Characteristics of Hydrogen and Oxygen Isotopes in the Nalenggele River Basin and Their Indicative Significance: Postprint

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Abstract

This study is based on the test results of 63 samples from the Nalenggele River basin, analyzing the distribution characteristics and controlling factors of hydrogen and oxygen isotopes and deuterium excess parameters of atmospheric precipitation, river water, groundwater, lake surface brine, and intercrystalline brine in the basin. The results indicate that: (1) Under the dual influence of evaporation and water vapor recycling, the δD and $ $18O values of atmospheric precipitation in the study area are both higher than the national average, and the slope of the local meteoric water line is smaller than that of the Global Meteoric Water Line but larger than those of other basins in the northwestern arid region. Long-distance transport by the East Asian monsoon is the main factor causing the low deuterium excess in atmospheric precipitation in August in the study area. (2) The slope of the river water line in the study area is smaller than that of the Global Meteoric Water Line. The deuterium excess of river water is negatively correlated with $ $18O and TDS, both of which are attributed to isotopic fractionation caused by strong evaporation of river water. Rainfall in the southern mountainous area of the study area is the main recharge source for river water, and the altitude effect causes variations in δD and $ $18O of river water in different sections. (3) The recharge-discharge relationships between groundwater and surface water differ among different sections. Moreover, groundwater mainly receives multi-source recharge from mountainous areas, resulting in both the slope and intercept of the groundwater line being greater than those of the Global Meteoric Water Line and the local meteoric water line. (4) Both lake surface brine and intercrystalline brine exhibit an "oxygen shift" phenomenon, and their deuterium excess parameters are both less than zero. This is closely related to excessive fractionation of hydrogen and oxygen isotopes caused by evaporation. The dissolution of saline minerals is the main reason why the deuterium excess value of intercrystalline brine is lower than that of lake surface brine.

Full Text

Preamble

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Hydrogen and Oxygen Isotopic Characteristics and Their Indicative Significance in the Nalenggele River Basin

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Abstract

Based on the analysis of 63 water samples from the Nalenggele River basin, this study examines the distribution characteristics and controlling factors of hydrogen and oxygen isotopes and deuterium excess parameters in atmospheric precipitation, river water, groundwater, lake surface brine, and intercrystalline brine. The results indicate: (1) The average δD and δ^{18}O values of atmospheric precipitation in the study area are higher than the national average for China. The slope of the local meteoric water line is smaller than the global meteoric water line but larger than those of other basins in the northwest arid region, reflecting the dual influence of evaporation and water vapor recycling. The East Asian monsoon's long-distance moisture transport is the primary factor causing low deuterium excess in August precipitation. (2) The river water line slope is smaller than the global meteoric water line, and deuterium excess shows a negative correlation with δ^{18}O and TDS, both attributed to strong evaporation-induced isotopic fractionation. Precipitation in the southern mountainous area constitutes the main source of river water recharge, with elevation effects causing isotopic variations along different river sections. (3) Groundwater-surface water interactions differ across sections, and groundwater receives multi-source recharge from mountainous areas, resulting in groundwater line slopes and intercepts that exceed both the global and local meteoric water lines. (4) Both lake surface brine and intercrystalline brine exhibit “oxygen drift” phenomena with deuterium excess parameters below zero, closely related to excessive isotopic fractionation from evaporation. The dissolution and filtration of salt minerals are the main reasons why intercrystalline brine has lower deuterium excess values than surface brine.

Keywords: hydrogen and oxygen isotopes; deuterium excess; arid watershed; Nalenggele River

1. Introduction

Water is composed of hydrogen and oxygen elements, and the mass differences between hydrogen and oxygen isotopes affect the thermodynamic properties of water molecules [1], leading to isotopic fractionation during the water cycle and resulting in varying hydrogen and oxygen isotope contents in different water bodies. Consequently, hydrogen and oxygen isotopes are widely applied in hydrological cycle tracing studies [2]. Additionally, hydrological processes such as rainfall, runoff, infiltration, evaporation, and water vapor condensation all influence hydrogen and oxygen isotopes [3], leaving distinct “fingerprints” that enable paleoclimate reconstruction [4], identification of water vapor recycling processes [5], determination of water transformation relationships [6], and tracing of plant water cycles [7].

The Nalenggele River (hereinafter referred to as “the Nalenggele River”) is located on the northern slope of the Kunlun Mountains and the southern margin of the Qaidam Basin. It is the largest inland river in the basin in terms of watershed area and water volume [8], and serves as an important source of groundwater recharge for the alluvial-proluvial plain area. The terminal salt lakes of the Nalenggele River contain abundant reserves of critical mineral resources in brine-type deposits [9]. Previous studies have investigated the sources of ore-forming materials in the Nalenggele River basin and its terminal salt lakes, including lithium sources [10] and rubidium-cesium sources and enrichment processes [11], but understanding remains limited. As water resources are important carriers for the migration and transformation of ore-forming materials, identifying the recharge sources and interaction relationships of different water bodies in the Nalenggele River basin through hydrogen and oxygen isotopes, and tracing the hydrological cycle processes, can provide a foundation for studying the sources and migration patterns of ore-forming materials.

The climate of the Kunlun Mountains’ northern slope region is influenced by the superposition of northwest monsoon and Asian monsoon circulations, characterized by low precipitation and high evaporation. Combined with high altitude, cold climate, and complex topography, this creates typical arid region climatic features where water resources become a key factor constraining regional environmental carrying capacity and influencing ecological vulnerability [12]. The Nalenggele River originates from the eastern Bukadaban area of the Kunlun Mountains, where the source region belongs to high-altitude, cold mountainous terrain. In addition to atmospheric precipitation, glacial meltwater from the source area is also an important recharge source for basin groundwater. Based on hydrogen and oxygen isotope characteristics, this study collected 63 water samples from the Nalenggele River basin and its terminal salt lakes for isotopic testing and analysis. Combined with regional geological structure and hydrogeological conditions, the study identifies the hydrogen and oxygen isotope characteristics and influencing factors of different water bodies, analyzes deuterium excess parameters and their controlling factors, reveals the interaction relationships between groundwater and river water in different river sections, and traces hydrological cycle processes in typical arid regions. These findings are significant for identifying the sources of ore-forming materials and enabling sustainable water resource development in the Nalenggele River basin.

2. Study Area Overview

The Nalenggele River basin exhibits typical inland plateau cold-arid climate characteristics, with intense evaporation and scarce precipitation. Statistical analysis of meteorological monitoring data from the past 20 years shows that the multi-year average temperature ranges from 2.6 to 4.3°C, the multi-year average precipitation is approximately 30.0 mm, and the multi-year average evaporation reaches about 1679 mm—making evaporation more than 50 times greater than precipitation. Precipitation shows extremely uneven intra-annual distribution, with July-August rainfall accounting for approximately 70% of the annual total. The Nalenggele River is located on the southern margin of the Qaidam Basin, formed by the confluence of the Hongshui River and Chulak Alagan River originating from the Kunlun Mountains [13]. The river stretches 435 km with a watershed area of approximately 21,900 km^2, making it the largest inland river in the Qaidam Basin. It flows through primary and secondary alluvial-proluvial fans before emptying into the Yiliping Salt Lake, West Taijinar Lake, Duck Lake, and East Taijinar Lake in the central Qaidam Basin (Fig. 1). July-August represents the river's high-flow period, accounting for about 70% of annual runoff, with annual discharge ranging from 8.73×10^{8} to 20.1×10^{8} m^3.

2.1 Geological Setting

Quaternary strata are widely distributed in the Nalenggele River basin, primarily including Lower Pleistocene glaciofluvial deposits, Middle Pleistocene alluvial-proluvial deposits, Upper Pleistocene proluvial deposits, and Holocene alluvial-proluvial deposits [14]. Lower Pleistocene glaciofluvial deposits are deeply buried, mainly composed of sandy gravel with sub-angular shapes and poor sorting. Middle Pleistocene alluvial-proluvial deposits consist primarily of muddy sandy gravel with relatively loose structure and good roundness. Upper Pleistocene proluvial deposits are extensively exposed at the surface. In the proluvial inclined plain, they are composed of sandy gravel, gravelly coarse sand, and gravelly sand with poor sorting and minor clay content. In the alluvial-proluvial plain, they consist of sandy gravel and gravelly sand with increased sand proportion and better gravel roundness. Holocene alluvial-proluvial deposits are widely distributed in the alluvial-proluvial plain area, mainly composed of sandy gravel, silt, and sub-clay, with some sand layers containing humus.

2.2 Hydrogeological Setting

Based on topography, hydrogeological conditions, and aquifer hydraulic properties, the Nalenggele River basin aquifer system can be divided into two types: Quaternary loose rock pore phreatic aquifer systems and Quaternary loose rock multi-layer confined artesian aquifer systems. These two aquifer systems exhibit significant zonal distribution patterns in hydrogeological structure, aquifer yield, and hydraulic properties [15].

Quaternary loose rock pore phreatic aquifer systems are mainly distributed from the piedmont to the middle of alluvial-proluvial fans and can be further subdivided into shallow phreatic zones and deep phreatic zones. The shallow phreatic zone has a burial depth of less than 50 m, with aquifers primarily composed of medium sand and silt, and water chemistry types mainly $Cl \cdot SO_4$-$Na \cdot Ca$ with TDS less than 1 $g \cdot L^{-1}$. The deep phreatic zone has a burial depth greater than 50 m, with aquifers composed of sandy gravel, strong water yield, and water chemistry types primarily Cl-Na with TDS greater than 1 $g \cdot L^{-1}$.

Quaternary loose rock multi-layer confined artesian aquifer systems are mainly distributed at the front edge of alluvial fans and plain areas, with significant vertical differences in aquifer media. From the fan front edge to the plain, aquifer lithology transitions from coarse to fine, aquitard thickness gradually increases, and hydraulic head rises. Shallow aquifers are primarily composed of medium-coarse sand and fine sand with thicknesses of 10-50 m and TDS of 1-15 $g \cdot L^{-1}$. Deep aquifers consist of gravel-bearing medium-coarse sand with thicknesses exceeding 50 m and TDS greater than 15 $g \cdot L^{-1}$, distributed in near-plain areas.

3. Methods

3.1 Sample Collection

Sample collection was conducted in the Nalenggele River basin during July-August 2021. A total of 63 sample sets were collected, including: 6 river water sample sets (2 from Chulak Alagan River, 2 from Hongshui River, and 2 from the upper Nalenggele River), 20 groundwater sample sets (4 from mountainous areas, 8 from the primary alluvial fan, and 8 from the secondary alluvial fan), 6 lake surface brine sample sets (2 from Yiliping Salt Lake, 2 from West Taijinar Lake, and 2 from Duck Lake), and 31 intercrystalline brine sample sets (15 from Yiliping Salt Lake, 8 from West Taijinar Lake, and 8 from East Taijinar Lake). Additionally, literature data on hydrogen and oxygen isotopes in atmospheric precipitation from the Nalenggele River basin were compiled [16]. All samples were collected in 250 mL polyethylene bottles that were rinsed three times with the water to be sampled. During collection, 0.45 m cellulose acetate membrane filtration was used to ensure no bubbles remained in the bottles, after which samples were stored at low temperature and sealed. To ensure accurate and reliable test data, groundwater samples were collected from phreatic and confined aquifers less susceptible to environmental interference. Before collection, pumping was conducted for 30 minutes to eliminate stagnant water contamination in the wellbore and ensure stable physicochemical parameters. River water and lake surface brine samples were collected at locations 5 m from the shore.

3.2 Testing and Analysis

Sample testing included field and laboratory analyses. Field tests measured pH, water temperature (T), and total dissolved solids (TDS) using a portable parameter meter (accuracy: $±$0.01 for pH, $±$0.1°C for temperature, $±1.0 $) relative to Vienna Standard Mean Ocean Water (VSMOW), with analytical precisions of 0.03‰ for δ^{18}O and 0.28‰ for δD. The isotopic ratio was calculated as:

δ{sample} = (R{sample} / R_{standard} - 1) × 1000

where R_{sample} and R_{standard} represent the ratios of heavy to light isotopes in the sample and standard, respectively. A positive δ_{sample} indicates enrichment of heavy isotopes relative to the standard, while a negative value indicates depletion. All samples were measured three times to ensure reliability.

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4. Results and Analysis

4.1 Hydrogen and Oxygen Isotopic Composition Characteristics of Different Water Bodies

The hydrogen and oxygen isotopes and deuterium excess values for atmospheric precipitation, river water, groundwater, lake surface brine, and intercrystalline brine in the Nalenggele River basin are presented in Table 1.

4.1.1 Atmospheric Precipitation The δD values of atmospheric precipitation in the study area range from -105.30‰ to -40.16‰ (average -66.30‰), while δ^{18}O ranges from -14.80‰ to -1.10‰ (average -7.95‰). Compared with the national average for atmospheric precipitation in China (δD: -190‰ to 20‰, δ^{18}O: -24‰ to 2.0‰) [17], the average hydrogen and oxygen isotope values in the study area are significantly higher, closely related to the high-cold arid climate characteristics. Strong evaporation and water vapor recycling during precipitation descent lead to isotopic enrichment.

The local meteoric water line (LMWL) for the Nalenggele River basin is $\delta D = 7.76\delta^{18}O + 7.23$ (n = 6, $R^2 = 0.96$). The global meteoric water line (GMWL) is $\delta D = 8\delta^{18}O + 10$ [18]. The study area's LMWL lies below the GMWL with a slightly smaller slope, indicating strong evaporation effects during precipitation, consistent with typical inland arid region characteristics. However, the slope is greater than those of other northwest inland arid region meteoric water lines (7.05-7.38) [19], likely due to atmospheric precipitation evaporation and recycling processes. When evaporated precipitation condenses and forms rainfall again, hydrogen and oxygen isotopes distribute along a condensation line with a slope of 8 [20]. Deuterium excess parameters also indicate complex moisture sources, with the East Asian monsoon's long-distance transport being a key factor causing low deuterium excess values in August precipitation [21]. Water vapor recycling dominated by evaporation is an important component of hydrological cycles in typical high-cold arid regions, where evaporated river water vapor is transported to upstream high-altitude cold regions to form rainfall. Such precipitation often plots above both the local and global meteoric water lines [22] with higher deuterium excess values than rainfall from external moisture sources [23]. Some precipitation samples in the Nalenggele River basin plot above the GMWL with high deuterium excess values, confirming the influence of local water vapor recycling.

4.1.2 River Water River water δD values range from -66.30‰ to -52.00‰ (average -58.10‰), while $\delta^{18}O$ ranges from -9.66‰ to -6.78‰ (average -8.50‰). The river water line is defined by linear regression as $\delta D = 4.69\delta^{18}O - 18.5$ (n = 6, $R^2 = 0.94$). Both the slope and intercept are smaller than the GMWL (Fig. 2), indicating evaporation effects along the entire river course from upstream to downstream. Previous studies show that strongly evaporated water bodies exhibit good negative correlations between deuterium excess and $\delta^{18}O$ [24]. Fig. 3 demonstrates this negative relationship for Nalenggele River water samples, confirming intense evaporation as the river flows from mountainous areas to the basin's interior plain.

For a single watershed, river water $\delta^{18}O$ values would gradually increase downstream under evaporation alone, with heavier isotopes becoming more enriched in downstream sections. However, Fig. 4 shows that $\delta^{18}O$ values do not consistently increase along the river course, indicating that besides evaporation, other water sources mixing and groundwater-surface water interactions also influence the isotopic composition. In mountainous areas, river water $\delta^{18}O$ is relatively depleted, showing an increasing trend along the flow direction. From the primary alluvial fan apex to its middle section, river water $\delta^{18}O$ suddenly decreases, approaching groundwater values, likely due to groundwater-surface water exchange [25]. Under the combined effects of evaporation and groundwater-river water interactions, the stable isotopes in Nalenggele River water show a dynamic “increase-decrease-increase” pattern along the flow path, characteristic of typical arid inland rivers in northwest China [26].

4.1.3 Groundwater Groundwater δD values range from -64.10‰ to -50.90‰ (average -58.00‰), while δ^{18}O ranges from -9.23‰ to -8.20‰ (average -8.80‰). The groundwater line is $\delta D = 11.77\delta^{18}O + 45.93$ (n = 20, $R^2 = 0.84$). Both slope and intercept exceed those of the GMWL and LMWL (Fig. 2), which is uncommon. Two main factors explain this anomaly: (1) The Nalenggele River originates in the high-altitude, cold mountainous region of eastern Bukadaban in the Kunlun Mountains, where groundwater receives recharge from both atmospheric precipitation and glacial meltwater; (2) Complex groundwater-surface water conversion relationships exist in different sections of the basin. Some river water samples plot in the same region as groundwater samples, both above the GMWL, indicating that river water also recharges groundwater.

Based on isotopic differences between groundwater and river water, their interaction relationships can be determined. When groundwater isotopic values exceed those of river water, river water recharges groundwater; when groundwater values are lower, groundwater recharges river water [1,11,27]. Analysis of isotopic variations along the river course (Fig. 5) reveals: (1) In upstream mountainous sections, river water δ^{18}O > groundwater δ^{18}O, indicating groundwater recharges river water; (2) From the near-mountain outlet to the middle of the primary alluvial fan, groundwater δ^{18}O > river water δ^{18}O, indicating river water recharges groundwater; (3) From the middle to the edge of the primary alluvial fan, river water δ^{18}O > groundwater δ^{18}O again, indicating groundwater recharges river water. No groundwater samples were obtained from the secondary alluvial fan, preventing analysis of water interactions in that section.

4.1.4 Lake Surface Brine and Intercrystalline Brine Lake surface brine δD values range from -51.70‰ to -13.00‰ (average -22.40‰), while δ^{18}O ranges from -6.62‰ to -0.08‰ (average -1.40‰). Intercrystalline brine δD ranges from 7.40‰ to 45.70‰ (average 27.00‰), and δ^{18}O ranges from 1.81‰ to 7.70‰ (average 6.40‰). The similar isotopic distributions of lake surface brine and intercrystalline brine (Fig. 2) indicate their common origin and similar hydrogeochemical evolution. Both plot in the upper-right region of the local and global meteoric water lines, showing significant “oxygen drift” phenomena. Their deuterium excess values are less than zero, indicating excessive isotopic fractionation from evaporation. The lower deuterium excess in intercrystalline brine compared to surface brine is likely caused by additional dissolution and filtration of salt minerals.

4.2 Recharge Sources of Different Water Bodies

4.2.1 River Water and Groundwater Recharge Sources Atmospheric precipitation in the study area plots in the upper-right region of river water and groundwater, with heavier isotopes than river water and groundwater (Table 1). If local precipitation directly recharged river water and groundwater, the latter should be more enriched in heavy isotopes due to evaporation during infiltration. However, the opposite pattern is observed, indicating that local precipitation is not the direct recharge source. Furthermore, river water and groundwater isotopes do not plot along the local meteoric water line. Given the climate characteristics (average annual precipitation < 50 mm, evaporation $>$ 2000 mm), local precipitation cannot be the main recharge source.

Previous studies established two meteoric water lines for the southern Kunlun Mountains at different elevations: $\delta D = 7.4\delta^{18}O + 18.39$ at 3550 m and $\delta D = 8.5\delta^{18}O + 13.2$ at 4700 m [28]. River water and groundwater samples plot below the 4700 m meteoric water line but near the 3550 m line, indicating that mountainous precipitation at approximately 4700 m is the main recharge source for basin groundwater.

4.2.2 Lake Surface Brine and Intercrystalline Brine Recharge Sources

Deuterium excess (d-excess = δD - $8\delta^{18}O$) reflects hydrological cycling processes. In the Nalenggele River basin, atmospheric precipitation d-excess ranges from 2.22‰ to 14.84‰ (average 9.79‰), river water from -5.10‰ to 25.70‰ (average 8.64‰), and groundwater from 9.60‰ to 14.70‰ (average 12.70‰). Lake surface brine d-excess ranges from -14.54‰ to 1.31‰ (average -5.10‰), while intercrystalline brine ranges from -33.78‰ to -7.04‰ (average -23.90‰). The low d-excess values indicate intense evaporation.

While hydrogen and oxygen isotopes suggest that lake brines receive recharge from river water, groundwater, and mountainous precipitation, the multi-solution nature of stable isotopes necessitates boron isotope tracing. Boron has two stable isotopes, ^{10}B and ^{11}B. Water-rock interaction causes the lighter ^{10}B to adsorb onto clay minerals, enriching water in ^{11}B [29]. Thus, boron isotopes are useful for salt lake source identification [30]. River water has extremely low boron content and weak water-rock interaction with clay minerals during rapid flow, resulting in low $\delta^{11}B$ values. Groundwater dissolves boron from clay layers, but adsorbed boron on clays has low $\delta^{11}B$ characteristics, so groundwater also shows low $\delta^{11}B$ values. Consequently, both river water and groundwater in the Nalenggele River basin have low $\delta^{11}B$ values. However, lake surface brine and intercrystalline brine have relatively high $\delta^{11}B$ values, indicating additional recharge sources.

Deep brines are known to have high $\delta^{11}B$ values [31], representing the high end-member, while river water and groundwater with low $\delta^{11}B$ represent the low end-member. The $\delta^{11}B$ values of terminal lake brines fall between these end-members (Fig. 6), suggesting they also receive deep paleo-brine recharge. Geologically, the terminal salt lakes are located along the unconformity fault zone of the Qaidam Basin, with a series of serial salt lakes distributed along the fault zone, providing pathways for deep brine upwelling [32].

4.3 Controlling Factors of Deuterium Excess Parameters

4.3.1 Atmospheric Precipitation Atmospheric precipitation d-excess reflects regional evaporation and precipitation processes. Precipitation from inland high-cold arid regions typically has d-excess $>$ 10‰, while coastal precipitation has d-excess 10‰ [33]. Most samples collected in August had d-excess $>$ 10‰, indicating precipitation primarily originated from evaporated water vapor. Samples with d-excess $<$ 10‰ were mostly collected in August. HYSPLIT back-trajectory modeling shows that moisture in this region during August comes from multiple directions, indicating complex moisture sources [34]. Although the East Asian summer monsoon travels long distances to reach the study area, it remains an important factor causing low d-excess values in August precipitation.

4.3.2 River Water River water d-excess characterizes environmental conditions. Evaporation causes isotopic fractionation, reducing d-excess values, with smaller values indicating stronger evaporation. Fig. 7 shows river water d-excess decreasing with increasing TDS, consistent with the region's climate characteristics of scarce rainfall and intense evaporation. Along the flow direction, enhanced evaporation causes increasingly significant isotopic fractionation, gradually enriching oxygen isotopes and reducing d-excess values.

4.3.3 Lake Brine Both lake surface brine and intercrystalline brine have d-excess values $<$ 0, indicating intense evaporation. The Nalenggele River basin has scarce rainfall and strong evaporation, causing surface water to undergo primary and secondary evaporation, which reduces lake water d-excess values. Intercrystalline brine has lower d-excess than surface brine, likely because it experiences not only evaporation but also salt mineral dissolution and filtration.

4.4 Elevation Effects on Hydrogen and Oxygen Isotopes

Atmospheric precipitation hydrogen and oxygen isotopes show strong continental and elevation effects. As moisture moves from coastal to inland areas, condensation precipitation causes isotopic fractionation, making precipitation isotopes gradually decrease with distance from the coast. Elevation effects also cause isotopic depletion with increasing altitude. As precipitation is the main recharge source for different water bodies, these effects influence their isotopic characteristics.

In the study area, lake surface brine and intercrystalline brine sampling points have similar latitude, longitude, and elevation, showing no continental or elevation effects. River water isotopes also show no continental effect. However, river water δD and δ^{18}O correlate well with elevation (E) (Fig. 8): δD = -0.0041E - 35.23 (R^2 = 0.85) and δ^{18}O = -0.0012E - 8.50 (R^2 = 0.87). For every 100 m increase in elevation, δD decreases by 1.96‰ and δ^{18}O by 0.31‰. Therefore, elevation effect is the dominant factor causing isotopic differences in river water, primarily because: (1) At altitudes above 3000 m, rapid temperature decreases cause atmospheric water vapor to condense easily, making precipitation isotopes vary with altitude; (2) High-altitude areas develop small-scale climate characteristics where temperature, water temperature, evaporation, and water-rock interaction change significantly with elevation, altering river water isotopic characteristics.

5. Conclusions

Analysis of hydrogen and oxygen isotopes and deuterium excess parameters in the Nalenggele River basin leads to the following conclusions:

1. **Atmospheric Precipitation**: The average hydrogen and oxygen isotope values exceed the national average, related to the high-cold arid climate. The LMWL slope is slightly smaller than the GMWL but larger than other northwest arid region basins. Some precipitation samples plot above the GMWL with high d-excess values, indicating water vapor recycling where evaporated precipitation re-condenses along a slope-8 line. Deuterium excess characteristics show complex moisture sources, with the East Asian monsoon causing low d-excess values in August precipitation.

2. **River Water**: The river water line $\delta D = 4.69\delta^{18}O$ - 18.5 has smaller slope and intercept than the GMWL. Negative correlations between d-excess and both $\delta^{18}O$ and TDS indicate increasingly significant evaporation-induced fractionation from mountains to plains, gradually enriching stable isotopes. The "increase-decrease-increase" pattern along the flow path is characteristic of arid inland rivers. Mountain precipitation is the main recharge source, with elevation effects being the primary cause of isotopic variations.

3. **Groundwater**: The groundwater line $\delta D = 11.77\delta^{18}O + 45.93$ has larger slope and intercept than both GMWL and LMWL, related to multi-source recharge and complex groundwater-river water interactions. Along the river course, groundwater recharges river water in upstream mountainous sections and from primary fan middle to edge sections, while river water recharges groundwater from the near-mountain outlet to primary fan middle sections. Groundwater isotopes plot along the mountainous precipitation line, indicating southern mountainous precipitation as the main recharge source.

4. **Lake Brines**: Lake surface brine and intercrystalline brine have similar isotopic distributions, indicating common origin and similar evolution. Large, shallow terminal lakes experience intense evaporation causing excessive fractionation and "oxygen drift." Both have d-excess < 0, with intercrystalline brine values lower than surface brine due to combined evaporation and salt mineral dissolution. Boron isotope analysis indicates

that besides river water, groundwater, and mountainous precipitation, the brines also receive deep brine recharge.

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References

[1] Zeng Di, Wu Jinkui, Li Hongyuan, et al. Hydrogen and oxygen isotopes in precipitation in the arid regions of Northwest China: A review[J]. Arid Zone Research, 2020, 37(4): 857-869.

[2] Yang Chenxi, Li Yunxia, Li Jiayan, et al. Variation of stable hydrogen and oxygen isotopes in precipitation and groundwater in northeast Hunan[J]. Journal of Earth Environment, 2024, 15(2): 326-341.

[3] Li Hanwei, Yao Junqiang, Rong Tao, et al. Characteristics of atmospheric precipitation isotope and path analysis of water vapor transport in the Taxkorgan River Basin Valley[J]. Arid Zone Research, 2024, 41(3): 399-410.

[4] Surma J, Assonov S, Bolourchi M J, et al. Triple oxygen isotope signatures in evaporated water bodies from the Sistan Oasis, Iran[J]. Geophysics Research Letter, 2015, 42(20): 8456-8462.

[5] Wang Yaxuan, Xiao Bei, Cui Buli, et al. The spatiotemporal characteristics of hydrogen and oxygen stable isotopes of Baimai Spring Group[J]. Journal of Earth Environment, 2024, 15(1): 69-77.

[6] Yong Liang, Feng Minquan. Characteristics of δD and δ^{18}O in Changhe River Basin and their recharge relationships[J]. Journal of China Hydrology, 2023, 43(6): 79-85.

[7] Gonfiantini R, Wassenaar L I, Araguas L, et al. A unified Craig-Gordon isotope model of stable hydrogen and oxygen isotope fractionation during fresh or saltwater evaporation[J]. Geochimica et Cosmochimica Acta, 2018, 235: 224-236.

[8] Zhao Xiangyu, Chen Qing, Wang Shou, et al. Indicative significance of hydrogen and oxygen isotopic composition of water bodies in the Fengpei Plain to water cycle and evaporation[J]. Earth and Environment, 2024, 52(1): 86-95.

[9] Liu Xin, Xiang Wei, Si Bingcheng. Hydrochemical and isotopic characteristics in the shallow groundwater of the Fenhe River Basin and indicative significance[J]. Environmental Science, 2021, 42(4): 1739-1749.

[10] Tan Hongbing, Lu Shicheng, Tuo Wanquan, et al. Water resource and mineral source significances of Nalenggele River Catchment in Qaidam Basin[J]. Journal of Hohai University (Natural Sciences), 2020, 48(5): 392-397.

[11] Zhao Chunhong, Shen Haoyong, Wang Zhiheng, et al. Hydrochemical and isotopic characteristic in the surface water of the Fenhe River basin and influence factors[J]. Environmental Science, 2022, 43(10): 4440-4448.

[12] Xiao Y, Liu K, Zhang Y Q, et al. Numerical investigation of groundwater flow systems and their evolution due to climate change in the arid Golmud river watershed on the Tibetan Plateau[J]. Frontiers in Earth Science, 2022, 10: 943075.

[13] Wang D, Han G L, Hu M M, et al. Evaporation processes in the upper river water of Three Gorges Reservoir: Evidence from triple oxygen isotopes[J]. ACS Earth and Space Chemistry, 2021, 5(10): 2679-2687.

[14] Xu Zhongbao, Yang Liping, Weng Baisha, et al. Stable isotopic characteristics of hydrogen and oxygen in different water bodies in the Qinghai Tibet Plateau[J]. South North Water Transfers and Water Science & Technology, 2024, 22(3): 521-533.

[15] Luz B, Barkan E. Variations of ^{17}O and ^{18}O in meteoric waters[J]. Geochimica et Cosmochimica Acta, 2010, 74(22), 6276-6286.

[16] Li Qingkuan, Wang Jianping, Wu Chan, et al. Hydrochemistry and Sr-S isotope constraints on the source of lithium in the Nalenggele River and its terminal lakes, Qaidam Basin[J]. Acta Geologica Sinica, 2021, 95(7): 2169-2182.

[17] Zhu Jianjia, Chen Hui, Gong Guoli. Hydrogen and oxygen isotopic compositions of precipitation and its water vapor sources in eastern Qaidam Basin[J]. Environmental Science, 2015, 36(8): 2784-2790.

[18] Yang Nuan. Characteristics of Groundwater Stable Isotopic Compositions in Eastern Qaidam Basin: Implications for Moisture Sources and Climate Change[D]. Beijing: China University of Geosciences (Beijing), 2021.

[19] Xiao Yong. Groundwater Circulation Patterns and Its Change Trend in Southern Qaidam Basin, Northwest China[D]. Beijing: China University of Geosciences (Beijing), 2018.

[20] Han Jibin, Zhang Haiyun, Zhang Baoyun. Vulnerability assessment of shallow groundwater of Nalenggele alluvial fan, Qaidam Basin[J]. Journal of Salt Lake Research, 2023, 31(3): 10-17.

[21] Li Qingkuan. Multi-index Study on the Source, Migration and Enrichment of Lithium in the Nalenggele River Drainage and Terminal Lakes[D]. Beijing: University of Chinese Academy of Sciences, 2020.

[22] Xu Wei. Groundwater Cycle Patterns and Its Response to Human Activities in Nalenggele Alluvial Proluvial Plain[D]. Changchun: Jilin University, 2015.

[23] Dang Yan. The Model of Evolution and Circulation of Groundwater in the Tataling River Basin, Qaidam Basin[D]. Xi'an: Chang'an University, 2020.

[24] Li Jiansen, Li Tingwei, Ma Yunqi, et al. Distribution and origin of brine type Li, B, K mineralization in the Qaidam Basin, NW China[J]. Scientia Sinica (Terrae), 2022, 52(3): 474-485.

[25] Guo Yawen, Tian Fuqiang, Hu Hongchang, et al. Characteristics and significance of stable isotopes and hydrochemistry in surface water and groundwater in Nanxiaohegou Basin[J]. Environmental Science, 2020, 41(2): 682-690.

[26] Wang Shuli, Zheng Mianping, Wang Yongming, et al. Advances and development history of geochemistry on salt lakes in China[J]. Science Technology and Engineering, 2019, 19(9): 1-9.

[27] Qi Haiping, Wang Yunhui, Xiaoy Yingkai, et al. The preliminary study on boron isotopes in the salt lakes of China[J]. Chinese Science Bulletin, 1993, 19(7): 634-637.

[28] Wei H Z, Jiang S Y, Tan H B, et al. Boron isotope geochemistry of salt sediments from the Dongtai salt lake in Qaidam Basin: Boron budget and sources[J]. Chemical Geology, 2014, 380: 74-83.

[29] Rao Wenbo, Li Yaowei, Tan Hongbing, et al. Stable hydrogen-oxygen isotope composition and atmospheric moisture sources of precipitation in an arid alpine region: A case study of the Golmud River Watershed on the north slope of the Kunlun Mountains[J]. Journal of Hydraulic Engineering, 2021, 52(9): 1116-1125.

[30] Li Jiansen. Enrichment and Metallogenic Mechanism of the Brine-type K, B, Li Resources in the Qaidam Basin[D]. Beijing: University of Chinese Academy of Sciences, 2022.

[31] Lu Jun, Pan Tong, Li Yongshou, et al. A preliminary investigation of hydrochemical characteristic and genesis of deep brine in the central Qaidam basin[J]. Acta Geologica Sinica, 2021, 95(7): 2129-2137.

[32] Su Huimeng, Zhang Fawang, Hou Suyu, et al. An analysis of groundwater circulation in the Pingyu mining area based on hydrochemical and isotopic characteristics of groundwater[J]. Hydrogeology & Engineering Geology, 2023, 50(5): 53-67.

[33] He Qixin, Cao Guangchao, Cao Shengkui, et al. Hydrogen-oxygen isotope characteristics of water bodies in the Xiangride River Basin and its influencing factors[J]. Arid Zone Research, 2022, 39(3): 820-828.

[34] Wang Bing, Qin Xiwei, Ren Erfeng, et al. Genesis of geothermal water in the Da Qaidam area, northern margin of the Qaidam Basin: Constraints from hydrochemistry and isotopes of hydrogen-oxygen-strontium[J]. Bulletin of Mineralogy, Petrology and Geochemistry, 2024, 43(1): 167-177.

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