Distribution characteristics, enrichment patterns and health risk assessment of dissolved trace elements in river water in the source region of the Yangtze River

Min Liu, Liangyuan Zhao, Qingyun Li, Yuan Hu, Huawei Huang, Jingyi Zou, Fei Gao, Jingxiang Tao, Yizhe Zhang, Ping Xu, Zhiguang Wu and Chan Yu

ABSTRACT

The security of water environment in the source region of the Yangtze River (SRYR) is vital to the water environment security of the whole basin. The results showed that the rivers in the SRYR were weakly alkaline and the values of total solid solubility (TDS), electrical conductivity (EC), turbidity concentration and salinity were higher than the values in the middle and lower reaches of the Yangtze River. The results showed that the dissolved trace elements detected displayed obvious regional distribution characteristics, showing a high concentration trend in the Chumar River, low in the Dangqu, and middle in the Tong River. All water quality indexes in the SRYR met the surface water environmental quality standard of class II based on GB 3838-2002 except Hg, while the average concentration of As exceeded 10 μg/L. The main enrichment elements in the SRYR were Li, Se, As and Pb, and their concentrations were far higher than the average concentration of the world rivers. Moreover, the HI and $HQ_{ingrstion}$ of children caused by As in the SRYR were greater than 1. This study could provide basic data for water environment protection and water resource management in the SRYR.

Key words | dissolved trace elements, distribution characteristics, enrichment, health risk assessment, source region of the Yangtze River, water quality

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HIGHLIGHTS

- All water quality indexes in the SRYR met the surface water environmental quality standard of class II.
- The main enrichment elements in the SRYR were Li, Se, As and Pb, and their concentrations were far higher than the average concentration of the world rivers.
- The average concentration of As in the SYRY exceeded the standard of WHO (2011); special attention should be paid to the adverse effects of As for local residents.

INTRODUCTION

Trace elements can be absorbed by organisms in aquatic ecosystems through physical, chemical and biological cycling processes (He & Charlet 2013; Kumar *et al.* 2017; Zhang *et al.* 2017). Enrichment of toxic metals in water systems makes the water unfit to drink, and the ingestion of considerable amounts of metal can lead to mental disease (Li *et al.* 2011). Trace elements are mainly derived from natural and human activities. Natural sources include bedrock weathering and erosion, soil leaching, volcanic eruptions and atmospheric precipitation, while human activities include mining,

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metal smelting and refining, agricultural runoff, industrial activities etc. (Singh *et al.* 2008; Li *et al.* 2011). In recent years, researchers have become increasingly concerned with the assessments of trace metals in the aqueous environment (Kavcar *et al.* 2008; Wu *et al.* 2009; Li & Zhang 2010; Li *et al.* 2011; Kumar *et al.* 2017; Zhang *et al.* 2017; Gao *et al.* 2019).

The ecological environment of the source region of the Yangtze River (SRYR) is vulnerable to external interference, and once damaged would be difficult to recover. With a small population and harsh natural environment the SRYR is a sensitive area for climate and ecological environment changes (Zhang & Zhun 1992; Ding *et al.* 2018). In recent years, the ecological environment in the SRYR has undergone changes due to the influence of natural processes, the intensification of human activities and the impact of global climate change (Shen *et al.* 2009; Li *et al.* 2018; Zhao *et al.* 2019), which has resulted in an increase of the regional water supplies, rising and expanding of lake levels and runoff changing of major rivers (Shen *et al.* 2009; Shiyin *et al.* 2009). What is more, the characteristics of the water environment have also changed, including changes in water quality, hydrological processes, and the aquatic environment (Huang *et al.* 2011; Jiang *et al.* 2015).

Some studies showed the total nitrogen concentration, total phosphorus and potassium permanganate index in the SRYR met I ~ II class water according to the environmental quality standard for surface water in China (GB3838-2002), while some trace elements such as the concentration of Fe and Mn in the water were relatively high based on the environmental quality standard for surface water in China (GB3838-2002) (State Environmental Protection Administration 2002) (Qu *et al.* 2015, 2019; Zhao *et al.* 2019). Zhang & Zhun (1992) investigated the levels of trace elements in the SRYR (Tuotuo River, Chumar River and Tongtian River) and there were no significant differences in dissolved trace elements. To date, there have been few studies on the distribution characteristics, enrichment patterns and human health risk assessment of dissolved trace elements in the main rivers of SRYR, especially for Dangqu.

In the present research, distribution characteristics, enrichment patterns and health risk assessment of dissolved trace elements in river water in the SRYR were investigated, aiming to provide basic data for water environment protection and water resource management in the SRYR.

STUDY AREA

The Yangtze River is the longest river in China and the third longest in the world. The SRYR is located in the hinterland of the Qinghai-Tibet Plateau, known as the water tower of China, and the runoff accounts for about 1.3% of the total flow of the Yangtze river (Chen 2013). The SRYR, with high altitude and low temperature, is semi-closed in terrain, covered by a large number of glaciers, ice sheets, snow caps and frozen soil all year round. The average precipitation is 398 mm and the evaporation capacity is 1,278–1,631 mm in the SRYR, which is the lowest precipitation and the driest region in the Yangtze River Basin (Wei 1988; Chen 2013). The area covers approximately 138,200 km^2, including the Dangqu (south source), the Tuotuo River system (main source), Chumar River (north source) and the Tongtian River in the main stream (Jiang *et al.* 2015). Dangqu originates from the marshland at the eastern foot of Xiasherjiaba mountain in the eastern section of Tanggula mountain. The major tributaries in the lower reaches of Dangqu have secondary tributaries Gaerqu, Buqu, Dongqu and Tingqu. The Tuotuo River originates from the Jianggendiru glacier on the east side of the Dandong snow mountain and mainly accepts melt water from the glaciers on both sides. The Chumar River originates from the southern foot of the black ridge mountain of Hohxil, the southern branch of Kunlun mountain. There are many plateau lakes in the upper reaches of the river basin (Shen *et al.* 2009). The Tongtian River originates from the confluence of Dangqu and Tuotuo River to the Batang estuary near Yushu, Qinghai Province. The main tributaries of Beilu River, Ran Chiqu, Moqu, Keqianqu, and Nieqiaqu are distributed on both sides of the Tongtian River (Li 2013).

METHODS

Sample collection

According to the regional characteristics of the SRYR, 34 sampling sites were set up (Figure 1) and detailed information of all sampling sites is shown in Appendix A. Thirteen sampling sites (D1–D13) were distributed in

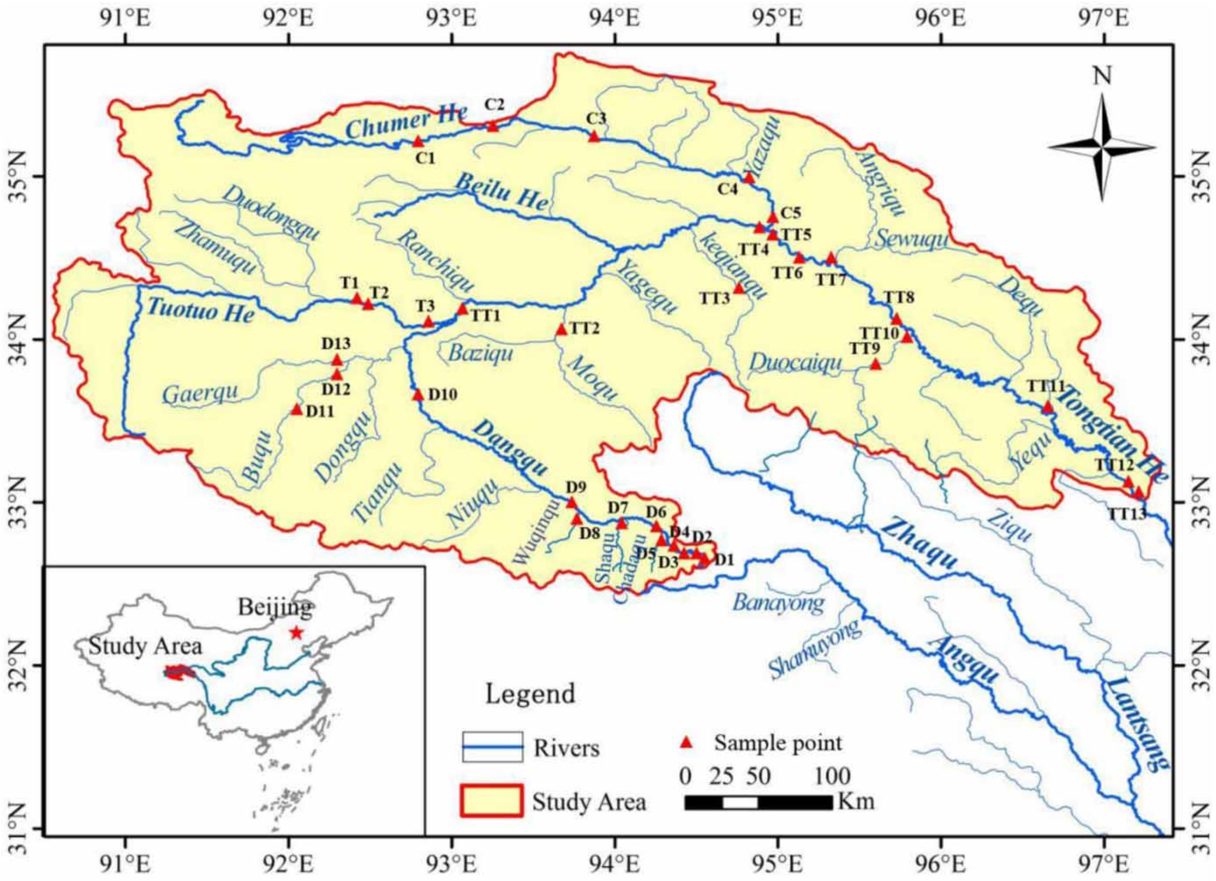

Figure 1 | Sample sites distribution of river water in the SRYR.

Dangqu, three (T1–T3) in Tuouo River, five (C1–C5) in Chumar River and 13 (TT1–TT13) in Tongtian River.

Surface water samples were collected at a depth of about 10 cm, and filtered through pre-washed 0.45 μm Millipore nitrocellulose filters. The initial portion of the filtration was discarded to clean the membrane, and the following ones were acidified to $pH < 2$ with ultra-purified 6 M HNO_3 and then stored in plastic bottles for trace metal analyses. Cleaning of plastic bottles was carried out by soaking in 20% (v/v) HNO_3 for 24 h and then rinsing with milli-Q deionised water (~18 MΩ/cm resistivity; TOC < 5 mg/L) from Milli-Q (Millipore, Direct 8).

Analysis methods

The pH, EC, TDS and turbidity in the water were measured by a portable water quality analyzer (Xylem, EXO2). Cu, Pb, Zn, Cd, Cr, As, Se, Ni, Ba, Mo, Sr, Li and V were analyzed by ICP-MS (Perkin-Elmer, NexION 300X) (Ministry of Environmental Protection of the Peoples Republic of China 2014; Zhao *et al.* 2019; Zhao *et al.* 2020). The detection limit was 0.06–0.41 μg/L and the recovery was 86.8–99.8%. An atomic fluorescence spectrophotometer (AFS-3100, China) was used to detect the concentration of Hg (Ministry of Water Resources of the People's Republic of China 2005); the detection limit was 0.01 μg/L, and the recovery rate was 93–104%. A standard was inserted to ensure data accuracy after every ten samples. The blank sample was below the detection limit. The mean of three runs was obtained for each sample.

Data below the analytical detection limits were placed at a value of half the detection limit when constructing all plots and statistical calculations (Yang *et al.* 2014). In order to better analyze the situation of trace elements in the SRYR, some data was used from the previous research conducted by Qu *et al.* (2015).

RESULTS AND DISCUSSION

Physicochemical properties of water

The results conducted from 2012 to 2019 are shown in Table 1. The pH value of the SRYR ranged from 7.6 to 9.1, with an average value of 8.2, indicating that the river water was weakly alkaline. The value of TDS ranged from 50 to 10,336 mg/L, which indicated that the regional geological structure was more complicated with a large variation (Noh *et al.* 2009). The average TDS concentration was 1,685 mg/L, which was ten times higher than the average TDS of the world's rivers (150 mg/L) (Gaillardet *et al.* 2014), and the average level of TDS is displayed as follows: Chumar River > Tuotuo River > Tongtian River > Dangqu. The water was divided into four categories by the TDS: fresh water (TDS < 1,000 mg/L), brackish water (1,000 < TDS < 3,000 mg/L), moderately salty water (3,000 < TDS < 10,000 mg/L), extremely salty water (10,000 < TDS < 35,000 mg/L) and brine (TDS > 35,000 mg/L) (Avid 1992; Su & Hong 1998). It could be found that the Dangqu (average concentration of 279.3 mg/L) and Tongtian River (average concentration of 567.6 mg/L) were fresh water, the Tuotuo River (average value of 1,439 mg/L) was brackish water, and the Chumar River (average value of 4,179 mg/L) was moderately salty. The value of EC ranged from 98.1 to 6,968 μS/cm with an average value of 1,812 μS/cm. The average value of the EC was in the following order: Chumar River > Tuotuo River > Tongtian River > Dangqu. The salinity hazard was divided into four categories: low (EC < 250 μS/cm), medium (250 μS/cm < EC < 750 μS/cm), high (750 μS/cm < EC < 2,250 μS/cm) and very high (EC > 2,250 μS/cm) (Xiao *et al.* 2019; Long & Luo 2020). It can be seen that the salinity hazard of the Dangqu (average value of 343.7 μS/cm) was medium, the salinity hazard of the Tuotuo River (average value of 1,739 μS/cm) and the Tongtian River (average value of 875.2 μS/cm) were high, while the salinity hazard of the Chumar River (average value of 4,292 μS/cm) was very high.

Table 1 | Physical and chemical properties of river water in the SRYR

River name	Type	pH	TDS (mg/L)	EC (μS/cm)	Salinity (ppt)
Dangqu	Min	7.6	70	98.1	210
	Max	9.1	514	465.6	270
	Mean	8.2	280	343.7	230
Tuotuo River	Min	8.0	706	549	660
	Max	8.6	1,960	3,290	1,060
	Mean	8.3	1,439	1,739	860
Chumar River	Min	8.0	774	1,535	1,740
	Max	8.5	10,336	6,968	3,090
	Mean	8.2	4,179	4,292	2,520
Tongtian River	Min	7.7	50	162	180
	Max	8.6	999	2,040	870
	Mean	8.2	567.6	875.2	460
SRYR	Min	7.6	50.00	98.10	180
	Max	9.1	10,336	6,968	3,090
	Mean	8.2	1,616	1,812	1,020

The value of salinity ranged from 180 to 3,090 mg/L with an average value of 1,020 mg/L. The average salinity values were in the following order: Chumar River > Tuotuo River > Tongtian River > Dangqu. The TDS and EC of SRYR were significantly higher than the middle- and downstream of Yangtze River (Chen *et al.* 2006; Li *et al.* 2014, 2020), which is mainly because the average precipitation and runoff in the SRYR were the lowest in the Yangtze River Basin (Wei 1988). The TDS, EC and salinity of the Dangqu were relatively low compared with the other rivers due to the high rainfall characteristics of Dangqu compared with the other rivers (Chen 2014), and glacial meltwater was an important supply (Zhao *et al.* 2019).

Evaluation of trace elements

The average concentration of 17 types of trace metals in the SRYR are presented in Table 2. The average value of EC followed the order of Sr > Li > Ba > As > Cu > V > Zn > Se > Cr > Ni > Ti > Mo > Pb > Co > Sb > Hg > Cd, and the results indicated that the concentrations of Sr, Li, Ba and As were relatively high in the SRYR (Ding *et al.* 2018). The trace elements from SRYR can be divided into three categories. The mean concentrations of Sr and Li exceeded 100 μg/L, which were identified as the most abundant elements. The concentrations of Ba, As, Cu, V, Zn, Se, C, Ni, Ti, Mo and Pb varied from 1 to 100 μg/L, which were the moderate elements. Sb, Hg, and Cd were lower than 1 μg/L, which were the low abundant elements. Next, we compared the trace elements in the SRYR with GB 3838-2002, the Standards for Drinking Water Quality (GB 5749-2006) in China (Ministry of Health of the People's Republic

Table 2 | Mean of trace elements concentrations (μg/L) in the SRYR, and comparison with guidelines

	GB3838-2002					US EPA (2009)		US EPA (2013)		
Element	**Grade I**	**Grade II**	**Grade III**	**GB5749-2006**	**WHO**	**MCLG**	**MCL**	**CMC, acute**	**CCC, chronic**	**Mean of the SRYR**
As	10	50	50	10	10	0	10	340	150	10.02
Hg	0.05	0.05	0.1	1	1	2	2	1	1	0.10
Cu	10	1,000	1,000	1,000	2,000	1,300	1,300	13	9	5.87
Zn	50	1,000	1,000	1,000		2,000	2,000	120	12	3.52
Pb	10	10	50	10	10	0	15	65	3	1.06
Cr	10	50	50	50	50	100	100	16	11	1.83
Cd	1	5	5	5	3	5	5	2	0.25	0.02
Se	10	10	10	10	10	50	50	0	5	1.92
Ba	–	–	–	700	700	2,000	2,000	–	–	61.23
Ni	–	–	–	20	70	–	–	470	52	1.73
Sr	–	–	–	–	–	–	–	–	–	592.8
Ti	–	–	–	–	–	–	–	–	–	1.35
Sb	–	–	–	5	20	–	–	–	–	0.2
Co	–	–	–	1,000	–	–	–	–	–	0.94
Li	–	–	–	–		–	–	–	–	175.6
V	–	–	–	–	–	–	–	–	–	5.63
Mo	–	–	–	70	–	–	–	–	–	1.09

CMC, criterion maximum concentration; CCC, criterion continuous concentration; MCLG, maximum contaminant level goal; MCL, maximum contaminant level.

China 2006; WHO 2011), for drinking water established by US EPA (2009), and the standard for the protection of freshwater aquatic life set by US EPA (2013). The average concentration of As in the SRYR met the water quality range of class II based on GB 3838-2002, but it was higher than GB 5749-2006, WHO (2011) and US EPA (2009, 2013). The average concentration of Hg exceeded the water quality range of class II based on GB 3838-2002, indicating that As and Hg were the main pollutant elements. The adverse health effects of high As intake included hypertension, neuropathy, diabetes, skin lesions, and cardiovascular and cerebrovascular diseases (Yang *et al.* 2014). Hg was one of the most toxic heavy metals, and in aquatic ecosystems, microorganisms can convert inorganic Hg(II) to methyl mercury, a toxic organomethane species (CH_3Hg^+) which is prone to bioaccumulation. Both inorganic Hg(II) and CH_3Hg^+ in aqueous solution were very toxic to bacteria, freshwater algae and fish (Jackson 1998). Therefore, the water may not be used for drinking and may be adverse to freshwater aquatic life in the SRYR.

Compared with the 20th century (Zhang & Zhun 1992), the concentration of trace elements in the SRYR has increased, which may be due to the continuous increase in population and global social and economic development, global warming and human activities (railway and road construction, tourism development and increased livestock production) (Shen *et al.* 2009; Li *et al.* 2018; Zhao *et al.* 2019). The concentration of trace elements in the water of the SRYR from 2012 to 2019 were higher than the Yangtze river, except for Cd, Sb and Mo (Wen *et al.* 2019). Except for Cd, Sb and Co, the concentration of trace elements was higher than the world river average (Figure 2). Compared with the source area of the Yellow River (Bu *et al.* 2004), except for Cd, Sb and Co, the concentration of trace elements was higher than the world river average. This indicates that the background value of the trace elements in the SRYR was high.

Correlation analysis was helpful to determine the relationship between variables and to analyze the sources of different trace elements (Kumar *et al.* 2017). Pearson

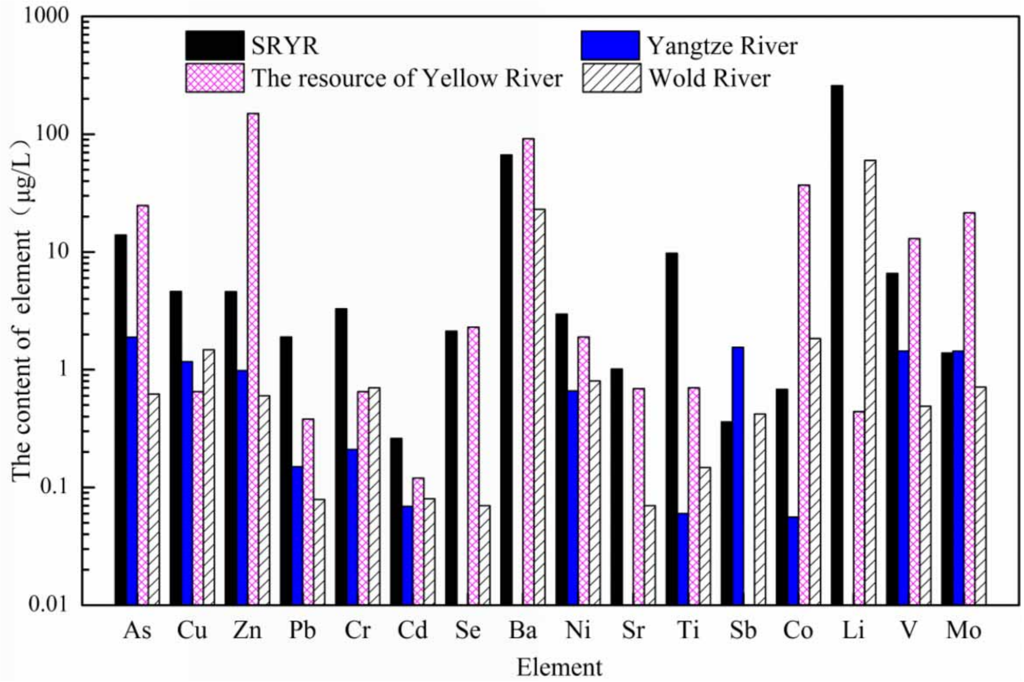

Figure 2 | Comparison of concentration of trace elements in the SRYR with other rivers.

correlations of trace elements in the SRYR are shown in Appendix B. The element As was significantly positively correlated with Pb ($r = 0.61$, $p < 0.01$). In summer, from June–September, the temperature of the SRYR is high, and the river water mainly comes from the melting of ice and snow, precipitation, the melting of permafrost and groundwater recharge, but the concentration of As in the melting of ice and snow and the rainwater was low (Dong *et al.* 2015), which can be basically ignored. Many hot springs were found in the SRYR (Qu *et al.* 2019). Xin *et al.* (2013) indicated that the As content of Tuotuo River exceeded the recommended limit of 10 μg/L in GB 5749-2006 and the World Health Organization (2011). Therefore, As may originate from the recharge of groundwater. Sb was significantly positively correlated with Li *(*$r = 0.61$, $p < 0.01$*)* and Se ($r = 0.54$, $p < 0.01$); Li comes from crustal dust in the Tibetan Plateau (Dong *et al.* 2015), and Sb had low abundance with no spatial differences. Therefore, these metals were mainly from natural sources such as bedrock weathering. V was significantly positively correlated with Cu, Zn, Pb, Cr, Ni, Co and Sb ($r = 0.44 \sim 1.00$, $p < 0.01$). On the one hand, Co and Ni were siderophile elements, which were mainly from parent material weathering and pedogenic processes (Xiao *et al.* 2019). On the other hand, abandoned rubbish from many parts of the plateau has not been properly managed for decades (Jiang *et al.* 2009). Abandoned rubbish may be one source of trace elements in the SRYR. Therefore, these trace metals may originate from natural and human activities. The atmospheric input of trace elements can be a significant source (Qu *et al.* 2019), but the contributions of various sources were unclear. Further studies are needed to confirm the influence of different sources on trace elements in rivers of the SYRY.

Distribution and enrichment of trace elements

From the spatial perspective (Figure 3), the total concentration of trace elements in the Dangqu was relatively low, while that in the Tuotuo River and Chumar River were relatively high. It could be interpreted that the Tuotuo River and Chumar River were more affected by evaporation and concentration, resulting in higher ion concentrations in the water (Qu *et al.* 2019). Except for Cd and Sb, the average concentration of As, Cu, Zn, Se, Ni, Sr, Ti, Co, Li, V, and Mo in Dangqu was the lowest; the average concentration

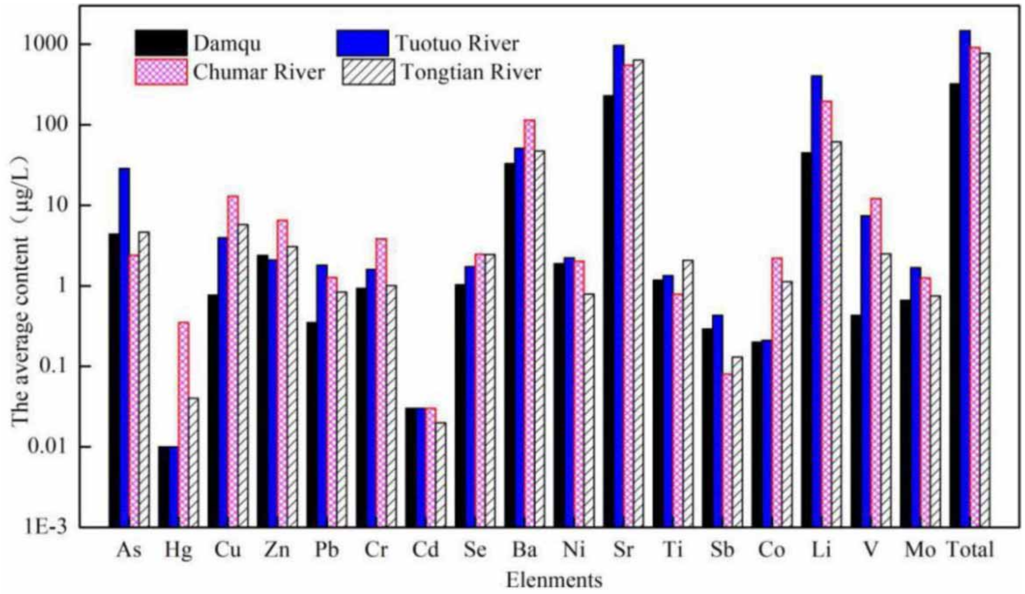

Figure 3 | Distribution of trace elements in different rivers in the SRYR.

of As, Pb, Sr and Li in the Tuotuo River was the highest; the average concentration of Hg, Cu, Zn, Pb, Se, Ba, V, and Co in the Chumar River was the highest but the concentration of Sb was the lowest; the average concentration of Ti in Tongtian River was the lowest.

In order to understand the trace elements enrichment of the SRYR, the enrichment factor (EF) was used for analysis. The enrichment factor is the ratio of the concentration of trace elements in the SRYR to the average concentration of rivers in the world (Gaillardet *et al.* 2014). According to the enrichment factor, the enrichment is divided into six categories: anomalous enrichment ($EF > 100$), super enrichment ($10 < EF < 100$), significant enrichment ($5 < EF < 10$), slight enrichment ($1.5 < EF < 5$), non-enrichment ($0.5 < EF < 1.5$), and depleted ($EF < 0.5$) (Long & Luo 2020). The trace metal EF declined in the order of Li > Se > As > Pb > Sr > V > Co > Zn > Cu > Sb > Ti > Ba > Cr > Mo > Ni > Cd. It was proved that the main enrichment elements were Li, Se, As and Pb, which were super enriched at levels more than 95.4, 27.5, 16.2 and 13.5 times to their global river water averages, respectively. The element of Li did not appear to be an essential element for life, as it caused disturbances in the development of invertebrates (Aral & Vecchio-Sadus 2008). Excessive Se will cause nail loss and hair loss (Li & Zhang 2010). Long-term drinking water with high arsenic concentration increased the risk of skin lesions, peripheral vascular disease, high blood pressure and cancer (He & Charlet 2013). Pb has a negative effect on the human nervous system, hematopoietic system, cardiovascular system and endocrine system (Wu *et al.* 2009; Gao *et al.* 2019). Therefore, some measures were taken to prevent the external input of Li, Se, As and Pb. Some trace elements were of high concentration with low enrichment coefficients, such as Ba. However, some elements with low concentration but high enrichment coefficients, such as Pb and Se, were mainly due to the different background values of different elements in world rivers.

Different rivers in the SRYR had different enriched elements and enrichment levels (Figure 4), which could be explained by the different migration and conversion rates with different trace elements in the environmental medium, different geological conditions and hydrological processes in different rivers on the plateau (Qu *et al.* 2019). The main enriched elements in Dangqu were Li and Se which were super enrichment, the main enriched elements in Tuotuo River were Li, Se, Pb, As and Sr, the main enriched elements in Chumar River were Li, Se, Zn, Pb, Co and V, and the main enriched elements of the Tongtian River were Li, Se, Pb, and Sr.

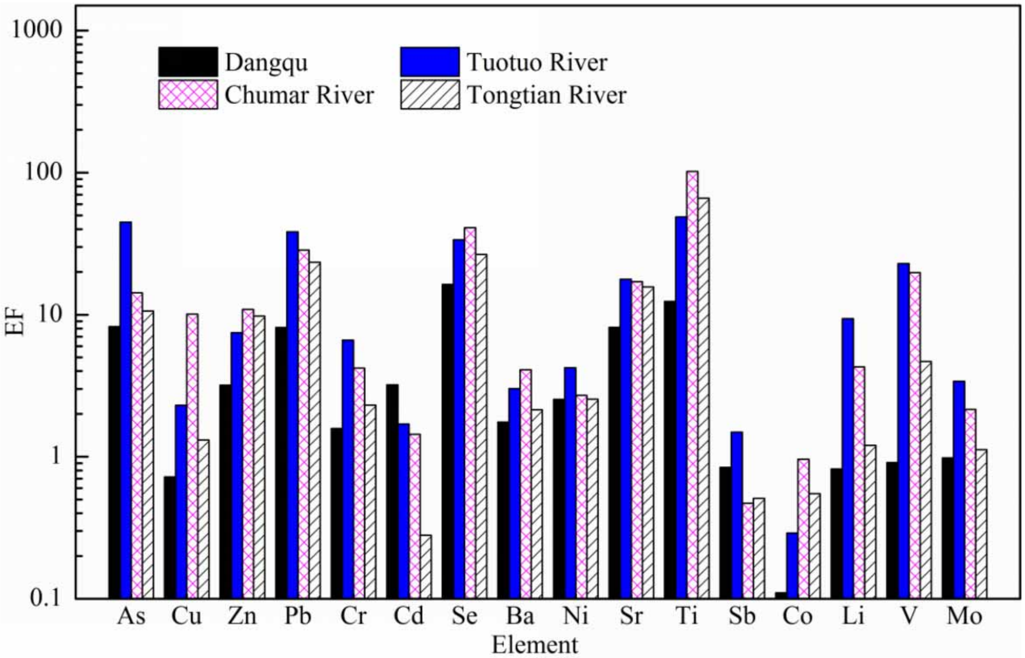

Figure 4 | Enrichment factor of trace elements in different rivers in the SRYR.

Health risk assessment

For health risk assessment of trace elements in the water environment, direct ingestion and dermal absorption of skin for human beings were usually considered. The average daily exposure to the health risk assessment was usually calculated using the calculation formula recommended by the NAS (US EPA 2009; Li & Zhang 2010; Giri & Singh 2014; Gao *et al.* 2019). The exposure dose for direct ingestion ($ADD_{ingestion}$) and dermal absorption (ADD_{dermal}) are as follows:

$$ADD_{ingestion} = \frac{C_w \times IR \times ABS_g \times EF \times ED}{BW \times AT} \quad (1)$$

$$ADD_{dermal} = \frac{(C_w \times S_A \times K_p \times ET \times EF \times ED \times 10^{-3})}{(BW \times AT)} \quad (2)$$

where C_w is the average concentration (μg/L); IR is the ingestion rate (L/day); ABS_{GI} is the gastrointestinal absorption factor; EF is the exposure frequency (days/year); ED is the exposure duration (years); S_A is the exposed skin area(cm^2); K_p is the dermal permeability coefficient; ET is the exposure time (h/day); BW is the body weight (kg); and AT is the average time for non-carcinogens (days). The reference values of exposure parameters are shown in Tables 3 and 4.

The risk index (HI) can assess the full potential non-carcinogenic risk of multiple pathways, and HI values more than 1 ($HI > 1$) indicate that the pollutant may have adverse effects on human health or require further study (Giri & Singh 2014):

$$HI = \sum (HQ_{irg} + HQ_{derm}) \quad (3)$$

Table 3 | Values of exposure parameters

Subject	C_w	IR	ABS_{GI}	EF	ED	S_A	K_p	ET	BW	AT
Adults	–	2[a]	See Table 4	350[b]	70[b]	18000[b]	See Table 4	0.58[a]	65[a]	25550[b]
Children	–	0.64[a]	See Table 4	350[b]	6[b]	6600[b]	See Table 4	1[a]	20[a]	219[b]

[a] Gao *et al.* (2019).

[b] US EPA (2009).

Table 4 | $RfD_{ingestion}$, RfD_{dermal}, ABS_{GI} and K_p values of each trace element

Element	As	Cu	Zn	Pb	Cr	Cd	Se	Mn	Ba	Ni	Sr	Sb	V
$RfD_{ingestion}$	0.3[a]	40[c]	300[a]	1.4[c]	3[c]	0.5[c]	5[d]	24[c]	200[c]	20[c]	600[d]	0.4[a]	5[d]
RfD_{dermal}	0.285[a]	8[c]	60[a]	0.42[c]	0.075[c]	0.025[c]	0.15[d]	0.96[c]	14[c]	0.8[c]	120[d]	0.06[c]	0.13[d]
ABS_{GI}	95%[b]	57%[b]	20%[e]	11.7%[e]	3.8%[b]	5%[b]	30%[b]	6%[b]	7%[b]	4%[b]	20%[e]	15%[b]	2.60[b]
K_p	0.001[b]	0.001[b]	0.0006[b]	0.0001[b]	0.003[b]	0.001[b]	0.001[b]	0.001[b]	0.001[b]	0.0002[b]	0.001[b]	0.001[b]	0.001[b]

$RfD_{ingestion}$: oral reference dose (μg/kg/day). RfD_{dermal}: the reference dose of the dermal absorption (μg/kg/day).

[a] Gao *et al.* (2019).

[b] US EPA (2009).

[c] Wang *et al.* (2017).

[d] Li & Zhang (2010).

[e] Xiao *et al.*(2019).

The health risk assessment results of trace elements in the SRYR are shown in Appendix C. $HQ_{ingrstion}$, HQ_{dermal} and HI values of metallic elements in all children were higher than those in adults, indicating that children were more sensitive than adults to the exposure hazards of trace elements (Wu *et al.* 2009). In addition to the $HI > 1$ of As, the $HI < 1$ of other metallic elements such as Cu, Zn, Pb, Cr, Cd, Se, Mn, Ba, Ni, Sr, Sb, and V was lower, indicating that other elements ingested orally and absorbed through the skin have lower health risks.

For children and adults, the HI value and $HQ_{ingestion}$ of Tuotuo River were both greater than 1, indicating that the water of the Tuotuo River was a greater health risk after being ingested by children and young people. $HQ_{ingestion}$ values of As in the Dangqu, Chumar River and Tongtian River were all greater than 0.1, indicating that special attention should be paid to the adverse effects of As for local residents, especially for children. Comparing different rivers in the SRYR, the health risks caused by As followed the order of Tuotuo River > Chumar River > Tongtian River > Dangqu. In general, the health risks of trace elements in Dangqu were lower than that of the Tuotuo River, Chumar River, and Tongtian River.

CONCLUSIONS

The surface water of the SRYR was shown to be weakly alkaline and brackish, and the TDS and EC were high compared with the Middle-Lower Yangtze River. The Hg concentration in surface water in the SRYR exceeded the water quality standard of Class II based on GB3838-2002, the level of As did not meet GB 5749-2006, and it could not be directly used for drinking purposes and was adverse to the freshwater aquatic life. The quality of Dangqu was better than other rivers. The element of Li, Se and As were super enrichment in the SRYR, especially for Li, and abnormal enrichment in the Tuotuo River and Chumar River. According to the health risk assessment of the trace elements, As was the most important pollutant causing adverse health effects, particularly for children. Much greater attention should be paid to As, Hg, Li, Pb and Se in surface water in the SRYR.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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