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Determination of groundwater recharge regime and flowpath in the Lower Heihe River basin in an arid area of Northwest China by using environmental tracers: Implications for vegetation degradation in the Ejina Oasis

Dajun Qin [a,*], Zhanfeng Zhao [a], Liangfeng Han [b], Yunping Qian [c], Lu Ou [a], Zhongqiang Wu [d], Mingchuan Wang [e]

[a] Key Laboratory of Engineering Geomechanics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] Isotope Hydrology Section, Division of Physical and Chemical Sciences, Department of Nuclear Sciences and Applications, International Atomic Energy Agency, P.O. Box 100, A-1400 Vienna, Austria
[c] Hydrology Bureaus, Yellow River Conservancy Commission, Zhengzhou 450004, Henan, China
[d] Cangzhou Hydraulic Science Institute, Cangzhou 061000, Hebei, China
[e] Dangdong Gold Administration, Dandong 118000, Liaoning, China

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ABSTRACT

Environmental tracers (CFCs, stable isotopes ^{18}O, ^{2}H, and ^{3}H) and major ions were employed to study river infiltration and groundwater recharge in the aquifer system in the basin of the Lower Heihe River, Northwest China. Three groups of waters have been recognized: (1) young groundwater, connected to the river, with large variation of CFC apparent ages ranging from <10 a to 40 a, and $\delta^{18}O$ and $\delta^{2}H$ values which are similar to the river water; (2) regional background water, unaffected by the river, having CFC apparent ages >40 a, and being depleted in ^{18}O and ^{2}H compared with the river water; and (3) groundwater in Gurinai, a grassland located about 100 km from the river, in which the predominant discharge is from the Badain Jaran desert, with CFC apparent ages ranging from 25 to >50 a and being enriched in ^{18}O and ^{2}H compared to the river water. The groundwater along the river contains CFCs and ^{3}H down to depths of about 120 m, and the shallow groundwater exhibits CFC apparent ages in a wide range which are not dependent on the well depth. Groundwaters along the river show a similar trend of enrichment in ^{18}O and ^{2}H as the river water whereas groundwaters in depression cones are depleted in heavier isotopes, and have low CFC and ^{3}H concentrations. The CFC apparent age of the groundwater increases with increasing distance downstream, indicating that the dominant part of the groundwater is from infiltration of river water in the upper reaches. Modifications of groundwater recharge are reflected in variations of stable isotope compositions, as well as CFC and ^{3}H concentrations in the groundwater that was recharged from the river over the last decades. Despite recharging from river water, groundwater abstraction has induced a water balance deficit. The riparian ecosystem in the Ejina Oasis is constrained by both decreased river flow and increased groundwater abstraction. The vegetation degradation in the Ejina Oasis is controlled not only by natural aridification but also worsened by heavy groundwater abstraction and decreased river flow.

1. Introduction

The Heihe River, which is the second largest inland river in China, has the second largest area of *Populus euphratica* and *Haloxylon ammondendron* forests in China (Wang, 2010) and is an important ecological defense against sandstorms in Northwest China (Jiang and Liu, 2010). In the past 50 a, discharge of river water at the Yingluoxia Gorge, from the Upper Heihe River, has not significantly changed, with an average annual flow of 15.8×10^8 m^3, maximum 23.2×10^8 m^3 and minimum 11.2×10^8 m^3. However, at the Zhengyixia Gorge the annual discharge of the river, from the Middle Heihe River (Zhangye Basin), had decreased from 10×10^8 m^3 in the 1940s, to 6×10^8 m^3 in the 1960s and to less than 2.5×10^8 m^3 in the 1990s (Liu et al., 2005). The duration of zero flow periods at the Langxinshan gauging station in the Lower Heihe River has increased from 100 days per/a in the 1950s to about 200 days/a currently. The East and West Juyan Lakes, the two terminal lakes of the river dried up in 1961 and 1992, respectively (Tian and Zhou, 2002). A significant area of *P. euphratica* forest has diminished; the total desertification area in Ejina had increased from 5000 km^2 (about 5% of the basin area) in the 1970s to 15,000 km^2 in the

* Corresponding author.
E-mail address: qindj@mail.iggcas.ac.cn (D. Qin).

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1990s (Ding and Zhang, 2002). The carrying capacity of pasture in the Ejina Oasis declined sharply and several rare animals have disappeared (Cao et al., 2004; Yang et al., 2005; Tang and Jiang, 2009).

Since 2000, water regulation has been in force with the aim of reducing the amount of water used in the Middle Heihe River and delivering it to the Lower Heihe River, to restore the ecosystem, particularly to sustain trees such as *P. euphratica* and vegetation along the river (Wu et al., 2004). The inflow from Zhengyixia Gorge had increased to 8×10^8 m^3 in 2000, 8.3×10^8 m^3 in 2001, 9×10^8 m^3 in 2002, 9.5×10^8 m^3 in 2003 (Jiang and Liu, 2010). The 10-a average flow at the Zhengyi Gorge from 2000 to 2009 was 10×10^8 m^3 (Zhang, 2011). The East Juyan Lake which had been dry for 10 a was refilled, with a water area of 23.7 km^2 in November 2002. It dried up in June 2003 and was refilled again, with a water area of 28 km^2 in August 2003. The area of the East Juyan Lake has increased from 35 to 42 km^2 from 2004 to 2009. The West Juyan Lake which had been dry for 40 a was refilled in 2003 (Si et al., 2005; Yang et al., 2003). The resulting improvement of ecosystems in the Ejina Oasis has been observed (Liu and Zhao, 2010).

An understanding of the leakage of river water and flowpath of groundwater in the Ejina Oasis is important not only to the policy makers for regional planning but also to scientists interested in hydrological cycles in arid environments and climate change in Northwestern China. This results in demands to estimate the scope and magnitude of infiltration of the river to groundwater, on which opinions differ. Studies using ^{3}H analysis suggested that the Heihe River may have reached as far as 100 km eastward to the aquifer in the Gurinai area (a grassland), over a period of 15–25 a (Wu et al., 2000; Chen et al., 2006; Zhang et al., 2006). Other studies, however, suggested that the river water may have negligible influence on the groundwater at Gurianai (Geyh and Gu, 1998; Qian et al., 2005). Since the 1970s the ^{3}H content of precipitation has decreased at approximately the same rate as ^{3}H decay in the Middle Heihe River (Zhangye Basin) (see Fig. 7 in Qin et al., 2011) and, consequently, dating with ^{3}H alone for groundwater recharged since the 1970s is difficult in this area. Thus, information on the time scale and scope of groundwater–river water interaction around the river is limited.

Environmental tracers are essential for determining recharge sources, ground water residence times, and the extent of mixing between local and intermediate flow systems (Clark et al., 1998; Böhlke et al., 2007; Morrissey et al., 2010; Brown et al., 2011). In addition to other environmental tracers chlorofluorocarbons, in particular CFC-11, CFC-12 and CFC-113, are widely used (Thompson and Hayes, 1979; Busenberg and Plummer, 1992; Ekwurzel et al., 1994; Oster et al., 1996; Böhlke et al., 1997; Cook and Solomon, 1997; Plummer et al., 1998a,b, 2000; IAEA, 2006; Darling et al., 2010). CFCs enter most natural water systems through surface waters and rainfall, which exchange dissolved gases with the atmosphere. During the passage of infiltrating water through the unsaturated zone, equilibration of CFC concentrations at the conditions in the soil near the groundwater table takes place (Klump et al., 2007). If the unsaturated zone is not deep, the CFC content in soil air will reflect the recent atmospheric mixing ratio (Cook and Solomon, 1995) and the CFCs dissolved in the groundwater will record the time of recharge. However, rivers are often not in equilibrium with the atmosphere. On the one hand, rivers can be over saturated with CFCs due to point source contamination (Clark et al., 1995; Böhlke et al., 1997; Beyerle et al., 1999). On the other hand, due to older groundwater discharge, rivers are often below saturation with atmospheric CFCs (Cook et al., 2003). In such cases CFCs can still provide information on groundwater mixing and river bank controlled groundwater recharge, although they cannot provide direct information on groundwater residence time (Beyerle et al., 1999). In this study area there are two favorable conditions for using CFCs: in this remote Lower Heihe River arid area neither point source contamination nor groundwater discharge to the river is likely to affect the CFC data interpretation (Qin et al., 2011).

In this paper CFCs are used to determine the ages and flowpath of groundwater in the Lower Heihe River area. Measurements and analyses of δ^{18}O, δ^2H and ^{3}H, as well as major ions in selected groundwater samples have also been carried out to provide evidence for river water–groundwater interaction.

2. The study area

The Ejina Oasis covers an area of 3.4×10^4 km^2 in Northwest China, extending between 40°20′–42°30′N and 99°30′–102°00′E. It has the Badain Jaran Desert on its southern and eastern side, the Dingxin Basin on the southwestern side, Mazong Mountains on the western and Sino-Mongolia boundary in the north (Fig. 1). The mean annual temperature is ~8 °C with a maximum temperature of 41 °C (July) and a minimum temperature of −36 °C (January). The mean annual precipitation is 42 mm, about 50 mm in the south and decreasing northward to less than 30 mm. The mean potential evaporation rate is 3700 mm/a (Wen et al., 2005). The basin is inclined from SW to NE, with an average slope of 1–3‰, and the land surface elevation varies from 1127 to 820 m above sea level (masl). The Juyan Lakes are the lowest parts of the Ejina Oasis. The dominant landscape of the Ejina Basin is the Gobi Desert, which is composed of wind-eroded hills, desert and alkaline soils.

The Heihe River originates in the Qilian Mountains, and flows through two basins with the Zhangye basin in the middle reaches

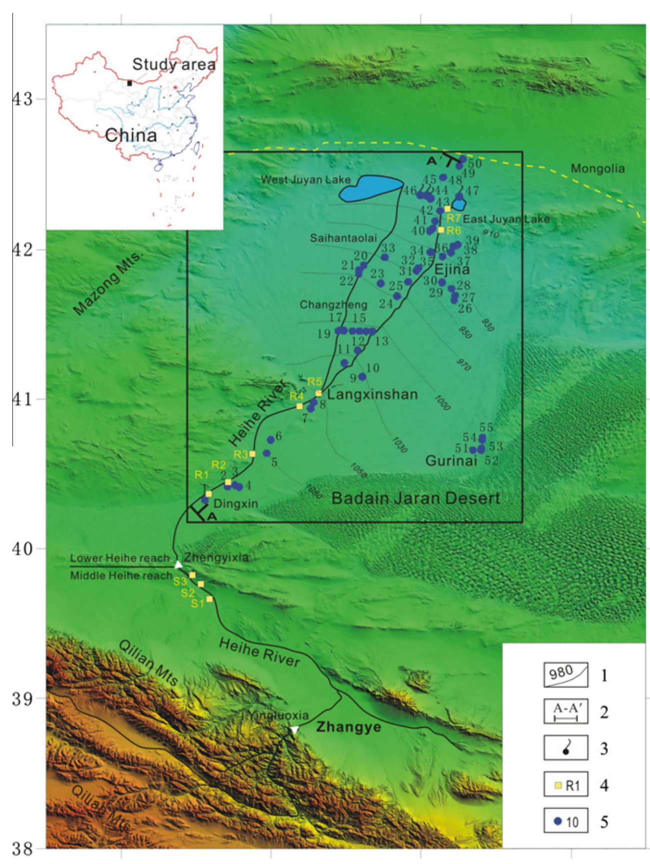

Fig. 1. Simplified hydrogeological map of the Ejina Oasis. 1: Ground water level contours (masl); 2: hydrogeological section line in Fig. 9; 3: spring; 4: location and number of river water sample; 5: location and number of groundwater sample. The insert rectangle indicates the scope of Figs. 5 and 6.

Table 1
Field data, major ion concentrations (mg/L) in groundwater.

Sample No.	EC (μs/cm)	PH	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	mNa/mCl[a]	mNa/mCa[a]	mCl/mSO4[a]	mMg/mCa[a]
4	2700	7.7	5	80	17	74	265	339	236	0.47	8.20	2.12	7.18
6	1290	7.4	4	50	9	133	122	163	273	0.63	9.69	2.03	24.37
7	1620	8.0	4	49	13	87	90	116	225	0.84	6.57	2.10	11.04
8	1250	8.3	4	48	5	94	101	171	267	0.73	16.74	1.60	31.00
14	1140	7.8	5	81	61	59	99	211	234	1.26	2.31	1.27	1.59
15	1700	7.7	5	74	74	79	132	291	288	0.87	1.74	1.23	1.76
17	920	8.0	4	44	35	48	90	142	238	0.75	2.19	1.72	2.26
18	2270	7.5	4	46	87	141	203	161	530	0.35	0.92	3.41	2.67
21	990	8.3	4	58	21	30	84	207	227	1.07	4.82	1.10	2.36
24	1690	8.3	5	64	46	61	202	280	218	0.49	2.43	1.95	2.19
25	1820	8.0	5	65	71	96	192	235	288	0.52	1.60	2.21	2.23
26	1840	8.2	5	82	74	77	332	271	380	0.38	1.93	3.31	1.72
27	2986	7.5	5	105	92	90	338	241	381	0.48	1.99	3.80	1.61
28	1870	7.7	4	50	76	87	185	187	240	0.42	1.15	2.68	1.89
30	612	7.6	3	56	53	45	48	84	213	1.80	1.84	1.55	1.40
32	1970	8.1	4	59	57	68	162	291	242	0.56	1.80	1.51	1.97
33	2180	7.7	5	66	95	113	213	291	343	0.48	1.21	1.98	1.96
35	1770	8.3	4	41	109	89	184	227	183	0.34	0.66	2.19	1.35
36	4440	7.7	5	80	139	340	529	135	617	0.23	1.00	10.60	4.03
37	2060	8.1	4	46	48	144	232	538	336	0.31	1.67	1.17	4.95
40	1002	8.4	3	44	33	51	126	181	204	0.54	2.32	1.88	2.55
41	1980	6.9	4	56	103	123	190	171	372	0.46	0.95	3.01	1.97
44	2490	8.0	3	34	102	36	410	291	128	0.13	0.58	3.81	0.58
45	2360	8.1	3	35	95	36	406	261	126	0.13	0.64	4.21	0.62
46	2290	7.9	3	35	102	36	381	248	118	0.14	0.60	4.16	0.58
47	2600	7.7	3	31	110	41	407	310	113	0.12	0.49	3.55	0.61
48	1780	8.0	2	40	105	30	225	227	130	0.27	0.66	2.68	0.47
49	1740	8.2	3	36	115	37	200	165	125	0.28	0.55	3.28	0.53
50	2170	7.9	3	50	126	41	271	295	128	0.28	0.69	2.49	0.54
51	2240	7.8		365	52	22	341	229	358	1.65	12.24	4.03	0.70
52	941	8.7		164	16	6	126	98	144	2.01	17.87	3.48	0.62
53	1234	8.1		185	24	17	127	160	227	2.25	13.44	2.15	1.17
54				414	46	26	333	243	486	1.92	15.69	3.71	0.93
55				193	19	20	122	133	289	2.44	17.71	2.48	1.74
a4[b]	697			48	63	26	29	145	195	2.56	1.33	0.54	0.68
a5[b]	694			44	65	23	28	139	192	2.43	1.18	0.55	0.58

Column Na^+ = K + Na content for samples Nos. 51–55.
[a] mNa/mCl: the mole ratio of Na/Cl.
[b] a4 and a5 are river water sampled from the Lower Heihe River.

and the Ejina Basin in the lower reaches. The Yingluoxia Gorge is the divide of the Upper and Middle Heihe River, and the Zhengyixia Gorge is the divide of the Middle and Lower Heihe River. The Lower Heihe River splits into two branches at Langxinshan in the Ejina Basin (Fig. 1), which flows to the East and West Juyan Lake, 240 km north of Langxinshan, respectively. Riverside grassland, with an area of 2457 km^2, is the main natural pastureland of the Ejina Oasis and is reliant on the Heihe River. The grassland at Gurinai is located 100 km east of the Heihe River, with an area of 6518 km^2 (Cao et al., 2004).

The basin is filled with unconsolidated Quaternary sediments with a depth of tens to 300 m. Its basement is the Jurassic. The Quaternary consists of single, dual or multi-layers separated by fine grained clay layers or lenses of aquifer sediment with grain size decreasing from coarse sands in the south to fine sands in the north. The hydraulic conductivity values found from pumping tests are in the range from 1×10^{-5} m/s to 5×10^{-4} m/s. Porosity is in the range from 0.2 to 0.30. The underlying bedrock aquifers are fractured fragmentary rocks of Jurassic, pre-Mesozoic fractured magmatic metamorphic rocks, which are primarily distributed on the basin boundaries in the south, west and north. In Jurassic rocks the yield of a single well is less than 100 m^3/d and in pre-Mesozoic rocks less than 10 m^3/d.

The general direction of groundwater flow is from south to north towards the Juyan Lakes, with a hydraulic gradient of about 0.6 % in the south and >1% in the north. The hydraulic gradient is less than 0.1% from Dingxin to Gurinai.

Evaporation of groundwater from the phreatic aquifer mainly occurs in the northern part of the basin and in the Gurinai area, resulting in salinization of groundwater and accumulation of salt in soil (Wen et al., 2005).

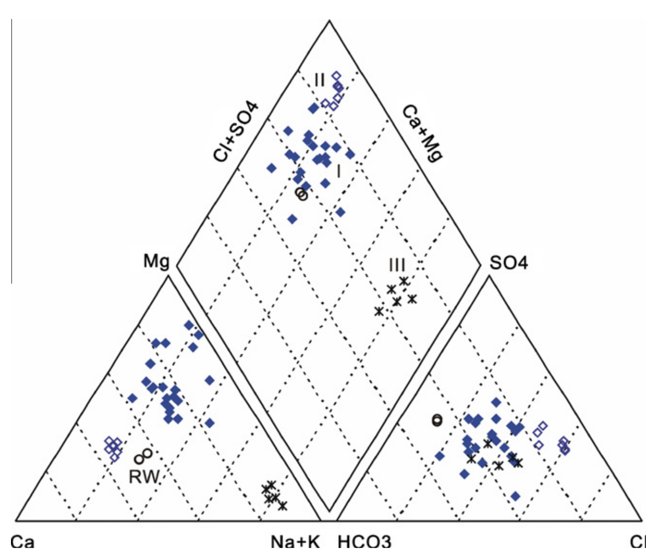

Fig. 2. Piper diagram of groundwater samples. Solid diamond: groundwater along the river channels (Group I water); open diamond: water near the Juyan Lakes (Group II water); asterisk: water from Gurinai (Group III water); open circle: river water (RW).

3. Sampling and measurements

Three sampling campaigns were carried out, in September–October 2002, June 2003, and July 2004, respectively. The sampling locations are shown in Fig. 1.

Samples for CFC analysis were collected by filling and capping glass bottles under water, a sampling method later published by the IAEA (2006). For each sample, 3–5 bottles were filled, 2 or 3 of which were analyzed. Temperature, pH, electric conductivity (EC), and dissolved O_2 (DO) were measured in the field with a handheld meter. CFC-11, CFC-12, and CFC-113 were measured by a purge-and-trap gas chromatography procedure in the Groundwater Dating Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG-CAS). The procedures are described in detail by Oster et al. (1996). The detection limit for each CFC is about 0.01 pmol/L of water. The analytical error of the CFC measurement is less than ±5%.

Waters for analyses of $\delta^{18}O$ were prepared using the CO_2 equilibration method (Epstein and Mayeda, 1953). The Cd-reduction method was used for determination of δ^2H. The $\delta^{18}O$ and δ^2H were determined with a Finnigan MAT 252 mass spectrometer. The isotope compositions were reported in standard δ-notation representing ‰ deviations from the V-SMOW standard (Vienna Standard Mean Ocean Water). Precisions for δ^2H and $\delta^{18}O$ determination are ±1.0‰ and ±0.2‰, respectively.

For ^3H analyses the water samples were enriched using the electrolytic enrichment method with a ^3H enrichment factor of about 20. Tritium was measured by the liquid scintillation counting method (Quantulus 1220™) with a detection limit of 0.5 TU.

Samples for cation analysis were stabilized by adding 1% HNO_3. Major anions (Cl, SO_4 and HCO_3) were determined by ion chromatography (Dionex DX-120). The analytical precision is 3% for the anion concentration based on reproducibility of replicate samples. The detection limit of the analysis is 0.1 mg/L for undiluted samples. Cations were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

4. Results

4.1. Major ions

The groundwater samples are characterized by a moderate degree of variability with respect to electrical conductivity (EC), ranging from 612 μs/cm to 4440 μs/cm (Table 1). In general the samples are neutral or slightly alkaline with pH values between 6.9 and 8.7. The water samples are divided into three major groups on the Piper diagram (Fig. 2), corresponding to the three groups identified with stable isotopes (see Section 4.2 below). Groundwater samples which were collected in the vicinity of the river (Group I) have different compositions to groundwater samples in Groups II and III.

The samples collected along the river channels (Group I samples) are characterized by a HCO_3–Cl–Ca or HCO_3–Cl–Ca–Na type of water. The EC values of these samples are 612–4440 μs/cm, and the temperature ranges from 10.6 to 20 °C, with the pH values between 6.9 and 8.4. Compared with the other two groups Group I waters have a broader range of EC, pH and temperature, indicating the impact of river water on the groundwater. The high mMg/mCa ratio (1.35–31) is indicative of dolomite weathering or carbonates containing a high concentration of Mg. The mineralization of groundwater is relatively low due to the recharge of river water in the south of Langxishan, while the overall mineralization and salinity increase northwards, especially in the depocenter of the Juyan Lakes.

Samples 44–50 collected near the Juyan Lakes (Group II) are characterized by a HCO_3–Cl–Na type of water. The EC values of these samples are 1740–2600 μs/cm, and the temperature ranges from 12.2 to 15.5 °C with the pH values between 7.7 and 8.2. The dissolution of evaporates may increase the Cl and Na concentrations. The lowest mMg/mCa ratio (0.53–0.62) is indicative of carbonate dissolution.

The samples collected from Gurinai (Group III) are characterized by a Cl–Ca type of water. The EC values of these samples are 941–2240 μs/cm, and the temperature ranges from 14.5 to 18.8 °C, with the pH values between 7.8 and 8.7. Chloride, SO_4 and HCO_3 concentration for groundwater from Gurinai are almost equally predominant anions, while Na and K are the most dominant cations (mNa/mCl >1) from dissolution of halite and related minerals in evaporites originating from high evaporation and soil salinization. The dissolution of silicates (e.g. albite) may be occurring, causing the high ratio of mNa/mCa (12.2–17.7). Evaporation is the primary control on the Cl concentration.

4.2. Stable isotopes

Three groups of groundwater in the Ejina Quaternary porous aquifer can be distinguished on the basis of the stable isotope data (Table 2), suggesting that they are from different recharge areas (Fig. 3).

Group I waters, collected along the river, have $\delta^{18}O$ values in the range of −8.4‰ to −6.7 ‰, and δ^2H values of −58‰ to −42‰, similar to the stable isotope composition of river water. They fall along the global and local meteoric water lines. This indicates that river water is the recharge source for the groundwater.

Group II waters are represented by samples collected near the Juyan Lakes (Nos. 44, 45, 46, 47 and 48). They have $\delta^{18}O$ values in the range of −9.7‰ to −10.2‰ and δ^2H values of −73‰ to −88‰, having a $\delta^2H/\delta^{18}O$ slope similar to the meteoric water line. The heavier stable isotopes of group II waters tend to be more depleted than Group I waters, indicating that these waters are hydraulically isolated from the Heihe River. Stable isotope data of the springs in this group indicate a discharge of regional groundwater to the Ejina Quaternary porous aquifer.

Group III waters are represented by samples collected from Gurinai (Nos. 51–55). These samples are more enriched in ^{18}O than ^2H, plotting below the global and local meteoritic water line (Fig. 3), with $\delta^{18}O$ values in the range −5.1‰ to −1.1‰, and δ^2H values of −63‰ to −36‰. Isotopic compositions of shallow groundwater samples from Gurinai have evolved from meteoric water similar to the Badain Jaran samples and have been similarly enriched by evaporation (Geyh and Gu, 1998; Gates et al., 2008a). Gates et al. (2008a) assume that Gurinai is a discharge zone for the Badain Jaran shallow aquifer based on regional hydraulic head patterns.

4.3. CFC apparent ages

Results of the age evaluation of groundwater CFCs are given as "apparent ages" and summarized in Table 2. Of the total 55 samples, 19 samples (Nos. 1–19) have CFC concentrations close to those in equilibrium with modern air, having younger CFC apparent ages (<30 a). The other 36 samples (Nos. 20–55) show relatively low CFC concentrations, having older CFC apparent ages (>30 a).

The annual mean air temperature in the plain area is ∼8 °C. The mean groundwater temperature is 14.2 °C, with 90% samples having temperature between 10 and 17.3 °C. The annual mean air temperature is relatively low compared with the temperature of shallow groundwaters. Because the local precipitation (<40 mm/a) cannot reach the groundwater in the Ejina Basin, the annual mean air temperature is not suitable for estimation of recharge temperature. Considering that the groundwater near the Heihe River receives recharge mainly from the river, the temperature of

Table 2
Analytical results of CFCs and isotopes for ground water in the Ejina Basin.

Sample No.	Sampling date (yy/mm/dd)	Well depth (m)	Temp. (°C)	EC (μc/cm)	Dissolved oxygen (mg/L)	*n*	CFC concentration pmol/kg			Apparent age years			$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H TU
							CFC-11	CFC-12	CFC-113	CFC-11	CFC-12	CFC-113			
1	2004-7-1	10	11	2940		2	1.99 ± 0.05	1.48 ± 0.03	0.2 ± <0.01	30	24	18			
2	2002-10-2	7	14.2	3630	7.4	2	1.26 ± 0.01	1.48 ± 0.44	0.09 ± 0.03	30	19	21			23.1
3	2002-9-26	200	14.5	1565	2.1	2	1.27 ± 0.04	0.21 ± 0.75	0.06 ± 0.02	30	39	25	−7.6	−50	14.2
4	2002-9-26	80	16.7	780	5.3	3	0.53 ± 0.01	0.06 ± 0.12	0.09 ± 0.02	34	47	20			
5	2002-9-26	60	14.8	1714	7.4	3	4.88 ± 0.11	2.28 ± 0.02	0.39 ± 0.01	M	M	M	−7.3	−47	16.3
6	2002-9-26	80	15.9	1066	8.9	3	4.36 ± 0.01	2.11 ± 0.1	0.51 ± 0.01	M	M	M	−7.5	−49	16.9
	2004-6-29	80	15.4	1290		2	4.86 ± 0.08	1.98 ± 0.14	0.38 ± 0.01	M	12	M			
7	2002-9-27	120	14.8	947	7.6	3	0.61 ± 0.04	0.28 ± 0.11	0.08 ± 0.01	34	36	22	−7.8	−51	
8	2002-9-27	79	13.2	1874	9.3	1	4.75	2.8	0.44	M	M	M	−7.0	−46	16.8
9	2003-7-5	40	13.8	2140		2	1.56 ± 0.03	0.69 ± 0.11	0.17 ± <0.01	30	31	17			7.8
10	2003-7-5	136	14.7	695		2	0.33 ± <0.01	0.11 ± 0.03	nd	39	45	>34	−7.9	−52	0.6
11	2002-10-1	120	10.3	1600	3.1	2	3.2 ± 0.08	1.73 ± 0.04	0.2	23	20	17	−7.5	−48	28.6
	2003-7-5	120	10.7	1820		2	2.29 ± 0.07	1.17 ± 0.06	0.17 ± 0.02	28	27	19			
12	2002-10-1	3	15.9	1540		1	0.41	0.16	nd	36	40	>34	−7.7	−50	4.1
13	2004-6-24	13	18.5	854		1	1.03	0.64	0.15	32	31	18			
14	2004-6-24	13	18	2050		1	1.92	1.05	0.13	27	25	19			
15	2004-6-24	13	15.6	1700		1	3.57	1.62	0.26	17	18	14			
16	2004-6-24	3	18	646		1	0.86	0.59	0.08	33	31	22			
17	2004-6-24	13	16.7	920		2	1.81 ± <0.01	1.13 ± 0.02	0.16 ± <0.01	28	24	18			
18	2004-6-24	13	14.6	1240		1	1.34	0.92	0.12	31	29	21	−7.3	−48	25.9
19	2004-6-24	13	19.5	1100		2	3.42 ± 0.02	1.46 ± 0.03	0.26 ± 0.01	12	17	12			
20	2002-10-1	20	12.1	1600	2.4	2	0.69 ± 0.29	0.49 ± 0.12	0.04 ± <0.01	34	33	28	−7.0	−48	
21	2002-10-1	20	12.1	2590	4.5	3	3.02 ± 0.04	1.49 ± 0.07	0.26 ± <0.01	22	21	14	−7.0	−46	
22	2002-10-1	10	17.3	4470	1.1	1	0.71	0.37	0.05	32	34	24			
23	2004-6-26	13	13.9	990		1	0.79 ± 0.08	0.46 ± 0.45	0.08 ± 0.13	35	35	25			
24	2004-6-26	13	13	1690		2	0.21 ± 0.02	0.17 ± 0.01	nd	42	43	>34			
25	2004-6-26	0.3	20	1828		2	0.82 ± 0.02	1.19 ± 0.01	0.06	33	21	24			
26	2004-6-24	3.5	12.5	2690		3	0.1 ± 0.02	0.12 ± 0.02	nd	47	46	>34			
27	2004-6-24	2.5	14.4	2986		2	0.7 ± <0.01	0.57 ± 0.04	0.07 ± 0.01	35	33	25			
28	2004-6-24	50	13.1	1970		2	0.86 ± 0.07	0.54 ± 0.11	0.09 ± 0.01	34	34	24			
29	2003-7-5	5	12.3	660		2	0.27 ± 0.06	0.21 ± 0.1	nd	40	41	>34			0.4
30	2004-6-24	120	14.3	612		1	nd	nd	nd	pre-1950	pre-1950	>34	−8.4	−58	2.3
31	2002-10-1	10	13.1	1140	4.3	1	0.37	0.2	nd	38	40	>34			
32	2004-6-26	13	11.8	1970		1	0.22	0.15	nd	43	44	>34			
33	2004-6-26	12	13	2180		2	1.48 ± 0.02	0.97 ± 0.01	0.15 ± <0.01	31	29	20			
34	2002-9-30	20	14.2	4720	1.5	2	2.66 ± 0.34	0.39 ± 0.56	0.09 ± 0.05	23	34	22	−6.8	−46	
35	2002-10-1	136	14.1	1710	4.7	1	0.24	0.15	nd	40	41	>34	−6.6	−50	3.1
	2004-6-26	100	14.2	1130		2	0.04 ± <0.01	0.06 ± 0.01	nd	50	50	>34	−6.8	−53	0.4
36	2004-6-28	120	12.6	2950		1	0.87	0.93	0.07	35	29	26	−7.5	−53	6.1
37	2004-6-28	120	10	4440		1	0.05	nd	nd	50	pre-1950	>34			
38	2002-9-30	45	11.7	3000	4.9	1	0.89	0.25	0.06	33	39	25	−6.8	−45	24.9
39	2002-9-30	9	14.9	4610	2.1	3	0.43 ± 0.12	0.51 ± 0.18	nd	36	32	>34			
40	2002-9-30	120	12.1	939	3.2	2	0.3 ± 0.09	0.1 ± 0.18	0.05 ± 0.05	39	46	27	−7.0	−49	6.5
41	2003-7-6	25	11.6	2640		1	4.44	2.45	0.47	16	11	<12	−6.7	−42	27.4
42	2003-7-6	12	12.4	1130		2	4.69 ± 0.13	2.55 ± 0.08	0.45 ± 0.04	14	C	<12			27.9
43	2002-9-30	80	12.4	2500	2.7	1	1.14	0.26	0.06	31	38	25	−7.8	−57	0.9
44	2004-6-27		14.6	2490		1	0.57	0.27	0.04	37	39	29	−9.7	−73	8.0
45	2004-6-27		13.5	2360		1	0.49	0.27	0.07	38	39	26			
46	2004–6-27		12.2	2290		1	0.16	0.08	nd	44	48	>34			
47	2002-9-28	120	12.8	2650	9.5	3	0.35 ± 0.03	nd	nd	38	pre-1950	>34	−10.2	−88	3.7
	2003-7-6		14.3	2600		1	0.04	nd	nd	49	pre-1950	>34			
	2004-6-27		14.5	2600		3	0.08 ± 0.02	0.04 ± 0.01	nd	47	52	>34			
48	2004-6-27	180	15.8	1780		1	0.71	0.59	0.07	35	32	24	−9.8	−73	1.4
49	2004-6-27	110	15	1740		3	0.3	0.14 ± 0.01	nd	40	43	>34			
50	2003-7-6	140	15.2	1910		2	0.13	nd ± 0.07	nd	44	pre-1950	>34			9.1
	2004-6-27	150	15.5	2170		2	nd	nd	nd	pre-1950	pre-1950	>34			
51	2003-7-3	5	13.8	2130		1	0.11	0.13	nd	45	43	>34	−3.0	−50	12.9
52	2002-9-28	6	13.8	1212	5.1	1	nd	nd	0.04	pre-1950	pre-1950	27	−2.9	−48	1.5
53	2002-9-28	10	15.3	1234	5.6	3	0.75 ± 0.1	0.4 ± 0.08	0.04 ± 0.02	33	34	28			
54	2002-9-28	12	16.3	1204	5.7	3	2.12 ± <0.01	0.88 ± 0.51	0.13 ± 0.01	25	26	17	−3.9	−53	
55	2003-7-3	5	13	1010		1	nd	0.35	nd	pre-1950	37	>34	−3.4	−53	9.5

EC: electrical conductivity; nd: not detected, or below detection limit (⩽0.03 pmol/kg). M: Modern water. *n*: Number.
Shallow groundwater with well depth ⩽80 m; deep groundwater with well depth >80 m.

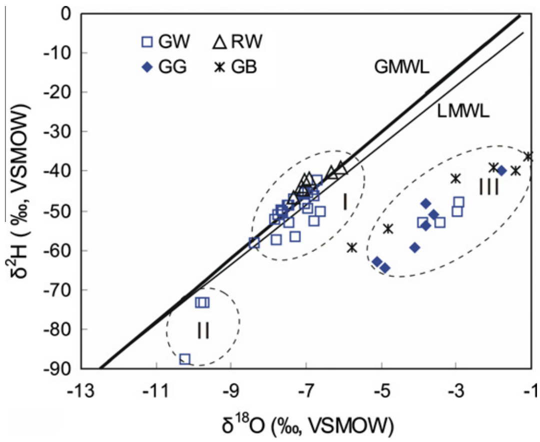

Fig. 3. Stable isotopic composition of groundwater in the Ejina Basin Porous Aquifer. Three groups of water can be identified. Group I: groundwater along the Heihe River, closely connected to the river water; Group II: regional background water north of Juyan Lakes, isolated from the river water; Group III: groundwater in Gurinai, discharge from the Badain Jaran Desert. GMWL: global meteoric water line. LMWL: local meteoric water line (Chen et al., 2006). GW: groundwater; RW: river water; GG: groundwater in Gurinai; GB: groundwater in Badain Jaran Desert (data for GG and GB are from Geyh and Gu, 1998).

river water should be closer to the recharge temperature. Table 3 shows the data for the river water. The samples collected in September 2002 have a mean temperature of 18.1 ± 1 °C, except for three samples (R5, R7 and R8, with data in parentheses). Using this temperature the calculated CFC concentrations are close to the equilibrated values. Samples R5, R7 and R8 (data in parentheses in Table 3) have lower temperatures. The CFC concentrations were lower than the equilibrium values with the 2002 air. Most probably these waters contain older groundwater discharge. Three samples were collected from upstream in the river in September 2004. Table 3 shows that the three waters were close to the equilibrated values with the 2004 air.

Since the river flow mainly occurs between July and September (at other times river flow is low, or even zero), the recharge temperature is estimated to be between 11 and 19 °C (see Table 3). The CFCs are more or less close to the equilibrium concentrations if the temperature of the river water is taken as the equilibrium temperature. The temperature range of the river water coincides with the groundwater temperature range (10–17.3 °C), indicating that temperature changes after infiltration are small. Therefore, the measured temperatures of groundwater are used as recharge temperatures to calculate the water age.

The impact of excess air on CFC concentrations is relatively small (Beyerle et al., 1999; Zuber et al., 2005). Samples 12 and 29 collected from wells with depths of 3 m and 5 m do not contain CFC-113, indicating that the shallow groundwaters do not trap and dissolve extra surface and unsaturated zone air. Many other low CFC (or even CFC-free) waters are found in shallow wells of less than 10 m in the Ejina Oasis (e.g. Nos. 10, 24–27, 31–34, 39 and 51–55). These findings indicate that CFCs entering groundwater by direct gas–water equilibration at the water table do not reach even shallow wells. In the absence of vertical recharge, the groundwater table acts as a virtually impermeable boundary for CFCs, since molecular diffusion through the water-filled pore space is lower by four orders of magnitude than that in soil air (Oster et al., 1996). For this reason the CFC data are not corrected for excess air that is entrained during infiltration of recharge through the unsaturated zone.

Dissolved O_2 concentrations are >2 mg/L in most samples and it is assumed that CFCs are conservative under the aerobic conditions in the aquifer systems. The Ejina Oasis is located at a remote and underdeveloped area, and local elevation of CFC concentrations in air is not observed (see river water samples in Table 3). The CFC input functions derived from the CFC mixing ratios in Northern Hemisphere air (IAEA, 2006) are used.

CFC-11 and CFC-12 apparent ages agree well for most of the samples (Fig. 4), and the difference of CFC-11 and CFC-12 apparent ages for 42 samples is less than 5 a (within the dashed lines in Fig. 4).

4.4. Spatial distribution of CFCs

Samples 5–8, 11, 13–19, 20–23, 41–42 have higher CFC concentrations, manifesting the degree and scope of river infiltration. Samples collected in the vicinity of the east bank of the Lower Heihe River (e.g. Nos. 1–4, 24, 26, 29–32, 35–36, 37 and 39) have low CFC concentrations, and many of them do not contain detectable CFC-113, indicating old ages (>30 a) and the decrease of river infiltration.

Three springs (samples Nos. 44, 45 and 46) located between the East and West Heihe Rivers contain relatively low CFC concentrations, with CFC-12 apparent ages of 39, 39 and 48 a, respectively. Camel Spring (sample No. 47), which is a spring in the Jurassic aquifer located at the north of the Juyan lakes, is CFC-free.

Table 3
Field data, CFC concentrations and isotope compositions in river water samples.

No.	Sampling date	Distance (km)	Temp. (°C)	pH	EC (μs/cm)	CFC-11 (pmol/kg)	CFC-12 (pmol/kg)	CFC-113 (pmol/kg)	$\delta^{18}O$ (‰)	δ^2H (‰)	^3H (TU)
R1	2002-9-24	0	19.3	8.4	730	4.88	2.33	0.40	−7.35	−46.6	
R2	2002-9-26	26	18.4	8.4	801	4.23	2.38	0.37	−7.12	−44.0	28
R5	2002-9-27	56	(11.1)	8.4	781	(4.31)	(2.37)	(0.39)	−7.07	−44.5	29.3
R7	2002-9-27	99	(14.2)	8.5	786	(4.02)	(2.11)	(0.35)	−7.04	−42.4	
R8	2002-9-27	112	(15.0)	8.4	789	(4.81)	(2.57)	(0.38)	−6.93	−41.8	26.6
R40	2002-9-28	241	17.1	8.5	815	3.74	1.98	0.33	−6.32	−40.4	27.6
R43	2002-9-28	266	17.4	8.7	835	4.24	2.20	0.35	−6.09	−39.0	
		Mean[a]	18.1 ± 1.0			4.27 ± 0.47	2.22 ± 0.18	0.36 ± 0.03			
		Calc.[b]				3.59	2.04	0.33			
S1[c]	2004-9-22	Luocheng bridge	21.7	8.4	597	3.15	1.63	0.26	−7.75	−47.4	
S2	2004-9-22	Luocheng Huo village	22.1	8.3	605	3.23	1.69	0.27	−7.96	−46.9	
S3	2004-9-22	Zhengyixia	22.1	8.1	618	3.12	1.63	0.27	−7.84	−46.9	
		Mean[a]	22 ± 0.2			3.17 ± 0.06	1.65 ± 0.03	0.27 ± 0.01			
		Calc.[b]				2.93	1.72	0.27			

[a] Mean measured values. For the samples collected in September 2002 the mean values without data in parentheses.
[b] Calculated values based on the measured mean water temperature.
[c] S1–S2: samples from the middle reach of Heihe River, south of the Zhengyixia Gorge (S3).

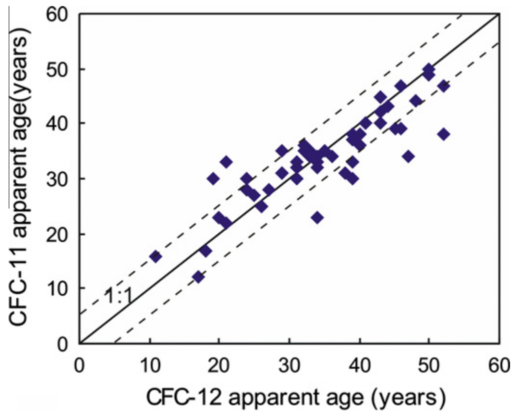

Fig. 4. Comparison of apparent CFC-11 and CFC-12 ages for the groundwaters sampled in 2002, 2003 and 2004.

Five groundwater samples were collected from Gurinai in 2002 (Nos. 52, 53 and 54) and 2003 (Nos. 51 and 55), at depths of 5–12 m. Except for sample 54, which contains relatively high CFC concentrations samples 51, 53 and 55 have very low CFC concentrations and sample 52 is CFC-free.

The CFC-12 concentration decreases from Langxinshan northward to the Juyan Lakes (Fig. 5). The apparent CFC-12 ages are <20 a around Langxinshan gauging station, 30–40 a between Langxinshan and Ejina, >40 a in Juyan Lakes and >50 a (Samples 49 and 50) north of the Juyan Lakes (Fig. 6). The apparent age of ground waters increases with distance downstream along the river channels, in agreement with groundwater level contours, where groundwater flows towards the NE and north (Fig. 1). The increasing CFC ages could be explained by lower groundwater velocities.

4.5. Tritium

In the study area quantitative ^{3}H dating is subject to many uncertainties but semi quantitative dating is possible and informative

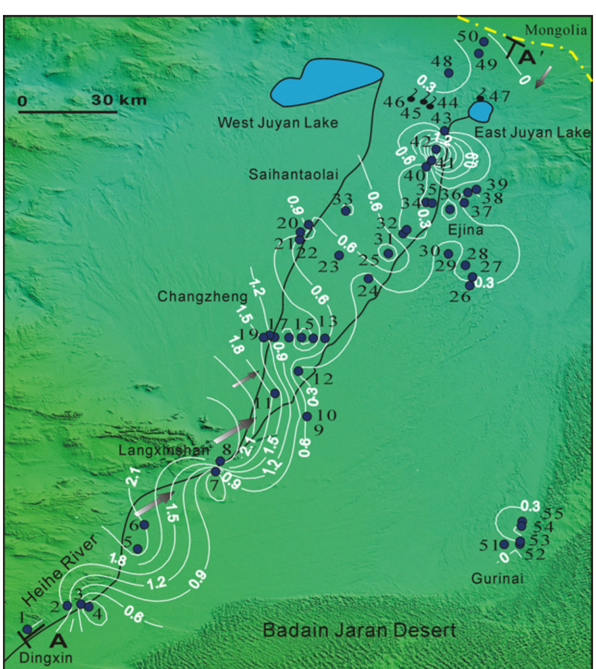

Fig. 5. Kriging spacial distribution of CFC-12 concentrations (in pmol/L) in the Ejina basin during 2002–2004. Legends are the same as in Fig. 1. The arrows indicate the predominant direction of river recharge to the groundwater.

(Chen et al., 2006; Ma et al., 2008; Qin et al., 2011). By 2001, the maximum 1963 bomb peak of ^{3}H would have been reduced to ~500 TU; and groundwater with ^{3}H activities above 50 TU could be an unmixed water recharged in the 1960s. A groundwater sample with ^{3}H concentration ranges between 15 and 45 TU could be an unmixed water recharged after 1970, or mixed water containing a bomb peak and a ^{3}H-free component. The ^{3}H range 1–15 TU is typical for groundwater mixtures of pre-1950 water with a ^{3}H -bearing contributor. Tritium concentrations <1.5 TU are regarded as indicative of pre-1952 water.

Tritium data are available for 26 groundwater samples, and they range from 1 to 29 TU. Groundwaters with high ^{3}H are dominantly distributed in the south of Langxinshan (within samples 1–19). Samples 2, 11, 18, 41 and 42 have ^{3}H contents of 23, 29, 26, 27 and 28 TU, close to that of the river water of 29.3 and 26.6 TU in 2002. The other samples have ^{3}H contents of <18 TU. Groundwaters having ^{3}H contents higher than 30 TU were not found in this study. Tritium values >10 TU are in groundwater samples collected near the river channel. The ^{3}H values decreased to 2–10 TU in groundwater samples collected far away from the river channels.

4.6. Variation of CFCs and tritium

Fig. 7 shows that ^{3}H and CFC concentrations decrease with depth. The shallow groundwaters (with depths ⩽80 m) have a wide range of CFC concentrations ranging from modern to CFC-free water. On the other hand, almost all deep groundwaters (with depths >80 m) have low CFC concentrations.

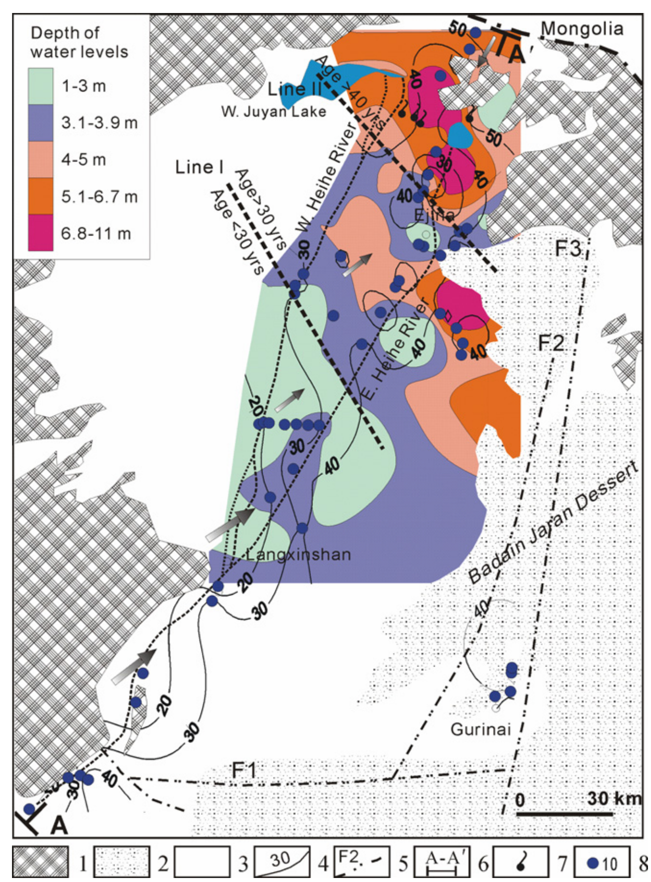

Fig. 6. Contour lines of CFC apparent ages for groundwaters in the Lower Heihe River area. Solid circles indicate sampling locations. The thick dashed line separates the groundwaters based on the CFC apparent age of <30 a (on the left) and >30 a (on the right). The data for depth of water levels are from Peng et al. (2011).

For two adjacent wells (samples 9 and 10), the CFC-12 apparent age of the shallow groundwater (No. 9, well depth 40 m) is younger (31 a) than the deep groundwater (No. 10, well depth 136 m) (45 a), while the ^3H content of the shallow groundwater is higher than the deep groundwater (7.8 TU compared to 0.6 TU). Similarly, the CFC and ^3H contents are higher in the shallow groundwater (No. 41, 27.4 TU) than in the deeper groundwater (No. 40, 6.5 TU).

At one site, two deep wells were sampled. One of which was sampled in 2002 (No. 35, at a depth of 136 m, ^3H = 3.1 TU) and the other well was sampled in 2004 (No. 35, at a depth of 100 m, ^3H = 0.4 TU). Both samples have low ^3H contents, consistent with low CFC concentrations, suggesting that these waters were emplaced before the nuclear bomb tests.

Samples 51 and 55 have ^3H concentrations of 12.9 TU and 9.5 TU, respectively. These two samples have low concentrations of CFC-11 and CFC-12, and contain no CFC-113. CFC and ^3H data indicate that these two waters contain dominantly pre-1970s recharge. The water sample collected from a spring at Gurinai (No. 52) has a ^3H concentration of 1.5 TU and this water is CFC-free, indicating old (pre-1950s) water.

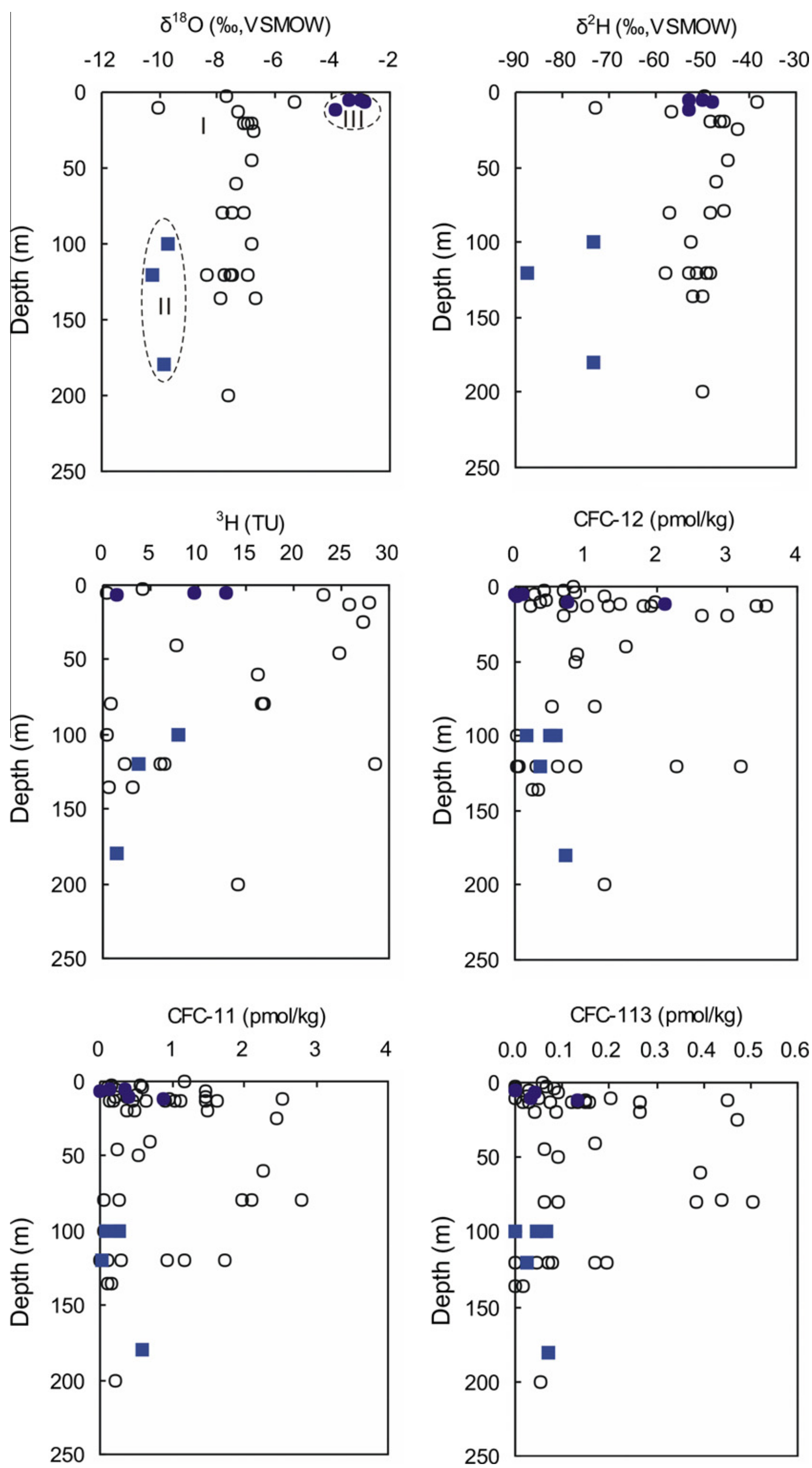

Fig. 7. Variation of $\delta^{18}O$, δ^2H, ^3H and CFC concentrations with well depth. I: Group I water (open diamonds); II: Group II water (solid squares); III: Group III water (solid circles).

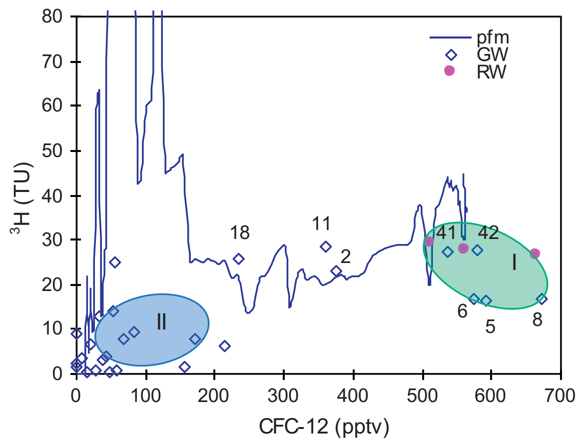

Fig. 8. Plots showing relationship of ^{3}H activity and CFC-12 atmospheric partial pressures for groundwater (open circle) sampled between 2002 and 2004 in the Ejina Basin. The data are compared to the model of piston flow (pfm), calculated using data from the Zhangye station in the middle Heihe River (Qin et al., 2011). GW: groundwater; RW: river water.

Fig. 8 is a plot comparing CFC-12 and ^{3}H data. Most of the data plot mainly in two regions: Region I (young end member) and Region II (old end-member). Waters plotting in Region I are located south of Langxinshan (southern part of the Ejina basin), whereas waters plotting in Region II are located in the Changzheng to Juyan Lakes area (northern part of the Ejina Basin). Three samples (Nos. 2, 11 and 18) plot between the two regions close to the piston-flow line. Except for samples 41 and 42 which plot in Region I, all the samples collected from north of Langxinshan (Region II) are relatively old (pre-1970s), as determined by CFC data. Fig. 8 also shows the importance of using CFCs. Samples 44, 50 and 55 which plot in Region II have similar ^{3}H values to samples 5, 6 and 8 which plot in Region I. Without the help of CFCs, ^{3}H data alone cannot distinguish between these two groups of samples.

5. Discussion

5.1. Direct recharge

Modern direct (diffuse) recharge within the Ejina Oasis is minimal due to low rainfall (<40 mm/a). Edmunds et al. (2006) show that the modern diffuse recharge is <3 mm/a in the Minqin Basin (several hundred km to the east, beyond the scope of Fig. 1) and Gates et al. (2008b) show that the modern diffuse recharge is about 1 mm/a in the Badain Jaran desert. Water heads in Gurinai are lower than the Heihe River to the west. They are also lower than the shallow groundwater level in the desert dune to the east. In principle, the Gurinai lowland can be recharged by both the Heihe River and the Badain Jaran desert. The close correspondence in major ion compositions and stable isotopes in Gurinai and Badain Jaran groundwaters implies a common hydrogeochemical history for the two areas (Fig. 2 and 3). Gates et al. (2008a) show that the Gurinai groundwater is recharged from areas east of the desert dunes. Diminishing base flow from outside the dune field has reduced supplies to the desert's shallow groundwater and discharge to groundwater in Gurinai. The Gurinai wetland is facing degradation and desertification.

5.2. Recharge pathway of groundwater along the Lower Heihe River

Fig. 9 shows that the infiltration of river water occurs along the river channels, heavy infiltration occurs particularly in the river section south of Langxinshan, where groundwater CFC apparent ages are <20 a, consistent with high leakages observed in run off (Zhang et al., 2003) and results of a lysimetric experiment on the riverbed (Cao et al., 2004). Groundwaters near the Juyan Lakes have CFC apparent ages of 30–40 a, implying that recharge of river water to the groundwater system decreases significantly.

The decreased recharge of river water is also reflected in the stable isotope data. The river water downstream becomes more enriched in heavier isotopes toward the Juyan Lakes, and correspondingly, the groundwater becomes progressively enriched in δ^{18}O and δ^2H from south to north (Fig. 10), indicating that the river water has experienced evaporation before infiltration. δ^{18}O and δ^2H values of both shallow and deep groundwaters (Group I) are more negative than the river water, but the groundwater and river water have similar patterns of change in isotopic composition downstream, showing a close hydraulic relationship.

Three zones can be outlined based on CFC and isotope data, revealing the recharge regime of infiltration of river water. The water in the three zones corresponds to water type I defined in Section 4.1.

(1) Recharge zone (water with high CFC concentrations and similar stable isotope compositions to river water)

This zone is located in the 0–100 km section of the river channel from samples 1 to 8, with samples 5, 6 and 8 having the youngest CFC apparent ages. The No. 8 groundwater has the same stable isotope values as the river water (Fig. 10), indicating direct infiltration of river water. The river water mainly recharges into the nearby groundwater system as it flows northwards, particularly in the river channel section south of Langxinshan. This is consistent with the observed maximum seepage capacity in Langxishan (Fig. 9) and the water table rise of 0–2 m from 2001 to 2009 after implementation of the water diversion project (Wang et al., 2011).

(2) Flowpath zone (water with low CFC concentrations and depleted in heavier isotopes)

In the 100–200 km river channel section, groundwater (from Sample 8 to 20) in the last decades has not received direct recharge through infiltration of river water. This is reflected in low CFC and ^{3}H contents (1 TU for Nos. 9 and 4 TU for No. 12). The shallow groundwater is relatively depleted in heavier stable isotopes, compared to river water (Fig. 10). A water table rise of 0–2 m was reported in this section of the river channel (Wang et al., 2011). Based on the present data, the rise of water table did not result from direct infiltration of river water, but was caused by increased discharge from the upper reaches (e.g. Langxinshan).

(3) Discharge zone (water with low CFC concentrations and depleted in heavier isotopes)

In general groundwater samples collected in the 200–260 km river channel section (from sample 20 to 44) have low CFC and ^{3}H contents, and are relatively depleted in heavy stable isotopes compared to river water (Fig. 10). This indicates a lack of river water infiltration, except for leakage in a few sites (Nos. 41 and 42) to shallow groundwater. The residence time of infiltrated river water in the Ejina Oasis is in the range of 30–40 a (Fig. 9), based on CFC data.

5.3. Leakage of river water

River water infiltration results in both CFC and heavier isotope enrichment in groundwaters. The following four hydrological processes are found to occur.

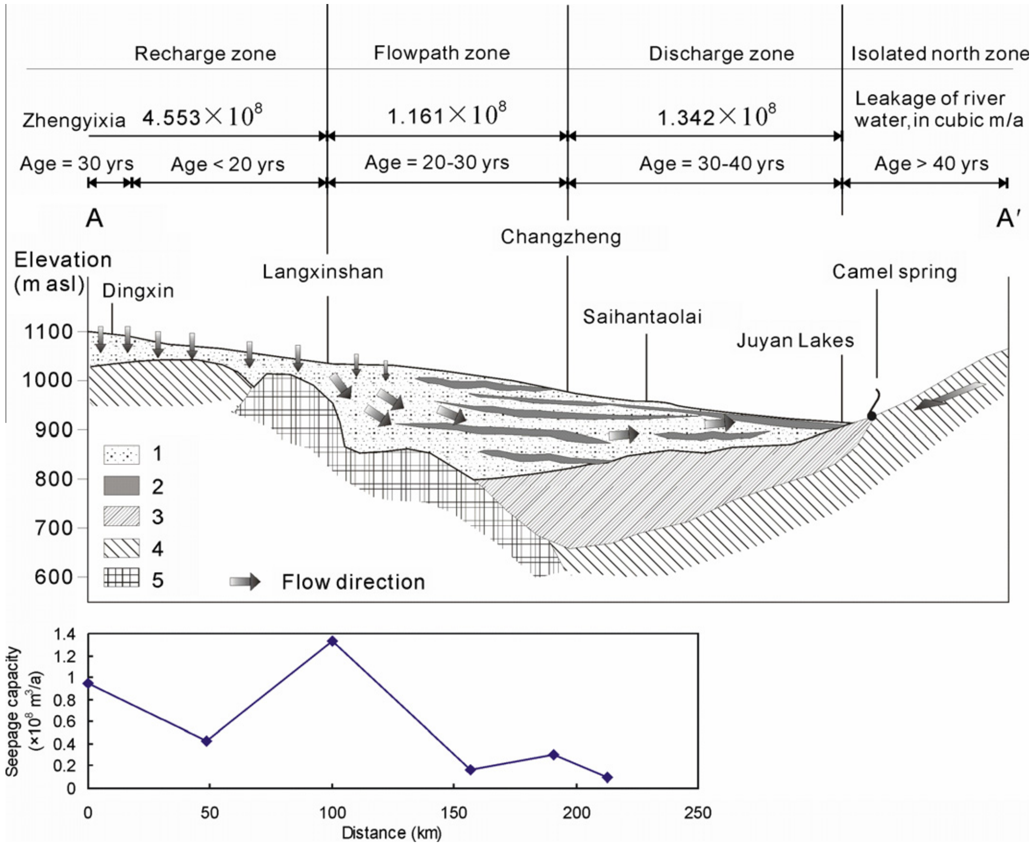

Fig. 9. Relationship of the monitored leakage of river water and CFC apparent ages in the Ejina Quaternary Aquifer. Distances are from well No. 1. 1: Quaternary sands and pebbles; 2: Quaternary clay; 3: Cretaceous mudstone; 4: Jurassic sandstone; 5: Proterozoic gneiss. Leakage amounts for river water are from Cao et al. (2004). Seepage capacity of the lysimetric experiment on the riverbed is from Zhang et al. (2003).

(1) Leakage of river water into the shallow aquifer in the discharge zone

The shallow groundwater (e.g. samples 41–42) has high CFC concentrations (Fig. 10) which are close to modern recharge, with ^{3}H content of 27–28 TU. The δ^{18}O and δ^2H values of sample 41 are close to those of river water ($\delta^{18}O = -6.7‰$ and $\delta^2H = -42‰$), and more enriched in heavier isotopes than the adjacent deep groundwater (No. 40). This indicates leakage of river water to the shallow aquifer. It seems that the leakage has not influenced the deep groundwater as indicated by the low CFC and ^{3}H contents (3 TU for No. 35 and 6 TU for No. 40) and more negative δ^{18}O and δ^2H values at 250 km downstream (Fig. 10).

(2) Cross-formational river water flow into the deep aquifer in the flowpath zone

The shallow groundwater 12 has low CFC and ^{3}H concentrations and the heavier isotopes are depleted (Fig. 10), indicating that it is not related to modern river water. Compared with sample 12, sample 11, which was collected from an adjacent deep well (Fig. 1), has relatively high CFC (with values close to those of the river water) and ^{3}H content (29 TU), and the heavier isotopes are enriched, indicating leakage of river water (Fig. 10D).

(3) Penetration of the shallow groundwater into the deep aquifer in the flowpath zone

The deep groundwater (e.g. wells 35 and 41) is older than the shallow groundwater (e.g. wells 34 and 40), and was recharged through penetration of the shallow groundwater.

(4) Upwelling of old groundwater

The deep groundwater 30 is depleted in ^{18}O and ^{2}H ($-8.4‰$ and $-58‰$), contains low ^{3}H (2 TU) and is CFC-free. Compared with sample 30 the deep groundwaters 35 and 40 are more enriched in heavier isotopes with δ^{18}O and δ^2H values close to those of shallow groundwater. This implies that sample 30 contains old water components resulting from upwelling of old groundwater, owing to groundwater over-exploitation.

5.4. Conceptual model of recharge

During humid climatic phases of the Pleistocene and periods within the early and middle Holocene, surface and groundwater were more abundant in the region (Mischke et al., 2005; Wang et al., 2008; Yang and Williams, 2003; Ma et al., 2003) and the Ejina Oasis shallow aquifer was probably replenished, in addition to the Heihe River, by rainfall through direct and mountain-front recharge. At the end of the mid-Holocene humid phase (approximately 6.5 ka BP), shallow groundwater levels were (15 m) higher than at present (Gates et al., 2008a), the discharge from the Badain Jaran desert was also a dominant source for the Eastern Ejina Oasis (e.g. Gurinai Oasis). Water tables, e.g. in Gurinai, fell as inputs diminished because of late Holocene aridification. Presently, direct infiltration of precipitation provides negligible recharge to the shallow phreatic aquifer, which is not able to support the current level of the Juyan Lakes and current head gradients. The Heihe River water becomes the only major input to the Ejina Oasis.

The mean leakage of the river water is 4.55×10^8 m^3/a between Zhengyixia and Langxinshan (Cao et al., 2004), as main recharge to the Dingxin Basin and the Ejina Oasis (Zhang et al., 2003). The fact

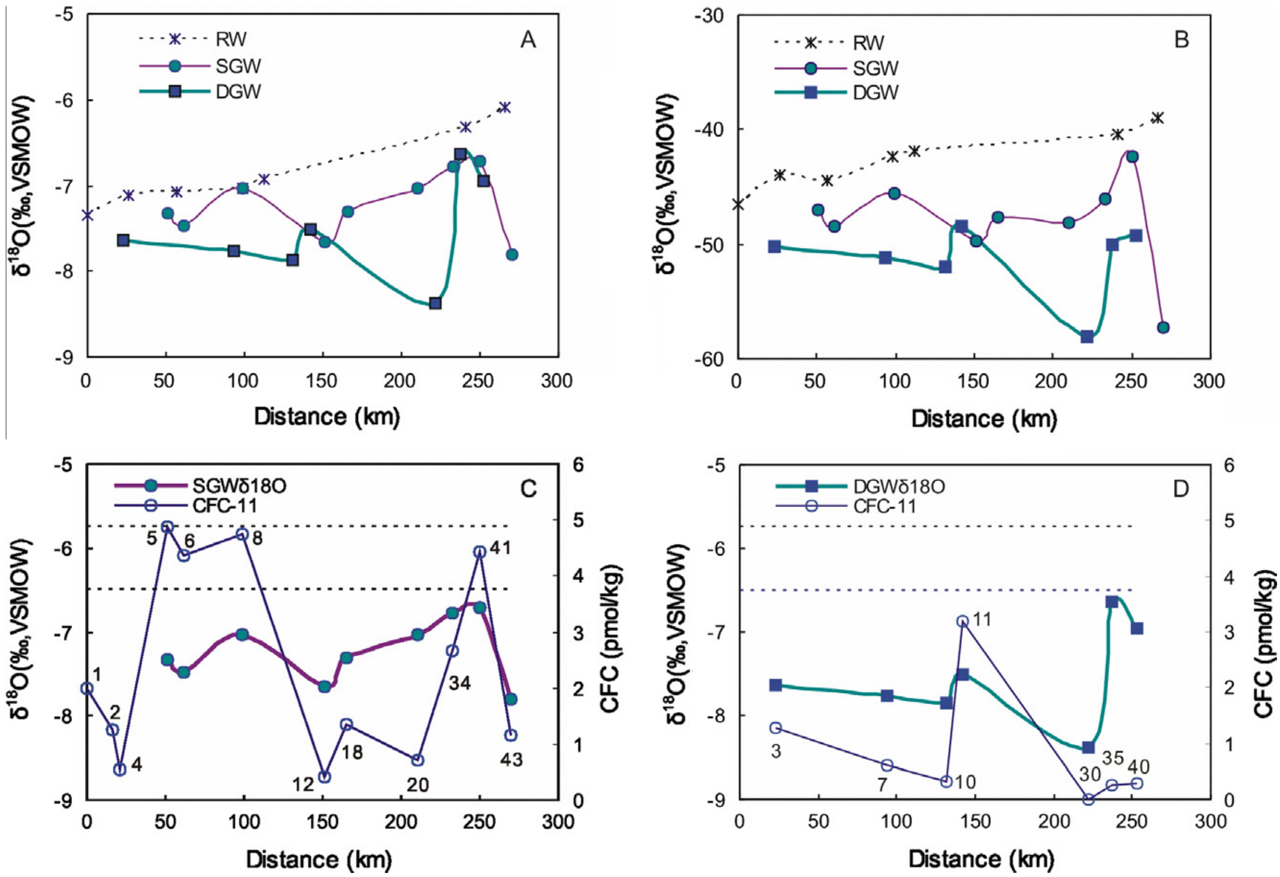

Fig. 10. Plots comparing $\delta^{18}O$, $\delta^{2}H$ and CFC values of river water and groundwater with distance downstream from Dingxin (Sample No. 1) (see Fig. 1 and 9). The dashed lines represent data for river water samples. For CFC-11 the measured highest and lowest values of the river water samples are given (see Table 3). RW: river water; SGW: shallow groundwater; DGW: deep groundwater. The numbers denote sample numbers of shallow (C) and deep groundwater (D).

that the regional distribution of CFC concentrations and variation of isotopic compositions in groundwater is in agreement with the general flow pattern indicates that this leakage is an effective recharge of groundwater in the Ejina Oasis. A new phenomenon is observed in the groundwater (Samples 1–4) in Dingxin, namely that CFC apparent ages in the range of 30–40 a are relatively old, compared with samples ca. 50 km downstream. Groundwater abstraction in the Dingxin Basin would cause reduced river water and groundwater discharge to the Ejina Oasis in the lower reaches. It implies that *in situ* infiltration of river water would be much less than current estimates.

In the section between Langxinshan and the Juyan Lakes, groundwaters contain low CFC and ^{3}H concentrations and they are more depleted in heavier isotopes, significantly distinct from the modern river water. This indicates that the leakage of 2.5×10^{8} m^{3}/a (the sum of leakage in the flowpath zone and discharge zone in Fig. 9) in this section cannot recharge the groundwater and is mostly consumed by evaporation and evapotranspiration. Zhao et al. (2007) suggested that the discharge of the Heihe River at Langxinshan hydrological station, should be 1.9×10^{8}–2.2×10^{8} m^{3}/a to maintain the present state of the Ejina Oasis, and that for the existing vegetation to reach the highest productivity, 4.3×10^{8}–5.2×10^{8} m^{3}/a would be needed to balance vegetation requirements and soil evaporation. The river leakage can only meet the water demand to maintain the present state of the Oasis without higher vegetation productivity.

The run off loss, monitored in gauge stations, could not reach the groundwater as effective recharge, because it would be lost to the atmosphere by evaporation and evapotranspiration. The evaporation capacity of groundwater at depths of <0.5 m in the Ejina area is up to 471 mm/a, with a maximum of 101 mm in June (Zhao et al., 2010). More water would be lost in the area of fine grained sediments, particularly in the low-lying part of the Juyan Lakes, resulting in salt accumulation.

Two deep (>6.8 m) water depression cones have formed in Ejina County and are spreading southwestward (Fig. 6). This has induced a "water loss" condition from the surface ecosystem and shallow groundwater system. A lower groundwater level would gradually lose its ability to maintain the ecosystems in the Ejina Oasis. CFC data also indicate that recharge from the area in Langxinshan does not reach Juyan Lakes in 50 a.

Although the river water in the arid regions has widely been regarded as the dominant source of recharge (Wu et al., 2000; Chen et al., 2006; Zhang et al., 2006), the present data indicate that the recharge is almost entirely consumed by evaporation and evapotranspiration and may make some of these earlier interpretations (the river water as a major recharge of groundwater) questionable.

6. Conclusions

The aquifer system along the lower reaches of the Heihe River has been investigated using environmental tracers to provide insight into river-groundwater interaction. Groundwater CFC apparent ages progressively increased in the direction of groundwater flow, approximately northeastward following the river channel, reaching a CFC apparent age of 40 a at the Juyan Lakes. Further north of the lakes, groundwater becomes CFC-free (age >50 a), containing only discharge from the regional groundwater system (Group II), with no admixed river water.

A clear age evolution along the flow line approximately parallel to the Heihe River is apparent, indicating that infiltration of river water is the dominant recharge mechanism. The direct recharge regime is located in Langxinshan and to the south. Two new findings have been obtained by integrated use of CFCs, isotopes and major ions: (1) due to the water diversion project, the shallow groundwater level has risen by 0–2 m in the upper reaches of the east Heihe River and in the areas of Saihantaolai–Dalaikubu from 2001 to 2009. However, river water is not directly related to the rise of the shallow water table beyond the regime of infiltration. The main cause for the rise of the water table in Saihantaolai–Dalaikubu is related to the increased river water discharge from the upper reaches; (2) the leakage of river water observed with run off loss does not always reach the groundwater through infiltration. In the section between Langxinshan and the Juyan Lakes, most of the observed leakage of river water would return to the atmosphere by evaporation and evapotranspiration. Groundwater recharge will be overestimated if monitored runoff losses are used. The recharge regime described in this paper confirms that inputs to the Ejina Oasis shallow aquifer are currently low and the exploitation of groundwater is unsustainable.

The depression cones near the river channels have withdrawn both young groundwater and old groundwater with CFC apparent ages >40 a. Obviously, the changes of water balance caused by anthropogenic activities have substantially altered the recharge regime of the unconfined aquifer. This modification is imprinted in the stable isotope signature of the old groundwater. Several factors may contribute to the decrease of $\delta^{18}O$ and $\delta^{2}H$ values in the groundwater, such as decreased infiltration of river water, a higher contribution of water depleted in heavier isotopes from the adjacent area, and upwelling of deep groundwater caused by groundwater abstraction.

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