Hydrochemical and Isotopic Characteristics of Water Bodies in the Ulungur River Basin and Their Implications: Postprint

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Abstract

Abstract: Hydrochemical and isotopic characteristics serve as important indicators for hydrological processes in different water bodies. Based on hydrochemical and stable isotope test data from different water bodies in the Ulungur River Basin in 2018, this study comprehensively employed methods including mathematical statistics, Gibbs diagrams, ion ratios, and Piper trilinear diagrams to identify the hydrochemical and isotopic characteristics of water bodies in the Ulungur River Basin, and to investigate the hydrochemical formation mechanisms, evolution trends, and water transformation relationships. The results indicate that: river water is influenced by rock weathering, evaporation concentration, and mixing, with a hydrochemical type dominated by HCO3 · SO4-Ca · Na; lake water is controlled by evaporation concentration, with a hydrochemical type of SO4 · Cl-Na; under the combined effects of rock weathering, evaporation concentration, and cation exchange, the hydrochemical type of phreatic water is HCO3 · SO4-Ca · Na and SO4 · HCO3-Na · Ca, while confined water is Cl · SO4-Na type; Piper diagrams of various water bodies indicate that surface water and phreatic water are further evolving toward the Cl · SO4-Na type; the enrichment degree of hydrogen and oxygen stable isotopes in various water bodies follows the order: Ulungur Lake > Jili Lake > river water > phreatic water > confined water; the hydrogen and oxygen stable isotope values of all water bodies are distributed on both sides of the local meteoric water line (δD=6.49$ $18O-8.63), indicating that evaporation and precipitation are the main factors influencing the isotopic characteristics of water bodies; influenced by geological and geomorphological conditions and stratigraphic structure, phreatic water has a close hydraulic connection with river water but a weak connection with confined water; in the study area, recharge is primarily from phreatic water to river water, with localized hydraulic connections existing between confined water and phreatic water.

Full Text

Abstract

Hydrochemical and isotopic characteristics serve as important indicators of hydrological processes in different water bodies. Based on hydrochemical and stable isotope test data from various water bodies in the Ulungur River Basin in 2018, this study employed mathematical statistics, Gibbs diagrams, ion ratio analysis, and Piper diagrams to identify the hydrochemical and isotopic characteristics of basin waters and investigate hydrochemical formation mechanisms, evolution trends, and water transformation relationships. The results indicate that river water chemistry is primarily influenced by rock weathering, evaporation, and mixing, with a hydrochemical type of $HCO_3 \cdot SO_4$-Ca·Na. Lake water chemistry is controlled by evaporation, exhibiting a Cl·SO_4-Na type. Groundwater, under the combined effects of rock weathering, evaporation, and cation exchange, shows phreatic water of $HCO_3 \cdot SO_4$-Ca·Na type and confined water of Cl·SO_4-Na type. Piper diagrams reveal that surface water and phreatic water are evolving toward Cl·SO_4-Na. Isotopic enrichment follows the pattern: Ulungur Lake > Jili Lake > Ulungur River > phreatic water > confined water. Hydrogen and oxygen stable isotope values for all water bodies plot near the local meteoric water line ($\delta D = 6.49\delta^{18}O - 8.63$), indicating that evaporation and precipitation are the main factors controlling isotopic composition. Influenced by geological structure, geomorphology, and stratigraphy, phreatic water maintains close hydraulic connections with river water but weak connections with confined water. The basin is characterized by phreatic water recharging river water, with localized hydraulic linkages between phreatic and confined water.

Keywords: Ulungur River basin; hydrochemistry; stable isotopes; formation mechanism; transformation relationships

1 Study Area Overview

The Ulungur River Basin is located in the Junggar Basin of northwestern China, geographically positioned between 87°00 -90°30 E and 46°08 -47°30 N, with elevations ranging from 470 to 1380 m. The terrain slopes higher in the northeast and lower in the southwest. The region experiences a continental arid to semiarid climate characterized by large diurnal temperature variations, low precipitation, and strong evaporation. Major surface water bodies include the Ulungur River, Ulungur Lake, and Jili Lake. The Ulungur River stretches 821 km with an average annual runoff of 9.9$×10^{8}$ m^3, recharged by snowmelt and rainfall. Due to Neogene uplift in the southern region forming a broad anticline, combined with southeastward subsidence of the Ulungur Lake basin, the river changed course near Fuhai County to its present channel. Ulungur Lake and Jili Lake represent the lowest depressions in the region and serve as the terminal points for the Ulungur River.

The study area comprises a complex anticline sedimentary basin formed by

Mesozoic and Cenozoic strata. Geomorphological units include mid-low mountainous areas, intermontane valley zones, and alluvial plains. In the mid-low mountainous area east of Saertiereke, phreatic water occurs primarily in bedrock fissures. The dense volcanic rocks provide poor aquifer storage capacity. From Saertiereke westward to the two-lake region, phreatic water is hosted in Quaternary sediments within intermontane valleys and alluvial plains, with lithology transitioning from gravel to medium-coarse sand, fine sand, and clayey sand. Phreatic water depth increases gradually from 3–8 m to 5–20 m from west to east. The eroded hilly areas north and south of the Quaternary-covered region consist of wind-eroded platforms, ridges, and ancient planation surfaces with extremely poor water abundance. Confined water is widely distributed beneath Tertiary strata across the basin (except in mid-low mountains), with lithology dominated by calcareous sandstone and tuffaceous breccia. Borehole and geophysical data indicate confined water depth increases gradually from west to east. The Tertiary aquitard is discontinuous in intermontane valley areas but becomes continuous and multi-layered in alluvial plain regions. Groundwater and river runoff directions are generally consistent, with mutual transformation along the flow path under the influence of topography and human exploitation activities, ultimately discharging into Ulungur Lake and Jili Lake.

2 Methods

2.1 Sample Collection and Testing

Field investigation and sampling were conducted in the Ulungur River Basin from May to June 2018. A total of 34 water samples were collected, including 11 surface water samples (river water and lake water) and 23 groundwater samples (13 phreatic water and 10 confined water). Additionally, one rainwater sample was collected for stable isotope analysis. Sample testing was completed at the Xinjiang Physics and Chemistry Analysis and Testing Center for Nuclear Industry following GB/T 570-2006 standards. Major cations (K^+, Na^+, Ca^{2+}, Mg^{2+}) were measured using inductively coupled plasma mass spectrometry (NexION350X). Major anions (Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-) were determined by ion chromatography (ICS1100). Bicarbonate was measured by hydrochloric acid titration. Charge balance errors for all samples were less than $\pm$5%, meeting analytical requirements. Hydrogen and oxygen stable isotopes were analyzed by the Ministry of Natural Resources Key Laboratory of Groundwater Science and Engineering using cavity ring-down spectroscopy (L2130i isotope analyzer), with analytical precisions of $\pm$0.5‰ for δD and $\pm$0.1‰ for δ^{18}O.

2.2 Analytical Methods

Based on hydrochemical and isotopic data, comprehensive analyses were performed. The Shukailev method was used to classify hydrochemical types. Piper diagrams were employed to reveal water chemistry types and evolutionary processes. Gibbs diagrams identified dominant controlling factors of hydrochemistry. Ion ratios and chlor-alkali indices (CAI-1 and CAI-2) were calculated to evaluate cation exchange intensity. Schoeller diagrams were used to analyze mixing processes between different water bodies. The relationship between δD and δ^{18}O was established to determine the local meteoric water line and assess evaporation effects.

3 Results

3.1 Hydrochemical and Isotopic Characteristics

3.1.1 Hydrochemical Characteristics Statistical analysis of major ions reveals distinct hydrochemical signatures among water bodies (Table 1). River water has TDS values ranging from 200-500 mg·L^{-1}, with dominant anions of HCO_3^- and SO_4^{2-} and dominant cations of Ca^{2+} and Na^+, classifying as HCO_3·SO_4-Ca·Na type. Upstream of the Dashan Reservoir, water chemistry transitions to SO_4·HCO_3-Ca·Na type, while downstream of Fuhai County it becomes SO_4·HCO_3-Na·Ca type. Lake water shows TDS > 1000 mg·L^{-1}, with dominant ions of Cl^-, SO_4^{2-}, and Na^+, exhibiting a Cl·SO_4-Na type. Phreatic water TDS increases gradually from 300 mg·L^{-1} in recharge areas to >1000 mg·L^{-1} in discharge areas, with hydrochemical types evolving from HCO_3·SO_4-Ca·Na to SO_4·HCO_3-Na·Ca. Confined water has TDS > 2000 mg·L^{-1}, dominated by Cl^-, SO_4^{2-}, and Na^+, with a Cl·SO_4-Na type.

Ion variation diagrams (Fig. 2) show that along the flow path, HCO_3^- content gradually decreases while SO_4^{2-} and Cl^- increase. Jili Lake (Q6-Q11) receives river inflow, causing fluctuating increases in most ion concentrations. Phreatic water in valley areas (Q9-Q11) shows reduced ion concentrations due to mixing with external water sources. In the recharge area, Q1-Q5 exhibits TDS > 1000 mg·L^{-1} due to infiltration of northern springs, differing significantly from other samples in the region. Confined water shows ion concentration trends similar to phreatic water but with overall higher values.

3.1.2 Stable Isotope Characteristics Statistical analysis of stable isotopes reveals significant variations among water bodies (Table 2). Precipitation δ^{18}O values range from -14.2‰ to -4.1‰ (mean -9.8‰), while δD ranges from -95.6‰ to -45.2‰ (mean -72.3‰). The local meteoric water line is established as $\delta D = 6.49\delta^{18}O - 8.63$ ($R^2 = 0.9869$). This slope is lower than the global meteoric water line (GMWL) and the Urumqi meteoric water line, indicating stronger evaporation effects typical of arid regions.

Surface water and groundwater isotopic values plot on both sides of the meteoric water line (Fig. 4), suggesting rainfall as the common recharge source. River water is more isotopically depleted than lake water, with δ^{18}O values increasing gradually downstream (Fig. 5). Phreatic water isotopes are generally more depleted than river water but more enriched than confined water. Confined water shows the most scattered distribution and largest variation coefficient, indicating significant spatial heterogeneity. Evaporation line slopes follow the order: Jili Lake (4.8) < Ulungur Lake (4.2) < river water (5.5) < phreatic water

(6.1) < confined water (6.8), reflecting strongest evaporation in Ulungur Lake.

3.2 Hydrochemical Formation Mechanisms and Evolution

3.2.1 Formation Mechanisms Gibbs diagrams (Fig. 6) reveal that river water and phreatic water plot between rock weathering and evaporation zones, indicating combined control by both processes. Upstream river samples deviate toward the precipitation zone due to rainfall recharge. Lake water and confined water plot in the evaporation zone, showing evaporation as the dominant control. Ulungur Lake experiences the most intense evaporation, plotting closest to the evaporation end-member. Although confined water has deep flow paths, its recharge zone evaporation effects cause most samples to also plot in the evaporation zone.

Mixing processes significantly influence water chemistry as water flows from recharge to discharge areas through different geomorphological units. Schoeller diagrams (Fig. 7) show similar ion variation trends between phreatic water and river water in intermontane valley and mid-low mountain areas, indicating significant mixing. In alluvial plains, however, ion variation trends diverge, suggesting weaker mixing effects. Confined water shows distinct ion variation patterns from both river water and phreatic water, indicating minimal mixing influence.

Cation exchange occurs when water interacts with aquifer media. The chlor-alkali index (CAI) quantifies this process. Fig. 9 shows confined water and lake water have positive CAI values, indicating exchange of Na^+ and K^+ from water for Ca^{2+} and Mg^{2+} in aquifer materials. Phreatic water and river water show alternating positive and negative CAI values with similar variation patterns, suggesting hydraulic connectivity between these water bodies.

3.2.2 Hydrochemical Evolution Piper diagrams (Fig. 10) illustrate water evolution patterns. River water and phreatic water plot in the central diamond zone, while lake water occupies the discharge zone and confined water plots primarily in the $Cl \cdot SO_4$ zone. Along flow paths from mid-low mountain recharge areas through valleys and plains to the lake discharge zone, river water and phreatic water evolve under combined effects of water-rock interaction, evaporation, ion exchange, and mixing. Dominant cations shift toward Na^+, while dominant anions evolve from HCO_3^- toward Cl^-. The overall hydrochemical transformation follows: $HCO_3 \cdot SO_4$-$Ca \cdot Na \rightarrow SO_4 \cdot HCO_3$-$Ca \cdot Na \rightarrow SO_4 \cdot HCO_3$-$Na \cdot Ca \rightarrow SO_4 \cdot Cl$-$Na \rightarrow Cl \cdot SO_4$-$Na$. With increasing flow path length and hydraulic residence time, TDS increases from $<0.3\ g \cdot L^{-1}$ to $>2.5\ g \cdot L^{-1}$ in deep confined zones where sulfate minerals become saturated and halite dissolution continues, driving anion evolution toward Cl^- dominance.

3.2.3 Water Transformation Relationships Based on isotopic and hydrochemical characteristics, combined with hydrogeological profiles (Fig. 11) and geomorphological features, water transformation relationships were established

(Fig. 12). In mid-low mountainous areas with steep hydraulic gradients and abundant rainfall, river water $\delta^{18}O$ values plot near precipitation means, indicating rainfall recharge. At the mountain outlet (R5–R6), decreasing river flow and significant mixing with phreatic water (which has lower $\delta^{18}O$) indicates phreatic water recharge to the river.

In intermontane valley zones, significant mixing occurs between river water and phreatic water. River water $\delta^{18}O$ values increase downstream due to evaporation and exceed precipitation means, while phreatic water values remain near precipitation, indicating phreatic water recharging the river. In the Q9–Q11 segment, phreatic water $\delta^{18}O$ rises rapidly due to river water recharge, then decreases in the Q11–Q12 segment, matching confined water trends. This reflects incomplete Tertiary aquitards and shallow confined water, enabling hydraulic exchange between phreatic and confined water.

In alluvial plains with reduced hydraulic gradients and slower flow, evaporation intensifies while continuous aquitards minimize phreatic-confined water interaction. Phreatic water $\delta^{18}O$ values plot between river water and precipitation means, showing two peaks that correlate with regional phreatic water patterns, indicating river water receives phreatic water discharge. At Q12, increased $\delta^{18}O$ due to southern anticline structure, channel migration, and northern phreatic water lateral recharge reflects phreatic water recharging confined water. In the southwestern lake area, independent flow systems yield both phreatic and confined water with $Cl \cdot SO_4$-Na type chemistry and isotopic values near precipitation means, significantly lower than lake and river water, confirming local rainfall as the primary groundwater source.

4 Conclusions

(1) In the Ulungur River Basin, lake water is dominated by Cl^- and ${SO_4}^{2-}$ with Na^+ as the main cation, exhibiting a $Cl \cdot SO_4$-Na type under strong evaporation control. River water, influenced by rock weathering, evaporation, and mixing, shows ${HCO_3}^-$ and ${SO_4}^{2-}$ dominance with Ca^{2+} and Na^+ as major cations, classifying as $HCO_3 \cdot SO_4$-$Ca \cdot Na$ type. Groundwater chemistry is controlled by rock weathering, evaporation, and cation exchange. Phreatic water evolves from $HCO_3 \cdot SO_4$-$Ca \cdot Na$ in mid-low mountains to $SO_4 \cdot HCO_3$-$Na \cdot Ca$ in alluvial plains, while confined water is primarily $Cl \cdot SO_4$-Na type.

(2) Isotopic enrichment follows: Ulungur Lake > Jili Lake > Ulungur River > phreatic water > confined water. The local meteoric water line ($\delta D = 6.49\delta^{18}O$ - 8.63) indicates evaporation significantly affects isotopic composition. All water bodies derive from precipitation recharge. Combined isotopic and hydrochemical evidence demonstrates frequent transformation between surface water and groundwater.

(3) Hydraulic connections vary by geomorphological zone. Mid-low mountain and intermontane valley areas are dominated by phreatic water recharging

river water, with localized hydraulic connections between phreatic and confined water where Tertiary aquitards are discontinuous. In alluvial plains, phreatic-confined water interaction is weak due to continuous aquitards, and river water receives phreatic water discharge.

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