Evaluation of the groundwater recharge process in a semiarid region of Tanzania, using $\delta$D and $\delta^{18}$O

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Abstract  The recharge mechanism of confined groundwater in Makutapora Basin, central Tanzania, was evaluated using the stable isotopes of hydrogen and oxygen in natural waters of this basin. The relationship between $\delta$D and Cl$^-$ implied that the groundwater recharge area was restricted to a part of the hillslopes, rivers and uplands underlain by fractured bedrock, and that groundwater recharge was rapid without effective evaporation. Moreover, the isotopic ratios of confined groundwater were lower than the weighted mean $\delta$D and $\delta^{18}$O values of local rainfall. This difference and the negative correlation between the amount of rainfall and stable isotopic ratios in the rainwater suggest that rainwater with low isotopic ratios from heavy rainfalls infiltrated more rapidly and preferentially than rainwater with high ratios from small rainfalls. This was observed in situ and was also interpreted from fingering mechanisms.

INTRODUCTION

Many studies have been conducted to estimate the value of natural groundwater recharge using various hydrological or tracer methods (Sharma, 1988, etc.), as groundwater is obviously a source of water for municipal use in semiarid zones. The confined groundwater in Makutapora Basin provides the water source for Dodoma City, the capital city of Tanzania (Fig. 1). In order to estimate the groundwater recharge, Shindo et al. (1990, 1994) and Hayashi & Chiba (1994) conducted general hydrological and environmental isotopic research of the area. Their results were summarized as follows: (a) the pressure head fluctuations at the various sites indicated that the possible area of groundwater
recharge was restricted to uplands and hillslopes covered with permeable greyish sandy soil; (b) the stream discharge at the weir in Madihi River and at the weir of Meia Meia in Little Kinyasungwe River implied groundwater recharge from the source area and the rivers; (c) most of the shallow groundwater or lakes had higher isotopic ratios than confined groundwater; and (d) both the isotopic ratios and chloride concentrations of confined groundwaters indicated two groundwater flows: one is the confined groundwater which originated in the northern hills, while the other is a mixture of this and the recharge water from the surrounding upland.

Onodera (1993) also indicated the rapid recharge process to shallow groundwater (2.5 m deep) in the Makutapora Basin using the tracer method and hydrological observations. However, the recharge process of shallow groundwater into confined groundwater through the fractures of the basement rocks was not made clear because of the few boreholes in the recharge area and insufficient hydrological research. The tracer method permits a relatively inexpensive characterization of hydrological processes (Sklash & Mwangi, 1991). In order to evaluate the recharge process of confined groundwater in this basin, it is necessary to associate the rapid recharge process in the soil layer (a thickness of around 2.5 m) with the recharge process of confined groundwater using the

**Fig. 1** Location of study area and sampling points. Contour interval is 30.48 m.
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... tracer method.

The objective of this research is to determine the isotopic compositions of natural waters, to confirm the rapid recharge process in the soil layer (2.5 m deep) and to evaluate the recharge process of confined groundwater using stable isotopes.

THE STUDY AREA

The study area is located in Makutapora Basin, 25 km north of Dodoma, Tanzania (Fig. 1). This basin mainly consists of four topographic units: hills, uplands, lowlands and swamps, with elevations of around 1200-2000, 1100-1150, 1090-1150 and 1060 m a.m.s.l., respectively. The Chenene Hills lie in the northeastern margin and constitute the source area of the Little Kinyasungwe River. Makutapora Swamp occupies the central part of the basin. Uplands surround Makutapora Swamp. The basement mainly consists of Precambrian granitic rocks. A thin soil layer covers the basement, except for a thick sediment layer on the swamps and lowlands. The soils covering the extensive area of uplands and hillslopes consist of greyish sand and silt, with a saturated hydraulic conductivity of around $10^{-3}$ cm s$^{-1}$, whereas the soil covering the lowlands and swamps consists of dark greyish silt or clay with a saturated hydraulic conductivity of $10^{-4}$ to $10^{-6}$ cm s$^{-1}$. The basement is faulted in a complex manner. The confined groundwater exists mainly in the weathered or fissure zone of basement rocks, and it is sealed by the clay layer.

The area has a tropical semiarid climate. Most of the annual rainfall, about 600 mm, occurs during the rainy season from December to April. The distributions of annual rainfall in the basin were measured at 10 stations by Shindo et al., (1994), and indicated that the rainfall at Chenene, on the northern hillside, was 1.5-2.6 times that at Makutapora in the centre of the basin. The potential evaporation is about 2500 mm.

METHODS

One hundred and twenty-three natural water samples were collected. They consisted of rainwater, soil water, river water, lake water, shallow groundwater (dug wells) and deep confined groundwater (boreholes) (as shown in Fig. 1). Chloride concentrations were analysed by ion chromatography and the isotopic ratios of hydrogen and oxygen analysed by stable isotope mass spectrometry. The isotopic results were reported in the conventional $\delta$ notation relative to V-SMOW. The analytical accuracies are $\pm 1.5'$ for $\delta D$ and $\pm 0.1'$ for $\delta^{18}O$.

Rainwater and soil water, in particular, were collected intensively from December to April 1991. A raingauge and rainwater collector were installed to sample water from every rainfall event at the meteoric station (Site M, 1080 m a.m.s.l.), located on the western side of Makutapora Swamp and rainwater collectors in which evaporation was prevented by liquid paraffin were installed to sample water at Chenene (1310 m a.m.s.l.), Mkondai (1200 m) and Meia Meia (1130 m). Rainfall was sampled once every two months. Tensiometers and soil water collectors were installed respectively at 20, 40, 60, 80, 100, 150, 190 and 225 cm and 50, 100, 150 and 220 cm below the land surface at the experimental site (Site U, 1110 m a.m.s.l.). Site U is on the upland in the western side of Makutapora Swamp.
RESULTS

Stable isotope compositions

Figure 2 shows the relationship between δD and δ18O in the water samples. The local meteoric water line based on the isotopic composition of rainfall at Site M is given by: 
\[ \delta D = 7.8 \delta^{18}O + 16.6. \]
The annual weighted average of \( \delta D \) and \( \delta^{18}O \) for the 1991 rainfall were \(-19.3\) and \(-4.29\)%o, respectively. Figure 3 shows the relationship between the rainfall amount and \( \delta^{18}O \). Rainfall amount and its \( \delta^{18}O \) indicates a negative correlation. This has been called the amount effect by previous researchers (Yurtsever & Araguas Araguas, 1993, etc.). However, the altitude effect, the relationship between the isotopic ratio of rainwater and the altitude (1080 m to 1310 m) was not recognizable.

The isotopic compositions of the confined groundwaters fell on the meteoric line in Fig. 2 and they were lower than those of shallow groundwater, lakes and ponds. The \( \delta^{18}O \) values of the confined groundwaters from the area from Chenene Hills to the eastern part of Makutapora Swamp were lower than \(-5.5\)%o and were lower than those of the confined groundwater on the western part of Makutapora Swamp and southern part of the basin. The isotopic compositions of the confined groundwaters from the eastern part of the swamp were similar to those of the soil water.

Seasonal variation in \( \delta^{18}O \) of rainwater and soil water

Figure 4(b) shows the seasonal variation in \( \delta^{18}O \) of rainfall in 1991. The result in 1991 did not clearly indicate seasonal isotopic variations. In the rainy season of 1991, the variation in \( \delta^{18}O \) may have resulted from the variation in the rainfall amount.
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Figure 4(c) shows the seasonal variation in $\delta^{18}O$ of soil water at a depth of 220 cm and Fig. 4(d) shows pressure heads at depths of 20, 100 and 225 cm. Pressure heads at all depths did not increase to the wet condition with the rainfall events of less than 10 mm in December 1990, but increased from the very dry condition to the wet condition, close to 0, on 7 January 1991. $\delta^{18}O$ of soil water was about $-6.0\%$ from 27 January to 19 February and $-3.4\%$ on 25 February 1991. $\delta^{18}O$ of rainwater on 7 January 1991 was $-5.1\%$, lowest of the rainfall events from 1 December to 27 January 1991. As the isotopic ratios were considered to be higher due to enrichment of heavy isotopes in the preceding dry season, the soil water with the low isotopic ratios at 220 cm must have been recharged by the isotopically lowest rainwater on 7 January, before 27 January 1991. Onodera (1993) observed the wetting front movement using borings at many positions and indicated that the rapid transport of tracer was caused by fingerling at the heavy rainfall event. In contrast to the heavy rainfall, rainwater from the small rainfall events stopped moving at the surface soil and was evaporated.

Relationship between $\text{Cl}^-$ and $\delta D$

In order to clarify the area of recharge to confined groundwater, the continuity of the isotopic and chemical compositions of the water during the water cycle has to be considered. Figure 5 shows the relationship between $\text{Cl}^-$ and $\delta D$. The weighted means of $\text{Cl}^-$ and $\delta D$ for rainfall were 2.0 mg l$^{-1}$ and $-19.3\%$, respectively. Both the chloride ion concentration and delta deuterium increase with evaporative enrichment (Sklash & Mwangi, 1991). The $\text{Cl}^-$ and $\delta D$ of lake water were higher than those of rainwater and some of the shallow groundwater values fell between rainwater and lake water. If rainwater recharges to groundwater without evaporation, the $\delta D$ would keep the same value as rainwater. However, though the $\text{Cl}^-$ of confined groundwater was higher than the
value of rainwater, $\delta^D$ of groundwater was about $-25\%$ which was lower than the value of rainwater. The chloride concentration suggests that the recharge process was accompanied by evaporative concentration and dissolution of Cl-bearing minerals in the rock and soil, whereas $\delta^D$ suggests a recharge process without evaporation. The results suggested a rapid groundwater recharge process with the dissolution of the accumulated salts on the surface layer and of Cl-bearing minerals. The Cl$^-$ and $\delta^D$ of the river water during the rainfall event with a low isotopic ratio at Madihi River and Little Kinyasungwe River and shallow groundwater at Mbalawara and Site U on the upland and at Mtungutu on the hillslope were lower than the values of confined groundwater. These areas can be characterized by the bedrock of faulted blocks with a thin permeable soil layer and were inferred as the possible recharge areas.

Shindo et al. (1990; 1994) have suggested that the possible recharge areas were uplands and hillslopes covered by permeable greyish sandy soil and the rivers. Moreover, the present results constrained the recharge areas for confined groundwater.

**DISCUSSION**

Both stable isotopic compositions and chloride concentrations of confined groundwater

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**Fig. 4** (a) Variations in rainfall at Site M; (b) $\delta^{18}O$ of rainwater at Site M; (c) $\delta^{18}O$ of soil waters at 220 cm deep below the ground surface of Site U from December to March 1991; and (d) pressure heads at 20, 100 and 225 cm deep at Site U.
suggested a rapid groundwater recharge process, as compared to most of the shallow groundwater. Moreover, the average δD (−25‰) of confined groundwater in the western part of Makutapora Swamp was lower than the weighted mean δD (−20‰) of rainfall. Three possible reasons can be considered for this fact: a dominant contribution of palaeo-water in the pluvial period, lateral inflow of confined groundwater with lower isotopic ratios, or preferential recharge by rainwater with lower isotopic ratios. As the palaeo-waters are often characterized by relatively low deuterium excess values (Yurtsever & Araguas Araguas, 1993), the palaeo-water may plot away from the local meteoric line. However, confined groundwaters plot on the local meteoric line. Therefore, the first of these reasons is unlikely. Because there is no clear altitudinal distribution of the isotopic ratios of rainwater, the spatial distribution of isotopic ratios of confined groundwater must be defined by a mechanism other than the altitude effect on isotopic ratios of rainfall.

A recharge process was proposed as follows, considering the second and third reasons and the results of hydrological observations: rainwater with a low isotopic ratio from heavy rainfall events infiltrates rapidly, whereas little rainwater with a high ratio from smaller rainfalls contributes to confined groundwater. The amount of rainfall at Chenene was 2.6 times that at Makutapora. In particular, the frequency of rainfall events of more than 50 mm day⁻¹ at Chenene was obviously greater than that at Makutapora. If rainwater from a heavy event preferentially recharges, rainwater with a low isotopic ratio would contribute more to groundwater in the area around Chenene than in the area around Makutapora.

The rapid recharge in the soil layer (the thickness of 2.5 m) was observed in situ to be caused by fingering (Onodera, 1993). Mechanisms of finger flow have been confirmed in a dry sand column by many studies (Grass et al., 1989, etc.). Grass et al. (1989) defined the flux \( q_f \) of a finger using the Darcy equation as \( q_f = K_z[1 - (\psi_b - \psi_f)/L_z] \) and showed the hydraulic gradient as \( 1 - (\psi_b - \psi_f)/L_z \). In the equation, \( K_z \) is the
saturated hydraulic conductivity, $\psi_b$ is the pressure head at the wetting front and equals the water entry value, $\psi_{we}$, $\psi_t$ is the pressure head at the ground surface and $L_s$ is the length of the saturated area. If $\psi_t$ is the positive value under ponded infiltration and equals the ponded depth, then $\psi_t$ becomes the air entry value, $\psi_{ae}$, under the redistribution process of infiltrated water after rainfall. Based on the equation, it is deduced that when $L_s$ approaches $\psi_{we} - \psi_{ae}$, the hydraulic gradient becomes zero and fingers will stop moving. If it is assumed that $\psi_t$ becomes $\psi_{ae}$ at the end of the rainfall and the wetting zone is the saturated condition ($\theta_s$), the critical rainfall amount ($R_{cr}$), at which significant percolation for groundwater recharge originates, is defined as $(\psi_{we} - \psi_{ae})\theta_s$.

However, it was difficult to determine $\psi_{we}$ and $\psi_{ae}$ simply in the field because of problems concerning the sample scale and various antecedent soil water conditions. Therefore, based on the relationship between the change ratio (cm H$_2$O day$^{-1}$) in the pressure head at a depth of 225 cm and the rainfall amount, the critical rainfall amount was estimated. The increment of the pressure head at a depth of 225 cm after a rainfall event suggests a contribution of the rainwater to a depth of 225 cm. The change ratio was defined as the change in pressure heads for a day. It was approximately zero for rainfall of less than 10 mm, whereas it increased at rainfalls more than about 10 mm. The relationship implied that the critical rainfall was about 10 mm.

From the above results, it can be assumed that any rainfall of less than 10 mm would be almost completely evaporated and the weighted mean $\delta D$ and $\delta^{18}O$ of rainfall of more than 10 mm were estimated to be $-23$ and $-4.4\%$, respectively. The values were close to the average value of confined groundwater in the western part of the Makutapora Swamp. Therefore, these results suggest the rapid and preferential recharge from rainwater during a heavy rainfall event.

**CONCLUSION**

The recharge mechanism for confined groundwater in the Makutapora Basin, central Tanzania, was evaluated using $\delta D$ and $\delta^{18}O$ in natural waters as follows:

(a) The relationship between Cl$^-$ and $\delta D$ implied that the groundwater recharge was restricted to a part of hillslopes, rivers and uplands underlain by fractured bedrock. Groundwater recharge was rapid without effective evaporation.

(b) In confined groundwater, the average $\delta D$ was lower than the weighted mean rainfall $\delta D$, the isotopic composition fell on the local meteoric water line and the spatial distribution of isotopic ratios was clear in spite of the indistinct altitudinal distribution of values of rainwater. These results suggested a preferential recharge process.

(c) Based on the results of hydrological observations and the negative relation between the rainfall amount and stable isotopic ratios of rainwater, a recharge process was suggested where rainwater with a low isotopic ratio from heavy rainfall events infiltrated rapidly and preferentially, whereas rainwater with a high isotopic ratio from small rainfall events was evaporated.

(e) The spatial distribution of rainfall amounts in the basin caused the spatial distribution of the isotopic ratios of confined groundwater by a rapid and preferential recharge process in areas of heavy rainfall.

(f) The critical rainfall deduced from the equation for finger flux was estimated to be about 10 mm. The weighted mean isotopic ratios of rainfall, except for rainfall of
less than 10 mm, were close to values of confined groundwater and this result indicated the preferential recharge.

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