Stable Isotope Characteristics of Precipitation, Surface Water, and Groundwater in the Ebinur Lake Basin (Postprint)

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Abstract

Precipitation, surface water, and groundwater in the Ebinur Lake watershed were selected as research objects. By integrating watershed hydrogeological data, the spatiotemporal variation characteristics of hydrogen and oxygen stable isotopes in different water bodies were analyzed using methods including field investigation, laboratory experiments, and statistical analysis. The results show that: (1) The variation ranges of $ $2H and $ $18O in precipitation in the Ebinur Lake watershed are -148.2‰ to -34.5‰ and -20.16‰ to 1.20‰, respectively, with the slope of the watershed' s meteoric water line being 6.69. The $ $18O values in precipitation exhibit a positive correlation with temperature and show a significant negative correlation with precipitation amount during summer. (2) The variation ranges of $ $2H and $ $18O in surface water are -101.0‰ to -17.0‰ and -14.54‰ to 0.29‰, respectively, with the highest values occurring in August, followed by May and October. Isotopic values in the Bortala River gradually increase from upstream to downstream along the river course, whereas the variation trend along the course is not obvious in the Jing River. River water $ $18O shows a positive correlation with temperature. (3) The ranges of $ $2H and $ $18O values in groundwater are -85.0‰ to -65.5‰ and -12.18‰ to -9.05‰, respectively, with mean values of -75.5‰ and -11.00‰. Groundwater isotopic values in the Bortala River region gradually increase from upstream to downstream along the river course, while the variation trend is not obvious in the Jing River region. The determination of stable isotopes in water bodies of the Ebinur Lake watershed provides isotopic evidence for elucidating watershed hydrological processes and is of great significance for the effective utilization of water resources and maintenance of watershed ecological security under changing environments.

Full Text

Stable Isotope Characteristics of Precipitation, Surface Water, and Groundwater in the Ebinur Lake Basin

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Abstract

This study investigated precipitation, surface water, and groundwater in the Ebinur Lake Basin, integrating hydrological and geological data to analyze the spatiotemporal variation characteristics of hydrogen and oxygen stable isotopes in different water bodies using field surveys, laboratory experiments, and statistical analysis. The results indicate that: (1) The δ^2H and δ^{18}O values of precipitation in the Ebinur Lake Basin range from −148.2‰ to −34.5‰ and −20.16‰ to 1.20‰, respectively. The local meteoric water line is defined by the equation $\delta^2H = 6.69\delta^{18}O + 8.2$ ($R^2 = 0.99$, $P < 0.01$). Precitation δ^{18}O shows a significant positive correlation with temperature and a negative correlation with precipitation amount during summer. (2) Surface water δ^2H and δ^{18}O values range from −101.0‰ to −17.0‰ and −14.54‰ to 0.29‰, respectively, with maximum variation in August, followed by May and October. The isotopic values of the Bortala River increase gradually from upstream to downstream, whereas the Jinghe River shows no clear longitudinal trend. Surface water δ^{18}O is positively correlated with temperature. Compared with river water, lake water exhibits significantly enriched isotopic values across all seasons, reflecting intense evaporation and concentration. (3) Groundwater δ^2H and δ^{18}O values range from −85.0‰ to −65.5‰ and −12.18‰ to −9.05‰, respectively, with mean values of −75.5‰ and −11.00‰. Groundwater isotopic values in the Bortala River region increase gradually from upstream to downstream, while no clear trend is observed in the Jinghe River region. The determination of stable isotopes in the Ebinur Lake Basin provides isotopic evidence for elucidating basin hydrological processes, which is crucial for effective water resource utilization and maintenance of ecological security under changing environmental conditions.

Keywords: precipitation; surface water; groundwater; stable isotopes; Ebinur

Lake Basin

1 Introduction

Northwest China represents a typical arid region characterized by fragile ecological environments, dramatic hydrological variations, and high sensitivity to global climate change. The region predominantly features a mountain-basin system structure, where the basin water cycle typically undergoes a series of processes including precipitation → surface runoff → groundwater flow → surface runoff → evapotranspiration. Precipitation serves as the primary driving factor, while surface water and groundwater flow processes and their interconversion constitute major components of the basin water cycle, with evapotranspiration representing the primary natural water consumption process.

Hydrogen and oxygen stable isotopes, as integral components of water molecules, serve as the "fingerprint" of water. As a novel research approach, stable isotope methods have been increasingly applied to investigate water cycle processes in arid region basins, enabling the tracing of water movement at both point and basin scales. Compared with traditional research methods, isotope techniques offer advantages of high measurement precision and minimal interference from external factors. By tracing isotopic information retained in water bodies that reflects environmental evolution at their source regions, researchers can explore water formation, transformation, and migration mechanisms, thereby improving understanding of groundwater flow and discharge processes as well as the interconversion relationships between precipitation, surface water, and groundwater in arid region basins.

The Ebinur Lake Basin is located in the southwestern Junggar Basin of Xinjiang, serving as a core area of the Silk Road Economic Belt and a regional center for water and salt accumulation. The basin features diverse landscape types, including wetland, desert, and mountain ecosystems that collectively maintain ecological balance, making it an ideal site for studying hydrological processes under changing environmental conditions. Recent research in this region has primarily focused on vegetation restoration, desertification control, and landscape pattern changes, while studies on the hydrological characteristics of water bodies remain limited, hindering efficient and rational local water resource utilization. Therefore, this study selected precipitation, surface water, and groundwater as key hydrological elements, focusing on analyzing their stable isotope characteristics and influencing factors to provide isotopic evidence for clarifying basin hydrological processes and to support effective water resource utilization and ecological security maintenance under changing environmental conditions.

2 Study Area and Methods

2.1 Study Area Description

The Ebinur Lake Basin (44°02 -45°23 N, 79°53 -83°53 E) experiences a typical temperate arid continental climate, with mean annual precipitation of 169.7 mm, mean annual temperature of 8.0°C, and mean annual evaporation of 1569–3421 mm. Rivers in the basin originate from mountainous areas, including the Kuitun, Jinghe, Daheyanzi, Bortala, Sikeshu, and seasonal rivers. Summer represents the high-flow period, while winter is the low-flow period. Ebinur Lake has an average depth of 1.7 m and is primarily recharged by surface rivers and groundwater, currently receiving surface runoff mainly from the Jinghe and Bortala rivers. The basin features diverse geomorphological landscapes, integrating wetland and desertification processes.

2.2 Experimental Design and Field Sampling

Surface water and groundwater samples were collected in May, August, and October (representing spring, summer, and autumn, respectively). Surface water sampling targeted the Bortala River, Jinghe River, Kuitun River, Daheyanzi River, and Ebinur Lake, with 35 samples collected each season: 12 from the Bortala River, 12 from the Jinghe River, 5 from the Kuitun River, 3 from the Daheyanzi River, and 3 from Ebinur Lake. Sampling sites were distributed across upper, middle, and lower reaches following an equidistant principle along main channels. Lake water samples were collected in the morning from lake margins (center areas were not sampled due to access limitations) at approximately 20 cm below the water surface.

Groundwater samples were collected from irrigation and drinking water wells, with 22 samples per season (including 2 spring water samples): 12 in the Bortala River region, 7 in the Jinghe River region, and 3 around Ebinur Lake. Precipitation samples were collected at the Ebinur Lake Wetland Nature Reserve Management Station during each precipitation event from start to finish, yielding 28 samples total.

Rainfall samples were directly transferred to sampling bottles and immediately sealed to prevent evaporative fractionation. Solid precipitation was first placed in plastic bags, sealed, and completely melted at room temperature. Surface water samples were collected from gentle river sections to avoid stagnant or contaminated water, taken several centimeters below the water surface. Groundwater sampling ensured on-site pumping, with water table depth and well depth recorded. All samples were stored in high-density polyethylene bottles, rinsed three times before filling completely to eliminate air bubbles, and sealed with Parafilm membrane. All water samples were filtered through 0.45 m membranes and refrigerated before analysis.

2.3 Hydrogen and Oxygen Stable Isotope Analysis

Hydrogen and oxygen stable isotope (δ^{2}H and δ^{18}O) analysis was conducted at the Xinjiang Laboratory of Lake Environment and Resources in Arid Area, Xinjiang Normal University, using a Los Gatos Research Model DLT-100 liquid water stable isotope analyzer. Each sample was analyzed three times using a cubic spline fitting method. To minimize memory effects, the first three analytical results were discarded and the average of subsequent measurements was used. Stable isotope contents were expressed as per mil deviations (‰) from Vienna Standard Mean Ocean Water (V-SMOW) using the formula:

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

where R_{sample} and R_{standard} represent the isotope ratios (^{2}H/^{1}H or ^{18}O/^{16}O) of the sample and standard, respectively. Measurement precision was \$±\$0.5‰ for δ^{2}H and \$±\$0.1‰ for δ^{18}O.

3 Results and Analysis

3.1 Precipitation Stable Isotope Characteristics

The δ^{2}H and δ^{18}O values of precipitation in the Ebinur Lake Basin exhibit distinct seasonal variations (Table 1). Seasonal averages are: spring (March-May) δ^{2}H = −88.4‰ to −78.4‰, δ^{18}O = −12.89‰ to −9.32‰; summer (June-August) δ^{2}H = −63.1‰ to −35.5‰, δ^{18}O = −5.94‰ to 1.20‰; autumn (September-November) δ^{2}H = −132.7‰ to −62.8‰, δ^{18}O = −17.74‰ to −5.64‰; and winter (December-February) δ^{2}H = −148.2‰ to −98.3‰, δ^{18}O = −20.16‰ to −14.38‰. Seasonal variation shows maximum values in summer, minimum in winter, and intermediate values in spring and autumn.

Statistical analysis yields the local meteoric water line (LMWL) for the region: $\delta^{2}H = 6.69\delta^{18}O + 8.2$ ($R^{2} = 0.99$, $P < 0.01$). Compared with the global meteoric water line (GMWL: $\delta^{2}H = 8\delta^{18}O + 10$) and the national meteoric water line (CMWL: $\delta^{2}H = 7.9\delta^{18}O + 8.2$), both the slope and intercept of the Ebinur Lake Basin LMWL are smaller. This primarily results from two factors: (1) the study area is located in an inland arid region with low precipitation amounts and low atmospheric humidity, causing strong evaporative fractionation during rainfall; and (2) the region is far from oceans, with a substantial portion of precipitation moisture originating from local evaporation. In arid regions, surface water bodies exhibit high deuterium excess (d-excess), and evaporated moisture also has high d-excess values. Combined with sub-cloud evaporation of raindrops during descent, these processes lead to enrichment of heavy isotopes in precipitation and reduction of the LMWL slope.

Table 1 Seasonal variation of precipitation δ^{2}H and δ^{18}O in the Ebinur Lake Basin

Season	δ^2H (‰)	δ^{18}O (‰)
Spring	−98.4 to −78.4	−12.89 to −9.32
Summer	−63.1 to −35.5	−5.94 to 1.20
Autumn	−132.7 to −62.8	−17.74 to −5.64
Winter	−148.2 to −98.3	−20.16 to −14.38

3.2 Surface Water Stable Isotope Characteristics

3.2.1 River Water Temporal and Spatial Variation The δ^2H and δ^{18}O values of river water vary seasonally, primarily due to differences in meteorological factors such as temperature and rainfall among seasons (Table 2). Seasonal averages show: Bortala River δ^2H = −96.1‰ to −81.2‰, δ^{18}O = −12.04‰ to −11.44‰; Jinghe River δ^2H = −84.1‰ to −79.1‰, δ^{18}O = −9.61‰ to −8.51‰; Kuitun River δ^2H = −101.1‰ to −90.8‰, δ^{18}O = −14.54‰ to −12.84‰; Daheyanzi River δ^2H = −88.5‰ to −85.1‰, δ^{18}O = −12.98‰ to −11.91‰. Variation is greatest in August, moderate in May and October, and smallest in January.

Figure 3 [Figure 3: see original paper] illustrates the longitudinal variation characteristics of the Bortala and Jinghe rivers. The Bortala River shows a gradual isotopic enrichment from upstream to downstream, resulting from varying recharge sources and evaporation intensity along different river sections. The upstream area near mountains is primarily recharged by isotopically depleted snow and ice meltwater, yielding the lowest isotopic values. In contrast, the middle and lower reaches flow through flat basins and plains where reduced flow velocity and higher temperatures enhance evaporative fractionation, causing progressive isotopic enrichment downstream. The Jinghe River exhibits no clear longitudinal trend, mainly due to its shorter course and lack of significant variation in recharge sources or meteorological factors. Comparatively, Jinghe River water is more isotopically depleted than Bortala River water overall, with smaller along-flow variation, attributable to its shorter course and more uniform recharge sources.

Table 2 Seasonal variation of river water δ^2H and δ^{18}O in the Ebinur Lake Basin

River	May δ^2H/δ^{18}O (‰)	Aug δ^2H/δ^{18}O (‰)	Oct δ^2H/δ^{18}O (‰)
Bortala River	−96.1/−12.04	−84.1/−9.61	−88.5/−11.91
Jinghe River	−84.1/−9.61	−79.1/−8.51	−85.1/−11.44
Kuitun River	−101.1/−14.54	−90.8/−12.84	−92.1/−13.54
Daheyanzi River	−88.5/−12.98	−85.1/−11.91	−90.8/−13.21

3.2.2 Ebinur Lake Water Hydrogen and Oxygen Stable Isotope Composition Ebinur Lake water stable isotopes show a distinct relationship (Figure 4). Based on the correlation between hydrogen and oxygen stable isotopes, the lake water line is defined by $\delta^2\text{H} = 4.07\delta^{18}\text{O} - 17.93$ ($\text{R}^2 = 0.98$, $\text{P} < 0.01$). The slope of this line is lower than both the GMWL and the LMWL, indicating that Ebinur Lake water undergoes non-equilibrium evaporation under dry conditions. Although the lake water line slope is lower than the river water line, lake water samples plot along the extension of the inflowing river water line, demonstrating that river water is the primary recharge source for the lake, while evaporation effects are more pronounced in the lake than in rivers.

Figure 4 [Figure 4: see original paper] Relationship between δ^2H and δ^{18}O of Ebinur Lake water

3.3 Groundwater Stable Isotope Characteristics

Groundwater sampling sites are distributed across both mountainous and plain areas of the Ebinur Lake Basin. Longitudinal variation characteristics of groundwater in the Bortala and Jinghe river regions are shown in **Figure 5** [Figure 5: see original paper]. In the Bortala River region, groundwater samples from upstream sites (G1-G3) exhibit significantly lower isotopic values than other sites, as these locations receive direct recharge from snow and ice meltwater in low-temperature conditions with minimal evaporative fractionation. Samples G4-G12 show a slight increasing trend with fluctuations, indicating influence from phreatic evaporation. The decreased isotopic values in October may result from agricultural irrigation recharge in downstream areas. Samples G13-G22, with shallow water tables, interact frequently with surface water, while nearby surface water becomes progressively enriched through evaporation.

In the Jinghe River region, groundwater isotopic values increase gradually from middle to downstream reaches. Notably, sample G18 has a well depth of 100 m, while G19 is only 30 m deep. Samples G15 and G16 show lower isotopic values due to exchange with river water, whereas G21 and G22, located near Ebinur Lake, exhibit elevated values likely resulting from exchange with isotopically enriched lake water.

3.4 Relationships Between Stable Isotopes and Environmental Factors

3.4.1 Precipitation Stable Isotopes and Their Relationship with Precipitation Amount and Temperature Variations in δ^{18}O are closely related to evaporation and condensation processes during precipitation formation, with temperature being a critical controlling factor. **Figure 6** [Figure 6: see original paper] shows the relationship between precipitation δ^{18}O and temperature, revealing a significant positive correlation at the event scale: $\delta^{18}\text{O} = 0.417\text{T} - 12.18$ ($\text{R}^2 = 0.572$, $\text{P} < 0.01$). Each 1°C temperature increase corresponds to approximately 0.417‰ increase in δ^{18}O.

Examining the relationship between precipitation δ^{18}O and precipitation amount shows no significant trend at the annual scale, indicating no precipitation amount effect in the study area. Classic isotope theory suggests that precipitation amount effects are typically insignificant in inland regions, being mainly manifested in mid-latitude coastal and island areas associated with strong convection. However, when considering only summer rainfall, a significant negative relationship emerges: $\delta^{18}O = -1.146P + 1.169$ ($R^2 = 0.473$, $P < 0.05$), demonstrating a notable precipitation amount effect during summer. Similar phenomena have been observed in other arid regions.

3.4.2 Surface Water Stable Isotopes and Their Relationship with Temperature Generally, temperature effects on water isotopes are pronounced in high-latitude regions, with positive correlations becoming more significant further inland. **Figure 7** [Figure 7: see original paper] and **Table 3** show the relationships between river water $\delta^{18}O$ and temperature in the Ebinur Lake Basin. Overall, river water $\delta^{18}O$ is positively correlated with temperature, with the downstream region showing the strongest response, followed by the middle reaches, and the upstream region showing the weakest correlation.

The Bortala River exhibits seasonal variations in the temperature-$\delta^{18}O$ relationship across different reaches. The strongest temperature effect occurs in August, while the weakest appears in January for upstream areas and October for middle and downstream areas. This reflects differences in river-environment interactions between upstream and downstream regions. Downstream areas, being desert environments with high temperatures and strong evaporation, experience intense isotopic fractionation, while upstream mountainous areas have low temperatures, high humidity, and minimal evaporation.

The temperature-$\delta^{18}O$ relationships for the Bortala and Jinghe rivers are: - Bortala River: $\delta^{18}O = 0.282T - 11.44$ ($R^2 = 0.572$, $P < 0.01$) - Jinghe River: $\delta^{18}O = 0.171T - 10.29$ ($R^2 = 0.473$, $P < 0.05$)

Each 1°C temperature increase corresponds to approximately 0.282‰ and 0.171‰ increases in $\delta^{18}O$ for the Bortala and Jinghe rivers, respectively. Temperature effects are more pronounced for the Bortala River due to its longer course through diverse landscapes (mountains, oases, desert), where each landscape type exerts different influences on river hydrological characteristics. The Jinghe River' s shorter course and more uniform recharge result in smaller temperature effects.

Table 3 Relationship between seasonal $\delta^{18}O$ and river temperature in the upstream, midstream, and downstream of the Bortala River

Reach	May $\delta^{18}O$-T relationship	Aug $\delta^{18}O$-T relationship	Oct $\delta^{18}O$-T relationship
Upstream	$\delta^{18}O = 0.035T - 12.04$	$\delta^{18}O = 0.256T - 12.98$	$\delta^{18}O = 0.578T - 14.54$

Reach	May δ^{18}O-T relationship	Aug δ^{18}O-T relationship	Oct δ^{18}O-T relationship
Midstream	$\delta^{18}O = 0.033T - 11.91$	$\delta^{18}O = 0.148T - 11.44$	$\delta^{18}O = 0.326T - 13.21$
Downstream	$\delta^{18}O = 0.024T - 9.61$	$\delta^{18}O = 0.239T - 8.51$	$\delta^{18}O = 0.454T - 12.84$

Figure 7 [Figure 7: see original paper] Relationship between δ^{18}O and river temperature for the Bortala and Jinghe rivers

4 Conclusions

(1) Precipitation δ^2H and δ^{18}O values in the Ebinur Lake Basin range from $-148.2‰$ to $-34.5‰$ and $-20.16‰$ to $1.20‰$, respectively. The local meteoric water line is $\delta^2H = 6.69\delta^{18}O + 8.2$ ($R^2 = 0.99$, $P < 0.01$). Precipitation δ^{18}O shows a significant positive correlation with temperature and a negative correlation with precipitation amount during summer.

(2) Surface water δ^2H and δ^{18}O values range from $-101.0‰$ to $-17.0‰$ and $-14.54‰$ to $0.29‰$, respectively. The Bortala River shows gradually increasing isotopic values from upstream to downstream, while the Jinghe River exhibits no clear longitudinal trend. Surface water δ^{18}O is positively correlated with temperature. The lake water line equation $\delta^2H = 4.07\delta^{18}O - 17.93$ ($R^2 = 0.98$, $P < 0.01$) indicates significant evaporative enrichment compared with inflowing river water.

(3) Groundwater δ^2H and δ^{18}O values range from $-85.0‰$ to $-65.5‰$ and $-12.18‰$ to $-9.05‰$, respectively, with mean values of $-75.5‰$ and $-11.00‰$. Groundwater isotopic values in the Bortala River region increase gradually from upstream to downstream, whereas no clear trend is observed in the Jinghe River region.

The determination of stable isotopes in the Ebinur Lake Basin provides isotopic evidence for clarifying basin hydrological processes, which is of great significance for effective water resource utilization and maintenance of ecological security under changing environmental conditions.

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