Hydrochemical characteristics and transformation relationships between different water bodies in the Qixing Lake region of the Hobq Desert, China Postprint

Authors: XI Cheng, YAN Min, Hejun Zuo, LIU Ruimin, ZUO Hejun

Date: 2025-11-17T00:00:00+00:00

Abstract

Desert lakes are an important link in the water cycle and an important reservoir of water resources in arid and semi-arid areas, playing an important role in maintaining the stability of the regional natural environment. However, studies on the hydrochemical evolution and transformation relationships between desert lake groups and potential water sources are limited. Taking the Qixing Lake, the only lake group within the Hobq Desert in China, as the area of interest, this study collected samples of precipitation water, Yellow River water, lake water, and groundwater at different burial depths in the Qixing Lake region from July 2023 to October 2024. The hydrochemistry of different water bodies was analyzed using a combination of Piper diagrams, Gibbs diagrams, ratio of ions, and MixSIAR mixing models to reveal the transformational relationships of lake water with precipitation, groundwater, and Yellow River water. Results showed that both groundwater and surface water in the study area are weakly-to-strongly alkaline, with HCO3-as the dominant anion and Na+, Ca2+, and K+ as the main cations. The hydrochemical type of groundwater and some lakes was dominated by HCO3--Na+, whereas that of other lakes was dominated by Cl--Na+ and HCO3--Mg2+. The hydrochemistry of groundwater and Yellow River water in the Qixing Lake region was controlled mainly by a combination of evaporite saline and silicate rock mineral dissolution. The local meteoric water line (LMWL) of the study area proved that regional water bodies are strongly affected by evaporative fractionation. The MixSIAR model revealed that shallow groundwater is the main recharge source of the lake group in the Qixing Lake region, accounting for 59.0%-64.2% of the total. The findings can provide references for the identification of water sources in desert lakes and the development and utilization of water resources in desert lake regions.

Full Text

Preamble

Journal of Arid Land (2025) 17(11): 1604-1622
doi: 10.1007/s40333-025-0066-y; CSTR: 32276.14.JAL.0250066y
Science Press Springer-Verlag

Hydrochemical Characteristics and Transformation Relationships Between Different Water Bodies in the Qixing Lake Region of the Hobq Desert, China

XI Cheng[1], YAN Min[1], ZUO Hejun[1],[2]*, LIU Ruimin[1]
[1] College of Desert Control Science and Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China
[2] State Key Laboratory of Water Engineering Ecology and Environment in Arid Area, Inner Mongolia Agricultural University, Hohhot 010018, China

Abstract: Desert lakes constitute a critical link in the water cycle and serve as important water resource reservoirs in arid and semi-arid regions, playing a vital role in maintaining regional environmental stability. However, research on hydrochemical evolution and transformation relationships between desert lake groups and their potential water sources remains limited. This study examined the Qixing Lake group—the only lake system within China' s Hobq Desert—by collecting samples of precipitation, Yellow River water, lake water, and groundwater at various depths from July 2023 to October 2024. Hydrochemical characteristics were analyzed using Piper diagrams, Gibbs diagrams, ion ratios, and MixSIAR mixing models to reveal transformation relationships between lake water and precipitation, groundwater, and Yellow River water. Results showed that both groundwater and surface water in the study area were weakly to strongly alkaline, with HCO_3^- as the dominant anion and Na^+, Ca^{2+}, and K^+ as the main cations. The hydrochemical type of groundwater and some lakes was dominated by HCO_3^--Na^+, while other lakes exhibited Cl^--Na^+ and HCO_3^--Mg^{2+} types. Hydrochemistry in the Qixing Lake region was controlled primarily by combined evaporite saline and silicate rock mineral dissolution. The local meteoric water line (LMWL) demonstrated that regional water bodies are strongly affected by evaporative fractionation. The MixSIAR model revealed that shallow groundwater is the main recharge source for the lake group, accounting for 59.0%-64.2% of the total. These findings provide references for identifying water sources in desert lakes and for developing and utilizing water resources in desert lake regions.

Keywords: hydrochemical type; cation exchange; stable isotope; MixSIAR model; desert lake sources; Qixing Lake

Citation: XI Cheng, YAN Min, ZUO Hejun, LIU Ruimin. 2025. Hydrochemical characteristics and transformation relationships between different water bodies in the Qixing Lake region of the Hobq Desert, China. *Journal of Arid Land*, 17(11): 1604-1622. https://doi.org/10.1007/s40333-025-0066-y;

https://cstr.cn/32276.14.JAL.0250066y

1 Introduction

Water is a fundamental resource for human survival and all living organisms [?]. Water scarcity and the resulting environmental crisis represent major global challenges, particularly in arid regions [?]. China is among the countries most severely affected by desertification, where the disparity between water supply and demand is increasingly pronounced, and water shortage and pollution problems are becoming ever more serious and complex [?, ?]. In arid and semi-arid areas, transformation between precipitation, surface water, and groundwater constitutes a critical process in the hydrological cycle and a prerequisite for watershed-scale water resource management and protection [?]. As essential components of the water cycle and important water reservoirs, lakes exhibit high ecological vulnerability and value, making the sustainable development and utilization of lake water resources crucial for regional socioeconomic development [?].

China possesses numerous lakes with wide distribution and diverse types. Desert lakes represent a unique category that plays an important role in maintaining and enhancing the natural environment of desert areas [?, ?]. In arid regions with dry climates, high evapotranspiration, and limited effective precipitation recharge, lakes can form without surface or subsurface runoff connections to the ocean or direct hydraulic links to other catchments, establishing independent water circulation systems essential for their long-term existence. Numerous studies have investigated desert lake formation and evolution, yielding substantial results regarding water level and area dynamics [?], salinization processes [?], climate impacts [?], and water cycle mechanisms [?], providing scientific foundations for lake protection and management in arid zones. However, due to limited recent monitoring data, research on water environments and lake evolution in arid regions has focused primarily on individual large and medium-sized lakes.

Most lakes in arid areas are closed systems representing the lowest drainage datum in basin plains. Consequently, such lakes receive recharge from precipitation, surface runoff, and subsurface runoff, with evaporation serving as the sole discharge mechanism when no outflow exists [?]. The Badain Jaran Desert in China contains numerous lakes and represents an active research area for desert lake studies. Under extremely arid conditions, intense evaporation significantly influences lake water levels and hydrochemistry, while groundwater recharge constitutes a critical factor sustaining the characteristic sand dune-lake landscape [?]. Moreover, lake groups affect regional groundwater circulation patterns and recharge intensity [?]. Variations in recharge processes among Badain Jaran Desert lakes lead to marked hydrochemical differences due to diverse hydrodynamic conditions, aquifer characteristics, and flow paths [?, ?], resulting in a lack of consensus regarding qualitative explanations of lake water sources.

Lakes interact with groundwater and other potential recharge sources to varying degrees [?]. The hydrochemical composition of natural water bodies reflects long-term interactions between water and its surroundings, providing records of formation, transport, and transformation pathways. Stable hydrogen (δD) and oxygen (δ^{18}O) isotopes are influenced by evaporative fractionation, condensation, and mixing, allowing identification of water sources through their characteristic isotopic signatures and relatively stable concentrations. Consequently, the combined application of hydrochemistry and stable isotope tracer techniques offers an effective approach for understanding complex hydrological processes in desert lakes [?]. However, few studies have investigated hydrochemical evolution and transformation relationships in desert lake groups using combined hydrochemical and isotopic approaches, leaving understanding of inter-lake differences unclear.

The Hobq Desert in China represents a desert system influenced by both monsoon activity and the Yellow River, with Qixing Lake being the only lake group distributed within it [?]. As a sensitive indicator of regional environmental change and human-natural environment interactions, Qixing Lake is located in an arid area with minimal precipitation, strong evaporation, and no natural surface runoff recharge. Due to insufficient water environment monitoring capacity and inadequate systematic information, the current status of the water environment and water cycle characteristics of Qixing Lake remain unclear. Additionally, the Yellow River forms the northern boundary of the Hobq Desert and lies only approximately 10 km from Qixing Lake, which has a higher elevation than the river. This raises critical questions: Does the Yellow River laterally recharge Qixing Lake? Is there a hydraulic connection between them? Under intense evaporative wind and sandy conditions, what water sources sustain Qixing Lake over long periods, and in what proportions? Currently, studies on hydrochemical types and transformation relationships among different water bodies in the Qixing Lake region are lacking. Therefore, it is crucial to determine whether the Yellow River actually recharges Qixing Lake, the rate of contribution, and the relationships between Qixing Lake and the Yellow River as well as other water bodies.

This study employed hydrochemical and stable isotope analysis methods to investigate the hydrochemical characteristics of Qixing Lake and elucidate complex transformation relationships among different water bodies. The findings can help reveal the hydrological, hydrophysical, and hydrochemical significance of desert lakes exemplified by Qixing Lake, providing resources to support sustainable development, utilization, ecological protection, and restoration of desert lakes and wetlands.

2.1 Study Area

The Hobq Desert [Figure 1a: see original paper] is located in Ordos City, Inner Mongolia Autonomous Region, China, forming an active sand sea in the semi-arid areas of northern China. It extends approximately 370 km from west to east and 15–50 km from north to south, forming a long narrow band covering an area of 17,300 km^2. The sand dunes of the Hobq Desert almost entirely cover the Yellow River terrace on the northern edge of the Ordos Plateau, with terrain rising in a step-like fashion from north to south. The Inner Mongolia section of the Yellow River Basin represents an important sand source area for regional sandstorms and dust storms and constitutes the main sediment source for the middle and lower reaches of the Yellow River. The Yellow River also forms the northern boundary of the Hobq Desert, representing an important water source supporting oasis existence at the desert edge and ecological construction.

The Hobq Desert Qixing Lake Ecotourism Zone, also known as Hobq National Desert Park, is a national 4A-level desert ecotourism resort located in Duguitala Town, Hanggin Banner, Ordos City. The park contains seven lakes: Dadaotu Lake (DDT), Zhangjinao Lake (ZJN), Zhahandaotu Lake (ZHDT), Wuritu Lake (WRT), Yueliangshen Lake (YLS), Naren Lake (NR), and Yikeershen Lake (YKES). These lakes collectively form the Qixing Lake group, the only lake system within the Hobq Desert. This study focused on the Qixing Lake region (40°37 40 -40°48 00 N, 108°15 00 -108°36 00 E), which lies in the transition zone between arid and semi-arid areas and experiences a typical temperate continental monsoon climate with annual average precipitation of 250 mm and annual average evaporation of 2100–2955 mm.

Based on aquifer lithological characteristics and groundwater storage and hydrodynamic conditions, the main groundwater recharge sources in the study area include infiltration from atmospheric precipitation, back-seepage from agricultural irrigation water (Yellow River), and lateral runoff from the desert interior in the core area of the southern Hobq Desert. Primary discharge modes include groundwater evaporation and subsurface runoff discharge. Hanggin Banner belongs to the Ordos Plateau, where rock formations are nearly horizontal with a slight northward dip at a regional dip angle of approximately 1° [Figure 1b: see original paper]. Due to the monoclinic water storage structure limiting the study area, groundwater generally flows from south to north, ultimately discharging to the Yellow River. During runoff, groundwater discharges to the surface and gullies through submerged aquifers or pools into lakes in low-lying areas through strong evaporation, representing the main regional discharge pathway. The Yellow River water and groundwater maintain a close mutual recharge-discharge relationship. Qixing Lake is located on the alluvial plain on the south bank of the Yellow River, with groundwater types consisting of unconsolidated rock pore water and confined water [**?**]. The Yellow River alluvial plain consists of gray-yellow fine sand and silt from the Quaternary Holocene, with the aquitard located at 50–80 m depth [Figure 1c: see original paper] composed of sandy clay. The mineral composition of soil in the Qixing Lake region is primarily quartz, followed by feldspar, calcite, muscovite, and chlorite, with low dolomite and tremolite content [**?**].

2.2.1 Sampling Methods

Categorical sampling was conducted from July 2023 to October 2024 across major water bodies in the study area, collecting a total of 36 water samples [Figure 2: see original paper]: 3 Yellow River samples (one every 15 km upstream, designated YR1-3), 7 precipitation samples (PP1-7, collected on 11 July 2023, 3 August 2023, 25 August 2023, 2 October 2023, 24 April 2024, 4 August 2024, and 17 October 2024), 5 groundwater samples (3 in Daotu village, GW-DT1-3, at depths of 17, 80, and 300 m; 2 in Dalatu village, GW-DLT1-2, at depths of 16 and 120 m), and 21 Qixing Lake samples (3 from each of the 7 lakes: DDT1-3, WRT1-3, ZJN1-3, ZHDT1-3, YLS1-3, NR1-3, and YKES1-3). Based on hydrogeological conditions, this study classified groundwater above the aquitard at depths of 16 and 17 m as shallow groundwater, and groundwater below the aquitard at depths of 80, 120, and 300 m as deep groundwater. All samples were collected by rinsing polyethylene bottles three times with raw water before filling, sealing the mouths with Parafilm M, and preserving them for laboratory analysis.

2.2.2 Measurement Methods

A portable conductivity water parameter meter (EASY Probe30; Water Land, Beijing, China) measured in-situ pH and total dissolved solids (TDS). Laboratory analysis using an ion chromatograph (ICS-600; Thermo Fisher, Waltham, USA) determined concentrations of Cl^-, SO_4^{2-}, F^-, K^+, Na^+, Ca^{2+}, and Mg^{2+}, with absolute relative errors for total anions and cations less than 5.0%. HCO_3^- concentration was determined by hydrochloric acid titration with three replicate tests per sample (average error <5.0%), using the average value. A high-precision liquid water isotope analyzer (L2130-i/L2140-i; Picarro, Santa Clara, USA) determined δD and $\delta^{18}O$ with accuracies of \$±\$0.40‰ and \$±\$0.10‰, respectively. Isotopic compositions were expressed conventionally as δsample (‰), representing the per mil deviation from V-SMOW, calculated as: δsample = (Rsample -Rstandard)/Rstandard × 1000‰, where Rsample is the $^2H/^1H$ (or $^{18}O/^{16}O$) ratio in water samples and Rstandard is the corresponding ratio in standard samples.

2.2.3 Analysis Methods

Gibbs (1970) classified natural water hydrochemical fractions into three controlling endmembers—rock weathering, atmospheric precipitation, and evaporation concentration—by plotting TDS against $Na^+/(Na^++Ca^{2+})$ and $Cl^-/(Cl^-+HCO_3^-)$. Gibbs diagrams help qualitatively determine hydrochemical composition influencing factors and are widely used in water body formation mechanism studies. This study employed Gibbs diagrams to identify main controlling factors for lake and other water body hydrochemistry. Piper diagrams facilitate water quality result analysis and comparison for improved understanding of hydrogeochemical processes [?].

Chlor-alkali indices (CAI-I and CAI-II) characterize cation exchange direction and strength [?, ?]. Positive values indicate reverse cation exchange ($Na^+ + CaX \rightarrow Ca^{2+} + Na_2X$, where X is the anion), where Na^+ and K^+ in groundwater exchange with Ca^{2+} and Mg^{2+} in soil. Negative values indicate cation exchange adsorption ($Na_2X + Ca^{2+} \rightarrow 2Na^+ + CaX$), where Ca^{2+} and Mg^{2+} in groundwater exchange with soil cations. Absolute values represent exchange strength. The indices were calculated as:

$\text{CAI-I} = [Cl^- -(Na^+ + K^+)]/Cl^-$
$\text{CAI-II} = [Cl^- -(Na^+ + K^+)]/(SO_4{}^{2-} + HCO_3{}^- + NO_3{}^-)$

The $[(Na^+ + K^+)\text{-}Cl^-]$ versus $[(Ca^{2+} + Mg^{2+})\text{-}(HCO_3{}^- + SO_4{}^{2-})]$ relationship indicates cation exchange adsorption occurrence. A linear relationship with slope near -1 suggests cation exchange adsorption. The $[(Na^+ + K^+)\text{-}Cl^-]$ term represents Na^+ changes from dissolution of substances other than rock salt, while $[(Ca^{2+} + Mg^{2+})\text{-}(HCO_3{}^- + SO_4{}^{2-})]$ represents Ca^{2+} and Mg^{2+} changes from dissolution of substances other than gypsum, calcite, and dolomite [?].

To analyze major ion sources and clarify hydrochemical evolution, this study utilized Ca^{2+}, Na^+, and $HCO_3{}^-$ relationships to determine ion sources during the water cycle, employed Na^+ versus Cl^- relationships to reveal rock salt dissolution sources, used $Ca^{2+}+Mg^{2+}$ versus $HCO_3{}^-$ relationships to determine Ca^{2+} and Mg^{2+} sources, and applied $Ca^{2+}+Mg^{2+}$ versus $HCO_3{}^-+SO_4{}^{2-}$ relationships to analyze participation of carbonic and sulfuric acids in carbonate rock dissolution [?, ?].

The deuterium excess (d-excess) parameter characterizes evaporation process disequilibrium and deviation from global atmospheric precipitation isotopic fractionation, defined as the intercept when LMWL slope equals 8.00 [?]. This study used Bayesian mixture model identification to calculate multiple source contributions to mixtures. The MixSIAR Bayesian mixture model quantitatively determines potential water source contributions, combining latest MixSIR and SIAR research results to provide more accurate source contribution estimates through source data type selection, fixed/random effects, error terms, and prior distributions. The model incorporates uncertainties from various isotopic compositions, multiple sources, and discrimination factors. Convergence must be determined before accepting final output; this study used Gelman–Rubin and Geweke diagnostic tests [?, ?, ?], expressed as:

$N\ \lambda\ \tau$

where Xij is the j-isotope value of mixture i (i = 1, 2, ···, n; j = 1, 2, 3, ··· , m); Pk is the contribution of source k (k = 1, 2, ···, K); Sjk is the j-isotope value of source k, normally distributed with mean (jk) and variance (ωjk^2); Cjk is the fractionation factor of source k in the j-isotope, expressed as mean (λjk) and standard deviation (τjk^2); and ij is the residual error of additional non-quantified differences, expressed as mean (0) and standard deviation (σj^2).

As Qixing Lake region lakes are closed systems without surface runoff recharge,

recharge occurs primarily through precipitation and groundwater, with evaporation as the sole discharge mechanism. Based on water balance principles, lake group water balance can be expressed as: $dV/dt = P + G - E$, where V is lake water volume (m^3), t is time, dV is volume change over dt, P is precipitation recharge (m^3), G is groundwater recharge (m^3), and E is evaporation (m^3). This study used Yan et al. (2024) methods to extract lake area parameters and calculated lake changes during the pre-sampling period (2018–2020). Regional precipitation and evapotranspiration data were obtained from the China Meteorological Data Center (https://data.cma.cn), with 3-year averages of 312 mm and 1232 mm, respectively.

3.1.1 Characterization of Hydrochemistry

Hydrochemical and hydrogen-oxygen isotope compositions of surface water and groundwater are detailed in Table 1 . pH and TDS varied considerably among water bodies, with marked differences in ionic composition. The dominant anion in Yellow River water, Qixing Lake water, and regional groundwater was HCO_3^-. The dominant cation in Yellow River water, regional groundwater, and lakes DDT, WRT, ZJN, ZHDT, and YKES was Na^+; YLS water was dominated by Ca^{2+}; and NR water by K^+. Yellow River water averaged pH 7.57 (neutral to weakly alkaline). Among lakes, ZJN was most alkaline (mean pH 10.63), YKES least alkaline (pH 8.65), and other lakes ranged 8.89–10.40. ZHDT showed highest TDS (mean 8550.0 mg/L), followed by WRT, DDT, and ZJN (1640.9–3081.8 mg/L), likely due to large surface areas with strong evaporation and limited recharge. YLS, NR, and YKES had lower TDS (~400.0 mg/L), closer to groundwater values, suggesting stronger groundwater recharge capacity. Groundwater showed low mineralization except GW-DLT2, with pH ranging 8.28–8.99. TDS in ZHDT, WRT, DDT, and ZJN lake water substantially exceeded groundwater values, indicating stronger surface water-rock interactions and higher soluble salt content [**?**].

Piper diagrams showed that water chemical ion distributions in different surface water bodies and groundwater concentrated in the diamond-shaped area [Figure 3: see original paper], indicating relatively consistent ion sources and close interconnections. Hydrochemical types were HCO_3^--Na^+ for Yellow River water, GW-DT1, GW-DT3, GW-DLT1-2, DDT, and ZJN; HCO_3^--Mg^{2+} for GW-DT2; Cl^--Na^+ for ZHDT; Cl^--Mg^{2+} for WRT; and HCO_3^--K^+ for YLS, NR, and YKES. In arid inland basins, groundwater ultimately discharges to salt lakes representing regional groundwater flow system termini [**?**]. ZHDT and WRT showed high average TDS (8550.0 and 3081.8 mg/L), consistent with this groundwater flow system modeling. Higher lake water mineralization compared to river and groundwater likely results from strong lake water evaporation causing salt accumulation. Through Ca and Mg mineral precipitation and cation replacement adsorption, Na^+ became the dominant lake water ion. Hydraulic connection between HCO_3^--Na^+ type groundwater and higher salinity Cl^--Na^+ type lake water through evaporation and concentration confirmed groundwater as a lake recharge source [?], where groundwater transports salts into lakes that subsequently evaporate, leaving salt aggregates.

3.1.2 Identification of Factors Controlling Hydrochemistry in Different Water Bodies

Rock weathering dominated hydrochemistry for Yellow River water, most groundwater, and YKES, NR, and YLS [Figure 4: see original paper]. ZHDT hydrochemistry was controlled by evaporation. Data points for WRT, DDT, and ZJN fell in the transition zone between evaporation-concentration and rock-weathering endmembers, consistent with these lakes' distribution in arid areas with strong evapotranspiration and groundwater recharge dominance under arid and semi-arid climates [?]. Overall, rock weathering controlled hydrochemical formation processes for all Qixing Lake region water bodies, while atmospheric precipitation effects were weak.

CAI-I and CAI-II values were negative for Yellow River water, lake water, and all groundwater samples [Figure 5: see original paper], indicating cation exchange adsorption as the main exchange type. Exchange of Na^+ and K^+ in rocks with Ca^{2+} and Mg^{2+} in water bodies increased Na^+ and K^+ while decreasing Ca^{2+} and Mg^{2+} in lake water and groundwater. The $[(Na^++K^+)-Cl^-]$ versus $[(Ca^{2+}+Mg^{2+})-(HCO_3{}^-+SO_4{}^{2-})]$ relationship for ZHDT deviated markedly from the theoretical -1 value, as Na^+, Ca^{2+}, and Mg^{2+} contents were also affected by Na and K feldspar dissolution and carbonate dissolution equilibrium effects [?].

3.1.3 Ion Source Analysis of Different Water Bodies

Data points for lake water, Yellow River water, and groundwater clustered near the silicate rock control endmember, indicating silicate mineral influence [Figure 6a: see original paper]. ZHDT and WRT points were slightly closer to the evaporation control endmember. Na^+/Cl^- ratios near 1 for most lakes (DDT, ZHDT, WRT, YLS, YKES) and Yellow River water indicated minimal anthropogenic disturbance [Figure 6b: see original paper]. Most groundwater and DDT, WRT, and ZJN water points plotted below the $(Ca^{2+}+Mg^{2+})/HCO_3{}^- = 1:1$ line [Figure 6c: see original paper], showing Ca^{2+} and Mg^{2+} depletion through cation exchange. No points plotted above the $(Ca^{2+}+Mg^{2+})/(HCO_3{}^-+SO_4{}^{2-}) = 1:1$ line [Figure 6d: see original paper], suggesting $SO_4{}^{2-}$ did not originate from gypsum dissolution in carbonate strata. Most groundwater points fell below this line, indicating $Ca^{2+}+Mg^{2+}$ concentrations were less than $HCO_3{}^-+SO_4{}^{2-}$ concentrations.

Generally, Na^+ and K^+ originate from atmospheric deposition, silicate mineral dissolution, and evaporite salt mineral dissolution, with rock salt dissolution releasing equal Na^+ and Cl^- concentrations [?, ?]. Except for Yellow River water, no samples plotted above the $Ca^{2+}+Mg^{2+}$ versus $HCO_3{}^-$ 1:1 line, indicating Ca^{2+} and Mg^{2+} did not derive from carbonate dissolution and that minimal carbonic, sulfuric, or nitric acid participated in carbonate rock dissolution [?]. The Ca^{2+}+Mg^{2+} concentration being less than HCO_3^-+SO_4^{2-} suggests SO_4^{2-} may originate from sulfide mineral dissolution in loess layers around the Yellow River, consistent with regional geochemical background [?].

3.2.1 Characteristics and Indicative Significance of Precipitation Equivalent Curves for Different Water Bodies

The study area LMWL was determined as $\delta D = 6.84\delta^{18}O + 1.38‰$ [Figure 7a: see original paper], compared to the global meteoric water line (GMWL) $\delta D = 8.00\delta^{18}O + 10.00‰$ [?]. The Qixing Lake region LMWL slope of 6.84 was smaller than the GMWL slope (8.00). Pei et al. (2023) reported a LMWL slope of 5.94 in the Hetao area of the Yellow River Basin; although Qixing Lake lies within this area, the Hetao study sites include several mountainous arid areas, resulting in a smaller slope. The Yinchuan area upstream of Qixing Lake had slightly better precipitation conditions with a LMWL slope of 7.21 [?]. These results indicate that atmospheric precipitation in the Qixing Lake region has undergone strong evapotranspiration, consistent with the local drought and low-rainfall environment [?].

Qixing Lake water d-excess ranged from -50.18‰ to -14.59‰ (mean -27.03‰) [Figure 7b: see original paper]. Groundwater d-excess ranged 0.92‰-3.70‰ (mean 2.01‰), and Yellow River water ranged 1.94‰-3.32‰ (mean 2.42‰) . Due to shallow groundwater depth and close hydraulic connection with Yellow River water, water-rock interaction continuously enriched $\delta^{18}O$ values during runoff while δD remained largely unchanged, resulting in some groundwater samples having d-excess <10.00. Negative d-excess in Qixing Lake region revealed secondary evapotranspiration effects on isotopic composition [?, ?]. Lake water TDS increased with decreasing d-excess, showing negative correlation (d-excess = -0.002TDS -22.91, $R^2 = 0.24$). WRT showed smallest d-excess, while ZHDT had largest TDS, possibly due to nearby agricultural and livestock operations. Excluding ZHDT strengthened the negative correlation (d-excess = -0.010TDS -13.41, $R^2 = 0.92$). During the water cycle, hydrogen and oxygen isotopes mix and exchange; strong evaporation causes kinetic isotope fractionation, decreasing d-excess to negative values while salts gradually accumulate [?, ?]. These d-excess results suggest that strong evapotranspiration in arid areas is an important mechanism driving desert lake salinization.

3.2.2 Water Cycle Indicated by δD and $\delta^{18}O$ in Different Water Bodies

The $\delta^{18}O$-δD relationship provides a reliable indicator for water source analysis [?, ?]. Precipitation isotope composition varies little over certain ranges, allowing LMWL representation by a single equation [?, ?]. The Qixing Lake region lake water relationship was $\delta D = 5.18\delta^{18}O -22.42‰$ ($R^2 = 0.98$), with slopes and intercepts smaller than LMWL, indicating surface water evaporative fractionation after precipitation recharge. Yellow River water and groundwater relationships were δD = 7.45δ^{18}O -2.95‰ (R^2 = 0.92) and δD = 7.76δ^{18}O - 0.22‰ (R^2 = 0.98), respectively, indicating most intense surface water evaporation in the Qixing Lake region. The smaller LMWL slope coincides with local drought and low-rainfall vapor conditions. High-latitude precipitation processes experience secondary evaporation, causing notable hydrogen and oxygen isotope fractionation that enriches water vapor δ^{18}O relative to δD, producing low LMWL slopes. Lake water δD averaged -37.83‰ to 12.74‰ and δ^{18}O averaged -2.90‰ to 7.47‰ [FIGURE:7c and d]. Lake water showed enriched δD and δ^{18}O, with highest values in WRT, deviating from other water bodies and indicating highest evaporation capacity. Overall, enriched hydrogen and oxygen isotopes in lake water related to higher evaporation intensity due to open lake environments.

Shallow groundwater isotopic composition reflects overall convective and advective precipitation component proportions, with broader relevance to groundwater isotope-precipitation type relationships [**?**]. Except for GW-DT1, groundwater sample data points distributed relatively concentrated with Yellow River samples [Figure 7a: see original paper], indicating Yellow River control over hydrogen and oxygen isotopic composition and strong hydraulic connection between the groundwater system and Yellow River.

3.3 Transformation Relationships Among Different Water Bodies and Composition of Water Sources Recharging Qixing Lake

Isotopic tracers are generally less affected by water evolutionary processes than hydrochemical methods, allowing better endmember discrimination and clearer mixing process interpretation [**?**, **?**, **?**]. Based on hydrogen and oxygen isotope mass conservation principles and using the Bayesian mixing model, Figure 8 [Figure 8: see original paper] shows Qixing Lake water source composition. Overall, lake water recharge was groundwater-dominated, with total contributions ranging 61.0%-69.2% and averaging 66.8%, with ZHDT receiving the most groundwater recharge.

Groundwater recharge to lakes was dominated by shallow groundwater. As shown in Figure 8b, 16–17 m shallow groundwater contributed 38.7% to lake water, exceeding half of total groundwater recharge, while deep groundwater below the regional aquitard contributed only 6.3%-9.8%. These results indicate that groundwater is the main lake water source, primarily shallow groundwater, consistent with Wang et al. (2017) findings that Ordos region surface and soil water are mainly groundwater-recharged, though without quantified source proportions.

Precipitation recharge to lake water ranged 18.2%-27.7%, averaging 21.2%. Among the seven lakes, YLS, YKES, and NR received slightly more precipitation recharge than the other four lakes, possibly due to smaller lake areas where precipitation effects on water volume are more pronounced. Pei et al. (2023) showed that atmospheric precipitation constitutes the main surface water recharge source (>80.0%) in the Yellow River Basin' s Hetao area, but that study covered a large area with primarily irrigation channels, Yellow River trunk and tributaries, and seasonal rivers, with fewer lake sampling sites. Nevertheless, precipitation occupying certain proportions in the Hetao area provides reference for Qixing Lake group water sources. Other scholars' studies in this and nearby semi-arid areas show precipitation contributions to surface water ranging 19.0%-38.0%, supporting Qixing Lake precipitation recharge [**?**, **?**].

Yellow River recharge to Qixing Lake averaged 12.0%. Among Yellow River recharge proportions at different depths, 16-17 m shallow groundwater received most Yellow River recharge [Figure 8c: see original paper]. We speculate that Yellow River recharge occurs through infiltration first recharging regional shallow groundwater, which then recharges Qixing Lake. Future research should focus on cycling processes among different regional water bodies, sources of different-depth groundwater, and relationships between groundwater at various depths.

Additionally, water balance calculations based on water balance principles showed Qixing Lake received average precipitation recharge of 20.6% ($±$5.7%) , consistent with Bayesian mixing model results. Among seven lakes, YKES received least precipitation recharge, possibly due to greater depth with outcropping springs. Groundwater recharge to Qixing Lake accounted for 75.2%-90.8%, which becomes reasonable when adding Yellow River recharge to groundwater (12.0%) to direct groundwater recharge (66.8%).

4 Conclusions

Through systematic sampling of different water bodies in the Qixing Lake region, this study comparatively analyzed Qixing Lake hydrochemical evolution characteristics and quantified transformation relationships among water bodies using MixSIAR hybrid modeling. In the Qixing Lake region, groundwater and surface water were weakly to strongly alkaline with strong lake water-rock interaction and high soluble salt content. Hydrochemical characteristics of lake water, groundwater, and Yellow River water were controlled mainly by joint evaporite saline and silicate rock mineral dissolution. Sufficient mineral component dissolution occurred in lake water and groundwater, with shallow groundwater serving as the main Qixing Lake recharge source. Future enhanced analysis of lake submerged sediment and groundwater layer sediment hydrochemical composition will help further understand specific ion exchange trajectories and pathways between desert lakes and sediments.

Conflict of Interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

This work was supported by the Inner Mongolia Autonomous Region "Unveiling the List of Commanders" Project (2024JBGS0019), the Inner Mongolia Autonomous Region Graduate Student Research Innovation Project (KC2024036B), the Innovative Team on Desertification Control and Sandy Area Resource Conservation and Utilization (BR241301), and the Desert Sand Ecological Protection and Management Technology Innovation Team (NMGIRT2408).

Author Contributions

Conceptualization: XI Cheng, YAN Min, ZUO Hejun; Data curation: XI Cheng, YAN Min; Methodology: XI Cheng; Formal analysis: YAN Min, LIU Ruimin; Writing - original draft preparation: XI Cheng; Writing - review and editing: YAN Min, ZUO Hejun; Funding acquisition: ZUO Hejun; Investigation: XI Cheng, LIU Ruimin; Resources: YAN Min, ZUO Hejun; Supervision: ZUO Hejun. All authors approved the manuscript.

References

Cao L, Nie Z L, Shen J M, et al. 2022. Stable isotopes reveal the lake shrinkage and groundwater recharge to lakes in the Badain Jaran Desert, NW China. *Journal of Hydrology*, 612: 128289, doi: 10.1016/j.jhydrol.2022.128289.

Chang H K, Gonçalves R D, Aggarwal P K, et al. 2020. Groundwater isotope ratios reflect convective and stratiform (paleo) precipitation fractions in Brazil. *Journal of Hydrology*, 585: 124801, doi: 10.1016/j.jhydrol.2020.124801.

Chen J, Qian H, Gao Y Y, et al. 2020. Insights into hydrological and hydrochemical processes in response to water replenishment for lakes in arid regions. *Journal of Hydrology*, 581: 124386, doi: 10.1016/j.jhydrol.2019.124386.

Chen J S, Li L, Wang J Y, et al. 2004. Groundwater maintains dune landscape. *Nature*, 432(7016): 459–460.

Chen J S, Sun X X, Gu W Z, et al. 2012. Isotopic and hydrochemical data to restrict the origin of the groundwater in the Badain Jaran Desert, Northern China. *Geochemistry International*, 50: 455–465.

Chen P, Wang S, Song S, et al. 2022. Ecological restoration intensifies evapotranspiration in the Kubuqi Desert. *Ecological Engineering*, 175: 106504, doi: 10.1016/j.ecoleng.2021.106504.

Craig H. 1961. Isotopic variations in meteoric waters. *Science*, 133(3465): 1702–1703.

Duan W L, Zou S, Chen Y N, et al. 2020. Sustainable water management for cross-border resources: The Balkhash Lake Basin of Central Asia, 1931–2015. *Journal of Cleaner Production*, 263: 121614, doi: 10.1016/j.jclepro.2020.121614.

Egbi C D, Anornu G K, Ganyaglo S Y, et al. 2020. Nitrate contamination of groundwater in the Lower Volta River Basin of Ghana: sources and related human health risks. *Ecotoxicology and Environmental Safety*, 191: 110227, doi: 10.1016/j.ecoenv.2020.110227.

Farid I, Trabelsi R, Zouari K, et al. 2013. Hydrogeochemical processes affecting groundwater in an irrigated land in Central Tunisia. *Environmental Earth Sciences*, 68: 1215-1231.

Fu C S, Wu H W, Zhu Z C, et al. 2021. Exploring the potential factors on the striking water level variation of the two largest semi-arid-region lakes in northeastern Asia. *CATENA*, 198: 105037, doi: 10.1016/j.catena.2020.105037.

Ge J, Chen J S, Ge L, et al. 2016. Isotopic and hydrochemical evidence of groundwater recharge in the Hopq Desert, NW China. *Journal of Radioanalytical and Nuclear Chemistry*, 310: 761-775.

Gibbs R J. 1970. Mechanisms controlling world water chemistry. *Science*, 170(3962): 1088-1090.

Han D M, Liang X, Jin M G, et al. 2009. Hydrogeochemical indicators of groundwater flow systems in the Yangwu River alluvial fan, Xinzhou Basin, Shanxi, China. *Environmental Management*, 44: 243-255.

Han Y F, Zhai Y Z, Guo M S, et al. 2021. Hydrochemical and isotopic characterization of the impact of water diversion on water in drainage channels, groundwater, and Lake Ulansuhai in China. *Water*, 13(21): 3033, doi: 10.3390/w13213033.

Hao S, Li F D, Li Y H, et al. 2019. Stable isotope evidence for identifying the recharge mechanisms of precipitation, surface water, and groundwater in the Ebinur Lake basin. *Science of the Total Environment*, 657: 1041-1050.

Juan G, Li Z X, Qi F, et al. 2020. Environmental effect and spatiotemporal pattern of stable isotopes in precipitation on the transition zone between the Tibetan Plateau and arid region. *Science of the Total Environment*, 749: 141559, doi: 10.1016/j.scitotenv.2020.141559.

Kumar S, Venkatesh A S, Singh R, et al. 2018. Geochemical signatures and isotopic systematics constraining dynamics of fluoride contamination in groundwater across Jamui district, Indo-Gangetic alluvial plains, India. *Chemosphere*, 205: 561-571.

Li P Y, Wu J H, Qian H. 2013. Assessment of groundwater quality for irrigation purposes and identification of hydrogeochemical evolution mechanisms in Pengyang County, China. *Environmental Earth Sciences*, 69: 2211-2225.

Li X Q, Han G L, Liu M, et al. 2022. Potassium and its isotope behaviour during chemical weathering in a tropical catchment affected by evaporite dissolution. *Geochimica et Cosmochimica Acta*, 316: 105-121.

Luo P P, Sun Y T, Wang S T, et al. 2020. Historical assessment and future sustainability challenges of Egyptian water resources management. *Journal of Cleaner Production*, 263: 121154, doi: 10.1016/j.jclepro.2020.121154.

Luo X, Jiao J J, Wang X S, et al. 2017. Groundwater discharge and hydrologic partition of the lakes in desert environment: Insights from stable $^{18}O/^{2}H$ and radium isotopes. *Journal of Hydrology*, 546: 189–203.

Ma F Y, Chen J Q, Chen J S, et al. 2022. Hydrogeochemical and isotopic evidences of unique groundwater recharge patterns in the Mongolian Plateau. *Hydrological Processes*, 36(5): e14554, doi: 10.1002/hyp.14554.

Mahindawansha A, Külls C, Kraft P, et al. 2020. Investigating unproductive water losses from irrigated agricultural crops in the humid tropics through analyses of stable isotopes of water. *Hydrology and Earth System Sciences*, 24(7): 3627–3642.

Meng Q S. 2023. Spatial distribution of particle size and geochemical characteristics of surface sediments in the hobg desert. MSc Thesis. Hohhot: Inner Mongolia Agriculture University. (in Chinese)

Oza H, Ganguly A, Padhya V, et al. 2020. Hydrometeorological processes and evaporation from falling rain in Indian sub-continent: insights from stable isotopes and meteorological parameters. *Journal of Hydrology*, 591: 125601, doi: 10.1016/j.jhydrol.2020.125601.

Pei S S, Duan L M, Miao P, et al. 2023. Water chemical isotope characteristics and water transformation relationship in Mongolian Section of the Yellow River Basin. *Environmental Science*, 44(9): 4863–4873. (in Chinese)

Piper A M. 1944. A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union*, 25(6): 914–928.

Qin W J, Han D M, Song X F, et al. 2021. Environmental isotopes (δ^{18}O, δ^{2}H, ^{222}Rn) and hydrochemical evidence for understanding rainfall-surface water-groundwater transformations in a polluted karst area. *Journal of Hydrology*, 592: 125748, doi: 10.1016/j.jhydrol.2020.125748.

Qu S, Zhao Y Z, Zhang K Y, et al. 2024. Multi-isotopes (δD, δ^{18}Owater, ^{87}Sr/^{86}Sr, δ^{34}S and δ^{18}Osulfate) as indicators for groundwater salinization genesis and evolution of a large agricultural drainage lake basin in Inner Mongolia, Northwest China. *Science of the Total Environment*, 946: 174181, doi: 10.1016/j.scitotenv.2024.174181.

Samani S, Moghaddam H K, Zareian M J. 2021. Evaluating time series integrated groundwater sustainability: a case study in Salt Lake catchment, Iran. *Environmental Earth Sciences*, 80(17): 603, doi: 10.1007/s12665-021-09888-w.

Stock B C, Jackson A L, Ward E J, et al. 2018. Analyzing mixing systems using a new generation of Bayesian tracer mixing models. *PeerJ*, 6: e5096, doi: 10.7717/peerj.5096.

Subyani A M. 2004. Use of chloride-mass balance and environmental isotopes for evaluation of groundwater recharge in the alluvial aquifer, Wadi Tharad, western Saudi Arabia. *Environmental Geology*, 46: 741–749.

Tantawi M A, El-Sayed E, Awad M A. 1998. Hydrochemical and stable isotope study of groundwater in the Saint Catherine-Wadi Feiran area, south Sinai, Egypt. *Journal of African Earth Sciences*, 26(2): 277-284.

Tay C K, Kortatsi B K, Hayford E, et al. 2014. Origin of major dissolved ions in groundwater within the Lower Pra Basin using groundwater geochemistry, source-rock deduction and stable isotopes of ^{2}H and ^{18}O. *Environmental Earth Sciences*, 71: 507-518.

Tweed S, Leblanc M, Cartwright I, et al. 2011. Arid zone groundwater recharge and salinisation processes; an example from the Lake Eyre Basin, Australia. *Journal of Hydrology*, 408(3-4): 257-275.

Urrutia J, Herrera C, Custodio E, et al. 2019. Groundwater recharge and hydrodynamics of complex volcanic aquifers with a shallow saline lake: Laguna Tuyajto, Andean Cordillera of northern Chile. *Science of the Total Environment*, 697: 134116, doi: 10.1016/j.scitotenv.2019.134116.

Valdivielso S, Vázquez-Suñé E, Custodio E. 2020. Origin and variability of oxygen and hydrogen isotopic composition of precipitation in the Central Andes: A review. *Journal of Hydrology*, 587: 124899, doi: 10.1016/j.jhydrol.2020.124899.

Vystavna Y, Harjung A, Monteiro L R, et al. 2021. Stable isotopes in global lakes integrate catchment and climatic controls on evaporation. *Nature Communications*, 12(1): 7224, doi: 10.1038/s41467-021-27569-x.

Wang H, Ni J, Song Q C, et al. 2021a. Analysis of coastal groundwater hydrochemistry evolution based on groundwater flow system division. *Journal of Hydrology*, 601: 126631, doi: 10.1016/j.jhydrol.2021.126631.

Wang J, Lu N, Fu B J. 2019. Inter-comparison of stable isotope mixing models for determining plant water source partitioning. *Science of the Total Environment*, 666: 685-693.

Wang T, Chen J S, Ge J, et al. 2017. Isotopic evidence of allogenic groundwater recharge in the Northern Ordos Basin. *Journal of Radioanalytical and Nuclear Chemistry*, 314: 1595-1606.

Wang W H, Chen Y N, Wang W R, et al. 2023a. Water quality and interaction between groundwater and surface water impacted by agricultural activities in an oasis-desert region. *Journal of Hydrology*, 617: 128937, doi: 10.1016/j.jhydrol.2022.128937.

Wang Y J, Tang Y, Xu Y, et al. 2021b. Isotopic dynamics of precipitation and its regional and local drivers in a plateau inland lake basin, Southwest China. *Science of the Total Environment*, 763: 143043, doi: 10.1016/j.scitotenv.2020.143043.

Wang Z Y, Su Q, Wang S, et al. 2022. Coupling hydrochemistry and stable isotopes (δ^2H and δ^{18}O) to identify the major factors affecting the hydrochemical evolution of groundwater in the Western Yellow Sea Coast, China. *Applied*

Geochemistry, 138: 105221, doi: 10.1016/j.apgeochem.2022.105221.

Wang Z Y, Xu D Y, Peng D L, et al. 2023b. Future climate change would intensify the water resources supply-demand pressure of afforestation in Inner Mongolia, China. *Journal of Cleaner Production*, 407: 137145, doi: 10.1016/j.jclepro.2023.137145.

Wolf A, Roberts W H, Ersek V, et al. 2020. Rainwater isotopes in central Vietnam controlled by two oceanic moisture sources and rainout effects. *Scientific Reports*, 10(1): 16482, doi: 10.1038/s41598-020-73508-z.

Woolway R I, Kraemer B M, Lenters J D, et al. 2020. Global lake responses to climate change. *Nature Reviews Earth & Environment*, 1(8): 388–403.

Wu H W, Song F, Li J, et al. 2022. Surface water isoscapes (δ^{18}O and δ^{2}H) reveal dual effects of damming and drought on the Yangtze River water cycles. *Journal of Hydrology*, 610: 127847, doi: 10.1016/j.jhydrol.2022.127847.

Wu Y, Wang N A, Zhao L Q, et al. 2014. Hydrochemical characteristics and recharge sources of Lake Nuoertu in the Badain Jaran Desert. *Chinese Science Bulletin*, 59: 886–895.

Xi C, Zuo H J, Yan M, et al. 2024. Grain size characteristics of different types of surface sediments around Qixing Lake in Kubuqi Desert. *Frontiers in Environmental Science*, 12: 1409260, doi: 10.3389/fenvs.2024.1409260.

Xia Z Y, Winnick M J. 2021. The competing effects of terrestrial evapotranspiration and raindrop re-evaporation on the deuterium excess of continental precipitation. *Earth and Planetary Science Letters*, 572: 117120, doi: 10.1016/j.epsl.2021.117120.

Xing L N, Guo H M, Zhan Y H. 2013. Groundwater hydrochemical characteristics and processes along flow paths in the North China Plain. *Journal of Asian Earth Sciences*, 70–71: 250–264.

Yan Y, Zuo H J, Yan M, et al. 2024. Lake number and area in Kubuqi Desert from 1986 to 2020. *Journal of Desert Research*, 44(2): 151-161. (in Chinese)

Yang Q C, Mu H K, Wang H, et al. 2018. Quantitative evaluation of groundwater recharge and evaporation intensity with stable oxygen and hydrogen isotopes in a semi-arid region, Northwest China. *Hydrological Processes*, 32(9): 1130–1136.

Zhang D X, Sial M S, Ahmad N, et al. 2020. Water scarcity and sustainability in an emerging economy: a management perspective for future. *Sustainability*, 13(1): 144, doi: 10.3390/su13010144.

Zhang M M, Wang S, Gao G Y, et al. 2019. Exploring responses of lake area to river regulation and implications for lake restoration in arid regions. *Ecological Engineering*, 128: 18–26.

Zhang Y, Liu W X, Cai Y, et al. 2021. Decoupling analysis of water use and economic development in arid region of China–based on quantity and quality of water use. *Science of the Total Environment*, 761: 143275, doi: 10.1016/j.scitotenv.2020.143275.

Zhao W J, Qian H, Xu P P, et al. 2024. Tracing groundwater-surface water sources and transformation processes in the Ba River Basin through isotopes and water chemistry. *Applied Geochemistry*, 106199, 10.1016/j.apgeochem.2024.106199.

Zhou Y, Dong J W, Xiao X M, et al. 2019. Continuous monitoring of lake dynamics on the Mongolian Plateau using all available Landsat imagery and Google Earth Engine. *Science of the Total Environment*, 689: 366-380.

Zhu G F, Yong L L, Zhang Z X, et al. 2021. Effects of plastic mulch on soil water migration in arid oasis farmland: Evidence of stable isotopes. *CATENA*, 207: 105580, doi: 10.1016/j.catena.2021.105580.

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

Source: ChinaXiv —Machine translation. Verify with original.