Isotopic Investigation of Groundwater Characteristics in the Ebinur Lake Basin: Postprint

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Abstract

Groundwater plays a crucial role in regulating the water cycle and ecosystems in arid regions, and understanding and managing groundwater resources is key to preventing reductions in river baseflow, land subsidence, and water quality degradation. Through analysis of hydrochemical parameters and stable hydrogen and oxygen isotopic characteristics of groundwater in the Ebinur Lake Basin, combined with methods such as linear regression, two-end-member mixing model, and GIS spatial analysis, this study investigates the recharge sources and dynamic variations of hydrochemical components in different regions. The results indicate: (1) Hydrogen and oxygen isotope ($ $2H and $ $18O) values are highest in the middle and lower reaches of the Bortala River (hereinafter referred to as the Bo River) and Jing River, followed by the area surrounding Ebinur Lake, and lowest in the upper reaches of the Bo River, suggesting different circulation processes for groundwater within the basin. (2) The deuterium excess (d-excess) and hydrochemical characteristics of groundwater reflect different recharge mechanisms and influencing factors: groundwater in the upper reaches of the Bo River is primarily recharged by glacial and snowmelt water; groundwater in the middle and lower reaches of the Bo River and Jing River mainly originates from surface water and precipitation, while being significantly influenced by rock formation properties, farmland development, and irrigation practices; groundwater in the vicinity of Ebinur Lake is mainly derived from glacial meltwater and precipitation. Groundwater in the middle and lower reaches and the river-lake confluence zones represents key areas for prevention, control, and remediation. (3) In groundwater flow system I, electrical conductance (EC) ranges between 210.00~2500.00 S·cm-1 and d-excess ranges between 6.47‰~9.70‰; in flow system II, EC ranges between 141.60~5260.00 S·cm-1 and d-excess ranges between 9.61‰~17.45‰, indicating different hydraulic connections within the groundwater aquifer. The findings from this investigation into the driving mechanisms of stable hydrogen and oxygen isotopes and hydrochemistry of groundwater in the Ebinur Lake Basin can provide a theoretical reference basis for the rational utilization and scientific development of groundwater resources in the basin.

Full Text

Characteristics of Groundwater in Ebinur Lake Basin Revealed by Isotopes

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Abstract

Groundwater plays a crucial role in regulating water cycles and ecosystems in arid regions. Understanding and managing groundwater resources is essential for preventing reductions in river baseflow, land subsidence, and water quality degradation. This study analyzed hydrochemical parameters and hydrogen-oxygen stable isotope characteristics of groundwater in the Ebinur Lake Basin, exploring recharge sources and dynamic changes of hydrochemical components in different regions using linear regression, two-end-member mixing models, and spatial analysis methods. The results demonstrate that: (1) Different circulation processes exist in various regions of the basin, with the maximum hydrogen and oxygen isotope values occurring in the middle and lower reaches of the Bortala and Jing Rivers, followed by the area around Ebinur Lake, and the minimum values in the upper Bortala River region. (2) The deuterium excess parameter (d-excess) and hydrochemical composition reflect distinct recharge mechanisms and influencing factors. Groundwater in the upper Bortala River area is primarily recharged by glacial and snowmelt water. Groundwater in the middle and lower reaches of the Bortala and Jing Rivers mainly originates from surface water and precipitation, significantly influenced by rock formation properties, farmland development, and irrigation practices. Groundwater around Ebinur Lake is primarily sourced from snow/ice melt and precipitation. The middle and lower reaches and the river-lake confluence zones are critical areas for groundwater protection and remediation. (3) Different hydraulic connections exist in aquifers. For flow system I, electrical conductance (EC) ranges from 210.00–2500.00 $\mathrm{S \cdot cm^{-1}}$ and d-excess ranges from 6.47‰–9.70‰. For flow system II, EC ranges from 141.60–5260.00 $\mathrm{S \cdot cm^{-1}}$ and d-excess ranges from 9.61‰–17.45‰. These findings on the driving mechanisms of hydrogen-oxygen isotopes and hydrochemistry in Ebinur Lake Basin groundwater provide theoretical references for rational utilization and scientific development of groundwater resources in the basin.

Keywords: hydrogen-oxygen isotopes; hydrochemical composition; groundwater recharge; groundwater flow system; Ebinur Lake Basin

Large-scale groundwater extraction causes land subsidence, reduced spring and river baseflow during dry periods, saltwater intrusion, water quality degradation, and even global sea-level rise, severely impacting ecosystems worldwide. Particularly in inland arid regions, groundwater is vital for regulating hydrological cycles and maintaining ecosystem health. The recharge sources, exchange mechanisms, and compositional characteristics of groundwater represent fundamental issues in hydrology and hydrogeology. When conventional methods struggle to obtain such information, isotope hydrology techniques have proven effective for addressing critical hydrological problems and processes. Combining multiple hydrochemical tracing methods with mutual verification can improve evaluation accuracy.

Previous studies have investigated groundwater recharge and water cycles in arid watersheds using hydrochemical and isotopic methods. By comparing isotopic compositions of groundwater and potential water sources, researchers have traced groundwater recharge in arid regions. Yapiyev et al. determined evaporation losses and groundwater inputs in Central Asia using water isotopes. Joshi et al. traced groundwater recharge sources in the Ganges Basin using water isotopes. Jesiya et al. studied groundwater recharge mechanisms based on stable isotope time series data. Combining hydrochemical and stable isotope indicators has become an effective approach for quantitatively evaluating groundwater-river water exchange. Scholars such as Wen et al., Xu et al., Zhang et al., and Zhang et al. have investigated surface water-groundwater transformation relationships in the Poyang Lake, Kongque River, Ili Valley, and Bayin River basins, respectively.

In Ebinur Lake Basin groundwater research, Hao et al. analyzed spatiotemporal variation characteristics of stable hydrogen-oxygen isotopes, revealing relationships between water isotopes and environmental factors. Zhu et al. combined hydrochemical and stable isotope techniques to analyze isotopic and hydrochemical characteristics of major inflow rivers to Ebinur Lake, though groundwater was minimally addressed. Therefore, this study builds upon previous research by comprehensively applying hydrochemical and stable isotope techniques to investigate groundwater in the Ebinur Lake Basin.

As a particularly important core region along the "Belt and Road" initiative, water and soil security in the Ebinur Lake Basin relates to national strategic implementation. The basin exhibits typical arid region ecological environment characteristics. In recent years, drought-induced lake area shrinkage has exposed large areas of dry lakebed with severe salinization. Groundwater resources are crucial for watershed ecological environment and regional water resource management. Providing stable isotope and hydrochemical composition evidence for groundwater can offer theoretical guidance for inter-basin water transfer and watershed management. The specific research objectives are: (1) to characterize groundwater isotopic and hydrochemical features in the Ebinur Lake Basin; (2) to identify recharge sources and characteristics; (3) to determine flow systems in the aquifer system.

1. Study Area Overview

The Ebinur Lake Basin is located in the northern part of Jinghe County, Bortala Mongol Autonomous Prefecture, Xinjiang Uygur Autonomous Region. The lake extends northwest-southeast with geographical coordinates of 44°34 – 45°08 N, 82°35 –83°16 E. The basin has low terrain, forming a semi-closed depression open to the east and surrounded by mountains on the other three sides, with the lake basin serving as the convergence center for surface water and groundwater. According to the Bortala Prefecture Water Resources Bulletin (http://www.xjboz.gov.cn/zjboz.htm), total surface water extraction in the basin increased from 1.35×10^{8} m^{3} to 9.98×10^{8} m^{3}, representing severe over-extraction. Based on statistics from 45 groundwater observation wells across the prefecture, the average groundwater depth decreased by 0.26 m (0.12 m more than the previous year).

2. Materials and Methods

2.1 Sample Collection and Testing

Surface water and groundwater samples were collected from the basin during May–June 2019. Sampling sites were primarily located along Bortala River (Bortala River) and Jing River sections and around Ebinur Lake management stations, totaling 45 groundwater samples and 15 surface water samples. All water samples were collected in 150 mL high-density polyethylene bottles, rinsed 2–3 times with sample water in the field to prevent diffusion and evaporation loss, then sealed and frozen. Samples were immediately transported to the laboratory for isotope analysis after fieldwork completion.

During sampling, sample coordinates and elevations were recorded using handheld GPS receivers. Hydrochemical analysis was conducted indoors. Electrical conductance (EC), total dissolved solids (TDS), and salinity were measured using a conductivity meter (Multi 3420 Set B, WTW GmbH, Germany) with the ion-selective electrode method, with final results recorded. Hydrogen-oxygen isotope testing used an automatic water extraction system (LI-2100) and liquid water stable isotope analyzer (TIWA-45-EP, Los Gatos Research) for sample extraction and measurement. Each sample was analyzed three times, with the last two results used considering memory effects. Measured hydrogen-oxygen stable isotope content is expressed as per mil deviation (‰) from Vienna Standard Mean Ocean Water (VSMOW), calculated as: $\delta(‰) = (R_{sample} -$

R_{standard})/R_{standard} × 1000, where R_{sample} is the sample and R_{standard} is the standard. Measurement precision: δ^2H $±$0.33‰, δ^{18}O $±$0.10‰.

2.2.1 Linear Regression Equation Fitting

The least squares method is a mathematical optimization technique that finds the best functional match for data by minimizing the sum of squared errors between actual and fitted targets. It can be used for curve fitting. This study used least squares to establish linear regression equations between different regional groundwaters. The fitted line formula is: y = kx + b, where y is the dependent variable, x is the independent variable, k is the slope, and b is the intercept. After calculating the slope, the intercept b is determined using the method of undetermined coefficients with known slope k.

2.2.2 Groundwater Recharge Rate Calculation

Based on linear regression fitting results and isotope conservation principles, assuming groundwater isotopic composition results from mixing two end-member components, the recharge rate can be calculated. The formula is: R_s = (δ_g - δ_s)/(δ_p - δ_s), where R_s is the surface water recharge rate to groundwater; δ_g, δ_s, and δ_p are the isotopic values of groundwater, surface water, and precipitation, respectively.

2.2.3 Rayleigh Fractionation Equation

The Rayleigh fractionation model originally described distillation processes of two different solutions mixed in phase reactions, later applied to describe non-equilibrium fractionation of stable isotopes in open systems. According to the Rayleigh fractionation formula: δ = δ_0 + · ln(f), where δ is the isotopic value after evaporation, δ_0 is the initial isotopic value, is the enrichment coefficient, and f is the remaining water proportion.

3. Results

3.1.1 Hydrogen-Oxygen Isotope Characteristics in Different Regions

Groundwater sampling points were mainly distributed in the Bortala River, Jing River, and Ebinur Lake surrounding areas. Due to sampling difficulties in the upper Jing River, only middle and lower reaches were sampled. Well depths were 15-100 m in the Bortala and Jing River areas and 30-260 m around Ebinur Lake management stations. Based on mean values, δ^2H and δ^{18}O values were highest in the middle and lower reaches of the Bortala and Jing Rivers, moderate around Ebinur Lake, and lowest in the upper Bortala River area. Deuterium excess (d-excess) was highest around Ebinur Lake, moderate in the upper Bortala River area, and lowest in the middle and lower reaches of the Bortala and Jing Rivers. As aquifers are distributed below the surface, regional heterogeneity of groundwater hydrogen-oxygen stable isotopes indicates that basin groundwater is influenced by recharge sources and water-rock interactions.

3.1.2 Spatial Characteristics of Groundwater d-excess

Deuterium excess (d-excess = δ^2H - 8δ^{18}O) was defined and quantified by Dansgaard to characterize evaporation processes, reflecting changes in air humidity, sea surface temperature, and wind speed, as well as water-rock oxygen isotope exchange degrees. Basin-wide d-excess ranged from 6.47‰ to 17.45‰, averaging 10.48‰. For spatial analysis, the global meteoric water line and its characteristic line at d-excess = 10‰ were plotted. The middle and lower reaches of the Bortala and Jing Rivers were mainly between the d-excess = 10‰ and d-excess = 0‰ characteristic lines, while groundwater around Ebinur Lake was primarily between the d-excess = 10‰ and d-excess = 20‰ characteristic lines, indicating different circulation processes in different basin regions.

Horizontally, Bortala and Jing River basin groundwater sampling points were distributed 0–8 km from rivers, showing clustering characteristics at different distances, indicating good lateral connectivity. Vertically, except for extreme samples like ABH12, regression analysis showed no significant relationship, with minimal correlation coefficients. Groundwater d-excess showed no depth effect, requiring more isotopic indicators for future analysis.

3.2.1 Relationship Between Groundwater δ^2H and δ^{18}O

Figure 4 shows the relationship between δ^2H and δ^{18}O in basin groundwater, with a significant linear relationship ($R^2 = 0.83$, $p < 0.001$): $\delta^2H = 4.79\delta^{18}O - 24.31$. The Ebinur Lake region lies in the westerly belt, influenced by monsoons, causing regional groundwater isotope values to deviate from meteoric and surface water lines. According to precipitation stable isotope statistics from Wang et al. on the northern Tianshan slope and Hao et al. in the Ebinur Lake Basin, the northern Tianshan slope meteoric water line is $\delta^2H = 7.51\delta^{18}O + 1.95$, while the basin meteoric water line is $\delta^2H = 6.69\delta^{18}O - 6.53$. The arid climate with low air humidity causes strong sub-cloud evaporation of precipitation, plus mixing of local recycled water vapor, leading to kinetic fractionation of isotopes in precipitation.

The groundwater δ^2H-δ^{18}O relationship line lies above both the northern Tianshan slope meteoric water line and basin meteoric water line, with smaller slope and intercept, and negative intercept, indicating groundwater receives precipitation recharge while experiencing some evaporation enrichment, consistent with studies in the arid Shiyang River Basin. Bortala River groundwater basically lies on the basin meteoric water line, indicating precipitation as the main source. Jing River groundwater lies above the basin meteoric water line, suggesting different evaporation fractionation during precipitation recharge compared to the Bortala River. Bortala and Jing River groundwater near the basin surface water line indicates surface water recharge influence, with main sources being surface water and precipitation. Groundwater around Ebinur Lake lies above the basin meteoric water line, with some on the extension of the surface water line, indicating snow/ice melt and precipitation sources, with partial surface water recharge.

3.2.2 Analysis of Groundwater Influencing Factors

Based on average values in surface water exchange zones and the recharge rate formula, calculations show surface water recharge rates of 79.7% and precipitation recharge rates of 20.3% for the middle and lower reaches of the Bortala and Jing Rivers. For river-lake confluence zones, surface water recharge is 93.9% and precipitation recharge is 6.1%. These results are higher than Hao et al.' s calculations, mainly due to large seasonal irrigation return flow, possibly also from differences between reference precipitation and actual sampling times. Lower correlation between groundwater isotopes and TDS indicates that surface water and precipitation recharge have greater influence on isotopic content than TDS content.

The most enriched groundwater sample had δ^{18}O = -3.70‰ and TDS = 96.81 mg $\cdot$ L^{-1}, while the most depleted had δ^{18}O = -12.97‰ and TDS = 94.87 mg $\cdot$ L^{-1}. According to Rayleigh fractionation, the remaining water proportion is 96.81%, but this differs significantly from actual TDS variations, indicating other factors influence TDS changes. TDS is mainly controlled by water temperature and rock weathering within the sampling area. The characteristics of high urbanization, developed industry and agriculture, and dense irrigation facilities are similar to studies on intensive agricultural impacts in Egypt' s Nile Basin. Irrigation return flow may explain evaporative enrichment of groundwater isotopic characteristics. Downstream groundwater d-excess fluctuations may result from deeper wells (100 m) with less surface water exchange and weaker evaporation fractionation.

3.2.3 Variation of Groundwater d-excess Along Flow Path

Figure 6 shows spatial variation of d-excess from upstream to downstream in the Bortala and Jing River basins. Upper Bortala River groundwater has higher d-excess, remaining relatively stable, while lower reaches show fluctuations. Middle and lower Jing River groundwater d-excess gradually decreases along the flow path but remains higher than the Bortala River middle and lower reaches, reflecting isotopic differences due to different distances from Ebinur Lake, consistent with Jing River surface water isotope characteristics. Lower d-excess indicates evaporative enrichment of recharging groundwater. According to recharge rate calculations, frequent groundwater recharge occurs from evaporatively enriched surface water.

3.3.1 Hydrochemical Characteristics and Variation in Different Regions

Except for sample ABH12 (pH = 6.39), basin groundwater pH ranged 6.78-9.23, averaging 7.81, indicating weak alkalinity. Except near ABH12, basin groundwater salinity approached $1\ \mathrm{dS \cdot m^{-1}}$. Mean values show all hydrochemical indicators around Ebinur Lake exceed those in the Bortala and Jing River basins. Minimum and maximum values indicate greater variation ranges around Ebinur Lake than in the Bortala and Jing River basins (Table 2).

Along-flow variations (Figure 7) show significant differences between upper Bortala River groundwater ($\mathrm{EC} < 200\ \ \mathrm{S \cdot cm^{-1}}$) and middle/lower reaches ($\mathrm{EC} > 200\ \ \mathrm{S \cdot cm^{-1}}$). Ebinur Lake surrounding groundwater shows the strongest EC variation range, followed by the Bortala River, then the Jing River. Combined with isotopic characteristics, close surface water-groundwater exchange occurs in middle/lower reaches and river-lake confluence zones, with significant human activity impacts from surrounding farmland irrigation, making these critical areas for groundwater protection and remediation.

3.3.2 Groundwater Flow Characteristics in Different Regions

Based on studies by Zhu and Lei, except for individual points, surface water δ^2H and δ^{18}O in the Jing and Bortala Rivers gradually become enriched from upstream to downstream, indicating groundwater and surface water flow in the same direction. According to d-excess variation characteristics, combined with hydrochemical indicator ranges, the basin can be divided into two different flow systems (Table 3). Flow system I has groundwater depths of 30-260 m, EC of $210.00\text{-}2500.00\ \ \mathrm{S \cdot cm^{-1}}$, and d-excess of 6.47‰-9.70‰. Flow system II has groundwater depths of 15-100 m, EC of $141.60\text{-}5260.00\ \ \mathrm{S \cdot cm^{-1}}$, and d-excess of 9.61‰-17.45‰. These systems likely belong to hydraulically different flow systems. Flow system I has smaller d-excess range and shallower wells, while flow system II has larger d-excess range and deeper wells, indicating different hydrogeochemical environments and limited lateral connectivity due to aquifer system heterogeneity and anisotropy.

4. Conclusions

This study combined linear regression, two-end-member mixing models, and spatial analysis to analyze spatial heterogeneity of groundwater hydrogen-oxygen isotopes and hydrochemistry in the Ebinur Lake Basin, discussing recharge characteristics and influencing factors, revealing flow system features of regional aquifers.

(1) Spatial heterogeneity exists in groundwater hydrogen-oxygen isotopes across different basin regions. Overall, maximum δ^2H and δ^{18}O values occur in the middle and lower reaches of the Bortala and Jing Rivers, moderate values around Ebinur Lake, and minimum values in the upper

Bortala River area, indicating basin groundwater is mainly affected by recharge sources and water-rock interactions. Horizontally, Bortala and Jing River basin groundwater shows clustering characteristics, while Ebinur Lake surrounding groundwater shows differentiation. Vertically, d-excess shows no depth effect.

(2) Different recharge mechanisms and characteristics exist in different basin regions. The slope and intercept of the groundwater δ^2H-δ^{18}O relationship line are smaller than both the northern Tianshan slope meteoric water line and basin meteoric water line, indicating groundwater experiences some evaporation fractionation. Combined with regional d-excess characteristics, upper Bortala River groundwater is mainly recharged by glacial/snowmelt water. Middle and lower Bortala and Jing River groundwater mainly originates from surface water and precipitation, significantly influenced by rock formation properties, farmland development, and irrigation measures. Ebinur Lake surrounding groundwater mainly comes from snow/ice melt and precipitation, with partial surface water recharge. Based on d-excess variation characteristics, middle and lower reaches and river-lake confluence zones are critical areas for groundwater protection and remediation.

(3) Significant along-flow variations exist in regional groundwater hydrochemical characteristics. Combined with hydrogen-oxygen stable isotope differences, basin groundwater can be divided into two different flow systems. Flow system I has EC of 210.00–2500.00 $\mathrm{S \cdot cm^{-1}}$ and d-excess of 6.47‰–9.70‰, while flow system II has EC of 141.60–5260.00 $\mathrm{S \cdot cm^{-1}}$ and d-excess of 9.61‰–17.45‰, indicating different hydraulic connections in aquifers.

This study effectively revealed groundwater characteristics in the Ebinur Lake Basin based on existing data. However, to further clarify multi-source recharge zones and methods and vertical differentiation patterns in such large-scale aquifer systems, hydraulic calculations are needed to verify our results. Future work should revisit these sampling points, increase sample numbers, and utilize multiple isotope tracers to clarify intra-annual and inter-annual differentiation characteristics of groundwater isotopic hydrochemistry, providing theoretical support for inter-basin water transfer, water rights, inflow allocation, and watershed management in arid and semi-arid regions.

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