NOTES AND CORRESPONDENCE

Behavior of Subsurface Water Revealed by Stable Isotope and Tensiometric Observation in the Tibetan Plateau

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Abstract

Intensive observation of the pressure head in subsurface water and sampling of subsurface water were performed to investigate the subsurface flow process in the Tibetan plateau from July 24 to September 12 the monsoon season-1998. Pressure head of the subsurface water was monitored using tensiometers and subsurface water was sampled using suction lysimeters installed at multiple depths from 10 to 100 cm. The pressure head of subsurface water ranged from $-10$ to $-100$ cmH$_2$O, and zero flux plane was often observed above the depth of 30 cm. The groundwater recharge was very active during this period, thus the groundwater table rose up to the depth of 55 cm in the beginning of September. The $\delta^{18}$O of
shallow subsurface water varied markedly with precipitation and evaporation, whereas those of groundwater were stable. The mean $\delta^{18}O$ of groundwater was 3.4% higher than the volume weighted mean $\delta^{18}O$ of precipitation. The difference of $\delta^{18}O$ between the groundwater and the precipitation would be caused by isotopic enrichment along with evaporation from the soil surface, and 27% of precipitation might be lost by evaporation from the soil surface.

1. Introduction

The environmental isotopes such as deuterium (D) and oxygen-18 ($^{18}O$) in precipitation, surface and subsurface waters are one of the excellent tools for elucidating the hydrological cycle in the terrestrial environment. This is due to the advantage of stable isotopes that they behave in the same way as water, and that the stable isotopic composition of water change along with the hydrological processes such as evaporation and the mixing of different waters. Especially, the stable isotope data of precipitation have been accumulated (Tian et al. 1996; 1997; Numaguti et al. 1999), and the moisture source of precipitation and the circulation process of vapor have been estimated using the isotopic data and water circulation model in the Tibetan plateau. However, the water cycle process cannot be well understood using only the isotopic data of precipitation, because the isotopic interaction between subsurface water and atmosphere is important to consider the isotopic variation process of water near the soil surface. In addition, the effect of the subsurface moisture condition in the Tibetan plateau on the Asian summer monsoon has been pointed out, and the spatial and temporal variation of land surface moisture and heat conditions has been described (Yabuki et al. 1998a; 1998b; Koike et al. 1999). Therefore, the stable isotopic composition in the subsurface water should be also considered for analysis of isotopic data of precipitation. However, information on the stable isotopes of D and $^{18}O$ of subsurface water is not enough previously in the Tibetan plateau, and also in other regions (e.g., Liu et al. 1995; Tsujimura and Tanaka 1998). Moreover, the relationship between the subsurface flow process and stable isotopic composition of subsurface water should be clarified, because it is the key for understanding the hydrological process near the soil surface. The objectives of this study are to make clear the behavior of subsurface water along with groundwater recharge and evapotranspiration processes, to clarify the temporal variation of stable isotopic ratio of subsurface water, and to consider the distillation process using stable isotopic data in subsurface water.

2. Study area and methods

Intensive observation and sampling of subsurface water was performed at Naqu flux station (31°22' 10"N, 91°53'59"E), approximately 20 km southwest of central Naqu mainly from July 24th to September 12th, 1998 (during GAME/Tibet IOP 98). This period corresponded to the summer monsoon season in the Tibetan plateau. The site is in the open and flat plane, central Tibetan plateau, covered by short grass with the height of approximately 2 to 3 cm, and the altitude is 4496 m above sea level. There is a small hill with a relief of 150 m and angle of approximately 5 degrees in 3 km north of the observation site. Except for the north direction, the soil surface is almost flat in approximately 8 km around of the site.

The tensiometers with mercury manometers were installed at the depths of 10, 30, 50, 70, and 100 cm to observe the change of pressure head of subsurface water. The height of mercury in the manometer was measured manually two to four times a day. Also, the suction lysimeters were installed at the depths of 10, 20, 30, 50, 70, and 100 cm to sample subsurface water. The suction lysimeter consists of a porous cup with a diameter of 17 mm, a glass-collecting bottle with a volume of 50 ml and a connecting tube with a diameter of 2 mm. To extract the subsurface water, a small hand pump was connected to the device and a 30 to 40 kPa suction was applied to the bottle and tube. Subsurface water extracted through the porous cup was collected in the bottle via the tube, and the water with a volume of approximately a few to more than 50 ml was taken by applying this method for one day. The subsurface water sampling was performed manually everyday. Additionally, the soil was sampled manually using a hand auger with a diameter of 21 mm. A small hole was dug by the auger down to the depth of 100 cm, and the soil sample with a weight of 50 to 90 g was taken at the depths of 10, 20, 30, 50, 70, 100 cm every day. The soil sample was preserved in a glass bottle with a volume of 50
ml and taken back to Japan, and the solution was extracted by the vacuum distillation method at the Center for Ecological Research, Kyoto University. The daily precipitation water was sampled using a funnel with a diameter of 20 cm.

Evaporation rate from the water surface was observed using a pan with a diameter of 22 cm. The weight of the pan including water was measured using an electronic balance and the water within the pan was sampled everyday.

The stable isotopic compositions of D and 18O were determined on the water samples using a mass spectrometer (Finnigan Mat, Inc., MAT 252) at the Center for Ecological Research, Kyoto University. The isotopic ratios, D/H and 18O/16O of water are expressed in terms of per mil deviation from that of the Standard Mean Ocean Water (SMOW), which is defined as,

$$\delta = (R_{\text{sample}} - R_{\text{SMOW}}) \times 1000/R_{\text{SMOW}},$$

where $R$ is the isotopic ratio of D/H or 18O/16O.

3. Results and discussion

3.1 Temporal variation of pressure head in subsurface water

Figure 1 shows the temporal change of pressure head of subsurface water and daily precipitation.
head (daily mean) of subsurface water at the depth of 10 to 100 cm and daily precipitation from July 24 to September 12. The pressure head at 10 to 50 cm depth increased and decreased along with rainfall, which means that the pressure head of the subsurface water above the depth of 50 cm was very responsive to rainfall infiltration and evapotranspiration. On the other hand, the pressure head at the 70 and 100 cm depths increased gradually and reached the maximum value in the beginning of September. After August 2 and August 26, the pressure head at 100 and 70 cm depths became the positive value, respectively. This shows the soil matrix of 70 and 100 cm depths became saturated after that time.

The vertical profiles of the pressure head and hydraulic head of subsurface water from August 2 to September 13 are shown in Fig. 2. The pressure head at all depths showed the value above -50 cm H₂O, which means the soil moisture condition was relatively humid throughout the soil profile in this season. At the beginning of August, the depth of the groundwater table was approximately 100 cm, however, the water table rose up to the depth of 55 cm on September 1. This shows that the groundwater recharge was very active from July to August.

For the hydraulic head profiles, the hydraulic gradient was relatively large (the value of hydraulic gradient was 0.5 to 1.0) throughout the soil profile and the groundwater recharge should have occurred actively in August, because the vertical percolation component was predominant. The soil surface is almost flat in the observation site, as mentioned previously. Therefore, the lateral hydraulic gradient would be much smaller as compared with the vertical one, and the rising of groundwater table (depth of 1 m to 55 cm) might be caused mainly by the precipitation infiltrated on the observation site. The hydraulic gradient below the depth of groundwater table (see Sep. 1 profile) was very small (the gradient value was almost zero). This suggests that the vertical flow component of groundwater was very small in the beginning of September, and it was probable that the lateral subsurface flow component was large.

Also, the zero flux plane was observed frequently during the rainless period at the depth of 30 cm. This means the upward soil water flux occurred from the 30 cm depth to the soil surface along with the evapotranspiration, and the subsurface water above the depth of 30 cm should be affected by evaporation from the soil surface. The evapotranspiration would occur most actively during
the monsoon season. Therefore, the deepest depth where the zero flux plane exists should be approximately 30 cm in the observation site. This means that the boundary depth where the evapotranspiration has an effect on the soil moisture is 30 cm in this site. This critical value of 30 cm would be important to discuss on the heat and water flux near the soil surface.

3.2 Stable isotopic compositions of rain and subsurface waters

The relationship between $\delta^{18}$O and $\delta D$ in precipitation and subsurface water is shown as $\delta$-diagram in Fig. 3. All data in subsurface water distributes along the local meteoric water line with a gradient of approximately 8. This means that the subsurface water was recharged mainly by precipitation, and that the hydrological process occurring at this site can be treated theoretically in terms of fractional distillation or condensation under equilibrium conditions and hence can be expressed by a Rayleigh (1896) equation.

The vertical profiles of $\delta^{18}$O in subsurface water from August 2 to August 21 are shown in Fig. 4. The $\delta^{18}$O value of 100 cm depth was very stable, and temporal variation was small as compared with that at the depth of 10 to 70 cm. This trend has been reported in some areas such as the semi-arid region in Arizona (Liu et al. 1995) and the warm humid region (Tsujimura and Tanaka 1998). This suggests that an isotopic homogenization might occur from the soil surface to the groundwater table. Tsujimura and Tanaka (1998) showed that frequent appearance and disappearance of a zero flux plane would cause stable isotopic homogenization in subsurface water, because the infiltrated water along with the rainfall should mix with the stored soil water at the depth of convergent zero flux plane. Also, Liu et al. (1995) showed that active movement of soil water in the top 60 to 80 cm zone tends to produce a consistent stable isotope composition in the soil water. As mentioned previously, the zero flux plane was observed frequently at the depth of 30 cm in the observation site during the rainless period, therefore the stable isotopic homogenization should be caused by the soil water movement around the depth of zero flux plane. It is worth noting that the similar phenomena occurred to the subsurface isotopic process in semi-arid, warm humid and Tibet regions. It is probable that a stable isotopic homogenization of soil water might occur commonly in the regions where the soil water moves actively in the top soil zone. On the other hand, the $\delta^{18}$O above the depth of 70 cm varied more than that at the depth of 100 cm. Especially, it should be notable that the $\delta^{18}$O at the depths of 50 and 70 cm on Aug. 9 was much smaller than that of Aug. 8, whereas the $\delta^{18}$O above the depth of 30 cm was the same between these two days. It is probable that this might be caused by the percolation of low $\delta^{18}$O soil water at the shallow depths observed on Aug. 2. However this cannot explain

![Fig. 3. Relationship between $\delta D$ and $\delta^{18}$O in precipitation and subsurface water. (LMWL: Local Meteoric Water Line)](image)

![Fig. 4. Vertical profile of $\delta^{18}$O in the subsurface water.](image)
Table 1. Mean or weighted mean $\delta^{18}$O in precipitation and subsurface water.

<table>
<thead>
<tr>
<th></th>
<th>Mean or weighted mean</th>
<th>Number of data</th>
<th>Standard deviation</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>-17.7</td>
<td>55</td>
<td>7.29</td>
<td>Jun.5 to Sep.9</td>
</tr>
<tr>
<td>Subsurface water</td>
<td>-14.3</td>
<td>25</td>
<td>0.62</td>
<td>Aug.2 to Aug.21</td>
</tr>
</tbody>
</table>

the $\delta^{18}$O profile on Aug. 8. The formation process of $\delta^{18}$O profile in soil water should be considered more with much data in the future.

Table 1 shows the volume weighted mean $\delta^{18}$O of precipitation (June 5 to Sep. 9) and the mean $\delta^{18}$O of subsurface water taken from the depth of 100 cm (Aug. 2 to Aug. 21). If only the vertical component of soil water percolation is predominant, the groundwater might be recharged by the precipitation fallen on that site. As mentioned previously, in August the vertical hydraulic gradient was 0.5 to 1.0. The lateral hydraulic gradient of groundwater might be much smaller than the vertical one, because the angle of soil surface is almost zero in the observation site. Therefore, the vertical subsurface flow component would be predominantly in August. The value of subsurface water at 100 cm depth would correspond to that of groundwater, because the soil was saturated by water at the depth of 100 cm in August as shown in Fig. 2. The mean $\delta^{18}$O of groundwater is 3.4 $\%$ higher than that of precipitation. If the groundwater was recharged by the precipitation that fell from June to September, the mean $\delta^{18}$O of groundwater should agree with that of precipitation. Considering the behavior of subsurface water, the groundwater table rose up more than 50 cm during the observation period as shown in Figs. 2 and 3, the groundwater may be recharged mainly by precipitation that fell during this monsoon season. Therefore, the isotopic enrichment process may occur from infiltration to groundwater recharge. As mentioned previously, the soil water above the depth of 30 cm would be affected by evapotranspiration during the rainy season, because the zero flux plane was often observed at the depth of 30 cm. Thus, the distillation of subsurface water could be caused along with the evaporation process from the soil surface under the assumption of predominance of vertical percolation component through the soil layer.

For the distillation process, the isotopic ratios ($R$) of initial water and remaining water are given by,

$$ R_{ir}/R_{ii} = f_1^{(1/\alpha - 1)}, $$

(2)

where $f_1$ is the fraction of remaining water, the suffixes $ir$ and $li$ represent remaining water and initial water, respectively, and $\alpha$ is the fractionation factor to be determined by water temperature. Using the $\delta$ values as shown by the equation (1), equation (2) can be rewritten as follows,

$$ \delta_{ir} - \delta_{li} = 10^\delta (1/\alpha - 1) \ln f_1. $$

(3)

Given a value of -14.3 $\%$ for $\delta_{ir}$, representing the mean $\delta^{18}$O in groundwater, a value of -17.7 $\%$ for $\delta_{li}$, representing the volume weighted mean $\delta^{18}$O in precipitation, then the equation (3) yields a value of 0.73. Consequently, it can be reasonably stated that 27% of precipitation was distilled during the process from infiltration to groundwater recharge. From the evaporation-pan experiment, about 60% of precipitation was evaporated from the water surface. Kaneko (1973) presented that the ratio of actual evapotranspiration to pan-evaporation ranges from 0.5 to 0.8 in the area except for paddy fields. It would be appropriate to consider the distillation rate of 27% might be caused by mainly evaporation from the soil surface, though we have few validation data. It is possible that the evaporation rate could be estimated using subsurface isotopic data with more long term data. However, more detail analysis using comparative data such as flux and volumetric water content in soil moisture is needed in the future.

4. Concluding remarks

The subsurface flow processes were investigated by stable isotope and tensiometric observation in the flat plane, central area, Tibetan plateau, from July to September, which is monsoon season, 1998. The results are summarized as follows:

1) Zero flux plane was often observed at the depth of 30 cm during the rainy periods. This
shows that upward soil water flux often appeared above the depth of 30 cm along with evapotranspiration. On the other hand, the vertical downward soil water movement was predominant below the 30 cm in July to August.

2) Groundwater table rose up to the depth of 55 cm in August. This shows that active groundwater recharge occurred during the observation period.

3) The stable isotopic ratios of D and $^{18}$O in subsurface water were distributed along the local meteoric water line in the $\delta$-diagram. This suggests that the hydrological process occurring at this site can be treated theoretically in terms of fractional distillation or condensation under equilibrium conditions.

4) The isotopic ratios of D and $^{18}$O in subsurface water were homogenized and very stable at the depth of 100 cm. The isotopic homogenization would be caused by the frequent emerging of zero flux plane during the rainless periods. It would be common that the isotopic homogenization occurs in the regions where the soil water movement is active in the top soil.

5) Mean $\delta^{18}$O of groundwater was 3.4 % higher than the volume weighted mean $\delta^{18}$O of precipitation. This suggests that 27% of the precipitation that fell from June to September might be evaporated from the soil surface during the monsoon season.

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References


