Environmental significance and hydrochemical characteristics of rivers in the western region of the Altay Mountains, China Postprint

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Abstract

Analysis of environmental significance and hydrochemical characteristics of river water in mountainous regions is vital for ensuring water security. In this study, we collected a total of 164 water samples in the western region of the Altay Mountains, China, in 2021. We used principal component analysis and enrichment factor analysis to examine the chemical properties and spatiotemporal variations of major ions (including F-, Cl-, NO3-, SO42-, Li+, Na+, NH4+, K+, Mg2+, and Ca2+) present in river water, as well as to identify the factors influencing these variations. Additionally, we assessed the suitability of river water for drinking and irrigation purposes based on the total dissolved solids, soluble sodium percentage, sodium adsorption ratio, and total hardness. Results revealed that river water had an alkaline aquatic environment with a mean pH value of 8.00. The mean ion concentration was ranked as follows: Ca2+>SO42->Na+>NO3->Mg2+>K+>Cl->F->NH4+>Li+. Ca2+, SO42-, Na+, and NO3-occupied 83% of the total ion concentration. In addition, compared with other seasons, the spatial variation of the ion concentration in spring was obvious. An analysis of the sources of major ions revealed that these ions originated mainly from carbonate dissolution and silicate weathering. The recharge impact of precipitation and snowmelt merely influenced the concentration of Cl-, NO3-, SO42-, Ca2+, and Na+. Overall, river water was in pristine condition in terms of quality and was suitable for both irrigation and drinking. This study provides a scientific basis for sustainable management of water quality in rivers of the Altay Mountains.

Full Text

Preamble

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Environmental and Hydrochemical Characteristics of Rivers in the Western Region of the Altay Mountains, China

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Abstract: Analysis of the environmental significance and hydrochemical characteristics of river water in mountainous regions is vital for ensuring water security. In this study, we collected a total of 164 water samples in the western region of the Altay Mountains, China, in 2021. We used principal component analysis and enrichment factor analysis to examine the chemical properties and spatiotemporal variations of major ions (including F^-, Cl^-, ${NO_3}^-$, ${SO_4}^{2-}$, Li^+, Na^+, ${NH_4}^+$, K^+, Mg^{2+}, and Ca^{2+}) present in river water, as well as to identify the factors influencing these variations. Additionally, we assessed the suitability of river water for drinking and irrigation purposes based on total dissolved solids, soluble sodium percentage, sodium adsorption ratio, and total hardness. Results revealed that river water had an alkaline aquatic environment with a mean pH value of 8.00. The mean ion concentration was ranked as follows: $Ca^{2+} > {SO_4}^{2-} > Mg^{2+} > K^+ > Cl^- > F^- > {NH_4}^+ > Na^+ > {NO_3}^- > Li^+$. Ca^{2+} and ${SO_4}^{2-}$ occupied 83% of the total ion concentration. In addition, compared with other seasons, the spatial variation of ion concentration in spring was more pronounced. An analysis of the sources of major ions revealed that these ions originated mainly from carbonate dissolution and silicate weathering. The recharge impact of precipitation and snowmelt merely influenced the concentration of Cl^-, ${NO_3}^-$, Ca^{2+}, and Na^+. Overall, river water was in pristine condition in terms of quality and was suitable for both irrigation and drinking. This study provides a scientific basis for sustainable management of water quality in rivers of the Altay Mountains.

Keywords: environmental significance; hydrochemical characteristics; water quality; soluble sodium percentage (SSP); ion concentration; Altay Mountains

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1 Introduction

Rivers, which support vital ecosystems, serve as crucial surface water resources that supply drinking water and irrigation water to the public (United Nations, 2019). In recent decades, the quality of river water has faced mounting pressures due to the impacts of human activities and climate-related stressors, leading to noticeable water environmental issues worldwide (Wen et al., 2015; He et al., 2020; Yapiyev et al., 2021). Consequently, there is an urgent requirement for continuous river monitoring to ensure sustainable management of water quality. The chemical composition of river water is an essential indicator of water environmental quality, regional environmental characteristics, and the distribution and transformation of water components (Ye et al., 2010; Mapoma et al., 2016; Niu et al., 2017). Monitoring the chemical conditions of river water provides valuable insights into regional chemical weathering and key processes that govern hydrochemistry (Wang et al., 2015; Iqbal et al., 2018). Additionally, analyzing the chemical properties of river water aids in identifying the sources of major chemical constituents and understanding the evolution of geochemical solutes (Li et al., 2017; Pant et al., 2017).

Studies on the chemical status of runoff water have revealed the major contributors affecting river water quality, including atmospheric inputs, rock weathering, and human activities (Li et al., 2019). The solutes in river basins (particularly in glacial catchments) predominantly originate from crustal mineral weathering (Li et al., 2022). Several qualitative and quantitative methods are used for assessing the physicochemical parameters and sources of solutes in river water. For instance, qualitative methods such as Piper histograms (Piper, 1944), Gibbs scatter plots (Gibbs, 1970), factor analysis (Vermette et al., 1988; Okay et al., 2002; Li et al., 2014), and ionic ratios (Villegas et al., 2013) have been applied to identify runoff water chemistry and mineral weathering. Quantitative methods, on the other hand, have been used to quantify the contribution of different solute sources based on chemical concentrations. For example, the forward model (Galy and France-Lanord, 1999) was utilized to determine the contribution of riverine solutes and could accurately assess the differences in the status of crustal mineral weathering (Yu et al., 2021).

Numerous previous studies have investigated the hydrochemistry of prominent rivers worldwide, including the Nile River (Dekov et al., 1997), Amazon River (Stallard and Edmond, 1983), and Ganges River–Yarlung Zangbo River (Galy and France-Lanord, 1999). In China, research has predominantly focused on hydrochemical characteristics of rivers originating from the Tibet Plateau (Li et al., 2019), Pamir Plateau (Wu et al., 2020), Qilian Mountains (Li et al., 2014), Tianshan Mountains (Yapiyev et al., 2021), and Altay Mountains (Liu et al., 2021). These studies have provided crucial insights into regional environmental changes, such as variations in the spatial and temporal distribution of river water chemistry (Jiang et al., 2015), as well as the sources of solutes in river water and the factors governing them (Li et al., 2019; Dong et al., 2022). Evaluating the hydrochemistry of rivers in these regions is vital for effective and sustainable management of water quality.

The western region of the Altay Mountains represents the northernmost concentration of modern glaciers in China (Wang et al., 2015). It not only serves as a representative arid region influenced by westerly circulation but also functions as a significant water source conservation area in northern Xinjiang Uygur Autonomous Region of China. In recent years, researchers have increasingly focused on water resources and environmental issues in the Altay Mountains, including river water chemistry (Liu et al., 2021), river water quantity (Zhang et al., 2010; Li et al., 2018), and soil-related concerns (Goenster-Jordan et al., 2021). However, studies on river water chemistry have typically relied on single-time-period sampling results to interpret concentration patterns, neglecting seasonal and annual variations (Liu et al., 2021). Furthermore, there is a lack of information on spatial patterns, such as the elevation distribution of ion concentration, due to scattered data and sampling discontinuities. The seasonal evolution and controlling factors of major ions in river water have not been systematically evaluated.

To explore the hydrochemical characteristics and controlling factors in this region, researchers established the Altay Observation and Research Station for Cryospheric Science and Sustainable Development in the Altay Mountains in 2016. The primary objectives of this study were to: (1) analyze the spatiotemporal variability of major ions in river water, (2) determine the chemical weathering processes and the mechanisms underlying the seasonal evolution of river water in the study area, and (3) assess the suitability of river water for drinking and irrigation purposes.

2.1 Study Area

The western region of the Altay Mountains is mainly the origin area of the Burqin River (86°48 -88°36 E, 47°42 -49°12 N) and Haba River (85°31 -87°09 E, 47°38 -49°09 N; Fig. 1 [Figure 1: see original paper]). The Burqin River is the largest tributary of the Ertix River, and the Burqin River Basin has a drainage area of approximately 8422.0 km^2, with elevations ranging from 470–4300 m. The glaciers in the Youyi Peak region (48°40 -49°10 N, 87°36 -87°53 E) supply water to the Burqin River Basin. The Haba River is the second largest tributary of the Ertix River, with a drainage area of approximately 7224.0 km^2.

In 2020, the Altay Mountains contained 1927 glaciers with a total area of 1096.0 km^2 (Chang et al., 2022). Glaciers with areas of 0.1-0.5 km^2 (815 glaciers) account for 42% of the total number of glaciers (Chang et al., 2022). The Altay Mountains above 3000 m are mostly covered by glaciers and seasonal snow, which begin melting in June when air temperatures rise above 0.0°C (Qin et al., 2020). The landscapes are characterized by glaciers, snow, permafrost, forestlands, and grasslands from high to low elevations.

The entire region has a typical temperate continental climate (Liu et al., 2021). The local climate may also be influenced by westerlies and polar air masses. The annual average air temperature is 5.0°C, with a maximum temperature of 39.8°C occurring in July and a minimum temperature of -27.9°C occurring in December. The average annual precipitation is 159 mm. Precipitation occurs mainly due to water vapor transported by westerly airflow throughout the year (Wang et al., 2015). These climatic characteristics are recorded by a meteorological station (86°87 E, 47°71 N; 483 m), situated about 5 km northeast of the confluence of the Burqin River and Ertix River. In addition to precipitation, glacier meltwater also supplies the region, accounting for 45%–50% of all water sources (Lanzhou Institute of Glaciology and Geocryology, 1982).

2.2 Sample Collection and Measurement

To investigate the hydrochemical characteristics of rivers in the western region of the Altay Mountains, we collected 164 samples from this region during January–December 2021. Field sampling was conducted every 2 hours from the 20th to the 21st of each month. The sampling sites are depicted in Figure 1 [Figure 1: see original paper]. First, empty sample bottles were washed using a dilute HCl solution. After sampling, the collected samples were filtered using a 0.45-μm Millipore filter membrane. Subsequently, each sample was poured into two pre-washed polyethylene bottles. One bottle, used for cation analysis, was acidified using HNO_3 to a pH value below 2.00. The other bottle was used for anion and isotopic analyses. All samples were stored at approximately 4.0°C before and during transportation to the laboratory for analyses in December 2021. Each sample was naturally thawed at room temperature (about 15.0°C) before laboratory determination.

The hydrochemical analysis was conducted at the State Key Laboratory of Cryospheric Science of the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences. The pH was measured by a pH meter (PHSJ-4A, INESA Scientific Instrument Co., Ltd., Shanghai, China). We determined the total dissolved solids (TDS) and electrical conductivity (EC) using a conductivity meter (DDSJ-308A, INESA Scientific Instrument Co., Ltd., Shanghai, China). The concentrations of cations (including Li^+, Na^+, $NH_4{}^+$, K^+, Mg^{2+}, and Ca^{2+}) were measured using an atomic absorption spectrometer (PE2380, Perkin Elmer, Massachusetts, USA), while those of anions (including F^-, Cl^-, $NO_3{}^-$, and $SO_4{}^{2-}$) were determined using an ion chromatography apparatus (Dionex100, Thermo Fisher Scientific, Massachusetts, USA). To ensure that the error between the analysis results of the water samples and those of the standard sample was less than 5%, we calibrated the apparatus after every 20 sample measurements.

2.3 Statistical Methods

Principal component analysis (PCA) is a robust multivariate analysis method employed to identify significant parameter variations within the data (Shrestha and Kazama, 2007; Wu et al., 2020). In this study, PCA was utilized to condense several interconnected major ions (i.e., F^-, Cl^-, $NO_3{}^-$, $SO_4{}^{2-}$, Li^+, Na^+, $NH_4{}^+$, K^+, Mg^{2+}, and Ca^{2+}) into fewer uncorrelated variables, thereby facilitating subsequent analyses. The PCA algorithm was carried out in SPSS 19.0 software.

To assess the role of mineral weathering as the source of ions in this region, we calculated the enrichment factor (EF) using Ca^{2+} and Na^+ as reference materials. Ca^{2+} and Na^+ serve as reference materials for soil and sea, respectively. The EF was calculated as follows:

$$\mathrm{EF}_{\mathrm{soil}} = \frac{[X/\mathrm{Ca}^{2+}]_{\text{water sample}}}{[X/\mathrm{Ca}^{2+}]_{\mathrm{soil}}}$$

$$\mathrm{EF}_{\mathrm{sea}} = \frac{[X/\mathrm{Na}^{+}]_{\text{water sample}}}{[X/\mathrm{Na}^{+}]_{\mathrm{sea}}}$$

where EF is the enrichment factor for soil; X is the concentration of a specific ion (mg/L); $[X/Ca^{2+}]$ is the ratio of the concentration of a specific ion to the concentration of Ca^{2+} in the water samples; $[X/Ca^{2+}]$ is the ratio of the concentration of a specific ion to the concentration of Ca^{2+} in soil (Okay et al., 2002); EF is the enrichment factor for sea; $[X/Na^+]$ is the ratio of the concentration of a specific ion to the concentration of Na^+ in the water samples; $[X/Na^+]$ is the ratio of the concentration of a specific ion to the concentration of Na^+ in sea (Keene et al., 1986); and Na^+ (mg/L) and Ca^{2+} (mg/L) represent the concentrations of Na^+ and Ca^{2+}, respectively.

2.4 Suitability Indices for Drinking Water and Irrigation Water

High concentrations of Na^+ in irrigation water can lead to sodium hazards. Na^+ replaces both Ca^{2+} and Mg^{2+}, resulting in lower permeability and soil hardening (Shaki and Adeloye, 2006). In this study, we assessed the suitability of the water samples for irrigation based on the soluble sodium percentage (SSP; %) and sodium adsorption ratio (SAR) (Wu et al., 2020), which were calculated using the following equations:

$$\mathrm{SSP} = \frac{\mathrm{Na}^{+} + \mathrm{K}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+} + \mathrm{K}^{+}} \times 100$$

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/2}}$$

where K^+ (mg/L) and Mg^{2+} (mg/L) represent the concentrations of K^+ and Mg^{2+}, respectively.

In addition, the total hardness (TH; mg/L), which refers to the combination of carbonate and non-carbonate hardness (Gao et al., 2017), was determined using the following equation:

$$\mathrm{TH} = 2.5 \times \mathrm{Ca}^{2+} + 4.1 \times \mathrm{Mg}^{2+}$$

On the basis of TH values, we classified the water samples into five classes: very soft water (TH $\leq$ 75 mg/L), soft water (75 mg/L $<$ TH $\leq$ 150 mg/L), slightly hard water (150 mg/L $<$ TH $<$ 300 mg/L), hard water (300 mg/L $\leq$ TH $\leq$ 450 mg/L), and very hard water (TH $>$ 450 mg/L). We compared the TH values with those reported for major rivers globally and the standard values derived from the World Health Organization (WHO, 2011), revealing the suitability of the water samples as drinking water.

3.1 Hydrochemical Characteristics and Ion Concentration

The pH, TDS, and ion concentrations of the water samples are presented in Table 1 . The pH values varied from 7.42 to 8.48, with a mean value of 8.00. The TDS ranged from 21.07 to 52.03 mg/L, with a mean value of 36.23 mg/L, suggesting alkaline characteristics and low salinity. The mean ion concentration was ranked as follows: $Ca^{2+} > {SO_4}^{2-} > Mg^{2+} > K^+ > Cl^- > F^- > {NH_4}^+ > Na^+ > {NO_3}^- > Li^+$. Ca^{2+} alone contributed 42% of the total ion concentration, and ${SO_4}^{2-}$ accounted for 41% of the total ion concentration. The cation concentration was ranked as $Ca^{2+} > Mg^{2+} > Na^+ > K^+$, which is consistent with standard crustal material ($Ca^{2+} > Na^+ > Mg^{2+} > K^+$). The anion concentration was ranked as ${SO_4}^{2-} > Cl^-$, which represents a notable difference compared to standard seawater ($Cl^- > {SO_4}^{2-}$). In addition, the order of major anions and cations remained the same across different seasons, while the proportions of anions and cations varied. Specifically, Ca^{2+}, ${SO_4}^{2-}$, Na^+, and ${NO_3}^-$ accounted for 81% of the total ion concentration in spring, while the corresponding proportions in summer, autumn, and winter were 84%, 83%, and 85%, respectively. These results indicate that there are differences in the hydrochemical characteristics of river water across seasons in the study area.

As depicted in Figure 2 [Figure 2: see original paper], the cations in the water samples were mainly concentrated in the lower right corner, indicating a dominance of Ca^{2+} in all seasons. Ca^{2+} accounted for 63% of the total cations. The combined proportion of Na^+ and K^+ in the total cations reached 26%, while the mean proportion of Mg^{2+} in the total cations was 10%. In contrast, the anions were characterized by the dominance of ${SO_4}^{2-}$ (63%). ${NO_3}^-$ and Cl^- accounted for 22% and 12% of the total anions, respectively. In general, the composition of cations and anions in most water samples exhibited minimal differences across seasons, demonstrating that the source of these ions was natural.

3.2 Spatiotemporal Variation of Anion and Cation Concentrations

As shown in Figure 3 [Figure 3: see original paper], in spring, except for ${NH_4}^+$, the maximum mean concentration of all ions occurred at 484 m, while the minimum mean concentration occurred at 879 m. The maximum and minimum mean concentrations of ${NH_4}^+$ were observed at 537 m and 484 m, respectively. In summer, except for ${NH_4}^+$, the maximum mean concentration of all ions was observed at 879 m, while the minimum mean concentration mainly occurred at 484 m. In autumn, the maximum mean concentration of all ions occurred at 879 m, while the minimum mean concentration mainly occurred at 484 m. In winter, the maximum mean concentration of Ca^{2+}, Na^+, Mg^{2+}, K^+, ${NH_4}^+$, ${SO_4}^{2-}$, Cl^-, and F^- occurred at 879 m, while the minimum mean concentration of these ions was mainly observed at 484 m. In general, there were significant seasonal and spatial variations in the maximum mean concentration of most ions. Furthermore, the minimum mean concentration of most ions was found at 879 m in spring and at 484 m in other seasons.

The temporal variations of anion and cation concentrations in river water are illustrated in Figure 4 [Figure 4: see original paper]. The concentrations of Cl^-, ${NO_3}^-$, ${SO_4}^{2-}$, Na^+, Mg^{2+}, and Ca^{2+} were characterized by significant seasonal variations, with maximum values observed in winter and minimum values observed in late spring and summer. These ion concentrations varied from 0.35 to 12.51 mg/L, with a mean value of 3.07 mg/L. Moreover, ion concentrations were higher in winter and early spring than in other seasons. This could be attributed to snowfall accumulation and low runoff in these seasons. The ion concentrations decreased significantly in late spring and summer. This result indicated that snowmelt recharges the river in spring, while precipitation replenishes the river in summer, thus diluting the major ions and reducing ion concentration.

3.3 Correlations Among pH, Electrical Conductivity (EC), and Ion Concentrations

Correlation analysis is a useful tool for examining the degree of dependence among different variables (Anshumali and Ramanathan, 2007). In this study, correlation analysis was performed to determine the relationships among pH, EC, and the concentrations of anions and cations (Table 2). The positive correlation between pH and SO_4^{2-} indicated that river water is alkaline. EC exhibited a significant positive relationship with all ions except for F^-. Moreover, the significant correlations of Ca^{2+} with NO_3^-, SO_4^{2-}, Cl^-, Na^+, K^+, and Mg^{2+} suggested that these ions come from a common source. No significant correlation was observed between F^- and other ions, indicating that F^- originated from different sources. The presence of Ca^{2+} and Mg^{2+} was primarily attributed to the dissolution of carbonates and evaporites. Similarly, the occurrence of SO_4^{2-} and Cl^- was predominantly linked to the dissolution of evaporites.

In the PCA, three parameters with eigenvalues greater than 0.600 explained 98% of the total variance in the water samples (Table 3). PC1 (principal component 1; 69%) presented a high load of most ions, except for F^- and NH_4^+, indicating a contribution from crustal sources (carbonates, evaporites, and sulfates). This was also confirmed by the positive correlations among Ca^{2+}, Li^+, Na^+, K^+, Mg^{2+}, Cl^-, and SO_4^{2-} (Table 2). Furthermore, PC2 (principal component 2) accounted for 15% of the total variance, with a high load of NH_4^+, indicating the same source for these ions. PC3 (principal component 3) explained 13% of the total variance, with a high load of F^-. This result suggested that F^- is mainly related to anthropogenic disturbances.

3.4 Sources of Major Ions in River Water

To identify the possible sources of major ions, we conducted enrichment factor analysis. Generally, an EF less than 1.00 indicates dilution compared to the reference material, while an EF greater than 1.00 indicates enrichment compared to the reference material (Zhang et al., 2007). Furthermore, when the EF equals 1.00, it indicates no dilution or enrichment relative to the reference material. As depicted in Table 4 , the EF value of Na^+ was less than 1.00, indicating that the concentration of Na^+ is primarily influenced by sea sources. The EF value of K^+ was lower than 1.00, while the EF value of K^+ was greater than 15.00. This result suggested that the concentration of K^+ is regulated by both sea and soil sources. The EF value of Mg^{2+} was lower than 1.00, while its EF value was higher than 1.00, suggesting that Mg^{2+} is derived from both soil and sea sources. The EF value of Ca^{2+} ranged from 69.36 to 79.31, indicating that Ca^{2+} predominantly comes from soil sources. In addition, F^- was affected by soil, as evidenced by its EF value. The EF value of Cl^- was below 1.00, while its EF value was higher than 10.00. This result demonstrated that the concentration of Cl^- is regulated by both sea and soil sources. Furthermore, NO_3^- was mainly affected by soil, with both EF and EF values above 1.00. SO_4^{2-} was mainly affected by soil, with an EF exceeding 1.00. In addition, differences were observed among seasons for all ions.

3.5 Factors Influencing Hydrochemical Characteristics of Rivers

The hydrochemical characteristics of rivers can be influenced by various anthropogenic activities, such as increased grazing intensity, which has been known to modify water chemistry in recent years (Goenster-Jordan et al., 2021). Additionally, it has been reported that the growth of tourism and local agricultural practices have the potential to alter natural water chemistry (Negrel et al., 1993). Therefore, to assess the impact of rock weathering and human activities on water quality, we calculated the ratios of NO_3^-, SO_4^{2-}, and Cl^- to Na^+ according to Gaillardet et al. (1999a, b). Figure 5 [Figure 5: see original paper] illustrates that no significant correlation was observed between the ratio of NO_3^- to Na^+ (NO_3^-/Na^+) and the ratio of SO_4^{2-} to Na^+ (SO_4^{2-}/Na^+) in different seasons, suggesting that the sources of these ions were different. Most of the NO_3^-/Na^+ values were below 0.8, indicating a minimal contribution from human activities.

Furthermore, we constructed a Gibbs diagram based on the ratio of Na^+ to Na^+ and Ca^{2+} ($Na^+/(Na^+ + Ca^{2+})$). The TDS content was employed to identify the predominant factors influencing hydrochemical characteristics of rivers, such as precipitation dominance, weathering dominance, or evaporation-crystallization dominance. As shown in Figure 6 [Figure 6: see original paper], most water samples had moderate TDS and low $Na^+/(Na^+ + Ca^{2+})$ values, indicating that rock weathering was the leading process regulating hydrochemical characteristics of rivers. To distinguish the main rock types (i.e., carbonates, evaporites, and sulfates), we calculated the ratio of Ca^{2+} to Na^+ (Ca^{2+}/Na^+) and the ratio of Mg^{2+} to Na^+ (Mg^{2+}/Na^+). The majority of water samples were found to lie between carbonate dissolution and silicate weathering, indicating that both processes contribute significantly to the hydrochemical characteristics of rivers.

The main ions in river water in the western region of the Altay Mountains were Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Fig. 2 [Figure 2: see original paper]). However, significant differences in ion concentration were observed as the elevation gradient changed (Fig. 3 [Figure 3: see original paper]). At low elevations (<500 m), Ca^{2+} and Cl^- were the dominant ions, while at high elevations (from 500 to 900 m), Ca^{2+} and SO_4^{2-} were the dominant ions. A related study observed that the vertical distribution of major ions can provide insights into the vertical distribution of rock formations (Li et al., 2018). The maximum values of K^+, NH_4^+, F^-, Li^+, and Mg^{2+} remained consistent across different seasons, suggesting that the concentrations of these ions were minimally affected by precipitation and meltwater recharge. The maximum values of Cl^-, NO_3^-, SO_4^{2-}, Ca^{2+}, and Na^+ first decreased and then increased from spring to winter. This result indicated that the concentrations of Cl^-, NO_3^-, SO_4^{2-}, Ca^{2+}, and Na^+ are affected by the recharge effects of precipitation and meltwater. However, the recharge effects of precipitation and meltwater on K^+, NH_4^+, F^-, Li^+, and Mg^{2+} were minimal.

3.6 Comparison of Hydrochemical Characteristics Between the Study Area and Other Mountains

The hydrochemical characteristics of the study area are consistent with those of other mountains (Table 5). For instance, the pH values of the Ertix River and Ulungur River were also alkaline, with a small range of variation. These rivers contained abundant Ca^{2+}, Na^{+}, HCO_3^{-}, and SO_4^{2-}, which are the most common cations and anions (Liu et al., 2021). Additionally, the average TDS in the Ertix River and Ulungu River is reported to be significantly higher than that in the western region of the Altay Mountains, which may be attributed to the comprehensive impact of geological conditions, supply sources, climatic factors, and human activities (Zabaleta et al., 2007). The hydrochemical characteristics of the Burqin River and Haba River were related to the weathering of carbonates and silicates. In contrast, it has been reported that the ion composition of the Ertix River and Ulungu River is influenced by various factors, including carbonate dissolution, silicate weathering, and evaporite dissolution (Liu et al., 2021).

The ion concentration of river water in the western region of the Altay Mountains was far lower than that in other mountains, which is attributed to the different and unique lithology and geographic conditions of these mountains (Table 5). For instance, the mean concentration of Cl^{-} in the study area was 0.91 mg/L, which is lower than that reported in other mountains. The TDS of the study area was also relatively low, due to lower Ca^{2+} and SO_4^{2-} concentrations. The mean concentrations of Ca^{2+} and SO_4^{2-} were 9.58 and 4.66 mg/L, respectively, which are more than 17 times lower than those in other rivers. In addition, the high concentrations of Ca^{2+}, HCO_3^{-}, and SO_4^{2-} in the rivers of the Tianshan Mountains demonstrated that hydrochemical characteristics are mainly affected by carbonate dissolution and silicate weathering (Ma et al., 2019; Liu et al., 2021; Feng and Yang, 2022). High concentrations of Ca^{2+}, Mg^{2+}, and HCO_3^{-} in rivers in southern and northern parts of the Tibetan Plateau were also affected by carbonate dissolution and silicate weathering (Huang et al., 2009; Qu et al., 2017, 2019). However, high concentrations of Na^{+}, Cl^{-}, and SO_4^{2-} in rivers of the central Tibetan Plateau were controlled by evaporite dissolution (Galy and France-Lanord, 1999). Furthermore, high concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{2-} in the Hulugou River of the Qilian Mountains were affected by the weathering and dissolution of dolomite (Li et al., 2014). However, it is reported that in the Shule River of the Qilian Mountains, the ion composition (Ca^{2+}, Mg^{2+}, and HCO_3^{-}) is mainly influenced by the weathering of carbonate and silicate (Qu et al., 2019).

3.7 Impacts on the Suitability of River Water for Drinking and Irrigation

Glaciers and snowmelt in the Altay Mountains are important water resources for residents and economic development of this region (Wang et al., 2015). However, due to the high sensitivity of small glaciers in the Altay Mountains, water scarcity may threaten this region. Therefore, considering the impact of water scarcity on human and ecosystem health, we conducted an assessment of river water quality. In accordance with the guidelines of the World Health Organization, we found that the TDS and ion concentrations in the study area were considerably below the maximum limits for drinking water (WHO, 2011). The water quality of this study area is similar to that of the Indus River and Ganges River–Yarlung Zangbo River (Qu et al., 2019). Furthermore, all water samples were classified as very soft water, indicating that the water is safe to drink (Fig. 7 [Figure 7: see original paper]).

We also assessed the suitability of river water for irrigation (Table 6). The mean SSP value in the region was 18% ($±4±$0.5), and the irrigation water quality at all sampling sites was excellent (Table 6). Overall, river water in the western region of the Altay Mountains is safe for drinking and irrigation.

We evaluated the suitability of river water for drinking and irrigation based on the TDS, TH, SSP, and SAR of the water samples. Future studies could also focus on comprehensive long-term field observations of water chemistry and isotopes in glacial areas. This will facilitate the systematic assessment of water quality and hydrochemical characteristics in headwater catchments, particularly in data-poor regions such as the Altay Mountains.

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4 Conclusions

In this study, the mean ion concentration was ranked as follows: $Ca^{2+} > {SO_4}^{2-} > Mg^{2+} > K^+ > Cl^- > F^- > {NH_4}^+ > Na^+ > {NO_3}^- > Li^+$. Among these ions, Ca^{2+} and ${SO_4}^{2-}$ accounted for 83% of the total ion concentration. The spatial variation of ion concentration exhibited greater stability in summer, autumn, and winter. Results from the Gibbs diagram showed that river water chemistry was primarily influenced by carbonate dissolution and silicate weathering. There were differences in hydrochemical characteristics at different elevations, with low elevations dominated by Ca^{2+} and Cl^-, while high elevations were dominated by Ca^{2+} and ${SO_4}^{2-}$. In addition, the recharge effects of precipitation and snowmelt primarily affected the concentrations of Cl^-, ${NO_3}^-$, ${SO_4}^{2-}$, Ca^{2+}, and Na^+. The suitability evaluation of river water revealed that river water is safe for drinking and irrigation. Nonetheless, this study is only a preliminary investigation, and follow-up research may focus on further strengthening field monitoring of water chemistry and isotopes in the glacial region of the Altay Mountains.

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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