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Source apportionment and risk assessment of fluoride and boron in groundwater in the oasis area of Ruoqiang County, Xinjiang (postprint)

Authors: Deng Bo, Zhou Jinlong, Jiang Feng, Qiang Haowei

Date: 2026-01-30T16:53:16+00:00

Abstract

Ruoqiang County is located on the southern margin of the Taklimakan Desert, and the quality of its water resources is crucial for local living and production, ecological maintenance, and high-quality development. Based on 30 water samples collected from the oasis area of Ruoqiang County during 2023–2025, this study analyzes the hydrochemical characteristics and the controlling factors of their components, employs the absolute principal component-multiple linear regression model to resolve the sources of fluoride and boron in groundwater, uses the entropy-weight water quality index to evaluate groundwater quality, and applies a health risk assessment model to quantitatively evaluate the health risks posed by fluoride and boron via drinking water to different population groups. The results show that: (1) Groundwater in the study area is predominantly neutral to weakly alkaline. The exceedance rates of fluoride and boron in unconfined groundwater with a single-layer structure and in multilayer unconfined-confined groundwater are 61.54%, 82.35% and 0.00%, 29.41%, respectively. The main hydrochemical facies are Cl SO4-Na and Cl SO4-Na Ca types, jointly controlled by evaporation-concentration, rock weathering, and cation exchange. (2) Weathering and dissolution of various minerals such as boron-bearing silicate rocks, salts, and fluorite are important sources of fluoride and boron in groundwater; the formation of groundwater chemical components is mainly controlled by lixiviation-enrichment (71.76%), primary geological factors (13.32%), and anthropogenic activities (8.43%). (3) Groundwater quality shows a deteriorating trend over time, and the potential risk associated with excessive fluoride is much higher than that of boron, especially for children. Reducing the concentration of fluoride in groundwater is the primary measure for improving groundwater health risk in the study area.

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Full Text

Source Analysis and Risk Assessment of Fluoride and Boron in Groundwater in the Ruoqiang Oasis, Xinjiang

DENG Bo[1,2,3], **ZHOU Jinlong**[1,2,3], **JIANG Feng**[1,2,3], **QIANG Haowei**[1,2,3]

[1]College of Hydraulic and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, Xinjiang, China
[2]Xinjiang Hydrology and Water Resources Engineering Research Center, Urumqi 830052, Xinjiang, China
[3]Xinjiang Key Laboratory of Hydraulic Engineering Security and Water Disasters Prevention, Urumqi 830052, Xinjiang, China

Abstract

Ruoqiang County, situated on the southern margin of the Taklimakan Desert, relies critically on groundwater quality to sustain local livelihoods, economic production, ecological stability, and high-quality development. This study analyzed 30 groundwater samples collected from the Ruoqiang Oasis between 2023 and 2025 to investigate hydrochemical characteristics and their controlling factors. The absolute principal component score-multiple linear regression (APCS-MLR) model was employed to identify the sources of fluoride and boron in groundwater. Water quality was evaluated using the entropy-weighted water quality index (EWQI), while health risk assessment models were applied to quantify potential risks to different population groups from fluoride and boron exposure via drinking water. The results reveal: (1) Groundwater in the study area is predominantly neutral to weakly alkaline, with fluoride and boron exceedance rates of 61.54% and 82.35% in single-structure phreatic water, and 0.00% and 29.41% in multi-structure phreatic-confined water, respectively. The primary hydrochemical facies are $Cl \cdot SO_4$-Na and $Cl \cdot SO_4$-$Na \cdot Ca$ types, controlled synergistically by evaporation concentration, rock weathering, and cation exchange processes. (2) Weathering and dissolution of boron-bearing silicate minerals and fluorite constitute the primary sources of fluoride and boron. Groundwater chemistry is mainly controlled by leaching and enrichment (71.76%), followed by primary geological conditions (13.32%) and anthropogenic activities (8.43%). (3) Groundwater quality shows a deteriorating trend over time, with fluoride posing substantially higher health risks than boron, particularly to children. Reducing fluoride concentrations represents the principal measure for mitigating health risks associated with groundwater consumption in the study area.

Keywords: Ruoqiang County Oasis Area; fluoride in groundwater; boron in groundwater; source analysis; risk assessment

1. Introduction

Water is the source of life, essential for production, and the foundation of ecosystems—an indispensable natural resource for sustaining human activities and socio-economic development in arid and semi-arid regions. Water quality directly determines survival security, regional sustainability, and the lifeline of sustainable development. Intensified human activities and accelerated urbanization have introduced substantial quantities of industrial wastewater, agricultural drainage, and domestic waste into groundwater systems, causing continuous water quality deterioration and increasingly complex pollutant sources. Consequently, comprehensive water quality evaluation and assessment of pollutant risks are crucial for the rational development, utilization, and protection of local water resources.

Fluoride, an essential trace element for human health, exhibits dual threshold characteristics. Appropriate intake strengthens health, while excessive consumption ($>4.0\ \mathrm{mg \cdot L^{-1}}$) may cause skeletal fluorosis and dental fluorosis ($>1.5\ \mathrm{mg \cdot L^{-1}}$), and insufficient intake ($<0.5\ \mathrm{mg \cdot L^{-1}}$) increases dental caries prevalence. Boron is also indispensable for maintaining normal physiological functions in plants, animals, and humans. However, long-term excessive intake can cause chronic poisoning and organ damage, particularly to the liver and kidneys. According to China’ s *Standard for Drinking Water Quality* (GB 5749-2022), the maximum allowable concentrations are $1.0\ \mathrm{mg \cdot L^{-1}}$ for fluoride and $0.5\ \mathrm{mg \cdot L^{-1}}$ for boron. In arid and semi-arid regions, fluoride and boron occur naturally as dissolved constituents due to evaporation concentration or geological processes such as weathering of volcanic and sedimentary rocks. When concentrations exceed safety thresholds, the combined health hazards from fluoride and boron exposure pose significant regional public health challenges.

Ruoqiang County, the largest county in China by administrative area and a historically important passage on the ancient Silk Road, is rich in mineral resources. The region exhibits extreme aridity due to strong evaporation and scarce precipitation, with water resources being severely limited. Local residents depend primarily on groundwater for domestic and agricultural water supply, making groundwater quality critical for public health protection. Previous evaluations based on the $1.0\ \mathrm{mg \cdot L^{-1}}$ fluoride standard revealed that fluoride was the primary 超标 indicator, with exceedance rates reaching 85.7% and 21.4% at monitoring points. Long-term consumption of drinking water with elevated fluoride and boron concentrations increases the risk of endemic fluorosis and boron-related health problems. However, existing research on Ruoqiang Oasis groundwater has focused primarily on water resource evaluation and heavy metal analysis, with insufficient investigation into the sources and health risks of fluoride and boron. This study aims to: (1) comprehensively analyze groundwater hydrochemical characteristics and controlling factors; (2) quantitatively assess fluoride and boron sources using the APCS-MLR model; and (3) objectively evaluate regional water quality and potential health risks to different populations using EWQI and health risk assessment models, providing scientific support for rational groundwater development, effective protection, and sustainable utilization.

1.1 Study Area Overview

Ruoqiang County (36°05′~41°23′N, 86°45′~93°45′E) is located in the southeastern part of the Bayingolin Mongol Autonomous Prefecture, bordering Yuli County to the north, Qiemo County to the west, the Tibet Autonomous Region to the south, and Gansu and Qinghai provinces to the east. The oasis area, situated in the county' s plain region, covers 880.09 km^2. The phreatic water depth typically ranges from 4.4–26.15 m, while confined water depth ranges from 27.3-42.93 m. The region experiences a typical continental desert climate with an average annual temperature of 11.8°C, annual precipitation of only 28.5 mm, and evaporation as high as 2920.2 mm, classifying it as an extremely arid zone. Scarce precipitation, intense evaporation, and persistent northeasterly winds result in frequent sandstorms during spring and autumn. Geomorphologically, the study area comprises piedmont alluvial-proluvial gravel plains, alluvial fine-soil plains, alluvial plains, and aeolian desert zones.

The southern Altun Mountains consist of Paleoproterozoic medium-to-high-grade metamorphic rocks of the Altun Group, primarily comprising metamorphic gneiss, marble, and magmatic rocks that provide the main ore-forming materials for fluorite deposits. A super-large fluorite deposit is located approximately 25 km southwest of Kaerqiaer in the southeastern part of the study area. This hydrothermal filling-replacement deposit contains fluorite (CaF_2) and calcite ($CaCO_3$) veins, with fluorite ore reserves of 6631.23$\times10^{4}$ tonnes and mineral reserves of 2248.91$\times10^{4}$ tonnes, representing a super-large scale.

Groundwater in the study area occurs as Quaternary unconsolidated rock pore water and bedrock fissure water. The aquifer structure shows significant spatial differentiation from the piedmont to the fine-soil plain zone. The piedmont zone primarily contains single-structure phreatic aquifers in gravel belts, transitioning gradually northward into multi-layer aquifer systems with both phreatic and confined water in the plain area. Aquifer lithology exhibits a clear granulometric zoning pattern, with particle size gradually decreasing from south to north, transitioning from sandy gravel, sand-gravel, and medium-coarse sand in the south to medium-fine sand and silt-fine sand in the north. The plain area contacts the Altun Mountain massif via a compressional-torsional fault with distinct water-blocking properties, limiting lateral recharge from mountain fissure water to plain pore water. Groundwater recharge occurs primarily through infiltration of mountain spring water and outflow rivers (including valley underflow) in the alluvial fan area, flowing northward to the fan front before entering the plain zone where it receives additional recharge from canal seepage and irrigation return flow. Groundwater flow direction aligns with topographic slope, generally moving from south to north, with shallower burial depths along the flow path. Discharge pathways include phreatic evaporation, plant transpiration, artificial extraction, and lateral flow to downstream areas [Figure 1: see original paper].

1.2 Data Sources and Processing

In May 2023, groundwater sampling was conducted at 30 monitoring points (well depths 20-180 m) across the Ruoqiang Oasis, covering the entire oasis area within the Cherchen River Basin. Among these, GW01-GW02 and GW04-GW07 had historical monitoring data from May 2022, while GW05-GW07 had data from May 2021. Based on groundwater occurrence conditions, the 30 sampling points were classified into single-structure phreatic water (0.4–1.0 m depth, 13 points) and multi-structure phreatic-confined water (17 points). Sampling density complied with the *Groundwater Monitoring Technical Specification* (SL183-2005) requirements for groundwater quality monitoring station density.

Sample collection, preservation, and analysis followed the *Technical Specification for Groundwater Environmental Monitoring* (HJ 164-2020). Field records included coordinates, elevation, and surrounding environment. Pretreatment measures involved pumping 3–5 times the well volume to stabilize physicochemical parameters, followed by rinsing sample bottles 3 times with the target water. A multi-parameter water quality meter (HANNA HI9828) measured pH, water temperature, electrical conductivity (EC), oxidation-reduction potential (ORP), and total dissolved solids (TDS) in situ. Water samples for cation and trace element analysis were filtered through 0.45 μm membrane filters, acidified to pH < 2 with ultra-pure nitric acid in acid-washed high-density polyethylene bottles. Samples for anion analysis were stored in 250 mL plastic bottles without acidification. All bottles were sealed with Parafilm after ensuring no air bubbles and transported promptly for analysis.

The Xinjiang Geological Bureau Hydrogeological and Environmental Survey Center Laboratory analyzed major anions and cations, including K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, $SO_4{}^{2-}$, $HCO_3{}^-$, $CO_3{}^{2-}$, F^-, B, and TDS. Boron was analyzed by the Xinjiang Nonferrous Metals Geological Exploration Bureau Testing Center. Data reliability was verified using charge balance error (CBE), with all samples showing CBE < $±5^{-}$ and B concentrations in monitoring wells from 2023-2025 ranged from 0.03–0.23 and 0.11–0.31, respectively, indicating minor temporal variation. Therefore, this study used 2023 sampling data for source analysis and health risk assessment .

1.3.1 Entropy-Weighted Water Quality Index

Common water quality evaluation methods include single-factor assessment, Nemerow index, artificial neural networks, and the water quality index (WQI). The WQI has been widely applied for groundwater quality evaluation. However, traditional WQI methods involve substantial subjectivity in weight assignment. To reduce this subjectivity, the entropy-weighted water quality index (EWQI) was adopted, which determines weights based on entropy values calculated from water quality data, converting monitoring data into representative values that reflect water quality status with greater objectivity and precision.

The EWQI calculation follows standard procedures, with results classified into five categories: <50 (excellent, suitable for drinking), 51-100 (good), 101-150 (poor), 151-200 (very poor), and >200 (extremely poor) .

1.3.2 Health Risk Assessment

The health risk model provided by the United States Environmental Protection Agency (USEPA) has been extensively used to assess potential health risks from groundwater contaminants. While dermal contact and ingestion represent primary exposure pathways, drinking water ingestion is considered the dominant route for potential health risks. This study evaluated non-carcinogenic health risks from fluoride and boron exposure via drinking water for children and adults using the following model:

The average daily dose (ADD) for the ith contaminant is calculated as:

$$ADD_i = \frac{C_i \times IR \times ED \times EF}{BW \times AT}$$

where: - C_i = concentration of contaminant i in groundwater ($\mathrm{mg \cdot L^{-1}}$) - IR = ingestion rate ($\mathrm{L \cdot day^{-1}}$) - EF = exposure frequency ($\mathrm{days \cdot year^{-1}}$) - ED = exposure duration (years) - BW = body weight (kg) - AT = averaging time (days)

The hazard quotient (HQ) is calculated as:

$$HQ_i = \frac{ADD_i}{RfD_i}$$

where RfD_i is the reference dose for contaminant i. $HQ_i \leq 1$ indicates acceptable non-carcinogenic risk, while $HQ_i > 1$ suggests unacceptable risk. Exposure parameters for different populations were obtained from the *Chinese Exposure Factors Handbook*, and RfD values were sourced from the USEPA Integrated Risk Information System .

2. Results and Discussion

2.1.1 Statistical Characteristics of Parameters

Statistical analysis of 12 physicochemical indicators from 30 groundwater samples is presented in Table 4. Median values were used to represent overall hydrochemical composition due to the presence of extreme outliers. Groundwater pH ranged from 7.61-8.28 (median 7.90), indicating neutral to weakly alkaline conditions. Median pH values were 7.88 for single-structure phreatic water and 7.92 for multi-structure phreatic-confined water. TDS concentrations ranged from 600.60-10804.80 $\mathrm{mg \cdot L^{-1}}$ (median 2056.85 $\mathrm{mg \cdot L^{-1}}$), classifying most groundwater as brackish or higher salinity. Specifically, 46.15% of single-structure phreatic water and 5.88% of multi-structure phreatic-confined water were fresh (<1000 $\mathrm{mg \cdot L^{-1}}$), while 23.08% and 30.77% were brackish (1000-3000 $\mathrm{mg \cdot L^{-1}}$), and 30.77% and 52.94% were saline (3000-10000 mg • L^{-1}), respectively. No samples exceeded 10000 mg • L^{-1}.

The dominance of Na^+ (median 589.99 mg • L^{-1}) and Cl^- (median 631.45 mg • L^{-1}) reflects the influence of evaporation concentration on groundwater evolution. Fluoride concentrations ranged from 0.51-2.40 mg • L^{-1} (median 1.04 mg • L^{-1}), with exceedance rates of 61.54% in single-structure phreatic water and 82.35% in multi-structure phreatic-confined water. Boron concentrations ranged from 0.17-4.22 mg • L^{-1} (median 1.15 mg • L^{-1}), with exceedance rates of 29.41% and 0.00%, respectively. Dominant cations followed the sequence $Na^+ > Ca^{2+} > Mg^{2+}$ in both water types, while dominant anions were $Cl^- > SO_4{}^{2-} > HCO_3{}^-$ in single-structure phreatic water and $SO_4{}^{2-} > Cl^- > HCO_3{}^-$ in multi-structure phreatic-confined water.

2.1.2 Hydrochemical Types and Controlling Factors

Durov diagrams effectively illustrate hydrochemical types and key processes in groundwater formation [Figure 2: see original paper]. Groundwater evolution is primarily controlled by simple mineral dissolution and cation exchange. The Cl • SO_4-Na • Ca type accounts for 53.85% of single-structure phreatic water and 35.29% of multi-structure phreatic-confined water, followed by Cl • SO_4-Na type (38.46% and 35.29%, respectively). The Cl • SO_4-Na • Ca • Mg type represents 11.76% of multi-structure phreatic-confined water.

Gibbs diagrams, widely used to analyze controlling factors, identify three major processes: atmospheric precipitation, rock weathering, and evaporation concentration [Figure 3: see original paper]. Groundwater chemistry is primarily controlled by evaporation concentration and silicate weathering dissolution. Although groundwater tables are shallow, the extremely low annual precipitation (28.5 mm) has negligible influence on hydrochemical genesis. Conversely, intense evaporation (2920.2 mm annually) drives ion concentration. Some sampling points fall outside the Gibbs model, suggesting additional influences from cation exchange or anthropogenic activities.

The ratio of $Na^+/(Na^++Ca^{2+})$ versus TDS and Cl^-/Na^+ versus Ca^{2+}/Na^+ helps identify rock weathering contributions. Most samples plot in the silicate weathering dominance zone, indicating silicate dissolution as the primary water-rock interaction. Some points trend toward evaporite rocks, suggesting minor evaporite participation in chemical weathering.

2.2.1 Principal Component Analysis

Principal component analysis (PCA) was applied to explore variations in groundwater chemical components and identify ion relationships and sources. The Kaiser-Meyer-Olkin (KMO) test (0.64) and Bartlett' s sphericity test ($p < 0.001$) confirmed strong correlations among variables, satisfying PCA prerequisites. Three principal components were extracted, explaining 93.526% of cumulative variance.

Principal component 1 (PC1) explains 71.769% of variance with high loadings for Na^+, Cl^-, ${SO_4}^{2-}$, TDS, and F^-, representing the dominant factor controlling groundwater chemistry. PC1 reflects dissolution of silicate, evaporite, and fluorite minerals, with contribution rates of 71.68% for Na^+, 75.36% for Cl^-, 62.01% for ${SO_4}^{2-}$, 75.99% for TDS, and 78.19% for F^-. PC2 explains 13.322% of variance, with high loadings for B and ${HCO_3}^-$, attributed to primary geological factors related to rock leaching. The similarity in loadings suggests water-rock interaction with boron-bearing silicate minerals as the primary boron source. PC3 explains 8.435% of variance, with high loadings for ${NO_3}^-$ and Ca^{2+}, identified as an anthropogenic activity factor .

2.2.2 Source Apportionment of Fluoride and Boron

Building upon PCA, the APCS-MLR model systematically evaluated each factor' s contribution to groundwater constituents [Figure 4: see original paper]. PC1 (leaching and enrichment) contributes 71.76% to the chemical composition, PC2 (primary geological factors) contributes 13.32%, and PC3 (anthropogenic activities) contributes 8.43%. Under this hydrochemical background, fluoride sources can be further resolved by examining the relationship between F^- activity and Ca^{2+} activity. Fluoride concentration is controlled by fluorite equilibrium (K_{fluorite} = $10^{-10\cdot 6}$). When sampling points plot below the fluorite dissolution equilibrium line, fluorite precipitation occurs; points along the trend line indicate co-dissolution of fluorite and calcite in a 200:1 ratio. This demonstrates that fluoride originates from fluorite dissolution, with dissolution intensity controlled by calcite precipitation behavior. Calcite precipitation reduces Ca^{2+} activity, disrupting fluorite solubility equilibrium and driving further fluorite dissolution [Figure 4: see original paper].

2.3.1 Water Quality Assessment

The entropy-weighted water quality index (EWQI) comprehensively evaluates the influence of hydrochemical parameters on overall water quality. Based on 30 groundwater samples from 2023 and using the *Groundwater Quality Standard* (GB/T 14848-2017) with 12 indicators, EWQI values were calculated [Figure 5: see original paper]. The results show that 63.33% of groundwater is classified as "extremely poor" (EWQI > 200), 36.67% as "very poor" (151-200), with no samples in the "excellent" or "good" categories. Multi-structure phreatic-confined water has a slightly higher proportion of "extremely poor" water (69.23%) compared to single-structure phreatic water (58.82%). Temporal analysis of monitoring wells shows a declining proportion of "good" quality water and an increasing trend in "extremely poor" categories from 2023 to 2025.

Correlation analysis between EWQI and individual parameters reveals that TDS, Na^+, Cl^-, and ${SO_4}^{2-}$ show extremely strong positive correlations ($r > 0.88$), identifying these as primary water quality determinants. The highest correlation with EWQI is observed for Cl^- ($r = 0.96$). The deteriorating trend likely results from secondary salinization processes induced by agricultural (including forestry) irrigation under intense evaporation.

2.3.2 Health Risk Assessment

The southern mountainous area of Ruoqiang County contains abundant fluoride-bearing minerals. Weathering and dissolution of fluoride-rich rocks, followed by migration and enrichment under specific conditions, create high-fluoride groundwater. The discovery of boron in Ruoqiang groundwater in 2024 further reduces available water resources. Health risk assessment models were applied to quantify potential health risks from fluoride and boron exposure.

For children and adults, the median hazard quotients (HQ) for fluoride are 0.68 and 0.54, respectively. In single-structure phreatic water, fluoride HQ ranges from 0.31-0.91 for children and 0.25-0.73 for adults. In multi-structure phreatic-confined water, fluoride HQ ranges from 0.49-1.17 for children and 0.39-0.93 for adults. Boron HQ values are significantly lower, ranging from 0.02-0.10 for children and 0.03-0.08 for adults in single-structure phreatic water, and 0.04-0.77 for children and 0.03-0.61 for adults in multi-structure phreatic-confined water. No samples exceed the acceptable risk level ($HQ > 1$). Children' s non-carcinogenic risks exceed those of adults due to lower body weight resulting in higher daily exposure doses. Fluoride poses substantially higher potential risks than boron, particularly for children. Therefore, reducing fluoride concentrations should be the primary target for improving groundwater health risks in the region [Figure 6: see original paper].

3. Conclusions

This study investigated the hydrochemical characteristics, controlling factors, and sources of fluoride and boron, along with associated risks, in the Ruoqiang Oasis using statistical analysis, source apportionment, EWQI, and health risk assessment models. The main conclusions are:

(1) Groundwater in the Ruoqiang Oasis is predominantly neutral to weakly alkaline, mostly brackish or higher salinity, with multi-structure phreatic-confined water showing higher salinization than single-structure phreatic water. Fluoride concentrations range from 0.51-2.40 $mg \cdot L^{-1}$, with exceedance rates of 61.54% in single-structure phreatic water and 82.35% in multi-structure phreatic-confined water. Boron concentrations range from 0.17-4.22 $mg \cdot L^{-1}$, with exceedance rates of 29.41% and 0.00%, respectively. The primary hydrochemical types are $Cl \cdot SO_4$-Na and $Cl \cdot SO_4$-$Na \cdot Ca$, controlled by evaporation concentration and silicate weathering dissolution.

(2) Weathering and dissolution of boron-bearing silicate minerals and fluorite are the primary sources of fluoride and boron. Groundwater chemistry is influenced by three main factors: leaching and enrichment (71.76%),

primary geological conditions (13.32%), and anthropogenic activities (8.43%).

(3) EWQI and health risk assessment results indicate that 63.33% of groundwater is classified as "extremely poor," with a deteriorating trend likely caused by secondary salinization from agricultural irrigation under intense evaporation. Fluoride poses substantially higher health risks than boron, especially to children. Reducing fluoride concentrations is the principal measure for mitigating groundwater health risks in the study area.

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

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