Hydrochemistry and its controlling factors of rivers in the source region of the Yangtze River on the Tibetan Plateau

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ABSTRACT

This study focuses on the chemical composition, and the factors controlling it, of the high mountain-rivers in the source region of the Yangtze River on the Tibetan Plateau. By comprehensive and systematic analysis, the chemical signatures, spatial variations of water quality, as well as the factors controlling them are studied. The value of the average total dissolved solids (TDS) is 778 mg/l, ranging from 117 to 5496 mg/l. In order of decreasing concentration, the main cations are Na^+ , Ca^{2+} , Mg^{2+} , and K^+ , while the main anions are Cl^- , HCO_3^- , SO_4^{2-} , and NO_3^- . Na^+ and Cl^- are the dominant ions, accounting for 74.2% and 63.7% of the total cations and anions, respectively, followed by Ca^{2+} and HCO_3^- , which account for 14.3% and 25%, respectively. The Piper diagram shows the main water type to be a $\text{Cl}^- \cdot \text{HCO}_3^- \text{--} \text{Na}^+ \cdot \text{Ca}^{2+}$ type. From the Gibbs boomerang model, we conclude that the chemistry of the river water is controlled by lithogenic weathering processes. The Na-normalized ratio end-member diagram indicates that the weathering of silicates and carbonates is relatively significant, on the whole. There exists pronounced regional heterogeneity in the water chemistry and the factors affecting it. The northern rivers, including Chumaer He, Beilu He, and Ranchiqu, are mainly affected by evaporation and crystallization processes, while the southern rivers (Tuotuo He, Gaerqu, and Buqu) show effects from the weathering of carbonates and silicates.

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1. Introduction

The source region of the Yangtze River (hereafter abbreviated as SRYR), which is well known as the “water tower of China” and which contributes nearly 25% of the total flow of the Yangtze River, is the main source of drinking water and is also crucial for agricultural use (Zhou et al., 2005; Hu et al., 2011). Due to the influence of natural processes and human activities, terrestrial surface water quality is experiencing different degrees of deterioration, and water environmental issues have become increasingly prominent all over the world (Chen et al., 2002; Li et al., 2008; Kumarasamy et al., 2014; Thomas et al., 2014). Thus, assessment of the hydrochemical status of surface water is urgently needed. Chemical studies on river water provide crucial information about environmental change, and contribute to determining the relationship between regional chemical weathering and hydro-geochemical reactions and their controlling factors (Han and Liu, 2000; Dalai et al., 2002; Wu et al., 2008). Additionally, they can be used to determine the origins of the main chemical signatures, the evolution of geochemical solutes, and relationship with the regional physical geography (Xia et al., 2008). Major-ion hydrochemistry studies of river water provide qualitative and quantitative research methods for

evaluating the formation and evolution of water bodies as well as for conservation of water resources (Huang et al., 2011; Zhang et al., 2011).

The quality of river water is influenced by natural factors, such as weathering of rocks, rainfall, and human activities (Kumarasamy et al., 2014). Generally, the solutes of surface water are mainly derived from the weathering of continental rocks and erosion of soils in the drainage basin; these processes are the major components of the exogenic cycle of elements in the continent–river–ocean system (Sarin et al., 1989; Kumarasamy et al., 2014). A number of studies have shown that the composition of river water can be attributed mainly to silicate weathering and carbonate weathering (Han and Liu, 2004). In light of the significance of the water source and ecological environment in SRYR, it is important to understand the special pattern of hydrochemistry and dominant chemical weathering processes in this region.

Many previous studies have reported the major ion chemistry of the world's largest rivers, such as the Amazon River system (Gibbs, 1967; Stallard, 1980; Stallard and Edmond, 1981; Stallard and Edmond, 1983; Stallard and Edmond, 1987) and the Ganges-Brahmaputra (Sarin et al., 1989; Galy and France-Lanord, 1999). In China, most studies have focused on the Yangtze River (Chen et al., 2002; Li and Zhang, 2005), the Yellow River (Chen et al., 2005), the Han River (Li et al., 2008, 2009), and the Huai River (Zhang et al., 2011). However, there have been only a few studies on the hydrochemistry of the river water in SRYR. Although some researchers have studied the Yangtze River,

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their studies either did not include the headwaters or were based only on a few samples, and therefore, a comprehensive analysis of the origin and chemical characteristics of the water has not yet been performed. In addition, variation in the water quality of the river water remains unclear. Therefore, more studies are required to elucidate the spatial patterns of the river chemistry and the chemical weathering processes within SRYR.

In this study, we characterized the hydrochemistry of the main rivers in the SRYR on the Tibetan Plateau. Based on the chemical analysis of water samples from different rivers, hydrochemical signatures and the spatial differences of the water chemistry were investigated along with the factors controlling them.

2. Study area

The SRYR (Fig. 1), with an area of $12.24 \times 10^4 \text{ km}^2$, lies in the north-eastern part of the Chuanxibei Plateau, the hinterland of the Qinghai–Tibet Plateau, which is called the roof of the world (Zhou et al., 2005; Yang et al., 2006). The SRYR is located between $90^\circ 33' - 95^\circ 20' \text{ E}$ and $32^\circ 26' - 35^\circ 45' \text{ N}$, stretching from the Tanggula Mt. in the south, to the Kunlun Mt. and the Hoh Xil Mt. in the north, and from the Ulan Ul and Jurhen Ul in the west, to the Bayan Har Mt. in the east (Fig. 1). The relief of SRYR is relatively flat, with a decreasing trend from west to east, and it has an average altitude of more than 4000 m a.s.l. (Deng, 1988). Owing to the high altitude, modern glaciers and permafrost are widespread in the SRYR (Pu et al., 1988). The river system in the SRYR has a fan-shaped distribution; the system includes the main tributaries, Qumaer He, Tuotuo He, Dam Qu, and Beilu He. Swamps and small lakes are scattered over the wide area (Su and Tang, 1987; Sun et al., 1988; Liang et al., 2011).

There are many different soil types in the SRYR, such as alpine desert soil, alpine meadow soil, alpine grassland soil, boggy soil, and mountain meadow soil. These soils are characterized by rough structure, a thin soil

layer, greater gravel content, and poor maturity (Su and Tang, 1987; Deng, 1988; Wang et al., 2001). In addition, the soils are affected to varying degrees by salt accumulation due to arid climate. For instance, soils display apparent salt accumulation phenomena in the topsoil in the Tuotuo He basin; in particular, halite and gypsum/anhydrite occur widely in the area (Zhang et al., 1992; Pu and Wang, 1995). The alpine climate environment limits the occurrence and development of vegetation, and thus, the SRYR has a unique alpine arid ecology. The vegetation mainly consists of alpine meadow and alpine steppe species (Wang and Cheng, 2000). Broad meadow grassland covers most of the SRYR area, and it is dominated by dwarf wormwood meadow, *Kobresia tibetica* meadow, alpine shrub meadow, and alpine steppe meadow. The vegetation is mainly composed of hardy plants, such as *Kobresia tibetica* Maxim., *Carex moorcroftii*, *Stipa aliena*, *Saussurea stoliczkaei*, *Trollius chinensis* Bunge, and *Saussurea involucrata*. Grass growth is slow and the vegetation is dwarf (Zhang et al., 1992; Wang et al., 2012).

The SRYR, which lies in the hinterland of the plateau and faces mountains to its north and south, is in a semi-closed state. With intensive solar radiation, the climate in the study area is cold and dry; it is mainly affected by warm moisture flow from the Indian Ocean–Bay of Bengal and upper westerlies, and belongs to the inland alpine semi-arid and semi-humid climate transition zone (Su and Tang, 1987; Deng, 1988; Chen et al., 2008). The annual mean temperature is below 0°C and the precipitation is approximately 372 mm, mainly falling in the rainy season from May to October; the rainfall in this season accounts for more than 92% of the total annual precipitation (Wang and Cheng, 2000; Zhou et al., 2005; Liang et al., 2011).

Geologically, the SRYR drains between the Bayan Har fold belt and the Tanggula fold belt, and the strata exposed in the study area are mainly marine-terrestrial facies deposits from Permian to Quaternary in age (Qian et al., 2014). The strata are very thick and generally affected by regional low-grade metamorphism. In the north of

Fig. 1. The SRYR basin showing the sampling sites, DEM and water system (samples#2, samples#3, and samples#4 are from Pu et al. (1988), Su and Tang (1987), and Zhou et al. (2001), respectively).

the Chumaer He-Tongtian He fault zone, the Permian and Triassic groups are well exposed, being composed of clastic rocks and carbonate sediments and clastic rocks, respectively, both of which are affected by regional low-grade metamorphism (Li et al., 2012). In the south, marine Jurassic strata are thick and widely exposed, mainly containing purple red clastic rocks, carbonate rocks intercalated with evaporates, and volcanic rocks (Wu et al., 2009). The other exposed strata are of Carboniferous, Triassic and Paleogene age. Among them, the Triassic strata are dominated by carbonate rocks, beneath which red clastic and carbonate rocks that are not affected by regional metamorphism are present (Li et al., 2011). Sporadic small granitic intrusions occur in the source regions of Tuotuo He and Gaerqu along the south bank of Tongtian He. The granite rocks consist of gray and off-white, medium- and coarse-grained biotitic granite and granodiorite. Overall, the outcropping rocks are dominated by clastic rocks whose main constituents are sandstone and limestone (Fig. 2; Zhang et al., 1992; The China Geological Survey, 2004).

3. Materials and methods

A field survey was conducted across the Buqu, Gaerqu, Tuotuo He, Ranchiqu, Beilu He, and Chumaer He rivers along the No. 109 national road in July 2011. A total of 39 samples were collected at a depth of 10 cm. Samples were stored in pre-cleaned polyethylene bottles free of air and filtered through 0.45 μm Millipore nitrocellulose filters (Merck-Millipore). Immediately after collection, a small portion of these samples was stored for anion analyses, while another portion was acidified with ultrapure HCl to a pH < 2.

The following parameters were measured in the field: pH, water temperature, and conductivity by a Horiba U53 (HORIBA Ltd, Kyoto, Japan) multi-meter, and carbonate alkalinity by titration using HCl and methylorange dye indicator. Upon returning to the laboratory at the Institute of Geographic Sciences and Natural Resources Research, CAS, the major cations (K^+ , Na^+ , Ca^{2+} , Mg^{2+}) were analyzed using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (model ICP-OES 5300DV (PerkinElmer Inc., USA)) with detection limit ranges of 0.1–1 ppb for K, Na and <0.1 ppb for Ca, Mg. Additionally, anions (Cl^- , NO_3^- , SO_4^{2-}) were determined by ion chromatography of model ICS-

2100 (Dionex Corporation, USA). The detection limits for Cl^- , SO_4^{2-} and NO_3^- are 0.006, 0.009 and 0.05 ppm, respectively. The average analytical precision for all ions is better than 5%.

In order to investigate the hydrochemical characteristics of different rivers of the SRYR, we also used some data from Pu et al. (1988), Su and Tang (1987), Zhao et al. (2003), and Zhou et al. (2001) regarding the Tongtian He, which is the main stream after the convergence of the Tuotuo He and Damqu. In total, we used 56 samples after elimination of some samples for data quality control (see data details in Appendix A).

A statistical program, SPSS v 20.0, was used to evaluate the relationships between various physiochemical parameters. The hydrochemical program, AquaChem v 4.0.278, was used to analyze the water quality and plot the water-type graph.

4. Results and discussion

4.1. Major elements

The statistical characteristics of all the samples are presented in Table 1. The mean pH of the waters is slightly alkaline (pH = 7.6), with values ranging from 6.0 to 8.7. The variation in pH is restricted to a limited extent with the coefficient of deviation being 8.5%. The mean total dissolved solids (TDS) of the SRYR's rivers is 778 mg/l, which is more than 7 times on average than the world average of 100 mg/l (Roy et al., 1999) and nearly 3 times that of the world's large rivers (283 mg/l) (Han and Liu, 2004). The values range from 117 to 5496 mg/l due to the different formations outcropping; the former value mainly occurs in the southern rivers (Gaerqu, Buqu), reflecting the weathering of clastic rocks, whereas the latter mainly occurs in the northern rivers (Beilu He, Chumaer He, Ranchiqu), probably due to dissolution of evaporites. Globally, the order of the mean concentration of major ions is $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$ for cations, and $\text{Cl} > \text{Alk} > \text{SO}_4 > \text{NO}_3$ for anions (Table 1), with Na and Cl accounting for 74.2% and 63.7% of the total concentration of cations and anions, respectively. However, all ions but Alk show a coefficient of variation (C.V.) higher than 50%. In particular, the C.V. > 100% of chloride, sodium, and sulfate reflects the high solubility of halites and gypsum/anhydrite, further supporting the interaction of the waters with evaporites.

Fig. 2. Lithology map of the SRYR. Loose sedimentary rock formation-complex includes alluvial, diluvial, eluvial, colluvial sedimentary strata, such as sand, gravel, claystone. Clastic sedimentary rock formation-complex includes sandstone, shale, and limestone. Carbonate rock formation-complex involves carbonate or carbonate-clastic formation complex. Granite rock formation-complex includes granite, granite porphyry, feldspars, and granodiorite.

Table 1
Descriptive statistics of hydrochemistry of all available water samples.

Parameter	Sample num	Unit	Min	Max	Average	S.D. ^a	C.V. ^b (%)
Ca	56	mg/l	7.0	182.0	53.4	39.1	73.2
Mg	56	mg/l	2.2	101.8	22.9	18.5	80.5
Na	56	mg/l	2.2	1854	157.7	298.4	189.3
K	56	mg/l	0.7	26.1	5.5	5.6	100.8
Cl	56	mg/l	1.5	2910	233.7	470.4	201.3
Alk ^c	56	mg/l	15.9	366.6	188.5	82.2	43.6
SO ₄	56	mg/l	8.7	830.7	114.9	150.5	131.0
NO ₃	45	mg/l	0.0	5.0	1.3	1.0	83.6
pH	49		6.0	8.7	7.6	0.6	8.5
TDS	56	mg/l	117	5496	778	915.7	117.8

^a S.D.: standard deviation.^b C.V.: coefficient of variation.^c Alk: (alkalinity) = $\text{HCO}_3^- + \text{CO}_3^{2-}$.

Correlation analysis for the major ions demonstrates that the TDS has a positive relationship with the rest of the variables, while NO₃ and Alk have low coefficients, which may be explained by their high variation. Chloride, Na, Ca, and Mg show positive correlations, and their significant contribution to the overall chemical composition is demonstrated by their significant correlation with the TDS ($P < 0.01$). Of all the correlation ion pairs, the positive correlation coefficients for “Cl–Na, K” ($R > 0.8$, $P < 0.01$) and “SO₄–Ca, Mg” ($R > 0.6$, $P < 0.01$) are highest, indicating that Na–K and Ca–Mg may have good homology and that they have a certain similarity of origins and existence modes. The correlation of SO₄ with Mg and Ca suggests that the sulfate is mainly associated with magnesium sulfate (e.g., epsom salt) or gypsum/anhydrite (Noh et al., 2009). Nevertheless, although the coefficient is low, SO₄ is negatively correlated with Alk (Table 2).

4.2. Spatial variation

To explore the regional differentiation and differences between rivers, the samples were classified into categories according to the river. We carried out statistical analysis of different categories (Table 3). The northern rivers refer to those to the north of Tongtian He, including Beilu He, Ranchiqu, and Chumaer He. The main characteristics of these rivers are: TDS greater than 1000 mg/l and water type being Na–Cl because of lower precipitation and higher evaporation (Yang, 2005). High salinity is due to concentration through evaporation, which accelerates the accumulation of salt in water. The Cl/Na molar ratios of Chumaer He and Beilu He are slightly greater than 1, almost the same as halite, reflecting the typical dissolution of evaporites (e.g., salt rock and gypsum strata) (Zhao et al., 2003). The southern rivers, Gaerqu, Tuotuo He, and Buqu, have less TDS than the northern rivers (order of magnitude of a hundred). The salinity of these rivers is relatively lower because glacier melt water is an important supply source for these rivers. The samples from these rivers are mainly composed of bicarbonate due to the widespread distribution of carbonate rocks there (Fig. 2).

Table 2
Pearson correlations of major ions and TDS in rivers.

	K	Na	Ca	Mg	Cl	SO ₄	NO ₃	Alk	TDS	pH
K	1									
Na	0.83**	1								
Ca	0.55**	0.57**	1							
Mg	0.58**	0.53**	0.41**	1						
Cl	0.82**	1.00**	0.62**	0.51**	1					
SO ₄	0.56**	0.63**	0.69**	0.73**	0.61**	1				
NO ₃	0.12	0.03	0.02	0.34*	0.02	0.22	1			
Alk	0.20	0.04	–0.11	0.36**	–0.01	–0.04	0.15	1		
TDS	0.84**	0.98**	0.66**	0.63**	0.98**	0.73**	0.08	0.1	1	
pH	–0.08	0.03	–0.55**	–0.01	–0.03	–0.04	0.18	–0.06	–0.05	1

Bold values represent correlation with significance.

** Correlation is significant at the 0.01 level.

* Correlation is significant at the 0.05 level.

Table 3
Statistical characteristics of different rivers (mean value).

Rivers	PH	K	Na	Ca	Mg	Cl	NO ₃	SO ₄	Alk	TDS
Gaerqu	7.1	2.8	19.2	42.4	12.4	15.5	0.9	62.7	132.2	288
Tuotuo He	7.8	6.4	118.7	30.7	25.4	133.4	2.1	78.8	273.1	668
Buqu	7.8	3.3	55.6	39.8	14.7	75.6	0.6	56.0	171.6	417
Chumaer He	7.8	5.9	271.9	47.6	38.9	433.0	1.4	141.1	173.3	1113
Beilu He	7.8	16.7	1089	123.3	58.1	1696	2.8	486.3	172.8	3645
Ranchiqu	7.9	7.1	266.3	65.6	36.7	345.3	0.7	310.6	231.9	1264
Tongtian He	7.6	5.9	105.8	70.8	20.0	187.4	1.3	82.9	184.0	657

Their Cl/Na molar ratios are no more than 0.88, except in some samples from Tuotuo He.

Piper ternary diagrams (Fig. 3) provide a way to visualize the compositions and water types of rivers, and therefore, can show the relative importance of different weathering regimes (Huh et al., 1998). The diagrams show the wide diversity of samples from different rivers. On the cation diagram, samples from Buqu, Gaerqu lie in the lower-left corner, where the Ca values are high (more than 50%), revealing that the dominant cation in these samples is calcium. On the contrary, the others mostly fall on the lower-right corner and on the middle line of Ca: Mg = 1: 1, where the dominant ion is sodium showing the characteristics of evaporites. On the anion diagram, the samples from Buqu, Gaerqu and Tuotuo He fall on the lower-left corner, the alkalinity apex, showing carbonate weathering features. However, samples from Tongtian He, Beilu He fall on the lower-right corner revealing chloride-dominated features. Nevertheless, the values of samples from Chumaer He are relatively scattered, but still show chloride-dominated features overall. Samples from Ranchiqu have very low alkalinity and their dominant ions, chloride and sulfate, are nearly equivalent, which makes them exceptional. According to the Piper diagram (Fig. 3), the water types of Gaerqu, Tuotuo He, Buqu, Chumaer He, Beilu He, Ranchiqu, and Tongtian He are HCO₃–Ca, HCO₃–Na, HCO₃–Ca·Ma, Cl–Na, Cl–Na, Cl·SO₄–Na, and Cl·HCO₃–Na·Ca, respectively. Overall the distributions are indicative of weathering of platform carbonates and evaporites.

On the whole, regional heterogeneity is obvious. Northern rivers have evaporite-related characteristics, i.e. Na–Cl water type. They drain sedimentary rocks, and ions probably come from halite, anhydrite, and gypsum because of the relatively higher SO₄ content. However, the southern rivers show carbonate features; most of the samples from here have a Na·Ca–HCO₃ water type due to the carbonate rock formations/complexes (Fig. 2).

4.3. Mechanisms controlling the major-ion chemistry

Gibbs (1970) defined the mechanisms controlling world surface water chemistry as three end-members: atmospheric precipitation, rock dominance, and the evaporation-crystallization process on the

Fig. 3. Piper diagram for the water samples in different rivers. In the key: BLH (Beilu He), BQ (Buqu), CMEH (Chumaer He), GEQ (Gaerqu), RCQ (Ranchiqu), TTHR (Tongtian He) and TTH (Tuotuo He).

basis of analyzing numerous rain, river, lake, and ocean samples. To distinguish the contribution of the three end-members, TDS versus $\text{Na}/(\text{Na} + \text{Ca})$ or TDS versus $\text{Cl}/(\text{Cl} + \text{HCO}_3)$ are used (Fig. 4; Gibbs, 1970). In general, samples with low salinity (TDS approximates 10 mg/l) and high ratio of $\text{Na}/(\text{Na} + \text{Ca})$ or $\text{Cl}/(\text{Cl} + \text{HCO}_3)$ (approaching to 1) fall on the lower-right corner, reflecting the influence of precipitation. Samples with medium salinity (about 70 to 300 mg/l) and low ratio of $\text{Na}/(\text{Na} + \text{Ca})$ or $\text{Cl}/(\text{Cl} + \text{HCO}_3)$ (less than 0.5) locate on the left side of the central area, indicating that the dominant end-member is rock weathering. The third case, samples with high salinity and high ratio of $\text{Na}/(\text{Na} + \text{Ca})$ or $\text{Cl}/(\text{Cl} + \text{HCO}_3)$ (approaching to 1) fall on the upper-right corner, indicating that the dominant factor is evaporation–crystallization (Stallard and Edmond, 1983; Chen, 1987).

The Gibbs schematic diagram is shown in Fig. 4. The diagram reveals that the river waters of Gaerqu and Buqu are characterized by low ratios of $\text{Na}/(\text{Na} + \text{Ca})$ and $\text{Cl}/(\text{Cl} + \text{HCO}_3)$ and moderate concentrations of

TDS, typical of rock dominance rivers. Beilu He, Chumaer He, and Ranchiqu are characterized by high ratios of $\text{Na}/(\text{Na} + \text{Ca})$ and $\text{Cl}/(\text{Cl} + \text{HCO}_3)$ and high concentrations of TDS, showing that the controlling factor is evaporation–crystallization processes. However, Tuotuo He and Tongtian He are in an intermediate state, having moderate values of TDS and ratios of $\text{Na}/(\text{Na} + \text{Ca})$ and $\text{Cl}/(\text{Cl} + \text{HCO}_3)$; they are controlled by rock weathering and evaporation–crystallization processes.

These results and conclusions are consistent with the ternary diagram (Fig. 3). The northern rivers are mainly affected by evaporation–crystallization, which is not surprising. From the meteorological point of view, strong radiation, strong evaporation, and low precipitation result in evaporite concentration. Taking the lithology into consideration, northern rivers are mainly controlled by lacustrine sediment, which provide a large amount of halite (NaCl) into dissolved ions (Zhang, 2009). Additionally, groundwater recharge brings leached salts to the surface, resulting in salt-accumulation. The southern rivers (except Tuotuo He) are mainly controlled by rock weathering. Tuotuo He and Tongtian He are controlled by two end members, rock dominance and evaporation–crystallization. Whatever the case may be, none of the rivers are affected by precipitation.

4.4. Chemical weathering

Weathering of different rocks yields different combinations of ions to a solution. For instance, Ca and Mg mainly originate from the weathering of carbonates, silicates, and evaporites, Na and K from the weathering of evaporites and silicates, HCO_3 from carbonates and silicates, and SO_4 and Cl from evaporites (Chen et al., 2002). Combinations of the three representative lithologies, i.e., evaporites, carbonates, and silicates, can be displayed on plots of Na-normalized molar ratios (Fig. 5). The mixing diagram is usually used to show the origins of the ions produced by chemical weathering in a basin with complex lithology (Gaillardet et al., 1999; Gao and Tao, 2010).

The samples from Beilu He, Chumaer He, Tuotuo He, and Ranchiqu plot between the silicate and the evaporite end-members, whereas the samples from Buqu and Gaerqu plot between the carbonate and the silicate end-members. Halite and gypsum/anhydrite are the two most common evaporites that can affect river water chemistry (Moon et al., 2007). Nevertheless, samples from Tongtian He distribute widely

Fig. 4. Plot of the major ions within the Gibbs boomerang envelope for rivers.

Fig. 5. Mixing diagrams using Na-normalized molar ratios by rivers: (a) Mg/Na versus Ca/Na and (b) HCO₃⁻/Na versus Ca/Na. End member compositions of carbonate, silicate and evaporite are from Gaillardet et al. (1999).

in the diagram. This is possibly due to the recharge with different chemical compositions of tributaries in the upper reaches.

Generally, K and Na are derived from evaporite dissolution and silicate weathering in rock weathering dominated rivers. The strong correlations between Cl, SO₄, Na, and K suggest that they originated from the weathering of evaporite, especially in Ranchiqu and Beilu He.

In summary, the samples from the northern and southern rivers exhibit distinct differences in the type of chemical weathering affecting them. The northern rivers are mainly dominated by evaporite dissolution, while the southern rivers and Tongtian He are dominated by silicate and carbonate weathering.

5. Conclusions

The hydrochemistry of surface water in the SRYR is slightly alkaline with high TDS, the average value of which is 778 mg/l, which is nearly three times that of the world's large rivers (283 mg/l). Na, Ca, Cl, and HCO₃⁻ are the principal chemical components in the surface water of the SRYR. The water types of Gaerqu, Tuotuo He, Buqu, Chumaer He, Beilu He, Ranchiqu, and Tongtian He are HCO₃-Ca, HCO₃-Na, HCO₃-Ca·Mg,

Cl-Na, Cl-Na, Cl·SO₄-Na, and Cl·HCO₃-Na·Ca, respectively. As a whole, the waters exhibit water type of chloride, bicarbonate-sodium, and calcium.

In addition, there is large spatial variability in the hydrochemistry of the water in the different rivers of the SRYR due to the complex geologic makeup of the drainage basins. The northern rivers, including Chumaer He, Beilu He, and Ranchiqu, are mainly affected by evaporite dissolution, while the southern rivers (Tuotuo He, Gaerqu, and Buqu) show weathering from carbonates and silicates, and Tongtian He are dominated by silicates and carbonates weathering. With respect to the water type, Chumaer He and Beilu He belong to a typical Na-Cl water type.

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Appendix A

Table A1. Major ion composition of rivers in the source region of Yangtze river.

Data source	NO ₃ ^a	Sample ID ^b	Location ^c	Elevation m	pH	K mg/l	Na mg/l	Ca mg/l	Mg mg/l	Cl mg/l	NO ₃ mg/l	SO ₄ mg/l	Alk mg/l	TDS mg/l	NICB ^d %
Gaerqu															
Pu et al., 1988	1	15	Jianggengqu	5900	7.76	1.94	8.25	36.0	6.01	4.43	–	27.6	112.8	198	7
Pu et al., 1988	2	18	Qiesumeiqu	5160	7.26	2.00	13.0	19.2	2.21	9.22	–	16.9	63.0	126	8.2
Zhou et al., 2001	3	Q9	Jianggengqu	4998	6.20	2.23	7.39	47.8	7.67	22.2	–	31.2	125.7	244	1.8
Zhou et al., 2001	4	Q8	Gaerqu	4570	6.00	4.96	43.8	105.3	14.3	47.7	–	94.6	314.2	625	–0.1
Zhao et al., 2003	5	–	Gaerqu	–	–	2.73	23.9	42.4	7.20	26.3	1.86	37.4	116.5	258	9.7
This study	6	20	Source of Gaerqu	4650	6.90	8.60	57.2	6.90	41.7	27.6	0.80	64.8	293.0	501	4.0
This study	7	29	Trib.1 of Gaerqu	4929	7.09	1.35	12.3	26.3	9.01	1.50	0.56	32.4	33.6	117	2.2
This study	8	30	Trib.2 of Gaerqu	4841	7.87	1.66	10.6	38.8	7.79	6.67	0.35	48.7	116.0	231	8.5
This study	9	31	Up. reach of Gaerqu	5007	7.95	1.73	11.4	32.2	6.70	6.87	0.45	34.3	131.1	225	0.2
This study	10	32	Trib.3 of Gaerqu	4870	6.95	0.71	3.95	67.6	21.3	2.24	1.23	238.8	15.9	352	3.1

(continued on next page)

Appendix A (continued)

Data source	NO ^a	Sample ID ^b	Location ^c	Elevation m	pH	K mg/l	Na mg/l	Ca mg/l	Mg mg/l	Cl mg/l	NO ₃ mg/l	SO ₄ mg/l	Alk mg/l	TDS mg/l	NICB ^d %
Tuotuo He															
Zhou et al., 2001	11	Q7	Bridge of Tuotuo He	4534	6.00	16.6	316.3	98.1	22.6	471	–	161.9	213.5	1300	3.4
This study	12	33	Lo. reach of Tuotuo He	4511	8.15	9.78	126.2	49.4	17.9	140.9	3.31	90.3	171.9	610	2.7
This study	13	T1	19 km from the source	4590	7.84	6.28	83.6	24.4	13.2	88.3	2.76	59.4	237.9	516	1.3
This study	14	T2	RB Trib.1 of Tuotuo He	4567	7.60	5.74	181.3	18.4	25.9	195.6	1.97	101.4	366.6	897	–8.2
This study	15	T3	12 km from the source	4585	8.65	5.11	73.2	7.90	19.5	53.1	1.53	21.7	266.3	448	–6.3
This study	16	T4	RB Trib.2 of Tuotuo He	4578	8.11	2.89	43.6	20.2	22.6	26.7	0.93	27.6	320.1	465	–2.0
This study	17	T5	RB Trib.3 of Tuotuo He	4565	–	4.33	129.6	18.2	33.1	113.7	1.64	60.3	329.1	690	–5.0
This study	18	T6	RB Trib.4 of Tuotuo He	4563	8.14	3.11	53.5	23.8	41.0	57.6	2.17	121.4	253.1	556	4.5
This study	19	T7	RB Trib.5 of Tuotuo He	4554	8.02	3.51	61.2	15.6	32.9	53.2	2.09	65.0	299.3	533	1.9
Buqu															
Pu et al., 1988	20	19	Up. reach of Buqu	4880	7.68	1.33	3.90	25.7	3.68	2.58	–	8.7	93.9	140	0.0
Zhao et al., 2003	21	–	Buqu	–	–	1.95	16.3	52.4	10.1	16.7	1.86	64.3	126.3	290	7.3
Zhao et al., 2003	22	–	Up. reach of Buqu	–	–	0.78	4.37	26.4	5.04	3.20	0.00	17.3	103.1	160	–9.8
Zhou et al., 2001	23	Q10	Yanshiping	4611	7.00	2.41	11.2	103.6	12.6	27.0	0.00	75.8	269.1	502	0.5
This study	24	10	G109-3195	4577	7.64	23.6	519.1	62.9	60.9	774.4	1.30	114.2	348.2	1905	4.7
This study	25	12	Yanshiping	4701	7.77	1.12	12.8	35.8	10.2	4.89	0.50	48.9	140.4	255	8.6
This study	26	13	Trib. of Buqu	4784	7.85	1.25	42.5	51.3	26.6	43.3	0.51	141.0	134.3	441	4.4
This study	27	14	G109-3289	4849	7.84	1.07	5.58	27.5	11.5	3.70	0.22	55.0	298.9	403	–4.3
This study	28	15	G109-3305	4895	7.93	1.70	12.4	27.4	10.8	3.52	0.46	49.6	143.5	249	–7.2
This study	29	19	Conf. of Gaerqu	4572	7.89	2.27	30.7	23.6	11.9	21.5	0.71	49.1	155.9	296	–9.0
This study	30	26	LB Trib. of Buqu	4778	8.09	1.47	6.64	17.8	8.02	3.91	0.48	29.1	154.2	222	–8.1
This study	31	28	Source of Buqu	4992	7.87	0.80	2.19	23.2	5.02	2.33	0.06	18.3	91.8	144	2.3
Chumaer He															
Zhao et al., 2003	32	–	Chumaer He	–	–	15.2	860	112.0	54.2	1380	0.00	288.0	139.1	2848	1.6
This study	33	1	G109-2908	4676	7.94	2.72	89.1	29.6	23.8	142.5	1.26	60.1	153.7	503	–4.0
This study	34	2	Bodongquan	4589	7.42	3.47	113.5	30.8	67.1	172.8	1.40	190.4	297.0	877	–6.7
This study	35	3	Xieshui He	4571	7.92	2.19	24.9	18.1	10.5	36.8	2.86	25.8	103.4	224	–6.5
Beilu He															
Zhao et al., 2003	36	–	South branch of Beilu He	–	–	26.1	1854	148.0	41.8	2910	0.00	367.7	148.8	5496	–2.6
This study	37	5	G109-3034	4583	7.72	12.4	605	137.2	101.8	925.3	4.99	712.5	162.6	2662	2.3
This study	38	7	G109-3049	4559	7.95	11.7	808	84.7	30.7	1253	3.44	378.7	207.1	2778	–2.4
Ranchiqu															
Zhao et al., 2003	39	–	North branch of Ranchiqu	–	–	14.4	529	182.0	53.8	830.7	0.00	830.7	126.3	2566	1.7
This study	40	22	G109-3097	4624	7.94	3.20	133.9	35.6	20.2	149.7	1.63	79.8	264.8	689	–9.4
This study	41	23	G109-3103	4595	7.73	3.55	205.9	16.7	15.9	163.5	0.43	131.2	265.2	802	–4.3
This study	42	25	G109-3111	4578	7.94	7.26	196.5	28.2	57.1	237.5	0.83	200.9	271.2	999	–2.9
Tongtian He															
Zhou et al., 2001	43	Q12	Qidukou	4223	6.50	5.93	136.1	133.5	22.1	371.9	–	99.4	114.2	883	0.4
Zhou et al., 2001	44	Q13	Bridge of Sewu He	4186	6.70	2.24	17.7	89.0	20.9	91.4	–	19.6	214.7	456	6.4
Zhou et al., 2001	45	Q14	Conf. of Nieqia He	4058	7.30	2.24	7.51	112.1	14.5	137.8	–	34.6	152.7	461	0.7
Zhou et al., 2001	46	Q15	Bridge of Tongtian He	4085	7.00	6.04	140.5	94.7	22.7	208.7	–	132.6	248.4	854	0.6
Zhou et al., 2001	47	Q17	South of Qumalai	4106	6.00	4.97	117.5	95.6	29.8	194.7	–	97.1	299.8	839	0.1
Su and Tang, 1987	48	1	Conf. of Ranchiqu	4444	7.90	17.8	315	60.0	25.8	490.8	1.12	158.6	160.9	1230	–2.5
Su and Tang, 1987	49	2	Conf. of Moqu	4389	7.95	9.40	155.5	65.0	23.2	242.8	1.72	140.2	174.3	812	–3.8
Su and Tang, 1987	50	3	Conf. of Beilu He	4329	7.85	5.60	72.5	51.1	17.5	97.8	1.12	77.9	188.1	512	–2.3
Su and Tang, 1987	51	4	Conf. of Keqianqu	4282	8.30	5.60	111.6	49.7	19.1	170.8	1.32	85.4	162.5	606	–2.2
Su and Tang, 1987	52	5	Conf. of Chumaer He	4216	8.10	5.20	106.4	48.9	19.2	161.9	2.08	76.0	177.5	597	–3.2
Su and Tang, 1987	53	6	Sewuqu	4156	8.05	4.40	82.0	46.9	17.4	121.1	0.90	64.2	175.9	513	–2.3
Su and Tang, 1987	54	7	Qumalai	4180	8.00	4.40	74.2	45.9	17.0	107.9	1.32	59.5	178.9	489	–2.6
Su and Tang, 1987	55	8	Dequ	3869	8.31	4.50	72.5	49.7	14.8	113.8	1.20	55.7	164.1	476	–1.3
Su and Tang, 1987	56	9	Zhimenda	3538	8.32	4.00	72.5	48.7	15.4	112.0	1.00	59.6	163.5	477	–1.7

–: data not available.

^a The number we designed.^b The original sample number.^c Conf. = confluence; LB. = left bank; Lo. = Lower; RB. = right bank; Trib. = tributary; Up. = Upper; G109-3xxx = milepost of road G109.^d NICB (Net Inorganic Charge Balance) = (TZ[–] – TZ⁺) / TZ⁺ × 100%, TZ⁺ (total dissolved cations) = Na⁺ + K⁺ + 2Mg²⁺ + 2Ca²⁺, TZ[–] (total dissolved anions) = Cl[–] + 2SO₄^{2–} + HCO₃[–].

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