Postprint: Characteristics of Hydrogen and Oxygen Stable Isotopes in Water Bodies on the Southern Slope of the Qilian Mountains

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Abstract

Hydrogen and oxygen stable isotopes in water bodies serve as important tracers for characterizing water transport and transformation, providing a diagnostic basis for investigating regional hydrological cycle processes. Employing stable isotope techniques, this study analyzes the hydrogen and oxygen isotopic composition characteristics of different water bodies on the southern slope of the Qilian Mountains and explores their influencing factors. The results demonstrate that: (1) The hydrogen and oxygen stable isotopic characteristics differ among various water bodies on the southern slope of the Qilian Mountains, with precipitation exhibiting a greater range of stable isotopic variation than river water, groundwater, and glacier meltwater; (2) The stable isotope data points for river water and groundwater are closely clustered, indicating strong hydraulic connectivity between the two; (3) The evaporation line equations for glacier meltwater, river water, and groundwater in the study area are y=6.331x+1.756 (n=8, R2=0.98), y=4.467x-11.716 (n=75, R2=0.80), and y=4.889x-7.481 (n=19, R2=0.76), respectively; all water bodies exhibit good linear relationships between their hydrogen and oxygen stable isotopic values, and the relationship between recharge sources of river water and groundwater is relatively complex; (4) Environmental effects on hydrogen and oxygen stable isotopes in glacier meltwater, river water, and groundwater are not significant, whereas precipitation shows relatively pronounced altitude, latitude, and continental effects.

Full Text

Hydrogen and Oxygen Isotope Characteristics of Water Bodies on the Southern Slope of the Qilian Mountains

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Abstract

Hydrogen and oxygen stable isotopes in water bodies serve as important indicators for characterizing water migration and transformation processes, providing a basis for investigating regional hydrological cycle mechanisms. Based on stable isotope techniques, this study analyzes the hydrogen and oxygen isotopic compositions of different water bodies on the southern slope of the Qilian Mountains and explores their influencing factors. The results indicate that: (1) The hydrogen and oxygen stable isotope characteristics differ among various water bodies on the southern slope of the Qilian Mountains, with precipitation showing a larger fluctuation range in stable isotope values than river water, groundwater, and glacier meltwater. (2) The stable isotope relationship points for river water and groundwater are closely positioned, indicating strong hydraulic connectivity between the two. (3) The evaporation line equation for glacier meltwater in the study area is =6.331 =4.467 =4.889 =0.98 =0.76 =0.80. All water bodies exhibit good linear relationships between their hydrogen and oxygen stable isotope values, though the relationship between river water and groundwater is relatively complex. (4) The environmental effects of hydrogen and oxygen stable isotopes in glacier meltwater, river water, and groundwater are not significant, whereas precipitation shows clear elevation, latitude, and continental effects.

Keywords: water body; hydrogen and oxygen stable isotopes; influencing factors; southern slope of the Qilian Mountains

1 Study Area and Methods

1.1 Study Area Overview

The Qilian Mountains, located in the northeastern Tibetan Plateau, constitute an important ecological security barrier in the arid regions of northwestern China and serve as a critical water source area for the Yellow River basin. In recent years, with the establishment of the Qilian Mountain National Park pilot and increasing recognition of its ecological value, isotopic hydrology research focusing on the Qilian Mountains in the inland arid and semi-arid regions of northwestern China has attracted considerable scholarly attention. Studies on stable isotopes and hydrochemistry across the entire Qilian Mountains have gradually increased. However, due to differences in natural geographical environments and water vapor sources between the northern and southern slopes, the hydrological cycle processes also exhibit significant variations. The southern slope of the Qilian Mountains serves as the source region for inland water systems such as the Heihe River, Tuole River, and Qinghai Lake, as well as the Yellow River basin' s exorheic system. Currently, isotopic research on water bodies in this region primarily focuses on watershed-scale hydrological units of precipitation, river water, and groundwater, concentrating on characteristics of precipitation hydrogen and oxygen stable isotopes and water vapor sources, transformation between different water bodies, groundwater dating, and hydrochemical characteristics.

Accordingly, this paper analyzes the hydrogen and oxygen isotopic characteristics and influencing factors of precipitation, glacier meltwater, surface water, and groundwater on the southern slope of the Qilian Mountains to understand the interconnections between different water bodies and provide a basis for rational water resource utilization and water cycle processes.

The southern slope of the Qilian Mountains is located in the northeastern part of Qinghai Province, with geographical coordinates of 98°08 13 -102°38 16 E and 37°03 17 -39°05 56 N [Figure 1: see original paper]. The region features a continental climate with an average annual temperature of -5.9°C and annual precipitation ranging from 300–400 mm. Solar radiation is intense, relative humidity is low, and evaporation is strong. The terrain is predominantly mountainous, with elevations between 2,400–5,235 m. Water storage is primarily in the form of glaciers, which generate the Qilian Mountains river system. The main rivers include the Heihe River and Datong River. The Qilian Mountains represent the source region for both the Heihe and Datong Rivers, with a theoretical hydropower reserve of 23.22$\times10^{6}$ kW. The Heihe River divides into eastern and western branches, with the eastern branch serving as the main stream. The upper reaches further split into eastern and western tributaries: the eastern tributary (Babao River) originates from Jinyangling (175 km long), while the western tributary (Yeniugou River) originates from the eastern slope of the Qilian Mountains main peak (100 km long). These two tributaries converge at Huangzangsi in Qilian County before exiting the mountains at Yingluoxia. The Tuole River, a first-order tributary of the Heihe River, originates from the southern slope of Tuole Mountain (110.8 km long). The Datong River, a first-order tributary of the Huangshui River system of the Yellow River, originates from Togele Nanshan in Tianjun County.

1.2 Sample Collection

Based on the topography, geomorphology, and river distribution characteristics of the southern slope of the Qilian Mountains, combined with field investigations, we collected a total of 116 water samples from precipitation, glacier meltwater, river water, and groundwater during July–August 2018. The collection included 6 ice and glacier meltwater samples, 47 river water samples, 17 precipitation samples (with precipitation >2 mm), 46 groundwater samples, and spring water samples. Precipitation was collected using self-made rain gauges; ice samples were collected from the surface layer (0–10 cm) at the terminus of the Bayi

Glacier; glacier meltwater was collected from glacier ablation areas in the upper Heihe River; river water was sampled from the middle sections of rivers with relatively fast flow rates, 10–60 m from the banks; groundwater was collected from drinking water wells in residents' homes; and spring water was collected from mountain-front springs. All samples were collected in pre-rinsed 60 mL polyethylene bottles, sealed with Parafilm membrane to prevent fractionation. A handheld GPS was used to record sampling point elevations and coordinates, along with sample numbers and water temperature data. All samples were refrigerated at 4°C until analysis.

1.3 Data Processing

The determination of hydrogen and oxygen stable isotopes in precipitation, glacier meltwater, surface water, and groundwater samples was conducted at the Qinghai Provincial Key Laboratory of Physical Geography and Environmental Processes. All water samples were filtered through 0.22 m filters and analyzed using an IWA-35EP liquid water isotope analyzer produced by Los Gatos Research, USA. Results are expressed as per mil (‰) relative to Vienna Standard Mean Ocean Water (VSMOW), with measurement precisions of $±$0.5‰ for δD and $±$0.1‰ for δ^{18}O. Statistical analysis was performed using SPSS software, and charts were produced using Origin and ArcGIS software.

2 Results and Analysis

2.1 Analysis of the Local Meteoric Water Line

The regional meteoric water line can characterize the fractionation rate of precipitation in a region. Numerous observational studies based on different periods and sampling points have shown that atmospheric precipitation line equations in the Qilian Mountains region consistently exhibit slopes less than 8, with precipitation isotope relationship points significantly deviating from the Global Meteoric Water Line (GMWL) and located to its lower right, reflecting that atmospheric precipitation in this region is generally affected by evaporation. The atmospheric precipitation line represents a statistical average model reflecting local precipitation patterns, and its accurate simulation requires long-term, high-frequency observations. However, due to the limited number of precipitation sampling points and short sampling period in this study, and after comprehensive consideration of observation duration, scope, and frequency, we adopted the Qilian Mountains atmospheric precipitation line proposed by Sun Congjian et al. [δD = 7.77δ^{18}O + 13.03 (R^2 = 0.99)] as the local meteoric water line, supplemented by measured precipitation data to discuss isotopic composition characteristics.

During the sampling period, 17 precipitation samples were collected, with δ^{18}O and δD values ranging from -14.63‰ to -2.12‰ and -102.65‰ to -16.33‰, respectively, with mean values of -7.70‰ and -46.99‰. The d-excess value ranged from 4.84‰ to 21.29‰, with a mean of 14.61‰. As shown in [Figure

2: see original paper], most precipitation isotope relationship points are located to the lower right of the local meteoric water line, with a precipitation line slope (k = 6.46) significantly smaller than that of the local meteoric water line, indicating that water bodies on the southern slope of the Qilian Mountains experience intense evaporation fractionation during summer.

2.2 Hydrogen and Oxygen Stable Isotope Characteristics of Glacier Meltwater

In the hydrogen and oxygen stable isotopic composition of ice, ice samples showed δ^{18}O and δD values of -8.60‰ and -50.15‰, respectively, with a d-excess of 18.69‰. Glacier meltwater exhibited δ^{18}O and δD values ranging from -11.42‰ to -5.98‰ and -69.31‰ to -34.21‰, respectively, with mean values of -8.88‰ and -50.87‰, and a d-excess of 20.13‰. As shown in [Figure 3: see original paper], ice sample isotopic values are located to the lower right of the meteoric water line, indicating intense ice surface melting during summer and the generation of surface runoff. The isotopic values of glacier meltwater are close to and located on the local meteoric water line, suggesting that glacier meltwater originates from atmospheric precipitation.

In the arid and semi-arid region of the southern Qilian Mountains, intense solar radiation during summer causes significant glacier surface ablation (forming shallow surface flows with large air contact areas during the melting process). Combined with strong evaporation in the region, the ablated glacier water experiences evaporation that causes light isotopes to escape into the atmosphere, leaving heavy isotopes enriched in the remaining water. Additionally, due to low air humidity and rapid evaporation, the d-excess values of glacier meltwater in this region are relatively high, with values concentrated between 15‰ and 25‰.

2.3 Hydrogen and Oxygen Stable Isotope Characteristics of River Water

River water sampling points on the southern slope of the Qilian Mountains were concentrated in the upper reaches of the Heihe River main stream, Tuole River, and Datong River. Hydrogen and oxygen isotope values showed relatively small variations, with maximum values of -5.98‰ for δ^{18}O and -34.21‰ for δD, minimum values of -11.42‰ and -69.31‰, respectively, and mean values of -8.88‰ and -50.87‰. The d-excess ranged from 15.23‰ to 25.98‰, with a mean of 20.13‰.

Comparing the average hydrogen and oxygen stable isotope values from the upper reaches of three watersheds on the southern slope of the Qilian Mountains, the order from most depleted to most enriched was: Heihe River < Tuole River < Datong River, with minimal difference between the Heihe and Tuole Rivers. The Heihe River upstream region had a mean δ^{18}O value of -8.60‰, representing relatively depleted isotopic values. In a river system, multiple tributaries converge, and different geographical factors in each sub-watershed affect the hydrogen and oxygen isotopic composition of these tributaries, thereby influencing isotopic variation in the main stream. Therefore, the convergence of tributaries affected by different geographical elements results in spatial differences in river water stable isotope values.

In the upper Heihe River on the southern slope of the Qilian Mountains, we collected 6 samples from the western tributary (Yeniugou River), 7 samples from the eastern tributary (Babao River), and 34 tributary samples. Among these, the main stream samples from both eastern and western branches totaled 13 groups. In the hydrogen and oxygen stable isotopic composition of main stream and tributary water, the mean values for main stream and tributary were -8.60‰ and -8.88‰ for δ^{18}O, respectively, and -50.15‰ and -50.87‰ for δD, respectively. Clearly, the main stream isotopic composition is more enriched than that of tributaries. As shown in [Figure 4: see original paper], the southeastern, southern, and northwestern areas represent high-value zones for river water hydrogen and oxygen isotopes, while the northern area represents a low-value zone. The high-value zones are located in high-altitude mountainous areas, while low-value zones are mainly in lower river reaches. This likely occurs because many rivers on the southern slope of the Qilian Mountains are initially recharged by glacier meltwater or precipitation from high-altitude mountainous areas. During downstream flow, river water interacts with relatively depleted groundwater, causing river water hydrogen and oxygen isotope values to decrease. This creates a pattern of higher stable isotope values in high-altitude areas and lower values in low-altitude areas, demonstrating spatial distribution differences in river water stable isotope values due to different recharge sources.

2.4 Hydrogen and Oxygen Stable Isotope Characteristics of Groundwater

In the hydrogen and oxygen isotopic composition of groundwater, δ^{18}O and δD values ranged from -11.42‰ to -5.98‰ and -69.31‰ to -34.21‰, respectively, with mean values of -8.88‰ and -50.87‰. The d-excess ranged from 15.23‰ to 25.98‰, with a mean of 20.13‰. As shown in [Figure 5: see original paper], groundwater hydrogen and oxygen isotope values are close to the local meteoric water line, located to its upper left, indicating that groundwater is recharged by precipitation.

In the hydrogen and oxygen isotopic composition, hot spring water shows more depleted values than well water, and the isotopic composition differs significantly between wells. Hot spring water exhibits "depleted δ^{18}O values," likely because precipitation infiltrates and migrates downward through the crust, undergoing isotopic exchange with surrounding rocks during deep circulation. Additionally, geothermal warming effects may enhance isotopic fractionation. Spring water, being exposed at the surface, is susceptible to evaporation fractionation, showing water depletion phenomena. Well water, retained underground with minimal external environmental influence, may show hydrogen and oxygen isotopic differences due to human activities or the altitude effect of groundwater isotopes. Groundwater d-excess values range from 15.23‰ to 25.98‰, with an average of 20.13‰. Precipitation in the arid northwest region occurs mainly in summer and autumn, when water vapor recycling is relatively pronounced. Evaporation from soil, vegetation, and rivers participates in the water cycle process, making groundwater recycling characteristics evident.

3 Discussion

3.1 Analysis of Hydrogen and Oxygen Stable Isotope Characteristics in Different Water Bodies

In the stable isotopic composition of all water bodies on the southern slope of the Qilian Mountains, $\delta^{18}O$ values range from -14.63‰ to -2.12‰, with a variation amplitude of 12.51‰, a mean of -8.60‰, and a standard deviation of 2.69‰. δD values range from -102.65‰ to -16.33‰, with a variation amplitude of 86.32‰, a standard deviation of 10.62‰, and a mean of -49.34‰. The d-excess value ranges from 4.84‰ to 25.98‰, with a mean of 18.48‰. As mentioned above, the stable isotopic range of precipitation is consistent with this, indicating that precipitation has a larger fluctuation range in stable isotope values than river water, groundwater, and glacier meltwater.

Comparison shows that glacier meltwater has higher $\delta^{18}O$ and δD values than river water and groundwater, while its d-excess is lower than that of river water and groundwater. The d-excess ranges of river water and groundwater overlap. One-way ANOVA shows that the d-excess values of glacier meltwater, river water, and groundwater all pass the homogeneity of variance test, with significant differences between water bodies ($P < 0.05$). Duncan' s multiple comparison test shows no significant difference in hydrogen and oxygen isotope values between river water and groundwater, with similar ranges and obvious correlation, indicating strong hydraulic connectivity.

As shown in , the enrichment degree of hydrogen and oxygen isotopes in different water bodies is evident. The Duncan test results show that river water and groundwater have no significant differences (same letters), while glacier meltwater differs significantly from both (different letters) at $P < 0.05$.

3.2 Analysis of Evaporation Line Characteristics

Affected by environmental and climatic conditions, evaporation intensity varies across different regions, resulting in different water body evaporation lines. Based on the $\delta^{18}O$ and δD values of glacier meltwater, river water, and groundwater on the southern slope of the Qilian Mountains, the overall evaporation trend line was fitted as: $y = 4.491$. Simultaneously, linear regression was performed on each water body separately to obtain evaporation trend line equations:

- Glacier meltwater: $y = 6.331 + 1.756$ ($R^2 = 0.98$)

- River water: y = 4.467 - 11.716 (R^2 = 0.80)
- Groundwater: y = 4.889 - 7.481 (R^2 = 0.76)

As shown in [Figure 6: see original paper], all water bodies in the study area exhibit good linear relationships between their hydrogen and oxygen isotope values. The slopes and intercepts of the evaporation trend lines for glacier meltwater, river water, and groundwater are all significantly smaller than the local meteoric water line slope, because the southern Qilian Mountains region has high altitude and intense solar radiation, causing strong evaporation from forests, shrubs, and grasslands. Local water vapor recycling significantly influences isotopic evolution, causing most water body δ^{18}O and δD values to deviate from the meteoric water line, with river water and groundwater showing greater deviation than glacier meltwater. By comparing the slopes of different water body evaporation lines, river water shows the greatest evaporation intensity, likely because the Qilian Mountains serve as river source areas with long flow paths. As open water bodies, rivers experience relatively strong evaporation.

3.3 Environmental Effects on Hydrogen and Oxygen Stable Isotope Composition

Hydrogen and oxygen isotope values (δ^{18}O and δD) exhibit different distribution characteristics due to variations in altitude, temperature, and distance from oceans, i.e., environmental effects of stable isotopes. Therefore, analyzing correlations between water body δ^{18}O and δD values and environmental factors such as altitude, water temperature, and geographic coordinates can clarify the elevation, continental, latitude, and temperature effects for each water body on the southern slope of the Qilian Mountains.

As shown in , the elevation, continental, latitude, and temperature effects of glacier meltwater, river water, and groundwater are all insignificant, indicating complex water sources and frequent internal water vapor recycling activities in the study area. However, precipitation δ^{18}O and δD values show significant negative correlations with altitude and latitude. The linear regression equations are:

- δ^{18}O vs. altitude: y = -0.004x + 32.42 (R^2 = 0.74)
- δD vs. altitude: y = -0.033x + 36.63 (R^2 = 0.58)
- δ^{18}O vs. latitude: y = -0.220x + 4.44 (R^2 = 0.78)
- δD vs. latitude: y = -0.61x + 4.44 (R^2 = 0.74)

Precipitation also shows high correlations with longitude, indicating that precipitation hydrogen and oxygen stable isotopes have elevation, latitude, and continental effects. The elevation effect means that higher altitudes have lower temperatures and more depleted isotopes. While temperature effects mainly occur in mid- and high-latitude regions, they are also significant in continental interiors, indicating that the elevation effect in the southern Qilian Mountains is closely related to atmospheric temperature. The latitude effect may be attributed to decreasing temperature and precipitation totals with increasing latitude, combined with intense internal recycling during summer that depletes precipitation isotope values. Additionally, the study area extends northwestward, with the southeastern part being closer to the ocean and first affected by warm, moist air from the Western Pacific and Indian Oceans, resulting in higher isotope values—this represents the continental effect of precipitation stable isotopes.

In summary, analysis of correlations between different water bodies' stable isotope values and environmental factors shows that precipitation hydrogen and oxygen stable isotope values are significantly affected by altitude, latitude, and longitude, with altitude being the primary factor. Glacier meltwater shows relatively high correlations with latitude and altitude, which are the main factors affecting its isotopic values, while temperature has minimal influence. River water hydrogen and oxygen stable isotope values show weak correlations with individual environmental factors, likely because river water has multiple recharge sources with complex isotopic compositions. Factors influencing its stable isotope values are often comprehensive rather than singular. Similarly, groundwater has diverse recharge sources, and its stable isotope values are also affected by multiple environmental factors, reflecting the diversity and complexity of its recharge—this will be further investigated in subsequent research.

4 Conclusions

(1) Different water bodies exhibit distinct hydrogen and oxygen stable isotopic composition characteristics. Summer water bodies on the southern slope of the Qilian Mountains experience intense evaporation fractionation. Compared with glacier meltwater, ice shows the most enriched hydrogen and oxygen isotopic composition, though both originate from atmospheric precipitation. The mean hydrogen and oxygen isotope values of river water follow the order: Heihe River < Tuole River < Datong River. Recharge from different water sources is the main reason for spatial differences in stable isotope values of Heihe River water. In groundwater hydrogen and oxygen isotopic composition, hot spring water is more depleted than well water, and significant differences exist in isotopic composition among wells.

(2) In the stable isotopic composition of water bodies on the southern slope of the Qilian Mountains, d-excess values are relatively large, and precipitation shows a larger fluctuation range in stable isotope values than other water bodies. Glacier meltwater, river water, and groundwater show significant differences in enrichment degree. Duncan' s multiple comparison test indicates no significant difference in stable isotope values between river water and groundwater, with similar ranges, obvious correlation, and strong hydraulic connectivity.

(3) The evaporation line equation for glacier meltwater in the study area is y = 6.331 + 1.756 (R^2 = 0.98), for river water is y = 4.467 - 11.716 (R^2 = 0.80), and for groundwater is y = 4.889 - 7.481 (R^2 = 0.76). All

water bodies show good linear relationships between their hydrogen and oxygen isotope values. Water body δ^{18}O and δD values mostly deviate from the atmospheric precipitation line, with river water and groundwater showing greater deviation than glacier meltwater, indicating more complex recharge sources.

(4) The environmental effects of hydrogen and oxygen stable isotopes in glacier meltwater, river water, and groundwater are not significant, whereas precipitation shows obvious elevation, latitude, and continental effects.

References

[1] Hoekstra, Arjen Y. Water scarcity challenges to business[J]. Nature Climate Change, 2014, 4(5): 318-320.
[2] Ding Yongjian, Zhang Shiqiang. Study on water internal recycle process and mechanism in typical mountain areas of inland basins, Northwest China: Progress and challenge[J]. Advances in Earth Science, 2018, 33(7): 719-727.
[3] Ruan Yunfeng, Zhao Liangju, Xiao Honglang, et al. The groundwater in the Heihe River Basin: Isotope and renew ability[J]. Journal of Glaciology and Geocryology, 2015, 37(3): 767-782.
[4] Wu Xiaobo, Li Quanlian, He Jianqiao, et al. Hydrochemical characteristics and inner year process of upper Heihe River in summer half year[J]. Journal of Desert Research, 2008, 28(6): 1190-1196.
[5] Li Zongxing, Gui Juan, Wang Xufeng, et al. Water resources in inland regions of Central Asia: Evidence from stable isotope tracing[J]. Journal of Hydrology, 2019, 570: 1-16.
[6] Qiu Xue, Zhang Mingjun, Wang Shengjie, et al. The test of the ecohydrological separation hypothesis in a dry zone of the northeastern Tibetan Plateau[J]. Ecohydrology, 2019, 12: e2077. https://doi.org/10.1002/eco.2077.
[7] Lian Yuntao, Wang Yu, Zheng Jian, et al. The trend of runoff and sediment transport in the upper reaches of Heihe Basin and its cause analysis[J]. Journal of Arid Land Resources and Environment, 2019, 33(3): 98-104.
[8] Yuan Jie, Cao Guangmin, Cao Guangchao, et al. Soil particle size characteristics under different vegetation types on southern slope of Qilian Mountains[J]. Bulletin of Soil and Water Conservation, 2019, 39(2): 76-82.
[9] Li Zongjie, Li Zongxing, Yu Haichao, et al. Environmental significance and zonal characteristics of stable isotope of atmospheric precipitation in arid Central Asia[J]. Atmospheric Research, 2019, 227: 24-40.
[10] Zhang Yinghua, Wu Yanqing. Characteristics of the δ^{18}O in precipitation in the upper and middle reaches of Heihe River[J]. Journal of Glaciology and Geocryology, 2007, 29(3): 440-445.
[11] Peng Min, Cao Guangmin, Ye Runrong, et al. Comprehensive Ecological Treatment of Small Watershed and Ecological Environment in Qilian Mountains of Qinghai Province[M]. Beijing: China Forestry Publishing House, 2017: 32-34.

[12] Zhang Yinghua, Wu Yanqing. Oxygen and hydrogen isotopes of precipitation in the upper and middle reaches of Heihe River Basin[J]. Journal of Glaciology and Geocryology, 2009, 31(1): 34-39.

[13] Zhao Liangju, Yin Li, Xiao Honglang, et al. Isotopic evidence for the water vapor sources and composition of surface runoff in the headwaters of the Heihe River Basin[J]. Chinese Science Bulletin, 2011, 56(1): 58-70.

[14] Sun Congjian, Zhang Ziyu, Chen Wei, et al. Spatial distribution of precipitation stable isotopes in the alpine zones in Central Asia[J]. Arid Zone Research, 2019, 36(1): 22-31.

[15] Zhang Yinghua, Song Xianfang, Wu Yiqin. Use of oxygen-18 isotope to quantify flows in the upriver and middle reaches of the Heihe River, Northwestern China[J]. Environmental Geology, 2009, 58(3): 645-653.

[16] Pan Zhao, Sun Ziyong, Ma Rui, et al. Isotopic investigation of rainfall-runoff generation in an alpine catchment in head water regions of Heihe River, Northeast Qinghai Tibet Plateau[J]. Earth Science, 2018, 43(11): 4226-4236.

[17] He Yuanqing, Pang Hongxi, Lu Aigang, et al. Spatial and temporal variation of the stable isotopes in snowpacks and glacial runoff in different types of glacier areas in Western China and its climatic effects[J]. Journal of Glaciology and Geocryology, 2006, 28(1): 22-28.

[18] Wang Yajun, Song Xianfang, Ma Ying, et al. Characterizing precipitation from different water vapor sources in Heihe River Basin, Northwest China[J]. Arid Land Geography, 2008, 31(3): 403-408.

[19] Wu Huawu, Li Xiaoyan, Zhao Guoqin, et al. The variation characteristics of δ^{18}O and δD in precipitation and river water, Qinghai Lake Basin[J]. Journal of Natural Resources, 2014, 29(9): 1552-1564.

[20] Hou Dianjiong, Qin Xiang, Wu Jinkui, et al. Characteristics of stable isotopes in precipitation and the water vapor sources in Urumqi[J]. Journal of Arid Land Resources and Environment, 2011, 25(10): 136-142.

[21] Yu Xiuxiu, Zhang Mingjun, Wang Shengjie, et al. Contribution of moisture recycling to precipitation in the arid region in Northwest China based on LMDZ model[J]. Arid Zone Research, 2019, 36(1): 29-43.

[22] Wang Jihua, Lin Yuanwu, Liu Chenglong, et al. Evidence for the formation of hydrogen and oxygen stable isotopes and dissolved gas components of the hot spring water in the southern area of Zhangjiakou[J]. Hydrogeology and Engineering Geology, 2000(4): 30-33.

[23] Hughes C E, Crawford J. Spatial and temporal variation in precipitation isotopes in the Sydney Basin, Australia[J]. Journal of Hydrology, 2013, 489: 42-55.

[24] Smith D B. Statistical treatment of data on environmental isotopes in precipitation: Technical report series no.331, International Atomic Energy Agency (IAEA)[J]. Journal of Hydrology, 1993, 146: 454-455.

[25] Li Wenbao, Li Changyou, Jia Debin, et al. Change of stable isotopes in summer precipitation in central Inner Mongolia[J]. Arid Zone Research, 2017, 34(6): 1214-1221.

[26] Li Zongxing, Feng Qi, Yong Song, et al. Stable isotope composition of precipitation in the south and north slopes of Wushaoling Mountain, Northwestern

China[J]. Atmospheric Research, 2016, 182: 87-96.