

Article

Analysis of Groundwater Chemical Characteristics and Boron Sources in the Oasis Area of the Cherchen River Basin in Xinjiang, China

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Abstract

The oasis area of the Cherchen River Basin (OACRB) is located in the southeast edge of the Tarim Basin in Xinjiang, China. High boron (B) groundwater is observed in the OACRB according to 40 groundwater samples collected in May 2023. Identification of the chemical characteristics and B sources of groundwater in the OACRB is of great significance for the sustainable development and utilization of groundwater resources and the protection of animals, plants and human health. To explore the chemical characteristics and main B sources of groundwater, Piper three-line diagram, Gibbs diagram, correlation analysis, hydrogeochemical simulation and absolute principal component analysis (PCA-APCS-MLR) were used for analysis. The contribution of different factors to groundwater B was quantitatively evaluated. The results showed that the groundwater is weakly alkaline (with an average pH of 7.94) and mainly brackish water and saline water with Cl^- and Na^+ as the main anions and cations. The groundwater is dominated by $\text{SO}_4 \cdot \text{Cl-Na}$ type. The average concentration (ρ) of groundwater B in the study area was $1.48 \text{ mg} \cdot \text{L}^{-1}$ with the over-standard rate was 45.0%. The APCS-MLR receptor model analysis revealed that groundwater chemical components including B were mainly derived from leaching-enrichment, human activity, primary geological factors, and unknown sources. Groundwater B is obviously greater than the standard limit, which is mainly due to agricultural activities (fertilizers and pesticides) and unknown sources.

Keywords: groundwater boron; hydrogeochemistry; PCA-APCS-MLR; source analysis; Cherchen River Basin



Academic Editor: Constantinos V. Chrysikopoulos

Received: 24 June 2025

Revised: 27 July 2025

Accepted: 4 August 2025

Published: 14 August 2025

Citation: Dong, J.; Gao, F.; Zhou, J.; Li, J.; Zhou, Y. Analysis of Groundwater Chemical Characteristics and Boron Sources in the Oasis Area of the Cherchen River Basin in Xinjiang, China. *Water* **2025**, *17*, 2397. <https://doi.org/10.3390/w17162397>

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1. Introduction

Boron (B) is an essential trace element for the growth and development of humans and plants, which mainly exists in the lithosphere and hydrosphere in the form of boron-containing minerals, boric acid (H_3BO_3), and borates [1,2]. In most cases, groundwater B is less than a few hundred $\mu\text{g/L}$ [3,4].

According to the World Health Organization [3], the limit of B in drinking water is 2.4 mg/L. According to China's "Sanitary Standard for Drinking Water" (GB5749-2006), the limit of B in drinking water is 0.5 mg/L, while it was modified from 0.5 mg/L to 1.0 mg/L

in the “Sanitary Standard for Drinking Water” (GB5749-2022). The effect of excessive B on human health is dose-dependent. Short-term acute exposure (>100 mg/L) can lead to gastrointestinal bleeding, characteristic blue-green vomiting and skin erythema. Long-term chronic exposure (>10 mg/L) can cause reproductive dysfunction (sperm reduction, menstrual disorders), children’s developmental retardation (bone age delay, IQ decline) and liver and kidney damage. Exposure to high B environment in pregnant women can significantly increase the risk of fetal malformation and low birth weight infants, while those with renal insufficiency are more prone to boron accumulation poisoning.

Groundwater B excess areas distributed worldwide, especially in Asia and Africa, including India, Mexico, Saudi Arabia, China, the United States, and Bangladesh, etc. [5–8]. Long-term high B water intake not only has adverse effects on human reproduction [9,10], but also affects the growth and yield of plants [11]. The human health risk of B in coastal areas of Bangladesh was determined by calculating the estimated daily intake (EDI) and hazard quotient (HQ) of infants, children, adolescents, and adults. According to the average HQ value, children were classified as high-risk groups, followed by adolescents, adults and infants [8].

The sources of groundwater B are related to the natural environment and human activities. Borate minerals, volcanic activities, geothermal energy, and seawater are regarded as important natural sources of boron in groundwater B [11,12]. Human activities can also contribute B to groundwater via different pathways such as agricultural irrigation [13,14], sewage discharge [15,16] and mineral exploitation [17].

The oasis area of the Cherchen River Basin is located in the southeastern margin of the Tarim Basin in Xinjiang, China. Due to the scarce precipitation and strong evaporation, the water source in this area is relatively scarce, and groundwater is the guaranteed water source for residents’ life and production. Previously, salinization and pollution of groundwater were studied [18]. In May 2023, high B content in river water and groundwater in the oasis area of the Cherchen River Basin was observed for the first time. The source of high B water is still unclear, resulting in further reduction in available water resources.

The research objective was to delineate the distribution area of high B groundwater and to quantitatively reveal the sources and main controlling factors of high B groundwater in the study area. Piper three-line diagram, Gibbs diagram, correlation analysis, and hydrogeochemical simulation were used based on the analysis of 40 groundwater chemical samples collected in the oasis area of the Cherchen River Basin in May 2023. The distribution and enrichment mechanisms of groundwater B in the Cherchen River Basin were analyzed and revealed from different perspectives, including distribution of soil B, high B groundwater irrigation, application of B-rich pesticides/fertilizers, and water-rock interaction, etc. This study could provide technical guidance to reduce the health risks of local high B groundwater, ecological environment protection and economic sustainable development of residents in the oasis area of the Cherchen River Basin and clarify the future monitoring work of in situ high B groundwater sampling point and seasonal variation pattern of high B groundwater. Due to the limitations of the study including lack of seasonal monitoring, speciation analysis, and isotopic tracing, there was merely preliminary speculation on the possible “unknown” sources. On this basis, B isotope analysis and mineral analysis of water-bearing media will be used for analysis of more detailed sources of high B groundwater in the future study, thereby providing a decision-making basis for reducing the health risks of high B groundwater in the study area.

2. Study Area

The study area ($83^{\circ}45'–90^{\circ}27'$ E, $36^{\circ}11'–39^{\circ}49'$ N) is located in Qiemo County and Ruoqiang County, Bayingolin Mongol Autonomous Prefecture in Xinjiang, China (Figure 1).

The study area is far from the ocean. Because the southern part is plateau and mountainous area, the wet air does not easily flow in [19]. The study area has a warm temperate extreme continental arid climate, with an average annual temperature of 10.1 °C. The average annual precipitation in the area is 18.6 mm, and the annual evaporation is 2506.9 mm, which is an extremely arid area. The Cherchen River originates from the Muztagh Peak on the northern slope of the Kunlun Mountains. The upper reaches of the Cherchen River converge to the glacier tributaries of the Kunlun Mountains and the Altun Mountains. It is a mixed recharge river of ice and snow melt water and groundwater. The average annual runoff is $8 \times 10^8 \text{ m}^3$ [19].

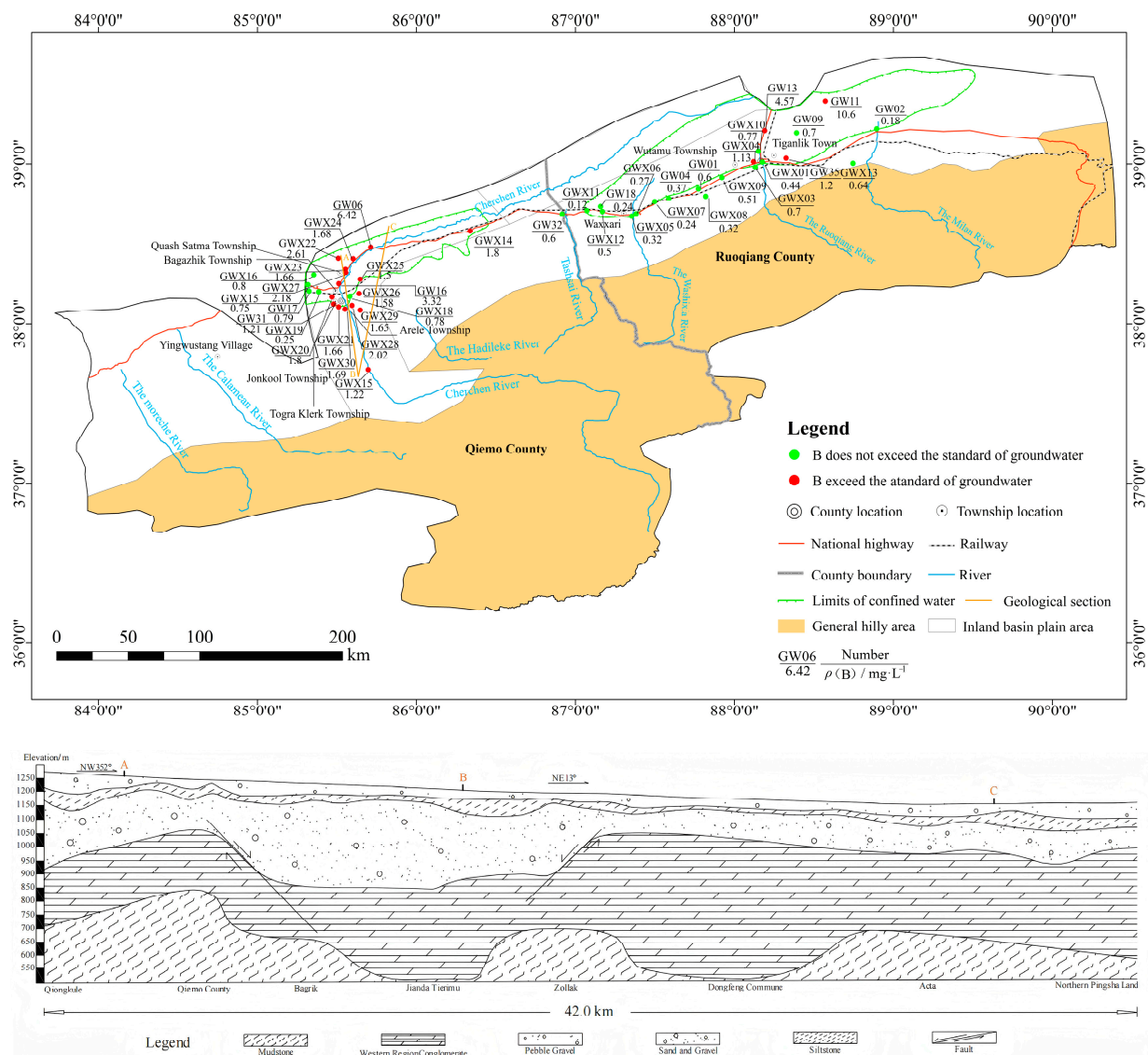


Figure 1. Distribution of groundwater sampling points and hydrogeological section in the Cherchen River Basin.

The topography of the Cherchen River Basin is generally high in the south and low in the north. The landforms in the plain area can be roughly divided into three types from south to north: the southern alluvial plain area, the central Cherchen River Valley plain area, and the northern eolian desert area. The outcropped strata is mainly Quaternary with fine sand and gravel as the main lithology, while is mostly distributed in the western conglomerate and mudstone are mostly distributed in the bottom. According to the type of aquifer, groundwater can be divided into single structure phreatic water and double-

layer structure phreatic-confined water. The groundwater depth ranges between 0.8 and 165 m [19]. The sampling points are distributed in the oasis area of a very narrow strip-shaped region. Hydraulic connection of phreatic water and confined groundwater in the confined water area is closely. In addition, since the groundwater in the confined groundwater area is extracted under the mixed phreatic-confined aquifer exploitation mode, no further classification of groundwater has been made. Groundwater is mainly recharged by river infiltration, canal system water, and irrigation water infiltration and lateral runoff recharge of piedmont rainstorm flood infiltration. Groundwater flows from southwest to northeast along the river. The main discharge mode of groundwater is phreatic evaporation, followed by lateral inflow and lateral outflow.

3. Materials and Methods

3.1. Sampling

In May 2023, 40 groundwater samples were collected in the study area (Figure 1), including 16 phreatic water samples and 24 confined water samples. Before groundwater sampling, according to the requirements of China's Groundwater Environmental Monitoring Technical Specification (HJ 164-2020) [20], the groundwater was pumped for more than 20 min, and the sampling was collected after the hydrochemical conditions tended to be stable. The sampling bottle was washed three times with the water sample. The water sample was filtered with a 0.22 μm microporous membrane and then acidified with 1:1 nitric acid to $\text{pH} < 2$ for cation analysis. After labeling, it was sealed and refrigerated at 4 $^{\circ}\text{C}$ for storage and determination.

3.2. Analytical Methods

The water temperature, conductivity (EC), dissolved oxygen (DO), redox potential (Eh), and pH value were measured on site by multi-parameter analyzer (HANNA, HI9828). According to the standard test method for drinking water (GB/T5750-2023) [21], K^{+} and Na^{+} were determined by flame atomic absorption spectrophotometry. Ca^{2+} , Mg^{2+} , HCO_3^{-} , CO_3^{2-} and total hardness (TH) were determined by ethylenediamine tetraacetic acid disodium titration. Cl^{-} was determined by silver nitrate volumetric method. SO_4^{2-} was determined by barium sulfate turbidimetry. NO_3^{-} was determined by ultraviolet spectrophotometry. F^{-} was determined by ion selective electrode method. Total dissolved solids (TDS) was determined by weighing method. B was determined by methylimine-H spectrophotometry. The reliability test was used to verify the accuracy of the results. It was found that the cation–anion balance error (E) values (-5.0% – -4.7%) of 40 samples were not greater than 5%.

3.3. Analysis Software

Principal component analysis (PCA) and multiple linear regression (MLR) were performed using SPSS 26.0, and the outliers ($>5\%$) in the data box were eliminated by the cation–anion balance test. The APCS-MLR was gradually achieved by the following methods: (1) calculating the absolute principal component score (APCS) of the standardized factor score matrix; (2) extracting the principal components by varimax rotation; establishing the source contribution rate equation; (3) using Monte Carlo simulation (1000 iterations) to evaluate the uncertainty.

4. Results and Discussion

4.1. Statistical Analysis of Conventional Chemical Index Content of Groundwater

The characteristic values of conventional chemical indexes of groundwater in the study area are shown in Table 1. It can be seen that the groundwater is weakly alkaline

as a whole, and the pH is between 7.35 and 8.33, with an average of 7.94. The ρ (TDS) of groundwater ranged from 641 to 151,239 $\text{mg}\cdot\text{L}^{-1}$, with an average of 6218 $\text{mg}\cdot\text{L}^{-1}$. Among them, fresh water [ρ (TDS) < 1000 $\text{mg}\cdot\text{L}^{-1}$] accounted for 33.3%, and brackish water and saline water accounted for 66.7%. Table 1 shows that the higher TDS in groundwater is mainly caused by higher Na^+ , Cl^- and SO_4^{2-} .

Table 1. Hydrochemical characteristic parameters of groundwater in oasis area of Cherchen River Basin.

Index	Boron Change Index	Maximum Value	Minimum Value	Mean Value	Standard Deviation	Coefficient of Variation
pH	1.00	8.33	7.35	7.94	0.23	0.03
TH	1.00	10,056	209	969	1681	1.74
TDS	1.00	151,239	641	6218	23,904	3.84
$\text{K}^+ + \text{Na}^+$	1.00	57,641	117	2053	9106	4.43
Ca^{2+}	1.00	1254	44	180	249	1.38
Mg^{2+}	1.00	1682	17	126	269	2.13
Cl^-	1.00	79,617	136	2846	12,580	4.42
SO_4^{2-}	1.00	10,978	84	916	1890	2.06
HCO_3^-	1.00	719	61	193	129	0.67
F^-	1.00	3.28	0.57	1.14	0.47	0.41
$\text{NO}_3^- - \text{N}$	1.00	20.34	0.06	3.72	4.82	1.30

Note: Except that the pH value and the coefficient of variation were dimensionless, the other parameter units were $\text{mg}\cdot\text{L}^{-1}$; n is the number of samples.

The average cation concentration of groundwater in the study area is $\text{K}^+ + \text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+}$, and the average anion concentration is $\text{Cl}^- > \text{SO}_4^{2-} > \text{HCO}_3^- > \text{NO}_3^- > \text{F}^-$. The coefficient of variation can reflect the spatial distribution difference of main ions in groundwater [22]. According to the coefficient of variation, only the coefficient of variation (CV) of pH is 1.0 among all the parameters of groundwater in the area, indicating that the spatial distribution of groundwater ion components is unstable, which is related to the distribution of different geomorphic types in the study area. Local areas may also be affected by human pollution.

4.2. Analysis of Groundwater Chemical Characteristics

The Piper three-line diagram has been widely used in the analysis of regional hydrogeochemical characteristics [23,24], and the changes of hydrochemical components can reflect the dynamic response of the effluent and the surrounding environment to a certain extent. Based on whether the percentage of milligram equivalent of major ions in groundwater is higher than 50%, the dominant ions and main hydrochemical types were determined [23,25], and the Piper three-line diagram of groundwater in the study area was drawn (Figure 2). From Figure 2, it can be seen that the cations of groundwater in the area are concentrated in Area D, and the dominant cations are mainly $\text{K} + \text{Na}$ type (68.8%), followed by non-dominant type (31.2%); the dominant anions are mainly Cl^- type (45.8%) and non-dominant (43.8%), followed by SO_4^{2-} type (8.3%) and HCO_3^- type (2.1%). According to the Shukalev classification method, there are 10 groundwater hydrochemical types in the study area, mainly $\text{SO}_4\cdot\text{Cl}\cdot\text{Na}$ type (29.3%), $\text{SO}_4\cdot\text{Cl}\cdot\text{Na}\cdot\text{Ca}$ type (12.0%), $\text{SO}_4\cdot\text{Cl}\cdot\text{Na}\cdot\text{Mg}$ type (10.3%), and $\text{SO}_4\cdot\text{Cl}\cdot\text{Na}\cdot\text{Ca}\cdot\text{Mg}$ type (5.1%). It shows that the enrichment degree of Na^+ , Cl^- , and SO_4^{2-} in the groundwater of the Cherchen River Basin is higher, followed by Ca^{2+} , Mg^{2+} , and HCO_3^- . Therefore, mineral dissolution may be an important factor controlling the hydrochemical types in the study area.

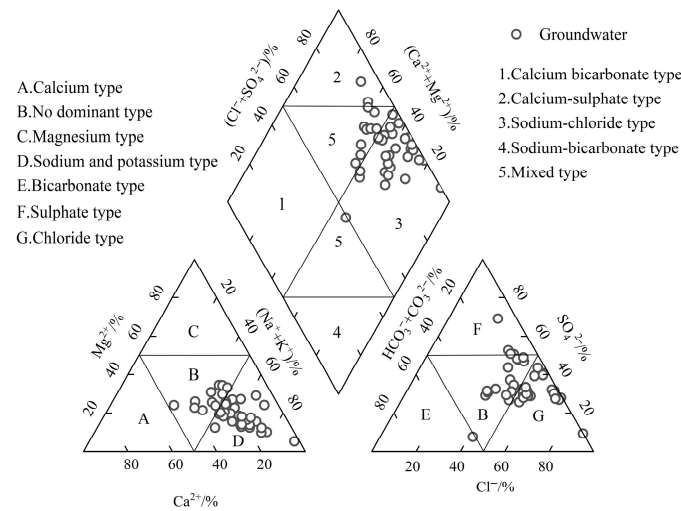


Figure 2. Piper diagram of main ions in groundwater.

4.3. Distribution Characteristics of Groundwater B

The ρ (B) in the groundwater in the oasis area of the Cherchen River Basin ranged from 0.12 to 10.60 $\text{mg}\cdot\text{L}^{-1}$, with an average of 1.48 $\text{mg}\cdot\text{L}^{-1}$ (Table 1). The average value of ρ (B) in groundwater is greater than 1 $\text{mg}\cdot\text{L}^{-1}$ (the limit of China’s drinking water health standard (GB 5749-2022)), and the highest value in groundwater is 10.6 times the limit. The high B groundwater are concentrated in the alluvial plain area, where agricultural activities with the application of B-rich fertilizer/pesticide are relatively concentrated, and soil B are relatively high in Qiemo County and Ruoqiang County. With the infiltration of agriculture irrigation water via soil, pollutants could enter the shallow groundwater and affect groundwater quality. Therefore, the causes of groundwater B-over-standard may be related to agricultural activities (large-scale use of B-containing fertilizers, B-containing insecticides and B-containing herbicides in agricultural production) [21].

4.4. Correlation Analysis Between B and Main Chemical Indexes in Groundwater

Correlation analysis can be used to determine whether the sources of groundwater ions are the same [26,27]. The correlation analysis between B and the main groundwater chemical indexes in the study area was carried out (Figure 3). The results showed that there was a significant positive correlation between B and TH, TDS, $\text{K}^+\text{+Na}^+$, Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , F^- ($r = 0.60\sim 0.76$), and there was a significant positive correlation between B and HCO_3^- ($r = 0.43$).

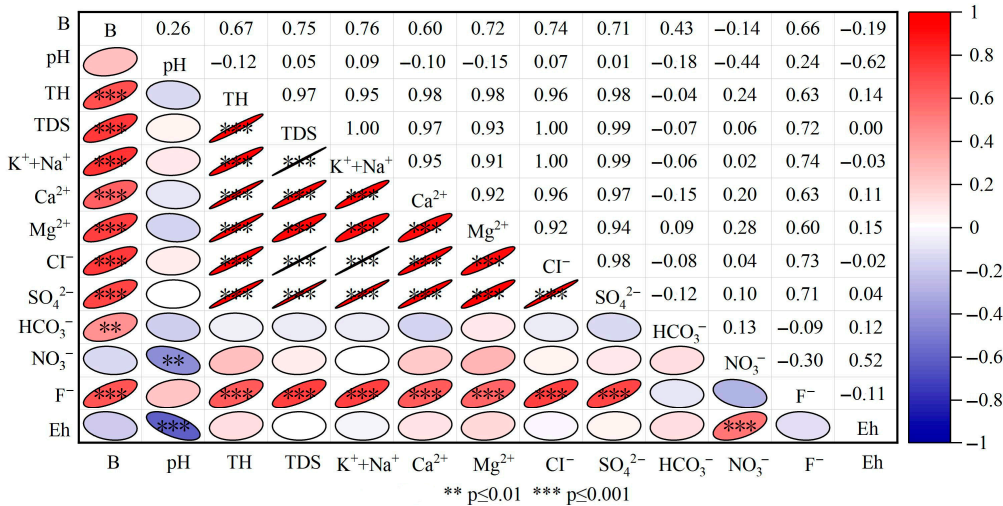


Figure 3. Pearson correlation matrix of hydrochemical parameters. (** and *** indicate that the correlation

coefficient is significant at the 0.01 level and 0.001 level, respectively. The long axis direction of the ellipse represents the positive and negative correlation coefficient. The upper right-lower left direction corresponds to the positive value, and the upper left-lower right direction corresponds to the negative value. The flatter the ellipse is, the larger the absolute value of the correlation coefficient is, and vice versa. The ribbon represents the range of the correlation coefficient).

There was a significant positive correlation between TH, TDS, K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- and SO_4^{2-} in groundwater in the study area, with the correlation coefficient $r > 0.91$, indicating the same source, which may be affected by the dissolution of evaporite or human activities [28].

5. Analysis of Chemical Causes of Groundwater

5.1. Rock Weathering

The interaction between groundwater and surrounding rocks or other water-bearing media leads to changes in the chemical composition of groundwater [29,30]. Gibbs diagram is often used to qualitatively determine the source of ions in river water by atmospheric precipitation, rock weathering, and evaporation concentration. The diagram was then improved to analyze groundwater [31,32]. The groundwater hydrochemistry in the oasis area of the Cherchen River Basin is mainly controlled by rock weathering and evaporation concentration (Figure 4). $\rho(Na^+)/\rho(Na^++Ca^{2+})$ and $\rho(Cl^-)/\rho(Cl^-+HCO_3^-)$ of most groundwater samples are greater than 0.5, indicating that groundwater Na^+ and Cl^- are the dominant ions. Some groundwater sampling points are located outside the control area, indicating that the groundwater quality in the study area may be affected by human activities.

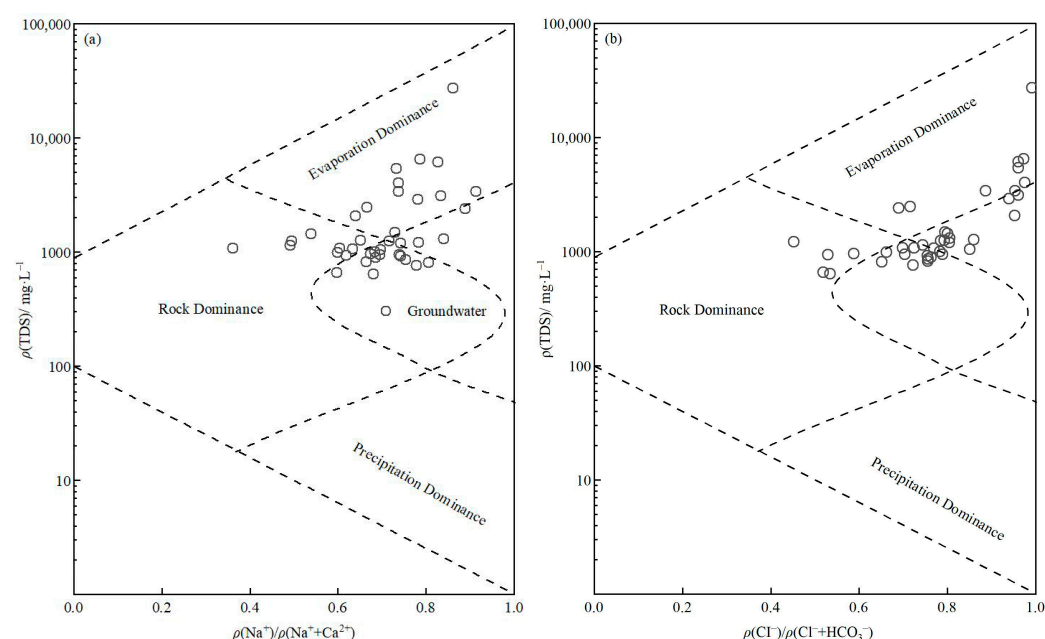


Figure 4. Gibbs diagram of groundwater (a) $\rho(TDS)$ vs. $\rho(Na^+)/\rho(Na^++Ca^{2+})$ and (b) $\rho(TDS)$ vs. $\rho(Cl^-)/\rho(Cl^-+HCO_3^-)$ in the study area.

The ion ratio can further determine the effect of different rock weathering on the chemical composition of groundwater [33]. The groundwater samples in the study area are between the evaporated salt rock and the silicate rock salt (Figure 5), which is more towards the silicate rock salt area, indicating that the rock weathering in the groundwater of the study area is mainly affected by weathering and dissolution of the silicate rock salt; a small

number of groundwater sampling points are close to the evaporite salt rock endmember, indicating that it is affected by the evaporite salt rock, especially the borate in the evaporite salt rock (symbiosis of borosilicate minerals, calcite and pyroxene dissolved in water under unsaturated conditions). Therefore it may be one of the sources of groundwater B.

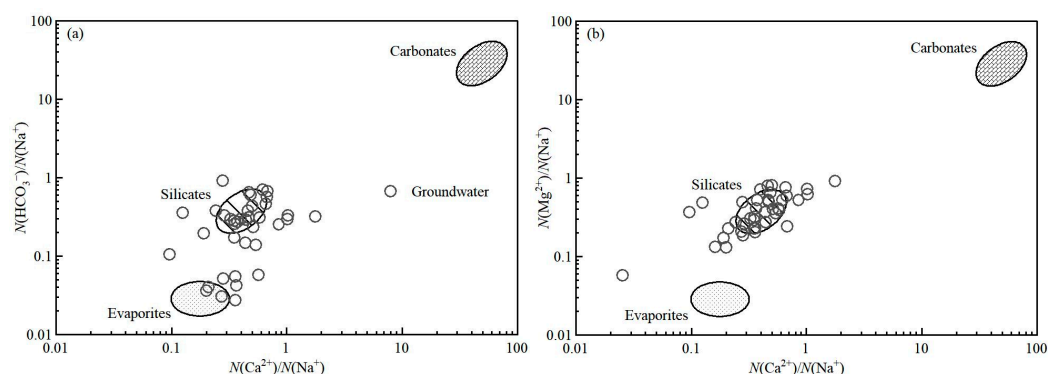


Figure 5. Endmember diagram of groundwater ion ratio (a) $N(\text{HCO}_3^-)/N(\text{Na}^+)$ vs. $N(\text{Ca}^{2+})/N(\text{Na}^+)$ and (b) $N(\text{Mg}^{2+})/N(\text{Na}^+)$ vs. $N(\text{Ca}^{2+})/N(\text{Na}^+)$ in the study area.

5.2. Hydrogeochemistry Modeling

The activity of various main components in groundwater and the saturation index of various minerals can be simulated using PHREEQC software (version 3). According to the test results of groundwater samples, 11 indexes including K, Na, Ca, Mg, Cl, S, C, pH, B, F, and N are selected for simulation. The main components of each index in the selected groundwater are shown in Table 2.

Table 2. Main elements in groundwater hydrochemical equilibrium model.

Element	K	Na	Ca	Mg	Cl	S	C	B	pH	F	N
chemical species	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	B	pH	F^-	NO_3^-

According to the PHREEQC simulation, groundwater B may occur as H_3BO_3 , H_2BO_3^- , $\text{BF}(\text{OH})_3^-$, $\text{BF}_2(\text{OH})_2^-$, BF_3OH^- , and BF_4^- . From Figure 1, the over-limit ratio of groundwater B near the Qiemo County, Ruqiang County and the Cherchen River is high (the concentration of B in the Cherchen River measured in May 2023 is $1.91\sim 3.23 \text{ mg}\cdot\text{L}^{-1}$); in the oasis irrigation area, along the Cherchen River, groundwater B tends to increase. H_3BO_3 is mostly used in industry, life, and fertilizer, and is easily soluble in water. Therefore, groundwater B may be derived from production and living pollution sources.

5.3. Impact of Human Activities

The oasis area of the Cherchen River Basin, including the oasis belt of Qiemo County and Ruqiang County (Figure 1), is dominated by agricultural activities, followed by industrial activities. Nitrate, chloride, and sulfate in groundwater are usually more sensitive components to pollutants produced by human activities [34]. Therefore, the relationship between Cl^- , Ca^{2+} , NO_3^- , and SO_4^{2-} ion ratios was used to study the effects of human activities on hydrochemical components. SO_4^{2-} is mainly derived from mining activities, whereas Cl^- , Ca^{2+} , and NO_3^- are mainly derived from agricultural activities, domestic sewage, etc. [35]. The groundwater in the study area has been affected by the combined effects of human activity emissions (e.g., detergents and disinfectants used in daily life) with urban sewage discharge (Figure 6a) [24] and natural sources, among which human activity emissions is the dominant factor. To further verify the impact of human activities, the ratio of NO_3^- , SO_4^{2-} , and Ca^{2+} in groundwater was shown in Figure 6b. It

indicated that groundwater is affected by both agricultural activities and industrial and mining activities (large-scale use of B-containing fertilizers, insecticides, and herbicides in agricultural production) [36].

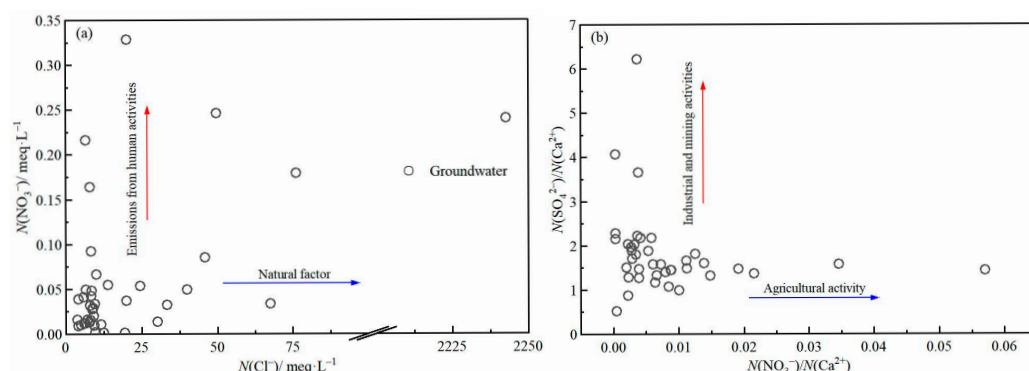


Figure 6. Effects of human activities on main ions in groundwater (a) $N(\text{NO}_3^-)$ vs. $N(\text{Cl}^-)$ and (b) $N(\text{SO}_4^{2-})/N(\text{Ca}^{2+})$ vs. $N(\text{NO}_3^-)/N(\text{Ca}^{2+})$ in the study area.

In July 2023, the mean values of ω (B) of soil of agricultural land in Qiemo County and Ruoqiang County were 60.41 and $52.62 \text{ mg}\cdot\text{kg}^{-1}$, respectively, both of which were higher than the background value of ω (B) of soil in Xinjiang ($40.90 \text{ mg}\cdot\text{kg}^{-1}$) [37]. During the irrigation period, B in the soil entered the groundwater along with the irrigation water, and result in the increase in groundwater B in the irrigation area.

6. Quantitative Assessment of Groundwater Chemical Composition Sources

6.1. Principal Component Analysis

Principal component analysis (PCA) can explain changes in hydrochemical data with fewer variables [38], and can help to determine the relationship and source of groundwater ions [39]. Before PCA, the applicability of the data should be checked using the Kaiser–Meyer–Olkin (KMO) method and Bartlett’s spherical test [38].

Principal component analysis was performed using 12 indicators (B, Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , HCO_3^- , NO_3^- , F^- , TDS, and TH) in 40 groundwater samples (Table 3). The KMO value was 0.644, and the significance level of Bartlett’s spherical test was close to 0, indicating that there was a strong correlation between the data and PCA could be carried out. A total of three principal components were extracted, and the cumulative variance contribution rate was 92.001%. The principal component F1 was the main controlling factor with the contribution rate of 66.909%. The main loads of F1 were K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , TDS, and TH, which were basically consistent with the results of correlation analysis, indicating that the chemical composition of groundwater was mainly affected by the dissolution of minerals such as silicate rock salt and evaporite rock, which was defined as the leaching-enrichment factor. The contribution rate of principal component F2 is 14.90%, and the main loads were B, NO_3^- , and F^- . NO_3^- concentration can reflect effects of human activities on groundwater component to a certain extent [40], which is defined as human activity factor. The contribution rate of F3 is 10.188% with the main load of HCO_3^- , which has a positive correlation with B and is defined as the primary geological factor [41].

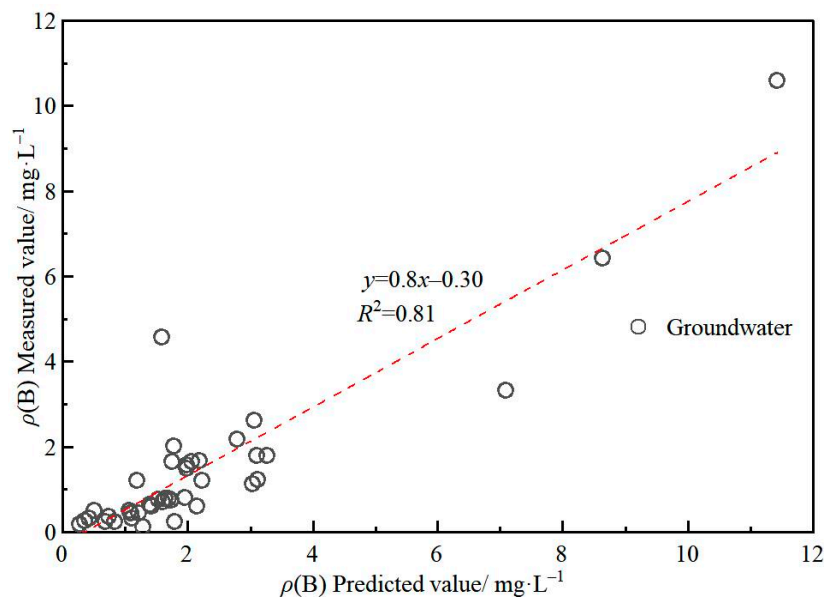
Table 3. Common factor eigenvalues and component matrix.

Total Variance Explained Rotated Component Matrix								
Common Factor	Initial Eigenvalue			Chemical Indicators	Common Factor			
	Total	Variance	Contribution Rate/%		1	2	3	
1	8.029	66.909	66.909	Mg ²⁺	0.994	−0.012	0.075	
2	1.788	14.904	81.813	TH	0.988	0.093	0.052	
3	1.223	10.188	92.001	K ⁺	0.984	−0.047	0.008	
4	0.700	5.834	97.834	TDS	0.982	−0.081	−0.002	
5	0.171	1.426	99.261	SO ₄ ^{2−}	0.982	0.164	0.015	
6	0.076	0.636	99.897	Cl [−]	0.975	−0.107	−0.009	
7	0.009	0.076	99.973	Na ⁺	0.974	−0.108	−0.007	
8	0.003	0.022	99.995	Ca ²⁺	0.901	0.273	−0.007	
9	0.001	0.005	100.000	F [−]	0.072	0.937	0.001	
10	0.000	0.000	100.000	B	0.458	0.645	0.552	
11	0.000	0.000	100.000	NO ₃ [−] -N	0.440	−0.557	0.226	
12	0.000	0.000	100.000	HCO ₃ [−]	−0.121	−0.066	0.964	

Note: The bold font indicates the highest load of the index of the factor.

6.2. Source Contribution Analysis of Groundwater B

On the basis of PCA, the APCS-MLR receptor model was used to analyze the contribution rate of each factor to the main ions in groundwater [35]. According to the analysis results of the APCS-MLR receptor model, a linear fitting (Figure 7) of the predicted results and groundwater B was established. The ratio of predicted to measured concentration is close to 1 ($R^2 = 0.81$), indicating that the constructed APCS-MLR receptor model is basically reliable [42].

**Figure 7.** Relationship between predicted and measured groundwater B.

According to the APCS-MLR receptor model, the contribution rate of each factor to each index in groundwater was calculated [43]. The results showed that (Figure 8 and Table 4) the contribution rates of leaching-enrichment factor (APCS1) to Na⁺, K⁺, Mg²⁺, Cl[−], SO₄^{2−}, TDS, and TH were 65.98%, 87.19%, 64.12%, 65.41%, 47.85%, 73.39%, and 51.40%, respectively, and the contribution to other indicators was small, indicating that weathering and dissolution of rocks were the main sources. The contribution rate of human activities

(APCS2) to B was 31.20%, indicating that human activities had a great influence on the enrichment of groundwater B, which was consistent with PCA.

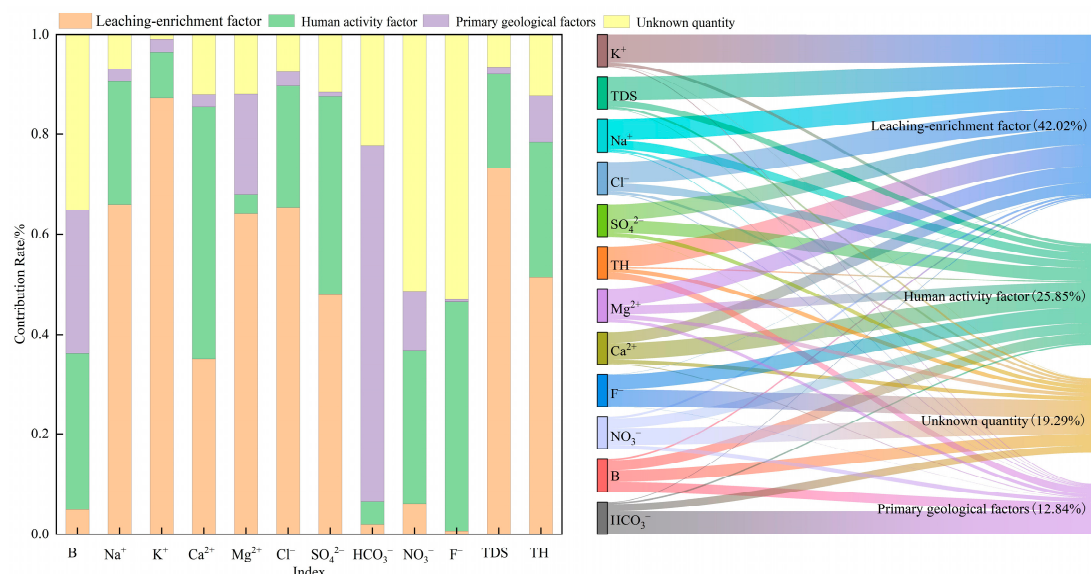


Figure 8. Contribution rate of different sources to B and main ions in groundwater.

Table 4. Contribution rate of different solute sources in groundwater.

Source	B	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	NO ₃ ⁻	F ⁻	TDS	TH
Leaching-enrichment	4.99	65.98	87.19	35.11	64.12	65.41	47.85	1.92	6.16	0.68	73.39	51.40
Human activities	31.20	24.70	9.29	50.36	3.94	24.25	39.78	4.69	30.67	45.74	18.65	26.93
Primary geology	28.66	2.41	2.65	2.52	20.03	2.85	0.84	71.09	11.68	0.48	1.42	9.40
Unknown sources	35.15	6.90	0.86	12.00	11.92	7.49	11.52	22.30	51.48	53.10	6.53	12.26

In addition, the unknown sources have a high contribution rate to B, NO₃⁻, and F⁻. Due to the limitations of the study including lack of seasonal monitoring, speciation analysis and isotopic tracing, there was merely preliminary speculation on the possible “unknown” sources. Possible recharge sources of B in groundwater will be further analyzed based on the coupling application of $\delta^{11}\text{B}$ and $\delta^{15}\text{N}$ for a better determination of different B and NO₃⁻ sources including precipitation, B-rich soil, river water, farmland drainage, chemical fertilizer, feces, and sewage, etc. [44].

On the whole, the contribution rates of leaching-enrichment factor, human activity factor, primary geological factor, and unknown sources to B and ion components in groundwater in the Cherchen River Basin are 42.02%, 25.85%, 12.84%, and 19.29%, respectively (Figure 8). Rock weathering is an important contribution source of major ions in groundwater, and human activities (especially agricultural activities) play an important role in the enrichment of groundwater B.

7. Conclusions

(1) The groundwater in the study area is weakly alkaline as a whole, with an average pH of 7.94. The groundwater is mostly brackish water and saline water. The decreasing order of cation concentration was K⁺+Na⁺, Ca²⁺, and Mg²⁺. The dominant cation was K⁺ + Na⁺ (68.8%), followed by non-dominant type (31.2%). The decreasing order of anion concentration was Cl⁻, SO₄²⁻, HCO₃⁻, NO₃⁻, and F⁻. The dominant anions are Cl type (45.8%) and non-dominant type (43.8%).

(2) The ρ (B) in groundwater is 0.12~10.60 mg·L⁻¹, with an average of 1.48 mg·L⁻¹, and the over-limit rate is 45.0%. There is a significant positive correlation between B and K⁺ +Na⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻, F⁻, and a significant correlation with HCO₃⁻, which is mainly affected by agriculture, industrial activities, and unknown sources, followed by the dissolution of silicate and evaporite (such as borate).

(3) According to the PCA-APCS-MLR receptor model, the B and hydrochemical components in groundwater are mainly derived from four sources, including leaching-enrichment factor, human activity factor, primary geological factor, and unknown sources, with contribution rates of 42.02%, 25.85%, 12.84%, and 19.29%, respectively. Rock weathering is an important source of major ions in groundwater, and human activity is an important factor for high B in groundwater.

(4) In order to reduce the health risk of drinking high B groundwater in the study area, the groundwater exploitation layout of the centralized drinking water sources in the urban area of Qiemo County and the decentralized drinking water sources in rural areas should be adjusted. The use of water supply wells in the high B groundwater distribution areas that have been identified from drinking water should be used for agricultural irrigation. The farmland irrigation wells with lower groundwater pollution risks in the low B groundwater distribution areas should be converted into drinking water supply wells.

(5) For the limitations of the study including lack of seasonal monitoring, the speciation analysis of B and the possible “unknown” sources, B isotope analysis, and mineral analysis of water-bearing media will be used for analysis of more detailed sources of high B groundwater in the future study, providing a decision-making basis for reducing the health risks of high B groundwater in the study area.

Author Contributions: J.D.: funding acquisition, project administration, investigation, conceptualization, data curation, writing—original draft. F.G.: methodology, software, conceptualization. J.Z.: funding acquisition, resources—review and editing. J.L.: data curation, writing—review and editing. Y.Z.: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by National Natural Science Foundation of China (42067035).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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