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Original Article

Stable isotopes of water as a tracer for revealing spatial and temporal characteristics of groundwater recharge surrounding Qinghai Lake, China

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Abstract: Studying spatial and temporal characteristics of regional groundwater recharge will guide the scientific management and sustainable development of regional water resources. This study investigated stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) of precipitation, groundwater, river water and lake water during 2019-2020 in Qinghai Lake Basin to reveal the spatial and temporal characteristics of groundwater recharge. The local meteoric water line was simulated using ordinary least squares regression ($\delta^{2}H = 7.80\ \delta^{18}O + 10.60$). The local evaporation lines of the river water, lake water and groundwater were simulated as $\delta^{2}H = 6.21\ \delta^{18}O - 0.72$, $\delta^{2}H = 5.73\ \delta^{18}O - 3.60$ and $\delta^{2}H = 6.59\ \delta^{18}O + 1.76$, respectively. The $\delta^{2}H$ and $\delta^{18}O$ of river water and groundwater were in more depleted values due to the recharge by precipitation at high altitudes or precipitation effects, and the $\delta^{2}H$ and $\delta^{18}O$ of the lake water were in more enriched values because of evaporation. The relationship between the $\delta^{2}H$ and $\delta^{18}O$ of groundwater and river water was not significantly different, indicating a strong hydrological connection between the groundwater and river water surrounding Qinghai Lake. Additionally, the maximum values of $\delta^{18}O$ and the minimum values of lc-excess of groundwater in most regions were both in August, and the minimum values of $\delta^{18}O$ and the maximum values of lc-excess of groundwater in most regions were both in October. Therefore, the groundwater was recharged by soil water with strong evaporation in August and recharged by precipitation at high altitudes in October. The recharge rate of groundwater was relatively fast in areas with large slopes and large hydraulic gradients (e.g., south of Qinghai Lake), and in areas with strong hydrological connections between the groundwater and river water (e.g., the Buha River Valley). Those results can provide data support for protection and utilization of water resources in Qinghai Lake Basin, and provide reference for groundwater research in closed lake basins on the Qinghai-Tibet Plateau.

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1 Introduction

Groundwater is a crucial freshwater resource worldwide; accounts for 96% of the earth's unfrozen fresh water resources; and provides 36%, 42%, and 24% of the world's drinking water, irrigation water, and industrial water (Shiklomanov and Rodda 2003; WWAP 2015; Lee et al. 2019). More than 50% of the global population relies on groundwater for drinking water, and 2.5 billion of these individuals depend entirely on groundwater for their daily water use (Upton et al. 2019). However, groundwater resources have deteriorated and have been depleted because of climate change, population growth, urban expansion, irrigation water and groundwater pollution (Edmunds et al. 2006; Werner et al. 2013; Zaidi et al. 2015; Feike et al. 2017; Jia et al. 2019; Sellerino et al. 2019). The United Nations predicts that by 2025, 1.7 billion people will live with water shortages and two-thirds of them will live without clean water (UN 2015). Continuous exploitation of groundwater leads to severe environmental and ecological problems, such as ground subsidence, aquifer unwatering, salt water intrusion, and ecological degeneration (Edmunds 2009; Gleeson et al. 2012; Goldin 2016; Cuthbert et al. 2019). Therefore, the storage and quality of groundwater must be considered and protected to ensure its sustainable use by humans and ecosystems (EC 2000; EC 2006; Rotiroti et al. 2019). The research results on spatial and temporal characteristics of groundwater recharge are the basis for the exploitation and protection of groundwater resources. Therefore, studying spatial and temporal characteristics of regional groundwater recharge will guide the scientific management and sustainable development of regional water resources (Chang & Wang 2010; Van Loon et al. 2016).

Hydrogen and oxygen stable isotopes ($^{2}H/^{1}H$ and $^{18}O/^{16}O$), components of water molecules, are natural tracers (Clark & Fritz 1997; Kendall & McDonnell 1998; McDonnell & Beven 2014). $\delta^{2}H$ and $\delta^{18}O$ are widely used in climatology, hydrology, ecology, and oceanography (Augustin et al. 2004; O'Driscoll et al. 2005; Levin et al. 2009; Klaus & McDonnell 2013; Thompson et al. 2013). Stable isotopes ($\delta^{2}H$ and $\delta^{18}O$) in groundwater mainly depend on groundwater recharge sources, and the difference and spatiotemporal variation in the isotope composition of different recharge sources are the basis for solving the problem of groundwater recharge sources using environmental isotope methods (Clark & Fritz 1997; Gu et al. 2011).

Qinghai Lake Basin is not only a key area for social and economic development (e.g., eco-tourism and grassland animal husbandry in Qinghai Province), but also an influential water body for maintaining ecological security in the northeast of Qinghai-Tibet Plateau. They also play an irreplaceable role in water conservation, climate regulation, and habitat provision (Cui & Li 2015; Gong et al. 2017). Qinghai Lake Basin is in the transition zone between the East Asian monsoon humid zone and the inland arid zone, which is extremely sensitive to global climate change (Li et al. 2018). Furthermore, Qinghai Lake Basin is an ideal area for studying global climate change and uplift processes, as well as the water cycle and eco-hydrological processes in the Tibetan Plateau, because of its sensitivity to global climate change and the closed nature of its basin. Studies that have investigated the geochemistry and water cycle of the Qinghai Lake Basin focus mainly on paleoclimate and environmental changes, lake evolution and its response to climate change, sources of precipitation, characteristics of river runoff, and groundwater quality (Cui & Li 2015; Fu et al. 2016; Tang et al. 2018; Li et al. 2021). However, there have been few detailed studies on the temporal and spatial characteristics of groundwater recharge around lakes. In the seasonal permafrost region, increasing temperatures lead to permafrost ablation and weaken the blocking effect of permafrost on groundwater runoff infiltration, which further deepens the underground runoff path and increases the infiltration amount of ice and permafrost melt water and the amount of surface water input to downstream areas (Ge et al. 2011; Frampton et al. 2013; Wellman et al. 2013). Therefore, studying the temporal and spatial characteristics of groundwater will improve the understanding of the regional hydrological cycle and its response to climate change in alpine regions.

In this study, hydrogen and oxygen stable isotope samples from precipitation, groundwater, river water and lake water in Qinghai Lake Basin were tested and analyzed to (1) characterize the hydrogen and oxygen isotope composition from precipitation, groundwater, river water, and lake water and (2) to reveal the spatial and temporal characteristics of groundwater recharge by comparing the stable isotope characteristics of groundwater (52 sites), river water (15 sites), and lake water (21 sites) in April, July, August, October 2019 and January 2020 surrounding the Qinghai Lake.

2 Study Area

Qinghai Lake lies in a closed basin with an area of 29661 km² (36°15'–38°20'N, 97°50'– 101°20'E) on the Qinghai-Tibet Plateau (Fig. 1). Qinghai Lake Basin lies in a critical transitional zone between the Asian summer monsoon-controlled (humid) and westerlies-influenced (arid) areas of Asia (Li et al. 2018). The area and water surface altitude of Qinghai Lake are 4425 km² and 3195.82 m above sea level (m.a.s.l.), respectively. The average annual air temperature and precipitation are -0.1°C and 357 mm, respectively (Cui & Li 2015). The study area has a temperate continental semiarid climate on the Qinghai-Tibet Plateau. The annual temperature and precipitation changes in Gangcha were 0.04°C yr^{-1} and 1.56 mm yr^{-1} from 1970 to 2016, respectively (Tang et al. 2018). Annual precipitation changed by 8.13 mm yr^{-1} from 2005 to 2016 (Tang et al. 2018). Li et al. (2018) divided three freeze and thaw periods based on the temperature of the soil at a depth of 5 cm: freezing period (1 Jan. – 11 Apr. 2014), thawing season (11 Apr. – 30 Oct. 2014), and the post-freezing period (31 Oct. – 31 Dec. 2014). The three largest rivers of Qinghai Lake Basin are the Buha, Shaliu, and Haergai Rivers, which account for 75% of the surface water inflow into Qinghai Lake (Zhang et al. 2022).

In the basin, mountains account for approximately 68.6% of the land area, and the valley and plain account for approximately 31.4% of the land area. Pre-Quaternary strata are mainly distributed in mountainous areas, and Quaternary loose deposits are mainly distributed in the piedmont, intermountain, and valley plains. The Mesozoic, Cenozoic, Paleozoic, and Late Proterozoic are mosaic

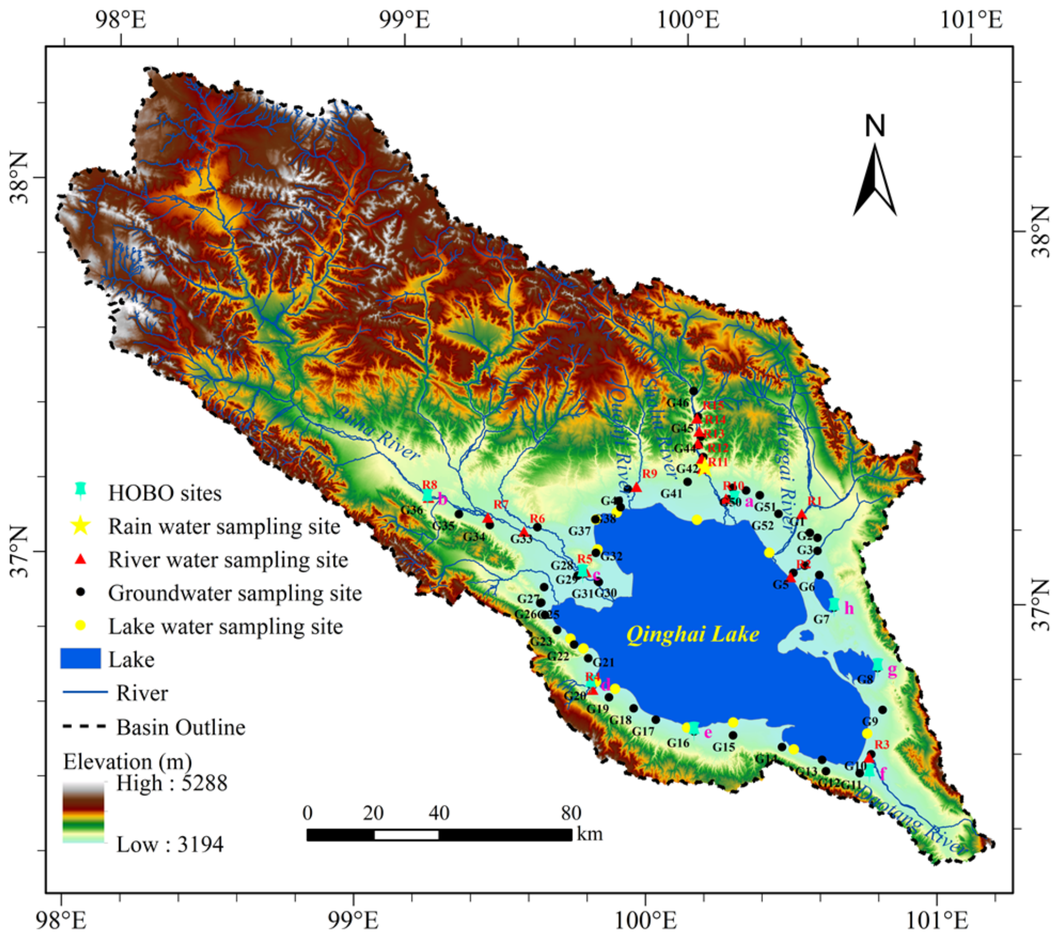

Fig. 1 Location of Qinghai Lake Basin and sampling sites.

distributions in the basin. The characteristics of groundwater in mountain areas, piedmont alluvial plains and lakeshore plains are the recharge zone, runoff infiltration zone and underground runoff discharge zone, respectively. The groundwater aquifers in the basin are primarily alluvial, carbonate, intrusive rock, and clastic rock aquifers, corresponding to Quaternary deposits, late Paleozoic marine limestone and sandstones, Triassic granite, and Silurian sandstone and schist, respectively (Cui & Li 2014). Bedrock fissure water was mostly distributed in the fracture and residual layers. The average depth of groundwater ranges from 4 to 7 m in the vicinity of Qinghai Lake, where the groundwater depths are the shallowest in sparsely populated areas (Xiao et al. 2012).

3 Data Source and Methods

Precipitation samples were collected during every precipitation event from March 2018 to February 2020 (261 samples of rainwater) at the meteorological bureau of Gangcha (3301.5 m a.s.l.), Qinghai Province, China (Fig. 1). Groundwater, river water, and lake water samples were collected from 52, 15, and 21 sites in April, July, August, and October 2019 and January 2020 (Fig. 1). A total of 425 water samples were collected, of which there are 259 groundwater samples, 73 river water samples, and 93 lake water samples. Groundwater samples were collected after the water conductivity stabilized after 3-5 min of well pumping. River water samples were collected 20 cm below the flowing water surface, and lake water samples were collected 50 cm below the lake water surface. The water samples were filtered using 0.45 μm nylon filters and stored in 30 mL high-density polyethylene bottles for isotopic analyses. All samples were sealed with PARAFILM and stored in refrigerators (4°C).

Stable isotopes were analyzed using a Los Gatos Research (IWA-45-EP) isotopic water analyzer. The measurement accuracy of the δ^2H and $\delta^{18}O$ content as per mill (‰) deviations from the international standard Vienna Standard Mean Ocean Water (V-SMOW) were ± 0.5‰ and ± 0.2‰, respectively. The water level and temperature of the groundwater were acquired using a water level logger-titanium (ONSET HOBO). The precipitation amount weighted least squares regression (PWLSR) equation was defined (Hughes & Crawford 2012). Deuterium excess (D-excess) was defined by Dansgaard (1964) as a second-order stable isotope parameter measured in meteoric water to understand the source of precipitation and the evolution of moisture during transport (Bershaw 2018). Line-conditioned excess (lc-excess) was defined by Landwehr and Coplen (2004) and can be used to distinguish fractionation hydrologic processes (Dansgaard 1964; Evaristo et al. 2015). Water that undergoes fractionation by evaporation has a negative lc-excess (Landwehr & Coplen 2004; Sprenger 2016).

4 Results and Discussion

4.1 Composition of stable isotopes in precipitation

Stable isotopes (δ^2H and $\delta^{18}O$) in precipitation are influential tracers used to evaluate the hydrological cycle (Clark & Frita 1997; Cui & Li 2015; Jung et al. 2022). The content of δ^2H and $\delta^{18}O$ in precipitation ranged from -192.19‰ to 36.32‰ (with an average of -53.86‰) and -25.18‰ to 4.71‰ (with an average of -8.26‰), respectively (Fig. 2). The local meteoric water line (LMWL) was simulated using ordinary least squares regression (δ^2H = 7.80 $\delta^{18}O$ +10.60 (R^2 = 0.967, N = 261)) (Fig. 2). Local precipitation is predominantly derived from the westerly circulation from September through May and the East Asian monsoon from June to August (Cui et al. 2021). The slope of the LMWL (7.80) was similar to the slopes that have been observed for meteoric water lines in Lasa (7.90; Tian et al. 2001) and western China (7.56; Huang et al. 2008) and was

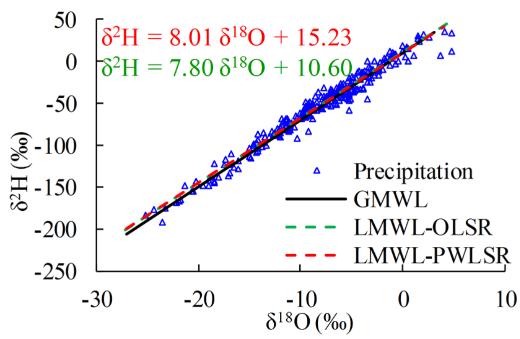

Fig. 2 Relationship between δ2H and δ18O in precipitation of Qinghai Lake Basin (GMWL: Global meteoric water line; LMWL-OLSR and LMWL-PWLSR: Local meteoric water line by Ordinary least squares regression and Local meteoric water line by Precipitation amount weighted least squares regression).

lower than that of the global meteoric water line (GMWL: δ^2H = 8.00 $\delta^{18}O$ + 10.00; Craig 1961). This result indicates that the precipitation processes in the basin are affected by below-cloud secondary evaporation (Liu et al. 2008; Gui et al. 2019) because humidity in the inland arid area is low, and raindrops undergo evaporation as they fall, causing isotope fractionation and thus a decrease in the LMWL slope (Araguas-Araguas et al. 1998; Cui & Li 2015; Zhang & Wang 2016).

The value of $\delta^{18}O$ was negatively correlated with precipitation, whereas the D-excess was significantly positively correlated with precipitation (p < 0.01) (Fig. 3). Therefore, raindrops in small rainfall events are more susceptible to secondary sub-cloud evaporation (Hughes & Crawford 2012). The LMWL (δ^2H = 8.01 $\delta^{18}O$ +10.60 (R^2 = 0.979, N = 261)) was simulated using an equation for a PWLSR (Fig. 2). The slope of the LMWL (8.01) was higher than that of the GMWL (8.00) because of the altitudinal effects of precipitation and low temperatures in the basin (Dotsika et al. 2010; Hughes & Crawford 2012; Cui & Li 2015).

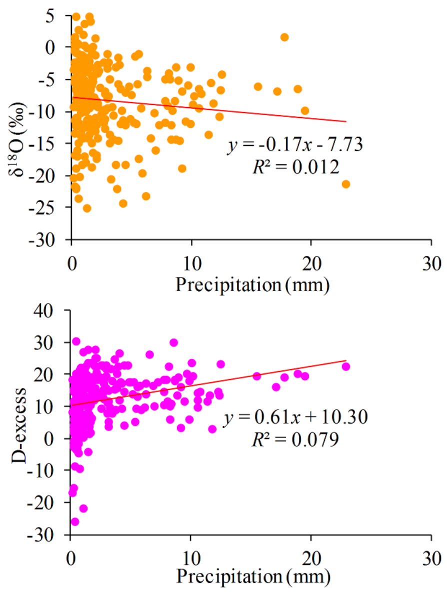

Fig. 3 Relationships between $\delta^{18}O$, D-excess of rain water samples and precipitation.

4.2 Stable isotopes compositions of surface water and groundwater

The contents of δ^2H and $\delta^{18}O$ in the river water ranged from -69.36‰ to -28.32‰ (with an average of -50.08‰) and -10.91‰ to -3.70‰ (with an average of -7.95‰), respectively (Fig. 4 and Fig. 5). δ^2H and $\delta^{18}O$ were within the isotope ranges measured in the local precipitation samples (Fig. 4). Most of the isotope points in the river water were close to the LMWL. The local evaporation line (LEL) of the river water was simulated as δ^2H = 6.21 $\delta^{18}O$ - 0.72 (Fig. 4), where the slope of LEL (6.21) was lower than that of the LMWL (7.80) and LEL of groundwater (6.59) (Fig. 4). These results are indicating that the river was primarily recharged by local precipitation that underwent varying degrees of evaporation before infiltration into the ground (Dotsika et al. 2010; Cui et al. 2014; Li et al. 2021). The slope of the LEL depends on the conditions (e.g., relative humidity, temperature, ambient vapor isotopic composition, mixing at the water–air interface, and thermodynamic activity [salinity] of water) (Gonfiantini et al. 2018). The stable isotopes (δ^2H and $\delta^{18}O$) in the different rivers differed (Fig. 5) because of the influence of recharge sources, runoff, and anthropogenic factors (Li et al. 2018). Slopes of the LEL of different rivers were ranked as follows: Quanji River (8.01) > Shaliu River (6.86) > Heima River (6.30) > Buha River (6.24) > Daotang River (5.77) > Ganzi River (5.64) > Haergai River (5.28) (Fig. 5). The contents of δ^2H and $\delta^{18}O$ of

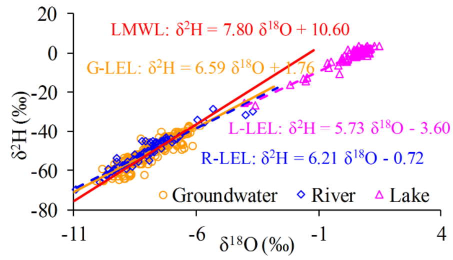

Fig. 4 Characteristics of stable isotope composition of groundwater samples in Qinghai Lake Basin (LMWL: Local meteoric water line; G-LEL: Local evaporation line of groundwater; R-LEL: Local evaporation line of river; L-LEL: Local evaporation line of lake).

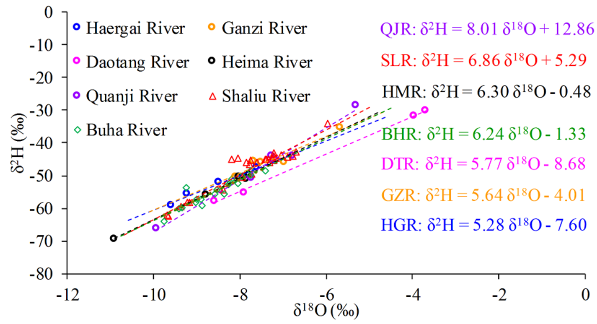

Fig. 5 Characteristics of stable isotope composition of river water samples in Qinghai Lake Basin.

the Buha, Shaliu, and Heima Rivers were relatively low, mainly due to the high recharge altitude, large runoff, and weak evaporation. The contents of δ^2H and $\delta^{18}O$ of the Ganzi and Daotang Rivers were relatively high, mainly due to low recharge altitude, small runoff, and strong evaporation. The contents of δ^2H and $\delta^{18}O$ of the Haergai River were relatively low, but the evaporation was strong, possibly because the high altitude of the recharge source reduces isotope contents. Additionally, the widened river of the lower reaches, diversion irrigation, and decreased runoff intensify evaporation. The contents of δ^2H and $\delta^{18}O$ of Quanji River were relatively high, but evaporation was weak. This may be because the recharge altitude of the recharge source was relatively low, which led to the relatively high isotope contents. Moreover, the river channel was reconstructed to protect the migration and reproduction of carp, resulting in increased runoff and weakened evaporation.

The contents of δ^2H and $\delta^{18}O$ for Qinghai Lake ranged from -26.31‰ to 3.82‰ (with an average of -1.76‰) and -4.02‰ to 1.50‰ (with an average of 0.32‰), respectively (Fig. 6). The contents of δ^2H and $\delta^{18}O$ in Haiyan were relatively high, and the δ^2H and $\delta^{18}O$ in Erhai were relatively low (Fig. 6). Slopes of the LEL of lakes surrounding Qinghai Lake were ranked as Erhai (6.24) > Qinghai Lake (5.75) > Gahai (3.84) > Haiyanwan (2.59) (Fig. 6). In Gahai and Haiyanwan, the lakes are relatively independent and have no surface runoff inflow, which results in relatively strong evaporation and enrichment of stable isotopes (Cui et al. 2016).

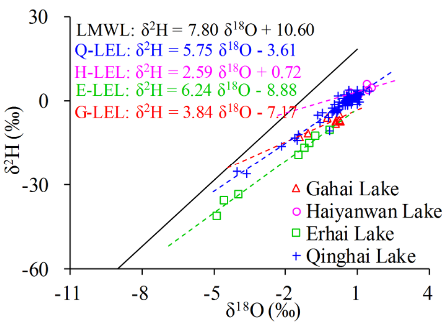

Fig. 6 Characteristics of stable isotope composition of lake water samples in Qinghai Lake Basin (Q-LEL, H-LEL, E-LEL and G-LEL: Local evaporation line of Qinghai Lake, Haiyanwan Lake, Erhai Lake and Gahai Lake).

The contents of δ^2H and $\delta^{18}O$ of groundwater ranged from -65.34‰ to -36.96‰ (with an average of -50.06‰) and -10.06‰ to -5.84‰ (with an average of -7.86‰), respectively (Fig. 4). Most isotope contents of the groundwater were close to the LMWL (Fig. 4). The LEL of groundwater was simulated as $\delta^2H = 6.59\ \delta^{18}O + 1.76$ (Fig. 4), where the slope of LEL (6.59) was lower than that of the LMWL (7.80) (Fig. 4), indicating that the groundwater was affected by the evaporation of soil water flows (Dotsika et al. 2010). The ranges of δ^2H and $\delta^{18}O$ of river water and groundwater were relatively close, with no significant differences (Fig. 4), indicating that their recharge sources were mainly from precipitation. This result also indicated a strong hydrological connection between the groundwater and river water surrounding Qinghai Lake. The slopes of the LEL of groundwater at different times were ranked as follows: April (7.18), January (6.89), July (6.81), October (6.43), and August (5.74).

4.3 Variations in water level and temperature of groundwater

The burial depth of the water table ranged from 1 to 16.7 m (with an average of 4.38 m). The depth range was similar to that reported in the literature (LZBCAS 1994; Xiao et al. 2013; Li et al. 2021). because the burial depth of the water table is influenced by geomorphology, topography, groundwater aquifers, and fault characteristics (Jin et al. 2009; Xiao et al. 2012), the burial depth of the water table around the lake was relatively shallow east of Qinghai Lake and south of Qinghai Lake, and relatively deep north of Qinghai Lake and west of Qinghai Lake. The difference in the hydraulic gradient between the groundwater level and the level of water in Qinghai Lake was calculated for each sampling site. The values obtained ranged from -0.06‰ to 13.47‰. The hydraulic gradient in the south of Qinghai Lake was relatively large, indicating that the potential flow energy was also relatively large (Boyraz & Kazezyilmaz-Alhan 2021).

The groundwater temperature showed an upward trend during the thawing period and a downward trend in freezing period (Fig. 7). The high- and low-water periods of groundwater were observed in May and March in Gangcha, respectively (Fig. 7a). The high water period of groundwater occurred before the rainy season, but there was an increase in the water level of groundwater in the rainy season and November. The high- and low-water periods of groundwater were observed in July and January,

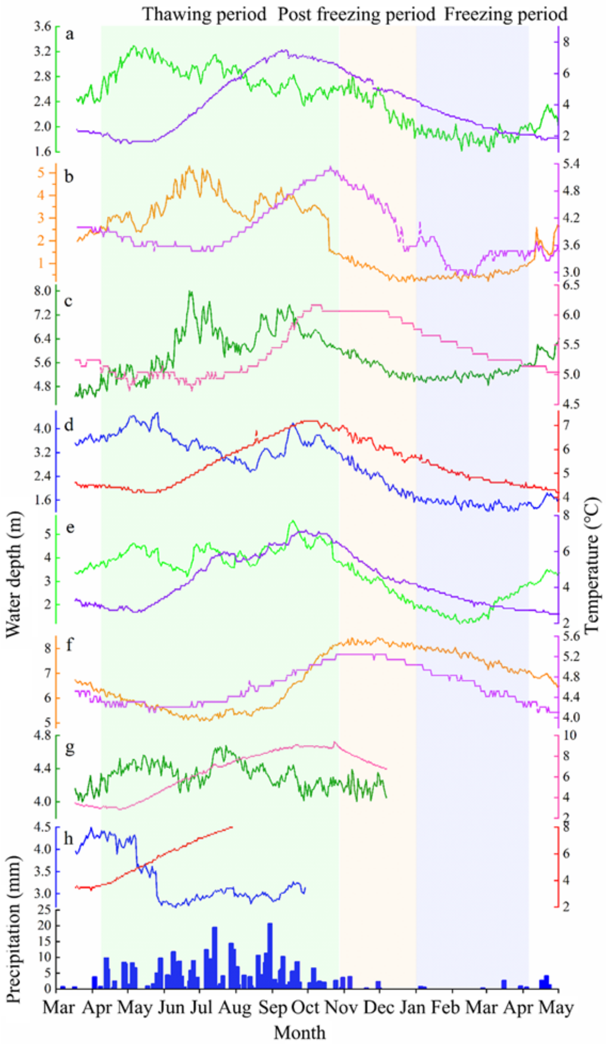

Fig. 7 Characteristics of water depth, groundwater temperature and precipitation in Qinghai Lake Basin (a. Gangcha; b. Tianjun; c. Niaodao; d. Heima River; e. Jiangxigou; f. Erhai; g. Haiyanwan; h. Gahai).

respectively, in the Buha River (Fig. 7b, 7c). Additionally, the high-water period of the groundwater was consistent with that of the rainy season. The high- and low-water periods of groundwater were observed in September and February in southern Qinghai Lake (Jiangxigou and Heima River), respectively (Fig. 7d, 7e). The high- and low-water periods of groundwater was observed in November and July, respectively, in Erhai (Fig. 7f). The high-water period was after the rainy season, and the characteristics of the temperature and water level were similar in this region; thus, this may have been recharged from bedrock fissure water. According to Fig. 7, most of the groundwater high-water period occurred during the freezing period. Groundwater exploitation should also be controlled during the freezing period to protect groundwater resources, stabilize the ecological environment, and prevent brackish water invasion.

4.4 Recharge source of groundwater

Investigating of spatial variability can provide basic information and identify locally significant parameters that affect isotopic distributions (Dotsika et al. 2010). To analyze the spatial characteristics, we divided the areas of interest surrounding Qinghai Lake into eight regions: north of Qinghai Lake (G50-G5, G37-G41), Gahai (G6-G7), Haiyanwan (G8), Erhai (G9-G11), south of Qinghai Lake (G12-G20), west of Qinghai Lake (G21-G27), Buha River (G28-G36), and Shaliu River (G42-G46) (Fig. 1 and Fig. 8).

The contents of δ^2H and $\delta^{18}O$ of groundwater in the Buha River were higher than those in the river water (Fig. 8a) because surface runoff has relatively strong evaporation (Liu et al. 2022). The contents of δ^2H and $\delta^{18}O$ of the groundwater decreased gradually from January to July and increased gradually from July to October. However, the isotope contents of river water were the smallest in April and the largest in August. Additionally, the fluctuation trend of the groundwater level was consistent with that of the river water level and runoff in the Buha River. Therefore, there is a close hydraulic connection between groundwater and river water, but with the change in the runoff, there may be a more complex interaction between groundwater and river water. The mean contents of $\delta^{18}O$ in different regions were ranked as follows: Shaliu River > north of lake > west of lake > Buha River > south of lake > Haiyanwan > Gahai > Erhai. The months with the maximum and minimum contents of $\delta^{18}O$ in most regions were August and October, respectively. According to the literature, the content of $\delta^{18}O$ in precipitation decreases with elevation, owing to altitude effects (Dotsika et al. 2010; Cui & Li 2015). Therefore, groundwater was mainly recharged by soil water with strong evaporation in August and recharged by precipitation at high altitudes in October. The slopes of the LEL of groundwater in different regions were ranked as follows: Erhai (6.69) > south of the lake (6.35) > Buha River (5.71) > north of the lake (5.01) > west of the lake (4.85) > Shaliu River (3.70) > Haiyanwan (3.09) > Gahai (1.40) (Table 1). The groundwater recharge altitude was ascertained using the altitude effect of oxygen isotopes in precipitation (Cui et al. 2014; Li et al. 2021). The recharge altitude of groundwater in Buha River, Shaliu River, north of lake, south of lake, west of lake, Erhai, Gahai and Haiyanwan was 3462.11, 3627.88, 3987.44, 3447.42, 3450.37, 4700.95, 3589.49, and 4135.46 m above sea level (m a.s.l.), respectively (Table 1).

4.5 Evaporative fractionation of groundwater

Stable isotopes of water molecules are often used to identify water sources and evaporative fractionation (Farrick & Branfireun 2015; Zhao et al. 2018). Lc-excess can be used to determine the degree of evaporative fractionation of groundwater during runoff recharge in hydrological processes (Evaristo et al. 2015). The contents of lc-excess of groundwater ranged from -10.23‰ to 10.41‰, with an average of 0.64‰ (Fig. 9). The mean contents of lc-excess of groundwater in different months were ranked as follows: October > January > April > July > August. The mean content of lc-excess of groundwater was the smallest in August, indicating that evaporation was the most intense in August. The contents of lc-excess of groundwater in G1-G3, G7-G13, G32, G37, G38, G45, G46, and G52 negatively deviated in August than in other months (Fig. 9), indicating that it was subjected to strong evaporation in August. The lc-excess of groundwater in G11-G23 deviated more positively in October than in other months (Fig. 9), this may be affected by precipitation effects. The contents of lc-excess of groundwater in G8, G9 and G37 were negative in different seasons (Fig. 9), indicating that it experienced strong evaporation throughout the year or recharge from the lower altitude of precipitation.

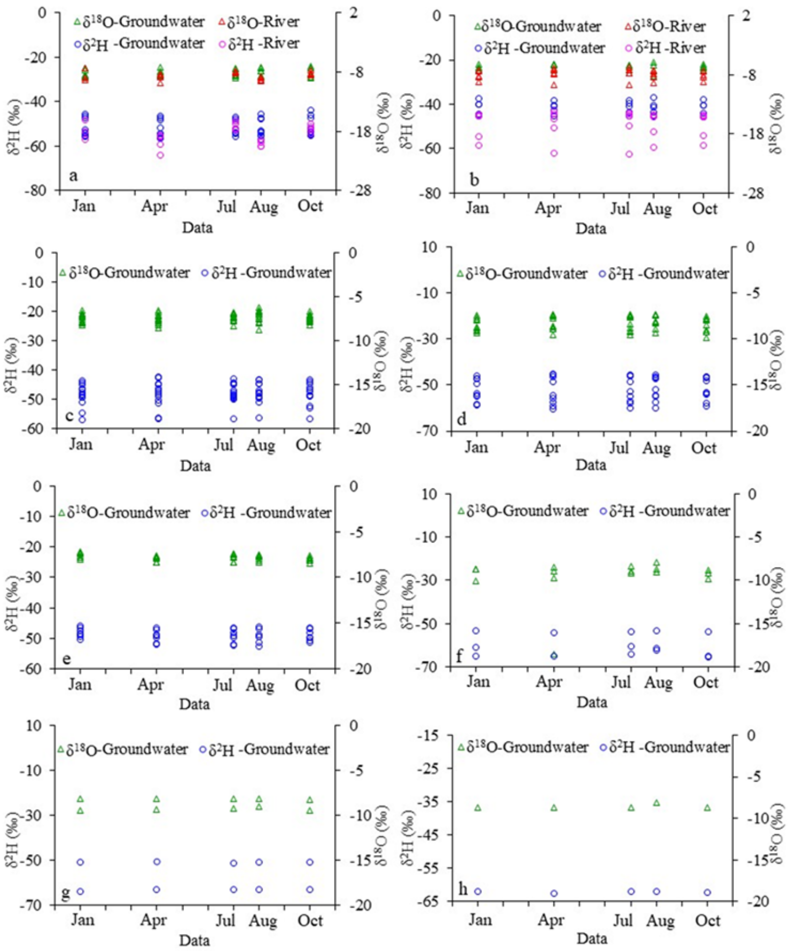

Fig. 8 Contents of δ^2H and $\delta^{18}O$ of groundwater in regions around Qinghai Lake (a. Buha River; b. Shaliu River; c. North of lake; d. South of lake; e. West of lake; f. Erhai; g. Gahai; h. Haiyanwan).

Table 1 Evaporation line, initial $\delta^{18}O$, and recharge altitude of groundwater in Qinghai Lake Basin

Regions	Evaporation line	Initial $\delta^{18}O$ (%)	Recharge altitude (m)
Buha River	$\delta^2H = 5.71\ \delta^{18}O - 4.68$	-8.66	3462.11
Shaliu River	$\delta^2H = 3.70\ \delta^{18}O - 16.20$	-7.29	3627.88
North of lake	$\delta^2H = 5.01\ \delta^{18}O - 11.04$	-8.76	3987.44
South of lake	$\delta^2H = 6.35\ \delta^{18}O + 0.78$	-8.70	3447.42
West of lake	$\delta^2H = 4.85\ \delta^{18}O - 10.90$	-8.27	3450.37
Erhai	$\delta^2H = 6.69\ \delta^{18}O - 0.15$	-11.65	4700.95
Gahai	$\delta^2H = 1.40\ \delta^{18}O -50.71$	-9.98	3589.49
Haiyanwan	$\delta^2H = 3.09\ \delta^{18}O - 35.28$	-10.27	4135.46

The mean contents of lc-excess of groundwater in the Buha River, Shaliu River, north of lake, south of lake, west of lake, Erhai and Haiyanwan were 1.95‰, 1.30‰, -0.89‰, 2.21‰, 1.62‰, 0.80‰ and -5.70‰, respectively. The mean contents of lc-excess of groundwater in the north of the lake were negative year-round, and the minimum occurred in August, indicating that groundwater was relatively strongly affected by evaporation, especially in August. The mean contents of lc-excess of groundwater in the south of the lake were positive year-round, indicating that groundwater has relatively weak evaporation or recharge from precipitation at high altitudes. This result also showed that groundwater was mainly affected by evaporation in Haiyanwan and north of the lake and was mainly affected by recharge altitude in the Shaliu River, west of the lake, Buha River, and south of the lake. Water surface slope is crucial to hydrological processes (Boyraz & Kazezyilmaz-Alhan 2021). Therefore, the recharge rate of groundwater is relatively high in areas with large slopes and hydraulic gradients (e.g., south of Qinghai Lake) and in areas with strong hydrological connections between groundwater and river water (e.g., the Buha River Valley) (Li et al. 2021). Additionally, the groundwater recharge rate was relatively slow in areas with relatively flat terrain and without large surface runoff (e.g., east and north of Qinghai Lake).

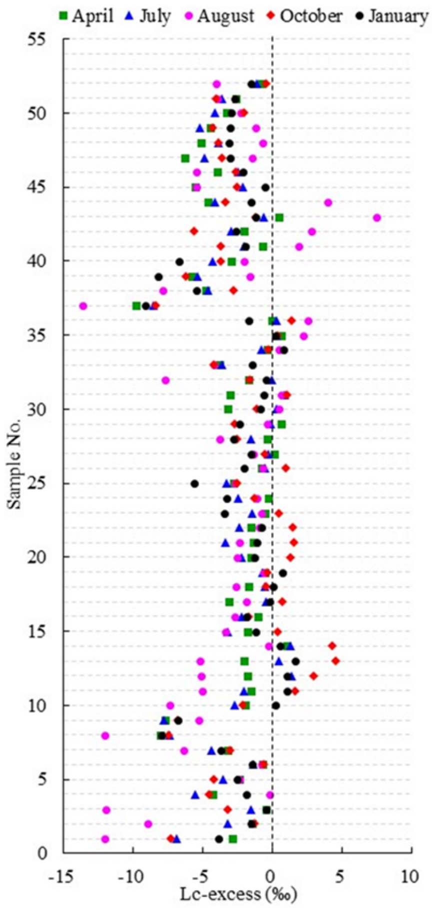

Fig. 9 Characteristics of lc-excess of groundwater around Qinghai Lake.

5 Conclusion

In this study, the characteristics of δ^2H and $\delta^{18}O$ in precipitation, groundwater, river water and lake water in the hydrological process were analyzed and discussed based on 686 water samples from Qinghai Lake, the spatial and temporal characteristics of groundwater recharge were determined by comparing the characteristics of δ^2H and $\delta^{18}O$ in different water bodies, and suggestions on the utilization of groundwater resources were proposed based on the groundwater level. The exploitation of groundwater should be controlled in freezing period. The LMWL (δ^2H = 7.80 $\delta^{18}O$ +10.60 and δ^2H = 8.01 $\delta^{18}O$ +10.60) were simulated using ordinary least squares regression (OLSR) and PWLSR, respectively. The contents of δ^2H and $\delta^{18}O$ increased from January to June and decreased from June to December. The slope of the LEL of the lake (5.73) was lower than that of the LMWL, LEL of the river (6.21), and LEL of groundwater (6.59). The mean contents of $\delta^{18}O$ in different regions were ranked as follows: Shaliu River > north of lake > west of lake > Buha River > south of lake > Haiyanwan > Gahai > Erhai. The slope of the groundwater LEL at different times was ranked as April (7.18), January (6.89), July (6.81), October (6.43), and August (5.74). Slopes of the LEL of groundwater in different regions were ranked as follows: Erhai (6.69) > south of Lake (6.35) > Buha River (5.71) > north of Lake (5.01) > west of Lake (4.85) > Shaliu River (3.70) > Haiyanwan (3.09) > Gahai (1.40). It was also found that the recharge by permafrost melt water and bedrock fissure water and the interaction of surface water with groundwater can affect the fluctuation of groundwater level, but determining the specific mechanism requires further research.

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