Journal of Hydrology (2007) 333, 47–57

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Stable isotopic and geochemical characteristics of groundwater in Kherlen River basin, a semi-arid region in eastern Mongolia

Maki Tsujimura [a,*], Yutaka Abe [b], Tadashi Tanaka [c], Jun Shimada [c], Satoru Higuchi [d], Tsutomu Yamanaka [a], Gombo Davaa [e], Dambaravjaa Oyunbaatar [e]

[a] *Graduate School of Life and Environmental Sciences, Laboratory of Advanced Research A, University of Tsukuba, 1-1-1 Ten-nodai, Tsukuba, Ibaraki 305-8572, Japan*
[b] *Metocean Environment Inc., Japan*
[c] *Faculty of Natural Science, Kumamoto University, Japan*
[d] *Nissaku Co., Ltd., Japan*
[e] *Division of Hydrology, Institute of Meteorology and Hydrology, Mongolia*

Received 24 October 2005; received in revised form 31 March 2006; accepted 24 July 2006

KEYWORDS
Groundwater;
Stable isotope;
Semi-arid;
Recharge;
Mongolia

Summary Inorganic solute ion concentrations and stable isotopes of oxygen and hydrogen in groundwater, river water and precipitation were investigated to gain insight into the groundwater recharge process in the Kherlen River basin, a semi-arid region in eastern Mongolia. The solute constituents in the river water (main stream) were of Ca–HCO_3 type, spatially invariant and low in concentration. Groundwater in the upstream region was also characterized by a Ca–HCO_3 type, though all ion concentrations were higher than in the river water. On the other hand, the chemical composition of the groundwater in the midstream region (southern and eastern) was spatially variable and the Na^+, Mg^{2+}, Cl^- and HCO_3^- concentrations were considerably higher than in the river water and upstream groundwater. The stable isotopic compositions showed an evaporation effect on the groundwater and river water, as well as an altitude effect in the precipitation and river water. Preferential recharge by relatively large rainfall events is thought to have caused the depleted isotopic ratio in the groundwater in the dry regions. The stable isotope, chemical and hydrological data suggest that the main stream water of the Kherlen River is recharged by precipitation that falls in a

* Corresponding author. Tel./fax: +81 29 853 2568.
E-mail address: mktsuji@atm.geo.tsukuba.ac.jp (M. Tsujimura).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2006.07.026

headwater region at an altitude of more than 1650 m, and that the interaction between the groundwater and river water is not dominant in the midstream and downstream regions of the river basin.

Introduction

In arid and semi-arid regions, domestic noncommercial, industrial and agricultural water uses depend largely on the amount of groundwater (Wang and Cheng, 1999). However, due to unsuitable management of water resources, several problems related to groundwater use have arisen such as extraordinary decline of the groundwater level in the High Plains, United States, the North China Plain, and the Delhi area, India (Brown and Halweil, 1998; Datta et al., 1996; Kondo et al., 2001; Rodell and Famiglietti, 2002; Tase, 2000). Sustainable control of water resources with sufficient understanding of the groundwater situation is therefore essential. In Mongolia, a semi-arid region of northeast Asia, more than 90% of the total population use groundwater for daily necessities (Sugita, 2003). Moreover, no management of the water resources has been carried out since destatization was established in 1990. Accordingly, it is highly probable that potential problems with groundwater resources will occur. In order to develop an effective water use system, it is first necessary to scientifically understand the behavior of groundwater. However, very few studies have previously documented groundwater resources in northeast Asia (Chelmicki, 1984).

The multi tracer approach using the isotopes and solute concentrations in water has been used for elucidating the origin of groundwater and the interaction between groundwater and river water in semi-arid and arid regions. Onodera (1996) suggested that preferential and partial infiltration under conditions of high rainfall intensity is a major mechanism of groundwater recharge in a tropical semi-arid region in Tanzania. In addition, Taniguchi et al. (1995), based on stable isotope and solute concentration data, clarified that in the Heife river basin, northwestern China, the groundwater originates from a mountain region. Moreover, Kabeya et al. (2002) compared the stable isotopic compositions of the groundwater between sand dunes and grassland in the Nu Us desert, China, and concluded that the stable isotopes of the groundwater in the grassland were concentrated as a result of evapotranspiration. Understanding the effect of evaporation on stable isotopes is an important factor in discussing the relationship between precipitation and groundwater (Boronina et al., 2005), and geochemical weathering is also known to affect the chemical compositions of groundwater and river water (Sami, 1992). Previous studies suggest the importance of temporal and spatial heterogeneity in infiltration, evaporation and groundwater recharge processes in arid and semi-arid regions (De Vries and Simmers, 2002; Gee and Hillel, 1988; Vogel and Van Urk, 1975). In other words, groundwater recharge is affected by site-specific conditions in these regions.

In the Kherlen River basin, eastern Mongolia, the spatial distribution of vegetation shows a clear change along the river. Mountain forest is distributed upstream in the basin while grassland, known as steppe, without any tall trees can be seen downstream. In addition, a discontinuous permafrost zone is also observed in the upstream region (Sharkhuu, 2001). Thus, there are many factors to be considered when discussing the hydrological processes in this basin. Hirabaru et al. (1999) described the geochemical composition of the groundwater in a central area of Mongolia and warned against a worsening of groundwater quality, while Davaa et al. (2002) investigated $\delta^{18}O$ and δD in the Tuul River, which flows into Ulaanbaatar, the capital city of Mongolia, and reported seasonal changes in the groundwater recharge system. Few studies, however, have investigated the isotopic and chemical characteristics of groundwater and discussed the recharge and flow system of groundwater on a catchment scale including multiple vegetation cover. The purpose of this study is to clarify the groundwater recharge and flow system in the Kherlen River basin, eastern Mongolia, using a multi-tracer approach.

Study area

The study area was located approximately 120 km east of Ulaanbaatar, the capital city of Mongolia (Fig. 1). The altitude of the main study area ranges from 1484 m at Mongenmorit (MNG) to 985 m at Underhaan (UDH), and the total length of the main stream of the Kherlen River is approximately 300 km from MNG to UDH. Mesozoic and Paleozoic granite and Carboniferous granite are dominant from the mountainous upstream area to Kherlenbayan-Ulaan (KBU) (Mineral Resources Authority of Mongolia, 1999). From KBU to UDH, the right bank of the Kherlen River mainly consists of Mesozoic sandstone, while Cenozoic sandstone or siltstone is distributed around the Darhan (DH) region and along the river. Sharkhuu (2001) showed that the southern boundary between the discontinuous permafrost region and no-permafrost region is found around Baganuur (BGN). Conifer trees such as larch are dominant in the mountainous region, upstream of MNG, whereas the flat plain downstream of BGN is dominantly covered by grass with a height of 5—10 cm during the growing season.

As summarized by Sugita et al. (2006) (Table 1) based on data obtained by the Institute of Meteorology and Hydrology (IMH), Mongolia, from 1993 to 2003 and aridity index data (AI; Budyko, 1974), it is relatively humid in the upstream regions of the Forest Site (FOR), MNG, BGN, and KBU, but relatively dry in the midstream region of DH and UDH. The discharge rate of the Kherlen River observed by the IMH at BGN, UDH and CHB from 1990 to 2000 is shown in Fig. 2. All gauging stations observe a high flow in the summer, with a slight decrease in the discharge rate as the river flows down from BGN to CHB, though the rate of decrease is small.

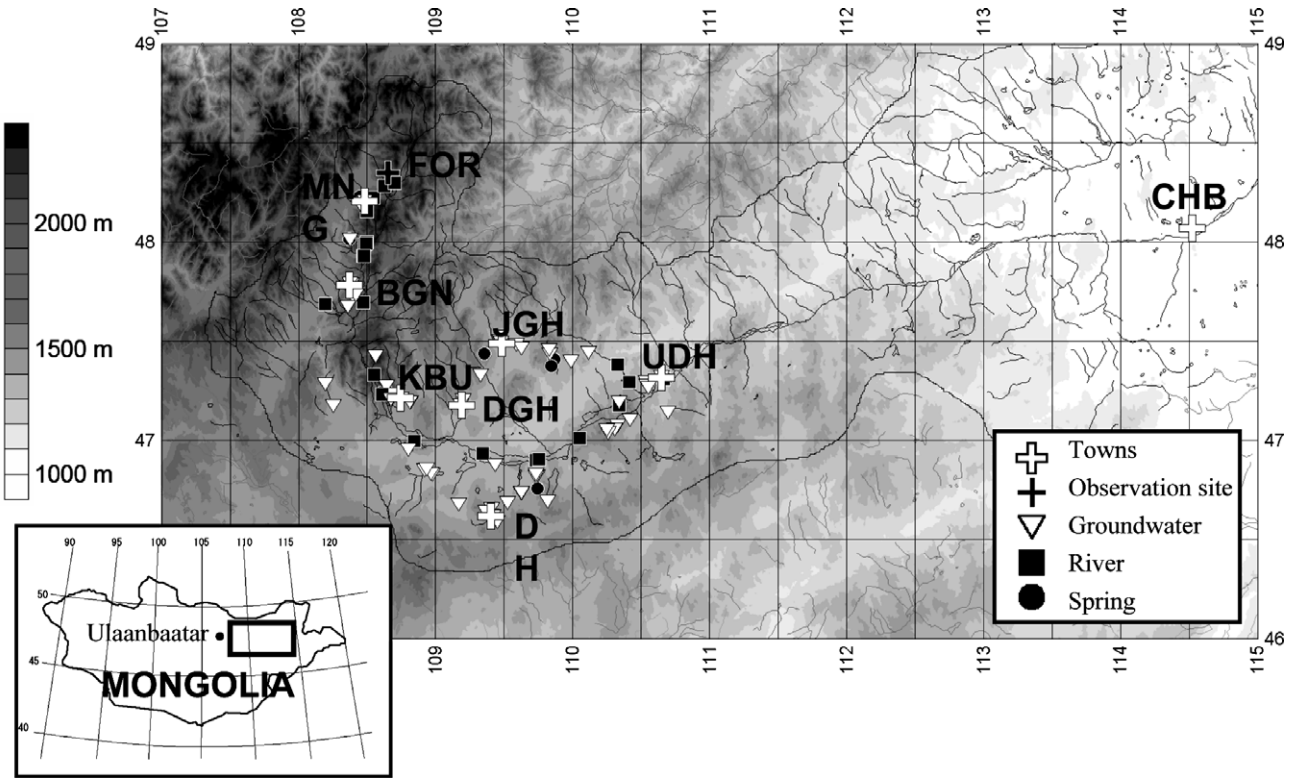

Figure 1 Location of the study area: FOR, Forest site; MNG, Mongenmorit; BGN, Baganuur; KBU, Kherlenbayan-Ulaan; DGH, Delgerhaan; JGH, Jargalthaan; DH, Darhan; UDH, Underhaan; and CHB, Choibalsan.

Methods

The field surveys and sampling of river water, groundwater and spring water were performed in the area from MNG to UDH in June 2002, and July and October 2003 as a part of the intensive field observation campaign of the RAISE project (Sugita et al., 2006). In total, 30 river water samples, seven spring water samples and 80 groundwater samples were collected to analyze the major ions and stable isotopes of deuterium (D) and oxygen 18 (^{18}O). In addition, monthly and daily precipitation were sampled separately for stable isotope analysis at MNG, KBU, and UDH from October 2002 to September 2003. Most of the groundwater samples were taken from wells with a depth of less than 10 m and set in an unconfined aquifer. Electrical conductivity (EC; HORIBA Ltd., Twin Cond B173), pH (HORIBA Ltd., Twin PH Meter B121), water temperature (Nikkyo Technos Co., Ltd., Petten Kocher), and groundwater level were measured on site. The locations of the wells were determined using a portable GPS meter (GARMIN Ltd., GPSMAP 76S). Each water sample was sealed in a polyethylene bottle with a volume of 100 mL then brought back to the laboratory in Japan where the anions, cations, and stable isotopic ratios of D and ^{18}O were analyzed. Major anions (F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-} and SO_4^{2-}) were analyzed using an ion chromatograph analyzer (Shimadzu, Co. Ltd., HIC-SP/VP Super). Bicarbonate (HCO_3^-) concentration was determined by the titration method with sulfuric acid. Major cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) were ana-

Table 1 Mean annual precipitation and aridity index (AI) (by Budyko (1974)) in the Kherlen River basin

Site ID	Annual precipitation (mm/y)	Aridity index
MNG	282	0.52
BGN	213	0.47
KBU	181	0.41
JGH	187	0.39
UDH	226	0.35
DH	216	0.35

The abbreviations are listed in Fig. 1.
The mean annual precipitation was obtained from 1993 to 2003 by IMH.The potential evaporation used for estimation of AI was calculated with Penman method (Penman, 1948) for 1988 (Sugita et al., 2006).

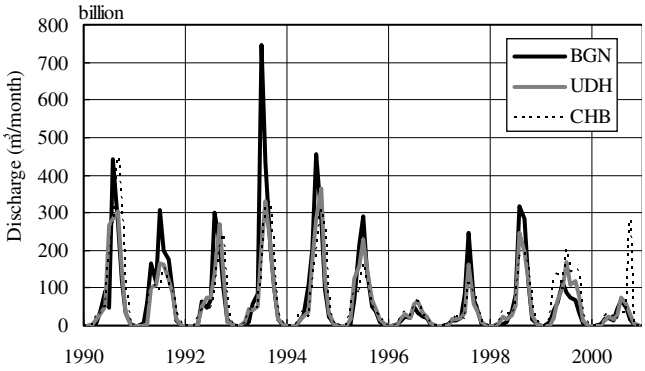

Figure 2 The monthly discharge rate of the Kherlen River at BGN, UDH and CHB gauging stations from 1990 to 2000 according to the IMH.

lyzed using an inductively coupled plasma atomic emission spectrometer (Nippon Jarrell-Ash Co., Ltd. Model ICAP-757). The stable isotopes of D and ^{18}O were measured with a mass spectrometer (Finnigan Inc., MAT 252). As pretreatment for stable isotopes analysis, water samples were equilibrated with CO_2 gas for ^{18}O and H_2 gas with a platinum catalyst for D. The isotopic ratios of D and ^{18}O are expressed by δD and $\delta^{18}O$, respectively, as follows:

$$\delta_{sample} = \frac{R_{sample} - R_{SMOW}}{R_{SMOW}} \times 1000 \ (‰) \quad (1)$$

where R is the ratio of D/H or $^{18}O/^{16}O$ in the sampled water (R_{sample}) or in Standard Mean Ocean Water, SMOW (R_{SMOW}). The analytical errors were 0.1‰ for $\delta^{18}O$ and 1‰ for δD, respectively.

Results and discussion

Stable isotopes

Fig. 3 presents the relationship between δD and $\delta^{18}O$ in precipitation sampled monthly from October 2002 to September 2003 at MNG, KBU and UDH. The slope of the Local Meteoric Water Line (LMWL) was similar to that of the Global Meteoric Water Line (GMWL: $\delta D = 8\delta^{18}O + 10$):

$$\delta D = 7.5\delta^{18}O + 2.1 \quad (2)$$

The monthly stable isotopic ratio of the precipitation at the three locations ranged from −33.3‰ to −7.1‰ for $\delta^{18}O$ and from −248.8‰ to −52.6‰ for δD during the observation period, and showed seasonal variation with lower values in winter and higher values in summer (Yamanaka et al., 2006). The variation range of δD and $\delta^{18}O$ in the groundwater was smaller than that of precipitation (Fig. 4). The slope and interception (d-excess) of the regression line of the groundwater data were lower than those of the LMWL:

$$\delta D = 6.7\delta^{18}O - 11.2 \quad (3)$$

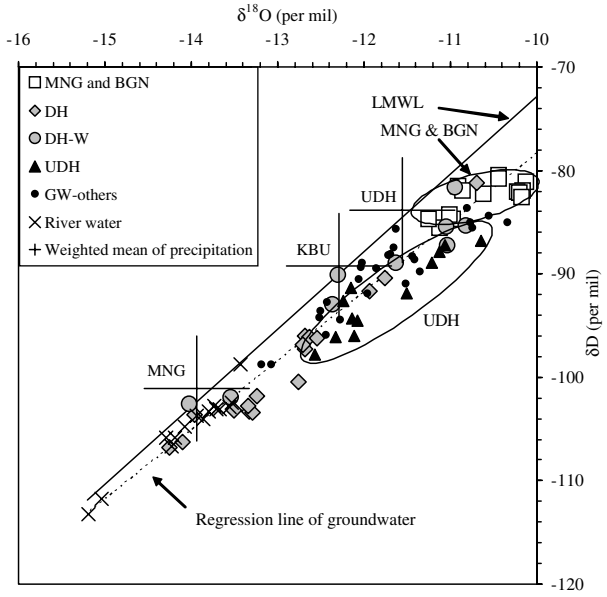

Figure 4 $\delta^{18}O$ versus δD in the groundwater and annual volume weighted mean precipitation. DH-W denotes the western region of DH. GW-others denotes the groundwater at KBU, DGH, and JGH. River water denotes the data of the main stream of the Kherlen River.

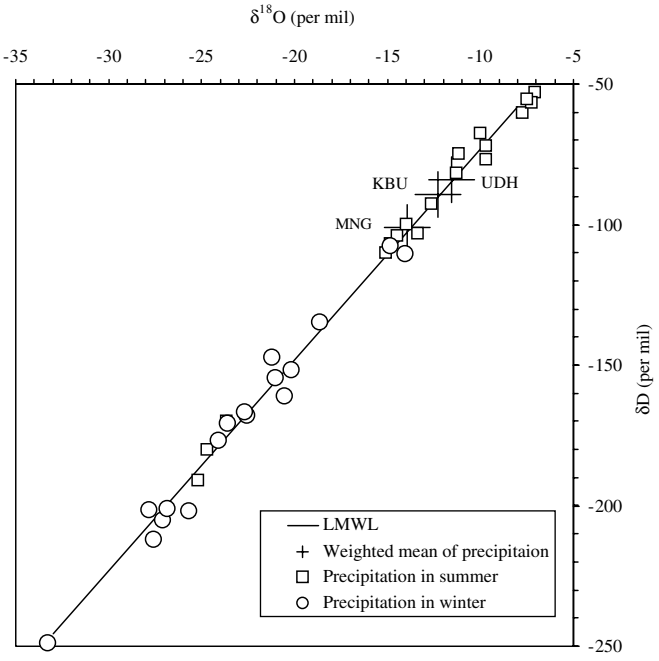

Figure 3 The relationship between the $\delta^{18}O$ and δD of monthly precipitation and the annual volume weighted mean precipitation (October 2002 to September 2003; the KBU data was missing for April. The summer season denotes May —October and the winter season November—April).

This shows that the groundwater is affected by evaporation. The stable isotopic compositions of the groundwater and precipitation show that the shallow groundwater mainly originates from precipitation that falls in the Kherlen River basin. The isotopic ratio of the groundwater tended to be higher than that of the river water, and among the groundwater samples, the δ values were the highest in the MNG and BGN (upstream) regions. The δ values in the UDH region were lower than those in the MNG and BGN regions, whereas the δ values in the DH and western region of DH (DH-W) showed wide variation ranging from $-14.3‰$ to $-10.7‰$ for $\delta^{18}O$. The stable isotopes of the groundwater in the MNG, BGN and UDH regions tended to be affected by evaporation more than those in the other regions. However, this was thought to have been caused by differences in the recharge process among regions; this will be discussed in more detail in the following section.

Chemical composition

Fig. 5 shows the spatial distribution of the geochemical characteristics of the river water and groundwater measured in July and October. No temporal change was found between July and October in most of the sampling locations, although two wells at MNG and KBU (W-MNG and W-KBU in Fig. 5) showed clear temporal changes. Because both wells were newly bored in June and July 2003, the solute concentrations of the water in the boreholes could have been affected by construction. Thus, the ion concentration data in these bore holes were excluded from the following discussion.

The concentrations of major ions in the groundwater were notably higher than those in the river water. The chemical composition of the main stream water was characterized as $Ca—HCO_3$ type, as was the groundwater in the BGN and KBU regions, though the concentrations of all ions in the groundwater were higher than in the river water. On the other hand, the groundwater in the surrounding region of DH (shown as well(W)36, W34, W70, W66 and W67 in Fig. 5) was characterized by a higher concentration of Na^+ and HCO_3^-, with some exceptions (W32 and W73). Stiff diagrams for the river and spring water are also shown in Fig. 6. The chemical patterns in the main stream water were uniform from MNG to UDH, though concentrations of the major ions increased slightly. The solute concentrations of the tributaries and springs were higher than those of the main stream water, though the chemical patterns were almost the same. A trilinear diagram is shown in Fig. 7 for the river water and in Fig. 8 for the groundwater. The solute constituents in the river (main and tributaries) and spring water were chemically unique and almost all the data fell into the category of $Ca—HCO_3$ type, whereas the chemical composition of the groundwater changed from place to place. The groundwater sampled in the BGN and the KBU regions was chemically similar to the river water from the main stream, whereas the chemical compositions of the groundwater in the region of DH, DH-W, Jargalthaan (JGH), and UDH are very different from

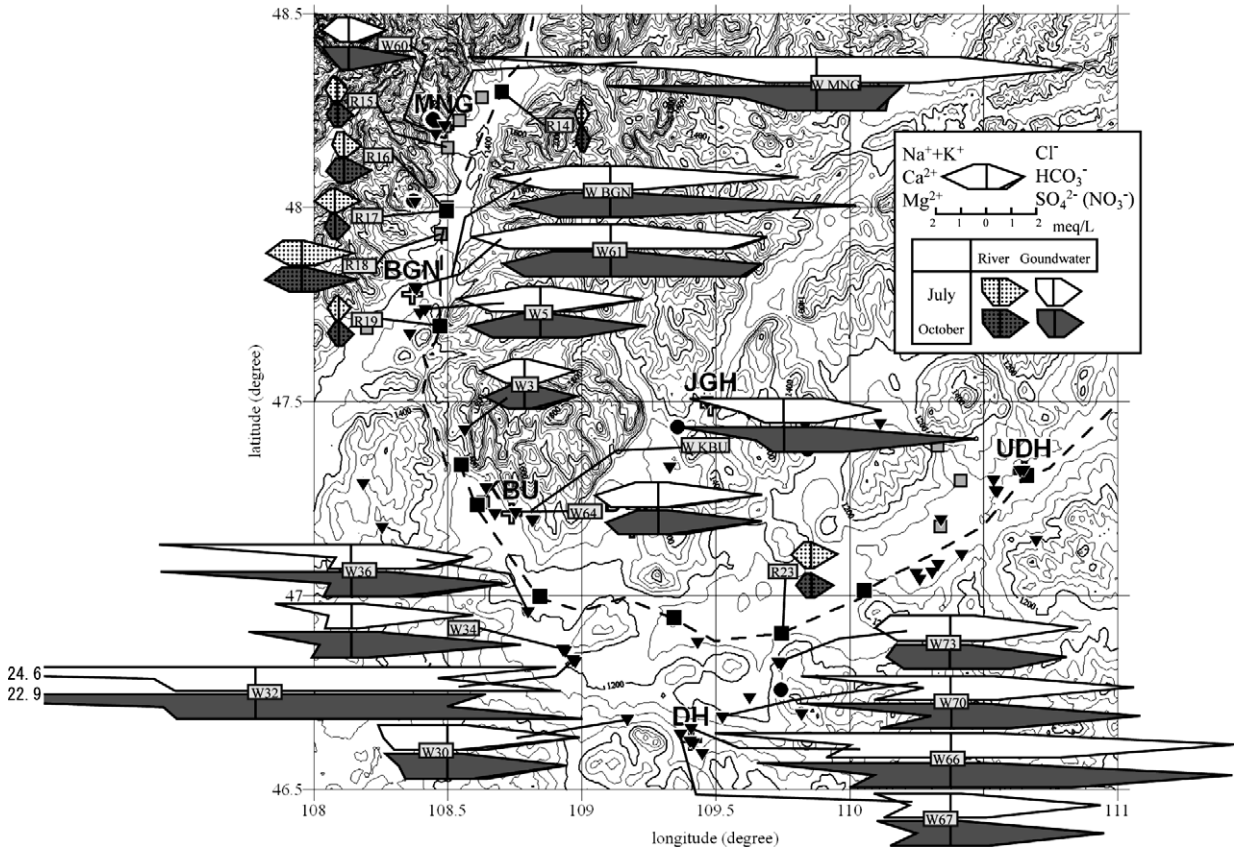

Figure 5 Spatial distribution of the chemical composition of the river water and groundwater.

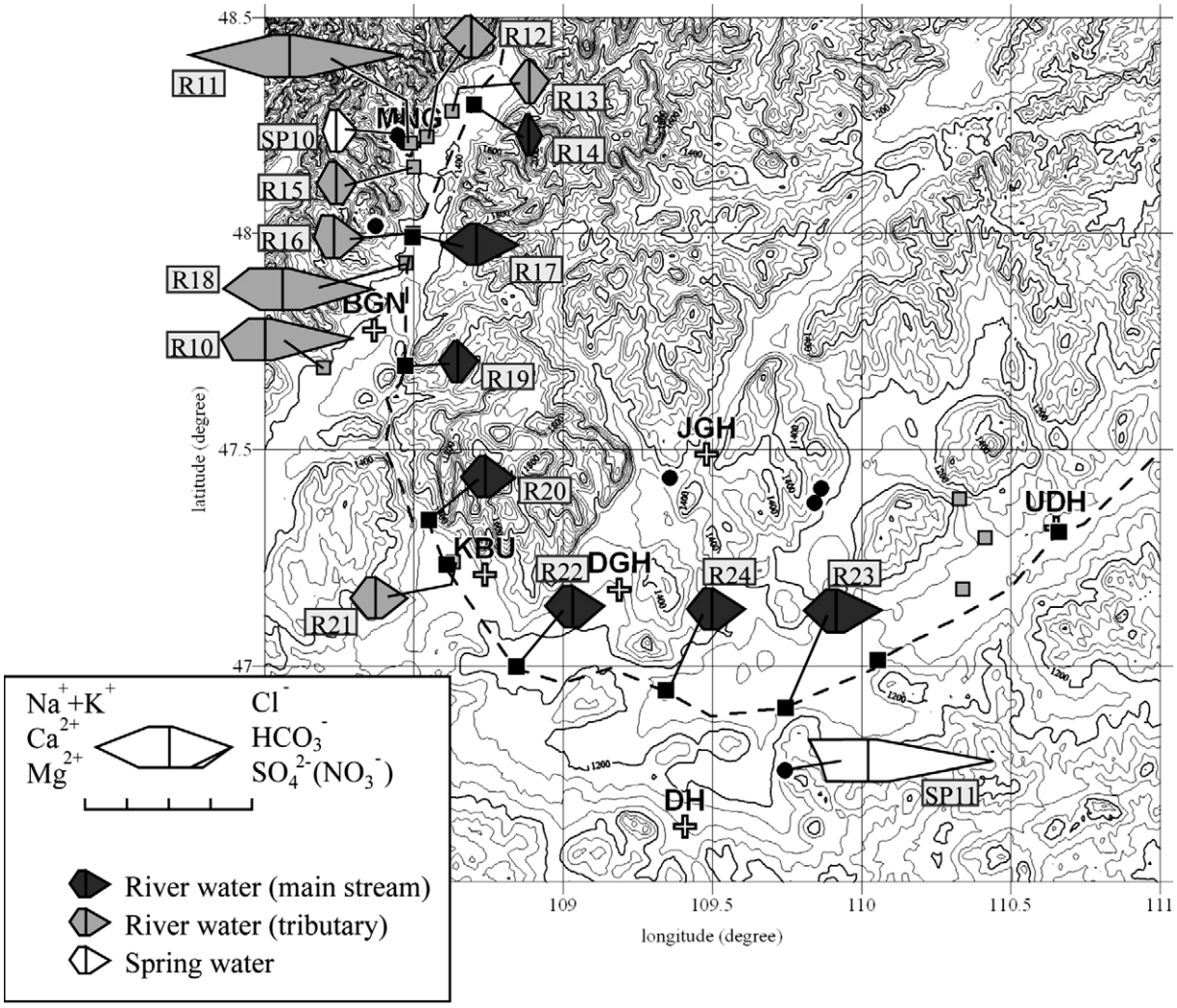

Figure 6 Spatial distribution of the chemical composition of the river water.

those of the river water. Thus, the interaction between the groundwater and river water is possibly not dominant in the midstream and downstream regions of the Kherlen River basin.

The Na^+ and Cl^- concentrations of the groundwater were considerably high in the DH-W region (W32, W36) as shown in Figs. 5 and 8. Fig. 9 shows the relationship between the Na^+ and Cl^- concentrations of the groundwater. All plots distributed far from the sea water line and the line of 1:1 (Fig. 9), thus meteoric NaCl is not the source of Na^+. Dissolution of sodium feldspars would increase Na^+ relative to Cl^- by way of the following reaction (Wischusen et al., 2004):

$$2NaAlSi_3O_8 + 9H_2O + 2H^+ \leftrightarrows Al^2Si_2O_5(OH)_4 + 2Na^+ + 4H_4SiO_4 \quad (4)$$

The ratio of Cl/Br varied throughout the Cl^- concentrations, suggesting that evaporation alone does not cause the high Cl^- concentration of the groundwater in the DH-W region. In addition, Ca^{2+} was the dominant cation in the groundwater in the upstream region and the river water. The weathering of calcite, dolomite and amphibole generally accounts for the Ca^{2+} concentration in the river and groundwater and can be expressed by the following reactions:

$$\text{Calcite}: CaCO_3 + H_2O + CO_2 \leftrightarrows Ca^{2+} + 2HCO_3^- \quad (5)$$

$$\text{Dolomite}: CaMg(CO_3)_2 + 2H_2O + 2CO_2 \leftrightarrows Ca^{2+} + Mg^{2+} + 4HCO_3^- \quad (6)$$

$$\text{Amphibole}: Ca_2Mg_5Si_8O_{22}(OH)_2 + 14CO_2 + 22H_2O \leftrightarrows 2Ca^{2+} + 5Mg^{2+} + 14HCO_3^- + 8Si(OH)_4 \quad (7)$$

The relationship between Ca^{2+} and HCO_3^- concentrations is shown in Fig. 10. The majority of plots distributed around the line of calcite, dolomite and amphibole weathering, thus suggesting that these weathering reactions mainly account for the Ca^{2+} concentration of the groundwater in the study area.

Origin of the Kherlen River water

Fig. 11 presents the relationship between $\delta^{18}O$ and altitude in the river water, groundwater, spring water and volume weighted mean (annual and summer season) precipitation at MNG, KBU and UDH. The $\delta^{18}O$ value of the river water and precipitation decreased with altitude based on the altitude effect (Siegenthaler and Oeschger, 1980; Ingraham, 1998; Pouge and Chamberlain, 2001), whereas the d-excess

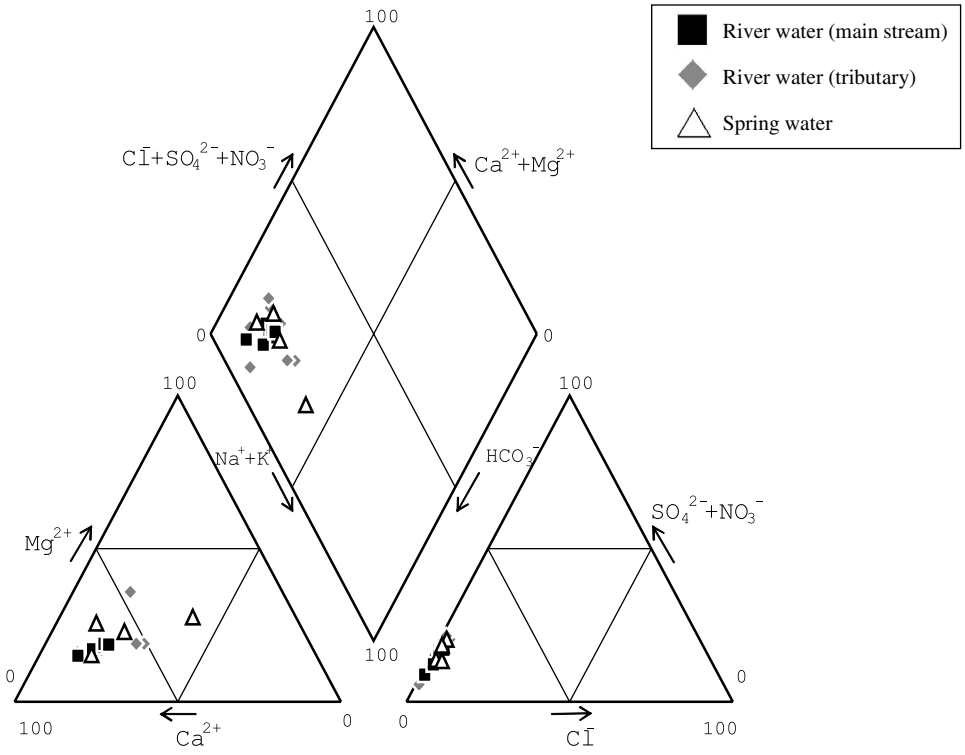

Figure 7 Trilinear diagram of the river water samples obtained in July.

value increased with altitude (Fig. 12). Thus, the $\delta^{18}O$ of the river water is determined by both the effect of distillation through evaporation from the river water surface and the altitude effect of precipitation. The majority of $\delta^{18}O$ in the groundwater in the upstream and midstream regions was notably higher than that of the river water, though

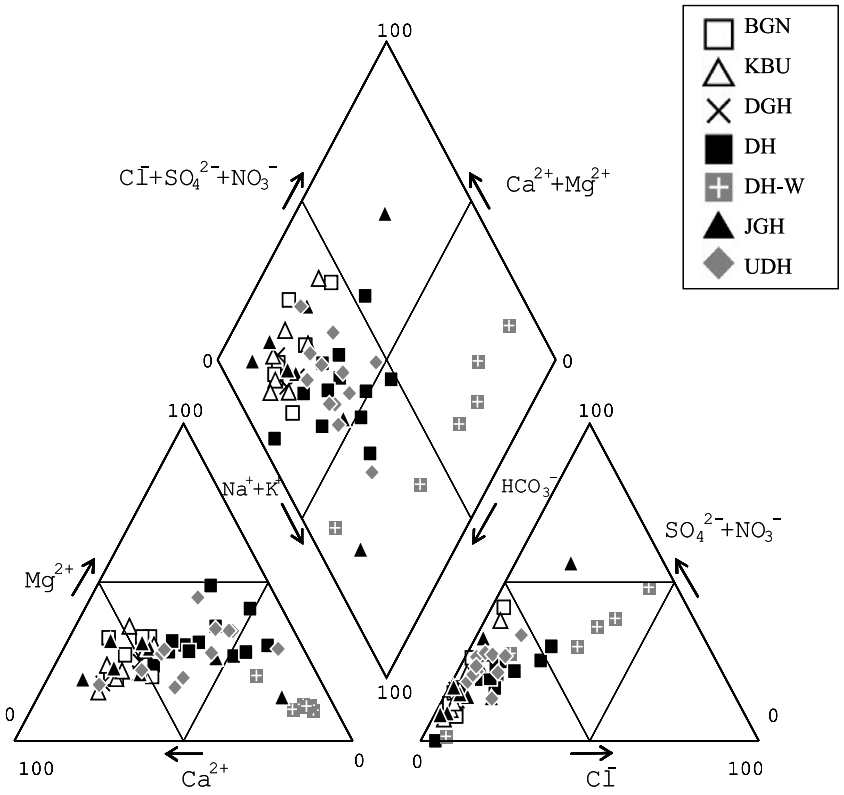

Figure 8 Trilinear diagram of the groundwater samples.

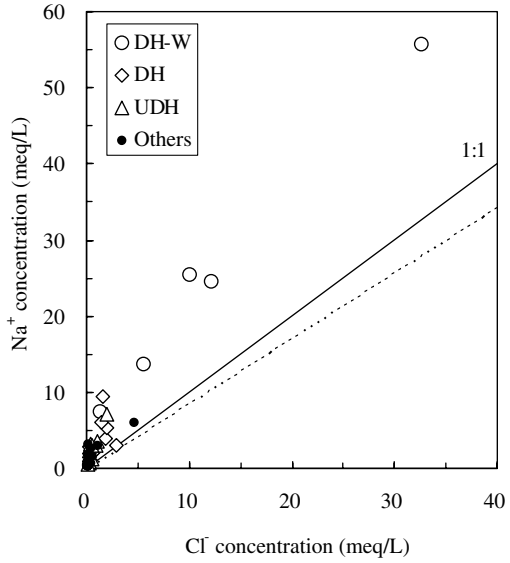

Figure 9 The Cl^- versus Na^+ concentration of the groundwater. The dotted line shows the ocean water line. 'Others' denotes all data except for DH-W, DH and UDH.

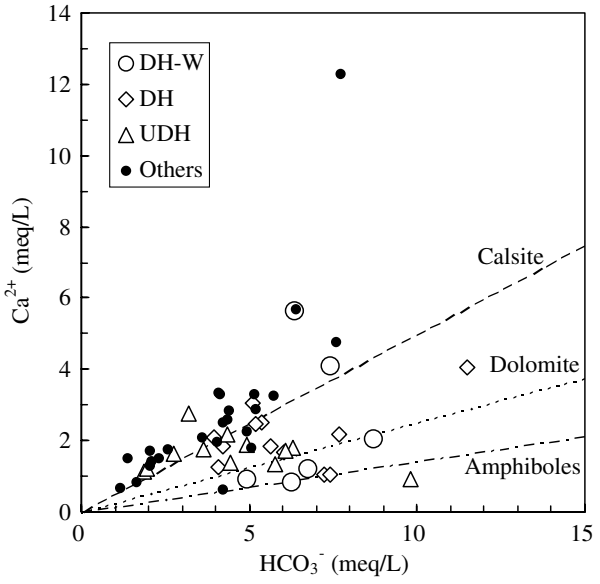

Figure 10 The Ca^{2+} versus HCO_3^- concentration of the groundwater. The 'others' are as in Fig. 9.

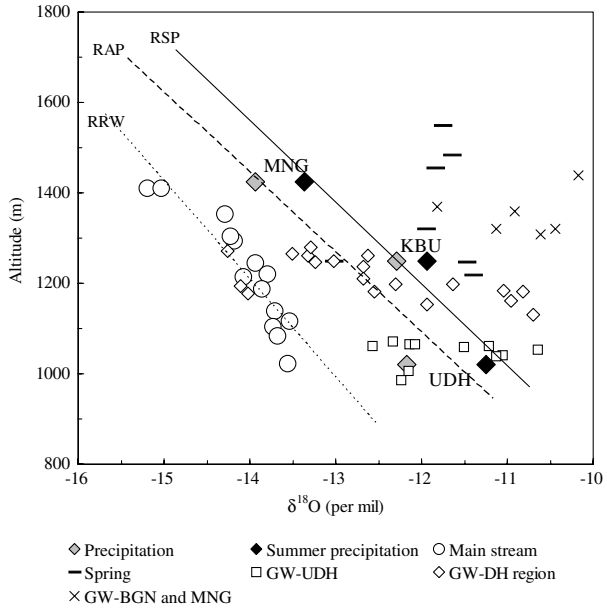

Figure 11 The altitude versus $\delta^{18}O$ of the river water, groundwater, spring water and annual/summer volume weighted mean precipitation. GW denotes the groundwater, and 'GW-DH' denotes the DH and DH-W regions combined. RRW, regression line of the river water; RAP, regression line of the annual volume weighted mean precipitation; and RSP, regression line of the volume weighted mean precipitation in the summer season (April—October).

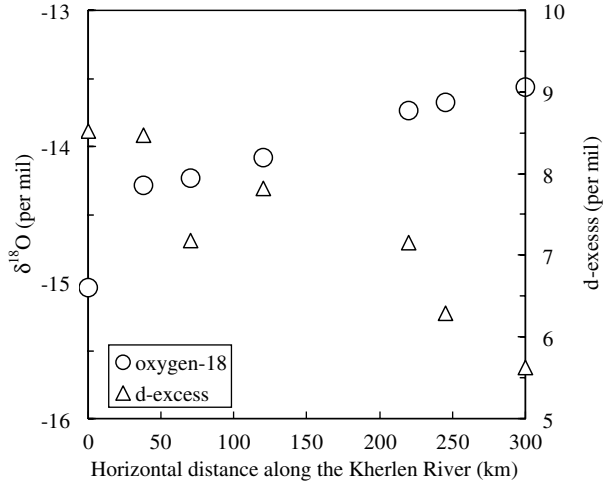

Figure 12 The spatial variation in $\delta^{18}O$ and the d-excess value along the Kherlen River starting at the R14 site (see Fig. 6).

the quantity of groundwater samples was not sufficient in the upstream region (Fig. 1). The chemistry of the river water was very different from that of the groundwater especially in the midstream and lower stream regions (Fig. 5). Additionally, the increase in discharge rate along the river (from BGN to CHB via UDH) was very small as shown in Fig. 2. Thus the stable isotope, chemical and hydrological evidence all indicate that groundwater inflow into the river is not dominant in the Kherlen River, and that the main stream water originates from precipitation that falls in the headwater region, an area with a higher altitude than MNG. The recharge altitude of the river water was evaluated by extrapolating the regression line of the precipitation as shown in Fig. 11. The altitude effect of the precipitation at MNG, KBU and UDH was estimated as 0.63‰/100 m for $\delta^{18}O$, which is a little higher than that reported previously (Siegenthaler and Oeschger, 1980; Pouge and Chamberlain, 2001). Suppose the $\delta^{18}O$ value of −15.2‰ observed at the R14 site (Fig. 6) represents the value of the river water in the headwater region, the recharge altitude of the stream can be estimated as approximately 1650 m by extrapolating the regression line of the precipitation. The highest altitude of the Kherlen River basin is approximately

2500 m. Therefore, the origin of the main stream water is precipitation that falls in the headwater region at an altitude of more than 1650 m, after which it flows downstream without major interaction with the groundwater. The $\delta^{18}O$ of the groundwater, however, in MNG and the spring water at an altitude of 1400 m was higher than that of the river water at the same altitude. This does not support the estimated recharge altitude of the Kherlen River water. There was no correlation between altitude and the $\delta^{18}O$ of the groundwater, and therefore we could not estimate the $\delta^{18}O$ of the groundwater at an altitude higher than 1650 m. Thus, how precipitation in regions higher than 1650 m recharges the river water cannot be explained at present. Nevertheless, the presented data suggest that precipitation in the headwater region is the origin of the Kherlen River water.

The recharge process of the groundwater

As shown in Fig. 4, the majority of stable isotopes in the groundwater in the upstream region (MNG and BGN) were higher than those midstream (DH, DH-W), though the variation range of the plots was large in the DH and DH-W regions. Fig. 13 shows the relationship between $\delta^{18}O$ and the d-excess in the groundwater; $\delta^{18}O$ was negatively correlated with the d-excess on a whole. The d-excess value is an index showing the evaporation effect on the physicochemical characteristics of water: that is, if the water evaporates, the d-excess decreases. The groundwater in BGN, MNG and UDH seemed to be affected by evaporation more than that in DH and DH-W. The aridity index (AI) listed in Table 1 suggests that the groundwater in the DH and DH-W regions might be most affected by evaporation. However, the question arises as to why the relatively dry DH region had a low δ value and high d-excess. Onodera (1996) revealed that rainfall of less than 15 mm did not contribute to groundwater recharge and that infiltrated soil water was evaporated soon after the rainfall event in a semi-arid region in Tanzania, central Africa. Moreover, he also showed that rainfall events with a volume of more than 20 mm and with a relatively lower stable isotopic composition preferentially contributed to groundwater recharge. Thus, it is probable that only large rainfall events with a lower stable isotope composition preferentially recharge the groundwater in the dry DH and DH-W regions, but not in BGN, MNG and UDH. Accordingly, as a result, the groundwater in DH and DH-W has a lower $\delta^{18}O$ value and higher d-excess. One more interpretation is that heavy stable isotopes tend not to be conserved in the soil if the infiltrated water is completely evaporated soon after the rainfall event in the DH and DH-W regions. When the infiltrated subsurface water is completely evaporated after a rainfall event isotopic evaporation signals do not remain in the soil because deuterium and oxygen-18 constitute the water molecules themselves. Thus, under highly dry conditions, the stable isotopes in the groundwater are depleted. In addition, the temporal heterogeneity of the recharge is thought to have caused the large variation in the stable isotopes in the groundwater in the DH and DH-W regions. On the other hand, in MNG, BGN, and UDH, the subsurface water infiltrated during a rainfall event is partly evaporated and condensed after the rainfall has ended, and therefore, the effect of evaporation on the stable isotopic composition of the soil water remains. As a result, the groundwater is probably recharged by soil water affected isotopically by evaporation, and thus, the mean stable isotopic composition of the groundwater is higher than the annual volume weighted mean precipitation seen in BGN. This process is also observed in warm humid regions (Tsujimura and Tanaka, 1998). Consequently, because only relatively large rainfall events can recharge the groundwater and the effect of the large amount of evaporation does not remain in the subsurface water in the dry DH and DH-W regions, the groundwater has a relatively low stable isotopic composition that varies largely and a high d-excess value. In the relatively humid MNG and BGN regions, on the other hand, the groundwater has a relatively higher isotopic value and lower d-excess.

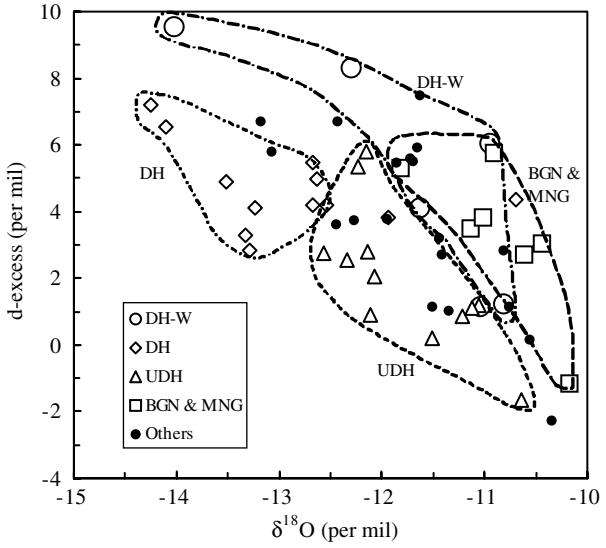

Figure 13 The $\delta^{18}O$ versus d-excess value of the groundwater. 'Others' denotes the samples obtained at KBU, DGH and JGH.

Under warm humid conditions, the stable isotopic composition of the groundwater is generally very constant both temporally and spatially compared to that of precipitation. Moreover, the stable isotopic ratio of the groundwater corresponds to a value a little larger than the annual volume weighted mean value of precipitation in that region (Tsujimura and Tanaka, 1998). On the other hand, the heterogeneity of the groundwater recharge process in arid and semi-arid regions was previously reported (Gee and Hillel, 1988). We adopted stable isotopic and chemical tracers to investigate the groundwater behavior in a semi-arid river basin in Mongolia where no such information was previously available, revealing important isotopic and chemical characteristics of the groundwater recharge process. Quantitative analysis is now necessary to determine the groundwater and river water recharge rate in the study area.

Conclusions

The present study examined the stable isotopic composition and chemical characteristics of groundwater, river water and precipitation in the Kherlen River basin, a semi-arid re-

gion in eastern Mongolia. The chemical composition of the groundwater was shown to differ from that of the main stream water. In addition, the solute constituents in the river water were of a Ca—HCO_3 type, spatially invariant and low in concentration. The groundwater in the upstream region was also characterized by a Ca—HCO_3 type, though all ion concentrations were higher than in the river water. On the other hand, the chemical composition of the groundwater in the southern and eastern regions was spatially variable and Na^+, Mg^{2+}, Cl^- and HCO_3^- concentrations were considerably higher than in the river water and upstream groundwater. The effect of evaporation and geochemical weathering were thought to have caused the high concentration of these ions considering the ion ratios of Na^+/Cl^-, Ca^{2+}/HCO_3^-.

The stable isotopic compositions showed an evaporation effect on the groundwater and river water, as well as an altitude effect in the precipitation and river water. The $\delta^{18}O$ and δD values of the groundwater were relatively high and invariant in the MNG and BGN regions, whereas in the DH and DH-W regions they were spatially variable and relatively low. In the relatively humid MNG and BGN regions, the evaporation effect during the recharge process caused groundwater with a high stable isotopic ratio and low d-excess. In contrast, preferential recharge by relatively large rainfall events with a relatively low stable isotopic composition likely resulted in the depleted isotopic ratio in the groundwater in the relatively dry DH and DH-W regions. The high d-excess and low δ values in the groundwater seem to be explained by the fact that isotopic evaporation signals do not remain in the soil when the infiltrated subsurface water is completely evaporated after a rainfall event. The stable isotope, chemical and hydrological data suggest that the main stream water of the Kherlen River is recharged by precipitation that falls in a headwater region located at an altitude of more than 1650 m, and that the interaction between the groundwater and river water is not dominant in the midstream and downstream regions of the river basin.

Acknowledgements

The authors would like to thank Dr. D. Azzaya, Director of the Institute of Meteorology and Hydrology, the National Agency for Meteorology, Hydrology and Environment Monitoring of Mongolia for support in the field survey. Thanks are also due to Dr. N. Jadambaa, Institute of Geoecology, Mongolian Academy of Sciences, and Dr. N. Sharkhuu, Institute of Geography, Mongolian Academy of Sciences, for providing important information on the groundwater in Mongolia. This work was supported by a CREST project (The Rangelands Atmosphere—Hydrosphere—Biosphere Interaction Study Experiment in Northeastern Asia) of the Japan Science and Technology Agency. Partial support also came from the Global Environment Research Fund of the Ministry of Environment, Japan, and the University of Tsukuba Research Projects A.

References

Boronina, A., Balderera, W., Renardb, P., Stichler, W., 2005. Study of stable isotopes in the Kouris catchment (Cyprus) for the description of the regional groundwater flow. J. Hydrol. 308, 214—226.

Brown, L.R., Halweil, B., 1998. China's water shortage could shake world food security. World Watch, July/August, 10—18.

Budyko, M.I., 1974. Climate and life. Academic Press, Orland, FL, 508pp.

Chelmicki, W., 1984. Water circulation in the steppe zone of Mongolia. Geogr. Pol. 50, 345—355.

Datta, P.S., Bhattacharya, S.K., Tyagi, S.K., 1996. ^{18}O studies on recharge of phreatic aquifers and groundwater flow-paths of mixing in the Delhi area. J. Hydrol. 176, 25—36.

Davaa, G., Oyunbaatar, D., Froehlick, K., 2002. Interaction of ground and surface waters revealed by stable isotopes in the Tuul river basin, Mongolia. In: Proceedings of the 2002 International Workshop on Terrestrial Change in Mongolia, pp. 6—9.

De Vries, J.J., Simmers, I., 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeol. J. 10, 5—17.

Gee, G.W., Hillel, D., 1988. Groundwater recharge in arid regions: review and critique of estimation methods. Hydrol. Process. 2, 255—266.

Hirabaru, O., Shimotsu, Y., Lkhamnorov, E., Punsantsogvoo, M., Bataagiin, B., 1999. Geochemistry and hydrological characteristics in the central and Gobi regions Mongolia. Yousui to haisui 41, 783—790 (in Japanese).

Ingraham, N., 1998. Isotopic variations in precipitation. In: Kendall, C., Mcdonell, J. (Eds.), Isotope Tracers in Catchment Hydrology. Elsevier, pp. 87—118.

Kabeya, N., Ohte, N., Sugimoto, A., Yoshikawa, K., Wang, L., 2002. Effects of the ground cover conditions on horizontal profiles of chloride concentration, oxygen and hydrogen stable isotope ratios of groundwater in Nu Us Desert. China Jap. Soc. Hydrol. Wat. Resour. 15, 13—22 (in Japanese).

Kondo, A., Tanaka, T., Thong, C., Sakura, Y., Shimada, J., Shibano, H., Liu, C., Zhang, W., Hu, C., Liu, X., Li, J., Chen, J., Shen, Y., 2001. Water problems in north China plain. Jap. Soc. Hydrol. Wat. Resour. 14, 376—387 (in Japanese).

Mineral Resources Authority of Mongolia, 1999. Geological Map of Mongolia 1:1,000,000. Institute of Geology and Mineral Resources, Mongolian Academy of Science.

Onodera, S., 1996. The mechanism of concentrated groundwater recharge in a tropical semiarid region. Jap. J. Hydrol. Sci. 26, 87—98 (in Japanese).

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy, Soc. London A 193, 120—145.

Pouge, M.A., Chamberlain, C.P., 2001. Empirical relationships between elevation and the stable isotope composition of precipitation: considerations for studies of paleoelevation change. Amer. J. Sci. 301, 1—15.

Rodell, M., Famiglietti, J.S., 2002. The potential for satellite-based monitoring of groundwater storage change using grace: the high plains aquifer Central US. J. Hydrol. 263, 245—256.

Sami, K., 1992. Recharge mechanisms and geochemical processes in a semi-arid sedimentary basin, Eastern Cape, South Africa. J. Hydrol. 139, 27—48.

Siegenthaler, U., Oeschger, H., 1980. Correlation of 18O in precipitation with temperature and altitude. Nature 285, 314—317.

Sharkhuu, N., 2001. Dynamics of permafrost in Mongolia. Tohoku Geophys. J. 36, 91—99.

Sugita, M., 2003. Interactions of water cycle processes and ecology. Sci. J. Kagaku 15, 559—562 (in Japanese).

Sugita, M., Asanuma, J., Tsujimura, M., Mariko, S., Lu, M., Kimura, F., Azzaya, D., Adyasuren, TS., 2006. An overview of the rangelands atmosphere—hydrosphere—biosphere interaction study experiment in northeastern Asia (RAISE). J. Hydrol. in press, doi:10.1016/j.jhydrol.2006.07.032.

Taniguchi, M., Kaihotsu, I., Kotoda, K., 1995. Isotope studies of precipitation, river water and groundwater in the HEIFE

area, northwestern China. J. Meteorol. Soc. Jap. 73, 1293—1299.

Tase, N., 2000. Groundwater development and its issues in the high plains of the United States. Research Report of Water Resources Research Center 20, 87—100 (in Japanese).

Tsujimura, M., Tanaka, T., 1998. Evaluation of evaporation rate from forested soil surface using stable isotopic composition of soil water in a headwater basin. Hydrol. Process. 12, 2093—2103.

Vogel, J.C., Van Urk, H., 1975. Isotopic composition of groundwater in semi-arid regions of southern Africa. J. Hydrol. 25, 23—36.

Wang, G., Cheng, G., 1999. Water resource development and its influence on the environment in arid areas of China–the case of the Hei River basin. J. Arid Environ. 43, 121—131.

Wischusen, J.D.H., Fifield, L.K., Cresswell, R.G., 2004. Hydrogeology of palm valley, central Australia; a pleistocene flora refuge. J. Hydrol. 293, 20—46.

Yamanaka, T., Tsujimura, M., Oyunbaatar, D., Davaa, G., 2006. Isotopic variation of precipitation over eastern Mongolia and continental-scale atmospheric water cycle. J. Hydrol., doi:10.1016/j.jhydrol.2006.07.022.