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Surfacewater-groundwater interaction in the Heihe River basin, Northwestern China

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Abstract

River discharge and groundwater level data were collected in the Heihe River basin, which is the second largest inland river in Northwestern China. The surfacewater-groundwater interaction, particularly in the lower desert reaches, was analyzed with the help of isotope data of water collected from the river. In the non-irrigation period, river water, which originated from the groundwater in the middle oasis reaches, was present throughout the period in the lower desert reaches. During this period, the river water recharged the groundwater not only in the riparian forest region located near the river but also in the desert-riparian fringe region located farther away from the river. In the irrigation period, the river was usually dried up in the lower desert reaches. The river water in the lower reaches appeared just after short-term releases from the middle reaches; the groundwater level in the riparian forest region rose rapidly, but it declined again just after the short-term releases finished. Since the mixing ratio of the short-term released discharge to the groundwater in the desert-riparian fringe region was smaller than that in the riparian forest region, the short-term released discharge did not contribute to the groundwater recharge in the desert-riparian fringe region.

1. Introduction

There are several vast inland river basins in northwestern China where people's survival is dependent on a very limited water resource. There is a fair amount of precipitation (more than 300 mm a^{-1}) in the upper mountainous reaches, while precipitation in the lower desert reaches is scanty (less than 50 mm a^{-1}). The melting of glaciers and snow on those mountains have provided water for irrigation to people living in oasis cities (Sakai *et al.,* 2005; Yang *et al.,* 2006).

However, in the Heihe River basin, the second largest inland river in China, it is obvious that the extensive overuse of surface water for irrigation in the middle oasis reaches has triggered a series of severe environmental problems such as the disappearances of the river and terminal lakes and a severe decline of the groundwater level in the lower desert reaches (Gong and Dong, 1998; Wang and Cheng, 1999; Chen *et al.,* 2005; Wang *et al.,* 2005). Two terminal lakes called west and east Juyan completely dried up in 1961 and 1992, respectively (Yang *et al.,* 2006).

In order to obtain proper water management, it is important to study the impact of glacier shrinkage, as reported by Sakai *et al.* (2004), on runoff characteristics and impact of human activities on the hydrological cycle, particularly surfacewater-groundwater interactions. Although many prior studies have focused on the runoff characteristics (Ujihashi *et al.,* 1998; Fujita *et al.,* 2003), there has been only fragmentary information about the interactions. Wang and Cheng (1999) suggested that groundwater outflowed in the form of spring water to surface streams or rivers in plain regions of the middle oasis reaches. Akiyama *et al.* (2003) suggested that the river water recharged groundwater in the lower desert reaches, using stable isotope tracers. But river stage is different with the season, and the seasonality of the flow direction between the river and groundwater should be considered.

The objectives in this study are to analyze the groundwater recharge mechanism in the lower desert reaches, with consideration of their seasonality. Hydrological data, such as river discharge and groundwater level, were used to detect the significance of the interactions. The isotopic fractionation theory was applied to interpret the isotopic characteristics of surface water, which are necessary to discuss the groundwater recharge mechanism.

2. Study area

Figure 1 shows the study area, the Heihe River basin. The basin encompasses Qinhai and Gansu Provinces and Inner Mongolia in China. The Heihe River originates from glacial melt water and a fair amount of precipitation in the Qilian Mountains forming the northern periphery of the Tibetan Plateau (Liu *et al.,* 2003), flowing through oasis cities and disappearing into terminal lakes. The length of the river is about 821 km long. The area of the drainage basin is about 130000 km^2.

The Heihe River can be divided into three reaches with boundaries at sites A and B: the upper mountainous, middle oasis and lower desert reaches, respectively. The upper reaches are mountainous with a glacier area of 73 km^2 which covers 0.7% of the reaches (Gao and Yang, 1985; Sakai, *et al.,* 2005). The middle reaches are made up of alluvial fans with a cultivated area of 1314 km^2 in 2002 (Yamazaki, 2006). The irrigation period in this region is from April to September ("Zhangye City Record" Compilation Committee, 1995). The lower reaches are an alluvial and lacustrine plain underlaid with unconsolidated sediments from the Quaternary age. The Quaternary alluvium, consisting of fluviatile sand, gravel, and silt to a depth of several hundred meters, is widely distributed in the lower reaches (Ding and Li, 1999; Wu *et al.,* 2003). The topography of the lower reaches inclines from the southwest to the northeast with an average slope of 1–3‰. The lower reaches include a larger expanse of desert and sparse vegetation.

The annual ranges of precipitation in the upper, middle and lower reaches are 300 mm to 500 mm, 100 mm to 300 mm, and less than 100 mm, respectively (Wang and Cheng, 1999). More than 90% of the precipitation in all the reaches occurs from April to September. Monthly maximum precipitation at a meteorological station in the upper reaches from 2002 to 2005 varied between 84 and 166 mm and appeared in July or August (Sakai *et al.,* 2006). Monthly mean

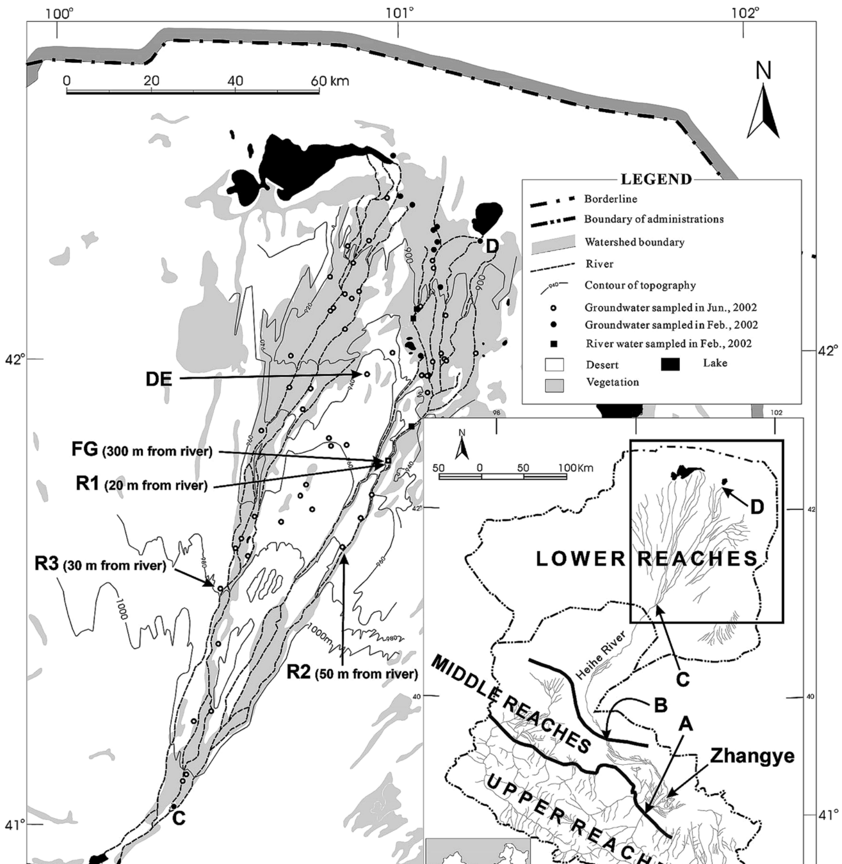

Fig. 1. Map of study area. Landscape classification was based on a grassland type map of Heihe River basin, China, edited by Chao and Gao (1988). Capital letters (A, B, C, D) indicate hydrological stations.

maximum precipitation at A and B from 1980 to 2000 were 42 mm and 16 mm, respectively.

3. Methods

3.1 Hydrological observations

We collected datasets of river discharges at the four major hydrological stations, A, B, C, and D, shown in Fig. 1. Elevations of sites A, B, C and D are 1698 m, 1276 m, 1056 m and 906 m, respectively. In addition, in the lower reaches, we observed the groundwater level from October 1, 2003 to December 31, 2004 to understand its response to river discharge using level meters with a data logger (MC-1100W, STS) at a riparian forest site 1 (R1) located 20 m from the river, at a desert-riparian fringe site (FG), 300 m from the river, and at a Gobi desert site (DE) about 10 km from the river, as shown in Fig. 1.

3.2 Stable isotope tracers

Stable isotopes of oxygen and hydrogen provide conservative tracers that are uniquely intrinsic to the water molecule (Craig and Gordon, 1965; Kendall *et al.,* 1995; Neal, 1997; Criss 1999; Hoeg *et al.,* 2000). We used these isotopic contents to identify water sources and to determine mixing ratio between waters.

The isotopic ratios of water, D/H and $^{18}O/^{16}O$, are expressed in terms of permill deviations from those of Standard Mean Ocean Water (SMOW), which is defined as

$$\delta = (R_{\mathrm{sample}}/\mathrm{R}_{\mathrm{smow}} - 1) \cdot 10^3, \quad (1)$$

where R is the isotopic ratio D/H or $^{18}O/^{16}O$.

In arid areas with high potential evaporation, the surface water is accompanied by kinetic fractionation in association with the impact of rapid evaporation. The kinetic fractionation effect, which depends on the water surface temperature and relative humidity near the water surface, is known as the Craig-Gordon model (Craig and Gordon, 1965). Moreira *et al.* (1997) simplified the model under the assumption that temperatures at water surface and in the atmosphere are the same.

$$\frac{\delta_E}{10^3} + 1 = \frac{\alpha_k}{1-h} \cdot \left[\alpha \cdot \left(\frac{\delta_L}{10^3}+1\right) - h \cdot \left(\frac{\delta_a}{10^3}+1\right)\right], \quad (2)$$

where δ_E, δ_L and δ_a stand for δ-values of evaporating water vapor, a liquid water body, and ambient air, respectively, α andα_k are the equilibrium and kinetic fractionation factors, and h is the relative humidity ($0 \leq h \leq 1$). Majoube (1971) expressed the equilibrium fractionation factor as a function of water surface temperature T (K):

$$\ln(1/\alpha) = 1.137 \cdot 10^3/T^2 - 0.4156/T - 2.0667 \cdot 10^{-3} \text{ for } ^{18}\mathrm{O}. \quad (3)$$

$$\ln(1/\alpha) = 24.844 \cdot 10^3/T^2 - 76.248/T - 52.612 \cdot 10^{-3} \text{ for } D. \quad (4)$$

α_k ranges 1.015−1.031 and 1.013−1.026 for $\delta^{18}O$ and δD, respectively, with high values for diffusive boundary layer and low values for turbulent boundary layers (Sofer and Gat, 1975; Merlivat, 1978; Flanagan and Ehleringer, 1991; Wang and Yakir, 2000). The values of δ_E and δ_L define a line in $\delta^{18}O$ vs. δD space called the evaporation line whose slope, S, is given by:

$$S = \frac{\left[h \cdot \alpha_k\left(\frac{\delta_a}{10^3}+1\right) - (\alpha \cdot \alpha_k + h - 1) \cdot \left(\frac{\delta_L}{10^3}+1\right)\right]_D}{\left[h \cdot \alpha_k\left(\frac{\delta_a}{10^3}+1\right) - (\alpha \cdot \alpha_k + h - 1) \cdot \left(\frac{\delta_L}{10^3}+1\right)\right]_{^{18}O}}. \quad (5)$$

Kinetic isotope effects are known to occur not only during evaporation (Craig and Gordon, 1965; Majoube, 1971; Merlivat, 1978) but also during ice formation from water (Gibson and Prowse, 2002). The Heihe River water is frozen during winter. When comparing the δ-values with those in a different season, we found it necessary to estimate δ-values as the underlying liquid of the frozen-over winter river water. The mass balance of isotopes during ice formation can be expressed in case of the absence of sublimation:

$$V_0 \cdot \delta_0 = V_w \cdot \delta_w + V_i \cdot \delta_i, \quad (6)$$

where V and δ are volume or depth and δ-values, respectively. Suffixes 0, w, i stand for initial water, fractionated water and frozen ice, respectively.

3.3 Water sampling and analysis

We conducted water sampling of river water and groundwater from February 2002 to September 2004. In the middle reaches, groundwater was collected once a month at a piedmont hill, an allvial-diluvial fan, and a fluvial plain covered by sand and silt; in addition, river water was also collected at site B (Fig. 1). In the lower reaches, groundwater was collected once a month at a riparian forest site 2 (R2), a riparian forest site 3 (R3) and the Gobi Desert site (DE). On October 2003, groundwater was collected at 6 sites along a 300-m line transect through the riparian forest site 1 (R1) to the desert-riparian fringe site (FG). On February and June in 2002, September and October in 2003, groundwater was collected at 56 sites in desert and riparian vegetated areas (Fig. 1). At the same time, the river water was also collected. Because of kinetic fractionation due to freezing in winter, we collected both surface ice and its underlying liquid water to estimate its original liquid δ-values using Eq. (6). All samples were filtrated by 0.20-μm filters before sealing in polyethylene or glass bottles.

The stable isotopic composition was analyzed for all samples using a water equilibration system coupled to a mass spectrometer (ThermoQuest DeltaPlus)

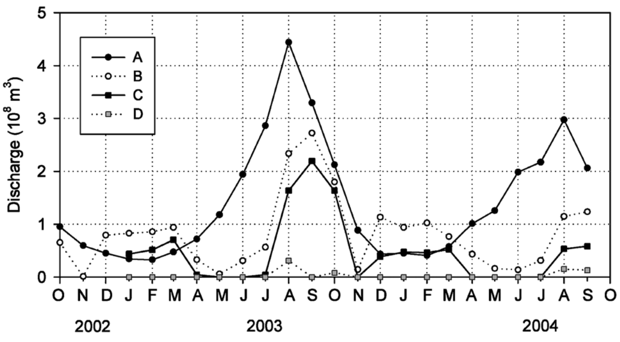

Fig. 2. Monthly discharges at sites A, B, C and D (Fig. 1) from 2002 to 2004.

maintained by the Hydrospheric Atmospheric Research Center (HyARC), Nagoya University, Japan. Reproducibility was 0.03‰ for δ^{18}O and 0.5‰ for δD (Members of Management Committee of Analytical System for Water Isotopes at HyARC, 2005).

4. Results

4.1 Discharge

Figure 2 shows monthly discharges at sites A, B, C and D (Fig. 1). Total discharges during the irrigation period, varying from 3.43×10^8 m^3 in 2004 to 6.31×10^8 m^3 in 2003, were released from middle reaches, while those at the terminus of the river (site D) varied from 0.28×10^8 m^3 in 2003 to 0.31×10^8 m^3 in 2004. In the irrigation periods, the river waters were released irregularly with short durations. We call such conditions short-term released discharge. The river water was observed at site D from August 14 to August 31, from October 20 to October 28 in 2003, and from August 20 to August 28 and from September 21 to November 4 in 2004, otherwise it was dried up in both years. The short-term released discharge led to revival of one of the terminal lakes. However, the river dried up again at site D in 9 to18 days in 2003 and in 12 to 45 days in 2004. On the other hand, river water was present at site C over the non-irrigation periods, but did not reach the terminus (site D).

4.2 Groundwater level in lower reaches

Figure 3a shows daily changes in the groundwater level in the riparian forest site 1 (R1), the desert-riparian fringe site (FG), and the Gobi Desert site (DE) with river discharge at site C from October 2003 to December 2004. At the riparian forest site 1 (R1), in both irrigation and non-irrigation period, groundwater levels rose rapidly after the river appeared due to the discharge released at site C. Once that flow subsided, the groundwater level gradually declined. Therefore, groundwater recharge occurs whenever the river water is present at around site C. In contrast, at the desert-riparian fringe site (FG), the groundwater level rose mainly in the non-irrigation period.

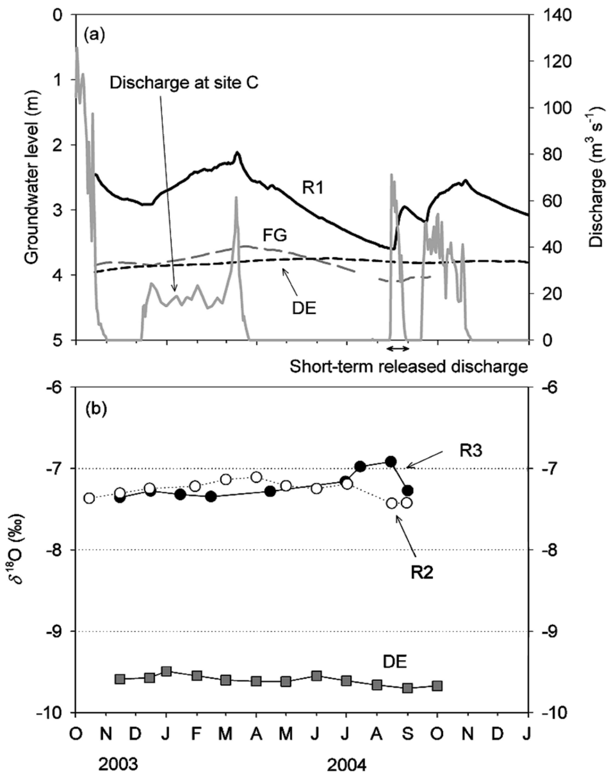

Fig. 3. (a) Daily mean groundwater levels at R1, FG and DE (Fig. 1) with daily mean river discharge at C (Fig. 1). (b) Seasonal change in δ^{18}O of groundwater at R2, R3 and DE (Fig. 1).

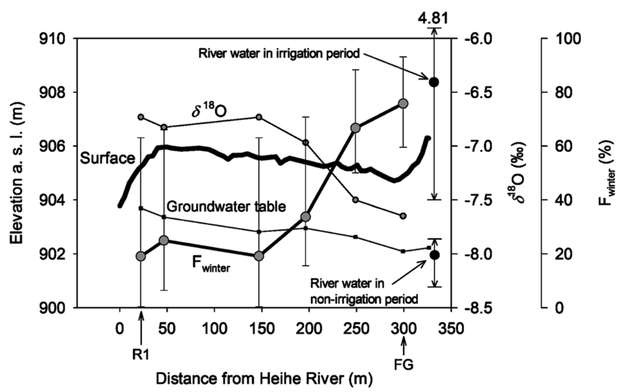

Fig. 4. Relations between distance from the river and groundwater level, δ^{18}O of groundwater and river water, and F_{winter}, which is a percentage derived from winter river water in its groundwater along a 300-m line transect through R1 to FG (Fig. 1) in lower desert reaches, October 2003. Error bars of F_{winter} were determined due to the δ^{18}O variations of river water in irrigation and non-irrigation period.

Short-term released discharge in August 2004 did not contribute to a recharge, suggesting that such transient discharge disappears before the water flux reaches the desert-riparian fringe site (FG). At the Gobi Desert site (DE), no change was found all year long, indicating that no river water is likely to recharge the groundwater in a desert area. Akiyama *et al.* (2003) also demonstrated that the source of groundwater at the Gobi Desert site is high-intensity precipitation.

Figure 4 shows a groundwater table profile from the river to the desert in October 2003. The surface was based on a topographic survey. The table was gradually inclined from the riverbed to the desert. It was obvious that a groundwater recharge occurred. Based on Darcian law (Darcy, 1856), average linear velocity V is given by

$$V=\frac{K\Delta h}{n}, \tag{7}$$

where $\Delta h=(h_R-h_G)/l$ is hydraulic gradient (h_R is river head, h_G is groundwater head, and l is distance), K is hydraulic conductivity (m s^{-1}), and n is effective porosity. Estimation using K for 0.002, n for 0.2 (Wu *et al.,* 2003), and Δh for 5.9×10^{-3} provided 5.1×10^{-5}m s^{-1}. For example, it would take more than 60 days for groundwater to flow from the river bank to 300 m away.

4.3 Stable isotopes in middle reaches

A δ-diagram of river water at site B (Fig. 1) is shown in Figure 5. The δ-values exhibited drastic seasonal variations. In the non-irrigation period, δ^{18}O at site B ranged from -8.59‰ to -6.71‰ and δD ranged from -55.0‰ to -39.0‰. The river water samples at site B in the period were plotted near the Global Meteoric Water Line (GMWL). The regression line was determined as

$$\delta D=7.07\delta^{18}O+6.28 \quad R^2=0.87. \tag{8}$$

The results showed that the river water in the non-irrigation period had no trace of significant kinetic evaporation.

In the irrigation period, on the other hand, δ^{18}O of the river water at site B ranged from -6.64‰ to -2.48‰, and δD ranged from -44.2‰ to -26.4‰. They were higher than in the non-irrigation period. The regression line was determined as

$$\delta D=4.30\delta^{18}O-16.0 \quad R^2=0.97. \tag{9}$$

In order to test the evaporation effect, we estimated its slope using Eq. (5). Unfortunately, no meteorological data were available at site B. We used the daily dataset measured at the Gobi Desert site (DE) in the lower reaches (Akiyama *et al.,* 2003) and at the Zhangye meteorological station in the middle reaches (Fig. 1). The latter dataset was obtained from National Climatic Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The annual potential evaporation estimated using wind speed, air temperature and relative humidity with no cloud cover were about 3500 mm and about 2000 mm at the DE and Zhangye meteorological station, respectively, based on the method by Kondo and Xu (1997). Comparing both slopes estimated based on such different meteorological conditions, the degree of kinetic evaporation effect could be obtained. The estimated slope ranged from 4.1 to 4.6 and from 5.3 to 7.3 at the DE and Zhangye meteorological station, respectively. The observed slope in Eq. (9) was similar to the estimated slope at the Gobi Desert site (DE). Therefore, the river water in the irrigation period at site B had a trace of strong kinetic evaporation effect.

A δ-diagram of groundwater in the middle reaches is also shown in Figure 5. The δ-values of groundwater in the middle reaches, which varied little all year long, were similar to those of the river water at B in the non-irrigation period. δ^{18}O of the groundwater ranged from -8.51‰ to -7.21‰ and δD ranged from -54.1‰ to -43.8‰. The regression line was determined as

$$\delta D=7.15\delta^{18}O+7.87 \quad R^2=0.62. \tag{10}$$

4.4 Stable isotopes in lower reaches

A δ-diagram of river water in the lower reaches is shown in Figure 5. The δ-values in river water in the lower reaches varied with the period, as they did at site B. In the irrigation period, δ^{18}O ranged from -7.51‰ to -4.81‰, and δD ranged from -49.3‰ to -32.9‰. In contrast, in the non-irrigation period, δ^{18}O ranged from -8.32‰ to -7.86‰, and δD ranged from -53.9‰ to -50.7‰. The δ-values were remarkably higher in the irrigation period than in the non-irrigation period.

In non-irrigation period, since the δ-values of the river water in the lower reaches were similar to those of the river water at site B (Fig. 5), the river water flowed down to the lower reaches without being affected by evaporation. On the other hand, in the irrigation period, the δ-values of the river water in the lower reaches were also similar to those of the river water at site B except when the river water was almost completely depleted. This was attributed to the fact that the almost completely depleted river water, which

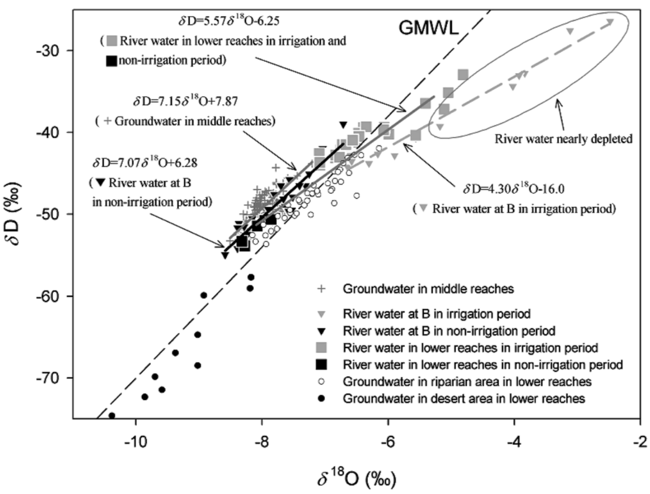

Fig. 5. δ-diagram of water samples collected from 2002 to 2004 within Heihe River basin.

Table 1. Result of statistical analysis of groundwater between riparian and desert areas. The analysis was made using samples on June and February in 2002 and on September and October in 2003.

	$\delta^{18}O$ (‰)		δD (‰)	
	Riparian area	Desert area	Riparian area	Desert area
Territorial mean	-7.2	-9.1	-47.8	-65.8
Minimum	-8.2	-10.4	-53.7	-75.4
Maximum	-6.1	-7.8	-42.0	-53.4
Standard deviation	0.5	0.8	2.9	7.0
t-test statistic	7.87		9.00	
Degree of freedom	15		13	
Level of statistical significance	< 0.001		< 0.001	

had higher δ-values, did not reach the lower reaches (Fig. 2).

A δ-diagram of groundwater in the lower reaches is also shown in Figure 5. The δ-values of groundwater were higher in the riparian than in the desert areas. The *t*-test results in Table 1 demonstrated that δ-values of groundwater in the riparian area were significantly different from those in the desert area, indicating that the sources of the groundwater must be different.

The δ-values of the groundwater in the riparian area were plotted within the river water in both the irrigation and non-irrigation periods (Fig. 5), suggesting that groundwater in the riparian area would be composed of the river water in both periods.

Figure 3b shows seasonal change of $\delta^{18}O$ in groundwater at the riparian forest site 2 (R2), riparian forest site 3 (R3) and the Gobi Desert rsite (DE). The values of $\delta^{18}O$ ranged from -7.36‰ to -6.92‰ at R2, -7.43‰ to -7.11‰ at R3, and from -9.70‰ to -9.49‰ at DE, respectively. There were only minor variations, which amounted to less than 0.44‰ for R2, 0.32‰ for R 3, and 0.21‰ for DE.

Here we examines spatial variation of $\delta^{18}O$ in groundwater along a 300-m line transect through riparian forest site 1 (R1) to desert-riparian fringe site (FG). Figure 4 shows the $\delta^{18}O$ profile in October 2003. The $\delta^{18}O$ was higher in the riparian forest region (0 m to 200 m), while lower in the desert-riparian fringe region (250 m to 300 m), averaging -6.81‰ for the riparian forest region and -7.57‰ for the desert-riparian fringe region, respectively.

5. Discussion

5.1 Formation of river water in lower reaches

In the irrigation period, most of the river water in the middle reaches is supplied by the melt water of glaciers together with a fair amount of precipitation from the upper reaches (Liu *et al.*, 2003). Most of that water is distributed to cultivated land in the reaches (Wang and Cheng, 1999). A very small amount of the rest is heavily affected by evaporation (Fig. 5), and finally disappears without reaching the lower reaches (Fig. 2). Only at the end of the irrigation period were the short-term discharges released from the middle reaches, and flowed down to the terminal lakes (Fig. 2).

In the non-irrigation period, although there was little precipitation in the middle reaches, the discharge at site B was more than at site A (Fig. 2). This means that the river water at site B is supplied by groundwater discharge in the middle reaches. The groundwater table inclining from piedmont hill to the lower edge of the fan (Wu *et al.*, 2003) also suggests the possibility of groundwater discharge. The isotopic compositions of groundwater in the middle reaches were similar to those of the river water not only at site B but also in the lower reaches (Fig. 5), suggesting that the river water derived from the groundwater in the middle reaches flowed down to the lower reaches without being affected by evaporation (Fig. 5).

5.2 Groundwater recharge mechanism in lower reaches

The groundwater recharge mechanism in the riparian area must be different from that in the desert area, because stable isotopic compositions were significantly different between the two areas (Fig. 5). Akiyama *et al.* (2003) studied the mechanism in the desert area, and carried out both water sampling for analyzing isotopic composition and observations of precipitation, evaporation, and soil water content at the Gobi desert site. They concluded that nothing but high-intensity precipitation infiltrated rapidly enough without being affected by evaporation was a source of groundwater in the Gobi Desert. Akiyama *et al.* (2003) also concluded that source of groundwater in the riparian area was river water. Because river water was released from the middle reaches in different manners between the irrigation and the non-irrigation periods (Fig. 2), and the amount of river water recharging groundwater should vary with seasons.

In the irrigation period, the river water obviously recharged at a riparian forest site 1 (R1) 20 m from the river (Fig. 3a). At a desert-riparian fringe site (FG) which is 300 m from the river, however, the river water scarcely recharged the groundwater at all (Fig. 3a). Based on Darcian law (Darcy, 1856), it would take more than 60 days for groundwater to flow from the river bank to 300 m away. However, the river dried up again at site D in less than 45 days. This is the reason why the short-term released discharge did not contribute to recharge the groundwater in the desert-riparian fringe region.

In the non-irrigation period, the river water stayed longer than in the irrigation period, and thus recharged the groundwater even at the desert-riparian fringe site (FG) (Fig. 3a). This conclusion is supported by the fact that the δ-values of the groundwater in the riparian area were plotted on a regression line within the two end members, which were the river water in irrigation and non-irrigation periods (Fig. 5).

Figure 4 shows that the $\delta^{18}O$ of groundwater in the riparian forest region (0 m to 200 m) was higher than that in the desert-riparian fringe region (250 m to 300 m). Their averages were $-6.81‰$ for the riparian forest region and $-7.57‰$ for the desert-riparian fringe region, respectively. These values were similar to the average δ-values of river water in the irrigation period ($-6.42‰$) and non-irrigation period ($-8.04‰$). Considering that the seasonal variations in any riparian area shown in Fig. 3 were small, the shape of the $\delta^{18}O$ profile shown in Fig. 4 can be assumed to be similar throughout a year. Therefore, we suggested that groundwater in the riparian forest region would be derived from river water in the irrigation period, while that in the desert-riparian fringe region would have originated from river water in the non-irrigation period.

Here, we estimate its mixing ratio in the same manner as an isotopic mass balance of Eq. (6) using δ-values of the groundwater, together with the river water in the irrigation and non-irrigation periods. Figure 4 shows the F_{winter}, which is the estimated percentage of river water in the non-irrigation period in the groundwater. The F_{winter} in the desert-riparian fringe region was higher than that in the riparian forest region. This is consistent with the fact that the groundwater level in the desert-riparian fringe site (FG), which is located 300 m from the river, did not rise due to short-term released discharge during the irrigation period (Fig. 3a). Therefore, we conclude that short-term released discharge in the irrigation period scarcely contributes to groundwater recharge in the desert-riparian fringe region.

6. Conclusion

We analyzed the surfacewater-groundwater interaction in the lower reaches by both hydrological analysis and tracer-based approaches with a consideration of its seasonality. The interaction was significantly different between the irrigation and non-irrigation periods. Isotopic analysis revealed that the river water in the non-irrigation period was mostly derived from the groundwater in the middle reaches, and recharged the groundwater in the lower reaches throughout the period. On the other hand, short-term released discharge from the middle reaches in the irrigation period scarcely contributed to groundwater recharge in the desert-riparian fringe region of the lower reaches.

To protect the groundwater resources in the lower reaches, we must take steps to prevent the disappearance of the river. Our results strongly suggest that water management of not only surface water but also groundwater throughout the entire basin is warranted. At the same time, further studies of the hydrological cycle in the entire basin are essential, taking account of the glacier shrinkage and climate change, particularly in the upper reaches as well.

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