

Characteristics of stable isotope and hydrochemistry of the groundwater around Qinghai Lake, NE Qinghai-Tibet Plateau, China

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Abstract The integrated use of isotopic and hydrochemical tracers is an effective approach for investigating complex hydrological processes of groundwater. The stable isotope composition and hydrochemistry of the groundwater around Qinghai Lake were investigated to study the sources and recharge areas. Most of the groundwater points lie close to the local meteoric water line, indicating that the ground waters were recharged primarily from precipitation in the basin, though it had undergone varying degrees of evaporation. The hydrochemical analysis showed that the groundwater was mainly freshwater and that the hydrochemical type was Ca–Mg–HCO₃; the results of the boomerang envelope model and solutes calculated indicated that the groundwater chemistry was mainly controlled by carbonate dissolution around Qinghai Lake. The recharge altitudes of groundwater were relatively low (at 3,400 m.a.s.l) on the northern shore of

Qinghai Lake (locations G1 and G5), relatively high (above 3,900 m.a.s.l) on the southern shore (locations G3 and G4), and approximately 3,700 m.a.s.l on the western shore (location G2). Furthermore, groundwater samples from the fault zone (e.g., G3) would be recharged in part from fissure or inter-basin water. High salinity of groundwater on the western shore (location G2) was related with the evaporite dissolution, the groundwater is unsuitable for drinking, and the drinking water should be improved and enhanced in this area. Knowledge of our research can promote effective management of water resources in this cold and semiarid region and add new data to global groundwater database.

Keywords Stable isotope · Hydrochemistry · Groundwater · Qinghai Lake

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Introduction

Groundwater, as a component of total water resources, is important for irrigation, industry, mining and domestic use. Especially in arid and semiarid regions with shortages of surface water, groundwater plays a dominant role in shaping the economy and ecological environment because of its stable quality and quantity. Therefore, comprehensive studies of the recharge source, refresh rate, residence time and flow path of groundwater are essential and contribute to the planning strategies and recommendations for the rational use of groundwater resources (Adams et al. 2001; Edmunds et al. 2006; Chang and Wang 2010). The integrated use of isotopic and hydrochemical tracers is an effective approach for investigating the complex hydrological processes of groundwater over a range of spatial and temporal scales (Clark and Frjtz 1997; Alyamani 2001; Gibson et al. 2005; Song et al. 2006; Carol et al. 2009; Wassenaar et al. 2011; Kanduč et al.

2012). For example, Weyhenmeyer et al. (2002) applied the altitude effect of the isotope composition in rainfall under stable climate conditions to locate the most important recharge areas and groundwater flow paths and to evaluate the groundwater recharge rates from different altitudes. Based on hydrochemical and isotope data, Carol et al. (2009) studied the salinization process and the hydrological dynamics of groundwater in the southern part of Samborombón Bay. Wassenaar et al. (2011) used stable isotopes to evaluate the sources of water in shallow and deep groundwater systems in the southern Okanagan. Kanduč et al. (2012) used hydrochemical and isotopic tracers to characterize the recharge area and flow paths of some of the most important Alpine aquifers in northern Slovenia. All of these studies demonstrate the applicability and value of isotopes and ions as conservative tracers for hydrologic research, particularly for groundwater systems with complex hydrological processes in arid regions.

The Qinghai Lake Basin, a closed basin with an area of 29,661 km², lies in the cold and semiarid region of the NE Qinghai-Tibet Plateau, China (Fig. 1). Qinghai Lake is the

largest inland lake in China, with surface area 4,400 km² within the basin. This lake is one of China's national nature reserves and an important water body for the ecological security of the NE Qinghai-Tibet Plateau (Tang et al. 1992). The region around the lake is a center of ecological tourism and animal husbandry for the Qinghai Province (Tang et al. 1992). However, Qinghai Lake is saline, and the water is not suitable for consumption by humans or animals; thus, the groundwater around the lake is an important freshwater source for irrigation and drinking. Therefore, studies of the recharge areas, ion concentrations and flow path of the groundwater around the lake are crucial. Such research contributes to knowledge of groundwater quality and to planning water strategies in the basin. Previously published studies on the groundwater in the Qinghai Lake Basin mainly focused on investigating the hydrochemical composition (Jin et al. 2010; Xu et al. 2010; Xiao et al. 2012a), but very few studies have used chemical and isotopic information to investigate recharge areas of the groundwater around the lake.

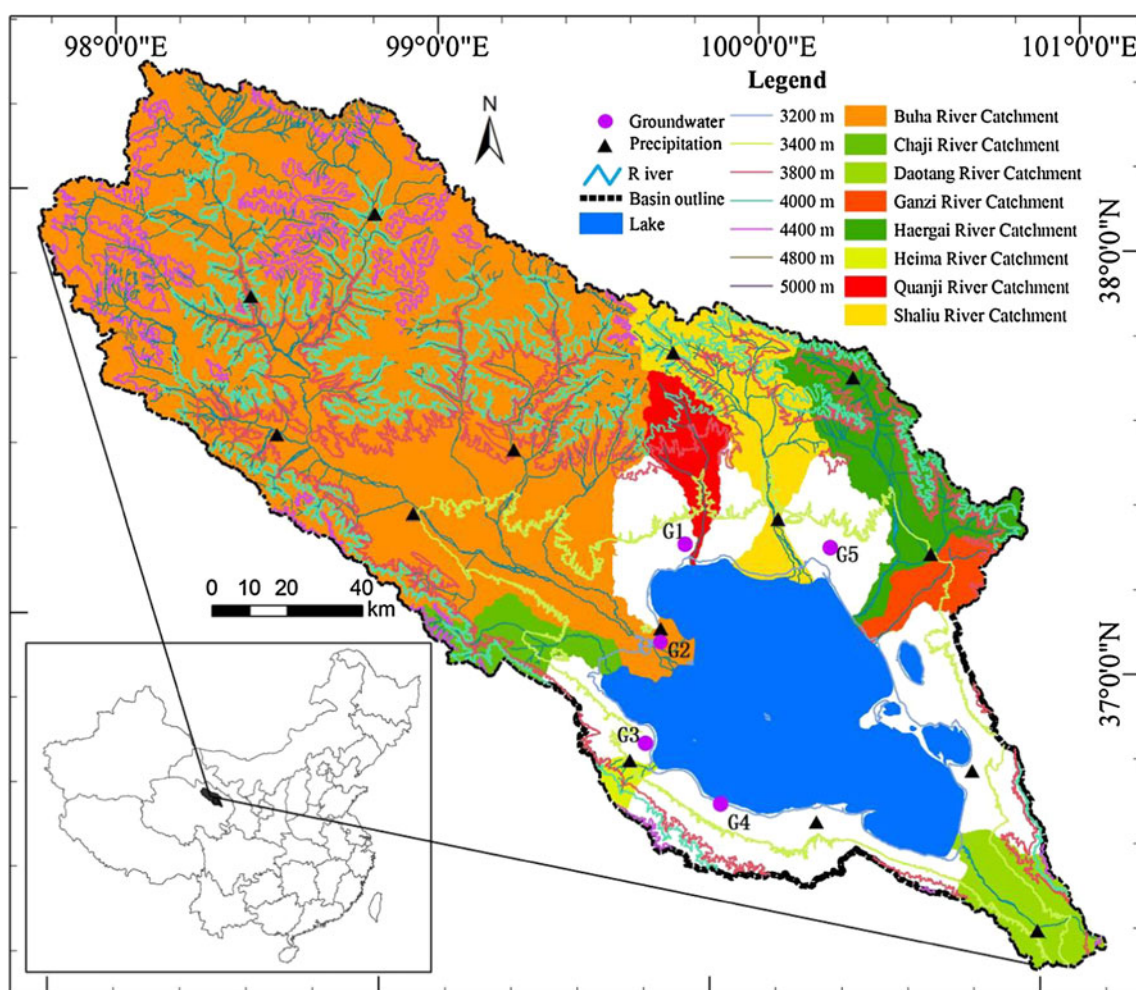


Fig. 1 Locations of Qinghai Lake, sampling sites for groundwater, and topography of the Qinghai Lake Basin

The objectives of this study were: (1) to investigate the characteristics of stable isotopes and hydrochemistry of the groundwater around Qinghai Lake and (2) to study the recharge areas of the groundwater for knowledge of groundwater quality and planning water strategies in the basin. Meanwhile, it is expected that the results will provide insight into the hydrological and geochemical processes of cold and alpine groundwaters in addition to water resource management in the basin and the northeastern Qinghai-Tibet Plateau.

Background of Qinghai Lake

Qinghai Lake (36°32'–37°15'N, 99°36'–100°47'E), is the largest inland lake in China with a surface area 4,400 km² that lies at an altitude of 3,194 m above sea level. It lies in the cold and semiarid region of China's NE Qinghai-Tibet Plateau (Fig. 1). Qinghai Lake has a water volume of

71.6 × 10⁹ m³ and has a watershed area of approximately 29,661 km². The lake water has a salinity of 15.5 g/L and pH of 9.06. Its water chemistry is characterized by Na⁺ > Mg²⁺ > K⁺ > Ca²⁺ and Cl⁻ > SO₄²⁻ ≈ CO₃²⁻ > NO₃⁻ (Sun et al. 1991). Around the lake, the average annual air temperature is ~1.2 °C. The average annual precipitation is 357 mm, but evaporation is 3 to 4 times higher than precipitation (Li et al. 2007).

There are more than 50 rivers or streams flowing into Qinghai Lake (LZBCAS 1994). The main rivers are the Buha River, Shaliu River, Haergai River, Quanji River and Heima River, which together produce a total discharge of 1.34 × 10⁹ m³/year. The discharge from these rivers accounts for over 80.3 % of the total volume of the inflowing surface water. Almost all of the rivers are seasonal rivers; 85 % of the total discharge occurs between June and September. The average total dissolved solids (TDS) of the river water is 300.66 mg/L (Xu et al. 2010), which is higher than the global average (115 mg/L; Hu

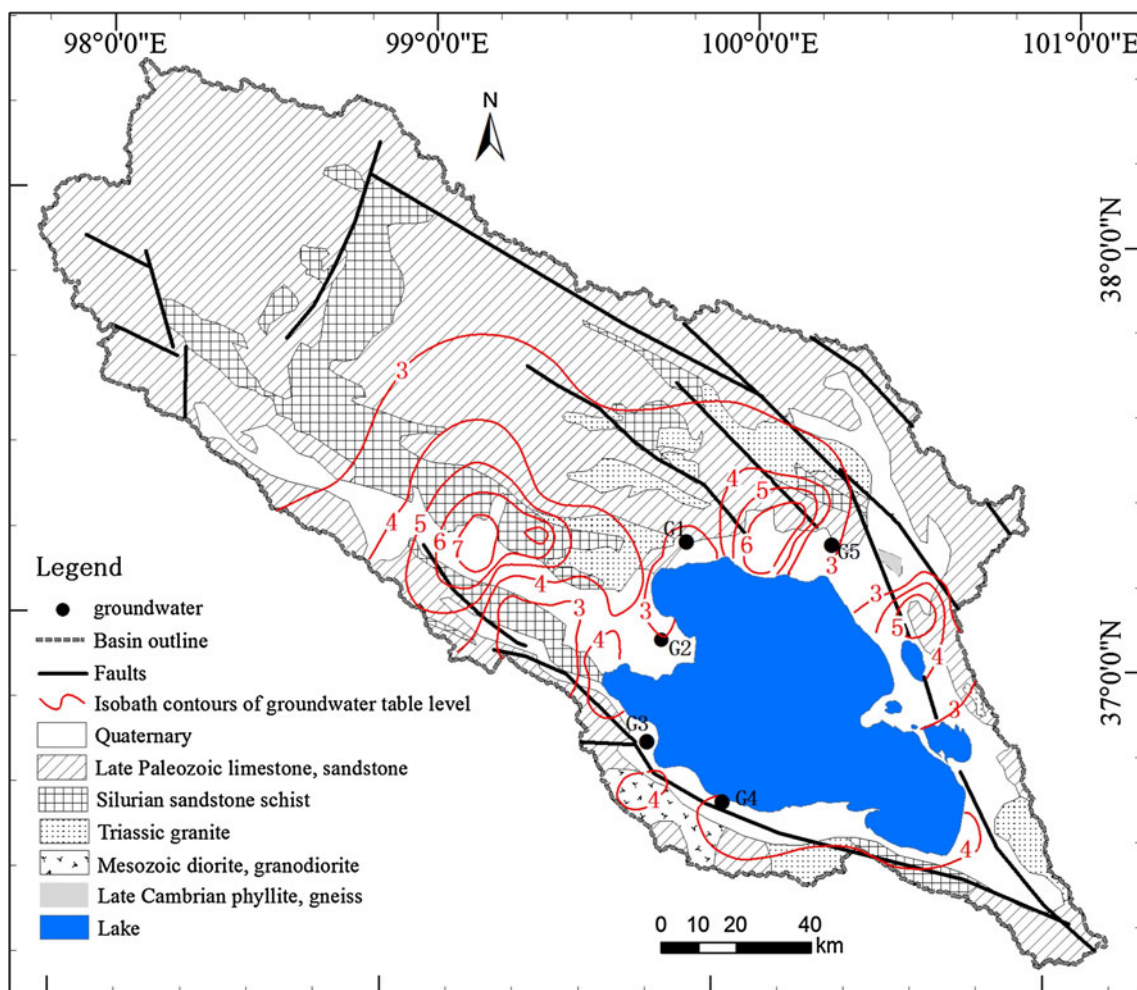


Fig. 2 Geological map and isobath contours of shallow groundwater table level of the Qinghai Lake Basin

Table 1 Stable isotope and hydrochemical compositions of the groundwater around Qinghai Lake

Sample	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	HCO_3^- (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	NO_3^- (mg/L)	TDS (mg/L)	EC (mS/cm)	TH (mg/L)	pH	Altitude (m)	Depth (m)	Aquifer type
G1	-6.54	-41.28	84.30	29.80	49.40	2.85	331.00	43.50	40.90	3.63	585.38	0.415	210.75	7.57	3,221	8.1	Carbonate aquifer
G2	-8.66	-54.91	148.00	107.00	464.00	8.93	733.00	390.00	328.00	85.40	2,264.33	2.380	370.00	7.61	3,203	5.2	Loose rock pore aquifer
G3	-8.61	-53.57	75.00	38.00	59.40	4.49	335.00	63.60	37.10	8.68	621.27	0.461	187.50	7.05	3,218	6.4	Loose rock pore aquifer
G4	-9.08	-58.09	50.80	15.50	49.00	2.23	287.00	17.00	14.30	2.28	438.11	0.219	127.00	7.16	3,201	1.3	Loose rock pore aquifer
G5	-7.32	-45.99	81.20	26.10	34.70	2.61	330.00	22.10	29.30	5.45	531.46	0.329	203.00	7.38	3,247	8.9	Loose rock pore aquifer

et al. 1982). The rivers are mainly located north and northwest of the lake; thus, their distribution is asymmetric in the Qinghai Lake Basin (Fig. 1; Yan and Jia 2003). In recent decades, 50 % of the rivers flowing into Qinghai Lake have dried up due to climate change and human activity (LZBCAS 1994; Li et al. 2007). The groundwater table around Qinghai Lake usually varies between 4 and 7 m. In the sparsely populated region, the groundwater table is approximately 3 or 4 m, which is shallower than the table in the densely populated region (Xiao et al. 2012a).

The Qinghai Lake Basin, situated on the southern edge of the Qilian Fold Belt, is a closed piggyback basin surrounded by several mountain ranges (Bian et al. 2000). These mountains, generally with elevations above 4,000 m (Fig. 1), are predominantly overlain by late Paleozoic marine limestone and sandstones, Silurian sandstone and schist, Triassic granite, Mesozoic diorite and granodiorite, and Quaternary alluvial and lacustrine sediments, with a minor contribution of late Cambrian phyllite and gneiss (Fig. 2). The distribution of these rocks is associated closely with NWW, NNW, and N-S trending faults (Bian et al. 2000). Fault escarpments and lacustrine sediment terraces have been extensively developed along the southern shore (Fig. 2). The groundwater aquifers in the regions of late Paleozoic marine limestone and sandstones, Silurian sandstone and schist, Triassic granite, and Quaternary are primarily carbonate aquifer, clastic rocks aquifer, intrusive rock aquifer and alluvial aquifer, respectively. The north-western part (Buha River Catchment) of the basin is predominantly covered by late Paleozoic marine limestone, sandstone, Silurian sandstone and schist (Figs. 1, 2). Triassic granites are spread over the northern part of the basin near the shores of Qinghai Lake. Mesozoic diorite and granodiorite are spread over the southern part of the basin. The areas surrounding the lake and rivers are overlain by alluvial and lacustrine sediments whose age ranges from Quaternary to recent times (Fig. 2). The mountain runoff in the diluvial and alluvial plains recharges the groundwater via infiltration. Groundwater discharge largely occurs in the lacustrine plain surrounding the lake (Xiao et al. 2012a).

Sampling and analytical methods

Precipitation samples were collected around the lake monthly from July 2009 to June 2010 at 14 locations that were evenly distributed throughout the basin, and groundwater samples were collected at 5 locations (Fig. 1). Information about location was acquired by global positioning system (GPS). A total of 135 samples, 75 of precipitation and 60 of groundwater (see online supplemental

material), were collected during the observation period. The precipitation samples were measured and stored in 100 ml high-density polyethylene square bottles for isotopic analyses. The groundwater samples were stored in 500 ml bottles for isotopic and chemical analyses. The pH and EC of the groundwater were measured in situ using a handheld meter with a probe.

The isotopic compositions of each sample was determined, and the major hydrochemical ions in the groundwater samples collected in July 2009 were determined and are listed in Table 1. The stable isotopes were analyzed using the Picarro L1102-i water isotope analyzer in the Stable Isotope Laboratory of the Institute of Geology and Geophysics at the Chinese Academy of Sciences. The isotopic values were reported using the standard δ notion relative to the V-SMOW (Vienna Standard Mean Ocean Water) standard; the precisions were ± 0.5 and ± 0.1 ‰ for $\delta^2\text{H}$ and $\delta^{18}\text{O}$, respectively. The major cations of the samples were determined using a Dionex-600 ion chromatograph, and the anions were measured using a Dionex-500 ion chromatograph in the Analytical Laboratory of the Beijing Research Institute of Uranium Geology.

The recharge areas and flow paths of groundwater were ascertained using the altitude effect of the oxygen isotope in precipitation (Payne et al. 1978; Bortolami et al. 1979; Weyhenmeyer et al. 2002; Song et al. 2006). The equation is described below:

$$H = \frac{\delta_G - \delta_P}{K} + h \tag{1}$$

where H is the altitude of the recharge area of the groundwater (m.a.s.l); h the altitude of the sampling site of the groundwater (m.a.s.l), δ_G and δ_P the $\delta^{18}\text{O}$ values of the groundwater and the local precipitation at the sampling site (‰), respectively, and K is the gradient of the altitude effect of $\delta^{18}\text{O}$ in precipitation (‰/m).

Results and discussion

Stable isotope in precipitation

According to the precipitation samples collected around the lake monthly from July 2009 to June 2010, the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of precipitation range from -16.69 to -2.80 ‰ and from -123.28 to -11.54 ‰, respectively. The ranges were within that previously reported for China: $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values ranging from -35.5 to $+2.5$ ‰ and from -280.0 to $+24.0$ ‰, respectively (Tian et al. 2001). The local meteoric water line (LMWL) was simulated by the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ content of precipitation in the Qinghai Lake Basin (Fig. 3):

$$\delta^2\text{H} = 7.91\delta^{18}\text{O} + 13.94 \text{ VSMOW} \quad (n = 75, R = 0.99). \tag{2}$$

The LMWL deviated slightly from the Global Meteoric Water Line (GMWL) because of the local variation in moisture sources and evaporation modes (Craig 1961; Clark and Frjtz 1997).

In successive precipitation samples, the altitude effect was a temperature-dependent phenomenon and explained by the rainout from adiabatic cooling (Coplen 1993). The altitude effect of $\delta^{18}\text{O}$ was significant in the annual precipitation, and the best-fit equation was:

$$\delta^{18}\text{O} = -0.0018 \text{ Alt} - 2.04 \quad (n = 14, P < 0.05, R = 0.55). \tag{3}$$

The equation indicates that the $\delta^{18}\text{O}$ was depleted at a rate of -0.18 ‰/100 m elevation (Fig. 4). The calculated value of the altitude effect for $\delta^{18}\text{O}$ was similar to that of the Tianshan Mountains, which are high-altitude (Pang et al. 2011), and was relatively smaller than the effect calculated in other regions (Niewodniczanski et al. 1981; Stowhas and Moyano 1993; Saravana et al. 2010).

Stable isotopes of the groundwater

The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of the groundwater range from -10.20 to -6.45 ‰ and from -66.79 to -39.61 ‰, respectively. The ranges were smaller than the ranges of precipitation (Fig. 3). Comparing the groundwater samples with the LMWL was useful for determining the water

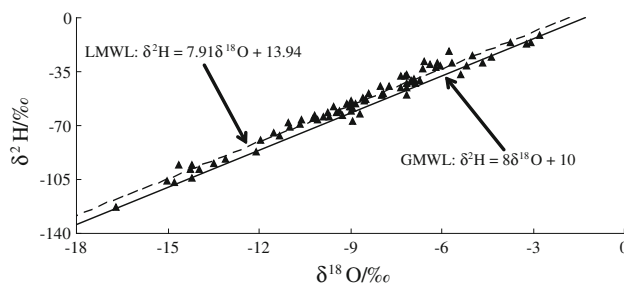


Fig. 3 The relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in precipitation of the Qinghai Lake Basin

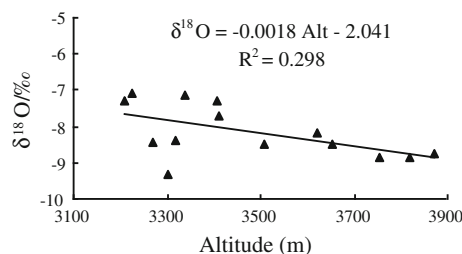


Fig. 4 The altitude effect of precipitation in the Qinghai Lake Basin

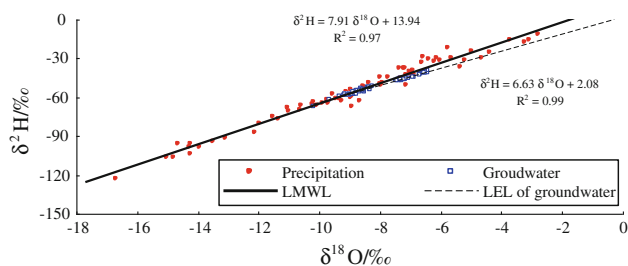


Fig. 5 Characteristics of the stable isotopes of the groundwater and precipitation

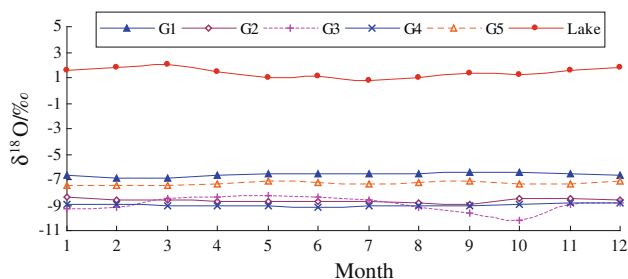


Fig. 6 Monthly $\delta^{18}\text{O}$ of the groundwater around Qinghai Lake

source in the investigation of the regional hydrology (Clark and Frjtz 1997). The relationship between groundwater samples and the LMWL is displayed by a bivariate plot of $\delta^{18}\text{O}$ versus $\delta^2\text{H}$ in Fig. 5. Most of the isotope data points lie close to the LMWL, and the slope of local evaporation line (LEL: $\delta^2\text{H} = 6.63 \delta^{18}\text{O} + 2.08$) of groundwater samples (6.63) was smaller than the slope of LMWL (7.91), indicating that the groundwater around Qinghai Lake mainly come from the precipitation in the basin that had undergone variable degrees of evaporation before infiltration (Friedman et al. 1962; Paul and Wanielista 2000).

As in Fig. 6, the $\delta^{18}\text{O}$ of the lake water was much higher than the $\delta^{18}\text{O}$ of the groundwater, and range from 0.77 to 2.02 ‰ with an average of 1.35 ‰, indicating that the lake water underwent high degree of evaporation. Meanwhile, the $\delta^{18}\text{O}$ of the groundwater was in the order: $\delta_{G1} > \delta_{G5} > \delta_{G2} > \delta_{G3} > \delta_{G4}$, with average $\delta^{18}\text{O}$ values of $-6.59, -7.28, -8.62, -8.95$ and -8.99 ‰, respectively. The $\delta^{18}\text{O}$ of the groundwater, excluding G3, fluctuated only slightly within the year (Fig. 6), indicating that the sources of groundwater were stable and weakly influenced by the external environment. The fluctuation of the $\delta^{18}\text{O}$ in location G3, ranging from -10.20 ‰ in October to -8.25 ‰ in May, was larger than that of the other locations, indicating that the groundwater sources in location G3 were relatively complex. According to the map of geological structure around the lake (Fig. 2), G3 and G4 are located on the fault zone of Zongwulongshan–Qinghai Nanshan; therefore, the groundwater in location G3 and G4

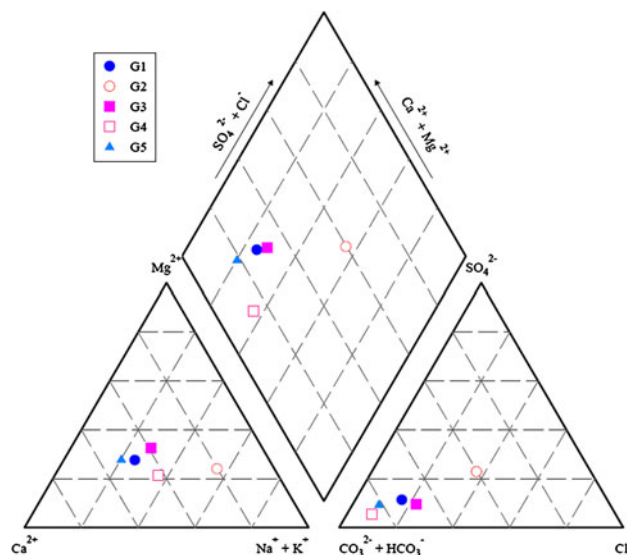


Fig. 7 Ternary plots of cations and anions of the groundwater around Qinghai Lake

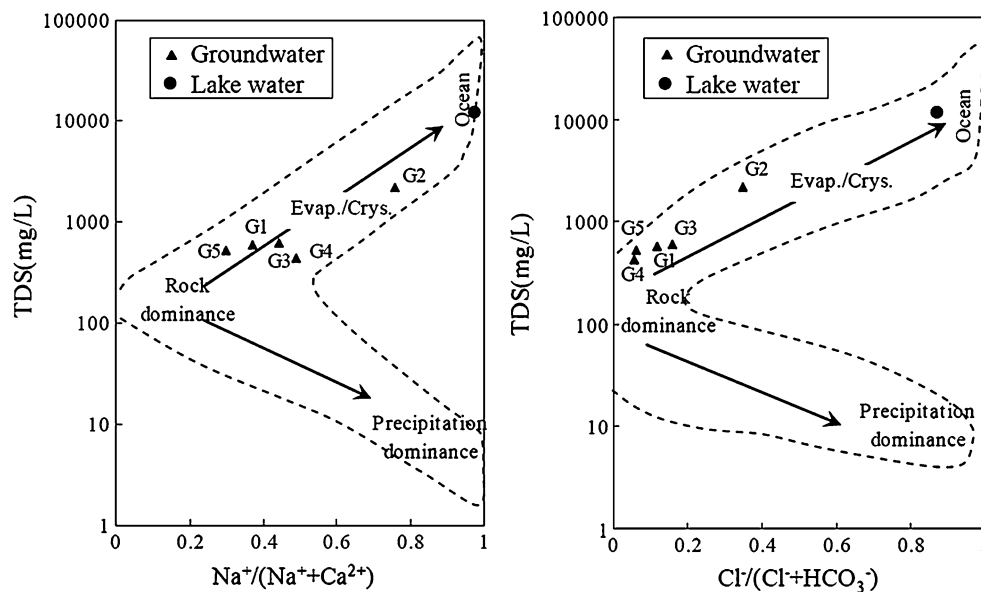
would be recharged by the fissure water. Overall, the groundwater around the lake was mainly recharged by precipitation, and the $\delta^{18}\text{O}$ values of the different locations suggest that the altitude of the recharge areas varied.

Hydrochemistry of the groundwater

The pH values of the water samples range from 7.05 to 7.61 with a median value of 7.35 (Table 1), indicating that the groundwaters were slightly alkaline. These pH values were relatively lower than those of the river waters (7.60–8.55) in the Qinghai Lake Basin (Jin et al. 2010). The TDS and electrical conductivity (EC) values of most of the groundwater samples (G1, G3, G4 and G5) range from 438.11 to 621.27 mg/L and from 0.219 to 0.461 mS/cm (Table 1), respectively, with averages of 544.06 mg/L and 0.356 mS/cm, respectively. Compared with the river water (the average TDS and EC were 377.78 mg/L and 0.20 mS/cm, respectively) (Cui 2011), the TDS and EC of the groundwater were higher, indicating that the interaction between water and rocks was stronger in the groundwater than in the river water. The hydrochemical type of groundwater, excluding G2, was Ca–Mg–HCO₃ (Fig. 7). The concentrations of Ca²⁺ and Mg²⁺ were relatively high, accounting for more than 60 % of the cations. This finding indicates that the groundwater chemistry may be mainly controlled by carbonate dissolution around Qinghai Lake.

The TDS and EC values of groundwater at G2 were 2,264.33 mg/L and 2.4 mS/cm, respectively, the hydrochemical type was Na–Cl–HCO₃ (Fig. 7), and the groundwater was brackish (TDS > 1,000 mg/L; Table 1). There could be two reasons for the high TDS and high concentrations of Na⁺, Mg²⁺, Cl⁻ and SO₄²⁻ in G2. One

Fig. 8 Plots of the major ions within the Gibbs boomerang model for groundwater around Qinghai Lake



possibility is that the longer flow path increased the interaction time between water and rocks and raised the dissolved solids; the second possibility is that the groundwater in location G2 was recharged by the lake water. G2 is near (3.6 km) Qinghai Lake and at a similar altitude, 3,196 m.a.s.l in July 2009 compared to the lake’s 3,193.38 m.a.s.l. Compared with the lake water, the $\delta^{18}\text{O}$ of G2 was much lower than the $\delta^{18}\text{O}$ of lake water and range from 0.77 to 2.02 ‰ with an average of 1.35 ‰ (Fig. 6), indicating there was no significant hydraulic contact between G2 and the lake. High TDS and high concentrations may be dominated by heavy evaporation or dissolved solids.

The boomerang envelope model developed by Gibbs (1970) describes three mechanisms that control the composition of the dissolved salts of the world’s waters: atmospheric precipitation, rock dominance, and the evaporation–crystallization. As shown in Fig. 8, all of the samples fell within the evolutionary path from “Rock dominance” to “Ocean” in the Gibbs boomerang envelope, suggesting that the chemical composition of the groundwater was dominated by rock-weathering. The results were supported by that rock-weathering, ion exchange and precipitation which are the major geochemical processes responsible for the solutes in the groundwater within the Qinghai Lake Basin (Xiao et al. 2012a).

Using the forward method, different sources of the groundwater solutes (atmospheric input, carbonate weathering, silicate weathering, and evaporite dissolution) were calculated (Xiao et al. 2012b) and are shown in Fig. 9. The results show that carbonate weathering, evaporite dissolution, silicate weathering, and atmospheric input contributed 41.8, 24.5, 22.4, and 11.3 % of the total dissolved cations for the groundwaters. Carbonate weathering dominated in G1, G3, G4 and G5, contributing 37.5, 38.7, 55 and 39 %

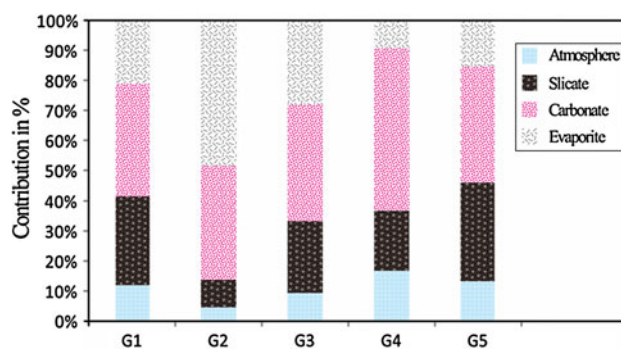


Fig. 9 Calculated contributions (in %) of the different groundwaters to the total cations

of the total dissolved cations, respectively. This finding indicates that the groundwater chemistry is mainly controlled by carbonate dissolution around Qinghai Lake. Evaporite dissolution dominated in G2, contributing 48 % of the total dissolved cations. Therefore, the high salinity of G2 was related to the evaporite dissolution in this area.

In drinking water, high SO_4^{2-} concentrations can cause diarrhea, dehydration and weight loss (World Health Organization 2008), and high NO_3^- concentrations can result in birth defects, hypertension and high-Fe hemoglobin (Carpenter et al. 1998). According to the Chinese State Standard of drinking water, the highest acceptable limits of TDS, total hardness (TH), pH and the concentrations of Na^+ , Cl^- , NO_3^- and SO_4^{2-} are 1,000, 450, 8.5, 200, 250, 20 and 250 mg/L, respectively (Ministry of Health 2006). As shown in Table 1, most of the groundwaters (G1, G3, G4 and G5) were slightly and moderately hard freshwater ($\text{TH} \leq 210.75$ mg/L) and fell within the standards for drinking water in all indices. The TDS, Na^+ , Cl^- , NO_3^- and SO_4^{2-} of the groundwater from location

G2 were all higher than the highest acceptable limits set by the standards, indicating that the groundwater in location G2 was not suitable for drinking and that the drinking water should be improved and enhanced in these areas.

Recharge sources of groundwater

Most of the isotope data points plot close to the LMWL (Fig. 5), indicating that the groundwater around Qinghai Lake came primarily from the precipitation in the basin and had undergone variable degrees of evaporation (Friedman et al. 1962; Paul and Wanielista 2000). Previous researchers have successfully used the altitude effect of oxygen isotope to ascertain the main recharge areas and flow paths of groundwater (Payne et al. 1978; Bortolami et al. 1979; Weyhenmeyer et al. 2002; Song et al. 2006). A clear altitude effect of -0.18 ‰/100 m (Eq. 3, Fig. 4) was revealed in the oxygen isotope of precipitation in the Qinghai Lake Basin. The relationship plot of $\delta^2\text{H}-\delta^{18}\text{O}$ for groundwater (LEL) in each location is listed in Table 2. The slopes of LELs, ranging from 3.0 to 7.32, were smaller than the slope of LMWL (7.91), indicating that all groundwater samples had undergone evaporation before infiltration (Weyhenmeyer et al. 2002). To eliminate the influence of evaporation on the groundwater, the intersections between the LELs of groundwater in each location and the LMWL of precipitation were calculated (Table 2). The values of $\delta^2\text{H}$ and $\delta^{18}\text{O}$ on the intersections were the recharge (initial) isotope values from precipitation to the groundwater. Then, the recharge altitude for each groundwater site was calculated from the altitude effect of precipitation and Eq. (1) (Table 2). The recharge altitudes of groundwater in locations G1 and G5 were relatively low (at 3,400 m.a.s.l), and the recharge altitudes in locations G3 and G4 were relatively high (more than 3,900 m.a.s.l). The recharge altitude for location G2 was approximately 3,700 m.a.s.l.

According to the contour lines in the Qinghai Lake Basin (Fig. 1), the altitude is approximately 3,400 m.a.s.l just to the north of locations G1 and G5, indicating that local precipitation was the source of G1 and G5. Because G2 lies in the Buha River Catchment, the source for G2 would be precipitation from the middle reaches (3,500–4,300 m.a.s.l) of the catchment (Fig. 1). The recharge area of the groundwater in location G4 should be above 3,900 m.a.s.l on the mountain Qinghai Nanshan. That site is in the south of the Qinghai Lake Basin and its flow path is relatively short, as indicated by the lower TDS and lower EC (Table 1). The fluctuation of the $\delta^{18}\text{O}$ in G3 (Fig. 6) would indicate that the recharge altitudes range from 3,500 m.a.s.l (May) to 4,300 m.a.s.l (October), but there is very little area exceeding 4,000 m.a.s.l above the G3 site (Fig. 1). Therefore, the groundwater source in

Table 2 Evaporation lines, initial $\delta^{18}\text{O}$ and recharge altitude of the groundwater in each location

Sample	Evaporation line	Initial $\delta^{18}\text{O}$ (‰)	Recharge altitude (m)
G1	$\delta^2\text{H} = 4.86 \delta^{18}\text{O} - 11.18$	-8.24	3,441
G2	$\delta^2\text{H} = 3.00 \delta^{18}\text{O} - 28.85$	-8.72	3,707
G3	$\delta^2\text{H} = 7.32 \delta^{18}\text{O} + 8.50$	-9.22	3,988
G4	$\delta^2\text{H} = 3.91 \delta^{18}\text{O} - 22.56$	-9.13	3,935
G5	$\delta^2\text{H} = 4.06 \delta^{18}\text{O} - 17.92$	-8.26	3,464

location G3 must be more complex, with groundwater recharged by fissure water or inter-basin water.

Conclusions

The chemical composition of the groundwater around Qinghai Lake was dominated by rock-weathering (mainly carbonate dissolution). Almost all groundwaters were Ca–Mg– HCO_3 type; few were Na–Cl– HCO_3 type on the west shore and were not suitable for drinking. The groundwater came primarily from precipitation in the basin. The recharge altitudes of groundwater were relatively low (at 3,400 m.a.s.l) on the northern shore of Qinghai Lake (locations G1 and G5), relatively high (above 3,900 m.a.s.l) on the southern shore (locations G3 and G4), and approximately 3,700 m.a.s.l on the western shore (location G2).

The groundwater source for location G3 was complex, possibly including fissure water or inter-basin water. The high salinity of G2 was related with the evaporite dissolution. Overall, the results indicated that the sources of groundwater around Qinghai Lake are very complex. Future studies should extend the period of observation and use multiple methods, e.g., tritium (^3H) and radiocarbon (^{14}C), to determine the groundwater residence times and to assess additional groundwater recharge sources along selected groundwater flow paths.

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References

- Adams S, Titus R, Pietersen K, Tredoux G, Harris C (2001) Hydrochemical characteristics of aquifers near Sutherland in the Western Karoo, South Africa. *J Hydrol* 24:191–203

- Alyamani MS (2001) Isotopic composition of rainfall and ground-water recharge in the western province of Saudi Arabia. *J Arid Environ* 49:751–760
- Bian QT, Liu JQ, Luo XQ, Xiao JL (2000) Geotectonic setting, formation and evolution of the Qinghai Lake. *Seismol Geol* 22(1):20–26 (in Chinese)
- Bortolami GC, Ricci B, Susella GF (1979) Isotope hydrology of the Val Corsaglia, Maritime Alps, Piedmont, Italy. In: *Isotope Hydrology*, Neuberger, Germany, pp 327–350
- Carol E, Kruse E, Mas-Pla J (2009) Hydrochemical and isotopic evidence of ground water salinization processes on the coastal plain of Samborombón Bay, Argentina. *J Hydrol* 365:335–345
- Carpenter SR, Caraco NF, Correll DL, Howarth RW, Sharpley AN, Smith VH (1998) Non-point pollution of surface waters with phosphorus and nitrogen. *Ecol Appl* 8:559–568
- Chang J, Wang GX (2010) Major ions chemistry of groundwater in the arid region of Zhangye Basin, northwestern China. *Environ Earth Sci* 61:539–547
- Clark ID, Fritz P (1997) *Environmental isotopes in hydrogeology*. Lewis Publishers, New York
- Coplen TB (1993) Uses of environmental isotopes. In: Alley WM (ed) *Regional groundwater quality*. Van Nostrand Reinhold, New York, pp 227–254
- Craig H (1961) Isotopic variation in meteoric waters. *Science* 133:1702–1703
- Cui BL (2011) Water cycle and transformation relations among precipitation, river water, groundwater and lake water in the Qinghai Lake Basin based on the stable isotope. PhD Dissertation, Beijing Normal University (in Chinese)
- Edmunds WM, Ma JZ, Aeschbach-Hertig W, Kipferd R, Darbyshire DPF (2006) Groundwater recharge history and hydrogeochemical evolution in the Minqin Basin, North West China. *Appl Geochem* 21:2148–2170
- Friedman I, Machta L, Soller R (1962) Water vapour exchange between a water droplet and its environment. *J Geophys Res* 67:2761–2766
- Gibbs RJ (1970) Mechanisms controlling world water chemistry. *Science* 170:1088–1090
- Gibson J, Edwards T, Birks S, Amour N, Buhay W, McEachern P, Wolfe B, Peters D (2005) Progress in isotope tracer hydrology in Canada. *Hydrol Process* 19:303–327
- Hu MH, Stallard RF, Edmond JM (1982) Major ion chemistry of some large Chinese rivers. *Nature* 298:550–553
- Jin ZD, Wang SM, Zhang F, Shi YW (2010) Weathering, Sr fluxes, and controls on water chemistry in the Lake Qinghai catchment, NE Tibetan Plateau. *Earth Surf Proc Land* 35:1057–1070
- Kanduč T, Mori N, Kocman D, Stibilj V, Grassa F (2012) Hydrogeochemistry of Alpine springs from North Slovenia: insights from stable isotopes. *Chem Geol* 300–301:40–54
- Li XY, Xu HY, Sun YL, Zhang DS, Yang ZP (2007) Lake-level change and water balance analysis at Lake Qinghai, west China during recent decades. *Water Resour Manage* 21:1505–1516
- LZBCAS (Lanzhou Branch of Chinese Academy of Sciences) (1994) *Evolution of recent environment in Qinghai Lake and its prediction*. Science Press, Beijing (in Chinese)
- Ministry of Health (2006) *Standards for drinking water quality, GB5749-2006*. Ministry of Health of the People's Republic of China, Beijing (in Chinese)
- Niewodniczanski J, Grabczak J, Baranski L, Rzepka J (1981) The altitude effect on the isotopic composition of snow in high mountains. *J Glaciol* 27:99–111
- Pang Z, Kong Y, Froehlich K, Huang T, Yuan L, Li Z, Wang F (2011) Processes affecting isotopes in precipitation of an arid region. *Tellus B* 63(3):352–359
- Paul G, Wanielist M (2000) Effects of evaporative enrichment on the stable isotope hydrology of a central Florida (USA) river. *Hydrol Process* 14:1465–1484
- Payne BR, Leontiadis J, Dimitroulas C (1978) A study of the Kalamos springs in Greece with environmental isotopes. *Water Resour Res* 14(4):653–658
- Saravana KU, Bishim K, Rai SP, Sharma S (2010) Stable isotope ratios in precipitation and their relationship with meteorological conditions in the Kumaon Himalayas, India. *J Hydrol* 391:1–8
- Song X, Liu X, Xia J, Yu J (2006) A study of interaction between surface water and ground-water using environmental isotope in Huaisha River basin. *Sci China* 49(12):1299–1310
- Stowhas L, Moyano JC (1993) Simulation of the isotopic content of precipitation. *Atmos Environ* 27(3):327–333
- Sun DP, Tang Y, Xu ZQ, Han Z (1991) A preliminary investigation on chemical evolution of the Lake Qinghai water. *Chin Sci Bull* 15:1172–1174 (in Chinese)
- Tang RC, Gao XQ, Zhang J (1992) The annual changes of the water level of the Lake Qinghai in the recent thirty years. *Chin Sci Bull* 37(6):524 (in Chinese)
- Tian LD, Yao TD, Sun WZ, Stievenard M, Jouzel J (2001) Relationship between δD and $\delta^{18}O$ in precipitation from north to south of the Tibetan Plateau and moisture cycling. *Sci China* 44(9):789–796
- Wassenaar LI, Athanasopoulos P, Hendry MJ (2011) Isotope hydrology of precipitation, surface and ground waters in the Okanagan Valley, British Columbia, Canada. *J Hydrol* 411:37–48
- Weyhenmeyer CE, Burns SJ, Waber HN (2002) Isotope study of moisture sources, recharge areas, and groundwater flow paths within the eastern Batinah coastal plain, Sultanate of Oman. *Water Resour Res* 38(10):1184–1206
- World Health Organization (2008) *Guidelines for drinking-water quality, incorporating 1st and 2nd addenda, vol. 1, Recommendations*, Geneva
- Xiao J, Jin ZD, Zhang F, Wang J (2012a) Solute geochemistry and its sources of the groundwater's in the Qinghai Lake Catchment, NW China. *J Asian Earth Sci* 52:21–30
- Xiao J, Jin ZD, Ding H, Wang J, Zhang F (2012b) Geochemistry and solute sources of surface waters of the Tarim River Basin in the extreme arid region, NW Tibetan Plateau. *J Asian Earth Sci* 54–55:162–173
- Xu H, Hou Z, An Z, Liu X, Dong J (2010) Major ion chemistry of waters in Lake Qinghai catchments, NE Qinghai-Tibet Plateau, China. *Quatern Int* 212:35–43
- Yan HY, Jia SF (2003) Water balance and water resources allocation of Qinghai Lake. *J Lake Sci* 15(1):35–40 (in Chinese)