



# Water environment in the Tibetan Plateau: heavy metal distribution analysis of surface sediments in the Yarlung Tsangpo River Basin

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**Abstract** To fully understand the environmental quality of sediments in the Yarlung Tsangpo River Basin, surface sediments of the main stream of the Yarlung Tsangpo River and its five major tributaries were studied. In 2016, a total of 201 water samples from the Yarlung Tsangpo River and its tributaries were collected during three water seasons. Fifteen trace elements (including Cd and heavy metals such as Cr, Cu, Pb, and As), which have great environmental effects, were analyzed. The results showed that Ti, Mn, and Cr were the main heavy metals in Yarlung Tsangpo River sediments, accounting for 51%, 10%, and 7% of the total heavy metals, respectively. There were no significant differences among the heavy metal contents in the sediments of Yarlung Tsangpo River among three water seasons, but there were significant spatial variations. During the same period, the

concentration of each element in the tributary sediments was generally higher than that in the main stream. According to three different ecological risk assessment models, it is calculated that the heavy metal elements in the surface sediments of the river basin are at low or no pollution risk.

**Keywords** Yarlung Tsangpo River · Sediments · Heavy metal · Spatial and temporal distribution · Source identification · Ecological risk assessment

## Introduction

The geographical location of the Tibetan Plateau and its ecological environment have always been the focus of attention both at home and abroad (Li et al. 2010). At present, research on heavy metal pollution and heavy metal risk assessment of sediments in various river basins is often carried out. The Yarlung Tsangpo River is the most important international river on the Tibetan Plateau, and it has attracted increasing attention from scientists. However, only a few studies have been conducted on the Yarlung Tsangpo, for example, research on arsenic pollution in the Tibetan Plateau (Li et al. 2014), water chemistry in the Yarlung Tsangpo River (Huang et al. 2011; Qu et al. 2017), and source of the major ions and trace elements in the Yangtze Tsangpo River (Qu et al. 2019). However, there is a lack of research on sediments in the basin. Therefore, a

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comprehensive study of the basin is of great practical significance.

Heavy metals significantly pollute water because of their high toxicity, durability, and non-degradability, and river sediments are often regarded as the source or sink of these heavy metals. The distribution of heavy metal pollution is very uneven in water environments of river basin. Their concentration and distribution are affected by both natural environment and human activities, and the content of heavy metals in sediments is significantly greater than that of overlying waters and suspended matter. Heavy metals are circulated in water and sediments through the geochemical cycle via ion exchange, complexation, chemical adsorption, and chemical precipitation (Rahman and Ishiga 2012; Gümğüm and Öztürk 2001; Yuan et al. 2004; Lalan et al. 2008; Yang et al. 2009). The heavy metals enriched in sediments not only have a direct toxic effect on benthic organisms, but also can be re-released as environmental conditions change, causing “secondary pollution” in water bodies (Yan et al. 2016), such as changes to oxidation, bioturbation, tidal currents, floods, and dredging (Daskalakis and OConnor 1995). In addition to clay minerals, many natural minerals such as iron–manganese oxides and hydroxides in sediments can strongly oxidize natural or exogenous organic compounds. Organic material in sediments strongly adsorbs toxic and organic compounds, which greatly reduces their biological toxicity and increases the environmental mobility of toxic organic pollutants through the adsorption of soluble organic matter (Feitosa-Felizola et al. 2009).

Recent studies on metal-contaminated water have focused on rivers in eastern China, while less research has been conducted on the western rivers. The uniqueness of the natural environment and geographical location of the Tibetan Plateau has often made its ecological environment the focus of research. The Yarlung Tsangpo River is representative of the western region, and its study would expand the understanding and improve the level of planning, development, and utilization of its water resources in a significant way (Li et al. 2010; Zhang et al. 2009; Franz et al. 2010).

## Materials and methods

### Study area

The Tibetan Plateau is an Asian water tower rich in freshwater resources that contains 100 rivers with a drainage area of more than 2000 km<sup>2</sup>, and 20 rivers have a drainage area of more than 10,000 km<sup>2</sup>. Plateaus have variable environmental conditions and ecological fragility, different geological structures from the plains, and environmental safety issues caused by global warming. These changes require timely and systematic research. Mastering the environmental water chemical changes in the main rivers in the plateau under the dual pressures of human activities and environmental changes is necessary for the sustainable management of plateau water resources. The Yarlung Tsangpo River is an important international river in Tibet whose source is the Gemma Yangzong Glacier located in the northern foothills of the Himalayas. The river flows from west to east and passes through the most densely populated areas in Lhasa, Tibet. The Yarlung Tsangpo River is divided into upper, middle, and lower reaches based on its horizontal and vertical gradient changes, and the area is a plateau climate zone with distinct dry and abundant wet periods (Zhou et al. 2014; Li et al. 2009).

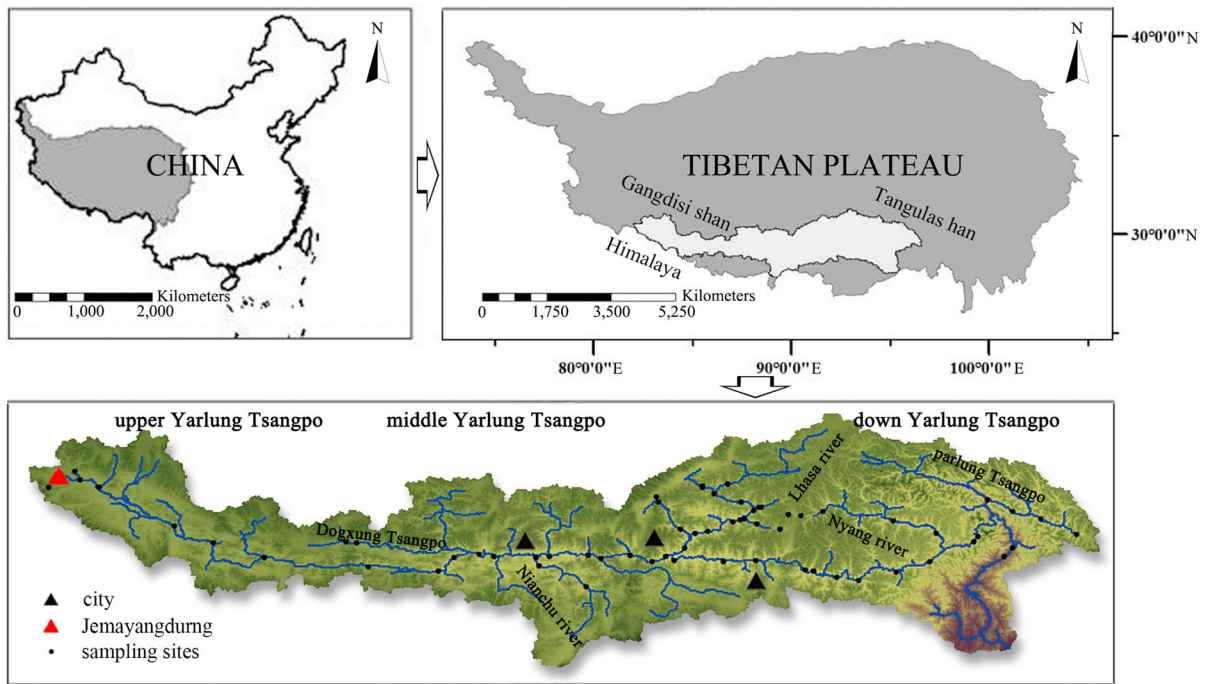
### Sample collection and preparation of heavy metal analysis

#### *Collection and preparation of sediment samples*

This paper studies the effects of heavy metal pollution in the sediments of the Yarlung Tsangpo River. To fully characterize heavy metal pollution in the basin sediments, 67 sediment samples from the Yarlung Tsangpo River and its tributaries were collected during three water flow regimes in 2016 in this study (Table 1). The sampling point distribution is shown in Fig. 1. Sediment samples were collected near river banks, which were sealed in polyethylene (LDPE) bags and stored at 4 °C. A total of 15 elements were analyzed, including Ag, Cd, Cr, Co, Cu, Zn, Li, Mn, Hg, Se, Mo, Ni, Pb, Ti, and As. Although As is a metalloid, since it has a similar toxicity to heavy metals, it has been treated as a heavy metal. Sediment samples were air-dried in a dust-free laboratory and

**Table 1** Related information on surface sediment sampling sites in Yarlung Tsangpo River Basin

River name	Number of samples	Elevation interval/m	Latitude/longitude
Yarlung Tsangpo River	31	648–5308	28°59′–30°28′/82°16′–95°24′
Dogxung River	3	3647–4755	29°18′–29°31′/86°19′–87°47′
Nianchu River	3	3842–4025	28°54′–29°18′/88°54′–89°35′
Lhasa River	19	3672–4381	29°26′–30°18′/90°32′–92°13′
Niyang River	6	2986–4587	29°38′–29°56′/92°20′–94°21′
Parlung River	5	2139–4361	29°29′–30°05′/95°03′–96°38′



**Fig. 1** Yarlung Tsangpo River sampling location

analyzed after being filtered through a 200-mesh nylon screen.

*Chemical reagents and sample digestion*

After undergoing pre-treatments that included drying, grinding, and sieving, collected sediment samples were digested with HNO<sub>3</sub>–HClO<sub>3</sub>–HF on a hot plate. Samples were heated to 120 °C for 5 min, 160 °C for 5 min, and raised to 180 °C for 15 min until the soil liquefied, which was then analyzed and tested by various methods. Ti and Mn contents were determined using inductively coupled plasma optical emission

spectrometry (PerkinElmer Optima 5300DV). Ag content was investigated with a full-spectrum direct-reading arc emission spectrometer (Focused Photonics Inc E500). As, Hg, and Se were analyzed by atomic fluorescence spectrometry (AFS-820; AFS-830). Cu, Pb, Zn, Cr, Ni, Co, Cd, Li, and Mo used inductively coupled plasma mass spectrometry (PerkinElmer NexION 300X). All reagents used in the analyses were of the highest purity to ensure no impurities affected the sensitivity and accuracy of the instruments. Prior to experiments, instruments were calibrated with a national water-based sediment standard material GBW (gbwhomecom) series, and accuracy

reached 99.9%, and the standard solution controlled the quality. Parallel double-sample simultaneous analysis was used to maintain a confidence level of 95% and relative standard deviations (RSD) less than 5%.

Data calculations were completed using Excel 2007, and statistical analyses were completed using IBM SPSS 24.0. Principal component analysis (PCA) was used to identify the main factors, analyze the load values of each heavy metal element, and calculate feature vectors to determine the uniformity of different metal sources. The maximum variance method was used for principal components rotation, and the Pearson correlation coefficient was used to analyze the correlation between heavy metals, while ArcGIS software and IBM SPSS 24.0 software were used to create charts.

### Heavy metal pollution level of sediment and risk assessment

#### Ground accumulation index method

The index of geoaccumulation was proposed by Müller (1969) and can be used to evaluate heavy metal pollution levels. The geoaccumulation index ( $I_{\text{geo}}$ ) is a parameter that determines heavy metal pollution levels based on the relationship between the concentration and background levels of heavy metals.

The formula for calculating the cumulative index method is:

$$I_{\text{geo}} = \text{Log}_2 \left[ \frac{C_i}{k\text{BE}_i} \right] \quad (1)$$

where  $I_{\text{geo}}$  is the index of geoaccumulation;  $C_i$  is the actual measured content  $\text{mg kg}^{-1}$  of heavy metal element  $i$  in the sediment;  $\text{BE}_i$  is the geochemical background value  $\text{mg kg}^{-1}$ ; and  $k$  is the background value correction index which generally has a value of 1.5. The relationship between  $I_{\text{geo}}$  and the pollution level is given in Table 2 (Müller 1981).

#### Potential ecological risk index method

The potential ecological risk index identifies the effects of various pollutants on the soil and highlights

**Table 2** Relationship between geoaccumulation index and contamination degree

$I_{\text{geo}}$	Assessment level	Pollution degree
$I_{\text{geo}} < 0$	0	No pollution
$0 \leq I_{\text{geo}} < 1$	1	Slightly polluted
$1 \leq I_{\text{geo}} < 2$	2	Moderately polluted
$2 \leq I_{\text{geo}} < 3$	3	Intermediately polluted
$3 \leq I_{\text{geo}} < 4$	4	Strongly polluted
$4 \leq I_{\text{geo}} < 5$	5	Extremely polluted

the impact of high concentrations of pollutants on the environmental quality of soil (Hakanson 1980).

The potential ecological risk index for a single heavy metal is:

$$C_f^i = C_s^i / C_n^i \quad (2)$$

Individual heavy metal potential ecological risk index is:

$$E_r^i = T_r^i \times C_f^i \quad (3)$$

Multiple heavy metals integrated potential ecological risk index is:

$$\text{RI} = \sum_{i=1}^n E_r^i = \sum_{i=1}^n T_r^i \times C_f^i = \sum_{i=1}^n T_r^i \times \frac{C_s^i}{C_n^i} \quad (4)$$

where RI is the multi-element environmental risk comprehensive index;  $E_r^i$  is the  $i$ th heavy metal environmental risk index;  $C_f^i$  is the pollution coefficient of heavy metal  $i$  relative to a reference value;  $C_s^i$  is the measured concentration of heavy metal  $i$ ;  $C_n^i$  is the evaluation reference value of heavy metal  $i$ ; and  $T_r^i$  is the toxicity response coefficient for heavy metals, which mainly reflects the toxicity level of heavy metals and the environmental sensitivity to heavy metal pollution (Hakanson 1980).

#### Sediment quality benchmark method (sediment quality guidelines, SQCs)

Sediment quality guidelines (SQCs) consider both the total amount of heavy metals and relevant factors that contribute to heavy metal pollution (Macdonald et al. 2011). High credibility and well-accepted uncertainty levels are widely used to assess the potential

ecological risks of heavy metals (Caeiro et al. 2005). Its formula is as follows:

$$(PEL - Q)_i = \frac{c_i}{PEL_i} \tag{5}$$

$$SQG - Q = \frac{\sum_{i=1}^n (PEL - Q)_i}{n} \tag{6}$$

where  $(PEL - Q)_i$  represents the concentration coefficient of possible ecological effects of the metal  $i$ , the probably effect level ( $PEL$ ) is the possible ecological effect concentration of heavy metals,  $c_i$  is the measured concentration of heavy metals, and  $SQG - Q$  is the calculated risk evaluation coefficient grade. In general, if  $SQG - Q \geq 1.0$ , an element is considered to pose a high ecological risk to the environment. When  $0.1 < SQG - Q < 1.0$ , heavy metals are considered to be moderately bioavailable, and an  $SQG - Q < 0.1$  indicates no heavy metal contamination, with little-to-no ecological risk. The probable effect level ( $PB$ ) and  $TEL$  may be used to evaluate the bioavailability of individual heavy metals. It is generally believed that the potential ecological risk level of one heavy metal element is lower than that of  $TEL$  (Tables 3, 4). When the measured heavy metal concentration is higher than  $PEL$ , the potential ecological risk level is higher (Macdonald et al. 2000).

## Results and discussion

### Content of heavy metal elements contained in sediments

The statistical calculation of heavy metal elements in the surface sediments of Yarlung Tsangpo River in 2016 showed that Ti, Mn, and Cr were the main heavy metals present in Yarlung Tsangpo River sediments, accounting for 51%, 10%, and 7% of the total heavy metal elements, respectively (Table 5). The comparisons of the heavy metal content in Yarlung Tsangpo

River surface sediments and other areas are given in Table 6. In these samples, Zn, Hg, and Ni are generally lower than the best standard limit of soil environmental quality in Environmental Quality Standard for Soils 1995. The background soil value of Tibet and China’s crustal abundance (Li 1994) is relatively close and is much lower than their global crustal abundance (Li 1976). It indicates that the presence of Zn, Hg, and Ni in sediments in this basin is mainly affected by the weathering of local parent rock, and the contribution from human activity is low. Cu, Pb, and Cd were generally more abundant than other elements and regions. Among these three kinds of heavy metals, the amount of Cd meets the national standard limit of Chinese soil standard value. However, Cu and Pb exceed the best Chinese soil standard value, and Pb concentration is twofold–threefold than that of China’s crustal abundance and the global crustal abundance. The accumulation of heavy metals is obvious and is closely related to rich mine resources in the basin. It is worth noting that As reaches the critical point of the Chinese soil standard value secondary-class standard Environmental Quality Standard for Soils (1995). As is present in significantly higher amounts than the crustal abundance, in 13 and 11 times China’s and the global crustal abundance, respectively. As is a carcinogen and has been identified as a potential threat to aquatic ecosystems (Sadiq et al. 2003), and it is present in such high amounts mainly as a result of human activities such as application of pesticides and fertilizers (Guo et al. 2008). Compared with typical rivers in eastern China, such as the Pearl River, other elements are present at higher values than Cr, as chrome or chromium-bearing minerals are all lower than the Pearl River (Cheng and Tian 1993). Since Cr is a nucleophilic element whose chemical form is mainly determined by geochemical properties, Cr in soil minerals is relatively stable and exists in some silicates. It is not easily decomposed from minerals, and most remaining Cr can combine with oxides, while a small portion combines with organic molecules (Martin et al. 1998). This study found no significant differences in its content, indicating that it is was stable, had poor mobility, had low bioavailability, and would not pollute the Yarlung Tsangpo River ecological environment.

The main sources of trace heavy metals in Yarlung Tsangpo River sediments are natural factors, not man-made sources. Compared with typical rivers in eastern

**Table 3** Reference values and toxicity coefficients of heavy metals

Metal	Hg	Cd	As	Pb	Cu	Cr	Zn
$C_n^i$	0.25	0.50	15.00	25.00	30.00	60.00	80.00
$T_r^i$	40	30	10	5	5	2	1

**Table 4** Grading criteria for potential ecological risk index

Potential ecological risk index	Individual risk level	< 40	40–80	80–160	160–320	≥ 320
		Mild	Moderate	Heavy	Severe	Extremely severe
	Comprehensive risk level (RI)	< 135	135–265	265–525	≥ 525	
		Mild	Moderate	Severe	Extremely severe	

**Table 5** Statistics of metal elements in the Yarlung Tsangpo River sediments at different water periods

Project	Low-flow season			High-flow season			Normal-flow season		
	MIN	MAX	AVG	MIN	MAX	AVG	MIN	MAX	AVG
Cu <sup>a</sup>	3.75	1360.0	53.5	2.60	481.0	44.6	3.45	715.0	44.2
Pb <sup>a</sup>	12.4	116.0	35.0	20.9	435.0	42.0	14.6	392.0	37.6
Zn <sup>a</sup>	37.8	215.0	78.6	21.0	504.0	81.5	21.3	415.0	73.5
Cr <sup>a</sup>	6.8	1200.0	87.7	1.2	222.0	74.9	3.6	741.0	91.9
Ni <sup>a</sup>	5.4	101.0	36.1	4.1	120.0	38.4	7.8	160.0	39.1
Co <sup>a</sup>	1.05	25.8	10.09	0.56	32.6	11.0	1.30	17.7	10.6
Cd <sup>a</sup>	0.027	1.16	0.16	0.031	2.56	0.18	0.036	2.04	0.16
Li <sup>a</sup>	14.6	73.6	33.3	11.9	64.8	31.6	12.6	63.8	31.1
Mo <sup>a</sup>	0.13	3.68	0.82	0.07	2.97	0.73	0.11	2.69	0.75
As <sup>a</sup>	2.22	210.0	27.2	1.79	89.9	22.6	1.27	77.1	23.5
Hg <sup>b</sup>	4	2.29	3.23	0.15	18.3	4.06	0.21	17.6	2.79
Se <sup>a</sup>	0.026	0.89	1.14	0.041	0.990	0.15	0.038	1.010	0.13
Ag <sup>a</sup>	0.030	1.01	0.09	0.030	1.10	0.09	0.030	1.010	0.08
Ti <sup>a</sup>	778	8140.0	3165.9	687	9340.0	3504.1	947.0	5710.0	3226.6
Mn <sup>a</sup>	94.5	1660.0	617.3	114	2160.0	658.2	168.0	4320.0	667.5

<sup>a</sup>Unit is mg kg<sup>-1</sup><sup>b</sup>Value of Hg is 10<sup>-9</sup>**Table 6** Heavy metal elements in Yarlung Tsangpo River surface sediments compared to other areas<sup>a</sup>

Name of area	Cu	Pb	Zn	Cd	Hg	Co	Ni	As	Cr
Average value of sediments in Yarlung Tsangpo River	47.4	38.2	77.8	0.2	0.03	10.9	37.9	24.4	84.8
Soil environment quality standard (first-class standard)	35	35	100	0.2	0.15	–	40	15	90
Soil environment quality standard (second-class standard)	100	300	–	0.3	0.5	–	–	25	300
China's crustal abundance	38	15	86	0.05	0.02	32	57	1.9	63
Global crustal abundance	63	12	94	0.2	0.45	25	89	2.2	110
Sediments in Pearl River	71.3	58.8	–	2.34	–	279	–	–	73.5

<sup>a</sup>Size of sediment sample is < 63 μm and the unit is mg kg<sup>-1</sup>

“–” no relevant data

China, the Pearl River was less polluted, but Pb, Cd, and As in Yarlung Tsangpo River sediments should be taken seriously.

#### Spatial and temporal distribution characteristics of heavy metals present in sediment

To understand the spatial distribution of heavy metals in the Yarlung Tsangpo River Basin surface sediments, data were used from three periods from the same level of the Yarlung Tsangpo River (Fig. 2a–c).

There were only small seasonal variations of the content of heavy metals, showing similar heavy metal enrichment during different water periods (Fig. 2; Table 5). The concentrations of Cu and Zn in Yarlung Tsangpo River Basin sediments are generally higher in the middle portions than that in low upstream and downstream. The high-value areas during wet and flat periods are mainly concentrated in the Lhasa River, which demonstrates that Cu in the Yarlung Tsangpo River Basin comes from the same source: a copper deposit along with the river section. The heavy metal leaches into the Lhasa River Basin from the tailings of the Julong Copper Mine Company on the Lhasa River, and there is a lower concentration during the dry season. The amount of Cu detected was lower when the mine stopped operations, which shows that the Yarlung Tsangpo River Basin mining influenced the Cu content.

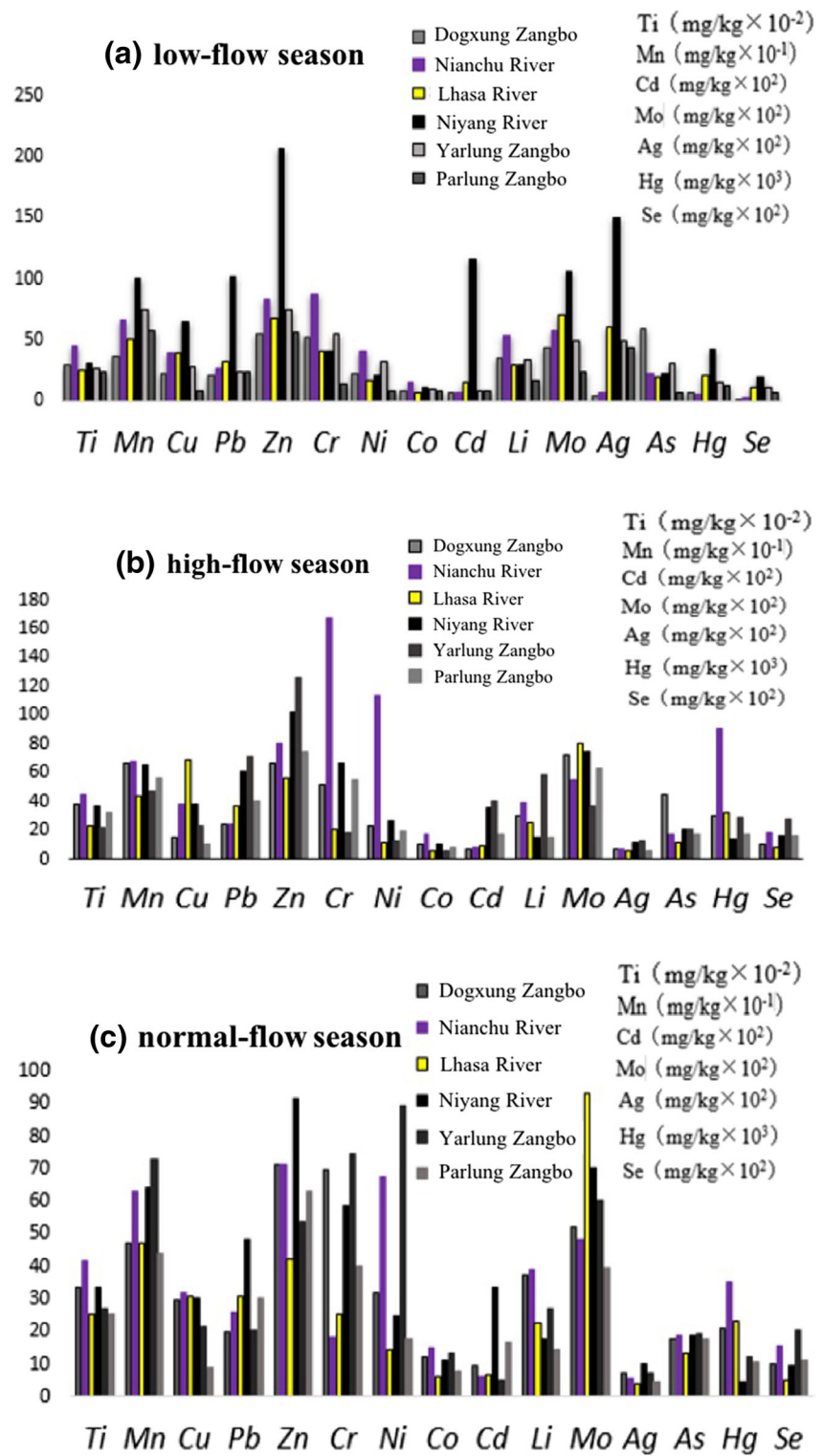
The concentration of As was generally lower in the upstream and middle reaches and higher in the lower reaches. The high-value areas in the dry season and the flat-water period are relatively confined to the Lhasa River. It indicates that the As in the Yarlung Tsangpo River Basin comes from the same source, likely the Yangbajing Hot Spring located on this river section. Heavy metals in hot springs along the Lhasa River enter the Lhasa River Basin, and the As concentration in the wet season is lower than the detected value. It is the potential reason that why the dilution of other makeup waters or large-scale water flow occurs during the flood season (Table 7).

Pb, Zn, and Cd have similar spatial distribution characteristics in the Niyang River (Table 8). Moreover, they have a significant positive correlation relationship (Table 8), indicating that they share similar geochemical behaviors or source elements. Pb, Zn, and Cd are highly concentrated in the Niyang River, and the variation trend does not decrease with

seasonal changes. It may possibly be due to progressive implementation of western development and new rural construction, which increasingly discharges sewage into the Niyang River Basin each year. However, there is no sewage treatment plant in the whole river basin, and the sewage outlets in various towns along the river are extremely simple, so the sewage can only be directly discharged into the river. It shows that the Niyang River pollution is due to human behaviors (Li et al. 2014). During the three water periods, Cr and Co showed high values in the Nianchu River, and there was a significant positive correlation between them ( $P = 0.0483$ ). The high value may be due to human activities such as the use of pesticides and fertilizers (Hudson Edwards et al. 2004) since the Nianchu River Basin in the Shigatse area is the main grain-producing area of Tibet. The barley planting time occurs in the first half of April; when the area of cultivated land was small, fertilizer and pesticides were used in large amounts and entered the water body through rainwater (Qian et al. 2010). The main heavy metals in chemical fertilizers are Cr and Co, and the main sources are industrial sulfuric acid, ores, etc. The high concentrations of Cr and Co in the Nianchu River Basin were mainly originated from human activities, and the abundance of As in the Dogxung Zangbo Basin is significantly higher than in other tributaries. This tributary is located in the upper reaches of the Yarlung Tsangpo River, and its high As content may be related to the widespread distribution of arsenic-rich shale and geothermal activity in Tibet.

High Cu concentrations were found primarily in the Lhasa River Basin. The hydrothermal mineralization conditions of the Lhasa block motivated the scientific research group of the Tibet Geological Sixth Team to study the Jiama Township (located in Mozbugongka County, Lhasa City). They have confirmed the presence of a copper- and gold-based polymetallic deposit in the Jiama mining area. In the mid-1990s, the first batch of mineral developers entered the Jiamagou mining area and illegally exploited the area due to the absence of funds, technology, and qualifications. This led to serious pollution of the Jiamagou mining area and even formed a “destroyed mud pond” (Yuan et al. 2002; Shama and Cuicheng 2011). It can be concluded that the high Cu content in the Lhasa River was mainly due to two factors: rich mineral resources and early unreasonable development. The dominant factor is human behavior of unreasonably developing the

**Fig. 2** **a** Spatial distribution of heavy metals in sediments of low-flow season. **b** Spatial distribution of heavy metals in sediments of high-flow season. **c** Spatial distribution of heavy metals in sediments of normal-flow season





**Table 7** Pearson correlation coefficients between heavy metals

Element	Cu	Pb	Zn	Cr	Ni	Co	Cd	Li	Mo	As	Hg	Se	Ag	Ti	Mn
Cu	1														
Pb	.325*	1													
Zn	.367**	.958**	1												
Cr	-.097	-.099	.033	1											
Ni	-.064	-.114	.057	.799**	1										
Co	.072	.05	.287*	.483**	.618**	1									
Cd	.390**	.985**	.969**	-.01	-.108	.111	1								
Li	.018	-.156	-.076	.372**	.541**	.214	-.199	1							
Mo	.668**	.714**	.776**	-.035	-.051	.366**	.762**	-.211	1						
As	.438**	.733**	.743**	.055	.037	.106	.728**	.131	.688**	1					
Hg	.022	-.158	-.083	.322*	.405**	.25	-.169	.483**	-.052	.091	1				
Se	.330*	.940**	.972**	.056	.05	.300*	.938**	-.054	.763**	.750**	-.05	1			
Ag	.355**	.987**	.983**	-.039	-.04	.16	.985**	-.124	.747**	.744**	-.115	.961**	1		
Ti	-.002	-.014	.209	.420**	.471**	.910**	.044	.045	.342*	.053	.186	.243	.093	1	
Mn	.134	.410**	.563**	.135	.197	.776**	.474**	-.213	.606**	.258	-.029	.563**	.493**	.791**	1

\*\*At 0.05 level (two-tailed), the correlation is obvious

\*At 0.01 level (two-tailed), the correlation is obvious

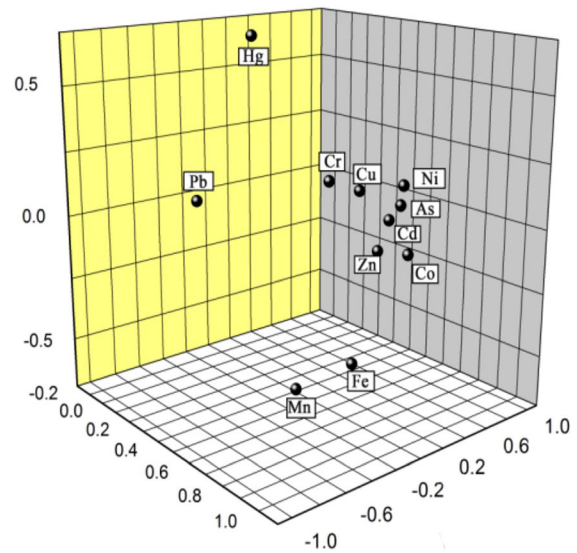
**Table 8**  $I_{geo}$  and contamination level of heavy metals in surface sediment

Project ( $I_{geo}$ )	Cu	Pb	Zn	Cd	Co	Ni	As	Cr
Low-flow season	0.70	− 0.30	− 0.49	1.0	− 0.79	− 0.42	− 0.04	− 0.40
High-flow season	0.44	− 0.04	− 0.43	2.25	− 0.67	− 0.32	− 0.30	− 0.62
Normal-flow season	0.43	− 0.20	− 0.60	1.0	− 0.71	− 0.30	− 1.02	− 0.34

mineral resources during the early stage. It can be seen from Fig. 1 that the abundance of Ti, Mn, Mo, Li, and Ni does not significantly change in the Yarlung Tsangpo River main stream or its five major tributaries, which may be due to natural factors such as high background values and weathering erosion of rock.

#### Main component and correlation analysis of heavy metals in sediments

To some extent, correlations between two different heavy metals reflect the degree of contamination of these elements or that they have similar sources (Bai 2015). The Pearson correlation coefficient matrix of 15 heavy metal concentrations in 57 sediments was obtained using IMP SPSS 24.0 software (Table 5). Heavy metal concentrations in sediments were used as the spin amount to perform a principal component analysis (Table 6). Based on retaining the original similarity factor information, this paper selects three main components. This study makes sense when the absolute value of the load on the three main components reaches its maximum value (Page et al. 2012). Table 6 shows that the accumulated variance contribution rate of  $PC1$ ,  $PC2$ , and  $PC3$  is 71.31%, and the characteristic values are all higher than 1. These three main components reflect the general distribution of 16 heavy metals in the Yarlung Tsangpo River sediments. In this case, analysis of the first three main components reflects most of the information of the data. The composition of the main component factors and the load distribution of each variable are shown in Fig. 3. The factor variance contribution rate of  $PC1$  is 32.63% which is far higher than that of the other factors. Thus, this factor would have a greater influence on the composition and distribution of heavy metals in the sediments, and  $PC1$  would have a comparatively high positive load on Pb, Zn, and Cu. Table 8 shows an obvious correlation between Pb, Zn, and Cu. The correlation coefficient between Pb and Zn is 0.958,

**Fig. 3**  $PC1$ ,  $PC2$ , and  $PC3$  loading of the Yarlung Tsangpo River catchments

between Pb and Cu is 0.325, and between Zn and Cu is 0.367. Therefore, the first main component dominates the source of Pb, Zn, and Cu in the sediments, since the Yarlung Tsangpo River has the most abundant mine resources on the plateau (mainly referring to Cu, Pb, and Zn ore). Large-scale mining has been conducted since the mid-1990s. The water body of the Tibetan Plateau is alkaline, the acidic wastewater is discharged into an alkaline environment, and the heavy metal elements will exist in the form of hydroxide colloids. The colloids are adsorbed to the suspended particles and finally merged into the surface sediments, so the water is a clear alkali. In the case of the Tibetan Plateau, surface sediments are important “sinks” of heavy metal elements. With the intensification of human activities on the Tibetan Plateau and the abundant mineral resources on the plateau, heavy metals discharged into the basin accumulate in surface sediments, resulting in a certain high content of heavy metals in some areas of the basin, resulting in slight

pollution. The *PC2* factor variance contribution rate is 26.49% (the main load elements are Ni and Mn), and the correlation coefficient between Mn and Ni is 0.799. The Ni content is typically positively correlated with crustal rock content (Proctor and Baker 1994; Filella et al. 2002), which has a low concentration. Abundant mineral resources in the basin and the mining activities of the previous management may be the main influencing factors for this content. The *PC3* factor variance contribution rate is 12.19%, which indicates a highly positive load on As, and As distributions are found in a generally even way without many changes along the river's path. Therefore, *PC3* reflects the natural sources that primarily include rock weathering and erosion and geothermal processes. Therefore, the measured heavy metal distributions in the Yarlung Tsangpo River basin surface sediments are reflected by three main components (Fig. 2): *PC1*, *PC2*, and *PC3*. *PC1* is 32.63%. (The main load elements are Cu, Pb, and Zn.) *PC2* was 26.49% (the main load elements are Mn and Ni), which is mainly due to more significant rock weathering and erosion processes in the basin. *PC3* was 12.19% (the main load element was As), which indicates that abundant geothermal resources and human activities in the basin influenced the composition and content of surface sediments.

#### Degree of pollution of heavy metals in sediment

In this paper, the soil background value of Tibet has been selected as the parameter ratio of heavy metal elements (Table 8). The pollution level of the geoaccumulation index is given in Table 2. The geoaccumulation index of heavy metals in sediments (Table 9) and pollution levels (Table 2) shows that the pollution level of heavy metal elements, ordered from small to large, is  $Cr < Co < As < Ni < Zn < Cd < Pb < Cu$ . On average, the  $I_{geo}$  of Cu in the three water periods is between 0 and 1, which poses a slight pollution hazard to the basin, while the  $I_{geo}$  of Cd reaches 1.0 in the withered and lever (Table 2) water periods, which poses a moderate pollution hazard in the basin. In the withered water period, the  $I_{geo}$  of Cd is 2.25, reaching 3 degrees of pollution geoaccumulation index which could pose a moderate or even strongly polluted hazard to the basin and should be examined. The accumulation index of other heavy metals was

less than 0 or close to 0, which may be interpreted to have no polluting effects.

#### Ground accumulation index method results

The ecological risk levels of heavy metals in Yarlung Tsangpo River sediments with respect to their spatial distribution are listed from low to high as follows: Dogxung Zangbo < Parlung Zangbo < Yarlung Tsangpo River main stream < Lhasa River < Nian-chu River < Niyang River. According to the calculation of the geoaccumulation index of 67 sampling points, Cu significantly pollutes 9 of the sampling points. To distinguish the water period, the sampling points were numbered according to their abundant water periods, as follows: F1 ( $I_{geo} = 1.06$ ), F11 ( $I_{geo} = 1.57$ ), F20 ( $I_{geo} = 2.7$ ), F21 ( $I_{geo} = 3.87$ ), F22 ( $I_{geo} = 2.16$ ), F27 ( $I_{geo} = 1.06$ ), F54 ( $I_{geo} = 1.79$ ), F56 ( $I_{geo} = 2.57$ ), and F57 ( $I_{geo} = 1.39$ ). The Cu pollution level of F20, F22, and F56 reached moderately serious pollution levels, and the highest value appeared at F21, where the Cu reached a geoaccumulation index of 3.87. The geoaccumulation index of the remaining samples generally fell within the range from 0 to 1, which indicates only slight pollution. The two highest values of elemental Zn appear in F56 ( $I_{geo} = 2.19$ ), which indicates a moderate pollution level, and F57 ( $I_{geo} = 1.15$ ), which indicates only a slight pollution level. For aquatic organisms in natural water sediments, Cu and Zn are micronutrients at low concentrations, but once their concentration surpasses a certain threshold value, they become toxic to aquatic organisms (Hall et al. Jr Hall et al. 1997). The highest values of Cd appeared in F56 ( $I_{geo} = 4.41$ ), which indicates a serious pollution level, and F57 ( $I_{geo} = 2.29$ ), which indicates a moderately serious pollution level. Pb reached a moderately serious pollution level in F56 ( $I_{geo} = 3.32$ ), and the highest value appeared in F57 ( $I_{geo} = 4.61$ ) to a serious pollution level. The  $I_{geo}$  of all other Pb samples was less than 0 or close to 0, which indicates an essentially non-polluting state. As would only be mildly polluting only in F56 ( $I_{geo} = 1.68$ ) and F57 ( $I_{geo} = 1.18$ ), potentially because the area is affected by human pollution. The calculated value of As in the rest of the area is less than 0, which indicates a non-polluting state. Ni has a slight pollution only in F16 ( $I_{geo} = 1.19$ ), F41 ( $I_{geo} = 1.25$ ), and F42 ( $I_{geo} = 1.32$ ), and in other areas, it is essentially non-polluting. The geoaccumulation index

**Table 9** Geoaccumulation index of heavy metals in sediments sampling sites of the Yarlung Tsangpo River Basin

Sample	Cu	Pb	Zn	Cr	Ni	Co	Cd	As
Dogxung River	<b>0.01</b>	– 0.63	– 0.60	<b>0.05</b>	<b>0.77</b>	– 0.20	– 0.26	<b>0.69</b>
	– 0.24	– 1.06	– 0.69	– 0.95	– 0.78	– 0.58	– 0.51	<b>0.87</b>
	– 0.60	– 1.10	– 1.00	– 1.15	– 1.15	– 1.14	– 0.98	<b>1.06</b>
Nianchu River	<b>0.47</b>	– 0.76	– 0.30	<b>0.29</b>	<b>0.97</b>	<b>0.02</b>	– 0.29	– 1.19
	<b>0.23</b>	– 0.75	– 0.28	<b>0.60</b>	<b>0.95</b>	– 0.23	– 0.55	– 0.54
	<b>0.24</b>	– 0.73	– 0.42	– 0.42	– 0.26	– 0.20	– 0.78	– 0.31
Lhasa River	– 2.06	<b>0.03</b>	– 1.34	– 2.92	– 2.57	– 1.92	– 0.53	– 1.17
	– 2.41	<b>0.17</b>	– 1.45	– 3.57	– 2.72	– 1.98	– 0.93	– 1.99
	– 1.43	– 0.70	– 0.81	– 1.57	– 1.59	– 1.10	<b>0.22</b>	– 0.13
	– 1.33	– 0.68	– 0.94	– 1.44	– 1.62	– 1.12	<b>0.22</b>	– 0.15
	<b>3.05</b>	– 0.15	– 0.22	– 1.95	– 1.06	<b>0.13</b>	<b>1.42</b>	<b>1.27</b>
	<b>0.58</b>	<b>0.53</b>	<b>0.09</b>	– 1.96	– 1.38	– 0.72	<b>1.58</b>	<b>1.33</b>
	– 1.79	– 0.99	– 1.68	<b>0.81</b>	– 0.10	– 1.51	<b>0.12</b>	<b>0.90</b>
	–	–	–	–	–	–	–	–
	– 2.65	<b>0.20</b>	– 1.46	– 4.82	– 2.94	– 3.16	– 1.91	– 1.87
	– 1.46	<b>0.29</b>	– 0.95	– 3.34	– 2.74	– 2.02	– 0.38	– 0.44
	<b>0.23</b>	– 0.44	– 0.71	– 1.51	– 1.52	– 1.40	<b>0.32</b>	– 0.50
	– 0.84	– 0.81	– 0.88	– 2.10	– 2.01	– 1.77	– 0.68	– 1.02
	<b>0.00</b>	– 0.52	– 0.98	– 0.81	– 1.60	– 1.44	<b>0.22</b>	– 0.96
	<b>5.37</b>	<b>0.67</b>	<b>0.64</b>	– 1.52	– 0.26	<b>0.57</b>	<b>2.58</b>	<b>1.73</b>
	– 0.58	– 0.55	– 1.09	– 1.40	– 1.75	– 1.49	– 0.13	– 0.94
– 1.51	– 0.31	– 1.15	– 1.54	– 1.84	– 1.92	– 0.46	– 1.18	
– 0.92	– 0.27	– 0.99	– 2.20	– 1.82	– 1.45	– 0.48	– 0.64	
– 1.33	<b>0.04</b>	– 0.63	– 2.12	– 2.09	– 1.58	<b>0.58</b>	– 0.66	
– 0.62	– 0.62	– 1.16	– 2.30	– 2.01	– 1.51	– 0.55	– 1.50	
Niyang River	– 0.24	<b>0.63</b>	– 0.24	– 0.88	– 0.54	– 0.95	<b>1.12</b>	<b>1.59</b>
	– 0.39	<b>0.50</b>	– 0.38	– 2.10	– 1.80	– 1.07	<b>1.00</b>	<b>1.19</b>
	<b>1.26</b>	<b>1.42</b>	<b>0.96</b>	– 1.13	– 0.94	– 0.57	<b>3.25</b>	<b>0.04</b>
	<b>0.98</b>	<b>1.23</b>	<b>0.90</b>	– 1.51	– 1.19	– 0.74	<b>3.27</b>	– 0.32
	– 1.13	– 0.57	– 0.89	– 2.03	– 1.93	– 1.43	<b>0.50</b>	– 2.08
– 1.42	– 0.93	– 0.98	– 2.09	– 1.79	– 1.49	<b>0.32</b>	– 2.01	
Parlung River	– 1.65	– 0.77	– 0.84	– 1.80	– 1.58	– 0.86	– 0.84	– 2.63
	– 1.29	– 0.52	– 0.83	– 1.73	– 1.58	– 1.30	<b>0.32</b>	– 0.62
	– 0.90	<b>0.42</b>	– 0.44	– 0.87	– 0.48	– 0.66	<b>0.58</b>	<b>0.17</b>
	– 1.57	<b>0.17</b>	– 0.76	– 1.88	– 1.12	– 1.25	<b>0.22</b>	– 1.06
	– 2.12	– 0.84	– 0.98	– 3.14	– 2.50	– 1.20	– 0.51	– 2.11
Yarlung Tsangpo	<b>0.59</b>	– 0.45	– 0.45	– 0.24	<b>0.02</b>	– 0.54	<b>0.58</b>	– 0.46
	<b>0.58</b>	– 0.70	– 0.19	<b>0.00</b>	– 0.11	– 0.03	<b>0.42</b>	– 0.65
	<b>0.51</b>	– 0.52	<b>0.12</b>	– 0.40	<b>0.37</b>	– 0.29	<b>0.32</b>	– 0.12
	<b>1.45</b>	– 0.61	– 0.36	– 0.59	<b>0.20</b>	– 0.56	– 0.28	– 0.14
	– 0.14	– 0.81	– 0.55	<b>0.02</b>	<b>0.36</b>	– 0.52	– 0.62	– 0.13
	– 0.50	– 0.77	– 0.40	– 0.38	<b>0.43</b>	– 0.72	– 1.13	– 0.60
	<b>0.80</b>	– 0.12	– 0.32	– 0.28	<b>0.51</b>	– 0.73	– 0.70	<b>0.51</b>
<b>0.07</b>	– 0.57	– 0.43	– 0.17	<b>0.30</b>	– 0.29	– 0.51	<b>0.14</b>	

**Table 9** continued

Sample	Cu	Pb	Zn	Cr	Ni	Co	Cd	As
	– 1.67	– 1.34	– 1.17	– 3.01	– 2.43	– 2.44	– 1.45	– 2.04
	<b>0.37</b>	– 0.58	– 0.43	– 0.23	<b>0.19</b>	– 0.41	– 0.29	<b>1.12</b>
	– 0.22	– 0.91	– 0.56	– 1.07	– 0.57	– 0.93	– 0.50	<b>0.13</b>
	<b>1.08</b>	– 0.26	– 1.35	– 2.14	– 1.41	– 2.40	– 1.62	– 0.44
	– 0.58	– 0.50	– 0.66	<b>0.44</b>	– 0.20	– 0.83	– 0.26	– 0.52
	– 0.49	<b>0.72</b>	<b>0.19</b>	– 2.67	– 1.95	– 1.49	<b>1.74</b>	<b>2.90</b>
	– 3.13	<b>0.34</b>	– 1.55	– 4.09	– 3.15	– 4.05	– 2.15	– 3.66
	– 0.13	– 0.10	– 0.83	– 0.14	<b>0.35</b>	– 0.98	– 0.58	– 1.56
	– 0.65	<b>0.24</b>	– 0.23	– 1.01	– 1.00	– 0.84	<b>0.32</b>	<b>0.70</b>
	– 0.49	– 0.73	– 0.60	– 1.06	– 0.81	– 0.93	– 0.74	<b>0.83</b>
	<b>0.07</b>	– 0.81	– 0.52	<b>0.29</b>	<b>0.74</b>	– 0.41	– 0.55	– 0.29
	– 1.08	– 0.74	– 0.86	– 1.90	– 1.35	– 0.56	– 0.88	– 2.60
	– 1.32	– 0.84	– 1.09	– 1.85	– 1.40	– 0.84	– 0.84	– 2.86
	– 0.32	– 1.81	– 0.40	– 0.35	– 0.06	<b>0.16</b>	<b>0.12</b>	– 2.43
	– 0.35	– 0.78	– 1.23	– 0.75	– 0.33	– 0.80	– 0.70	– 0.87
	– 0.76	– 0.77	– 0.21	– 0.76	– 0.35	– 0.90	– 1.32	– 1.09
	– 0.38	– 0.69	– 0.44	– 0.73	– 0.11	– 0.48	– 0.50	– 0.51
	– 0.82	– 0.79	– 0.61	– 0.17	– 0.34	– 0.95	– 0.82	– 0.88
	– 0.65	– 0.65	– 0.59	– 0.70	– 0.34	– 0.86	– 0.13	– 0.79
	– 0.35	– 1.03	– 0.61	<b>3.37</b>	<b>1.07</b>	– 0.31	– 0.78	– 0.53
	– 0.43	– 0.71	– 0.67	<b>0.58</b>	<b>0.10</b>	– 0.62	– 0.46	– 1.07
	<b>1.63</b>	– 0.65	– 0.80	– 0.34	– 0.72	– 0.80	– 0.86	– 0.96
	– 0.58	– 0.70	– 0.74	– 0.42	– 0.17	– 0.77	– 0.88	– 0.72
Dogxung River	<b>0.27</b>	– 0.79	– 0.47	– 0.08	<b>0.46</b>	– 0.11	– 0.64	– 0.15
	– 0.12	– 0.90	– 0.70	– 0.16	– 0.48	– 0.24	– 0.60	– 1.24
	– 1.10	– 0.83	– 0.74	– 1.16	– 1.03	– 0.70	– 0.86	<b>0.68</b>
Nianchu River	<b>0.19</b>	– 0.87	– 0.46	<b>0.52</b>	<b>1.25</b>	– 0.03	– 0.60	– 0.74
	– 0.08	– 0.69	– 0.64	<b>0.65</b>	<b>1.32</b>	– 0.05	– 0.98	– 0.57
	<b>0.04</b>	– 0.71	– 0.40	– 0.70	– 0.40	– 0.30	– 1.05	– 0.11
Lhasa River	– 2.17	<b>0.19</b>	– 1.33	– 3.26	– 2.22	– 1.78	– 1.18	– 2.71
	– 2.58	– 0.06	– 1.50	– 3.54	– 2.55	– 2.12	– 1.86	– 3.03
	– 1.48	– 0.73	– 0.78	– 1.78	– 1.42	– 1.14	– 0.13	– 0.58
	– 1.27	– 1.01	– 1.36	– 2.17	– 1.82	– 1.48	<b>0.00</b>	– 0.92
	– 1.21	– 0.36	– 0.71	– 2.58	– 2.10	– 1.62	– 0.13	<b>0.19</b>
	1.20	– 0.42	– 0.74	– 2.18	– 1.74	– 0.97	<b>0.32</b>	<b>0.31</b>
	–	–	–	–	–	–	–	–
	– 2.53	– 0.52	– 1.63	– 3.29	– 2.34	– 2.20	– 1.62	– 2.14
	– 2.77	<b>0.06</b>	– 1.94	– 4.72	– 2.57	– 2.80	– 1.86	– 3.19
	– 2.25	– 0.07	– 0.19	– 5.86	– 2.76	– 2.64	– 1.23	– 2.78
	<b>1.43</b>	– 0.49	– 1.07	– 1.36	– 1.58	– 1.47	– 0.40	– 0.43
	<b>3.87</b>	– 0.07	– 0.28	– 1.32	– 1.25	– 0.95	<b>1.46</b>	<b>0.32</b>
	<b>2.16</b>	<b>0.03</b>	– 0.32	– 1.78	– 1.29	– 0.61	<b>1.22</b>	<b>0.75</b>
	– 1.34	– 0.43	– 1.13	– 0.97	– 1.46	– 1.51	– 0.13	– 1.03
	– 1.70	– 0.33	– 1.13	– 1.64	– 1.72	– 1.80	<b>0.00</b>	– 1.36

**Table 9** continued

Sample	Cu	Pb	Zn	Cr	Ni	Co	Cd	As
	– 1.19	– 0.41	– 0.84	– 1.58	– 1.48	– 1.02	– 0.35	– 1.54
	– 1.84	– 0.33	– 1.32	– 2.25	– 1.85	– 1.87	– 0.26	– 1.36
	<b>1.06</b>	– 0.24	– 0.97	– 2.49	– 2.01	– 1.56	– 0.45	– 1.27
	<b>0.96</b>	– 0.41	– 0.95	– 1.55	– 1.32	– 1.42	<b>0.00</b>	– 0.59
Niyang River	<b>2.57</b>	<b>3.33</b>	<b>2.19</b>	– 1.01	– 0.70	– 0.26	<b>4.42</b>	<b>1.68</b>
	<b>1.39</b>	<b>2.21</b>	<b>1.15</b>	– 0.63	– 0.72	– 0.56	<b>2.97</b>	<b>1.17</b>
	<b>0.19</b>	<b>0.49</b>	– 0.12	– 0.81	– 0.85	– 0.69	<b>1.58</b>	– 0.40
	– 0.03	<b>0.32</b>	– 0.23	– 1.07	– 1.10	– 0.94	<b>1.74</b>	– 0.75
	– 0.86	– 0.26	– 0.68	– 1.81	– 1.46	– 1.36	<b>0.74</b>	– 1.65
	– 1.91	– 0.84	– 1.26	– 2.26	– 2.02	– 1.60	– 0.13	– 2.91
Parlung River	– 1.26	– 1.05	– 0.80	– 1.70	– 1.46	– 0.38	– 0.13	– 2.07
	– 1.62	– 0.81	– 0.98	– 1.90	– 1.78	– 1.10	– 0.13	– 1.56
	– 1.69	– 0.10	– 0.57	– 1.06	– 1.29	– 1.04	<b>0.50</b>	– 0.66
	– 1.44	<b>0.09</b>	– 0.81	– 1.47	– 1.09	– 1.00	<b>0.22</b>	– 0.65
	– 1.62	– 0.85	– 0.70	– 5.93	– 2.72	– 0.83	– 0.13	– 3.09
Yarlung Tsangpo	<b>0.08</b>	– 0.67	– 0.39	– 0.37	<b>0.22</b>	– 0.49	– 0.38	– 0.20
	– 0.09	– 0.64	– 0.38	– 0.51	<b>0.30</b>	– 0.43	– 0.38	– 0.57
	– 0.55	– 0.77	– 0.51	– 0.40	– 0.07	– 0.86	– 0.76	– 0.47
	– 0.38	– 0.66	– 0.46	– 0.64	– 0.12	– 0.84	– 0.84	– 0.60
	– 0.42	– 0.84	– 0.64	– 0.73	<b>0.09</b>	– 0.86	– 0.62	– 0.62
	– 0.21	– 0.70	– 0.42	<b>0.57</b>	<b>0.74</b>	– 0.29	– 0.26	– 0.51
	– 0.09	– 0.87	– 0.54	<b>0.07</b>	<b>0.49</b>	– 0.44	– 0.78	– 0.58
	– 0.17	– 0.87	– 0.71	– 0.43	<b>0.15</b>	– 0.52	– 0.50	– 0.31
	– 0.22	– 0.63	– 0.66	– 0.08	<b>0.08</b>	– 0.54	– 0.91	– 0.14
	– 0.12	– 0.80	– 0.75	– 0.39	– 0.02	– 0.50	– 1.18	<b>0.24</b>
	<b>1.58</b>	– 0.80	– 1.04	– 1.31	– 1.03	– 1.33	– 0.58	<b>0.18</b>
	– 1.75	– 0.25	– 1.57	– 1.00	– 0.91	– 1.54	– 0.72	<b>0.27</b>
	– 0.53	– 0.81	– 0.12	– 0.28	– 0.49	– 0.41	– 0.78	<b>0.50</b>
	– 0.76	<b>0.41</b>	– 0.18	– 1.06	– 1.00	– 0.81	<b>0.74</b>	<b>0.04</b>
	– 1.57	<b>0.05</b>	– 1.09	– 0.77	– 0.64	– 1.69	<b>0.94</b>	<b>0.19</b>
	– 0.04	– 0.32	– 0.24	<b>0.16</b>	<b>1.20</b>	– 0.11	<b>0.22</b>	<b>0.66</b>
	– 3.66	<b>0.27</b>	– 2.40	– 6.60	– 3.55	– 4.34	– 1.95	– 0.64
	– 0.82	– 0.82	– 1.16	– 0.83	– 0.72	– 1.16	– 0.82	– 3.97
	<b>0.66</b>	– 0.47	– 0.19	– 0.19	<b>0.65</b>	<b>0.25</b>	– 0.13	<b>0.38</b>
	–	–	–	–	–	–	–	<b>0.00</b>
	<b>0.50</b>	– 0.70	– 0.01	– 0.73	– 0.12	0.91	0.94	–
	–	–	–	–	–	–	–	– 1.53
	– 0.61	– 0.70	– 0.80	– 0.55	– 0.33	– 0.66	– 0.68	–
	– 0.21	– 0.81	– 0.74	– 0.33	– 0.13	– 0.49	– 0.55	– 0.95
	– 0.53	– 0.81	– 0.88	– 0.23	– 0.28	– 0.67	– 0.48	– 0.68
	– 0.20	– 0.65	– 0.67	– 0.71	– 0.29	– 0.55	– 0.40	– 0.58
	– 0.22	– 0.76	– 0.75	– 0.40	– 0.21	– 0.54	– 0.37	– 0.72
	– 0.17	– 0.82	– 0.61	<b>0.29</b>	– 0.26	– 0.56	– 0.40	– 0.65
	– 0.59	– 0.55	– 0.91	<b>0.94</b>	– 0.18	– 0.73	– 0.72	– 0.22

**Table 9** continued

Sample	Cu	Pb	Zn	Cr	Ni	Co	Cd	As
Dogxung River	<b>1.80</b>	– 0.50	– 0.20	– 0.56	<b>0.41</b>	– 0.07	<b>0.32</b>	– 0.89
	<b>0.35</b>	– 0.56	– 0.50	– 0.63	– 0.05	– 0.33	– 0.13	<b>0.08</b>
	<b>0.21</b>	– 0.74	– 0.42	– 0.38	<b>0.33</b>	– 0.10	– 0.31	<b>0.69</b>
	– 0.15	– 1.13	– 0.63	– 0.75	– 0.61	– 0.52	– 0.35	– 0.71
Nianchu River	– 0.75	– 1.05	– 0.88	– 1.06	– 1.06	– 0.84	– 0.78	<b>1.01</b>
	– 0.05	– 0.75	– 0.64	<b>0.62</b>	<b>0.49</b>	– 0.27	– 1.02	– 0.60
	– 0.04	– 1.28	– 0.81	<b>1.46</b>	<b>1.74</b>	– 0.25	– 1.26	– 0.90
Lhasa River	<b>0.16</b>	– 0.61	– 0.43	– 0.70	– 0.32	– 0.20	– 0.88	– 0.17
	– 1.22	– 0.04	– 0.91	– 2.03	– 1.68	– 1.14	– 0.26	<b>0.17</b>
	– 1.17	<b>0.13</b>	– 0.64	– 2.25	– 1.88	– 1.20	– 0.13	– 0.22
	– 1.95	– 1.05	– 1.46	– 1.75	– 1.77	– 1.61	– 0.57	– 0.72
	– 0.51	– 0.47	– 0.38	– 1.48	– 1.39	– 0.72	<b>1.00</b>	<b>0.14</b>
	<b>1.69</b>	– 0.24	– 0.49	– 2.14	– 1.65	– 0.78	<b>0.94</b>	<b>0.31</b>
	– 0.49	0.00	– 0.53	– 1.86	– 1.95	– 1.25	<b>0.66</b>	– 0.20
	– 0.55	<b>0.29</b>	– 0.39	– 2.26	– 1.98	– 1.15	<b>0.42</b>	<b>0.61</b>
	– 2.46	– 0.66	– 1.53	– 3.12	– 2.75	– 2.14	– 1.91	– 2.00
	– 2.38	<b>0.11</b>	– 1.88	– 4.97	– 2.70	– 2.86	– 2.45	– 1.46
Niyang River	– 2.50	– 0.04	– 1.86	– 3.15	– 2.76	– 2.54	– 0.91	– 1.35
	– 0.86	– 0.74	– 1.38	– 2.07	– 1.80	– 1.81	– 1.18	– 0.74
	<b>3.02</b>	<b>0.06</b>	– 0.32	– 0.04	– 1.36	– 0.83	<b>1.00</b>	– 0.26
	<b>4.44</b>	<b>0.30</b>	<b>0.27</b>	– 1.69	– 0.75	<b>0.02</b>	<b>1.97</b>	<b>1.13</b>
	– 1.16	– 0.48	– 1.23	– 1.56	– 1.55	– 1.48	– 0.13	– 1.14
	– 1.69	– 0.43	– 1.10	– 1.79	– 1.56	– 1.83	– 0.13	– 1.04
	– 1.41	– 0.52	– 1.12	– 1.48	– 1.48	– 1.44	– 1.18	– 1.31
	– 1.60	– 0.49	– 1.28	– 0.34	– 1.47	– 1.70	– 0.13	– 1.11
	– 0.11	– 0.51	– 1.40	– 2.22	– 1.77	– 1.61	– 0.88	– 1.11
	<b>1.63</b>	– 0.17	– 0.74	– 0.81	– 1.44	– 1.20	0.32	– 0.66
Parlung River	<b>2.65</b>	<b>3.18</b>	<b>1.91</b>	– 0.91	– 0.80	– 0.42	<b>4.09</b>	<b>1.46</b>
	<b>1.05</b>	<b>1.73</b>	<b>0.72</b>	– 0.49	– 0.58	– 0.38	<b>2.35</b>	<b>1.36</b>
	– 0.12	<b>0.15</b>	– 0.28	– 1.00	– 0.96	– 0.69	<b>1.46</b>	– 0.58
	<b>0.06</b>	<b>0.31</b>	<b>0.06</b>	– 1.29	– 1.08	– 0.95	<b>1.97</b>	– 0.79
Yarlung Tsangpo	– 1.23	– 0.73	– 0.93	– 1.95	– 1.70	– 1.47	<b>0.22</b>	– 2.04
	– 1.44	– 0.75	– 1.08	– 2.06	– 2.15	– 1.66	– 0.28	– 2.69
	–	–	–	–	–	–	–	–
	– 1.98	– 0.82	– 1.30	– 1.96	– 1.51	– 1.49	– 1.18	– 2.20
Yarlung Tsangpo	– 1.95	– 0.54	– 0.81	– 1.55	– 1.46	– 1.23	<b>0.42</b>	– 0.70
	– 1.84	– 0.67	– 1.29	– 1.73	– 1.04	– 1.31	– 0.76	– 1.47
	– 1.27	– 0.89	– 0.49	– 4.72	– 2.38	– 0.47	<b>0.50</b>	– 3.13
	– 0.29	– 0.66	– 0.95	– 0.14	<b>0.16</b>	– 0.54	– 0.32	– 0.57
	<b>0.02</b>	– 0.64	– 0.58	– 0.33	<b>0.34</b>	– 0.33	– 0.29	– 0.34
	– 0.14	– 0.88	– 0.61	– 0.36	<b>0.23</b>	– 0.40	– 0.57	– 0.30
	– 0.07	– 0.71	– 0.55	– 0.34	<b>0.27</b>	– 0.47	– 0.64	– 0.18
– 0.43	– 0.72	– 0.76	– 0.03	<b>0.20</b>	– 0.60	– 0.53	– 0.45	
– 0.27	– 0.52	– 0.36	<b>0.01</b>	<b>0.40</b>	– 0.55	– 0.28	– 0.42	

**Table 9** continued

Sample	Cu	Pb	Zn	Cr	Ni	Co	Cd	As
	– 0.05	– 0.69	– 0.37	<b>0.14</b>	<b>0.42</b>	– 0.43	– 0.37	– 0.16
	– 0.37	– 0.75	– 0.82	– 0.24	<b>0.11</b>	– 0.66	– 0.72	<b>0.06</b>
	– 0.47	– 0.72	– 0.77	<b>0.05</b>	<b>0.12</b>	– 0.66	– 1.00	– 0.24
	<b>0.03</b>	– 0.78	– 0.42	– 0.36	<b>0.21</b>	– 0.13	– 0.31	<b>0.45</b>
	– 0.64	– 0.41	– 0.46	– 1.01	– 0.80	– 0.61	<b>0.50</b>	<b>0.74</b>
	– 2.37	– 0.38	– 2.06	– 2.54	– 1.50	– 2.42	– 1.32	– 0.30
	– 0.28	– 0.52	– 0.67	<b>0.24</b>	<b>0.13</b>	– 0.38	<b>0.42</b>	<b>0.19</b>
	– 1.93	– 0.30	– 1.41	– 1.21	– 0.86	– 1.58	– 0.95	<b>0.92</b>
	– 1.58	– 0.11	– 0.73	– 1.13	– 0.97	– 1.44	<b>1.27</b>	<b>1.10</b>
	– 1.84	– 0.20	– 1.71	<b>0.91</b>	<b>1.35</b>	– 0.97	– 0.43	– 1.47
	– 3.25	0.33	– 2.38	– 5.01	– 2.62	– 3.74	– 1.74	– 0.16
	– 0.44	– 1.01	– 0.92	– 0.53	– 0.34	– 0.72	0.50	<b>0.69</b>
	– 0.07	– 0.69	– 0.55	– 0.38	0.31	– 0.48	– 0.40	<b>0.08</b>
	– 0.76	– 0.77	– 0.92	– 1.36	– 0.79	– 0.49	– 0.26	– 2.26
	– 0.35	– 0.78	– 0.62	– 1.05	– 0.52	– 0.01	– 0.26	– 2.09
	– 1.17	– 1.57	– 1.50	– 0.89	– 0.92	– 0.65	– 1.18	– 4.47
	– 0.38	– 0.95	– 0.73	– 0.87	– 0.27	– 0.67	0.00	– 0.83
	– 0.13	– 0.87	– 0.56	– 0.72	– 0.16	– 0.40	– 0.62	– 0.53
	– 0.33	– 0.85	– 0.76	– 0.88	– 0.27	– 0.51	– 0.45	– 0.66
	– 0.39	– 0.65	– 0.39	<b>0.29</b>	– 0.14	– 0.44	– 0.38	– 0.63
	– 0.42	– 0.79	– 0.86	– 0.32	– 0.35	– 0.67	– 0.78	– 0.97
	– 0.62	– 1.10	– 1.04	<b>2.67</b>	<b>0.89</b>	– 0.44	– 1.32	– 0.56
	– 0.57	– 1.22	– 0.99	<b>0.96</b>	<b>0.13</b>	– 0.80	– 1.26	– 0.99
	<b>0.49</b>	– 0.36	– 0.30	<b>0.09</b>	<b>0.07</b>	– 0.20	0.00	– 0.32
	– 0.20	– 0.59	– 0.57	– 0.47	– 0.16	– 0.45	– 0.26	– 0.71

Bold indicates all values greater than 0. Corresponding to the ecological risk level in Table 2, the bold points are expressed as Slightly polluted or Extremely polluted

“–” no relevant data

of Co at all sampling points was always less than 0, and the lowest value appeared in F17 ( $I_{geo} = -4.35$ ). Co appears in a pollution-free environment, and the pollution level of the sampling points F56 and F57 of Cu, Pb, and As was the highest of the entire river. During the survey period, the construction of the Lalin Railway was carried out in F56 (the source of the Niyang River). F57 (downstream of the Niyang River, Songduo Town) contained construction sites along the other side and flowed through human habitats that had significant piles of domestic garbage at the sampling points. Apart from Pb, Cd, and As which pose high ecological risks to the Niyang River Basin, the geoaccumulation index of the other sites is less than 0. When no man-made pollution is present, the concentration of heavy metals is dependent on the

interaction of water with soil and rock. Such values are generally very low (Shi 2015), it can be concluded that human emissions seriously affect the Niyang River Basin (consistent with the conclusions of the second part), and harmful human activities should be reduced.

#### *Potential ecological risk index method results*

The potential ecological risk index of the Yarlung Tsangpo River surface sediments (Table 10) and their potential risk levels (Table 4) show that most heavy metals have potential risk levels ( $< 40$ ) that are either mildly polluting or non-polluting. The comprehensive potential risk index ( $RI = 55.0 < 135$ ) also indicates low-to-moderate risk levels are present at individual sampling points, mainly due to the high background



**Table 10** Potential ecological risk indexes for surface sediments in the Yarlung Zangbo River

Project	Cr	Co	Ni	Cu	Zn	As	Pb	RI
Max	7.12	8.86	9.35	19.72	33.32	41.06	22.21	111.15
Mix	2.30	3.67	3.18	13.88	28.91	32.77	11.19	42.36
Avg	3.39	5.58	7.66	19.10	31.15	38.86	14.43	52.15

**Table 11** PEL/TEL guideline level and SQG-Q of sediment heavy metals

	Cr	Cu	Zn	Pb	Cd	As	Ni	SQG-Q
Avg	99.43	53.5	78.6	35	0.16	27.2	36.1	
TEL	45.3	76.7	46.12	42.4	0.41	16.8	20.1	
PEL	84	205	336	99.7	2.89	25.1	24.3	
PEL-Q	1.00	0.22	0.56	0.33	0.02	1.77	1.58	0.913

values of the region. Cr and Co show the lowest risk levels and essentially pose no risk, possibly because they are relatively stable in nature, have poor mobility, and are mostly naturally occurring. The ecological risk grades of heavy metals in the Yarlung Tsangpo River are ordered from Cr < Co < Ni < Cu < Zn < Pb < As.

*Sediment quality benchmark method results*

The heavy metal reference values of the Yarlung Tsangpo River surface sediments and the SQG-Q coefficients (Table 11) show that the pollution coefficients of Ni and As are relatively high, 1.58 and 1.77, respectively, which indicate they pose high ecological risks to the local environments. Many other heavy metals present moderate risk levels, while Cd has the lowest pollution coefficient, indicating it has no pollution behavior. In addition, relative to TEL and PEL, the Cr, Ni, and As contents are higher than both the possible ecological effect concentration (PEL) and the critical effect concentration (TEL). It indicates that the three heavy metals pose high ecological risks to the environment. The amounts of Cu, Zn, and Pb were lower. The mass reference coefficient (SQG-Q) of the overall Yarlung Tsangpo River sediment is 0.913, which is  $0.1 < SQG-Q < 1$ . It indicates that the Yarlung Tsangpo River surface sediments present a moderate ecological risk and are only contaminated by certain heavy metals.

In summary, the three evaluation results are nearly identical to the low ecological risk status of the basin.

Cu, Zn, Pb, As, and Cd were the most polluting, and Cr, Co, and Ni were only slightly polluting. These results indicate the Lhasa River Basin needs special attention.

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