論文

Accelerating Human Impacts on the Water Resources in the Heihe River Basin, Northwestern China

Tomohiro AKIYAMA[*]

Abstract

River discharge and groundwater level data are collected within the Heihe River basin in Northwestern China. The surfacewater-groundwater interaction, particularly in the lower desert reaches, is analyzed with the help of isotope data of water of this river. In the irrigation season, 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. A short-term released discharge is scarcely contributed to groundwater recharge in the desert-riparian fringe region in the lower desert reaches. In the non-irrigation season, river water in the lower desert reaches comes from the groundwater of the middle oasis reaches. In the lower desert reaches, the river water should recharge the groundwater even in the desert-riparian fringe region. Therefore, most of the groundwater in the region is recharged by the river water in the non-irrigation season. To examine these data, it is concluded that various attempts which have been carried out to recover from the environmental degradation result in a further degradation.

Keywords: Heihe River basin; groundwater exploitation; water allocation; groundwater recharge; stable isotope

1. Introduction

There are several vast arid inland river basins in northwestern China where people's survival is dependent on quite limited water resources. There is moderate precipitation (more than 300 mm year^{-1}) in the upper mountainous reaches, whereas precipitation in the lower desert reaches is scanty (less than 50 mm year^{-1}). Historically, the melt water of the glaciers and snows on those mountains was used for irrigation by the people living in the oasis cities (Sakai *et al*., 2005; Yang *et al*., 2006).

Here, I mention the Heihe River basin, the second largest mountain-fed inland river basin in China as an example. In the middle oasis reaches in this basin, an extensive overuse of surface water for irrigation has triggered a series of severe environmental problems such as the disappearance of the

[*] Postdoctoral fellow, International Center for Chinese Studies (ICCS), Aichi University.
E-mail address: akiyamat@aichi-u.ac.jp

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).

To recover from such an environmental degradation, various efforts have been made. Groundwater resources have become significantly exploited in the middle oasis reaches (Wang, *et al*., 2005). In addition, Heihe River Water Allocation Scheme has been executed to allocate certain amount of the river water to the lower desert reaches since 2000 (Yang, *et al*., 2006). Water saving irrigation and also construction of new concrete channels have been developed since 2002 (Chen *et al*., 2005). However, we are not certain at present whether such human activities can improve the water supply in the lower desert reaches.

For evaluation of effects by human activities, it is important to understand not only runoff characteristics of glacier shrinkage (Sakai *et al*., 2004) but also surfacewater-groundwater interaction. Several prior studies have focused on the runoff characteristics (Ujihashi *et al*., 1998; Fujita *et al*., 2003), but there have been only fragmentary information about the surfacewater-groundwater interaction. Wang and Cheng (1999) found hydrological pathways in the entire basin. Akiyama *et al*. (2003) concluded the sole source of groundwater in the desert area to be due to high-intensity precipitation there, on the contrary in the riparian area to be the river water. However, they did not mention the surfacewater-groundwater interactions and their seasonal differences.

This study should contribute to a better understanding of surfacewater-groundwater interactions with a consideration of their seasonality, particularly in the lower desert reaches of the Heihe River basin. How these human activities give any impacts on the water resources should also be mentioned. In this study the hydrological data and stable isotopic tracer techniques have been used.

2. Study Area

Figure 1 shows study area, the Heihe River basin. The basin encompasses Qinhai and Gansu Provinces and Inner Mongolia, China. The Heihe River, the second largest inland river in China, originates from the glacial melt water, and collects a fair amount of precipitation in the Qilian Mountains forming the northern periphery of the Tibetan Plateau (Liu *et al*., 2003), and flows through several oasis cities, finally disappearing into the terminal lakes. The river attains about 821 km long, covering the drainage basin of ca. 130,000 km^2.

The basin can be divided into three reaches by the lines of A and B: the upper, middle and lower reaches, respectively. The

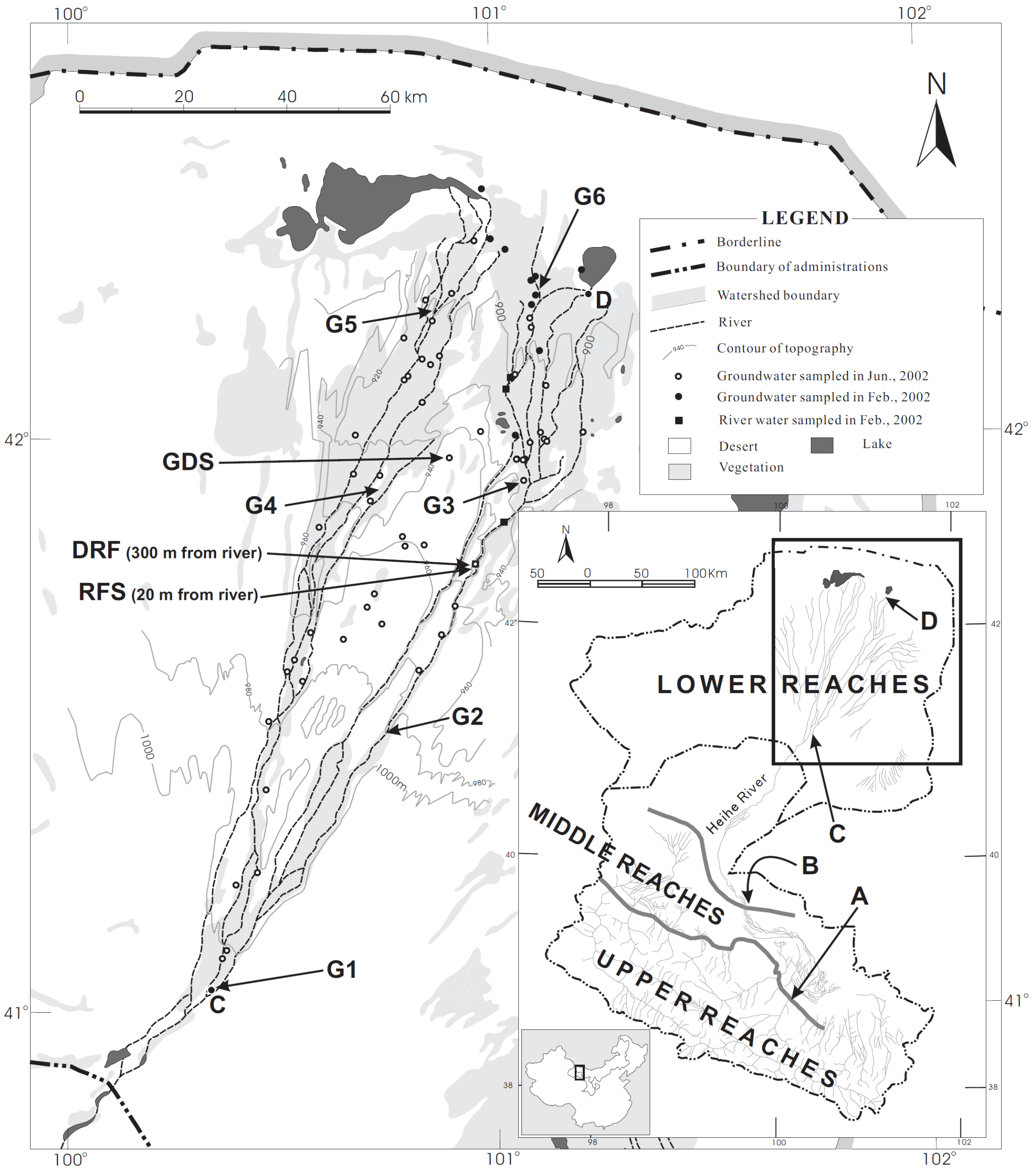

Fig. 1 **Map of study area. Vegetation classification is based on a Grassland type map of Heihe River basin, China (Chao and Gao, 1988).**

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 including several oasis cities with a cultivated area of 1,314 km^2 (data in 2002) (Yamazaki, 2006). The irrigation season in this region is from April to September.

The lower reaches are an alluvial and lacustrine plain underlaid with unconsolidated sediments of 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 riparian 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 of the reaches is supplied from April to September.

3. Methods

Hydrological Observations

I collected datasets of river discharges monitored at the four major hydrological stations, A, B, C, and D, shown in Fig. 1. In addition, in the lower desert reaches, I observed the groundwater level from October 1, 2003 through 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 (RFS) located 20 m from the river, at a desert-riparian fringe site (DRF), 300 m from the river, and at the Gobi Desert site (GDS) about 10 km from the river, as shown in Fig. 1.

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). 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

$$\delta = \left(R_{sample} / R_{smow} - 1\right) \cdot 10^3 \qquad (1)$$

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

In the arid areas with high potential evaporation such a case as my studied areas, the surface water is accompanied by a kinetic fractionation in association with the impact of rapid evaporation. Such an effect depends on both the water surface temperature and relative humidity near the water surface, and is modeled by Craig and Gordon (1965). Based on the assumption that temperatures at the surface and in the atmosphere are the same, Moreira *et al.* (1997) simplified the model as follows:

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

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 and α_k are the equilibrium and kinetic fractionation factors, and h_a is the relative humidity $(0 \le h_a \le 1)$. Majoube (1971) represented the equilibrium fractionation factor as a function of water surface temperature T (K) :

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

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

α_k ranges 1.015-1.031 and 1.013-1.026 for δ^{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 *et al.*, 1991; Wang and Yakir, 2000). The values of δ_E and δ_L define a line in δ^{18}O vs. δD space called the evaporation line whose slope, S, is given by the equation:

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

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). As for ice formation, the mass balance of isotopes can be represented by the following equation in the absence of sublimation:

$$V_0 \cdot \delta_0 = V_w \cdot \delta_w + V_i \cdot \delta_i \tag{6}$$

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.

Water Sampling and Analysis

I conducted water sampling of precipitation, river water, and groundwater from February 2002 to September 2004 within the Heihe River basin. In the middle oasis reaches, groundwater was collected once a month in the following areas: a piedmont hill, allvial-diluvial fan, and a fine earthy plain; in addition, river water was collected at site B (Fig. 1). In the lower desert reaches, the river water and groundwater were collected in desert and riparian vegetated areas, whose sites are shown in Fig. 1. On October 2003, groundwater was collected at 6 sites along a 350 m line transect through RFS to DRF. 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, I collected both surface ice and its underlying liquid water to estimate its original liquid δ-values using Eq. (6). All samples are filtrated by 0.20-μm membrane 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) maintained by the Hydrospheric Atmospheric Research Center (HyARC), Nagoya University, Japan. Reproducibility is 0.03‰ and 0.5‰ for $\delta^{18}O$ and δD, respectively (Members of Management Committee of Analytical System for Water Isotopes at HyARC, 2005).

4. Results

Discharge

Figure 2b shows discharge changes during irrigation (from April to September) and non-irrigation (from October to March) seasons at sites A and B (Fig. 1) from the 1960s to the 2000s. I calculated 10 years mean using the dataset in Fig. 2a. The discharge in the 2000s is based on the dataset from 2000 to 2004. Significant change is found only at site B. In the irrigation season, the discharge at site B has decreased in the 1990s. The discharge increased from $2.7\times10^{8}\,m^{3}$ in the 1990s to $3.4\times10^{8}\,m^{3}$ in the 2000s due to Heihe River Water Allocation Scheme since 2000. During non-irrigation season, the discharge at site B has continuously decreased since the 1980s. The discharge in the 2000s was only $3.6\times10^{8}\,m^{3}$, limited to 60% of the discharge in the 1960s.

Figure 2 shows monthly discharges at sites A, B, C and D (Fig. 1). Total discharges during the irrigation season, varying from $3.43\times10^{8}\,m^{3}$ in 2004 to $6.31\times10^{8}\,m^{3}$ in 2003, were released from middle reaches, while those at the terminus of the river (site D) varied from $0.28\times10^{8}\,m^{3}$ in 2003 to $0.31\times10^{8}\,m^{3}$ in 2004. In the irrigation seasons, the river waters were released irregularly with short durations. I 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 winter, but did not reach the terminus (site D).

Groundwater Level in the Lower Reaches

Figure 3a shows the annual changes of groundwater level in the lower desert reaches from 1990 through 2003. Groundwater level has scarcely changed in the upper parts (sites G1, G2, G3, G4), whereas a significant decline is recognized at the terminuses (sites G5 and G6). At site G6, the level has declined at a rate of 0.2 m $year^{-1}$.

Figure 3b shows daily changes in the groundwater level at RFS, DRF, and GDS together with the river discharge at site C from October 2003 to December 2004. At RFS, both in the irrigation and the non-irrigation seasons, groundwater levels rose rapidly soon after the river's appearance due to the discharge released at site C. Once that flow subsided, the groundwater level

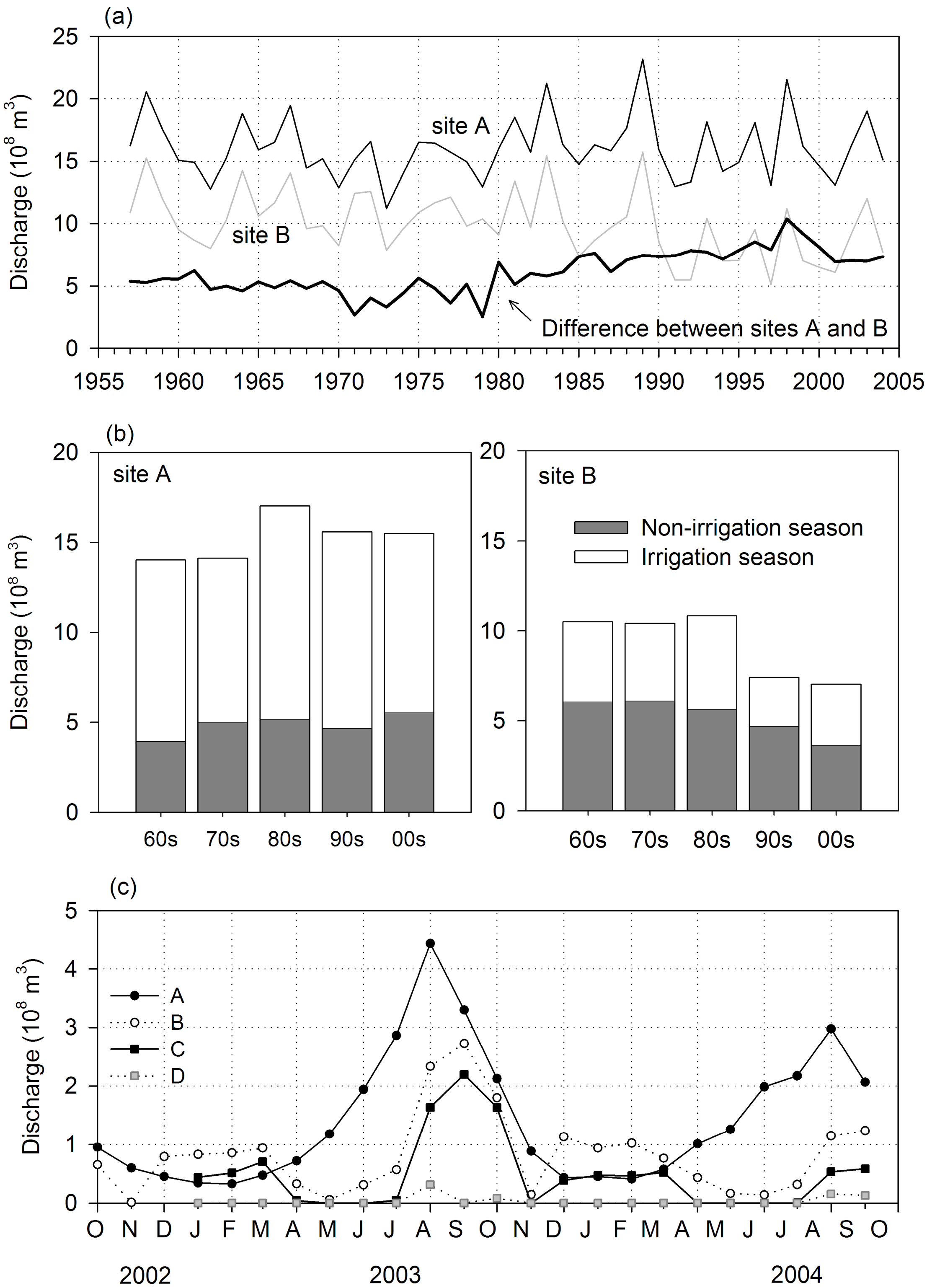

Fig. 2 **Time Series for River Discharges Observed at Sites A, B, C and D (Fig. 1). (a) Annual Discharges with Difference between Sites A and B from 1957 to 2004. (b) 10 Years Mean Discharges from the 1960s to the 2000s. (c) Monthly Discharges from 2002 to 2004.**

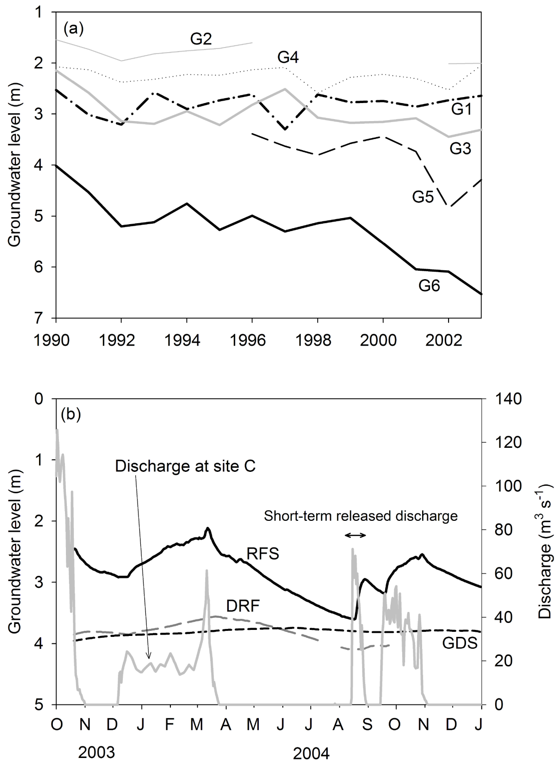

Fig. 3 Time Series for Groundwater Level in the Lower Desert Reaches. (a) Annual Mean Groundwater Level at Sites G1, G2, G3, G4, G5 and G6 (Fig. 1). (b) Daily Mean Groundwater Levels at RFS, DRF and GDS (Fig. 1) with Daily Mean River Discharge at Site C (Fig. 1).

shows gradual decline. Therefore, the groundwater recharge takes place whenever the river water is present at around site C. In contrast, at DRF, the groundwater level rises only in the non-irrigation season. Short-term released discharge in August never contributes to a recharge, suggesting that a short-term released discharge disappears before the water reaches DRF. At GDS, no change was found all year long, suggesting almost non river water to recharge the groundwater in a desert area. Akiyama *et al.* (2003) also demonstrated that the sole source of groundwater at GDS is high-intensity precipitation there.

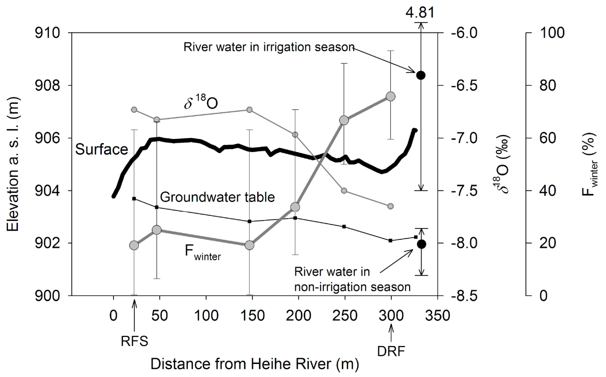

Fig. 4 Relations between Distance from the River and Groundwater Level, $\delta^{18}O$ and F_{winter}, Which Represents Percentage Derived from River Water in the Non-irrigation Season in its Groundwater at RFS (Fig. 1) in Lower Desert Reaches, October 2003.

Figure 4 shows a groundwater table profile from the river to the desert in October 2003. The surface elevation is based on a topographic survey. The table is gradually inclining from the riverbed toward the desert. Groundwater recharge from the river is to take place. Its hydraulic gradient is about 3‰, almost is the same as the topographic gradient, so the recharge rate is seems to be slow.

Stable Isotopes in Middle Oasis Reaches

Figure 5 shows a δ-diagram of river water collected at site B (Fig. 1). The δ-values exhibit noticeable seasonal variations. In the

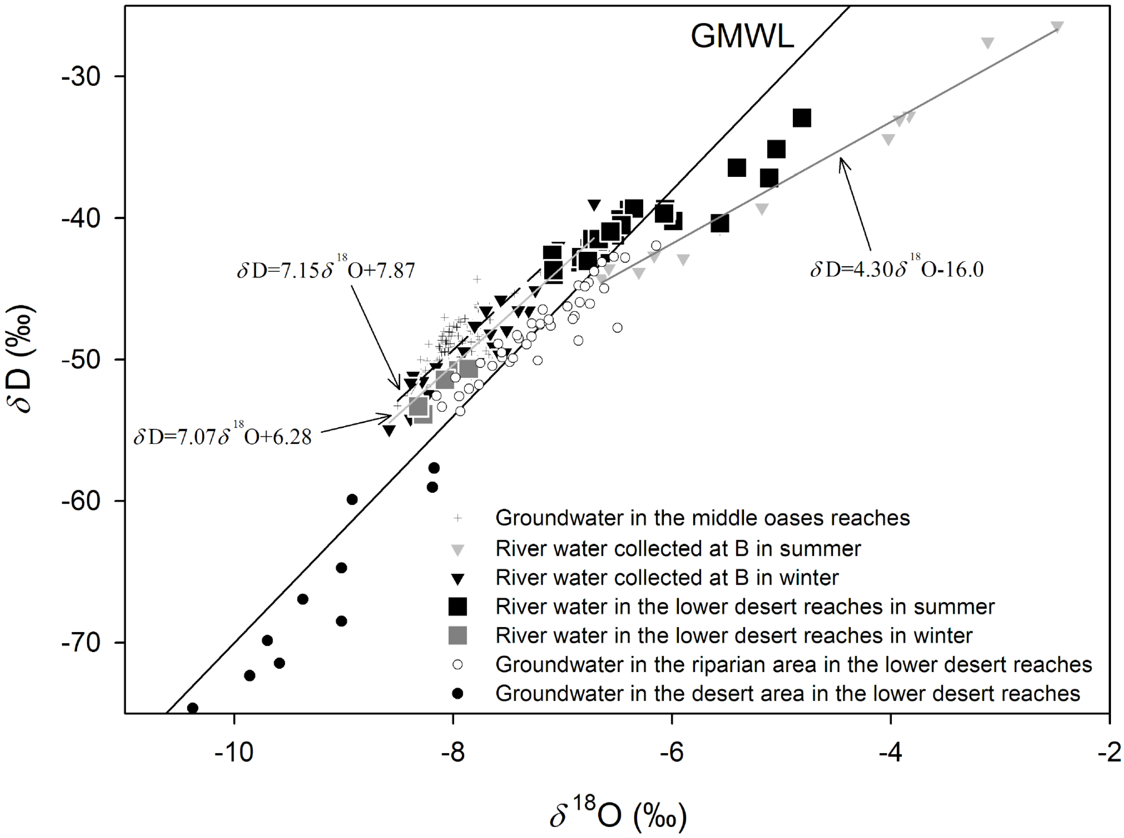

Fig. 5 ***δ*-diagram of Water Samples Collected from 2002 through 2004 within the Heihe River Basin.**

non-irrigation season, δ^{18}O and δD range from -8.59‰ to -6.03‰ and -55.0‰ to -39.0‰, respectively. The river water samples are plotted near the Global Meteoric Water Line (GMWL). The regression line is determined as

$$\delta D = 7.07\delta^{18}O + 6.28$$

$$R^2 = 0.87 . \qquad (7)$$

The results indicate that the river water in the non-irrigation season has no traces of significant kinetic evaporation.

In the irrigation season, δ^{18}O and δD of the river water at site B are in the range of -6.64‰ to -2.48‰, and -44.2‰ to -26.4‰, respectively, and they are clearly higher than in the non-irrigation season. The regression line is determined as

$$\delta D = 4.30\delta^{18}O - 16.0$$

$$R^2 = 0.97 . \qquad (8)$$

To test the evaporation effect, I estimated its slope using Eq. (5). Unfortunately, no meteorological data are available at site B. I used the dataset measured at GDS, since the land cover of site B is similar to that of GDS. The observed slope in Eq. (8) is similar to the estimated slope at GDS ranging from 4.1 to 4.6. Therefore, the river water in the irrigation season at site B has a trace of strong kinetic evaporation effect.

The δ-values of groundwater in the middle oasis reaches, with little variation for all year long, are similar to those of the river water collected at site B in the non-irrigation season. δ^{18}O and δD in the groundwater range from -8.51‰ to -7.21‰ and from -54.1‰ to -43.8‰, respectively. The regression line was determined as

$$\delta D = 7.15\delta^{18}O + 7.87$$
$$R^2 = 0.62 . \tag{9}$$

Stable Isotopes in Lower Desert Reaches

Figure 5 shows a δ-diagram of water samples collected in the lower desert reaches. The δ-values in river water in the lower desert reaches vary with the season, as well as site B. In the irrigation season, the values of δ^{18}O and δD range from -7.51‰ to -4.81‰ and from -49.3‰ to -32.9‰, respectively. In the non-irrigation season, δ^{18}O and δD range from -8.32‰ to -7.86‰ and from -53.9‰ to -50.7‰, respectively. The δ-values are remarkably higher in the irrigation season than in the non-irrigation season.

In the non-irrigation season the δ-values of the river water are similar to those of the river water collected at site B (Fig. 5), the river water flowed down to the lower reaches without evaporation effect. Whereas in the irrigation season, the δ-values of the river water are similar to those of the river water collected at site B except a case which the river water is almost completely depleted. The river water of high δ-values is completely depleted and it does not reach to the lower desert reaches (Fig. 2).

The values of δ18O and δD in groundwater differ between the riparian and desert areas (Fig. 5). The δ-values are higher in the riparian than in the desert areas (Fig. 5). During the sampling period, there occur minor variations less than 0.44‰ for the riparian area and 0.21‰ for the desert area, respectively. The t-test results (Table 1) demonstrate that the δ-values of groundwater in the riparian area are significantly different

Table 1 Result of Statistical Analysis of Groundwater between Riparian and Desert Areas

	δ^{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	-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	

from those in the desert area, suggesting the difference of their sources. Moreover, the δ-values of the groundwater in the riparian area are plotted within the river water both in the irrigation and the non-irrigation seasons (Fig. 5), suggesting the groundwater in the riparian area to be composed of the river water in both the seasons.

Figure 4 shows $\delta^{18}O$ profile of groundwater along a 350 m line transect through the river bank to the desert in October 2003. The $\delta^{18}O$ is higher near the river (0 m to 200 m), while lower farther away (250 m to 300 m), its averages are, respectively, -6.81‰ nearer the river and -7.57‰ farther from it. They are respectively similar to the average δ-values of river water in the irrigation season (-6.42‰) and river water in the non-irrigation season (-8.04‰). Therefore, I can conclude that the groundwater near the river would have been derived from river water in the irrigation season, while the groundwater far away from the river has originated from river water in the non-irrigation season.

5. Discussions

Formation of River Water in the Lower Desert Reaches

In the irrigation season, most of the river water in the middle oasis 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 provided 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 leading to the disappearance without reaching the lower desert reaches (Fig. 2). Only at the end of the irrigation period the short-term discharges are released from the middle reaches, and flow down to the terminal lakes (Fig. 2).

In the non-irrigation season, the discharge at site B is more than the discharge at site A (Fig. 2) in quantity in spite of little precipitation (Wang and Cheng, 1999; Sakai *et al*, 2006a). In the middle oasis reaches river water is supplied by groundwater discharge at site B. Because the middle reaches are on the alluvial fan, the groundwater discharges into the river at the lower edge of the fan (Wang and Cheng, 1999). I examined several springs in this area. The inclination of groundwater table from the piedmont hill to the river (Wu *et al*., 2003) also suggests the possibility of groundwater discharge. The isotopic compositions of groundwater are similar to those of the river water collected at site B (Fig. 5). My isotopic analysis revealed that the groundwater discharge provided most of the river water, which flows to the lower reaches without evaporation (Fig. 5).

Groundwater Recharge Mechanism in the Lower Desert Reaches

The groundwater recharge mechanism in the riparian area may differ from that in the desert area, because stable isotopic compositions are significantly different between the two areas (Fig. 5). The sole source of groundwater is high-intensity precipitation in the desert area, while it is river water in the riparian area (Akiyama *et al*., 2003). The mechanism in the riparian area should vary with the season, since the river water is released from the middle oasis reaches in a manner to be different between the irrigation and the non-irrigation seasons (Fig. 2).

In the irrigation season, river water obviously recharges at RFS (Fig. 3). At DRF, however, the river water scarcely recharges the groundwater at all due to its ephemeral character (Figs. 3 and 4).

In the non-irrigation season, the river water stayed longer than in the irrigation season, indicating groundwater recharge for whole the season even at DRF (Fig. 3). This conclusion is supported by the fact that the δ-values of the groundwater in the riparian area are plotted on a regression line tying the two end members of the river water in the irrigation and the non-irrigation seasons, respectively (Fig. 5).

Here, I estimate its mixing ratio in the manner same as an isotopic mass balance of Eq. (6) using δ-values of the groundwater, together with the river water in the irrigation and the non-irrigation seasons. Figure 4 shows the estimated percentage of winter river water in the non-irrigation season in the groundwater as F_{winter}. The value is lower near the river but it is higher more than 250 m away from the river. This is consistent with the fact that the groundwater level at DRF does not rise even when the short-term released discharge occurs in the irrigation season (Fig. 3). Therefore, I can conclude that the short-term released discharge in the irrigation season scarcely contributes to groundwater recharge at DRF.

Human Impacts on the Groundwater in the Lower Desert Reaches

Groundwater has been significantly exploited due to the restriction of surface water intake in the middle oasis reaches since 1980s (Yang, *et al*., 2006). The groundwater exploitation has caused drastic decline of groundwater level in the high-altitude areas of alluvial-diluvial fan in the middle oasis reaches (Wang *el al*., 2005). It led to the decrease in groundwater flux to the river (Wu *et al.*, 2003). Thus, the discharge to the lower desert reaches in the non-irrigation season has continuously decreased since the 1980s (Fig. 2).

In the irrigation season, the discharge at site B had decreased in the 1990s (Fig. 2) due to the increase of water demand for irrigation. The cultivated land became nearly doubled from 1987 to 2003 (Yamazaki, 2006). Owing to the Heihe River Water Allocation Scheme since 2000 (Yang *et al*., 2006), the significant amount of the river discharge was released in 2003 (Fig. 2) leading to the revival of one of the terminal lakes.

However, I found that such a short-term released discharge as flash flood, does not so much contribute to the groundwater recharge in desert-riparian fringe region of the lower desert reaches (Fig. 4 and 5).

Therefore, the groundwater level has continuously declined at the terminus like as site G6 (Fig. 3) due to the synergetic negative effect of decreasing discharges both in the irrigation and the non-irrigation seasons (Fig. 2) since the 1990s. Exclusively in the irrigation season a short-term released discharge's contribution is quite small for its ephemerality (Figs. 3 and 4). This is conformable with the anecdotal testimony of the nomads that the river had never reached the terminus since the 1980s except for the 2000s. The natural vegetation should have been severely degraded at the terminus and also desert-riparian fringe region.

6. Discussions

The surfacewater-groundwater interaction in the lower desert reaches is revealed based on hydrological data and tracer-based approaches, and its seasonal variations are examined. In the irrigation season, the Heihe River originates in glacial melt water and precipitation in the upper mountain reaches (Liu *et al.*, 2003). This water is supplied to cultivated land in the middle oasis reaches (Wang and Cheng, 1999). Limited amount of the river water is lost by evaporation, and finally disappears without reaching the terminus. At the time when the discharge is enough, the river reaches the terminus. Short-term released discharge from the middle oasis reaches scarcely contributed to groundwater recharge in the desert-riparian fringe region. In the non-irrigation season, no glacial melt water is available (Sakai *et al.*, 2006b) and precipitation is quite limited in the entire basin (Matsuda *et al.*, 2004; Sakai *et al.*, 2006a), the river water should have originated from the groundwater discharge in the middle oasis reaches. In the lower desert reaches the river water remains longer in the non-irrigation season than in the irrigation season, so it recharges the groundwater for whole the non-irrigation season. Most of the groundwater in the desert-riparian fringe region is recharged by the discharge in the non-irrigation season.

Groundwater resources have been significantly exploited in the middle oasis reaches since 1986, leading to the drastic decline of groundwater level (Wang *et al.*, 2005). Its resultant decrease of groundwater discharge (Wu *et al.*, 2003) led to the decrease in river discharge to the lower desert reaches in the non-irrigation season. The discharge in the non-irrigation season is one of the main sources of groundwater in the lower desert reaches, so more usage of the groundwater involves a risk of its further reduction. Further in the irrigation season, the discharge to the lower desert reaches has significantly decreased since the 1990s. Although the Heihe River Water Allocation Scheme has made the discharge in the irrigation season increase, the groundwater recharge by short-term released discharge is slight in the desert-riparian fringe region. The groundwater level rapidly declined at the terminus due to synergetic negative effect of decreasing recharge both in the irrigation and in the non-irrigation seasons and also for a small contribution of short-term released discharge in the irrigation season.

For the preservation of the groundwater resources in the lower desert reaches, water flow of the river should be maintained for a full year. My study suggests that integrated water management of not only surface water but also groundwater for the entire basin should be necessary.

Acknowledgments

The author would like to express my appreciation for financial support by the Inoue Field Science Research Foundation, Japanese Society of Snow and Ice. I wish to thank T. Hiyama (Nagoya University) and O. Abe (Nagoya University) for analyses of the isotopic compositions, and also to many local people who cooperated with me. I would like to thank the reviewers for their helpful comments. This research is one of the results of the Oasis Project (Historical evolution of adaptability in an oasis region to water resource changes), promoted by the Research Institute for Humanity and Nature (RIHN), Japan.

References

Akiyama, T., Nakawo, M., Kubota, J., Ageta, Y. and Konagaya, Y. (2003): The groundwater recharge mechanism revealed by stable isotopic and chemical composition analysis in an arid area, Western China. Proceedings of General Assembly of the International Union of Geodesy and Geophysics, Sapporo, 340-340.

Chao, B. and Gao Q. (1988): Grassland type map of the Heihe River basin, China. Institute of Desert Research Academia Sinica. Xi'an Cartographic Publishing House.

Chen, Y., Zhang, D., Sun, Y., Liu, X., Wang, N. and Savenije, H.H.G. (2005): Water demand management: A case study of the Heihe River Basin in China. Physics and Chemistry of the Earth, 30, 408-419.

Craig, H. and Gordon, L. (1965): Deuterium and oxygen-18 in the ocean and the marine atmosphere, in: Tongiorgi, E. (Eds.), Stable isotopes in Oceanographic Studies and Paleotemperatures. Spoleto, 9-130.

Criss, R. E. (1999): Principles of Stable Isotope Distribution. Oxford University Press, New York. 573p.

Ding, Y., Li, Z., 1999. Tectonic characteristics of Yinen-Ejina Banner Basin reflected by aeromagnetic survey. Geophys. Geochem. Exploration, 23, 191-194 (In Chinese).

Flanagan, L. B. and Ehleringer, J. R. (1991): Stable isotope composition of stem and leaf water: Applications to the study of plant water use. Functional Ecology, 5, 270-277.

Fujita, K., Ohta, T. and Ageta, Y. (2003): Runoff characteristics from a cold glacier and climatic sensitivity on the Tibetan Plateau. Journal of Japan Society of Hydrology and Water Resources, 16, 152-161.

Gao, Q. and Yang, X. (1985): The features of interior rivers and feeding of glacial meltwater on the Hexi region, Gansu Province. Memoirs of Lanzhou Institute of Glaciology and Cryopedology, Chinese Academy of Sciences, 5, 131-141.

Gibson, J. J. and Prowse, T. D. (2002): Stable isotopes in river ice: identifying primary over-winter streamflow signals and their hydrological significance. Hydrological Processes, 16, 873-890.

Gong, J. and Dong, G. (1998): Environmental degradation of the Ejin Oasis and comprehensive rehabilitation in the lower reaches of the Heihe River. Journal of Desert Research, 18, 44-49.

Hoeg, S., Uhlenbrook, S. and Leibundgut, Ch. (2000): Hydrograph separation in a mountainous catchment – combining hydrochemical and isotopic tracers. Hydrological Processes, 14, 1199-1216.

Kendall, C., Sklash, M. G. and Bullen, T. D. (1995): Isotope tracers of water and solute sources in catchments, in: Trudgill, S.T. (Eds.), Solute Modeling in Catchment Systems. Wiley, Chichester, U. K., 261-304.

Liu, S., Sun, W., Shen, Y. and Li, G. (2003): Glacier changes since the Little Ice Age maximum in the western Qilian Shan, northwest China, and consequences of glacier runoff for water supply. Journal of Glaciology, 49, 117-124.

Majoube, M. (1971): Fractionnement en oxygen-18 et en deuterium entre leau et sa vapeur. Journal of Chemical Physics, 68, 1423-1436.

Matsuda, Y., Sakai, A., Fujita, K., Nakawo, M., Duan, K., Pu, J. and Yao, T. (2004): Glaciological observation on July 1st Glacier in Qilian Mountains of west China during summer 2002. Bulletin of Glaciological Research, 21, 31-36.

Members of Management Committee of Analytical System for Water Isotopes at HyARC. (2005): Management for daily analyses of various stable isotope samples of water at HyARC, Nagoya University. Journal of Japan Society of Hydrological and Water Resources, 18, 531-538 (In Japanese with English abstract).

Merlivat, L. (1978): Molecular diffusivities of $H_2{}^{16}O$, $HD^{16}O$, and $H_2{}^{18}O$ in gases. Journal of Chemical Physics, 69, 2864-2871.

Moreira, M. Z., Sternberg, L. D. L., Martinelli, L. A. Victoria, R. L., Barbosa, E. M., Bonates, C. M. and Nepstad, D. C. (1997): Contribution of transpiration to forest ambient vapour based on isotopic measurements. Global Change Biology, 3, 439-450.

Neal, C. (1997): A view of water quality from the Plynlimon watershed. Hydrology and Earth Systems Science, 1, 743-754.

Sakai, A., Fujita, K. Matsuda, Y., Kubota, J., Duan, K., Pu, J., Nakawo, M. and Yao, T. (2004): Five decades of shrinkage of the July 1st Glacier in the Qilian Mountains of China. The 4th International Symposium on the Tibetan Plateau, Lhasa, China.

Sakai, A., Fujita, K., Nakawo, M. and Yao, T. (2005): Role of glacier runoff in the Heihe Basin. Project Report on an Oasis-region, Research Institute for Humanity and Nature, 5, 229-238.

Sakai, A., Matsuda, Y., Fujita, K., Matoba, S., Uetake, J., Satow, K., Duan, K., Pu, J., Nakawo, M. and Yao, T. (2006): Meteorological observation at July 1st Glacier in northwest China from 2002 to 2005. Bulletin of Glaciological Research, 23, 23-32.

Sakai, A., Matsuda, Y., Fujita, Duan, K., Pu, J., Yamaguchi, S. Nakawo, M. and Yao, T. (2006): Hydrological observation at July 1st Glacier in northwest China from 2002 to 2004. Bulletin of Glaciological Research, 23, 33-39.

Sofer, Z. and Gat, J. R. (1975): The isotopic composition of evaporating brines: Effect of the isotopic activity ratio in saline solutions. Earth and Planetary Science Letters, 26, 179-186.

Ujihashi, Y., Liu, J. and Nakawo, M. (1998): The contribution of glacier melt to the river discharge in an arid region. Proceedings of the International Conference on Ecohydrology of High Mountain Areas, Kathmandu, Nepal, 24-28 March 1996, 413-422.

Wang, G. and Cheng, G. (1999): Water resource development and its influence on

the environment in arid areas of China –the case of the Hei River basin–. Journal of Arid Environments, 43, 121-131.
Wang, G., Yang, L., Chen, L. and Kubota, J. (2005): Impacts of land use changes on groundwater resources in the Heihe River Basin. Journal of Geographical Sciences, 15, 405-414.
Wang, X. F. and Yakir, D. (2000): Using stable isotopes of water in evapotranspiration studies. Hydrological Processes, 14, 1407-1421.
Wu, Y., Chen, C., Shi, S. and Li, Z. (2003): Three dimensional numerical simulation of groundwater system in Ejina Basin, Heihe River, Northwestern China. Journal of China University Geoscience, 28, 527-532 (In Chinese).
Yamazaki, Y. (2006): Impacts of agricultural development on hydrological cycle in the Heihe River basin in Northwestern China. Ph. D. thesis, Institute of Agriculture, Kyoto University (In Japanese). 98p.
Yang, X., Dong, J. and White, P. D. (2006): The key role of water resources management in ecological restoration in Western China. Geographical Research, 44, 146-154.