# Distribution Characteristics of Boron in Surface Water and Groundwater and Their Influencing Factors in the Qiemo County Oasis Area (Postprint)

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## Abstract

High-boron surface water and groundwater exist in the oasis area of Qiemao County, Xinjiang, seriously affecting residents' health. To preliminarily investigate the hydrochemical characteristics and main sources of boron in the oasis area of Qiemao County, 24 water samples (4 surface water and 20 groundwater) were collected in 2023; using methods such as Piper trilinear diagram, Gibbs diagram, correlation analysis, hydrogen and oxygen isotopes, and the APCS-MLR (Absolute Principal Component Scores-Multiple Linear Regression) model to conduct a preliminary analysis of the hydrochemical characteristics and boron sources of surface water and groundwater in the oasis area of Qiemao County, and quantitatively evaluate the contributions of different factors to boron and other hydrochemical components in water. The results show: (1) The surface water and groundwater in the oasis area of Qiemao County are overall weakly alkaline, with a mean pH of 8.22; the groundwater is mainly brackish water, and the main anions and cations are $SO_4^{2-}$ and $Na^+$. (2) There are many hydrochemical types, and both surface water and groundwater are dominated by the $SO_4 \cdot$ Cl-Na $\cdot$ Mg type. (3) The mean boron concentration in surface water in the study area is 2.34 $mg \cdot L^{-1}$, with an exceedance rate of 100.00%; the mean boron concentration in groundwater is 1.73 $mg \cdot L^{-1}$, with an exceedance rate of 70.00%. (4) APCS-MLR receptor model analysis reveals that the sources of hydrochemical components and boron mainly include the leaching-enrichment factor (F1-58.21%), primary geological factor (F2-15.42%), anthropogenic activity factor (F3-11.18%), and unknown sources. Boron exceedance in water is evident in the area, and the geological environment has a significant influence on boron enrichment in water.

Full Text

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# Distribution Characteristics and Influencing Factors of Boron in Surface Water and Groundwater in the Oasis Area of Qiemo County

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### Abstract

High boron concentrations in surface water and groundwater in the oasis area of Qiemo County, Xinjiang, seriously affect residents' health. To preliminarily identify the hydrochemical characteristics and main sources of boron, 24 groundwater samples and 20 surface water samples were collected in 2023. Piper diagrams, Gibbs plots, correlation analysis, hydrogen-oxygen isotopes, and an APCS-MLR (absolute principal component-multiple linear regression) model were employed to analyze the hydrochemical characteristics and boron sources, quantitatively evaluating the contribution of different factors to boron and other hydrochemical components. The results indicate: (1) Surface water and groundwater in the oasis area of Qiemo County are weakly alkaline, with mean pH values of 8.22. Groundwater is primarily brackish, with main anions and cations being $SO_4 \cdot Cl\text{-}Na \cdot Mg$. Multiple hydrochemical types exist, with $SO_4 \cdot Cl\text{-}Na \cdot Mg$ as the dominant type in both surface water and groundwater. (2) The mean boron concentration in surface water is 2.34 $mg \cdot L^{-1}$ (exceedance rate: 100%), while in groundwater it is 1.73 $mg \cdot L^{-1}$ (exceedance rate: 70%). (3) APCS-MLR receptor model analysis reveals that hydrochemical components and boron originate mainly from leaching-enrichment factors (58.21%), native geological factors (15.42%), human activity factors (11.18%), and unknown sources. Boron exceedance is significant, and the geological environment substantially influences boron enrichment in water.

**Keywords:** high boron groundwater; high boron surface water; hydrochemical characteristics; influencing factor analysis; Qiemo County

Boron is the only non-metal element in Group IIIA. In nature, boron typically combines with oxygen and other elements to form compounds rather than occurring in elemental form, and is widely distributed in the Earth's lithosphere and hydrosphere. Boron is an essential trace element for plant, animal, and human growth and development. It plays a crucial role in plant metabolism, sugar translocation, hormone secretion, and normal growth. Insufficient boron supply in plants causes various damages, including retarded root and leaf growth, bark cracking-type injuries, delayed enzyme reactions and leaf photosynthesis, and even plant death. For animals and humans, boron affects immune function, bone metabolism, and central nervous system function. However, the mechanism of boron toxicity remains unclear, and toxicity depends on exposure duration, frequency, and level, making quantification difficult.

Domestic scholars have investigated boron content and enrichment mechanisms in groundwater. Zhang et al. reported boron concentrations of 1.05–2.08 $mg \cdot L^{-1}$ in the Qaidam Basin, where the environment favors boron enrichment through large active faults, volcanic craters, and other macro-structures serving as fluid conduits, combined with dry climate and strong evaporation. Liu's research indicates that geothermal water in Tibet contains average boron concentrations of 89.4 $mg \cdot L^{-1}$, with significant variation between geothermal fields. The Yangyi geothermal field ranges from 90.9–530.8 $mg \cdot L^{-1}$, while the Semiri geothermal field varies from 6.9–10.9 $mg \cdot L^{-1}$. This region's boron-enriched environment is characterized by alkaline conditions, high temperature, high pH, and strong reducibility. Our research group has identified significant boron exceedance in groundwater and surface water in Xinjiang's oasis areas, affecting local water safety, though studies on the causes remain limited.

Qiemo County is located in the Cherchen River basin in southern Xinjiang. The Cherchen River basin is a major inland river system on the southern margin of the Tarim Basin and historically one of the nine major water systems of the Tarim River. Due to scarce precipitation and intense evaporation, water resources are relatively limited, with both surface water and groundwater serving as essential sources for domestic and agricultural use. Previous studies have documented groundwater salinization and pollution in this area, investigating hydrochemical characteristics and surface water-groundwater transformation mechanisms. Boron exceedance in surface water and groundwater has been discovered, with unclear sources further reducing available water resources.

Therefore, this study collected 24 groundwater samples and 20 surface water samples in the Qiemo County oasis area in 2023. Based on hydrochemical analysis and hydrogen-oxygen isotopes, we analyzed the spatial distribution characteristics of boron, delineated high-boron areas in surface water and groundwater, and investigated hydrogeochemical processes during high-boron water formation using Piper diagrams, Gibbs plots, correlation analysis, principal component analysis, and isotopic methods. This research provides a preliminary analysis of boron sources, offering scientific evidence for rational water resource utilization and drinking water safety in Qiemo County's oasis area, and serves as a reference for analyzing boron distribution and sources in surface water and groundwater in arid inland basins.

### 1.1 Study Area Overview

Qiemo County lies on the southeastern margin of the Tarim Basin in Xinjiang. The terrain is higher in the south and lower in the northwest, with the oasis belt sloping from west to east, forming a narrow band distributed along water systems. Qiemo County has a warm temperate extreme arid continental climate, with anomalous precipitation timing—more at the beginning and end of the year, less in mid-year—and an aridity index as high as 80, classifying it as an extremely arid region. The county has relatively abundant water resources, with the Cherchen River primarily fed by alpine snowmelt, mountain precipitation, and spring water, having an annual runoff of $5.6\times10^{8}$ $m^3$, accounting for 31.0% of the county's total runoff. The aquifer consists mainly of gravel layers, thinning gradually from south to north with minimal variation perpendicular to the river channel.

According to the hydrogeological map (Fig. 1), the Cherchen River basin terrain is generally high in the south and low in the north. The plain area geomorphology can be divided into three types from south to north: southern alluvial-pluvial plain, central Cherchen River valley plain, and northern aeolian desert area. Exposed strata are primarily Quaternary, with lithology mainly consisting of fine-over-coarse sandy loam and gravel, underlain by Xiyu conglomerate and mudstone. Groundwater receives recharge from river infiltration, canal and irrigation water infiltration, and lateral runoff from storm flood infiltration. Groundwater flows from southwest to northeast along the river course. Main discharge occurs through areal vertical evaporation and plant transpiration in shallow groundwater zones, followed by channel discharge, lateral flow, and artificial extraction.

### 1.2 Sample Collection and Methods

From May to July 2023, 24 groundwater samples and 20 surface water samples were collected from the Qiemo County oasis belt. Sampling and analysis strictly followed the "Technical Specifications for Groundwater Environmental Monitoring" (HJ 164-2020). Before groundwater sampling, pumping continued for over 20 minutes until hydrochemical conditions stabilized. Sample bottles were rinsed three times with the water being collected. Surface water samples were collected 0.5 m below the water surface. Samples for cation and boron analysis were filtered through 0.45  m cellulose acetate filters and acidified to $pH < 2$ with $HNO_3$. Samples for anion analysis were stored in polyethylene bottles.

Field measurements included water temperature, electrical conductivity (EC), dissolved oxygen (DO), oxidation-reduction potential (ORP), and pH using a multi-parameter analyzer (HANNA HI9828). According to GB/T 5750-2023

"Standard Examination Methods for Drinking Water," major ions were analyzed: $K^+$ and $Na^+$ by flame atomic absorption spectrophotometry; $Ca^{2+}$, $Mg^{2+}$, and total hardness by EDTA titration; $Cl^-$ by silver nitrate titration; ${SO_4}^{2-}$ by barium sulfate turbidimetry; ${HCO_3}^-$ by acid-base titration; ${NO_3}^-$ by UV spectrophotometry; $F^-$ by ion-selective electrode; total dissolved solids (TDS) by gravimetry; and boron by azomethine-H spectrophotometry. Hydrogen-oxygen isotopes ($\delta$D, $\delta^{18}$O) were measured using a liquid water isotope analyzer (LGR). All samples had ion charge balance errors within \$±\$5%, confirming reliable results.

## 2 Results and Analysis

pH values ranged from 7.62–8.33 for groundwater and 8.30–8.44 for surface water, with averages of 8.22 and 8.37, respectively, indicating weakly alkaline conditions. TDS ranged from 641.0–6154 $mg \cdot L^{-1}$ (mean: 1433 $mg \cdot L^{-1}$) for groundwater and 701.0–1596 $mg \cdot L^{-1}$ (mean: 995.3 $mg \cdot L^{-1}$) for surface water. Based on the milligram-equivalent percentages of major ions, a Piper diagram was constructed for the study area [Figure 2: see original paper]. According to the classification, groundwater is mainly brackish, with dominant anions and cations being $SO_4 \cdot$Cl-Na$\cdot$Mg. Multiple hydrochemical types exist, with surface water and groundwater primarily showing $SO_4 \cdot$Cl-Na$\cdot$Mg type. Along the Cherchen River from south to north, boron concentrations in both groundwater (except western areas) and surface water show an increasing trend.

### 2.1 Hydrochemical Characteristics and Spatial Distribution

In May 2023, boron concentrations in surface water and groundwater ranged from 1.91–3.23 $mg \cdot L^{-1}$ (mean: 2.34 $mg \cdot L^{-1}$, exceedance rate: 100%) and 0.25–6.42 $mg \cdot L^{-1}$ (mean: 1.73 $mg \cdot L^{-1}$, exceedance rate: 70%), respectively. Both means exceed the 1.00 $mg \cdot L^{-1}$ limit specified in GB 5749-2022 "Standards for Drinking Water Quality."

In the study area, the average cation content order for both groundwater and surface water is $Na^+ > Mg^{2+} > Ca^{2+}$. The average anion content order for groundwater is ${SO_4}^{2-} > Cl^- > {HCO_3}^-$, while for surface water it is $Cl^- > {SO_4}^{2-} > {HCO_3}^-$. The similar ordering suggests close hydraulic connection between surface water and groundwater. The coefficient of variation (C ) reflects spatial distribution differences in major ion content. Except for pH and ORP, all parameters show moderate variation (C $> 0.3$), indicating unstable spatial distribution of ion components, related to different geomorphological types in the study area, with local areas possibly affected by human pollution.

### 2.2 Recharge Sources

Isotopic composition can reflect recharge sources of groundwater and surface water. As shown in [Figure 3: see original paper], most sample points distribute near the LMWL (local meteoric water line), indicating atmospheric precipitation as the main recharge source. Most high-boron surface water samples and some high-boron groundwater samples plot below the precipitation line, suggesting they have undergone varying degrees of evaporation. High-boron surface water samples (except Q10) cluster relatively closely, indicating similar average recharge elevations in the catchment area. The anomalous position of Q10 may result from mixing with tributary water from lower elevations, as the boron concentration measured at Q10 ($3.23\ mg \cdot L^{-1}$) exceeds other points.

Evaporation lines for high-boron groundwater, low-boron groundwater, and high-boron surface water are $\delta D = 5.75\delta^{18}O - 9.99$, $\delta D = 7.31\delta^{18}O + 6.61$, and $\delta D = 5.32\delta^{18}O - 27.62$, respectively. All slopes and intercepts are smaller than the local meteoric water line, indicating evaporation effects. However, high-boron groundwater and surface water have even smaller slopes and intercepts than low-boron groundwater, suggesting stronger evaporation concentration. The deuterium excess parameter (d) reflects evaporation intensity, with smaller values indicating stronger effects. Ranges for high-boron groundwater, low-boron groundwater, and high-boron surface water are -5.724‰ to 16.724‰, 6.997‰ to 22.997‰, and -9.997‰ to 16.997‰, with means of 4.997‰, 14.997‰, and 0.997‰, respectively. Thus, high-boron surface water experiences the strongest evaporation, while low-boron groundwater experiences the weakest.

### 2.3.1 Rock Weathering

Gibbs diagrams can analyze whether natural water chemistry is controlled by atmospheric precipitation, rock weathering, or evaporation concentration, and study influencing factors. Gibbs plots for high-boron groundwater and surface water [Figure 4: see original paper] show that high-boron surface water and low-boron groundwater plot in the rock weathering and evaporation concentration zones, while high-boron groundwater plots in the rock weathering zone, indicating rock weathering as the primary control on hydrochemistry.

### 2.3.2 Ion Ratio Analysis of Hydrochemical Component Sources

Water-rock interactions in aquifers release different ions, and different rock types release distinct ions. These ion ratios are often used to interpret how groundwater chemistry is affected by rock weathering and other factors. The milligram-equivalent ratio relationship between $\gamma(Na^+ + K^+ - Cl^-)$ and $\gamma({HCO_3}^- + {SO_4}^{2-} - Ca^{2+} - Mg^{2+})$ can identify $Ca^{2+}$ and $Mg^{2+}$ sources [Figure 5: see original paper]. All high-boron surface water and low-boron groundwater samples plot above the y = x line, indicating $Ca^{2+} + Mg^{2+}$ originate from silicate and evaporite dissolution. Most high-boron groundwater samples plot below y = x, with only a few above, suggesting $Ca^{2+} + Mg^{2+}$ mainly come from silicate and evaporite dissolution, closely related to carbonate dissolution.

The $\gamma(Ca^{2+} + Mg^{2+})$ versus $\gamma({HCO_3}^- + {SO_4}^{2-})$ relationship can determine ${HCO_3}^-$ and ${SO_4}^{2-}$ sources. High-boron surface water and low-boron groundwater samples all plot below y = x, indicating $HCO_3^-$ + $SO_4^{2-}$ originate from silicate weathering and evaporite dissolution. Most high-boron groundwater samples plot below y = x, with a small portion above, suggesting $HCO_3^-$ + $SO_4^{2-}$ mainly come from silicate and evaporite dissolution, also related to carbonate dissolution.

### 2.4 Cation Exchange

During long-term rock-groundwater interaction, negative charges on rock surfaces can adsorb groundwater cations, releasing previously adsorbed cations through cation exchange. The milligram-equivalent ratio relationship between $\gamma(Na^+ - Cl^-)$ and $\gamma[(Ca^{2+} + Mg^{2+}) - (HCO_3^- + SO_4^{2-})]$ can identify cation exchange occurrence [Figure 6: see original paper]. Sample points near the y = x line (slope 1) indicate strong ion exchange influence on regional groundwater chemistry.

Chlor-alkali indices (CAI-I and CAI-II) further analyze cation exchange direction and intensity. Negative CAI-I and CAI-II values indicate reverse cation exchange, where $Na^+$ comes from halite dissolution with silicate dissolution; positive values indicate forward cation exchange. The study area shows mainly forward cation exchange in high-boron groundwater, with some reverse exchange, while high-boron surface water and low-boron groundwater are dominated by forward cation exchange.

### 2.5 Boron Enrichment Mechanisms in Surface Water and Groundwater

**2.5.1 Influence of pH on Boron Content** pH significantly affects boron content in groundwater and surface water, playing an important role in boron enrichment. The relationship between boron content and pH [Figure 7: see original paper] shows that in high-boron groundwater, boron content increases with pH up to pH 8.45, then decreases. In low-boron groundwater, boron content increases with pH, potentially converting to high-boron groundwater when pH > 8.45. In high-boron surface water, boron content increases with pH.

As pH increases, $OH^-$ competes with borate for adsorption sites. When pH > 9.00, $OH^-$ with greater affinity coefficient displaces adsorbed borate, causing rapid decrease in adsorbed boron and increase in aqueous boron content. The relationship can be expressed as: $B(OH)_3 + H_2O \quad B(OH)_4^- + H^+$

When pH is too high or too low, boron solubility increases. Increasing pH consumes $H^+$, promoting forward reaction of the above equation and increasing boron dissolution. Decreasing pH increases $H^+$, also promoting forward reaction and increasing boron solubility. Thus, extreme pH values increase boron content in groundwater.

**2.5.2 Relationship Between Boron and Major Chemical Indicators** [Figure 8: see original paper] shows that in high-boron groundwater, boron content initially increases with $Ca^{2+}$ and $Mg^{2+}$ content, then decreases when $Ca^{2+} + Mg^{2+}$ exceeds 75.00 $mg \cdot L^{-1}$ or TDS exceeds 2500.00 $mg \cdot L^{-1}$. Boron content increases with $HCO_3^-$ content, initially decreases with $SO_4^{2-}$ content then increases when $SO_4^{2-}$ exceeds 1.10 $mg \cdot L^{-1}$. In low-boron groundwater, boron content decreases with increasing $Ca^{2+} + Mg^{2+}$ content. Boron content increases with $NO_3^-$ content and decreases with $F^-$ content.

High-boron surface water shows increasing boron content with $NO_3^-$ and $SO_4^{2-}$ content, and decreasing boron content with $HCO_3^-$ content. The relationship between boron and ORP shows that boron content in high-boron groundwater and surface water decreases with increasing ORP. Lower ORP values indicate more reducing conditions. Under reducing conditions, boron struggles to act as a reducing agent, leading to boron enrichment. These results indicate that boron content in high-boron and low-boron groundwater is closely related to redox conditions in the aquifer system, with reducing conditions favoring boron enrichment.

The relationship between boron and $F^-$ content shows that high-boron groundwater and surface water contain certain amounts of fluorite ($CaF_2$). When $Ca^{2+}$ content is high, fluorite dissolution equilibrium shifts toward precipitation, decreasing $F^-$ content. The increase in $F^-$ content with decreasing boron content indicates that $Ca^{2+}$ is a major factor affecting boron content. Under reducing conditions, $Fe^{3+}$ transforms to lower-valence compounds, and the decrease in $Fe^{3+}$ content indicates a reducing environment. The presence of silicate rocks, evaporite rocks, and fluorite in the study area collectively increases boron content in groundwater and surface water.

**2.5.3 Human Activities** Groundwater hydrochemistry is influenced by both natural environments and human activities. According to hydrogeological survey data, agriculture is the main activity in the Qiemo County oasis area, with relatively little industrial activity. In agricultural concentration areas, 11 groundwater samples had boron content exceeding GB 5749-2022 standards. To investigate potential human impacts, nitrate, chloride, and sulfate—sensitive indicators of human pollution—were analyzed using ion ratio relationships. [Figure 9: see original paper] shows that surface water and groundwater are affected by both human discharge (detergents, cleaning agents, disinfectants in municipal wastewater) and natural sources, with human discharge showing a more pronounced influence.

Further analysis using $NO_3^-/Cl^-$ and $SO_4^{2-}/Cl^-$ ratios indicates groundwater is affected by both agricultural and industrial/mining activities (large-scale use of boron-containing fertilizers, pesticides, and herbicides). Additionally, soil boron content in Qiemo County's agricultural land (60.41 $mg \cdot L^{-1}$) exceeds the Xinjiang soil average (40.90 $mg \cdot L^{-1}$). During irrigation periods, soil boron enters groundwater with irrigation water, increasing groundwater boron content.

**2.5.4 Quantitative Assessment of Surface Water and Groundwater Chemical Component Sources Principal Component Analysis (PCA).** PCA can explain complex relationships among multiple variables with fewer variables. Before PCA, data suitability was checked using Kaiser-Meyer-Olkin (KMO) and Bartlett's sphericity tests. Since surface water and groundwater form a continuous transforming system, unified PCA was performed on 11 hydrochemical parameters. With KMO $> 0.5$ and Bartlett's test significance $< 0.05$, the data were suitable for PCA. Three principal components were extracted, with cumulative variance contribution of 84.81%: PC1 (leaching-enrichment factor, 58.21% contribution) with high loads of $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $Cl^{-}$, $SO_4{}^{2-}$, $HCO_3{}^{-}$, and TDS; PC2 (native geological factor, 15.42% contribution) with high boron load; PC3 (human activity factor, 11.18% contribution) with high $NO_3{}^{-}$ load, reflecting impacts from agricultural activities and domestic sewage.

**Source Contribution Analysis of Boron in Surface Water and Groundwater.** Source apportionment methods include PCA, which is simple but only qualitative, and APCS-MLR, which offers advantages in data requirements, non-concentration indicator processing, and quantitative analysis. Based on PCA, APCS-MLR was used to analyze contribution rates of each factor to major ions [Figure 10: see original paper]. The leaching-enrichment factor (APCS1) contributed 61.91% to $Ca^{2+}$, 57.14% to $Mg^{2+}$, 71.21% to $Na^{+}$, 70.81% to $Cl^{-}$, and 72.92% to $SO_4{}^{2-}$, indicating rock weathering dissolution as the main source. The native geological factor (APCS2) contributed 71.50% to boron, showing significant geological influence on boron enrichment, consistent with PCA results.

### 2.6 Geological Genesis

Quaternary genetic types in the study area include aeolian deposits, alluvial deposits, and alluvial-pluvial deposits [Figure 11: see original paper]. High-boron surface water (mean: $2.61\ mg \cdot L^{-1}$) and high-boron groundwater (mean: $1.88\ mg \cdot L^{-1}$) mainly co-occur in aeolian and alluvial deposits. High-boron groundwater shows higher mean values in aeolian deposits ($2.75\ mg \cdot L^{-1}$) than in alluvial deposits ($1.88\ mg \cdot L^{-1}$). High-boron surface water shows higher mean values in alluvial deposits ($2.07\ mg \cdot L^{-1}$) than in aeolian deposits ($1.88\ mg \cdot L^{-1}$).

Aeolian deposits contain weathering products from surrounding metamorphic and igneous rocks or fluorine-rich minerals like hornblende and fluorite. During infiltration of irrigation water and atmospheric precipitation, leaching increases $Ca^{2+}$ content. As $Ca^{2+}$ content increases, boron content also increases. Alluvial deposits are mainly distributed near rivers and river migration zones, with lithology of fine sand, silt, and sandy loam. River biological residues form organic-rich clay layers. Natural organic matter degradation promotes reducing dissolution, which favors boron enrichment under reducing conditions. Therefore, aeolian deposits influence groundwater boron content, while alluvial deposits affect surface water boron content.

## 3 Conclusions

Analysis of 44 water samples (24 groundwater, 20 surface water) yields the following main conclusions:

1. Boron content in surface water and groundwater in the Qiemo County oasis area generally exceeds standards, with mean values of 2.34 $mg \cdot L^{-1}$ (surface water, 100% exceedance) and 1.73 $mg \cdot L^{-1}$ (groundwater, 70% exceedance). The water is weakly alkaline (mean pH 8.22), mostly fresh to brackish, with dominant ions $Na^+$, $Mg^{2+}$, $SO_4{}^{2-}$, and $Cl^-$. Close hydraulic connection exists between surface water and groundwater, with multiple hydrochemical types dominated by $SO_4 \cdot Cl$-$Na \cdot Mg$ in high-boron groundwater and $Cl \cdot SO_4$-$Na \cdot Mg$ in high-boron surface water.

2. Isotope and hydrochemical analysis reveals that atmospheric precipitation is the main recharge source, with varying degrees of evaporation. High-boron surface water experiences the strongest evaporation concentration, while low-boron groundwater experiences the weakest. High-boron groundwater and surface water are controlled by both rock weathering and evaporation concentration, with rock weathering as the primary factor. Low-boron groundwater is mainly affected by evaporation concentration.

3. Cation exchange significantly influences regional groundwater chemistry, with forward cation exchange dominating. In high-boron groundwater, $Na^+$ mainly comes from halite dissolution with silicate dissolution, while $Ca^{2+}$ and $Mg^{2+}$ originate from silicate and evaporite dissolution, also related to carbonate dissolution.

4. pH significantly affects boron content, influencing its enrichment. When pH is too high or low, boron solubility increases. Boron content is closely related to $Ca^{2+}$, $Mg^{2+}$, $HCO_3{}^-$, $SO_4{}^{2-}$, and other ion contents, indicating that dissolution of silicate rocks, evaporite rocks, and fluorite are important sources of boron enrichment. Reducing conditions favor boron enrichment, consistent with the reducing conditions of groundwater in the study area.

5. Human activities (use of boron-containing fertilizers, pesticides, and domestic sewage discharge) and Quaternary sediments (leaching of weathering products from metamorphic and igneous rocks in aeolian deposits, reducing dissolution promoted by organic matter degradation in alluvial deposits) collectively exacerbate boron enrichment in water bodies.

6. PCA extracted three factors controlling hydrochemical components: leaching-enrichment factor (58.21%), native geological factor (15.42%), and human activity factor (11.18%). APCS-MLR shows the native geological factor contributes 71.50% to boron, indicating significant geological influence on boron enrichment.

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