Hydrology I: Impact of Glacier Shrinkage on the Water Cycle of Mount Kenya

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U-shaped valley in the western foothills of Mount Kenya. The Teleki River flows along the valley, and the river water is used by the inhabitants at the base of the mountain for agriculture and domestic use

Abstract This study focuses on the shrinkage of glaciers on Mount Kenya (5199 m), which is located in central East Africa. Based on field observations, isotope ratio analyses, groundwater age measurements, and interview surveys, here we have discussed the impact of Mount Kenya's glacial shrinkage on the water environment and the

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availability of water resources in the surrounding areas. In the study area, which is located at approximately 2000 m elevation, the level of precipitation is generally low, and therefore, the usage of water for agricultural and household activities depends on river water and spring water from Mount Kenya. The average elevation of the recharge zones of river water used by the residents of this mountainous basin is 4650 m, and that of spring water is 4718 m. It is evinced that water from the glacial zone contributes significantly to river water at the base of the mountain. Furthermore, it takes 40–60 years for glacial meltwater to be discharged at the base of the mountain. The glaciers of Mount Kenya are expected to disappear by 2030, which might have a considerable impact on water resources at the foot of the mountain.

Keywords Mount Kenya · Glacier shrinkage · Water environment · Stable isotope · Groundwater age

1 Introduction

The rapid increase of global warming in recent years has significantly impacted the glaciers. Mountain glaciers around the world are shrinking rapidly, and the most prominent ones include the high-mountain glaciers of tropical Africa. In this region, glaciers are present on Kilimanjaro, Mount Kenya, and Mount Rwenzori, and all of them are shrinking (Hastenrath 1984, 2005, 2008). It has been predicted that these glaciers would disappear by 2030 (Thompson et al. 2009). Most notably, the glaciers of Mount Kenya, which has been designated a World Heritage Site, are shrinking at rates of 7–10 m/year (Mizuno and Fujita 2014). Therefore, monitoring programs are urgently required to record the relationship between glacier contraction, and the surrounding water environment and ecosystem.

Kenya generally has low rainfall with significant annual fluctuations. Therefore, relying solely on rainfall to provide a stable water supply for agricultural and domestic use is difficult in this region. On the other hand, Mount Kenya brings significant water resources to such dry lowlands, which makes it a “water tower” in the East African region (Njeru and Liniger 1994; Liniger and Weingartner 2000). The water from Mount Kenya makes it possible to grow coffee, tea, roses, and other crops in areas surrounding the mountain (Enjebo and Öborn 2012). However, the extent to which glacier meltwater contributes to this water supply is not yet known.

Melted water from the mountainous glaciers is considered an important resource for downstream residents in the Andes region. Vergara et al. (2007) showed that the abundance of glaciers in Bolivia, Venezuela, and several other tropical glaciers located near the equator is declining. For example, a glacier that was 2,940 km^2 in size in 1970 was reduced to 2,493 km^2 in 2002. By analyzing selected areas that are likely to be affected by the reduction of water resources due to glacial contraction, Vergara et al. (2007) demonstrated the contribution of glacial meltwater to river water. The authors found that approximately 50% of the river water in the area was derived from glacial meltwater. This indicates that glacial contraction has the potential to severely impact the agricultural productivities in the area.

Similar to the Andes, a decrease in water resources has been recently observed in Mount Kenya and its surrounding regions (Liniger et al. 2005). Although river water and groundwater derived from Mount Kenya are widely used for agricultural and domestic purposes (Enjebo and Öborn 2012), its source and water cycle have not been yet determined.

A study conducted at Kilimanjaro using tritium dating of water showed that groundwater was recharged approximately 50 years ago (McKenzie et al. 2010). However, such studies are yet to be conducted for Mount Kenya.

There is ample evidence of glacial melting on Mount Kenya. However, the timescale for groundwater recharge from glacial melt and mountain precipitation is unknown. Therefore, the extent to which the recent glacial contraction has affected the aquatic environment at the base of the mountain has not yet been determined. The present study is the first to investigate the influence of glacial meltwater on the water circulation of Mount Kenya and its surrounding regions. The results have the potential to predict and mitigate changes in the water environment around Mount Kenya, which is of great significance for the local community.

2 Overview of the Survey Area

2.1 Alpine Zone (Elevation >4000 m)

Most of the surface of the alpine zone of Mount Kenya is covered with snow, glaciers, debris separated from columnar basalt joints, and alpine plants (Fig. 1a). The average annual precipitation above 4200 m is 790 mm, and most of it falls as snow (Hastenrath 2005). The average annual temperature at 4800 m is 4 °C. Liniger et al. (1998) classified the dominant type of soil in this zone as Regosol (immature soil composed of freshly deposited alluvial stratification or sand). Soils of this type are often found in landslide areas and are poor in O layers.

Studies conducted at elevations of 4000 m and above in Mount Kenya have focused on glacier facies (Hastenrath 1984; Mahaney 1990) and the appearance of new plant species with glacial retreat (Coe 1967; Mizuno 1998, 2005; Mizuno and Fujita 2014). The glaciers of Mount Kenya are shrinking rapidly owing to climate change, and plant species are expanding their range as the receding glaciers expose more land surfaces.

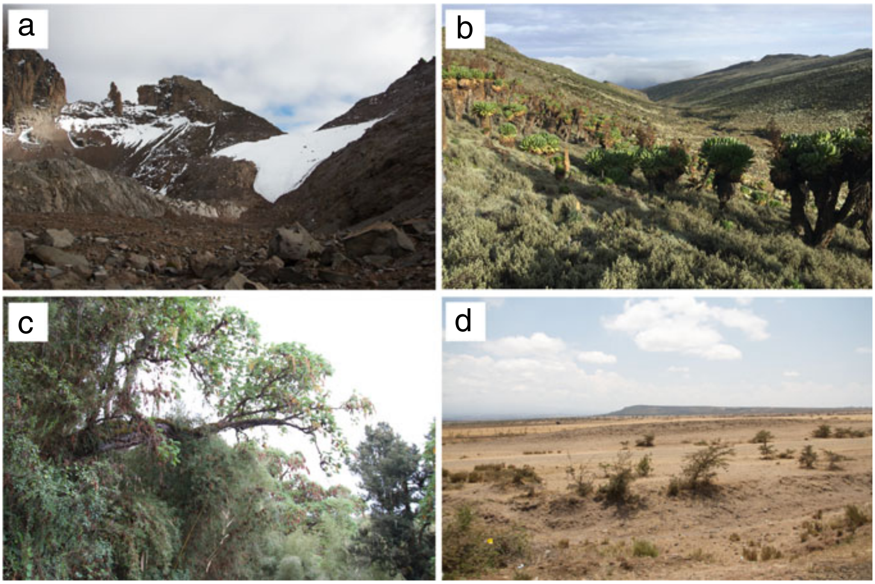


Fig. 1 Regional landscape of Mount Kenya sorted according to their elevation. **a** Alpine Zone (>4000 m), **b** Moorland Zone (3200–4000 m), **c** Forest Zone (2,300–3,200 m), and **d** Mountain Foot Zone (<2300 m)

2.2 Moorland Zone (3200–4000 m)

This represents a rough area, where the Teleki River flows through the bottom of a large U-shaped valley (Fig. 1b). The Teleki River is a valuable source of water for irrigation and human consumption in Naromoru village, which is located downstream at an altitude of 2000 m. The soil in the upper parts of the Moorland zone has good permeability, and therefore, groundwater veins are easily formed in this region. On the other hand, the lower part of the zone consists of poorly permeable soil, called Histosol (Liniger et al. 1998). The vegetation in the upper Moorland zone is similar to that found in the alpine zone; however, the lower part of the zone is dominated by wetland and heathland with *Erica* and *Philippia* shrubs being the dominant species (Decurtins 1992).

2.3 Forest Zone (2300–3200 m)

The annual average precipitation at an altitude of 3000 m is approximately 1500 mm, and the average annual temperature is 11.5 °C, which permits the growth of forests in the region (Fig. 1c). The soil above 3000 m consists of Andosol (black and white soil) with good drainage and humus. The surface soil is black or gray with thick organic matter-rich O layers. The soil undergoes transition from Andosol to Acrisol (a red-yellow podzolic soil) below 2500 m (Liniger et al. 1998).

Most parts of this elevation zone are located within the Mt. Kenya national park; however, most natural forests below 2400 m were cleared before the establishment of the national park, and subsequently the forests were harvested. Since several harvested areas are used as farmland, the demand for irrigation water in this area is increasing, and appropriate quantitative management of river water and groundwater derived from Mount Kenya is necessary.

2.4 Mountain Foot Zone (<2300 m)

Several areas such as Nanyuki and Naromoru are situated around Mount Kenya outside the boundaries of the national park. Nanyuki is a busy relay point for transportation, and the route leads to the northern part of Kenya. Nanyuki is also considered the initial base point for mountain climbing in Kenya. The average annual rainfall in the Naromoru region (altitude of ~2,000 m), which is located at the western base of Mount Kenya, is approximately 640 mm, and the average annual temperature is 16 °C.

Steep terrain and steep cliffs are found at approximately 2300 m above sea level, and the regions are sparsely populared. However, the land is extremely flat and dry below 2200 m (Fig. 1d). This area contains many villages and residents. Five villages in the Naromoru region are located alongside the river flowing from Mount Kenya.

The primary soils in this elevation zone are iron-rich Luvisol and Acrisol (Liniger et al. 1998). Luvisol are reddish brown fertile soils. Due to their physical properties, they are well-drained and extremely favorable for cultivation. Luvisol are often formed in semi-humid and semi-arid climate zones if the host rock is limestone.

Kenya experiences both rainy and dry seasons. Precipitation during the rainy season (March–May, October–December) is caused by the absorption of water vapor evaporated from the Indian Ocean, and its subsequent transportation by winds flowing from the southeast direction. On the other hand, the dry season is associated with winds from the northeastern regions of the Indian Ocean during January–June and June–September (Levin et al. 2009). At an altitude of approximately 2000 m at the foot of Mount Kenya, rainfall of 50–140 mm/month is recorded during the rainy season (Apr–Dec, Oct–Dec), and 30–60 mm/month in the dry season (WRMA 2016).

3 Application of Isotope Analysis

The total amount of groundwater cannot be determined by visual observations, which complicates the efforts pertaining to water resource management. Therefore, stable isotope ratios of hydrogen (δD) and oxygen ($\delta^{18}O$) have been used to characterize groundwater (Criss and Davisson 1996; Rowland et al. 2011). Isotope analyses have been also used to map the origin of the mountainous spring water. The variations in δD and δ^{18}O values in precipitation can aid in determining the altitude effects; for example, δD and δ^{18}O generally decrease with an increase in altitude. When clouds move from the ocean to the foot of the mountain, the precipitation at low altitudes possesses preferentially heavier δD and δ^{18}O due to gravity. Consequently, δD and δ^{18}O decrease with snowfall at higher altitudes and in glacial meltwater originating at higher altitudes of the mountainous body. In the present study, the contribution of melt water from glaciers and snow to the spring water at the foot of the mountain was estimated based on the differences in δD and δ^{18}O values between water found in the glaciers and snow versus the precipitation samples collected from the bottom of the mountain. δD and δ^{18}O in spring water at the base of the mountain were found to be lesser than in precipitation falling in the same elevation zone, thereby evincing that the spring water is fed by melting glaciers and snow.

In mountains whose upper regions are composed of volcanic basalt (Baker 1967), such as Mount Fuji (Tsuchi 2017), both precipitation and meltwater can easily permeate the ground in the upper parts of the mountain. However, dense lava flows in the lower regions of such mountains prevent the precipitates to deeply permeate the ground. Thus, surface water and shallow groundwater flow down to the foot of the mountain, while water at the upper elevations flows deep underground, and emerges at the base of the mountain as confined groundwater. It is possible that the base of Mount Kenya, which is composed of basalt (similar to that of Mount Fuji), is recharged by meltwater from the upper regions of the mountain, and not by precipitation at middle and lower regions.

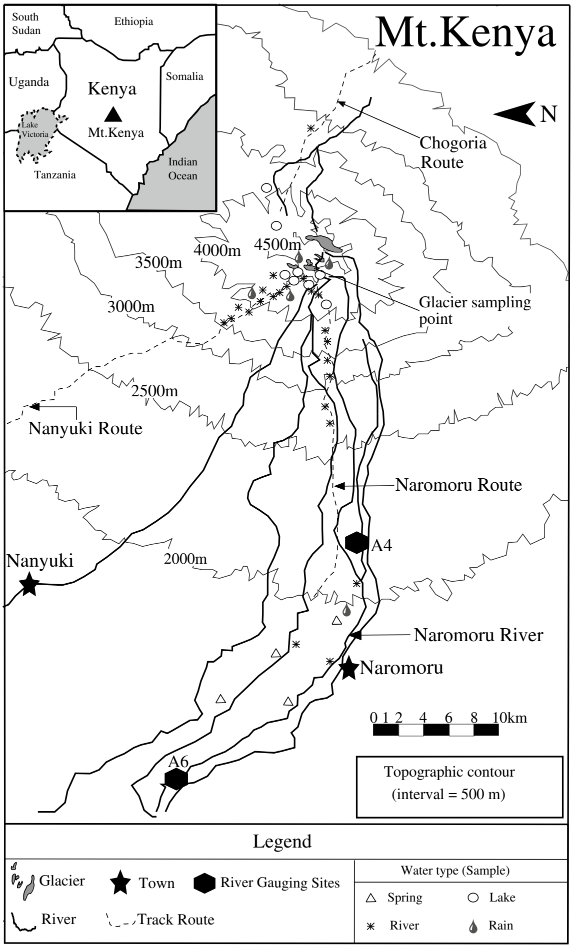
To understand the contribution of glacial meltwater to spring and river water at the western base of Mount Kenya, we carried out δD and δ^{18}O analyses as well as trace element analyses of glaciers, river water, spring water, lake water and precipitation. The investigation was conducted during 2015–2016 dominantly on the western parts of Mount Kenya, which includes Tyndall glacier.

3.1 Sampling Method and Sampling Locations

Spring water, river water, glacial meltwater, lake water, and precipitation were sampled from August 2015 to October 2016, and from July to September 2016. The objective was to assess the hydrological characteristics of the Naromoru region at the western foot of Mount Kenya (Fig. 2). All sampling activities were performed during the dry season. Samples were collected in 100 mL plastic water bottles. Water temperature and electrical conductivity (EC) were measured by placing a portable conductivity meter (ES-71, HORIBA), attached to a 1.5 m long cord, directly in the water in an area where the water flow was relatively gentle. The sensor of the compact pH meter (B-712, HORIBA) was rinsed before each measurement to remove contaminants. GPS coordinates were recorded for all sampling and measuring points.

Spring water was sampled at four points located 2 km away from the urban area of Naromoru in Mount Kenya. A total of 23 river water samples were collected from

Fig. 2 Study area in Mount Kenya with marked water sampling sites (Otani 2018)



the rivers running from 4500 to 2000 m above sea level on the climbing routes of Nanyuki, Naromoru, and Chogoria mountains. Two glacial meltwater samples were collected from Tyndall glacier at 4600 m above sea level, and two more samples were collected from ice bodies buried in debris beneath the Tyndall glacier. A total of eight lake water samples were collected from glacial lakes located at an altitude of 4500 m. Rainwater was sampled by collecting rain in polyethylene vinyl sheets at seven points (7 samples) in the 5000–2000 m zone of the Nanyuki and Naromoru routes.

4 Results

4.1 *Effects of High-Altitude on Precipitation and the Estimation of Recharge Altitude of Mountain Spring Water*

Table 1 shows the statistical values of δD and δ^{18}O of spring water, river water, lake water, rain water, and glacier water. Figure 3 shows the relationship between δD and δ^{18}O for each sample. Glacial meltwater, spring water, river water, and precipitation were found to plot on the global meteoric water line (GMWL).

The pattern in the variation of lake water in Mount Kenya with altitude was different compared to that of rainwater. During evaporation, the light isotopes of water selectively evaporate from the lake water such that the residual lake water gets preferentially enriched in heavy isotopes (Weitz and Demlie 2014). Due to the presence of heavier isotopes in the lake water of Mount Kenya compared to that in the rainwater, the lake water samples plotted at an inclination lower than of the rainwater line in the δD versus δ^{18}O plot. In addition, it was found that d-excess ($= \delta D - 8\delta^{18}O$), an index of dynamic fractionation defined by δD and δ^{18}O of water, changes with relative humidity and water temperature mostly when water evaporates. For example, when water evaporated under dry conditions, water vapor was affected by large dynamic fractionation, and eventually the sample exhibited high d-excess (20‰ or higher).

Therefore, evaporative water is expected to show high d-excess in the dry mountain ranges of Mount Kenya. The mean δD value of water sampled from Mount Kenya was 0.5‰, which was lower than that of the water evaporated under dry conditions.

Table 1 Stable isotope data of water samples in Mount Kenya

	No. of Samples		δ^{18}O (‰)	δD (‰)
Spring water	4	Mean Minimum Maximum	–3.74 –4.12 –3.33	–17.77 –20.66 –15.91
River water	23	Mean Minimum Maximum	–4.24 –6.32 –1.63	–22.03 –40.72 1.92
Lake water	8	Mean Minimum Maximum	–1.78 –4.63 4.93	–13.75 –30.47 17.44
Rain water	6	Mean Minimum Maximum	–0.77 –2.23 3.17	7.28 1.80 18.94
Glacier water	4	Mean Minimum Maximum	–2.73 –4.35 –1.88	–15.74 –27.44 –9.83

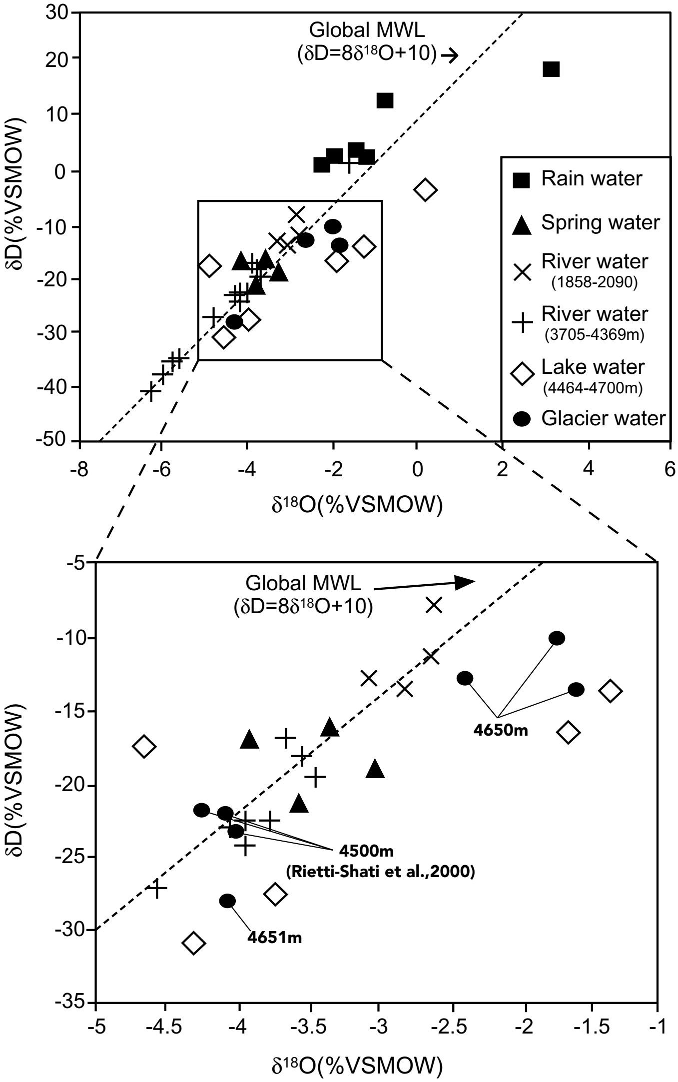


Fig. 3 Relationship between δD and δ18O in water samples collected along the Naromoru River watershed, Mount Kenya (Otani 2018). The dotted line indicates the global meteoric water line (GMWL)

This might be a result of the low d-excess of the residual lake water owing to the selective evaporation of water with high d-excess.

As shown in Fig. 3, the δ^{18}O of spring water at an elevation of 1943–2085 m ranged from −4.12‰ to −3.33‰, and δD ranged from −20.66‰ to −15.91‰. The δ^{18}O of river water at an elevation of 1858–2090 m ranged from −3.29‰ to −2.85‰, and δD ranged from −13.42‰ to −7.58‰. From Fig. 3, it is evident that

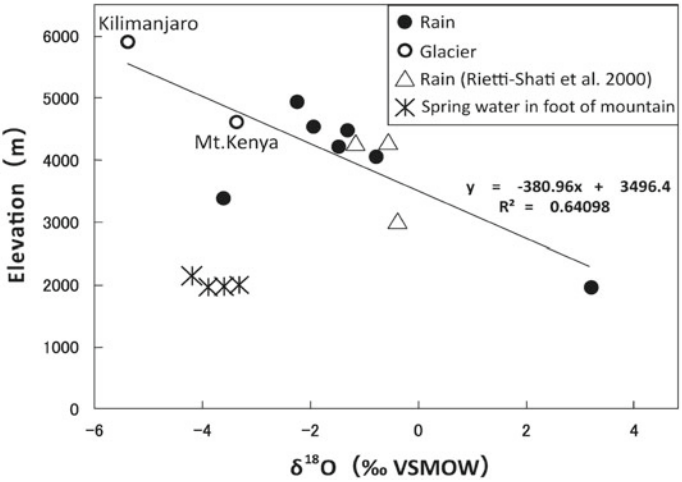


Fig. 4 Effect of altitude on the isotopic composition of precipitation on Mount Kenya (Otani 2018). The solid line indicates the approximated relationship between the δ^{18}O values of precipitation and elevation

these isotope values are close to those of the glacier meltwater originating at heights of 4500–4651 m (i.e., δ^{18}O = −4.35‰ to −1.88‰, δD = −27.44‰ to −9.83‰) and river water from high elevation zone of 3,705–4,396 m (δ^{18}O = −4.82‰ to −3.55‰, δD = −26.81‰ to −15.15‰). Therefore, it is likely that the primary sources of recharge in the foothill springs and rivers of Mount Kenya during dry season are glacial meltwater and river water originating in the high-altitude zone.

Figure 4 reflects that the δ^{18}O of the precipitation samples collected at each altitudinal zone exhibited a high altitudinal effect (i.e., δD and δ^{18}O values decreased with increasing altitude). The moisture mass that brings precipitation to Kilimanjaro and Mount Kenya originates from the Indian Ocean (Levin et al. 2009; McKenzie et al. 2010). The δ^{18}O of glacial meltwater and precipitation at 5895 m on Kilimanjaro is −3.7‰ (Moser and Stichler 1970), which is consistent with the altitude effect line shown by the approximated relationship between the δ^{18}O value of precipitation and elevation in Fig. 4. Therefore, we used samples collected from Kilimanjaro at 4600 m for comparison. The altitude effect line, expressed as E (m) = −380.96 × δ^{18}O + 3496.4, was calculated by combining the values of δ^{18}O at two points per altitude zone obtained in a previous study (Rietti-Shati et al. 2000) with the values for precipitation samples obtained in the current study (Fig. 4). Thus, we estimated the recharge altitude of the spring water at the foot of the mountain. The δ^{18}O values of spring water sampled at 1943 m, 1965 m, 1972 m, and 2085 m were −3.89‰, −3.60‰, −3.33‰ and −4.12‰, respectively. In the altitude effect line, the values corresponded to altitudes of 5065 m, 4978 m, 4867 m, and 4761 m, respectively. Considering the mean value of δ^{18}O (3.03‰) for river water at the base of the mountain, the average recharge elevation of river water was estimated to be 4650 m based on the sample's position in the altitude effect line. From these results, it is apparent that water in the glacier zone at high altitudes flows to the base the mountain as groundwater and river water.

4.2 High-Altitude Effects on Precipitation

The effect of high-altitude on precipitation, calculated in the present study, demonstrated that $\delta^{18}O$ decreased by approximately 0.18‰ with every 100 m increase in altitude. Rietti-Shati et al. (2000), who examined the altitude effect on Mount Kenya using stable isotopic composition of water, found that the $\delta^{18}O$ of precipitation samples was −0.44‰ and −1.44‰ at 3050 m and 4200 m, respectively. The results indicate that $\delta^{18}O$ decreases with an increase in altitude. However, the altitude effect was weaker in Mount Kenya compared to that in other African mountainous regions (Rietti-Shati et al. 2000). Previous studies on altitudinal effects (Clark and Fritz 1997) have shown that $\delta^{18}O$ decreases from −0.15‰ to −0.5‰ for every 100 m increase in elevation, whereas $\delta^{18}O$ values of precipitation samples collected by Rietti-Shati et al. (2000) from Mount Kenya decreased by only −0.09 to −0.02‰. The cause of this discrepancy is unknown, which could be revealed by further comparative research.

Studies by Levin et al. (2009) have shown that $\delta^{18}O$ values in the precipitation samples collected during the rainy season were lower than those collected during the dry season. The $\delta^{18}O$ values of precipitation in Addis Ababa region of Ethiopia were approximately −5‰ higher in the rainy season compared to the dry season. As all precipitation samples analyzed in the present study were collected during the dry season, and the $\delta^{18}O$ values were lower in the rainy season, it is expected that the mid-mountain precipitation made a greater contribution to river water at the base of the mountain. Therefore, future studies should analyze samples collected during the rainy season to better understand the effects of altitude on precipitation.

5 Groundwater Dating with Chlorofluorocarbons and Tritium

5.1 Chlorofluorocarbons

It is essential to determine the age of groundwater to evaluate groundwater resources, flow conditions, and safety of drinking water. Chlorofluorocarbons (CFCs) are organic compounds that were artificially produced in the 1930s, and are characterized by extremely stable properties. CFCs, which are mainly used in industrial applications such as coolants and detergents, are eventually released into the atmosphere. As a result, large quantities of CFCs have accumulated in the atmosphere with their increasing usage since the 1930s.

The concentration of CFCs increased at a high rate of 3% per year over a 50-year period from the 1940s to the 1990s, which has established the potential to apply CFC concentration for groundwater dating (Thompson et al. 1974). In the 1990s, the use of CFCs alongside tritium was initiated to measure the age of young groundwater. Since 2006, the concentration of CFC has been used to date volcanic mountain spring water and alluvial fan groundwater in Japan (Asai et al. 2006).

Groundwater dating using CFCs is based on the principle of solubility equilibrium between air and groundwater. Precipitation infiltrated into the ground reaches a state of concentration dissolution equilibrium with the gas in the soil when it descends and penetrates through the unsaturated zone (i.e., the range from the ground surface to the groundwater table), and is recharged as groundwater. As CFCs are not present in the crust, contamination from underground sources is not relevant. In other words, the concentration of CFCs in groundwater reflects the atmospheric concentration of CFCs during recharge. Therefore, the age at which the spring water was recharged can be deduced by comparing the CFC concentration of spring water with the historical atmospheric CFC concentrations (Asai and Tsujimura 2010).

5.2 Tritium

Tritium has also been used for estimating the recharge age of groundwater (Szabo 1996). Such estimates are based on the half-life of tritium (12.4 years) and on the variations in tritium concentrations resulting from hydrogen bomb experiments conducted during 1950s and 1960s. The baseline tritium concentration in precipitation during the first hydrogen bomb tests was 5.0 TU. The concentration of tritium in groundwater decreases over time given its 24-year half-life. It is reported that tritium concentration of groundwater decreased to 2.5 TU in 1964, 1.8 TU in 1976, 1.1 TU in 1988 TU, 0.6 TU in 2000, 0.3 TU in 2012, and 0.1 TU in 2016. Therefore, if the tritium concentration of groundwater sampled in 2016 is higher than 0.1 TU, we can consider that the groundwater was recharged after 1952 due to the large quantities of tritium released when hydrogen bomb tests were conducted. On the other hand, if the value is lower than 0.1 TU, it can be deduced that the water was recharged before 1952. The tritium concentration in African precipitation at the peak of hydrogen bomb testing (1952–1970) was 10–1,000 TU (IAEA 2016). As the concentration of tritium in the spring water sampled in the present study were lower than 10–1,000 TU, it is likely that the water recharge occurred prior to 1952.

6 Age of Spring Water at the Foot of Mount Kenya

Tritium concentration in the spring water of Mount Kenya was found to be 0.3 TU. After the peak nuclear testing period, the tritium concentration in the precipitation of Africa ranged from 10 to 1,000 TU, and in Kenya the concentration was 10–90

TU in 1968. If tritium concentration was 10 TU during this period, the half-life of tritium requires that its concentration should be 0.6 in 2016. As the concentration measured in the present study was 0.3 TU, the spring water at the base of Mount Kenya can be considered as groundwater that was recharged before 1950.

Three kinds of CFCs were detected in the spring water. The concentration of CFCs in spring water was converted to its atmospheric concentration during recharge, and compared with the historical atmospheric CFC concentrations in the Northern Hemisphere. The residence time was thereby estimated to be approximately 40 years. The difference in residence time, estimated by plotting tritium vs. CFCs concentrations, might be due to the fact that the analytical sensitivity of CFCs is higher than that of tritium. Thus, trace contamination of young groundwater during the runoff process might have decreased the estimated residence time. The results show that spring water at the base of Mount Kenya has a recharge age of at least 40 years.

7 Conclusion

The present study confirmed the existence of large ice bodies beneath the layers of debris at downstream of the glacier. We measured the contribution of such icy bodies to the processes of water cycle using isotope analyses. Previous studies on the aquatic environment in the African alpine region are remarkably scant compared to the other regions. The results of this research are expected to make a significant contribution to the understanding of the volcanic hydrology in Africa. Future research should investigate large-scale agricultural regions in the eastern and southern parts of Mount Kenya to comprehensively understand the processes involved in water cycle in the region, and its effect on the region’s inhabitants.

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