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Hydrogeochemical characterization and water quality assessment in Altay, Xinjiang, northwest China

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Abstract The safety of drinking and irrigation water is an issue of great concern worldwide. The rational development and utilization of water resources are vital for the economic and societal stability of Altay, an extremely arid area. In this study, three types of water samples (25 river waters, 10 groundwaters, 6 lake waters) were collected from main rivers and lakes in Altay and analyzed for electrical conductivity, total dissolved solids, pH, major ions (i.e., K^+, Na^+, Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, F^-), and trace elements (i.e., Al, Li, B, Sc, Ti, Mn, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, I, Ba, U). The water quality index (*WQI*), hazard quotient, carcinogenic risk, Na percentage, and Na adsorption ratio were then calculated to evaluate the water quality for drinking and irrigation. The results showed that the main hydrochemical type of river waters and groundwaters was Ca-HCO_3, whereas that of lake water was mainly Na-SO_4. The *WQIs* (9.39–170.69) indicated that the water quality in Altay ranged from poor to excellent. The concentrations of As, Ni, and U need to be carefully monitored since their average carcinogenic risks (for all waters collected, for adults) reached 0.05686, 0.06801, and 0.14527 and exceeded the safety risk levels (10^{-4}–10^{-6}) by at least 568 times, 680 times, and 1452 times, respectively. The result of Na% and *SAR* indicated that lake waters (with *Na%* of 62.92 and *SAR* of 41.63) and groundwaters (with *Na%* of 37.88 and *SAR* of 5.58) in Altay were unsuitable for irrigation, while river water (with *Na%* of 29.24 and *SAR* of 3.33) could meet the irrigation quality requirements. The results of this study could help promote reasonable water resource use among three types of waters and population protection in Altay.

Keywords Hydrogeochemistry · Major ions · Trace elements · Water quality · Health risk assessment

Introduction

Humans need several trace elements to maintain health but only at trace levels (Chen et al., 2018;

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Mora et al., 2009; Tudi et al., 2019). Unfortunately, rapid developments in the global economy, increasing construction of factories, intensified mining, and wider use of motor vehicles, fertilizers, and herbicides, among others, have promoted the release of large amounts of trace elements into the environment (Cheng et al., 2018; Li and Zhang, 2010). When trace elements accumulate in the surrounding environment, they pose a threat to biology because of their toxicity (Xiao et al., 2019; Zeng et al., 2015). Previous studies indicated a certain relationship between increased exposure to As contamination in drinking water and increased risk of lung, skin, kidney, and bladder cancer (Tudi et al., 2019). U poses threats to human health mainly through drinking water; for example, U concentrations exceeding the recommended value of 30 μg/L in drinking water may harm the kidney (Bjørklund et al., 2020). Ni has carcinogenic effects and could lead to dermatitis (Zambelli et al., 2016). Furthermore, once accumulated in the human body, trace elements may require several decades for complete excretion (Tudi et al., 2019). Trace elements enter human body through several pathways, such as oral take, inhalation, and dermal contact. Drinking water and consumption of agricultural products are the two main pathways through which trace elements are ingested orally (Beccaloni et al., 2013; Doabi et al., 2018).

The majority of the pasture land of Xinjiang is used for cultivation. Among different regions in China, Xinjiang has the largest area of reclaimed land. The area of agricultural land in Xinjiang is approximately 51,718.7 thousand hectares, which ranks second in terms of agricultural land area in China. The agricultural land area in Altay accounts for 16.66% of the total of Xinjiang (China Statistical Yearbook, 2019; Xinjiang Altay Statistical Yearbook, 2017). As a result, owing to the large area of agricultural land in Altay, the trace elements in waters may be easily affected by the use of fertilizers and herbicides. On the other hand, nomadic life is quite common in Altay. For herdsmen, natural water that was simply treated in the wild during nomadic life is their main source of drinking water (Xinjiang Altay Statistical Yearbook, 2017). Besides, Altay is an extreme arid area (Li et al., 2006), so the rational and effective utilization of various types of water bodies is particularly important.

Apart from trace elements, major ions, such as Na^+, K^+, and SO_4^{2-}, could induce hazardous effects on waters for irrigation use and, thus, should be rigorously surveyed. High Na concentrations in irrigation water can lead to saturation and increase the salinity of agricultural soil, which interferes with the nutrient and water uptake of plants (Saleh et al., 1999).

Many investigations on water quality and associated health risk have been carried out worldwide, but these works mainly concentrated on industrial or mining areas with rapid economic development (Li et al., 2018; Oguri et al., 2018). However, less attention was paid to the quality of waters in farming, pastoral, and economically backward areas. Previous studies that focused on water resources and hydrogeochemistry in Xinjiang province were mainly conducted in the middle part, especially the Tarim River Basin. However, very few results on waters in Altay have been published. Research on hydrochemical features and water quality in Altay over the last two decades is generally limited. Knowledge of the concentration of trace elements in main rivers, lakes, and groundwater in Altay is vital to maintaining the health of the city's inhabitants and promoting sustainable development in the northwestern regions of China.

Based on the aforementioned consideration, we conducted a study on water quality and health risk assessment by the river, lake, and groundwater at Altay, Xinjiang province. This study aims to (1) investigate the trace elements and major ions in Altay waters and summarize their hydrological characteristics, (2) evaluate the quality of Altay waters for drinking and irrigation use, and (3) assess the health risk of the detected trace elements to humans exposed through ingestion. The results of this study are helpful for the effective management of water resources and the protection of residents from contamination of harmful components in local rivers, lakes, and groundwaters.

Materials and methods

Study area

Altay is located in the northern portion of Xinjiang Uygur Autonomous Region, northwest China. A geological map of the study area is shown in supplementary materials. The northwestern region of Altay is connected to Kazakhstan and Russia, and the northeast is bordered by Mongolia. Altay is an extremely arid area with annual precipitation of 200 mm and an evaporation of 1814.9 mm (Li et al., 2006). Altay is often monitored for serious drought events (Wu et al., 2015). Many tributaries in Altay originate from the southern part of the Altai Mountains and merge into the Irtysh River. Mountain rivers originate from the eastern portion of the Altai Mountains and merge into the Ulungur River (He, 2017).

The Irtysh River is the largest tributary of the Ebi River. After flowing out of Habahe County, the Irtysh River flows through Kazakhstan, enters Russian territory, merges into the Ebi River, and finally flows into the Arctic Ocean. The Irtysh River has a total length of 4,248 km, an area of 1.64×10^6 km^2. The Irtysh River is a critical water resource in the arid areas of Kazakhstan and Xinjiang Uygur Autonomous Region of China (Lei et al., 2012). The Ulungur River is an inland river of the Junggar Basin with a total length of 573 km and a total area of 3.79×10^4 km^2 (Wang & Jiang, 2000). It originates from the Altai Mountains in Qinghe County, flows from the east to the west through Fuyun County, and injects into Jili Lake. The river then flows through the Kuigo River over a distance of 8 km and finally merges into Ulungur Lake. Ulungur Lake and Jili Lake are mainly located in Fuhai County.

Sampling

In this work, 41 water samples, including 25 river water samples, 6 lake water samples, and 10 groundwater samples, were collected from Altay (Fig. 1, Table 1). Approximately 1.5 L of water was collected from each sampling site into a plastic bottle using a plexiglass water collector. Before water sample collection, the sampler and sample bottle were rinsed with distilled water and sample water. The sample number was noted on the plastic bottle, and the surrounding conditions of the sampled river or lake, including the presence of residents nearby or sources of pollution, were recorded. Water samples collected daily were stored in fridge at the work site before delivering to the laboratory. Parameters like pH, DO, EC, and TDS were analyzed in situ. Samples for NO_2^- detection were required to be sent to the laboratory immediately and tested immediately after the bottle is opened. The analysis of NO_2^- should be completed within 12 h from sampling. Other major ions and trace elements were tested within 15 days after sampling.

Analytical methods and quality control

The basic parameters of the water samples, such as their temperature, dissolved oxygen (DO), electrical conductivity (EC), TDS, and pH, were measured in the field using a multiparameter water quality analyzer (multi 3430, WTW GmbH, Germany).

All water samples were divided into two portions: (1) the original water without any processing and (2) another samples filtered through a polyethersulfone filter with a pore size of 0.45 μm. Exactly 30 mL of

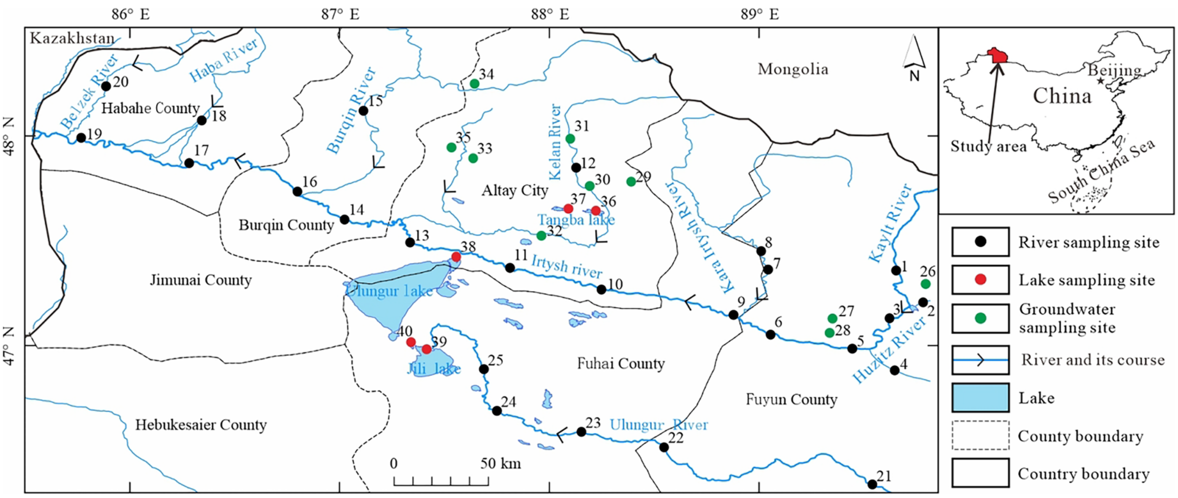


Fig. 1 The map of the study area and sampling sites. Note: Sampling site No. 41 is located in Aiding Lake, southern Xinjiang. The site is far from the Altay area and was not drawn on the map

Table 1 Sampling information of waters in Altay

Sampling time	Sampling number	Longitude	Latitude	Water type	Location
2019.10.9	1	89.6534	47.3577	River water	Kaylt river, tributary of Irtysh river
2019.10.9	2	89.7901	47.2096		tributary of Irtysh river
2019.10.9	3	89.5000	47.0000		Huzitz river, tributary of Irtysh river
2019.10.10	4	89.5261	46.9737		tributary of Irtysh river, close to Fuyun county central area
2019.10.9	5	89.5248	46.9851		Irtysh river, after tributaries 1, 2, 3, and 4 converged
2019.10.11	6	89.0562	47.0516		Irtysh river
2019.10.10	7	89.0400	47.4600		Kara Irtysh river, tributary of Irtysh river
2019.10.10	8	89.0110	47.4489		Kara Irtysh river, tributary of Irtysh river
2019.10.11	9	88.8786	47.1460		Irtysh river, after tributaries 7 and 8 converged
2019.10.11	10	88.2499	47.2670		Irtysh river
2019.10.11	11	87.8125	47.3707		Irtysh river
2019.10.13	12	88.1283	47.8482		Crane river, tributary of Irtysh river
2019.10.12	13	87.3377	47.4907		Irtysh river
2019.10.12	14	87.0253	47.6005		Irtysh river, after tributaries 12 converged
2019.10.12	15	87.1155	48.1198		Burqin river, tributary of Irtysh river
2019.10.12	16	86.8000	47.7339		Irtysh river, after tributaries 15 converged
2019.10.13	17	86.2846	47.8700		Irtysh river
2019.10.13	18	86.3449	48.0737		Haba river, tributary of Irtysh river
2019.10.13	19	85.7694	47.9907		Irtysh river, after tributaries 18 converged
2019.10.13	20	85.7058	48.0031		Belzek river, tributary of Irtysh river
2019.10.14	21	89.5405	46.3366		Ulungur river
2019.10.14	22	88.5486	46.5132		Ulungur river
2019.10.14	23	88.1535	46.5875		Ulungur river
2019.10.14	24	87.7513	46.6876		Ulungur river
2019.10.14	25	87.6891	46.8864		Ulungur river
2019.10.9	26	89.8167	47.2059	Groundwater	Water from a mine pit at Koktohai rare metal mine
2019.10.10	27	89.3305	47.0934		spring water
2019.10.10	28	89.3383	47.1009		Spring water
2019.10.19	29	88.3912	47.7812		Wuzhiquan spring
2019.10.19	30	88.1938	47.7598		Bokenbulake spring
2019.10.19	31	88.1013	47.9858		Spring water from Dadonggou
2019.10.19	32	87.9627	47.5232		Well water from Keletiekeyi village, Hongdun town
2019.10.19	33	87.6384	47.8930		Wutubulake spring
2019.10.19	34	87.6450	48.2481		Tasitebulake spring
2019.10.19	35	87.5342	47.9450		Taledebulake spring
2019.10.21	36	88.2256	47.6260	Lake water	Tangba lake (east)
2019.10.21	37	88.1276	47.6525		Tangba lake (west)
2019.10.11	38	87.5578	47.4228		Ulungur lake
2019.10.21	39	87.3753	47.0085		Jili lake
2019.10.13	40	87.3418	47.0161		Ulungur lake
2019.10.16	41	89.2536	42.6921		Aiding lake

the filtered water was collected into a polyethylene bottle and added with 0.3 mL of 7.5 mol/L nitric acids for preservation. All the samples were sent to the Chinese National Geological Experimental Testing Center for analysis: original water samples were analyzed to detect concentrations of major ions, while filtered water samples were analyzed for trace elements. Na^+, K^+, Ca^{2+}, and Mg^{2+} were detected by atomic absorption spectrometry method using plasma spectrometer (PE8300); HCO_3^- and CO_3^{2-} were determined by alkalimetric titration method; Cl^- and SO_4^{2-} were analyzed by ion chromatography method. Trace elements (Al, Li, B, Sc, Ti, Mn, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Mo, I, Ba, U) were analyzed by NexION 300D quadrupole inductively coupled plasma mass spectrometry (PerkinElmer, USA). The water samples collected in this study do not contain high concentrations of trace elements, so no dilution is required before detection.

In this study, quality control of the water sample analysis was conducted by following measurements: (1) reagent blank determinations were done during the batch determination of samples, (2) repeat samples were inserted randomly, and (3) standard recovery experiments were performed. The difference between the test results of repeat samples ranged from 2 to 5%, and the standard recovery rates were in the range of 90–110%; these values demonstrated that our analysis meet the quality requirements.

Maps of the sampling site and research area were constructed by ArcGIS 10.5. Box plots, piper diagrams, and other statistical graphs were drawn by OriginLab 2018.

Calculation

Water quality index

In this study, water quality was assessed by water quality index (*WQI*). WQI is widely used to characterize water quality (Sahu & Sikdar, 2008) and was calculated in this work as Eq. (1) (Şener et al., 2017):

$$WQI = \sum \left[RW_i \times \frac{Ci}{Si} \times 100 \right] \tag{1}$$

where RW_i represents the relative weight of parameter i, which is calculated by $\frac{w_i}{\sum w_i}$. *Wi* is a weight assigned to parameter i based on its effect on human health and importance in drinking water assessment. The weight and relative weight of the parameters were shown in supplementary material. We assigned As, Mn, and NO_3^- with a maximum weight of 5 because of their importance in drinking water assessment. Co, Ni, Zn, and U were assigned a minimum weight of 1 because of their insignificance in drinking water quality. Ci refers to the concentration of parameter i, and Si is the guideline value of parameter i from the Chinese state standard for drinking water (Ministry of Health, 2006). Chinese state standard for drinking water is abbreviated as CSS below.

Hazard quotient

The noncarcinogenic health risk caused by trace elements was characterized by the hazard quotient (*HQ*), which is the quotient of the average daily dose (*ADD*) and oral reference dose (*RFD*) of an element of interest. *ADD* was calculated by Eq. (2):

$$\mathrm{ADD} = \frac{\mathrm{C} \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \tag{2}$$

where *C* is the concentration of trace elements in μg/L and *IR* is the daily water consumption and assigned values of 2 L/day for adults and 0.63 L/day for children (Wang et al., 2017). The frequency of exposure (*EF*) is 365 days/year. ED refers to the duration of exposure and is assigned values of 70 years for adults and 6 years for children (USEPA, 2004). BW refers to the average body weight and is assigned values of 72 kg for adults and 15 kg for children in north China (Mahfooz et al., 2019; Rehman et al., 2018). AT refers to the average time of exposure. For noncarcinogenic risk, AT is assigned values of 25,500 days for adults and 2190 days for children. For carcinogenic risk assessment, AT is assigned values of 25,500 days for adults and children (USEPA, 2014). *HQ* was calculated by Eq. (3):

$$\mathrm{HQ} = \frac{\mathrm{ADD}}{\mathrm{RFD}} \tag{3}$$

Here, *RFD* values were obtained from the corresponding concentration tables provided in the official USEPA website and previous literature (Wu et al., 2009; USEPA, 2020). In the present study, we considered 11 trace elements, including Al, Li, B, Mn, Zn, Se, Sr, Mo, I, Ba, and U. Since trace elements enter the human body mainly by ingestion (Wang et al., 2017), only ingestion is taken into account in the present study (the same below). *HQ* values greater than 1 are believed to indicate potential adverse effects on human health (USEPA, 2004).

The hazard index (HI) can be used to evaluate the noncarcinogenic risk caused by mixed trace elements and is calculated by Eq. (4). HI values higher than 10 are believed to indicate potential noncarcinogenic risk to humans (USEPA, 2004):

$$HI=\sum_{n}^{i} HQ \tag{4}$$

Carcinogenic risk

Carcinogenic risk (*CR*) refers to the potential cancer risk over a lifetime due to exposure to trace elements such as As, Ni, Cd, and U. *CR* was evaluated by using Eq. (5):

$$CR=ADD \times CSF \tag{5}$$

where *CSF* is the cancer slope factor for individual trace elements. Previous studies revealed the *CSFs* for As, Ni, and U as 1.5, 0.84, and 0.4, respectively (Fakhri et al., 2018; Mahfooz et al., 2019;). Thus, in this study, *CRs* for As, Ni, and U were calculated.

The total carcinogenic risk (*TCR*) of trace elements can be calculated by Eq. (6):

$$TCR=\sum_{n}^{i} CR \tag{6}$$

where *CR* is the individual carcinogenic risk of each trace element and i is an element that can induce cancer risk.

Sodium percentage

Water quality for irrigation purposes can be evaluated in terms of salinity hazard (i.e., *EC*) and Na hazard (i.e., Na percentage, *Na%*, and Na adsorption ratio, *SAR*). Salinity hazard can be divided by *EC* value into four levels (Table 2).

Table 2 *WQI*, *HQ*, *HI*, salinity hazard, *Na%*, and *SAR* classes

Index	Value	Grade	Reference
WQI	$WQI < 50$	Water quality: excellent	Sahu and Sikdar (2008)
	$50 \leq WQI < 100$	Water quality: good	
	$100 \leq WQI < 200$	Water quality: poor	
	$200 \leq WQI < 300$	Water quality: very poor	
	$WQI \geq 300$	Water quality: unsuitable for drinking	
HQ	$HQ \leq 1$	Have no potential adverse effects on human health	USEPA (2004)
	$HQ > 1$	Have potential adverse effects on human health	
HI	$HI \leq 10$	Have no potential noncarcinogenic risk to humans	
	$HI > 10$	Have potential noncarcinogenic risk to humans	
Salinity hazard	$EC < 250$ μs/cm	Low	Richards (1954); Wilcox (1948)
	250 μs/cm $< EC <$ 750 μs/cm	Moderate	
	750 μs/cm $< EC <$ 2250 μs/cm	High	
	$EC > 2250$ μs/cm	Very high	
Na%	$Na\% < 20$;	Excellent	Qaisar et al. (2018)
	$20 < Na\% < 40$	Good	
	$40 < Na\% < 60$	Permissible	
	$60 < Na\% < 80$	Doubtful	
	$Na\% > 80$	Unsuitable	
SAR	$SAR < 10$	Low	Xiao et al. (2019); Raju et al. (2011)
	$10 < SAR < 18$	Moderate	
	$18 < SAR < 26$	High	
	$SAR > 26$	Very high	

$Na\%$ was calculated by Eq. (7). According to previous studies (Richards, 1954; Wilcox, 1948), $Na\%$ can be divided into five categories (Table 2):

$$Na\% = \frac{Na + K}{Ca + Mg + Na + K} \times 100 \tag{7}$$

Sodium adsorption ratio

SAR was calculated by Eq. (8).

$$\mathrm{SAR}=\frac{\mathrm{Na}}{(\mathrm{Ca}+\mathrm{Mg})^{0.5}} \tag{8}$$

SAR can be divided into four categories (Table 2).

Results and discussion

The statistical results of the physical and chemical parameters of Altay water are shown in Table 3. In general, the physical and chemical parameters of most Altay water samples met the safety requirements specified in the CSS guidelines for drinking water. Given 41 water samples and 18 physicochemical parameters for which safety values were available, 94.99% of the obtained figures did not exceed the threshold value.

Characterization of geochemical facies

Water samples in Altay were alkaline with a pH ranging from 7.032 to 8.969. *EC* values were in the range of 67.2–5630 μs cm^{-1}. The sample with the highest pH and *EC* was obtained from Tangba lake, whereas the lowest pH and *EC* were determined in two spring water samples (Table 3).

Ten water samples from the Irtysh River had an average pH of 8.19 and EC of 278.25 μs/cm. The average pH and *EC* of samples obtained from the Ulungur River were 8.18 and 612.4 μs/cm, respectively. Ten groundwater samples had an average pH and *EC* of 7.45 and 656.12 μs/cm, respectively, and 6 lake water samples had an average pH and *EC* of 8.06 and 2138.98 μs/cm, respectively. Compared with river water (with average *EC* of 395.82 μs/cm) and groundwater (with average *EC* of 656.12 μs/cm), lake water (with average EC of 2138.98 μs/cm) had higher EC values, which may be caused by the intense evaporation of lake water.

Owing to the stronger water–rock reaction degree of groundwater and the more closed environment of lakes compared to river water, lake water (1069.49 mg/L), and groundwater (328.06 mg/L) in Altay had remarkably higher TDS and ion concentrations than river water (197.91 mg/L). For river waters, water samples from the Ulungur River had higher TDS values and ion concentrations compared with those obtained from the Irtysh River and its tributaries. The highest ion concentrations in river water were found in the tributaries of the Irtysh River in Fuyun County, which may be affected by the discharge of domestic sewage from residential areas (according to the field record of sampling sites, only this sampling point in the river water samples is located in the center of the residential center).

Hydrochemical piper diagrams can help evaluate geochemical facies (Piper, 1944); thus, the major cations and anions of water samples in Altay were plotted in a piper diagram (Fig. 2). Because the K^+ concentration is very low with a milliequivalent percentage of 0.42 to 2.36% in natural water and shows similar characteristics of Na^+, the two ions were calculated together in Fig. 2. The 80% water samples from Irtysh River, 70% samples of the tributaries of Irtysh River, and 80% of groundwater samples showed the following features, i.e., higher concentrations of alkaline earth metal ions than alkali metal ions and greater weak acid contents than strong acid contents. For all 25 river water samples and 10 groundwater samples, higher concentrations of alkaline earth metal ions were witnessed than those of alkali metal ions. However, for lake water samples, compared with those of alkali metal ions, half of them had higher concentrations of alkaline earth metal ions; others did not (Fig. 2). Water samples from Altay varied in the geochemical facies. The water types in this study were $Ca\text{-}HCO_3$ (main type, including 18 river water samples, 9 groundwater samples, and 2 lake water samples), $Na\text{-}SO_4$ (4 lake water samples), and $Ca\text{-}SO_4$ (7 river water samples and 1 groundwater sample from a well in a village).

Correlations among major ions in Altay waters

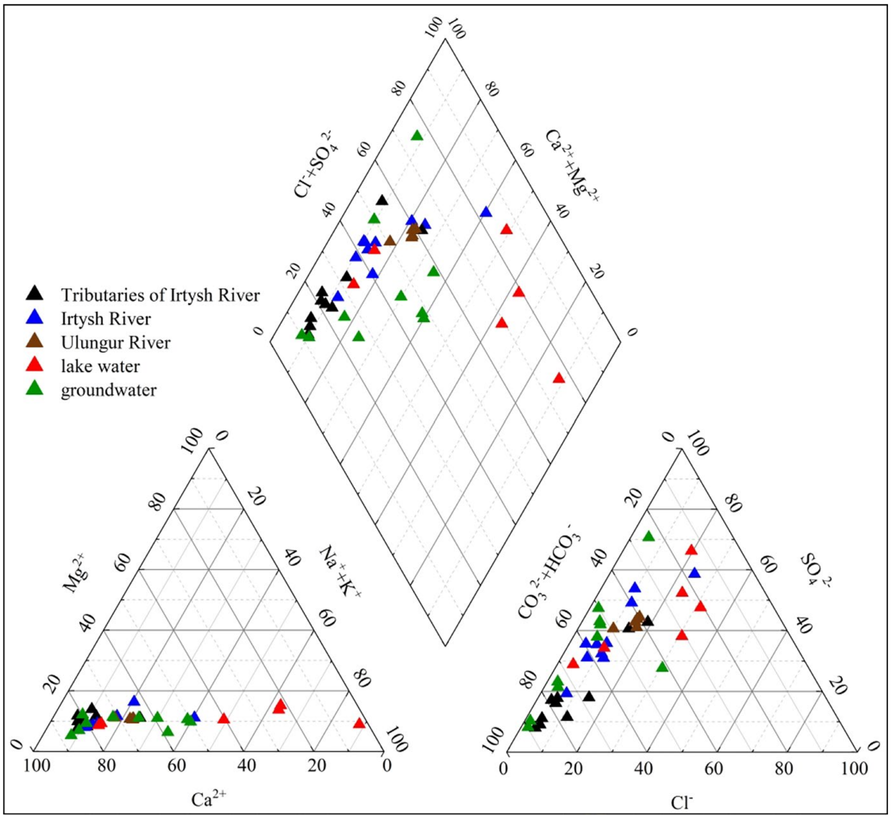
The most abundant cation in natural water was Ca^{2+}, the main source of which is the dissolution of gypsum, calcite, and dolomite. Altay water was mainly dominated by the cations Ca^{2+} and Na^+ and the

Table 3 Statistical results of physical and chemical parameters and the guideline values of waters in Altay

Parameters	River water				Lake water				Groundwater				Guideline
	Min	Max	Ave	SD	Min	Max	Ave	SD	Min	Max	Ave	SD	values
pH	7.65	8.75	8.15	0.32	7.19	8.97	8.06	0.67	7.03	8.35	7.45	0.44	6.5–8.5
DO (mg/L)	8.03	10.40	8.83	0.55	3.32	8.71	6.14	2.27	5.2	9.96	7.77	1.32	/
EC (µs/cm)	86.70	2900.00	395.82	568.32	182.10	5630.00	2138.98	2013.50	67.20	1553.00	656.12	431.51	/
TDS (mg/L)	43.35	1450.00	197.91	284.16	91.05	2815.00	1069.49	1006.75	33.60	776.50	328.06	215.76	1000
K^+ (mg/L)	2.03	395.00	32.93	77.88	8.84	1272	396.23	467.91	2.16	132	49.82	38.38	/
Na^+ (mg/L)	10.50	209.00	37.66	41.22	16.4	104	49.3	36.04	9.67	300	82.22	85.15	200
Ca^{2+} (mg/L)	1.51	57.70	7.69	11.35	3.07	68.1	34.27	27.16	1.36	22.2	11.45	6.81	/
Mg^{2+} (mg/L)	11.70	316.00	91.29	67.29	52.7	832	330.93	314.78	35.8	387	205.38	110.62	/
HCO_3^- (mg/L)	1.19	261.00	21.95	51.55	3.06	489	201.5	193.39	0.38	51.5	15.66	15.97	/
Cl^- (mg/L)	3.55	855.00	82.64	169.75	25.9	1451	527.2	523.06	3.28	600	147.79	178.63	250
SO_4^{2-} (mg/L)	0.78	8.47	2.68	2.00	BDL	6.25	3.01	2.42	1.12	29.4	8.24	9.01	250
NO_3^- (mg/L)	BDL	0.23	0.08	0.06	BDL	0.81	0.31	0.34	BDL	0.01	0.01	0	10
NO_2^- (mg/L)	0.07	0.92	0.24	0.18	0.19	6.49	1.85	2.41	0.05	1.85	0.77	0.63	/
F^- (mg/L)	1.07	27.40	5.74	5.42	2.94	38.73	20.21	15.06	0.68	29.82	14.15	9.88	/
Li (µg/L)	BDL	370.00	60.00	82.53	19.9	2175	641.32	797.4	BDL	200	75.51	56.89	/
B (µg/L)	BDL	30.00	20.00	5.11	0.53	30	11.03	10.31	BDL	20	8.07	8.96	500
Al (µg/L)	2.14	10.00	5.13	2.09	0.19	10.4	4.09	4.53	0.44	16.3	4.9	6.34	200
Sc (µg/L)	BDL	6.20	5.85	0.40	BDL	6.38	3.01	2.85	0.41	9.22	2.84	3.7	/
Ti (µg/L)	BDL	173.00	23.66	44.12	BDL	51.44	15.45	24.1	BDL	34.6	10.34	16.3	/
Mn (µg/L)	BDL	3.76	/	/	BDL	0.28	0.18	0.1	BDL	0.48	0.15	0.16	100
Co (µg/L)	BDL	11.60	2.83	2.39	1.26	5.33	2.63	1.61	0.59	9.8	3.23	2.75	50*
Ni (µg/L)	BDL	6.84	3.82	2.62	BDL	2.72	1.49	0.85	BDL	3.98	1.12	1.3	20
Cu (µg/L)	2.11	33.70	8.33	7.16	0.63	14.4	5.56	6.52	0.23	6.82	2.18	2.4	1000
Zn (µg/L)	BDL	0.98	0.53	0.27	0.57	11.1	4.45	3.83	0.13	4.14	1.25	1.56	1000
As (µg/L)	BDL	0.35	0.18	0.10	BDL	18.26	6.03	8.29	BDL	6.07	1.82	1.91	10
Se (µg/L)	BDL	3.88	1.63	1.02	BDL	3.92	2.05	1.32	BDL	5.19	1.59	2.22	10
Rb (µg/L)	45.30	2285.00	316.55	460.09	145	2120	800.08	718.69	5.97	864	323.39	290.1	/
Sr (µg/L)	BDL	22.20	3.15	4.83	1.21	26.11	10.7	10.52	BDL	20.28	7.56	6.41	/
Mo (µg/L)	BDL	44.00	7.14	8.61	4.62	124	28.75	46.87	1.23	47.3	16.75	13.61	70
I (µg/L)	4.23	45.30	18.38	12.98	8.86	61.4	33.58	24.01	0.39	46.36	20.93	17.73	/
Ba (µg/L)	BDL	62.50	8.57	13.57	1.36	108.24	23.96	41.73	0.13	42.1	15.9	13.41	700
U (µg/L)	35.30	2900.00	465.76	662.23	124.8	5630	1834.27	2174.6	67.2	1553	602.22	413.45	30*

*The guideline values of Co and U are from WHO (World Health Organization., 2011). The standard of U is a tentative guideline value. The others are based on China State standards (CSS). BDL means below detection limit. Detection limit for NO_2^-(0.002 mg/L), F^-(0.04 mg/L), for trace elements in µg/L: Al(10), Li(1), B(10), Sc(1), Ti(5), Mn(1), Co(1), Ni(1), Cu(2), As(0.01), Se(0.01), Rb(1), Mo(1), I(1), Ba(50), U(1)

Fig. 2 A piper diagram of waters in Altay



anions HCO_3^- and SO_4^{2-}. Some of the major ions in Altay water showed a definite positive correlation (Fig. 3). The molar concentration of Ca^{2+} and SO_4^{2-} in most river water samples and groundwater samples were close to the evaporation line of $CaSO_4$, thus indicating that the source of Ca^{2+} and SO_4^{2-} in most river waters and groundwaters in Altay water is probably the dissolution of gypsum. Most of the lake water samples are far away from the 1:1 evaporation line of $CaSO_4$, indicating that the Ca^{2+} and SO_4^{2-} in lake water were not all derived from the dissolution of gypsum.

The concentrations of Mg^{2+} and HCO_3^- in waters in Altay were far from the evaporation line of $Mg(HCO_3)_2$, because Mg^{2+} is mainly derived from the dissolution of dolomite but HCO_3^- is derived from the dissolution of calcite and dolomite. Thus, Mg^{2+} increases with the HCO_3^- concentration, but the molar concentration of the former is much lower than half of that of the latter.

Except for several lake water samples with high Na^+ concentration, the molar concentrations of Na^+ and Cl^- in rivers were relatively close to the evaporation line of NaCl, which indicates that Na^+ and Cl^- may be derived from the dissolution of soluble salts, such as NaCl. The concentration of Cl^- varied over a wide range, while the K^+ concentration maintained stable levels. This indicates that K^+ is not entirely derived from the dissolution of KCl. K^+ in Altay water may be related to the mineral weathering process. For example, weathering of K feldspar into kaolin can produce free K^+ (Berner, 1980). Because the CO_2 content involved in the weathering process of the environment is relatively stable, the K^+ concentration in water does not change remarkably in different areas without anthropogenic contributions. The chemical equation for the weathering of K feldspar into kaolin is as follows:

$$2KAlSi_3O_8 + 2CO_2 + 11H_2O = Al_2Si_3O_5 + 2K^+ + 2HCO_3^- + 4Si(OH)_4$$

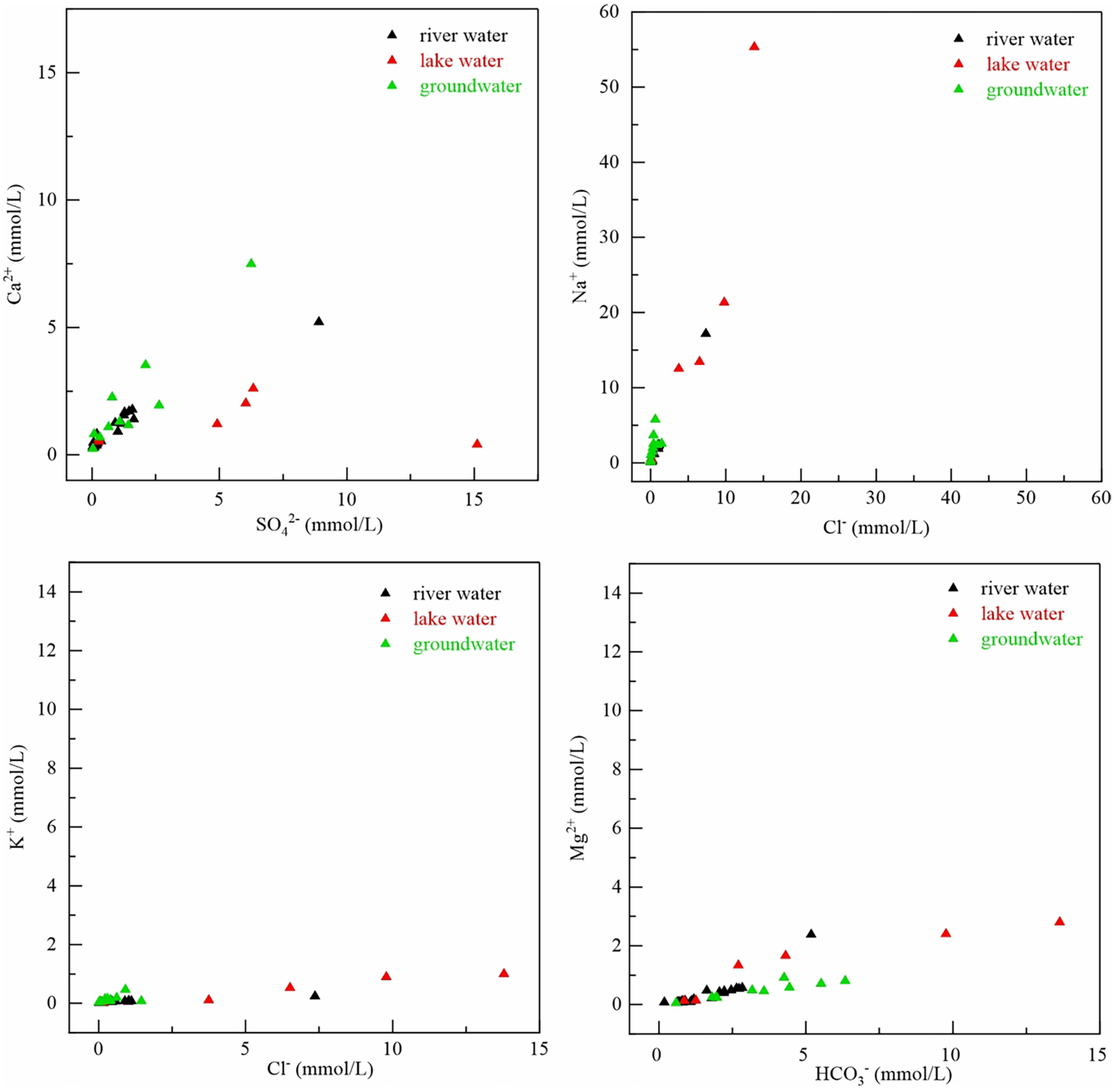


Fig. 3 Correlations among major ions in waters in Altay

Trace element concentrations in Altay waters

Statistical characterizations of the trace elements detected in Altay water are shown in Table 3 and Fig. 4. The average concentrations of Al, Li, B, Sc, Ti, Mn, Ni, Zn, As, Se, Rb, Sr, Mo, I, Ba, and U in 25 river water samples obtained were 20, 5.75, 60, 5.13, 5.85, 23.66, 2.83, 0.53, 0.18, 1.63, 316.55, 3.15, 7.14, 18.38, and 8.57 µg/L, respectively.

Among the three types of water samples, lake water showed the highest average concentrations of Li (641.32 µg/L), B (11.03 µg/L), As (6.03 µg/L), Se (2.05 µg/L), Rb (800.08 µg/L), Sr (10.7 µg/L), Mo (28.75 µg/L), I (33.58 µg/L), Ba (23.96 µg/L), and U (1834.27 µg/L). River water had the highest concentrations of Al, Sc, Ti, Mn, Ni, and Cu. However, groundwater revealed the highest concentrations of Co. The concentration of several trace elements in

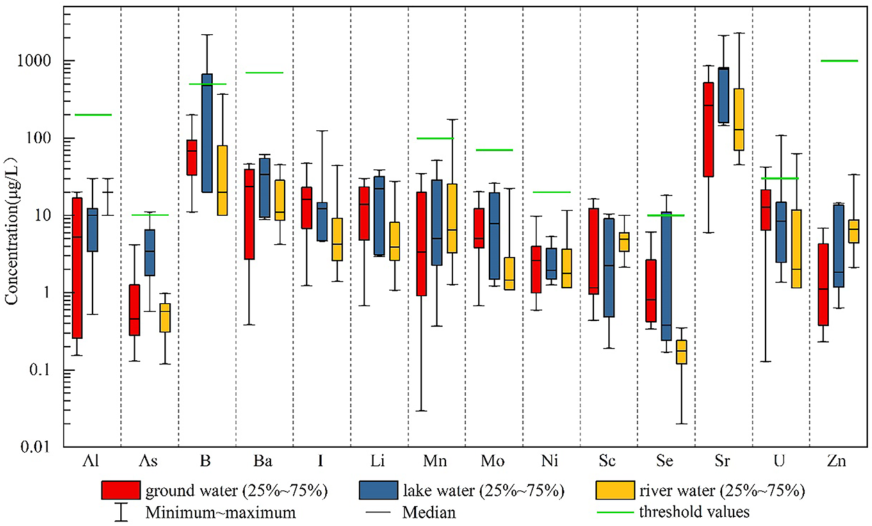


Fig. 4 A boxplot of trace element concentrations of waters in Altay. Note: Threshold values of Co and U are from WHO (World Health Organization., 2011) Others are based on CSS

seven water samples exceeded the threshold values of the CSS and WHO safety standards. For instance, the respective U concentrations of samples No. 4 (river water near a residential area), No. 37 (Tangba lake west), No. 28 (spring water), and No. 32 (well water) were 2.08 and 1.4 times greater than the threshold value of WHO, and the respective Mn concentrations of samples No. 14 (Irtysh River) and No. 15 (Burqin River, a tributary of the Irtysh River) were 1.5 and 1.73 times greater than CSS standards. The B concentrations of water from Aiding lake, Jili lake, and Tangba lake west were generally high and exceeded the threshold value specified in the CSS. The U concentration of river waters (25 samples with an average value of 8.57 μg/L), groundwaters (10 samples with an average value of 15.90 μg/L), and lake waters (6 samples with an average value of 23.96 μg/L) were higher than the average value of all rivers (4.98 μg/L), and all well water or spring water (6.08 μg/L) in Xinjiang (Wang et al., 2016) also was higher than the values of drinking water in other areas in China, such as Inner Mongolia (8.2 μg/L, Tian et al., 2013), Gansu (3.4 μg/L Li, 1996), and Guangzhou (0.185 μg/L, Peng et al., 2012). No. 4 sampling site is near the residential area, so the high U concentration may derive from an anthropogenic source. The sampling site 37 (Tangba lake west, located in downtown Altay) was witnessed to have the highest concentration of U (108.24 μg/L), which may be the combined effects of high evaporation of lake water and human activities in Altay City. On the other hand, Altay features several types of rare-metal resources, such as Li, Be, Rb, Sr, and U, so enrichment of U resources may explain the high concentration of this element in the No. 33 spring water sample and No. 32 well water sample. Since Aiding lake is relatively far from residential and industrial agricultural areas, the high concentration of B from Aiding lake is mainly because of the high evaporation of Aiding lake. There are coal mines under exploitation in Burqin County, which may be the main reason for the high Mn concentration at sampling Nos. 14 and 15. The trace elements U, Mn, B, As, and Se are likely to pose threats to residents in Altay and should be monitored carefully by the public. Moreover, the quality of some water sources in Altay, such as river sections near residential areas, lakes, and springs, must also be meticulously observed.

Drinking and irrigation water quality

The results of *WQIs* for Altay waters were shown in Table 4 and Fig. 5. Except for 4 lake water samples, 1 groundwater sample, and 1 river water samples, the quality of the remaining 35 water samples was classified as excellent. The two river water samples with water quality of good (sampling No. 4 and sampling

Table 4 *WQIs* for individual water samples in Altay

Sample number	Location	*WQI*	Eater type
1	Kaylt river	10.07	Excellent water
2	Unnamed river	15.89	Excellent water
3	Huzitz river	11.73	Excellent water
4	Unnamed river	73.96	Good water
5	Irtysh river	12.97	Excellent water
6	Irtysh river	11.86	Excellent water
7	Kara Irtysh river	12.83	Excellent water
8	Kara Irtysh river	12.62	Excellent water
9	Irtysh river	13.79	Excellent water
10	Irtysh river	14.58	Excellent water
11	Irtysh river	15.20	Excellent water
12	Kelan river	11.80	Excellent water
13	Irtysh river	19.71	Excellent water
14	Irtysh river	42.89	Excellent water
15	Burqin river	30.36	Excellent water
16	Irtysh river	22.89	Excellent water
17	Irtysh river	13.58	Excellent water
18	Haba river	10.71	Excellent water
19	Irtysh river	18.18	Excellent water
20	Belzek river	13.19	Excellent water
21	Ulungur river	20.10	Excellent water
22	Ulungur river	21.44	Excellent water
23	Ulungur river	26.31	Excellent water
24	Ulungur river	24.64	Excellent water
25	Ulungur river	21.17	Good water
26	Water from mine pit	17.74	Excellent water
27	Spring water 2	33.99	Excellent water
28	Spring water 1	25.92	Excellent water
29	Spring water 5	16.81	Excellent water
30	Spring water 4	40.03	Excellent water
31	Spring water 3	9.39	Excellent water
32	Well water	73.58	Good water
33	Spring water 6	23.39	Excellent water
34	Spring water 8	25.73	Excellent water
35	Spring water 7	25.51	Excellent water
36	Tangba lake (east)	15.11	Excellent water
37	Tangba lake (west)	170.69	Poor water
38	Ulungur lake	14.41	Excellent water
39	Jili lake	82.56	Good water
40	An unnamed small lake	53.91	Good water
41	Aiding lake	53.00	Good water

No. 25) were collected from a river in Fuyun County located near a residential area and Ulungur river, respectively. No. 4 river water may be affected by sewage discharge. The water quality of the lakes is relatively poor, except for the Ulungur Lake and the Tangba Lake (east); other 4 lake water samples were classified into good or poor water. This result demonstrates that lake water is unsuitable for use as drinking water and that groundwater and most river waters, except those obtained from locations near residential areas, are of suitable drinking water quality. The one groundwater sample that was classified into the good water category (sampling No. 32) was collected in a well in a village. A case study on the water quality of the Huaihe River in Anhui Province revealed a *WQI* of 59.4–1734.79; thus, water quality in the area is poor or unsuitable for drinking (Wang et al., 2017). Other similar cases have been reported in Shenzhen City (Lu et al., 2015). These findings demonstrate that the waters in Altay are of better water quality compared with those in other more economically developed areas in China.

The *HQs* and noncarcinogenic risks of trace elements of water in Altay based on oral consumption are summarized in Table 5 and Fig. 6. The *HQs* of 10 trace elements for adults and children are lower than 1. The observed HIs, which reflect the noncarcinogenic risk of different types of water by mixed trace elements to adults and children, were lower than 10. Among the three water types evaluated for noncarcinogenic risk, river water was the most suitable water source for drinking. Moreover, children in Altay may have more serious noncarcinogenic risks than adults via three types of drinking water. These results are consistent with Ricolfi et al. (2020); i.e., river water is more suitable for drinking compared with groundwater in the study area.

The results of the cancer risk assessment are shown in Table 6. The results of the current work revealed that U (for adults 0.14527 and for children 0.22269) presents greater carcinogenic risks than As (for adults 0.05686 and for children 0.00749) and Ni (for adults 0.06801 and for children 0.00895) to both adults and children in Altay. The cancer risk levels of As, Ni, and U exceeded the established safety (1×10^{-4}) and acceptable risk (1×10^{-6}) levels and even higher than the results of previous research carried out in Bay County, Xinjiang (Tudi et al., 2019). The high U and Ni risk in water may be attributed to the abundant rare metal resources in Altay, especially Ni resources in Altay rank the third in China (Xinjiang Altay Statistical Yearbook, 2017). The

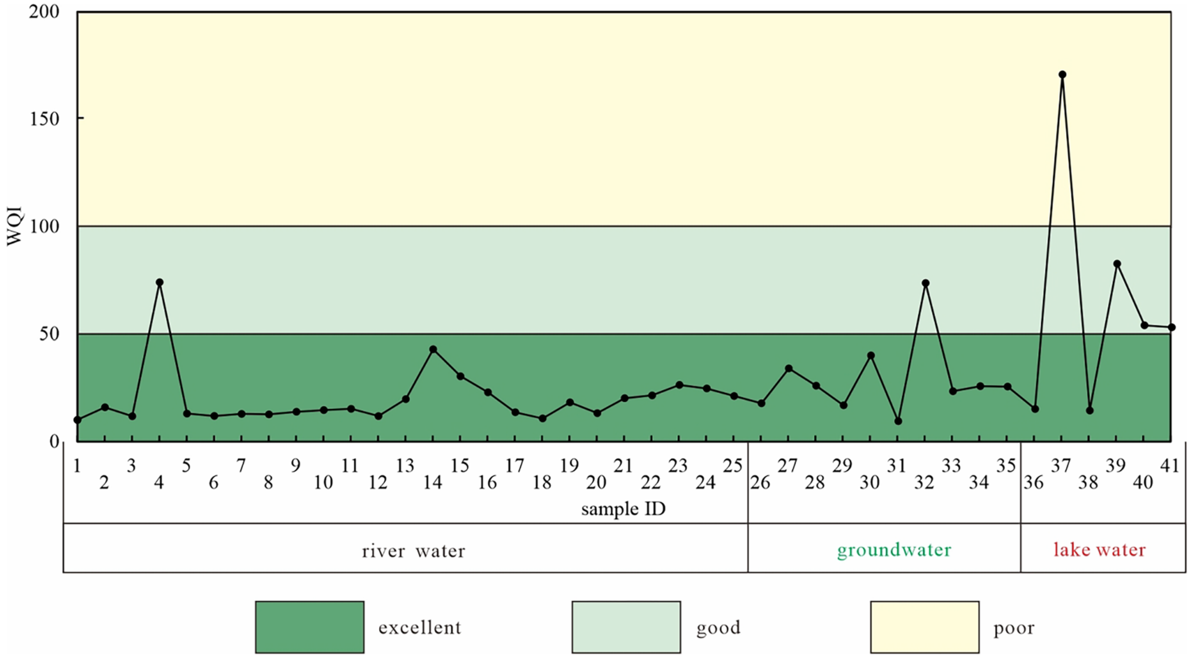


Fig. 5 The *WQIs* of waters from Altay

TCRs for adults and children were 2.701×10^{-1} and 2.391×10^{-1}, respectively, which means the combined effect of As, Ni, and U may pose an extreme threat to the Altay population. For example, As in drinking water can lead to chronic toxicity even at relatively low concentrations (< 100 µg/L; Guo et al.,

Table 5 Average *HQs* of individual trace elements for adults and children of waters in Altay

Trace elements	$RFD_{ingestion}$	HQ_{adults}				$HQ_{children}$			
		Total	Groundwater	Lake water	River water	Total	Groundwater	Lake water	River water
Li[a]	20	0.01379	0.01969	0.02813	0.00799	0.02114	0.03018	0.04312	0.01225
B[b]	200	0.02320	0.01051	0.08925	0.00835	0.03556	0.01611	0.13681	0.01280
Al[a]	1000	0.00045	0.00022	0.00031	0.00056	0.00069	0.00034	0.00047	0.00085
Mn[c]	20	0.02918	0.01439	0.02150	0.03293	0.04474	0.02206	0.03295	0.05048
Zn[b]	300	0.00060	0.00020	0.00052	0.00077	0.00091	0.00031	0.00079	0.00118
Se[a]	5	0.00781	0.01012	0.03357	0.00101	0.01197	0.01552	0.05146	0.00155
Sr[a]	600	0.01804	0.01500	0.03711	0.01468	0.02766	0.02300	0.05689	0.02251
Mo[a]	5	0.03186	0.04210	0.05954	0.01751	0.04884	0.06454	0.09128	0.02685
I[a]	10	0.03558	0.04663	0.08000	0.01987	0.05454	0.07148	0.12265	0.03046
Ba[c]	70	0.00844	0.00832	0.01335	0.00731	0.01294	0.01276	0.02046	0.01120
Hazard index		0.1689	0.1672	0.3633	0.1110	0.2590	0.2563	0.5569	0.1701

The *RFD* values were collected from concentration tables on USEPA official websites and previous studies.

[a] Tables from USEPA website

[b] Wu et al. (2009)

[c] *RFD* in µg/kg/day

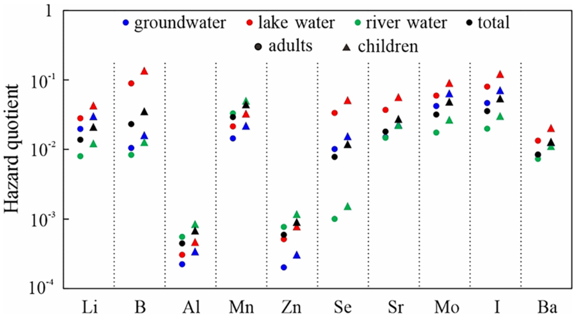


Fig. 6 The noncarcinogenic risks for adults and children

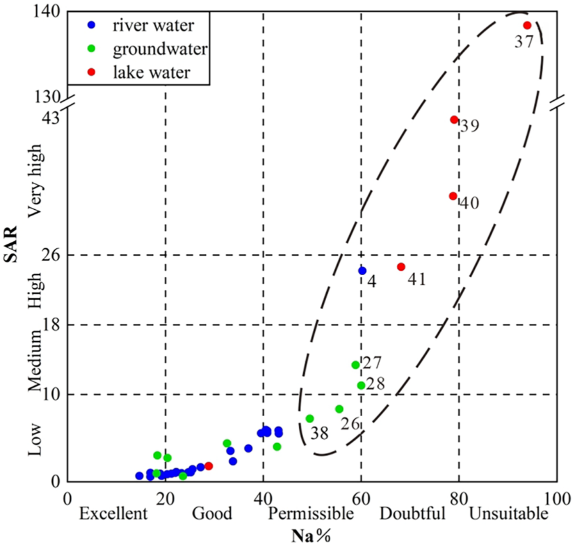


Fig. 7 *SAR* and *Na%* of waters in Altay

2007, 2012). The local government should be aware of the potential threats arising from exposure to As, Ni, and U, especially when choosing drinking water sources in Altay.

The results of water quality for irrigation use (*Na%* and *SAR*) in Altay are shown in Fig. 7. Compared with river water (with average *Na%* of 29.24% and *SAR* of 3.33), lake water (with average *Na%* of 62.92 and *SAR* of 40.15) and groundwater (with average *Na%* of 37.99 and *SAR* of 5.28) had higher *Na%* and *SAR*. In the same figure, nine water samples of low irrigation water quality, including one river water sample obtained near a residential area in Fuyun County, four lake water samples, and four groundwater samples, are encircled by dotted lines. Among the samples obtained, the water sample from Tangba Lake west had the highest *Na%* and *SAR*, indicating very high levels of Na hazard and low irrigation water quality. According to the classification of salinity hazard (i.e., EC), the salinity hazard of Altay water ranges from low to very high: low salinity hazard level, including 20 water samples, including 16 river water samples, 2 lake water samples from Ulungur lake and Tangba lake east, and 2 groundwater samples; moderate salinity hazard level, including 13 water samples, of which 8 are river water samples and 5 are groundwater samples; high salinity hazard level, including 5 water samples, of which 2 are lake water and 3 are groundwater samples; very high salinity hazard level, only including 3 water samples, one river water sample from Fuyun county near to the residential area and two lake water samples (one is from Tangba lake west; another is from Jili lake). These results of irrigation water quality revealed that river water is more suitable for irrigation than lake water or groundwater in Altay. These results can help with the reasonable utilization of different types of water resources in the city.

Table 6 Carcinogenic risks for As, Ni, and U of waters in Altay

Trace elements	CR_{adults}				$CR_{children}$			
	Total	Groundwater	Lake water	River water	Total	Groundwater	Lake water	River water
As	0.05686	0.05231	0.18557	0.02225	0.00749	0.00689	0.02443	0.00293
Ni	0.06801	0.07563	0.06139	0.06619	0.00895	0.00996	0.00808	0.00871
U	0.14527	0.17698	0.26674	0.09546	0.22269	0.27130	0.40891	0.14634

Conclusions

Altay is an extremely arid region, where the efficient use of water resources is crucial. However, there are few studies on water quality evaluation in Altay, so it is necessary to study the quality of the different types of waters in Altay to put forward the scientific application methods of different water types. In this study, the geochemical features and water quality of water in Altay were systematically assessed.

The chemical type of the river waters and groundwaters was mainly Ca-HCO_3, while that of lake waters was mainly Na-SO_4. The water quality of Altay was better than that of other areas with a better economy and industry. Although the physical and chemical parameters of most water samples fell within the threshold values established by the Chinese government and WHO, some trace elements that could pose health risks to Altay's residents via drinking water were still detected. The excessive Mn, B, U, As, and Se concentrations in some waters maybe because of the existence of the local coal mines, the high evaporation of the lakes, as well as the enrichment of rare-metal minerals in Altay.

Among Altay residents, children had more serious potential noncarcinogenic risks than adults through drinking water. All waters collected in Altay could put As, Ni, and U carcinogenic risk both to children and adults. The average carcinogenic risk of all water samples in Altay of As, Ni, and U for adults exceeded the safety risk levels (10^{-4} to 10^{-6}) by at least 568 times, 680 times, and 1452 times, respectively, indicating that the natural water in the study area is highly unsuitable for drinking. Given these findings, the local government should be aware of the potential carcinogenic risks of As, Ni, and U to the residents in Altay and choose the drinking water source more prudential. This study also revealed that the groundwater and lake water in Altay, as well as water from some severely polluted rivers near the residential areas of the region, are unsuitable for irrigation use. The high quality of agricultural land in Altay may be maintained by using river water for irrigation.

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Data availability statement All data generated or used during the study are available from the corresponding author by request.

Declarations

Conflict of interest The authors declared no competing interests.

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