Recharge Characteristics of Shallow Groundwater in Different Periods in the Shaliu River Basin of Qinghai Lake

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Abstract

Spatiotemporal variations in stable isotope composition of groundwater can reflect differences in recharge sources across different periods and regions. This study investigated the spatiotemporal variation characteristics of hydrogen and oxygen stable isotopes in shallow groundwater in the Shaliu River Basin of Qinghai Lake, as well as the recharge relationships among groundwater, river water, and precipitation, and reached the following conclusions: During the monsoon period, groundwater recharge is dominated by rainfall infiltration and lateral river recharge, with evaporation being the primary factor influencing stable isotope values in groundwater during the recharge process; During the non-monsoon period, ice and snow meltwater significantly affects groundwater in low-value areas, while rapid precipitation infiltration constitutes one of the main recharge mechanisms for groundwater in high-value areas. In groundwater isotope high-value areas, the recharge interaction between groundwater and river water is relatively weak, with recharge times exceeding 5 months; In groundwater isotope low-value areas, the recharge relationship between groundwater and river water is relatively close, with recharge times ranging from 1 to 4 months. The conclusions obtained from this study can preliminarily reflect the basic patterns of stable isotope characteristics and recharge mechanisms in groundwater within arid and semi-arid inland basins, providing a scientific basis for investigating the transformation between groundwater and other water bodies in the basin to a certain extent, and offering theoretical guidance for groundwater resource management and water environment governance.

Full Text

Recharge Characteristics of Shallow Groundwater in Different Periods in the Shaliu River Basin of Qinghai Lake

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Abstract: The spatiotemporal variation characteristics of stable isotope composition in groundwater can reflect differences in groundwater recharge sources across different periods and regions. By analyzing the spatiotemporal variation characteristics of hydrogen and oxygen stable isotope compositions in shallow groundwater in the Shaliu River Basin of Qinghai Lake, as well as the recharge relationships among groundwater, river water, and precipitation, the results show that during the monsoon period, groundwater is mainly recharged by rainfall infiltration and lateral river recharge; during the recharge process, evaporation is the main factor affecting the stable isotope values of groundwater. During the non-monsoon period, snow and ice meltwater has a significant influence on groundwater in low-value areas, while rapid infiltration of precipitation is also one of the main recharge modes for groundwater in high-value areas during this period. In groundwater isotope high-value areas, recharge between groundwater and river water is relatively weak, and the recharge duration exceeds 5 months; in groundwater isotope low-value areas, the recharge relationship between groundwater and river water is relatively close, with recharge occurring between January and April. These conclusions can preliminarily reflect the basic patterns of stable isotope characteristics and recharge modes of groundwater in semi-arid inland basins, and to a certain extent provide scientific evidence for studying exchanges between basin groundwater and other water bodies, as well as theoretical guidance for groundwater resources management and water-environment governance.

Keywords: shallow groundwater; hydrogen and oxygen stable isotopes; groundwater recharge; Qinghai Lake; Shaliu River Basin

Article number

The impacts caused by global change are acting constantly upon the natural environment and human life. For example, climate warming and uneven distribution of water resources are among a series of environmental problems affecting the development of human society1. As an important terrestrial water resource, groundwater plays an important role in ecosystems and in the sustainable development of human life, especially in semi-arid or semi-humid regions[2-3]. Groundwater is a product of the hydrological cycle over geological history and is controlled over time by different climatic conditions; therefore, groundwater characteristics are closely linked with environmental factors[4]. For example, hydrogeologists have carried out studies in the Arctic region and found that large-scale climate change during the Pleistocene and Holocene caused repeated alternation of continental glaciers and marine transgressions, as well as unusually active sea-level fluctuations. These changes further altered the spatial distribution and chemical composition of groundwater in the region[1,5-6]. Human activities also, to a certain extent, change groundwater storage and its evolutionary processes, especially in productive aquifers[7-8]. Some well-known karst springs in northern China, such as the Niangziguan Spring, Jinci Spring, and Heilongdong Spring, have experienced various environmental problems over the past several decades, including drying of spring water, continuous decline of water levels, and deterioration of water quality[9]. Therefore, understanding the interference of natural processes and human activities with groundwater is of great significance for the sustainable management of groundwater in water-scarce regions[10]. The premise of the above research is often to establish a clear understanding of groundwater recharge characteristics and evolutionary mechanisms.

Because groundwater is affected by differences in regional natural conditions, its recharge characteristics often exhibit different manifestations in different regions. In humid regions, precipitation is abundant and evaporation is relatively small; many studies have shown that precipitation is the main recharge source of groundwater[11–12]. In arid regions, precipitation is scarce and evaporation is strong; scholars still hold different understandings as to whether precipitation can recharge groundwater[13–15]. Owing to climatic differences, seasonal precipitation often recharges groundwater unevenly: for example, in early spring in temperate regions, groundwater is strongly recharged by snow and ice meltwater and soil water, and the groundwater recharge rate is relatively high[16–18]; in summer, evaporation and transpiration rates are very high, and groundwater is recharged by precipitation and runoff, but the recharge rate is often very low[16,18]. Therefore, groundwater recharge sources differ under different regional and temporal backgrounds. Because the environment in which groundwater occurs is special and its flow processes are complex, being influenced by natural conditions such as geology and geomorphology and constrained by human and physical factors, traditional hydrological methods are clearly insufficient for in-depth investigation of the spatiotemporal variation characteristics of groundwater recharge sources.

In recent years, isotope hydrology methods have been widely applied to

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research on the origin, age, and recharge pathways of water bodies[^19]. Hydrogen and oxygen are elements that constitute water; their stable isotopes can indicate the sources of water and the migration and transformation of water under different environmental conditions, and can directly reflect the cycling processes of groundwater. They are ideal tracers of the water cycle; therefore, this technique has been widely applied in groundwater recharge and other hydrological-cycle processes[^20–^24]. MALOV et al.[^1], through a study of groundwater isotopes and hydrochemical characteristics in northwestern Russia, found that groundwater in this region is affected to a large extent by glacial melt. LIU et al.[^7] confirmed that groundwater in North China is recharged by precipitation infiltration after evaporation, and found that, in fault zones and karst conduits, groundwater preferentially interacts with surface water along flow paths. SAMIE et al.[^25], using the recharge and flow characteristics of groundwater, found that groundwater in the arid transitional zone of Nubia mainly originates from precipitation during flood periods. WANG et al.[^26], by means of the recharge characteristics of runoff, found that groundwater sources in the Yinchuan area are mainly precipitation, bedrock fissure water, and irrigation return flow, and that discharge is dominated by evaporation, artificial pumping, and recharge to surface water bodies. WANG et al.[^27], combining the characteristics of isotopic variation in surface water in the Kaidu River Basin of the northwestern arid region, found that groundwater is mainly recharged by surface water bodies.

Qinghai Lake, located in the arid and semi-arid region of the northeastern Qinghai–Tibet Plateau of China, is the largest inland lake in China and one of the national nature reserves. Owing to the unique natural conditions of the Qinghai Lake region, such as its hydrology and climate, hydrological processes and characteristics are highly representative of basins in arid and semi-arid regions[^28]. Grassland, as the principal type of surface cover in the Qinghai Lake Basin, accounts for 73.9% of the entire basin area[^10]. It is the basis for maintaining ecological stability in the basin and is also an important material resource related to the production, livelihood, and development of local farmers and herders. The occurrence state of shallow groundwater in the basin and changes in its water level are often closely related to the diversity and growth conditions of surface vegetation types[^28]. Therefore, research on shallow groundwater is of great scientific significance for the ecological sustainable development of the Qinghai Lake region. Existing studies on shallow groundwater in the Qinghai Lake Basin include, for example, XIAO et al.[^29], who used Sr isotopes (87Sr/86Sr) to explain the hydrochemistry of shallow groundwater in the Qinghai Lake Basin and the input modes of its related ions; and Jin Zhangdong et al.[^28], who, through groundwater burial depth and isotope analysis, verified that shallow groundwater in the Qinghai Lake Basin is mainly recharged by infiltration of rainfall. The above studies have generally focused on the stable-isotope composition and recharge processes of groundwater at a single time or single-point scale, and have not comprehensively analyzed their spatiotemporal variability. Therefore, based on stable-isotope techniques, this paper analyzes the spatiotemporal distribution characteristics of groundwater in the Shaliu River Basin of Qinghai Lake, and on this basis explores the interaction relationships among precipitation, river water, and groundwater in the basin, thereby providing a theoretical basis for groundwater-resources management and water-environment governance in the basin.

1

The Shaliu River, also known as the Yike Wulan River, is located in the northeastern part of the Qinghai–Tibet Plateau and in the northern part of Qinghai Lake. It originates on the southern foot of the first high peak in Gangcha County, the Sangsi Zhaxi Mountain[^30]. The Shaliu River has a total length of 106 km, and its annual runoff accounts for 1/5 of the total inflow of rivers entering Qinghai Lake within the Qinghai Lake Basin[^31], making it the second-largest river in the Qinghai Lake Basin. The Shaliu River Basin (37°10$'$55.92$''$-37°51$'$2.16$''$ N, 99°37$'$10.20$''$-100°17$'$9.96$''$ E) has an area of 1,679.2 km^2, accounting for 1/12 of the total area of the Qinghai Lake Basin. The region belongs to a semi-arid temperate continental climate, with an annual mean temperature of 0.1 °C, annual precipitation of approximately 400 mm, and annual evaporation of approximately 1,300 mm; evaporation mainly occurs in the warm summer season. The basin is mainly controlled by two air masses: the Asian southeast monsoon and the westerlies. In summer, it is affected by the Asian southeast monsoon, and about 65% of precipitation is concentrated in this period (June-September)[^32]; the remaining precipitation occurs in the non-monsoon period (October-May). In winter it is mainly affected by the westerly circulation, resulting in marked seasonality of precipitation in the region[^33].

Three major deep faults and multiple structural units are developed within the basin, and the geological structure is complex. Their formation and evolution are controlled by the activity of the Middle Qilian southern-margin major fault zone and other NW- and NNW-trending fault activities, as well as by the uplift of the Qinghai–Tibet Plateau and the evolution of Qinghai Lake, to which they are closely related[^34-^35]. Groundwater storage in the Shaliu River Basin is relatively abundant. In the northern mountainous area of the basin, sandstone and breccia are mainly distributed, with bedrock fissure water developed between them, and the groundwater is relatively shallow. In the central part, granites and Permian marine–continental alternating breccia and shale are mainly distributed. In the plain area, sand–gravel–pebble belts are distributed, with good permeability, and the main groundwater occurrence form is pore water in piedmont and intermontane plain sand–gravel layers. This groundwater is recharged by upstream water, and groundwater is abundant in this area. Downstream to the lakeshore area, Quaternary alluvial deposits are present, with pore water in sand–gravel and silty-sand layers as well as confined water in lakeshore plain layers; groundwater discharges in the form of springs[^29,^36].

2 Sample collection and data sources

To better understand the spatiotemporal variation characteristics of groundwater isotopes in the Shaliu River Basin, this study regularly collected samples of groundwater, river water, spring water, and other waters in the middle and lower reaches of the Shaliu River in the second half of 2017. A total of 210 groundwater samples, 60 river-water samples, 24 snow/ice and meltwater samples, and 7 spring-water samples were collected. Considering seasonal differences in precipitation and changes in river discharge, two periods with representative and temporally continuous sampling, July–September and October–November, were selected as the sample-collection periods, representing the monsoon and non-monsoon periods, respectively. During sampling, well water was collected after pumping with a water pump for 15–30 min, spring water was collected at

Fig. 1 Study area geology and sampling points distribution

Figure 1: Fig. 1 Study area geology and sampling points distribution

the outcrop, and river-water samples were collected 1-2 m from the riverbank and 0.2 m below the water surface.

Fig. 1 Study area geology and sampling points distribution

flowing river water, so as to ensure that the river water body was fully mixed and to avoid fractionation of isotopes caused by evaporation of surface water. Before sampling, the sampling bottle was rinsed 3–5 times with the water to be collected; the sample was then divided into two portions and placed in 60 mL high-density polyethylene plastic bottles (HDPE) that had been pre-rinsed with ultrapure water. The bottles were sealed with Parafilm and then stored under refrigeration at $-4\,^{\circ}\mathrm{C}$ in the Key Laboratory of Natural Geography and Environmental Processes, Qinghai Normal University. The automatic meteorological observation system was installed in the Wayanshan river-source wetland in the source region of the Shaliu River, and can provide real-time monitoring of the meteorological environment.

Measurements of hydrogen and oxygen stable isotopes (δ^{18}O and δD) for all samples were carried out in the Key Laboratory of Natural Geography and Environmental Processes of Qinghai Province, Qinghai Normal University. The instrument used was a liquid water isotope analyzer produced by LGR. The final results are expressed in per mil relative to Vienna Standard Oceanic Water (Vienna Standard Oceanic Water, VSMOW)[37]:

$$\delta = \left(R_{\text{sample}}/R_{\text{standard}} - 1\right) \times 1\,000 \qquad (1)$$

where R is D/H or ^{18}O/^{16}O.

In 1953, EPSTIEN et al.[38] and FRIEDMAN[39], through analyses of non-marine water and atmospheric water samples, discovered a linear relationship between the stable isotopes of hydrogen and oxygen. Based on this relationship, CRAIG[40] defined the linear relationship between δ^{18}O and δD in atmospheric precipitation as the meteoric water line, and further extended it to the global meteoric water line (GMWL). Comparing the linear relationships between δ^{18}O and δD in water bodies from different regions with the GMWL can be used to determine the causes of changes in stable isotopes in regional water bodies; this is of great significance for the development of isotope hydrology and for studying stable-isotope variations during the hydrological cycle. The hydrogen and oxygen stable-isotope data of groundwater samples were analyzed using statistical methods and interpreted with the aid of meteoric-water-line relationship diagrams:

Global meteoric water line (GMWL):

$$\delta D = 8\delta^{18}O + 10^{[40]}$$

Local meteoric water line (LMWL):

$$\delta D = 8.17\delta^{18}O + 16.2^{[40]}$$

On the basis of the measured groundwater $\delta^{18}O$ data, this study uses

Table 1 Spatial interpolation error distribution

Tab. 1 Spatial interpolation error distribution

Month	n	Mean absolute error	Root mean square error	Variance
7	56	0.40	0.63	0.13
8	36	0.46	0.63	0.13
9	40	0.41	0.53	0.15
10	39	0.48	0.62	0.27
11	39	0.35	0.44	0.17

Using ArcGIS software, the inverse distance weighting method (IDW) [41–48] was selected to conduct spatial-difference simulation analysis, yielding spatial distribution maps of $\delta^{18}O$ and deuterium excess (*d*-excess). Table 1 shows the distribution of spatial interpolation errors based on the inverse distance weighting method.

3 Results and Analysis

3.1 Overall characteristics of groundwater stable isotopes

The linear relationship between $\delta^{18}O$ and δD among different water bodies in the Shaliu River Basin shows (Fig. 2a) that the $\delta^{18}O$ ranges of groundwater, river water, spring water, and precipitation are $-9.2‰$ to $-5.7‰$, $-10.0‰$ to $-6.5‰$, $-7.8‰$ to $-6.9‰$, and $-11.4‰$ to $-3.8‰$, respectively; their mean values are $-6.8‰$, $-7.8‰$, $-7.4‰$, and $-9.2‰$, respectively. The ranges of $\delta^{18}O$ in the water bodies, from largest to smallest, are: precipitation > river water > groundwater > spring water; the mean $\delta^{18}O$ values, from largest to smallest, are: groundwater > spring water > river water > precipitation.

River water, groundwater, and spring water are distributed on both sides of the LMWL (local meteoric water line), are closely related to precipitation, and at the same time the isotope fluctuation ranges among the three are relatively small and the mean values are comparatively close; therefore, there is a relatively strong hydraulic connection. The isotopic relationship points of precipitation lie

Fig. 2 Relationship between ( )18O and δD in different water bodies in Shaliu River Basin

Figure 2: Fig. 2 Relationship between ( )18O and δD in different water bodies in Shaliu River Basin

above the LMWL, and the fluctuation range differs relatively greatly from the mean values of the other water bodies. Affected by evaporation, the intercept and slope of the groundwater line deviate markedly and are smaller than those of the local meteoric water line and the global meteoric water line. Therefore, during the process by which precipitation recharges groundwater, the fractionation experienced by precipitation is successively weakened; the slopes of the evaporation lines for river water, groundwater, and spring water decrease in turn (6.5‰, 5.6‰, and 3.4‰, respectively), and the three water bodies are successively more strongly affected by evaporation or by recharge-derived precipitation fractionation.

3.2 Variation characteristics of groundwater stable isotopes

Because of seasonal climatic differences and environmental changes such as temperature/humidity, different periods have different recharge characteristics, and groundwater stable isotopes exhibit different variation characteristics. The related values of groundwater stable isotope compositions δ^{18}O and δD from July to November are shown in Table 2. Among them, the ranges of δD are −60.3‰ to −34.3‰, −53.6‰ to −34.6‰, −52.5‰ to −35.8‰, −52.9‰ to −37.3‰, and −49.9‰ to −36.9‰, respectively, with mean values of −41.6‰, −42.0‰, −41.0‰, −42.7‰, and −41.8‰; the ranges of δ^{18}O are −9.2‰ to −5.7‰, −8.5‰ to −5.7‰, −8.3‰ to −5.7‰, −9.2‰ to −6.0‰, and −8.2‰ to −5.9‰, respectively, with mean values of −6.7‰, −6.7‰, −6.6‰, −7.3‰, and −6.8‰.

Figures 3a–3e present the spatial distribution of groundwater δ^{18}O values in the study area from July to November. Based on the spatial-difference result maps, the δ^{18}O values are divided into 17 classes using a gradual color scheme. In this paper, areas with δ^{18}O values greater than −6.8‰ are defined as high-value zones (orange-red parts in the figure), areas with δ^{18}O values from −7.5‰ to −6.8‰ are defined as medium-value zones (yellow parts in the figure), and areas with values less than −7.5‰ are defined as low-value zones (green parts in the figure). From July to September, the high-value areas of δ^{18}O

Figure 2 Relationship between δ^{18}O and δD in different water bodies in the Shaliu River Basin

Fig. 2 Relationship between δ^{18}O and δD in different water bodies in Shaliu River Basin

Table 2 Changes in hydrogen and oxygen stable isotope values of groundwater in the middle and lower reaches of the Shaliu River

Basin

Tab. 2 Changes of hydrogen and oxygen stable isotope values of groundwater in the middle and lower reaches

Month	n	δD / ‰ Maximum	δD / ‰ Minimum	δD / ‰ Mean	δ^{18}O / ‰ Maximum	δ^{18}O / ‰ Minimum	δ^{18}O / ‰ Mean	d-excess / ‰ Maximum	d-excess / ‰ Minimum	d-excess / ‰ Mean
7	56	−34.3	−60.3	−41.6	−5.7	−9.2	−6.7	14.2	9.3	11.8
8	36	−34.6	−53.6	−42.0	−5.7	−8.5	−6.7	15.0	8.3	11.8
9	40	−35.8	−52.5	−41.0	−5.7	−8.3	−6.6	14.4	8.8	11.6
10	39	−37.3	−52.9	−42.7	−6.0	−9.2	−7.3	21.1	9.9	15.4
11	39	−36.9	−49.9	−41.8	−5.9	−8.2	−6.8	15.9	8.0	12.8

(a) 2017-07 (b) 2017-08 (c) 2017-09

(b) 2017-10 (e) 2017-11 (f) July-November mean

I. Northwestern high-value area
II. Northern low-value area
III. Central high-value area
IV. Southern low-value area

δ^{18}O / ‰

Fig. 3 Temporal and spatial variability of groundwater stable isotope δ^{18}O in different months

The area showing an increasing trend expanded and extended toward both the south and north, while the low-value area shifted toward both the south and north under the influence of the high-value area. From October to November, the ranges of high and intermediate δ^{18}O values expanded, whereas the range of low values contracted and shifted northward. During the monsoon period (Fig. 3a–3c), δ^{18}O was dominated mainly by high- and intermediate-value zones (the orange and green portions in the figure), whereas during the non-monsoon period (Fig. 3d–3e) it was distributed mainly in intermediate- and low-value zones (the yellow and green portions in the figure). From the monsoon period to the non-monsoon period, the δD and δ^{18}O values of groundwater changed markedly and showed a decreasing trend.

3.3 Relationship between groundwater and stable isotopes in atmospheric precipitation

The monthly mean values of stable isotopes in groundwater in the Shaliu River Basin vary as shown in Fig. 4a. During the sampling period, the range of

$\delta^{18}O$ values was $-7.3‰ \sim -6.6‰$, and the range of δD values was $-42.7‰ \sim -41.0‰$, with fluctuation amplitudes of 0.7‰ and 1.7‰, respectively. The isotopes in atmospheric precipitation reached their maximum in June–July and then gradually decreased. From July to November, the ranges of $\delta^{18}O$ and δD were $-5.6‰ \sim -12.9‰$ and $-30.5‰ \sim -88.9‰$, respectively, with fluctuation amplitudes of 7.3‰ and 58.4‰.

During the sampling period, the stable isotopes in atmospheric precipitation changed markedly, showing a month-by-month decreasing trend beginning in July. This change was consistent with the temperature trend (Fig. 4b), further confirming the conclusion that temperature is one of the factors controlling the stable-isotope values of precipitation[^19]. According to Rayleigh fractionation theory, the magnitude of evaporative effects on precipitation is closely related to air humidity[^43-^44]. During the sampling period, air humidity showed a decreasing trend (Fig. 4b), indicating that during precipitation, fractionation gradually weakened, the depletion of light isotopes and enrichment of heavy isotopes diminished, and the values of $\delta^{18}O$ and δD gradually decreased. The fluctuation of groundwater stable isotopes was gentler than that of precipitation, and recharge to groundwater is a complex process. While groundwater receives recharge from precipitation, runoff, soil water, and evaporation also affect the isotopic values of groundwater. Thus, recharge from different sources is one of the reasons why groundwater fluctuates less than precipitation. It should be noted that, unlike atmospheric precipitation, groundwater storage conditions are relatively closed and are strongly affected by the surrounding geological environment, such as strata, lithology, and burial depth. Therefore, stable isotopes exhibit considerable spatial variability; changes in the overall mean values alone are insufficient to explain their actual characteristics, and different regions need to be studied separately.

3.4 Relationship between groundwater and stable isotopes in river water

To further analyze the temporal variation characteristics of stable isotopes in groundwater in the middle and lower reaches of the Shaliu River Basin, according to the spatial distribution of mean $\delta^{18}O$ values (Fig. 3f), the basin was divided into two major categories: high-value areas and low-value areas (further subdivided into four major regions: the northwestern high-value area, northern low-value area, central high-value area, and southern low-value area) (Fig. 5).

In the northern low-value area, the range of groundwater $\delta^{18}O$ fluctuation was $-9.2‰ \sim -6.2‰$, with a mean fluctuation value of $-7.4‰$; the fluctuation range of river water was $-9.7‰ \sim -7.6‰$, with a mean fluctuation value of $-8.5‰$. From July to September, the groundwater isotope values fluctuated only slightly and changed gently; from September to October they began to decrease sharply, reaching the minimum $\delta^{18}O$ value in October, and then rebounded. River-water $\delta^{18}O$ showed an increasing trend from July to November, with the most obvious change from August to September; after September, the

Fig. 4. Variation characteristics of atmospheric precipitation isotopes and meteorological factors

Figure 3: Fig. 4. Variation characteristics of atmospheric precipitation isotopes and meteorological factors

Fig. 5 Relationship between groundwater and river water isotopic changes in different regions

Figure 4: Fig. 5 Relationship between groundwater and river water isotopic changes in different regions

increase became gentler. This indicates that groundwater–river water interaction in this area was not obvious from July to September, with relatively large differences in isotopic values; from October to November, the isotopic-value differences between the two decreased, and mutual recharge became evident. In the southern low-value area, the range of groundwater $\delta^{18}O$ fluctuation was $-9.0‰ \sim -6.5‰$, with a mean value of $-7.1‰$; the range of river-water $\delta^{18}O$ fluctuation was $-8.6‰ \sim -6.1‰$, with a mean value of $-7.4‰$. From July to November, groundwater stable isotopes fluctuated relatively gently; river-water $\delta^{18}O$ exhibited a small peak in August and then gradually increased. The difference in stable isotopes between river water and groundwater in this area was relatively small, and there was clear overlap between the two, indicating a close hydraulic connection between them.

In the northwestern high-value area, the range of groundwater $\delta^{18}O$ was $-7.1‰ \sim$

Fig. 4 Variation characteristics of atmospheric precipitation isotopes[^18-^19] and meteorological factors

Fig. 5 Relationship between groundwater and river water isotopic changes in different regions

$-5.7‰$, and the mean value during the sampling period was $-6.2‰$; the range of river-water $\delta^{18}O$ was $-8.2‰$ to $-7.3‰$, with a mean value of $-7.9‰$. Groundwater $\delta^{18}O$ increased slightly from July to August, and then decreased slowly from August to November; this characteristic was similar to the variation in the precipitation isotopes during the sampling period. Except for a slight decrease from September to October, river-water $\delta^{18}O$ varied relatively steadily in the other months. In this region, the difference in stable-isotope characteristics between groundwater and river water was relatively large, and the interaction between the two was not significant. In the central high-value area, groundwater $\delta^{18}O$ varied within the range of $-7.3‰$ to $-5.7‰$, with a sampling-period mean of $-6.3‰$; river-water $\delta^{18}O$ fluctuated between $-10.6‰$ and $-6.4‰$, with a mean of $-7.4‰$. Groundwater isotopes changed steadily from July to September, began to decrease from September to October, and rose slightly from October to November. Except in July, the variation trend of river-water $\delta^{18}O$

was basically consistent with that of groundwater. From October to November, the difference in stable isotopes between groundwater and river water began to decrease; in November, the isotopes of the two intersected and tended to be consistent.

In summary, in the high-value area of groundwater stable isotopes, the monthly mean δ^{18}O line was distributed above that of river water; the groundwater stable-isotope values were relatively concentrated and differed greatly from those of river water, indicating that the groundwater recharge source was single and that the mutual recharge between the two was not obvious. A possible reason is that an aquitard with relatively poor permeability exists between river water and groundwater in the region, reducing the recharge rate and, to a certain extent, hindering the hydraulic connection between the two. Comparison of isotope variation characteristics shows that the time of mutual recharge between groundwater and river water in this region exceeded 5 months. In the low-value area of groundwater stable isotopes, the difference between groundwater and river-water isotope values was small; the distributions were relatively scattered and fluctuated greatly. In this type of region, groundwater and river water had broad recharge sources and close relationships. Comparison of isotope distribution characteristics shows that the recharge time between the two was between 1 and 4 months.

4 Discussion

Because of seasonal differences, the isotopic characteristics of groundwater in the Shaliu River Basin during the monsoon and non-monsoon periods showed certain differences. To further analyze the causes of differences in hydrogen and oxygen stable isotopes of groundwater in the basin, this paper uses the spatial distribution map of groundwater δ^{18}O to explore the characteristics of groundwater isotopes in high-value and low-value areas and the transformation of recharge sources.

During the monsoon period (Fig. 6a), groundwater isotope relationship points were located to the lower right of the LMWL and formed a groundwater evaporation line slightly smaller than the former, GWL_1 ($\delta D = 6.6\delta^{18}O + 2.5$). During this period, the isotope relationship points in the low-value area were concentrated at the left end of GWL_1 and near the intersection of GWL_1 with the LMWL, indicating that groundwater in the low-value area was recharged by precipitation and was little affected by evaporation. Compared with the low-value area, isotope relationship points of groundwater in the high-value area were concentrated on the right side of GWL_1, far from the intersections of the LMWL and GMWL, indicating that the recharge water bodies for groundwater in this area entered groundwater only after further evaporation. River-water isotope relationship points were also located to the lower right of the LMWL (Fig. 6c). The slopes and intercepts of evaporation lines GWL_1 and RWL_1 differed little, being 6.6 and 6.9, and 2.5 and 4.8, respectively. The two evaporation lines were nearly coincident, indicating that river water and groundwater

Fig. 6 Distribution of groundwater isotope relation points in different periods and the relation with other water

Figure 5: Fig. 6 Distribution of groundwater isotope relation points in different periods and the relation with other water

had the same source during this period and that both were recharged by precipitation. The groundwater relationship points overlapped with river-water relationship points at many locations, indicating that groundwater in this region was strongly recharged by river water, and river water seeped laterally into groundwater. Meanwhile, in the upper-right part of GWL_1, a large number of groundwater relationship points were distributed ahead of the river-water relationship points; the degree of groundwater evaporation exceeded that of river water during the same period. It can be inferred that the groundwater circulation rate was faster than the rate at which river water recharged groundwater.

During the non-monsoon period (Fig. 6b), groundwater isotope relationship points were distributed on both the left and right sides of the LMWL, and the corresponding evaporation line GWL_2 ($\delta D = 4.7\delta^{18}O - 9.1$) intersected the LMWL. During this period, groundwater isotope relationship points in the high-value area were concentrated near the intersection of GWL_2 and the LMWL, indicating that groundwater in the high-value area during the non-monsoon period was mainly recharged by precipitation. The low-value groundwater area was distributed on both sides of the LMWL and was relatively scattered,

Fig. 6 Distribution of groundwater isotope relation points in different periods and the relation with other water

This further indicates that, in this area, other water bodies still exert an influence on it. Groundwater located to the right of the LMWL is recharged after strong evaporation; groundwater relation points located to the left of the LMWL have relatively low isotope values and may be recharged by snowmelt and other sources, because the isotope values in snowmelt are relatively low[^45]. Accordingly, in the non-monsoon period, because the groundwater lies in different zones, the effect of precipitation recharge is not entirely the same, and can be broadly classified into two types of processes. Process 1: because, during melting, snow and ice experience inconsistent evaporation at the surface and in the interior, the stable isotope composition differs greatly. Meltwater that is less affected by evaporation carries large amounts of light isotopes to recharge groundwater in the northern part of the basin, thereby causing the isotopes in this area to become depleted. Process 2: groundwater is directly recharged by precipitation; during recharge, because the infiltration rate is relatively fast, the water body is less affected by evaporation. This is also the main reason why isotope relation points in the high-value area are concentrated near the intersection of the evaporation line and the meteoric water line. Similarly to groundwater, river-water relation points are also distributed on both sides of the LMWL. The slopes and intercepts of the groundwater and river-water evaporation lines are 4.7 and 5.0, and −9.1 and −7.2, respectively. The two have similar degrees of evaporation and the same recharge source. During this period, precipitation is relatively small, temperature is relatively low, and snow has already accumulated in high-altitude areas of the basin; therefore, some groundwater and river water are recharged by snowmelt. At the same time, the river also recharges groundwater through leakage, and groundwater runoff in the non-monsoon period is also the main recharge source for the river.

In summary, comparison of the stable-isotope characteristics among water bodies in the two different periods shows that, in the monsoon period (July–September), stable-isotope values change relatively smoothly, whereas in the non-monsoon period (October–November) they change strongly and the fluctuations in isotope values become smaller. From the monsoon period to the non-monsoon period, the groundwater relation points shift from the lower right of the LMWL to the upper left, the corresponding evaporation-line slope increases, and the correlation between $\delta^{18}O$ and δD weakens. River water remains basically in synchronous variation with groundwater. This is mainly attributable to environmental differences between the two periods: in the monsoon period, rainfall is abundant and river discharge is large, so evaporation has relatively little influence on groundwater and river water; in the non-monsoon period the opposite is true, and strong evaporation is the reason for the increase in the slope of the evaporation line during this period.

5 Conclusions

(1) The spatial distribution of stable isotopes in groundwater in the Shaliu River Basin exhibits marked seasonal differences. During the monsoon period (July–September), it is mainly controlled by high- and low-value zones.

The median value is dominant; in the non-monsoon period (October–November), medium and low values are dominant. Meanwhile, as time progresses, the fluctuations in the stable-isotope values at the same locations decrease.

(2) Seasonal variation in the stable isotopes of atmospheric precipitation has little influence on groundwater, and the fluctuations in groundwater stable-isotope values are smaller than those in precipitation. In areas where river water and groundwater are more closely hydraulically connected and groundwater isotope values are high, the interaction between groundwater and river water is relatively weak, and the recharge time exceeds 5 months. In areas where groundwater isotope values are low, the recharge relationship between groundwater and river water is close, and the recharge time is 1–4 months.

(3) During the monsoon period, groundwater is recharged mainly by rainfall infiltration and by lateral recharge from rivers. During the recharge process, evaporation is the principal factor affecting groundwater stable-isotope values. During the non-monsoon period, snow and ice meltwater

has a significant influence on groundwater in low-value areas, while rapid infiltration of precipitation is the main recharge mode for groundwater in high-value areas during this period.

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Recharge Characteristics of Shallow Groundwater in Different Periods of Shaliu River Basin around the Qinghai Lake

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Abstract: The Shaliuhe River basin is located in Gangcha County, Qinghai Province, China, in the northern part of Qinghai Lake. Situated in the transition zone between the westerlies and the monsoon, the basin experiences significant seasonal variation in precipitation, with approximately 65% of precipitation concentrated during the monsoon period. Groundwater resources are relatively abundant in the Shaliuhe River basin, mainly including bedrock fissure water in the northern mountainous region of the basin, phreatic water in the gravel layers of piedmonts and intermontane plains, and confined water in the downstream lakeside plains. From July to November 2017, the authors collected about 300 samples of shallow groundwater, spring water, glacier snowmelt water, and river water in the middle and lower reaches of the Shaliuhe River basin. Using GIS spatial interpolation and stable isotope techniques, the spatiotemporal variation characteristics of the hydrogen and oxygen stable isotope composition of shallow groundwater and the recharge relationship between groundwater and other water bodies in different periods were studied in the Shaliuhe River basin of Qinghai Lake. The conclusions were as follows: (1) during the monsoon period, groundwater is mainly recharged by rainfall infiltration and lateral recharge from rivers, and evaporation is the main factor affecting the stable isotope values of groundwater. In the non-monsoon period, glacier snowmelt water has a significant impact on groundwater in the low-value area, and the rapid infiltration of precipitation is one of the main recharge pathways of groundwater in the high-value area. (2) In the high-value area of groundwater isotopes, recharge between groundwater and river water is weak, and the recharge time is more than 5 months. In the low-value area of groundwater isotopes, groundwater has a close recharge relationship with river water, and the recharge period is from January to April. At present, there are few studies on groundwater stable isotopes in China, especially on the Qinghai–Tibet Plateau, where seasonal differences in groundwater recharge pathways remain insufficiently understood. Therefore, the results of this study can preliminarily reflect the stable isotope characteristics of groundwater and the basic laws of recharge patterns in arid and semi-arid inland basins to a certain extent. The results also provide a scientific basis for studying the transformation between groundwater and other water bodies within the basin, as well as theoretical guidance for groundwater resource management and water environment treatment.

Key words: shallow groundwater; hydrogen–oxygen stable isotope; groundwater supply; Qinghai Lake; Shaliu River basin

Note: Figure translations are in progress. See original paper for figures.