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The Content Level, Spatial and Temporal Distribution Characteristics, and Health-Risk Assessment of Trace Elements in Upper Lancang River (Changdu Section)

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Abstract: Evaluation of trace elements in the water of Lancang River during the wet season (October) and dry season (December) was carried out to analyze the content of trace elements in the water, spatial and seasonal variations, enrichment, and health risks of dissolved trace metal. The results showed that the content of trace elements in the main stream of the upper Lancang River met the "Environmental Quality Standard for Surface Water" (GB3838-2002) Class I water-quality standard, but the Fe content in sampling points during the wet season exceeded the limit value of water-quality standard. Compared with other rivers in Tibet, the contents of As, Fe, and Pb in the study were relatively high. While Pb, As, and Zn were the mainly enriched trace elements. The water temperature, dissolved oxygen, conductivity, As, Cr, and Cu in the main stream of the upper Lancang River with significant seasonal variations. The content of trace elements in the front of the dam was lower than that in the tail and under the dam. The trace elements in the water of the reservoir area increased with an increase in the depth, and the reservoir had a certain interception effect on the trace elements. The As content in the main stream of the Lancang River was greatly affected by the branch of Angqu with high content of As. The $HQ_{ingestion}$ and HI of As in the part of the river in the study exceeded 1, and the water-quality health risks of the Guoduo reservoir tail and urban reaches were higher than those of other reaches, which should be paid more attention.

Keywords: the upper Lancang River; trace elements; distribution characteristics; reservoir; enrichment; health risks

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1. Introduction

Trace elements in water have been highly enriched, difficult to degrade, and highly toxic, especially the excessive accumulation of toxic trace elements which not only threaten safety of invertebrates and fish ecosystems, but also cause serious health effects on human beings [1–4]. Some trace elements are extremely toxic even at low concentrations, such as arsenic (As) and lead (Pb) [5]. As has been classified as a Group I carcinogen by the International Agency for Research on Cancer [6] and can cause lung, bladder, and skin cancer even at low doses when inhaled by humans [5,7]. Exposure to Pb could seriously damage the kidney, liver, central nervous system, and blood system [8], and Pb has been one of the 67 important risk factors leading to global diseases [9]. Although iron (Fe) and Mn (manganese) are critical in organisms at specific concentrations, they have toxic effects on organisms when the concentration increases [10]. Under certain conditions, As adsorbs on manganese and iron oxides and hydroxide surface is released into the water [11], thus affecting the migration and transformation behavior of As in the aquatic environment [12].

Lancang-Mekong River is an international river, the tenth-largest river in the world [13], and one of the important cradles of human civilization in Southeast Asia [14]. It is called Lancang River with a total length of 2354 km in China. With the high-speed development of the economy in recent years, in the Lancang River basin, the urbanization process has accelerated, and trace elements have been influenced by city human activities. The compounds enter the river through hydropower development, mining, and urbanization construction. Trace element pollution is caused by geochemical background in local reach [15], and severe pollution of As and Pb in parts of Lancang River [16]. Zhang et al. [17] analyzed the sediment of the Lancang River and showed that the middle and lower of Lancang River was greatly affected by human activities. Trace elements such as copper (Cu), Pb, and As mildly or moderately polluted some parts of the Lancang River. In recent years, the Guoduo reservoir hydropower station [18] in the upper Lancang River had been put into operation, and the construction of the dam changed the original hydrological regime and form of Zhaqu [17,19]. The trace elements in the water would experience different physical and geochemical processes. In addition, the economy of Changdu city showed a trend of rapid development [20]. The study area belongs to the plateau cold and arid region, and there was a shortage of water resources in the area, which could not meet the living needs of the local people. In addition, due to the complex terrain of the local area, it is difficult to carry out relevant research work. At present, there are relatively few studies on trace elements in the upper reaches of the Lancang River, and the influence of urban development and hydropower station construction on trace elements in the upper of Lancang River is unclear. Therefore, this study took the urban section of Changdu city of Lancang River and the upper Zhaqu (80 km from the upper estuary of Zhaqu River) as the research object, carried out water environment investigation, analyzed the spatial and temporal distribution characteristics of major trace elements As, Pb, Fe, Mn, chromium (Cr), Cu, and zinc (Zn) in the water body, understood their enrichment status, and evaluated their health risks. To provide a scientific basis for water ecological environment protection in the upper Lancang River. this study provided a reference for water environment evolution of rivers and the utilization of water resources in the plateau area.

2. Materials and Methods

2.1. Study Area

Lancang River originates from the northern foot of Tanggula Mountain on The Qinghai–Tibet Plateau in China. It flows out of the border through Yunnan and Nanla Estuary, and then into the South China Sea through Laos, Thailand, Cambodia, and Vietnam [17]. The Lancang River passes through the parallel vertical valley of Hengduan Mountain. It is a steep and narrow river running from north to south with an elevation drop of 4700 m. Soil erosion, landslide, and debris flow frequently occur here [13]. The length of the source of the Lancang River to Changdu is 565.5 km, which is the upper of the Lancang River, namely, Zhaqu. Zhaqu is 448 km long in Qinghai Province and 117.5 km after exiting Qinghai to Changdu. The riverbed elevation of this section is 3150–3700 m, with an average gradient of 4.0‰–4.5‰, which is the river section with the largest river decline in the whole basin [21]. Zhaqu and Angqu flows into the Lancang River after confluence in the Changdu. The soil-forming part materials of Changdu mainly include Cretaceous, Jurassic, Triassic, Tertiary, and other multi-period magmatic rocks, sedimentary rocks, and metamorphic rock weathering residues, gravity deposits, slope deposits, etc. Zhaqu mainly contains Jurassic purple red sand and mudstone mixed with limestone [22,23]. Changdu is an important part of the Southwest Sanjiang Pb–Zn–Cu–Ag metallogenic belt [24]. In the region, a large number of Pb–zinc deposits have been produced in carbonate rocks, and depositional mercury, antimony, arsenic, and lead–zinc deposits occur [25].

Changdu is located in the semi-arid monsoon climate zone, with annual average precipitation of 473 mm and annual average temperature of 7.5 °C [26]. Zhaqu water is mainly resupplied by melting water of snow and ice in spring, and by rainwater and groundwater in summer, autumn, and winter. The water amount in spring accounts for about 12% of the annual water volume. Summer accounts for about 50% of the annual water volume [21]. From December to April of the following year, due to the influence of the westerly climate, precipitation is rare and the air is dry. Precipitation mainly concentrates from May to November [27], with sufficient sunshine, strong solar radiation, large diurnal temperature difference, and small annual temperature difference [28].

2.2. Sampling

According to the geographical characteristics of the study area, 11 sampling sites were set up in this study (Table 1). Two sites were set up in urban areas after Zhaqu merges into the Lancang River. One of them was set up at the estuary of the tributary Angqu River, and two sample sites were set up under the dam of the Guoduo reservoir. Six sample sites were set up from the dam site of the Guoduo reservoir to the 20 km upstream section (Figure 1). The survey was conducted in the wet season (October) and dry season (December) in 2018. The temperature, pH, dissolved oxygen, conductivity, and turbidity of the water were monitored on-site by a portable multi-parameter water-quality analyzer (EXO2, Yellow Springs Instrument Incorporated, Yellow Springs, OH, USA) when collecting water samples. The surface water was collected from 0.5 m below the water surface. In order to better understand the water-quality changes in the Guoduo reservoir, a vertical line was drawn in the 0.5 km section in front of the Guoduo reservoir dam, and water samples were collected at 0.5, 5, 10, 20, 30, 40, and 60 m below the water surface. After the water sample was collected, 500 mL of the sample was filtered through the 0.45 μm cellulose acetate filtration membrane on the sampling day. To filtered samples were added suprapure nitric acid until the pH of the samples was less than 2, and they were then refrigerator-stored until analysis.

Table 1. Basic information table of sampling points.

Number	Sampling Sites	Longitude	Latitude	Main Stream or Tributary
L01	The tail of reservoir	97°05′20.30″	31°38′54.17″	Main stream
L02	11 km in front of the dam	97°06′49.13″	31°35′25.11″	Main stream
L03	9 km in front of the dam	97°07′4.33″	31°35′19.17″	Main stream
L04	5 km in front of the dam	97°09′07.68″	31°33′14.07″	Main stream
L05	3 km in front of the dam	97°09′41.55″	31°33′01.76″	Main stream
L06	0.3 km in front of the dam	97°11′18.84″	31°32′03.85″	Main stream
L07	1 km under the dam	97°07′40.69″	31°34′56.02″	Main stream
L08	50 km under the dam	97°10′58.00″	31°10′3.00″	Main stream
Z01	The estuary of Angqu	97°09′09.38″	31°09′00.33″	Tributary
L09	1 km downstream of Lancang river	97°10′37.7″	31°07′58.4″	Main stream
L10	40 km downstream of Lancang river	97°21′34.8″	31°55′50.0″	Main stream

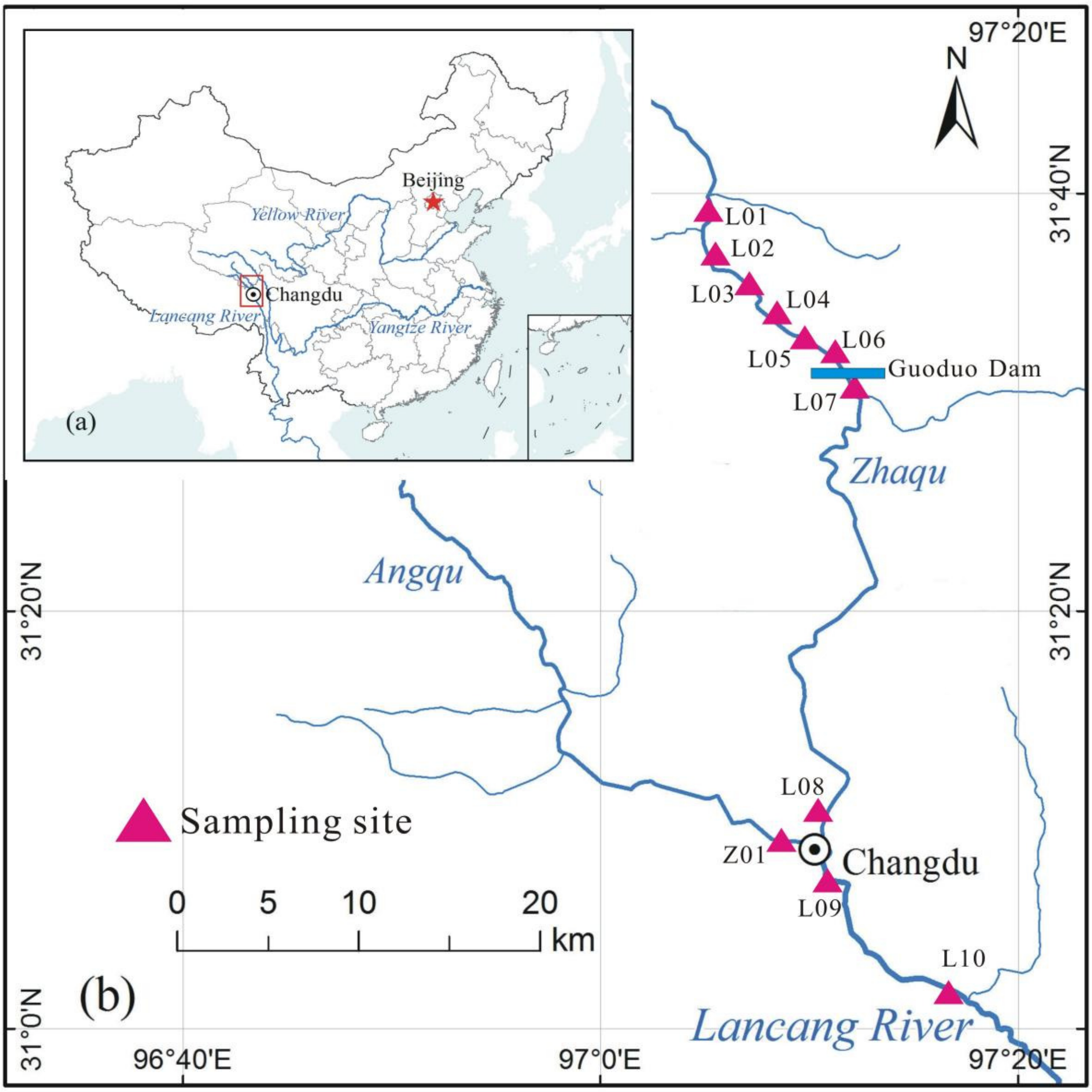

Figure 1. Sampling sites in the study area ((**a**): Map of China; (**b**): The study area.).

2.3. Data Collection and Data-Quality Assessment

The temperature, pH, dissolved oxygen, and conductivity of all samples were calibrated before testing, with the pH electrode calibrated with buffers of pH 4.01, 7.00, and 10.01. As, Fe, Mn, Pb, Cr, Cu, and Zn were analyzed by ICP-MS (NexION 300X, PerkinElmer, Waltham, MA, USA) [29,30]. Standard reagent produced by the National Research Center for Standard Materials was used to formulate the standard curve before sample analysis. Blank samples were added to each batch of samples. The detection limits of As, Fe, Mn, Pb, Cr, Cu, and Zn (μg/L) were 0.12, 0.82, 0.12, 0.09, 0.11, 0.08 and 0.67, respectively. The recoveries (%) were 91.8, 97.2, 95.5, 92.4, 93.2, 94.6 and 96.1, respectively. All the data below the detection limit were analyzed and calculated using half of the detection limit [31].

2.4. Analytical Method

(1) Enrichment of trace elements

In order to understand the enrichment status of metal elements in the study area, enrichment factor (EF) was used for analysis. The enrichment factor was the ratio of the metal element content in the water body of the study area to the average river content in the world [32]. According to the enrichment factor, the enrichment conditions could be divided into 6 categories: when EF > 100, it was abnormal enrichment; 10 < EF < 100, indicating super enrichment; 5 < EF < 10, indicating significant enrichment; 1.5 < EF < 5, indicating slight enrichment; 0.5 < EF < 1.5, indicating that it is not enriched. If EF < 0.5, this indicates a loss [33].

(2) Health-risk assessment model

Health-risk assessment is a method to quantitatively describe the risk of health hazards caused by human exposure to polluted environments, which could be caused by two main ways: drinking water and skin contact. The United States Department of Environmental Protection (US EPA) had recommended a health-risk assessment model [34,35].

Risk entropy (*HQ*) reflects the potential risk status of non-carcinogenic risk: *HQ* < 0.1, indicating that the pollutant would not cause adverse health effects; 0.1 < *HQ* < 1, indicating that further investigation is required before action is taken; *HQ* > 1, indicating that pollutants are likely to cause adverse health effects [35].

$$HQ = ADD/RfD \tag{1}$$

The risk index (*HI)* can be used to assess the total potential non-carcinogenic risk from multiple pathways, and *HI* > 1 indicates that the pollutant might have adverse effects on human health or require further study.

$$HI = \sum (HQ_{irg} + HQ_{derm}) \tag{2}$$

(i) Calculation of average daily dose:

$$ADD_{ingestion} = \frac{C_w \times IR \times ABS_g \times EF \times ED}{BW \times AT} \tag{3}$$

(ii) Calculation of skin exposure dose to water:

$$ADD_{dermal} = \frac{(C_w \times S_A \times K_p \times ET \times EF \times ED \times 10^{-3})}{(BW \times AT)} \tag{4}$$

Reference values of exposure parameters are shown in Table 2.

Table 2. Statistics of disclosure parameters.

Subject	C_w	*IR*	ABS_{GI}	*EF*	*ED*	*SA*	K_p	*ET*	*BW*	*AT*
Adults	–	2 [a]	See Table 3	350 [b]	70 [b]	18,000 [b]	See Table 3	0.58 [a]	65 [a]	25,550 [b]
Children	–	0.64 [a]	See Table 3	350 [b]	6 [b]	6600 [b]	See Table 3	1 [a]	20 [a]	219 [b]

[a] Gao et al. [36]; [b] US EPA [37].

Table 3. $RfD_{ingestion}$, RfD_{dermal}, ABS_g, and K_p values of trace elements.

Element	As	Cu	Zn	Pb	Cr	Mn
$RfD_{ingestion}$	0.3 [a]	40 [c]	300 [a]	1.4 [c]	3 [c]	24 [c]
RfD_{dermal}	0.285 [a]	8 [c]	60 [a]	0.42 [c]	0.075 [c]	0.96 [c]
ABS_{GI}	95% [b]	57% [b]	20% [d]	11.7% [d]	3.8% [b]	6% [b]
K_p	0.001 [b]	0.001 [b]	0.0006 [b]	0.0001 [b]	0.003 [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. [36]; [b] US EPA [37]; [c] Wang et al. [38]; [d] Xiao et al. [39].

Values of $RfD_{ingestion}$, RfD_{dermal}, ABS_g, and K_p of each (class) metallic element are shown in Table 3.

3. Result and Discussion

3.1. Trace Elements in Water

The contents of trace elements in the main stream of Lancang River were as follows: Fe > Mn > Zn > As > Cu > Pb > Cr. The contents of trace elements in all the sample points meet the Class I water-quality standard of Surface Water Environmental Quality Standard (GB3838-2002), but the Fe content in some sample points exceeded the limit value of water-quality standard (300 μg/L). The average content of As was 7.28 μg/L, which was lower than that of Sengzangbo River and Shiquan River, and much higher than that of Niyang River, Lhasa River (see Table 4), and the world river average. The average Pb content was 2.65 μg/L, which was lower than the lower Lancang River, but higher than other rivers in Tibet and the world river average. The average content of Fe was 153.1 μg/L, which was lower than that of Niyang River and far higher than that of other Tibetan rivers and the world river average. The average content of Mn was 10.84 μg/L, which was lower than that of Niyang River and the world river average, but higher than that of other Tibetan rivers. The average content of Cr was 2.27 μg/L, which was higher than that in the Niyang River and lower Lancang River. The average content of Cd was 0.06 μg/L, which was lower than that of other rivers in Tibet. The average Cu content was 6.25 μg/L, which was only lower than that of Niyang River, but much higher than the lower Lancang River. The content of Zn was only lower than that of Niyang River, but much higher than that of the lower Lancang River. Except for As, the mean contents of all other metal elements in this research were lower than the rivers of Bangladesh, but the contents of As, Fe, Pb, Cu, and Zn in the water of the Lancang River were higher than the corresponding elements' contents in water of the world river average and other rivers of Tibet, which may be attributed to the weathering products of mineral resources and rocks outcropping in the drainage basin [40].

According to the analysis in Figure 2, different trace elements were enriched in different regions. As, Pb, and Zn were heavily enriched, Fe and Cr were moderately enriched, and Mn and Cu were slightly enriched or below in the reservoir tail water. In the reservoir water, Pb and Zn were heavily enriched, As was moderately enriched, and Fe, Mn, and Cu were slightly enriched or below. Pb and Zn were heavily enriched, As was moderately enriched, and Fe, Mn, Cu, and Cr were slightly enriched or below. Pb and As were heavily enriched, As was moderately enriched, and Fe, Mn, Cu, and Cr were slightly enriched or below. In conclusion, As, Pb, and Zn were the mainly enriched trace elements in the water in the study area.

3.2. Temporal and Spatial Distribution Characteristics of Trace Elements

The water temperature of the Lancang River mainstream in the study area fluctuated little in both the wet season (4.45–6.83 °C) and dry season (0.1–1.0 °C), but the average water temperature in the wet season (5.71 °C) was significantly higher than that in the dry season (0.37 °C) (Table 5). The pH value of river water in the wet season (8.16–8.36) and dry season (8.13–8.31) fluctuated little. The pH value of river water in the wet season (8.21) and dry season (8.22) had no significant difference, but the river water was slightly alkaline on the whole, which was similar to other rivers in Tibet [15,26]. The content of dissolved oxygen in river water in the wet season (8.86–10.24 mg/L) was higher than that in the dry season (6.52–7.25 mg/L), which was mainly due to the larger water quantity, faster flow rate, and faster exchange between water and air in the wet season. The conductivity of the river water in the wet season (226–385.3 μS/cm) was lower than that in the dry season (448–743 μS/cm).

Table 4. Trace elements in rivers.

River	As (μg/L)		Pb (μg/L)		Fe (μg/L)		Mn (μg/L)		Cr (μg/L)		Cu (μg/L)		Zn (μg/L)		Literature
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	
This study	7.28	1.00–14.1	2.65	ND-10.0	153.1	26.90–836.3	10.84	0.94–39.37	2.27	ND-5.99	6.25	ND-17.18	9.87	ND-39.81	/
Niyang River, Tibet	0.10	/	1.16	0.012–5.18	360.0	160.0–600.0	27.65	0.02–400	1.75	0.34–3.28	7.11	0.06–34.2	36.34	0.15–187	[41]
Lhasa River, Tibet	2.28	0.65–4.27	/	/	11.83	ND-111.0	4.05	ND-21.7	/	/	3.95	0.12–14.00	4.32	0.51–15.80	[42]
Sengzangbo River, Tibet	58.40	2.4–252.0	0.09	0.05–0.22	14.00	0.16–98.1	3.63	2.18–14.7	/	/	2.58	0.36–4.98	1.25	0.75–4.01	[43]
Yarlung Tsangpo, Tibet	10.80	1.97–83.2	0.06	0.03–0.31	8.30	0.46–82.28	2.37	0.65–19.2	/	/	1.69	0.77–3.30	0.97	0.41–2.10	[43]
Shiquan River, Tibet	68.00	3.10–150	/	/	/	/	/	/	/	/	/	/	/	/	[43]
Xiangquan River, Tibet	5.99	4.91–7.06	/	/	/	/	/	/	/	/	/	/	/	/	[43]
Naqu, Tibet	5.89	5.87–5.91	/	/	/	/	/	/	/	/	/	/	/	/	[43]
The downstream of Lancang river, Tibet	/	/	11.82	8.43–15.2	100	70–130	13.3	12.5–14.1	0.39	0.28–0.50	1.53	0.86–2.2	1.88	0.83–2.93	[26]
Six major river basins, Bangladesh	6.53	1.3–32	12.41	2.9–31	2476	215–21,800	233.8	15.3–1170	27.7	2.1–86	/	/	53.24	10–190	[11]
Wainivesi River, Bangladesh,	/	/	190	153–204	1623	570–4260	45	5–96	104	55–122	46.8	10–107	183	21–753	[44]
Nakuvadra-Rakiraki River, Ra Province	/	/	12.4	5.11–21.3	198	57.1–444	358	168–531	133	63–181	22.4	5.2–43.7	46.1	9.02–99.7	[45]
Average of the world's rivers	0.62		0.079		66		34		0.70		1.44		5.34		[32]
Class I of surface water	50		10		300		100		/		10		50		Water-quality standards for surface water in China

Note: "/" means no detection, and "ND" means detection limit in the table.

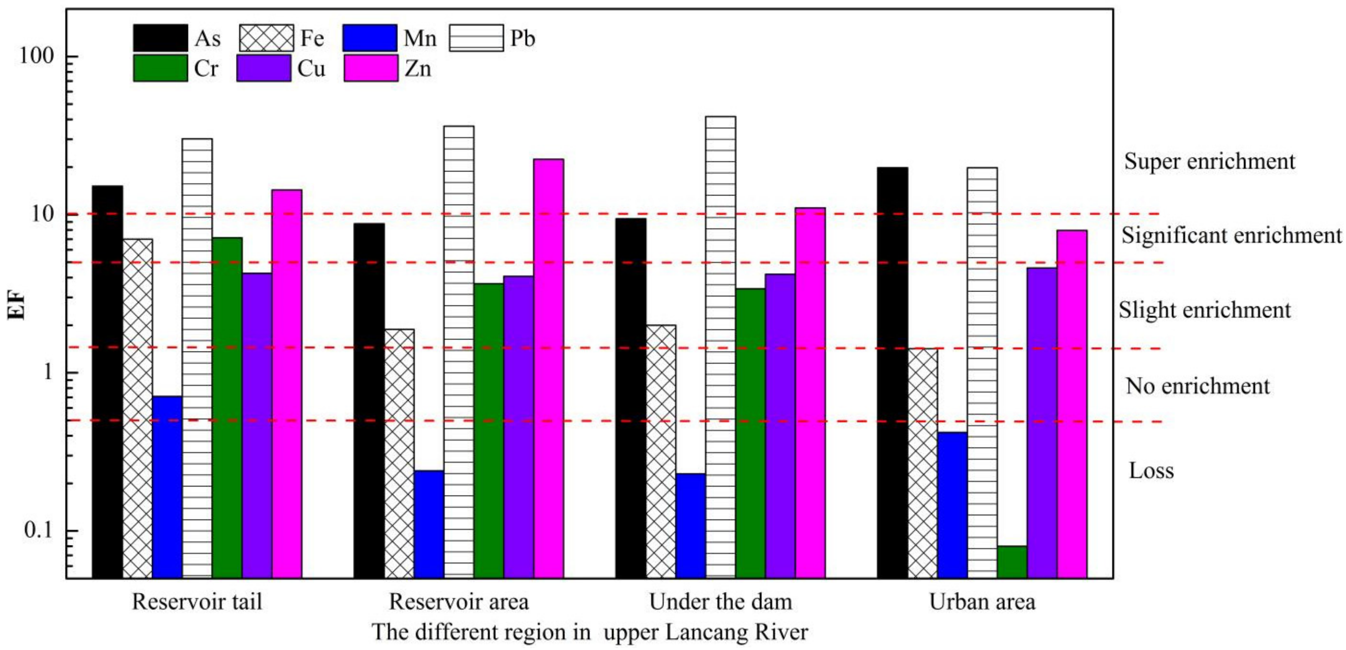

Figure 2. Enrichment of trace elements in water in different regions.

Table 5. Field parameters and trace element concentrations in surface waters from the upper Lancang River.

Sampling Time	Category	T (°C)	pH	DO (mg/L)	EC (µS/cm)	As (µg/L)	Fe (µg/L)	Mn (µg/L)	Pb (µg/L)	Cr (µg/L)	Cu (µg/L)	Zn (µg/L)
Wet season (October 2018)	mean	5.71	8.21	9.32	357	5.49	207.7	10.29	3.11	0.58	0.86	8.80
	min	4.45	8.16	8.86	226	1.00	26.90	0.94	ND	ND	ND	ND
	max	6.83	8.36	10.24	385	14.06	836.3	39.37	10.00	5.29	2.38	39.81
Dry season (December 2018)	mean	0.37	8.22	6.90	604	9.06	98.49	11.39	2.18	3.96	11.64	10.93
	min	0.10	8.13	6.52	488	7.65	64.62	2.60	1.95	ND	9.98	8.20
	max	1.00	8.31	7.25	743	12.70	179.3	19.09	2.60	5.99	17.18	13.03

Note: "ND" means detection limit in the table.

The average content of As in the main stream of Lancang River in the wet season (5.49 µg/L) was significantly lower than that in the dry season (9.06 µg/L), but the content of Fe (average 207.7 µg/L) in the wet season was significantly higher than that in the dry season (average 98.49 µg/L) (Table 5). There was no significant difference between Mn content in the wet season (mean 10.29 µg/L) and dry season (mean 11.39 µg/L), and there was no significant difference between Pb content in the wet season (mean 3.11 µg/L) and the dry season (mean 2.18 µg/L). The contents of Cr, Cu, and Zn in the wet season were all lower than those in the dry season (Figure 3), which was similar to electrical conductivity. The main reason was that glacial meltwater and rainfall merge into rivers in the wet season, which reduces the contents of trace element plasma in water bodies [15]. According to analysis of Figure 2, the content of Fe and Pb in the wet season was higher than that in the dry season, which may be related to the higher value of local geological background. The fluctuation of As, Pb, Fe, Mn, and Cr in the main stream of the Lancang River was relatively large in the wet season, but relatively small in the dry season. This was mainly due to the high sediment content in the wet season and the continuous adsorption and desorption of trace elements in the sediment [46,47], and it was also affected by the merging of surrounding rainfall and melting water of snow and ice. In general, the contents of As, Cr, and Cu in the water body of the main stream of the Lancang River in the dry season were higher than those in the wet season, mainly because the water amount in the wet season was larger and the trace elements in the water body diluted [15].

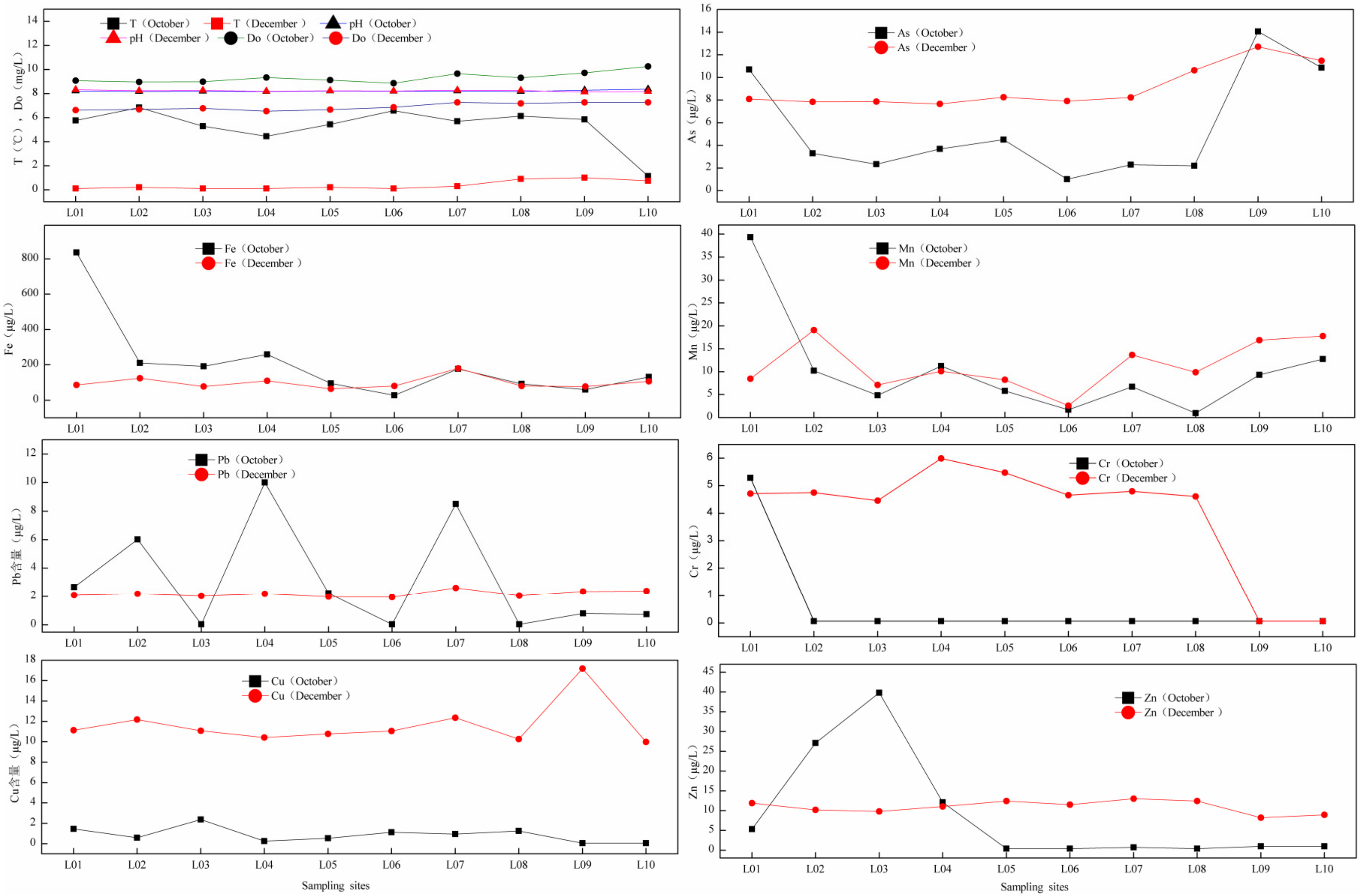

Figure 3. Temporal and spatial distribution of trace elements in upper Lancang River.

From the changes of water quality along the main stream of the upper Lancang River, it could be seen that the variation trend of Fe and Mn in the main stream of Lancang River is similar, which was mainly because Mn was the associated element of Fe. The contents of As, Pb, Fe, Mn, Cr, and Zn were the lowest at L06 (0.3 km in front of the dam), which was the closest point to the dam site and has a slow flow rate. Most of the granular As, Pb, Fe, and Mn in the water body had sunk to the bottom of the reservoir. The contents of As, Pb, Fe, Mn, Cr, and Zn in surface water were low [48–50]. The As increased sharply at L09, especially during the wet season, which was mainly due to the high arsenic content (As: 18.84 μg/L) flowing into the upstream branch of L09. As, Pb, Fe, Mn, Cr, and Cu all rose suddenly at L07, mainly because L07 was located about 1 km downstream of the dam site of Guoduo reservoir, and might be due to the release of trace elements in the sediment due to the relatively large influence of water disturbance under the dam from the power station [51].

3.3. Vertical Distribution of Trace Elements

The water temperature slightly decreased with the deepening of the water depth, mainly because the local sunshine was strong, and the effect of heat conduction makes the external heat gradually decrease in the water body, so that the surface temperature is high and the bottom temperature is low (Figure 4). The vertical range of As and Fe content was 1.00–4.90 μg/L and 26.90–902 μg/L, respectively. The vertical range of Mn content was 1.16–92.23 μg/L. The vertical range of Pb content was 0.05–3.99 μg/L. The vertical range of Cr content was 0.06–2.87 μg/L. The vertical range of Cu content was 0.29–3.53 μg/L. The vertical range of Zn content was 0.33–6.48 μg/L. The contents of As, Fe, Mn, Pb, Cr, Cu, and Zn all increased gradually with the increase in water depth. The contents of trace elements in the water at 40 m increased obviously, and the highest concentrations were found in the bottom water. This was mainly due to the trace elements adsorbed on the particles settling at the bottom of the reservoir with the particles, and the bottom water being close to the bottom mud, significantly affected by sediment release [48]. Cu fluctuated greatly in the vertical direction, but the change rule was not obvious and the content of Cu was higher at 30 m and 60 m, which requires further study.

3.4. Health-Risk Assessment

Water-quality health-risk assessment could quantitatively evaluate the probability of health hazards to humans caused by water environmental pollutants [42]. According to the analysis of potential risks of trace elements in the wet season (Table 6), the average *HI* values of trace elements were as follows: As > Pb > Cr > Mn > Cd > Cu > Zn. Except for As, the values of *HQ* and *HI* of all trace elements were less than 1, indicating that Mn, Pb, Cr, Cu, and Zn in the study posed a lower health risk. The $HQ_{ingestion}$ of As in the reservoir tail and urban water body was lower than 1, indicating that there were health risks after As was ingested in the reservoir tail and urban water through the mouth. The $HQ_{ingestion}$ of As the dam was between 0.1 and 1, indicating that the health risk of oral ingestion needs to be further investigated. The $HQ_{ingestion}$ and HQ_{dermal} values of all children were lower than those of young people, indicating that the health risk of children through oral ingestion and skin contact was higher than that of young people. The HQ_{dermal} values of all trace elements in children and young adults were much less than 0.1, indicating that trace elements in the study area basically did not pose health risks through the skin.

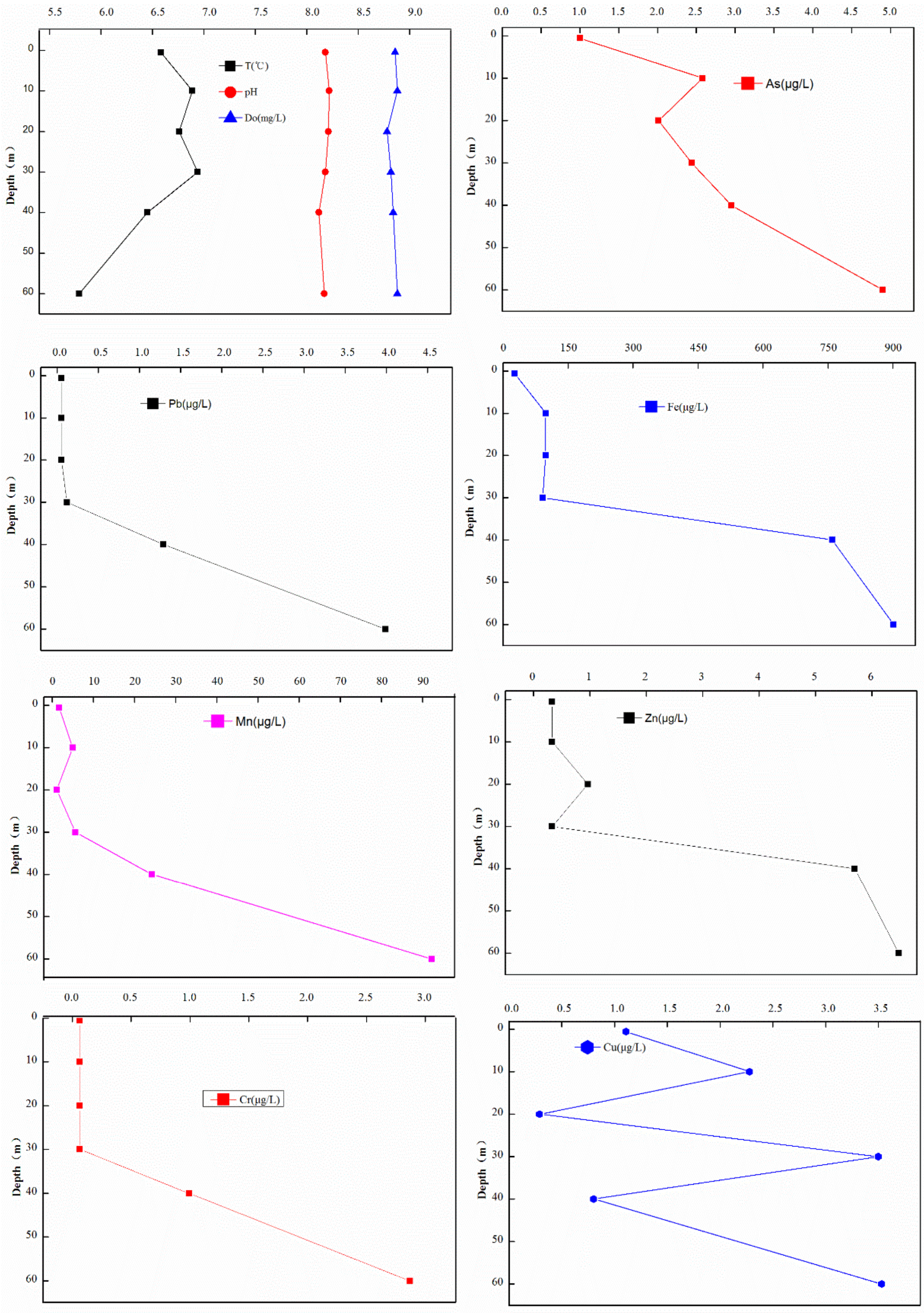

Figure 4. Vertical distribution of physicochemical properties in the water column of the Guoduo reservoir.

Table 6. Health-evaluation index of trace elements in the main stream of Lancang River during the wet season.

Elements	Reservoir Tail						Reservoir Area						Under the Dam						Urban Area					
	$HQ_{ingestion}$		HQ_{dermal}		HI		$HQ_{ingestion}$		HQ_{dermal}		HI		$HQ_{ingestion}$		HQ_{dermal}		HI		$HQ_{ingestion}$		HQ_{dermal}		HI	
	Adult	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**
As	1.0527	1.0948	0.0058	0.0119	1.0585	1.1067	0.2917	0.3034	0.0016	0.0033	0.2933	0.3067	0.2201	0.2290	0.0012	0.0025	0.2214	0.2314	1.2255	1.2745	0.0067	0.0138	1.2323	1.2884
Mn	0.0484	0.0503	0.0063	0.0130	0.0547	0.0633	0.0083	0.0086	0.0011	0.0022	0.0094	0.0109	0.0047	0.0049	0.0006	0.0013	0.0053	0.0062	0.0135	0.0141	0.0018	0.0036	0.0153	0.0177
Pb	0.0561	0.0584	0.0001	0.0002	0.0562	0.0586	0.0773	0.0804	0.0001	0.0003	0.0774	0.0807	0.0901	0.0937	0.0002	0.0003	0.0902	0.0940	0.0163	0.0170	0.0000	0.0001	0.0164	0.0171
Cr	0.0520	0.0541	0.0326	0.0669	0.0846	0.1210	0.0005	0.0006	0.0003	0.0007	0.0009	0.0013	0.0005	0.0006	0.0003	0.0007	0.0009	0.0013	0.0005	0.0006	0.0003	0.0007	0.0009	0.0013
Cd	0.0033	0.0034	0.0003	0.0007	0.0036	0.0041	0.0072	0.0075	0.0008	0.0015	0.0079	0.0090	0.0065	0.0067	0.0007	0.0014	0.0071	0.0081	0.0015	0.0015	0.0002	0.0003	0.0016	0.0019
Cu	0.0011	0.0011	0.0000	0.0001	0.0011	0.0012	0.0007	0.0007	0.0000	0.0000	0.0007	0.0008	0.0008	0.0008	0.0000	0.0000	0.0008	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Zn	0.0005	0.0005	0.0000	0.0000	0.0005	0.0006	0.0016	0.0016	0.0000	0.0001	0.0016	0.0017	0.0001	0.0001	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0001	0.0001

Table 7. Health-evaluation index of trace elements in the main stream of Lancang River during the dry season.

Elements	Reservoir Tail						Reservoir Area						Under the Dam						Urban Area					
	$HQ_{ingestion}$		HQ_{dermal}		HI		$HQ_{ingestion}$		HQ_{dermal}		HI		$HQ_{ingestion}$		HQ_{dermal}		HI		$HQ_{ingestion}$		HQ_{dermal}		HI	
	Adult	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**	**Adult**	**Child**
As	0.7962	0.8281	0.0044	0.0090	0.8006	0.8371	0.7773	0.8084	0.0043	0.0088	0.7815	0.8171	0.9280	0.9651	0.0051	0.0105	0.9331	0.9756	1.1883	1.2358	0.0065	0.0134	1.1948	1.2492
Mn	0.0104	0.0108	0.0014	0.0028	0.0118	0.0136	0.0116	0.0121	0.0015	0.0031	0.0131	0.0152	0.0145	0.0151	0.0019	0.0039	0.0164	0.0189	0.0213	0.0222	0.0028	0.0057	0.0241	0.0279
Pb	0.0443	0.0461	0.0001	0.0002	0.0444	0.0462	0.0436	0.0454	0.0001	0.0002	0.0437	0.0455	0.0490	0.0510	0.0001	0.0002	0.0491	0.0511	0.0497	0.0517	0.0001	0.0002	0.0498	0.0518
Cr	0.0464	0.0482	0.0290	0.0597	0.0754	0.1079	0.0498	0.0518	0.0312	0.0641	0.0810	0.1160	0.0463	0.0481	0.0290	0.0596	0.0753	0.1077	0.0005	0.0006	0.0003	0.0007	0.0009	0.0013
Cd	0.0015	0.0015	0.0002	0.0003	0.0016	0.0019	0.0015	0.0015	0.0002	0.0003	0.0016	0.0019	0.0015	0.0015	0.0002	0.0003	0.0016	0.0019	0.0015	0.0015	0.0002	0.0003	0.0016	0.0019
Cu	0.0082	0.0085	0.0002	0.0004	0.0084	0.0090	0.0082	0.0085	0.0002	0.0004	0.0084	0.0090	0.0083	0.0087	0.0002	0.0004	0.0086	0.0091	0.0100	0.0104	0.0003	0.0005	0.0103	0.0110
Zn	0.0012	0.0012	0.0000	0.0000	0.0012	0.0013	0.0011	0.0011	0.0000	0.0000	0.0011	0.0012	0.0013	0.0013	0.0000	0.0000	0.0013	0.0013	0.0008	0.0009	0.0000	0.0000	0.0009	0.0009

According to the analysis of potential health risks of trace elements in the dry season (Table 7), the average *HI* values of trace elements were As > Cr > Pb > Mn > Cd > Cu > Zn. Only the values of $HQ_{ingestion}$ and *HI* of As in the urban area were greater than 1, while the values of $HQ_{ingestion}$ and *HI* in other trace elements were all less than 1, but close to 1, which should be paid great attention to by coastal residents.

The health risk of trace elements in the reservoir tail in the wet season was higher than that in the dry season (Figure 5), and *HI* was greater than 1, as shown in Figure 5. The health risk of trace elements in the reservoir area and under the dam in the wet season was much less than that in the dry season, but the *HI* value of the urban area in the wet season was almost the same as that in the dry season, and the *HI* was more than 1. The effects of trace elements on health risks of children and young people in the wet season were not significant, especially in the reservoir area and under the dam, while in the dry season, the effects of trace elements on health risks of children were greater than for young people. From upstream to downstream, the *HI* value in the wet season decreased first and then increased, and the *HI* value at the tail of reservoir was the largest. In the dry season, the *HI* value showed an increasing trend, and the highest in the urban areas.

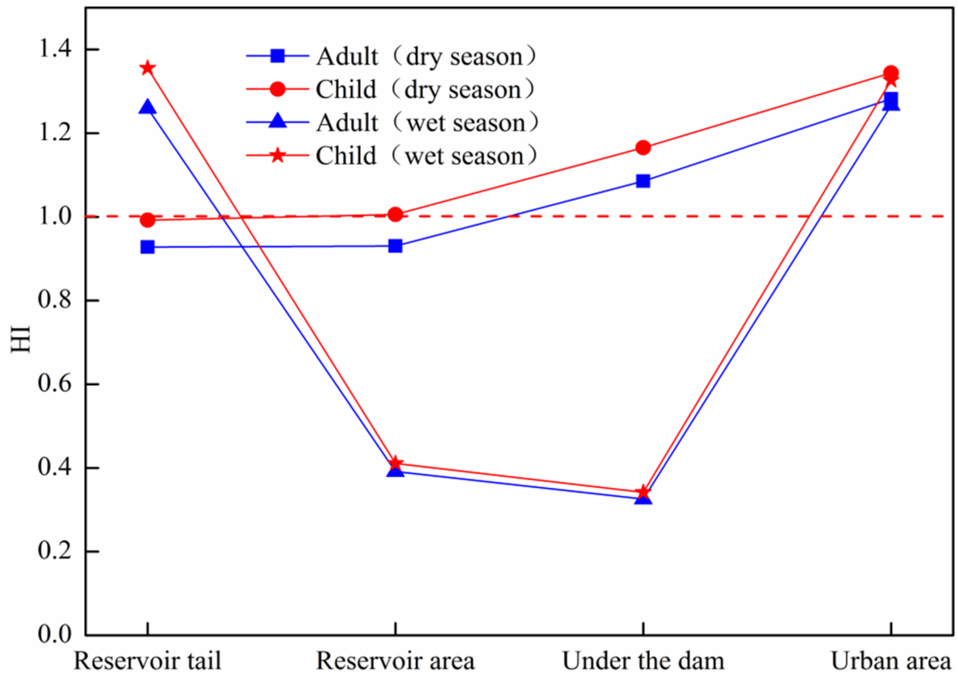

Figure 5. Health risks of trace elements in different regions in upper Lancang River.

The EPA and other documents emphasize uncertainty in the risk assessment of metals. Different ages and receptors, exposure conditions, pollutant concentrations, and daily water intake lead to different water–skin contact coefficients [33]. The exposure parameters used in the study were from the US EPA and the World Health Organization (WHO) and were not necessarily applicable to China. The risks of (class A) metal elements in the main stream of Lancang River need to be further studied.

4. Conclusions

The content of trace elements in the upper Lancang River meet the quality standard of Surface Water Environment (GB3838-2002) Class I, but the content of Fe in local sampling points during the wet season exceeds the limit of water-quality standards. Seasonal variation in trace elements in the upper Lancang River was obvious. The contents of Fe and Pb in the water in the wet season were higher than those in the dry season, while the contents of As, Mn, Cr, Cu, and Zn in the wet season were lower than those in the dry season. The As content in the upper Lancang River was greatly affected by the branch

Angqu confluence. The reservoir has a certain interception effect on the distribution of the trace elements in the water, the trace elements in the front of the dam were lower than those in the tail and under the dam, and the trace elements in the water in the reservoir increased with the depth. The mean value of HI of trace elements followed this order: As > Cr > Pb > Mn > Cd > Cu > Zn. The health risk of Mn, Pb, Cr, Cu, and Zn in the study area was relatively low, but the health risk of As in some reaches was a certain health risk, which needs to be taken seriously. The research results provide basic data support for the comprehensive utilization of local water resources and water ecological environmental protection. In addition, several trace elements were investigated in this study, but further study on various other potential pollutants in the upper Lancang River is need to be enable more accurate assessment.

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