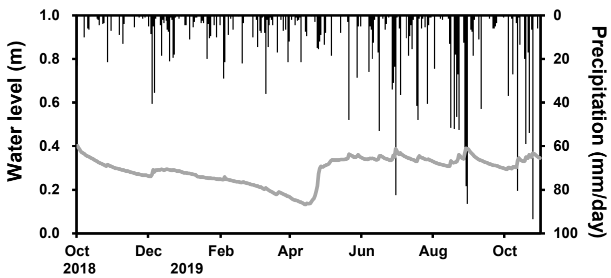

Fig. 2. Temporal variation of precipitation and water table level of stream

Stream levels monotonically decreased during the winter season, except during some precipitation events. This may be because precipitation during this period was deposited as snow, and the precipitation component discharged into stream water was limited. Water levels seemed to be higher during the May-October period when liquid precipitation was observed, compared to the winter period. Especially in May, the end of the winter season, the water level rose largely in a short period of time (range: about 0.2 m). This could be due to the inflow of large amounts of snowmelt water into the stream with the rise in temperature. In summer, when precipitation was particularly concentrated, the water level rose in response to high-intensity precipitation events.

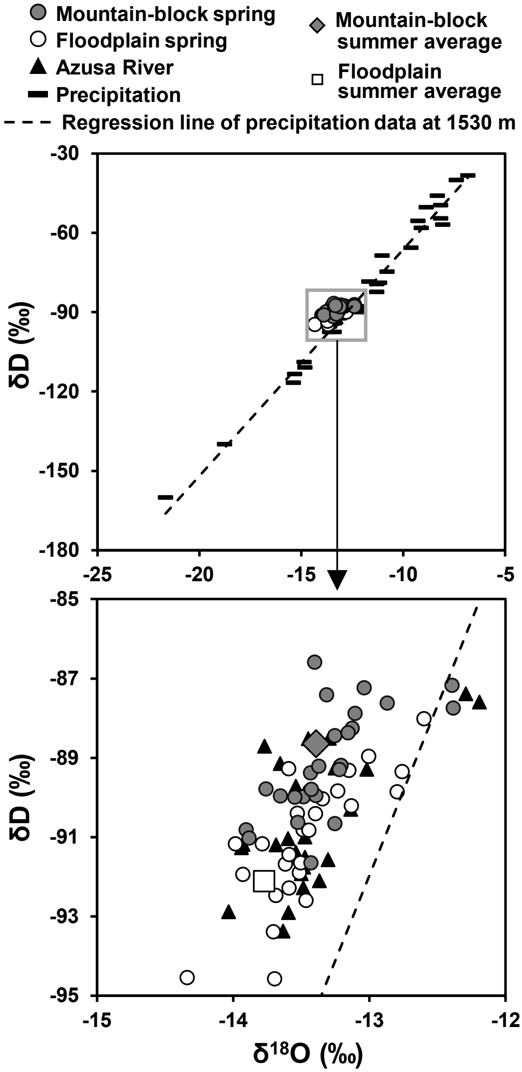

Fig. 3. Relationship between $\delta^{18}O$ and δD of collected water samples

Stable isotopic characteristics and water origin

Fig. 3 shows the relationship between stable isotope ratios of oxygen and hydrogen in precipitation, spring water, and river water. The precipitation samples showed the largest variations during the study period ($\delta^{18}O$: -21.7 to -6.8‰, δD: -159.9 to -38.0‰). In contrast, the isotope ratios of the spring and river water samples ranged from -14.3 to -12.2‰ for $\delta^{18}O$ and -94.6 to -86.6‰ for δD. The smaller isotope ratio variations in spring water and river water compared to precipitation samples may be due to the fact that these waters are not rapidly converted from precipitation to discharge, but are discharged after storage and mixing processes in the surrounding mountain areas after precipitation. Assuming that the regression line of the precipitation plot in the δ-diagram (see Fig. 3) is the Local Meteoric Water Line (LMWL), the majority of the spring and river water is plotted at a distance from the LMWL. This means that the origin of spring and river water is not precipitation in the Kamikochi region, but water with a high d-excess. In Japan, water with a high d-excess is typically water originating from the Japan Sea in winter [10]. Therefore, the main source of discharge in this study could be winter precipitation (snowfall and snowpack). In other words, the water with a high d-excess flows into springs and rivers during the warm season as the snow melts, forming discharge. On the other hand, there were seven spring and river waters plotted near the LMWL. All samples were collected during the winter season (December-February). Due to the low temperatures, snowmelt cannot occur during the winter season, and the above argument does not hold. Therefore, this point is discussed in the next section.

Seasonal groundwater discharge processes

(See Fig. 4) shows the temporal variation of d-excess in spring water, river water, and precipitation. The d-excess of precipitation is higher in winter and lower in summer. On the other hand, the d-excess of spring water and river water decreases in winter and increases in summer. In particular, the d-excess of spring water and river water in summer was close to that of winter precipitation. This may be due to the contribution of the winter precipitation component during the summer season, when a large amount of snow melts. (see Fig. 2) showed that the stream level rose in May, the season of snowmelt, which coincides with the period when the d-excess of spring water and river water increases.

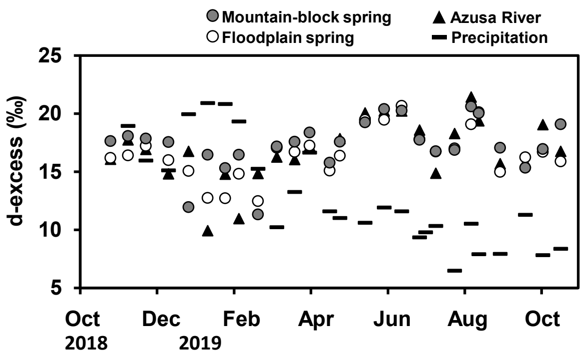

Fig. 4. Temporal variation of d-excess of water

In winter, precipitation is fixed to the ground surface as snow accumulation. Therefore, it is difficult for the winter precipitation component to discharge. Instead of precipitation, summer precipitation stored in the mountain bodies could be the main source of discharge. Therefore, the d-excess of spring water and river water during the winter season is expected to decrease and become similar to that of summer precipitation. This may explain the different trends of spring water and river water in winter observed in the δ-diagram (see Fig. 3). Considering the delayed discharge of summer and winter precipitation, the precipitation component would be stored in the mountain body for at least half a year before discharging, resulting in the d-excess change trend in (see Fig. 4). However, the d-excess of spring and river water was slightly higher than that of summer precipitation. This means that the d-excess of spring water and river water is not 100% of summer precipitation, but some winter precipitation may be mixed in.

The contribution of snowmelt to discharge in summer has been described in studies in mountainous areas of Europe and the United States [11]. They stated that the contribution of liquid precipitation should be small due to the small amount of summer precipitation. In contrast, our study site has plenty of summer precipitation, hence, the summer precipitation can contribute to water discharge. Thus, the summer liquid precipitation could be a main source of water discharge in mountain catchments under the Asian monsoon climate.

Finally, a comparison of stable isotope ratios among the springs showed that the mean δ values of the mountain springs would be significantly higher than those of the floodplain springs during summer (Table 1). This suggests that mountain springs may discharge a larger amount of isotopically different water than floodplain springs during the summer, when the discharge increases. However, the δ values of mountain springs tend to be higher than those of floodplain springs, which is opposite to the altitude effect of the isotopic ratio. This is an issue to be addressed in the future for a better understanding mountain hydrological cycle.

Table 1. Average $\delta^{18}O$ and δD of mountain-block and floodplain springs during the summer season (June to August).
* p< 0.05, **<0.01

Springs	$\delta^{18}O$ (‰)*	δD (‰)**
Mountain-block (n=7)	-13.4±0.3	-88.6±1.5
Floodplain (n=7)	-13.8±0.3	-92.1±1.8

4 Conclusions

Two mountain springs and a river in a mountainous area were investigated for clarifying the water discharge characteristics based on stream water levels and stable isotope ratios of oxygen and hydrogen. Stream water levels decrease in winter, and rose significantly in spring (May). This was attributed to the rapid melting of snowpack that could not contribute to discharge during the winter. The stable isotope ratios of oxygen and hydrogen in precipitation showed a large variation compared to those of spring water and river water, with a clear trend of higher d-excess in winter and lower d-excess in summer. On the other hand, the oxygen/hydrogen stable isotope ratios of the spring water and river water varied little, and their compositions were far from LMWL. The d-excess of spring water and river water was higher in summer and lower in winter, which was opposite to that of precipitation. These results suggest that precipitation does not flow out quickly after precipitation events, but rather is stored and mixed in the surrounding mountainous areas before discharging. This time lag of precipitation component discharge from precipitation input to the mountain would be at least half a year. The increase in d-excess in the spring and river water coincided with the rise in the stream level in May, suggesting that the snowmelt during summer brought in winter precipitation with a high d-excess. On the other hand, in winter, summer precipitation stored in the mountain bodies becomes the main source of discharge, and d-excess is assumed to have decreased. The mean δ values of the mountain springs were significantly higher than those of the floodplain springs during the summer season, suggesting that isotopically different water is discharged from the mountain springs during the summer season. However, this is opposite to the altitude effect on isotopic ratios, and it is necessary to study the recharge sources of mountain springs in the future.

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