

Article

Pollution Characteristics and Health Exposure Risks of Heavy Metals in River Water Affected by Human Activities

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Abstract: Under the influence of human activities, surface water quality has been significantly affected, which threatens human health and sustainability. In order to clarify the potential risks of heavy metal pollution to human health in river water, two tributaries of the Tumen River with significant differences in human activity interference were selected for investigation. Comparative analysis of the contents of chromium (Cr), cuprum (Cu), arsenic (As), cadmium (Cd), mercury (Hg), and plumbum (Pb) in the surface water of the two tributaries showed that the concentrations of As and Hg in some sampling sites exceeded the pollution standard values, and the Buerhatong River had a higher pollution level. Further analysis of the health risks revealed that the hazard quotient values of Cr, Cu, As, Cd, Hg, and Pb were <1, but the cumulative risk value of the Buerhatong River was higher than 1 for children, indicating adverse effects on human health. The As levels under the fish ingestion scenario had unacceptable carcinogenic risks, while the Cr in the Buerhatong River for adults and Cr and Pb in the Buerhatong River and Hunchun River for children had acceptable carcinogenic risks. Moreover, the As in the incidental water ingestion scenario also had acceptable carcinogenic risks. Therefore, the increase in human activity intensity can promote the increase in the health exposure risk of heavy metals in river water, and fish ingestion was the main exposure pathway, while children had higher exposure risks than adults.

Keywords: surface water; heavy metal; distribution; health risk; human activity



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1. Introduction

With the intensification of the impact of human activities, such as the discharge of industrial wastes, the application of pesticides and fertilizers, and the discharge of traffic exhaust [1,2], a large number of heavy metal pollutants enter the environment and cause environmental quality degradation and human health hazards, so heavy metal pollution has become a hot environmental issue at home and abroad [3–5]. Heavy metal pollutants can enter rivers through atmospheric sedimentation, surface runoff, solid waste dumping, and other ways, and continuously accumulate and affect the function of the aquatic ecosystem [6,7]. However, river water is not only a sink of heavy metals. In the process of interaction between human beings and rivers, such as edible aquatic products, domestic water sources, swimming, etc., heavy metals in rivers as pollution sources may enter the human body through the food chain, skin contact, or accidental drinking [8], causing potential harm to human health. For example, after heavy metal pollutants enter the human body and accumulate to a certain concentration, the heavy metal of As could cause central and peripheral nervous system damage [9], and Cd could cause hepatic, skeletal, renal, and reproductive effects [10], while Pb is harmful to the nervous system, hematopoietic system, and kidneys, causing anemia and kidney diseases [11]. Therefore, heavy metals are particularly dangerous pollutants in aquatic environments due to their toxicity, persistence, and high bioaccumulation, and clarifying river water quality and assessing its health threats are critical points for effective water management [12].

Scholars have carried out a series of studies around the heavy metal pollution characteristics of rivers, and many studies have shown that the intensity of human activities is closely related to the heavy metal pollution degree of rivers [13–15]. It has been found that heavy metal pollutants are widely distributed in Chinese rivers, such as the Beiyun River, Han River, Liuyang River, Wen Rui Tang River, Yangtze River, Yongding River, etc. [16–23]. The Pearl River Delta and Houjing River basin, which are more developed in industry, especially have a relatively prominent heavy metal content in river water bodies [13,21], and from a global perspective, the problem of heavy metal pollution in rivers such as the Kali River, Buriganga River, and Soan River is more prominent [24–26]. Heavy metals entering river water bodies can migrate with the flow of water under the adsorption of suspended solids, and accumulate in algae and sediment, which can be adsorbed by fish and shellfish. Heavy metals can enter the human body during direct contact with water, and drinking or consuming aquatic organisms, posing a potential threat to human health. Therefore, as the environmental conditions of heavy metal pollution have gradually intensified, the quantitative estimation of the potential risk of heavy metals in environmental media to human health has received extensive attention, and the health risk assessment methods of heavy metals has been widely studied [22,27,28]. The hazard quotient (HQ), total hazard index (HI), lifetime cancer risk index (CR), and the cumulative cancer risk (CCR) are widely used to assess non-carcinogenic risks and carcinogenic risks [29,30]. For example, the health risks of heavy metals in the Beiyun River, Yangtze River, Houjing River, Soan River, Ajay River, and other rivers have been systematically assessed by using relevant models and evaluation methods at home and abroad [13,16,22,26,31]. The heavy metal pollution status of different rivers is obviously different, which is mainly due to the interference from and intensity of human activities [5].

As an important waterway in northeast China, the Tumen River has many functions. It is not only a major traffic route on the border between China and Russia, but also an important channel for economic and cultural exchanges between northeast China and Russia's Far East, as well as an important shipping channel and ecological corridor. To protect and manage the Tumen River well is of great significance to the sustainable development of northeast China [32]. Although the Buerhatong River and Hunchun River are both important tributaries of the Tumen River, they are different in basin scope, hydrological characteristics, geographical location, and function, and the Buerhatong River basin has a higher proportion of agricultural land and urban land. The studied rivers are the secondary protection area of the surface water source of the centralized domestic drinking water, the aquatic products supply area, and the swimming areas. Understanding the distribution and health risks of heavy metal pollution is not only the basis for reducing the content of heavy metal pollutants in water bodies and improving the aquatic ecosystem, but also the basis for ensuring the health of residents in the basin. Therefore, it is of great significance to study the health risks of exposure to heavy metal pollution in the two tributaries, which can help the government and the public better understand the situation of heavy metal pollution in the local environment, formulate more effective pollution control measures, and protect human health. In the current study, the pollution characteristics and health exposure risks of heavy metals in the surface water of the Buerhatong River and Hunchun River were studied, and the non-carcinogenic risks and carcinogenic risks of heavy metals for children and adults were assessed under three exposure scenarios.

2. Materials and Methods

2.1. Study Area

The sites of the two studied rivers are shown in Figure 1. The Buerhatong River (BR) is a medium-sized river that flows through Jilin Province and Heilongjiang Province in China. It is approximately 242 km in length and is one of the important transportation routes between China's northeast and Russia's Far East. The river is famous for its rich natural resources, including coal, iron, and timber, as well as its strategic location between China and Russia. The Hunchun River (HR) is a relatively short river that flows through

Jilin Province and Heilongjiang Province. It is approximately 200 km in length and is a crucial waterway for local agriculture and urban development. The river is famous for its clean water and fertile soil, which are essential for the growth of local crops and the development of local industries. In terms of pollution, both BR and HR are affected by heavy metal pollution, and the heavy metal pollution of these rivers is mainly caused by human activities, such as mining, smelting, and agricultural fertilizer production. The resulting pollution has a negative impact on the local environment and human health.

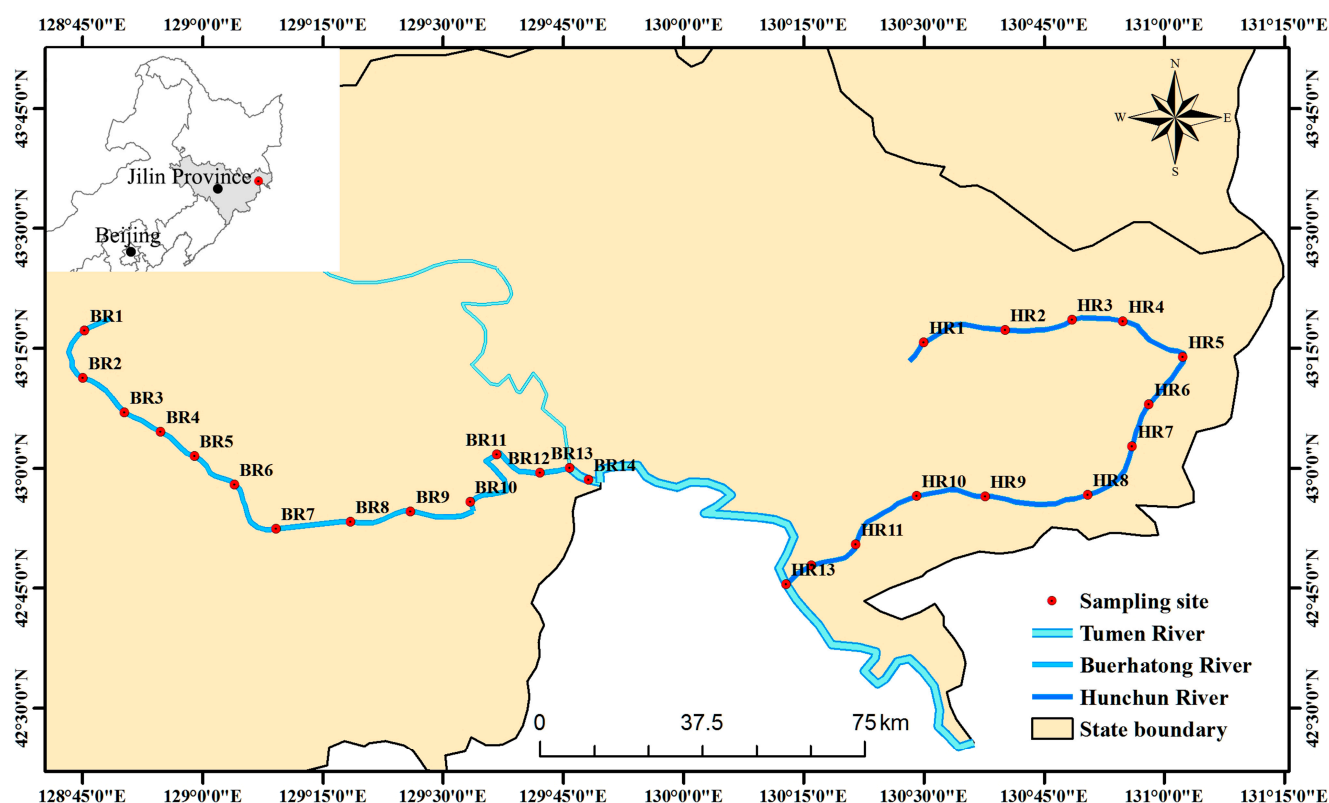


Figure 1. Sampling sites of Buerhatong River and Hunchun River.

2.2. Sample Collection and Chemical Analysis

In order to systematically understand the overall distribution of heavy metal pollution in river water, the equidistant method was used to set up sampling points. A total of 27 surface water samples (14 for BR and 13 for HR) were collected along BR and HR with pre-cleaned 1 L dark glass bottles, and the sampling distance was 10–15 km (Figure 1). When flowing through heavily polluted rivers in cities or industrial areas, the position of the sampling points and the distance between the drainage outlets were adjusted as needed. In this study, the river water depth was less than 5 m, so only surface water samples (0.5 m below the water surface) were collected (SL187-96). Water samples were collected within 1 day, and then filtered through a 0.45 μm filter membrane immediately, and the storage conditions were pH less than 2 (adjusted with hydrochloric acid) and temperature 4 $^{\circ}\text{C}$. The contents of Cr, Cu, As, Cd, Hg, and Pb in the water samples were determined in the current study. The determination of Cr, Cu, Cd, and Pb in samples was carried out using nitric acid and perchloric acid solutions for digestion, and the digestion solution was mixed to a constant volume and then determined by atomic absorption spectroscopy (refer to HJ 757-2015 and GB 7475-1987 for specific experimental procedures). The determination of As in samples was carried out using nitric acid, perchloric acid, and hydrochloric acid solutions for digestion, while Hg was carried out using hydrochloric acid and nitric acid solutions, and the digestion solution was mixed to a constant volume and then determined by atomic fluorescence spectrometry (refer to HJ 694-2014 for specific experimental procedures). In

this study, 5 samples were randomly selected for spiked recovery rate determination, with 4 subsamples taken from each of the 5 samples. Two subsamples were subjected to parallel background determination and the other two subsamples were subjected to parallel spiked recovery rate determination. The other two subsamples were added with a quantitative standard substance and analyzed along with other samples according to the processing steps. The samples with low heavy metal contents were concentrated and determined. The methods of blank samples, use of certified reference material, and labeling recovery were used to control the quality of heavy metal determination. The certified reference material was surface water quality control sample (LGC-PT-NJ-EN024-X). The relative standard deviations of the duplicate samples were <10%, and the recovery rate ranged from 87% to 110% for 6 metals. The limits of quantification of the 6 heavy metals were 0.03 mg/L for Cr, 0.05 mg/L for Cu, 0.0003 mg/L for As, 0.05 mg/L for Cd, 0.00004 mg/L for Hg, and 0.2 mg/L for Pb.

2.3. Statistical Analysis

The statistical analysis of heavy metals in water samples was conducted with the software of SPSS version 21 and Origin Pro 8.0.

According to actual condition, the current study focused on three exposure scenarios of freshwater fish ingestion, dermal contact, and incidental water ingestion during swimming. First, the average daily exposure dose (*ADD*) of heavy metals through fish ingestion, dermal contact, and incidental water were calculated, and then compared with the risk reference dose to analyze their non-carcinogenic risk. Moreover, *ADD* and cancer slope factors were multiplied to obtain the carcinogenic risk values. The non-carcinogenic and carcinogenic health risks for adults and children were evaluated in different exposure scenarios, considering the significant differences in body weight, intake, skin area, exposure frequency, and exposure duration between adults and children. The concentrations of heavy metals in the fish tissue were estimated by Formula (1).

$$C_{fish} = C_{water} \times BCF \quad (1)$$

where C_{fish} is the content of heavy metals in fish tissue (mg kg^{-1}), C_{water} is the content of heavy metals in the water (mg L^{-1}), *BCF* is represented as the ratio of heavy metals in the surface water to fish tissue, which is calculated based on the average content of heavy metals in tissues of different fish species, such as bighead carp, crucian carp, grass carp, common carp, catfish, and so on [33,34], and they are mainly distributed and commonly consumed in the study area.

The exposure doses for each metal and exposure pathway are calculated by the Formulas (2)–(4):

$$ADD_{fish} = C_{fish} \times A \times \frac{EF_{fish} \times ED_{fish}}{BW \times AT} \quad (2)$$

$$ADD_{der} = C_{water} \times \frac{SA \times k \times ET_{der} \times EF_{der} \times ED_{der}}{BW \times AT} \times 10^{-3} \quad (3)$$

$$ADD_{ing} = C_{water} \times \frac{IngR \times ET_{ing} \times EF_{ing} \times ED_{ing}}{BW \times AT} \quad (4)$$

where ADD_{fish} is the average daily exposure dose of heavy metals through fish ingestion ($\text{mg kg}^{-1} \text{ day}^{-1}$), ADD_{der} is the average daily exposure dose of metals through dermal contact while swimming ($\text{mg kg}^{-1} \text{ day}^{-1}$), ADD_{ing} is the average daily exposure dose of metals through ingestion ($\text{mg kg}^{-1} \text{ day}^{-1}$), and the other exposure factors for those models are shown in Table 1.

Table 1. Exposure parameters and abbreviations used in the current study.

Parameters		Adult		Children		Reference	
A	Fish ingestion rate				0.0457 kg/d		[35]
EF_{fish}	Exposure frequency				365 d		[34]
ED_{fish}	Exposure duration	70 y		6 y			[34]
ET_{der}/ET_{ing}	Daily exposure time for swimming				0.5 h/d		[13]
EF_{der}/EF_{ing}	Exposure frequency for swimming				15 d/y		[13]
ED_{der}/ED_{ing}	Exposure duration for swimming	30 y		4 y			[36,37]
$IngR$	Incidental water ingestion rate				0.044 L/h		[13]
SA	Exposed skin area	16,106 cm ²		8640 cm ²			[38]
BW	Body weight	60 kg		30 kg			[34]
AT					365 d y ⁻¹ × ED		
		Cr	Cu	As	Cd	Hg	Pb
BCF	Bioconcentration factor (L kg ⁻¹)	24.22	18.60	3.00	1.78	7.62	5.77
k	Permeability constant of heavy metals (cm h ⁻¹)	0.002	0.001	0.001	0.001	0.001	0.0001
RfD_{fish}	Reference doses of heavy metals (mg kg ⁻¹ d ⁻¹)	0.003	0.04	0.0003	0.001	0.0003	-
RfD_{der}	Reference doses of heavy metals (mg kg ⁻¹ d ⁻¹)	7.5×10^{-5}	0.04	0.0003	2.5×10^{-5}	2.1×10^{-5}	-
RfD_{ing}	Reference doses of heavy metals (mg kg ⁻¹ d ⁻¹)	0.003	0.04	0.0003	0.0005	0.0003	-
SF_{fish}	Cancer slope factors ((mg kg ⁻¹ d ⁻¹) ⁻¹)	0.012	-	1.5	-	-	0.0085
SF_{der}	Cancer slope factor ((mg kg ⁻¹ d ⁻¹) ⁻¹)	0.48	-	1.5	-	-	-
SF_{ing}	Cancer slope factor ((mg kg ⁻¹ d ⁻¹) ⁻¹)	0.012	-	1.5	-	-	0.0085
ADD_{fish}	Average daily exposure dose of heavy metals through fish ingestion						
ADD_{der}	Average daily exposure dose of metals through dermal contact						
ADD_{ing}	Average daily exposure dose of metals through ingestion						
HQ_{fish}/CR_{fish}	Non-carcinogenic/carcinogenic risk of heavy metals through fish ingestion						
HQ_{der}/CR_{der}	Non-carcinogenic/carcinogenic risk of heavy metals through dermal contact						
HQ_{ing}/CCR_{ing}	Non-carcinogenic/carcinogenic risk of heavy metals through incidental water ingestion						
HI_{fish}/CCR_{fish}	The cumulative non-carcinogenic/carcinogenic risk of heavy metals through fish ingestion						
HI_{der}/CCR_{der}	The cumulative non-carcinogenic/carcinogenic risk of heavy metals through dermal contact						
HI_{ing}/CCR_{ing}	The cumulative non-carcinogenic/carcinogenic risk of heavy metals through incidental water ingestion						

Note: “-”: Not available. Adult: ≥18 years old; Child: <18 years old.

Under the three exposure pathways, the non-carcinogenic and carcinogenic risks of heavy metals are represented by hazard quotient (HQ) and lifetime cancer incidence risk index (CR) using Formulas (5) and (6), respectively [13].

$$HQ_i = \frac{ADD_i}{RfD_i} \quad (5)$$

$$CR_i = ADD_i \times SF_i \quad (6)$$

where HQ_i is the non-carcinogenic risk of heavy metal i ; CR_i is the carcinogenic health risk of heavy metal i ; ADD_i is the daily exposure amount of heavy metal i through the three exposure pathways (mg kg⁻¹ day⁻¹); the other exposure factors for these models are shown in Table 1.

The total hazard index (HI) and the cumulative cancer risk (CCR) are calculated by Formulas (7) and (8):

$$HI = \sum_{i=1}^6 HQ_i \quad (7)$$

$$CCR = \sum_{i=1}^6 CR_i \quad (8)$$

where the values of $HQ_i/HI \leq 1$ indicate no adverse health effects and >1 indicate possible adverse health effects [41]. For the carcinogenic health risk (CR_i) and cumulative carcinogenic risk (CCR), the acceptable lifetime cancer risk level ranges from 10^{-4} to 10^{-6} (USEPA, 2000), the carcinogenic risk is negligible if $CR_i/CCR \leq 10^{-6}$, and the carcinogenic risk is unacceptable if $CR_i/CCR > 10^{-4}$.

3. Results

3.1. Contents and Distribution of Heavy Metals in the Surface Water of BR and HR

The current study mainly focused on the contents of the heavy metals Cr, Cu, As, Cd, Hg, and Pb in the surface water of the BR and HR, and the heavy metal concentrations in the BR and HR surface water are presented in Table 2. The order of the average concentration of heavy metals is As > Cu > Pb > Cr > Cd > Hg for the BR, and the highest concentrations of Cr, Cu, As, Cd, Hg, and Pb in the BR occurred at the sampling sites of BR4, BR3, BR9, BR14, BR9, and BR13, respectively (Figure 2). The mean concentration of each heavy metal in the HR followed the order: As (0.03420 mg/L) > Pb (0.01153 mg/L) > Cu (0.00752 mg/L) > Cd (0.00140 mg/L) > Cr (0.00191 mg/L) > Hg (0.00011 mg/L), and Cr and Cu at HR1, Hg at HR12, and As, Cd, and Pb at HR 13 showed the highest concentration in the HR.

Table 2. Concentrations of heavy metals in BR and HR.

Elements	BR		HR	
	Mean (mg L ⁻¹)	Range (mg L ⁻¹)	Mean (mg L ⁻¹)	Range (mg L ⁻¹)
Cr	0.00456	0.00035–0.01470	0.00191	0.00079–0.00520
Cu	0.01344	0.00382–0.03204	0.00752	0.00311–0.02052
As	0.03527	0.02678–0.08050	0.03420	0.02675–0.04618
Cd	0.00151	0.00112–0.00197	0.00140	0.00097–0.00241
Hg	0.00108	0.00033–0.00470	0.00011	0.00007–0.00016
Pb	0.00820	0.00206–0.01900	0.01153	0.00719–0.02048

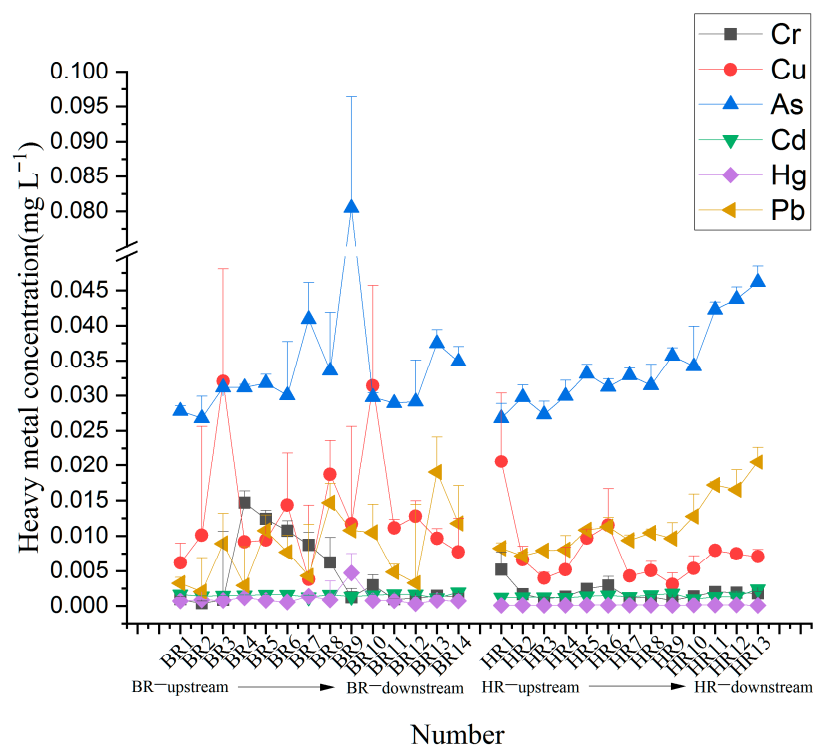


Figure 2. Heavy metal concentrations in the surface water of BR and HR.

Based on the national environmental quality standard of GB3838-2002, the BR and HR are classified as the third type of water functional area, which is the secondary protection area of the surface water source of the centralized domestic drinking water, and the fishery waters, such as fish and shrimp wintering grounds, migration channels, aquaculture areas, etc., and the swimming areas. The surface water environmental quality standard basic item standard limit values are Cr ≤ 0.05 mg/L, Cu ≤ 1.0 mg/L, As ≤ 0.05 mg/L,

$Cd \leq 0.005$ mg/L, $Hg \leq 0.0001$ mg/L, and $Pb \leq 0.05$ mg/L, respectively. In this study, the contents of As and Hg in the surface water of some sampling sites exceeded the standard values; the point exceeding rate was 7.1% for As and 100% for Hg in the BR, respectively, and the point exceeding rate of Hg in the HR was 53.8%.

3.2. Human Health Risk Assessment of Heavy Metals in BR and HR

In the current study, the average daily exposure doses of heavy metals in the BR and HR through freshwater fish ingestion (ADD_{fish}) were significantly higher than dermal contact (ADD_{der}) and incidental water ingestion (ADD_{ing}) during swimming, and the ADD_{ing} was higher than the ADD_{der} . The exposure dose of Cu for the ADD_{fish} and As for the ADD_{der} and ADD_{ing} were the highest, respectively. Based on the ADD_{fish} , ADD_{der} , and ADD_{ing} , the HQ_{fish} , HQ_{der} , and HQ_{ing} for the non-carcinogenic risk assessment were calculated in the current study. The HQ_{fish} of Cr, Cu, As, Cd, Hg, and Pb were significantly higher than the HQ_{der} and HQ_{ing} (Figure 3), and the HQ_{fish} of As in the BR and HR were the highest, which showed a higher non-carcinogenic risk, followed by Cr. All the HQ_{fish} of Cr, Cu, As, Cd, Hg, and Pb were lower than 1, showing no adverse health effects, but the cumulative risk value of the BR for children was higher than 1, indicating adverse effects on human health. Except for Cd, the heavy metals of Cr, Cu, As, Hg, and Pb in the BR had a higher non-carcinogenic risk than the HR through the exposure pathway of fish ingestion. For the exposure scenarios of dermal contact and incidental water ingestion, the non-carcinogenic risks of Cu and As in surface water through dermal contact were higher than incidental water ingestion. For the dermal contact scenario, Hg and Cr had higher non-carcinogenic risks for adults and children, respectively, and there were higher risks of As for adults and children through incidental water ingestion. The values of HQ_{der} , HQ_{ing} , HI_{der} , and HI_{ing} of Cr, Cu, As, Cd, Hg, and Pb were lower than 1 (Figure 3), showing no adverse health effects. Non-carcinogenic risks of heavy metals and three exposure pathways for children were higher than adults.

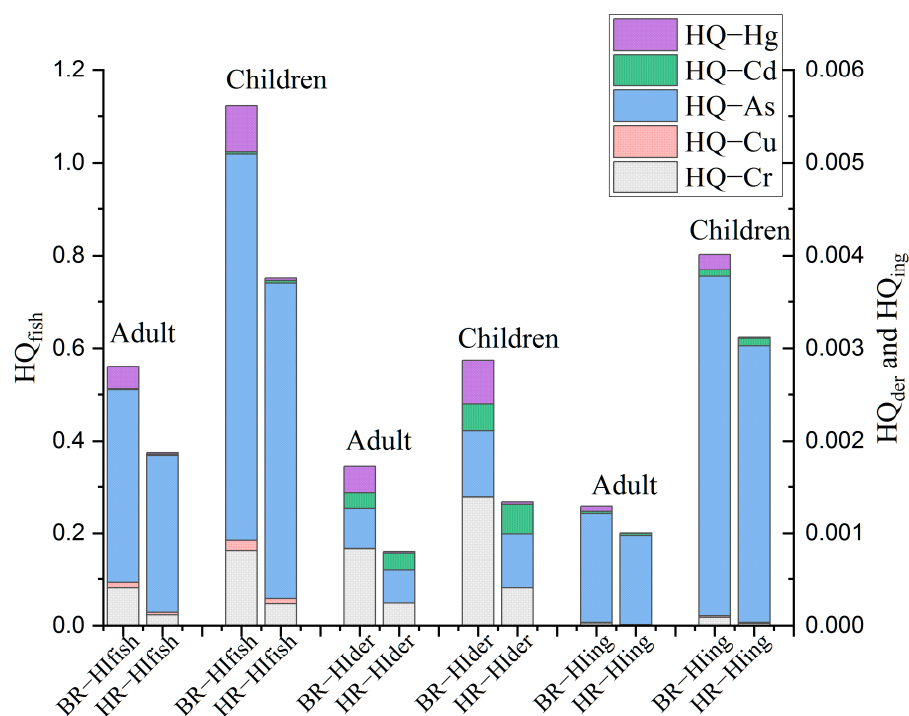


Figure 3. Hazard quotient values of different exposure scenarios of BR and HR.

According to the obtained parameter values, the carcinogenic risks of Cr, As, and Pb under the scenarios of freshwater fish ingestion and incidental water ingestion were estimated, and the carcinogenic risks of Cr and As through the exposure pathway of dermal

contact were estimated. The CR_{fish} of fish ingestion was significantly higher than the CR_{der} and CR_{ing} , and As in the two rivers had the highest CR_{fish} , CR_{der} , and CR_{ing} , showing higher carcinogenic risks for human health (Figure 4). Moreover, the carcinogenic risks of Cr and As in the BR were higher than the HR under different scenarios. The CR_{fish} for As in the BR and HR were $>10^{-4}$, indicating unacceptable carcinogenic risks, and the CR_{fish} of Cr in the BR for adults and Cr and Pb in the BR and HR for children were in the range of 10^{-6} to 10^{-4} , indicating an acceptable carcinogenic risk, and the CR_{ing} of As in the BR and HR for children also had acceptable carcinogenic risks. The cumulative carcinogenic risks for Cr, As, and Pb under the scenario of freshwater fish were unacceptable for adults and children, and those were acceptable for children under the exposure pathway of incidental water ingestion in the BR and HR.

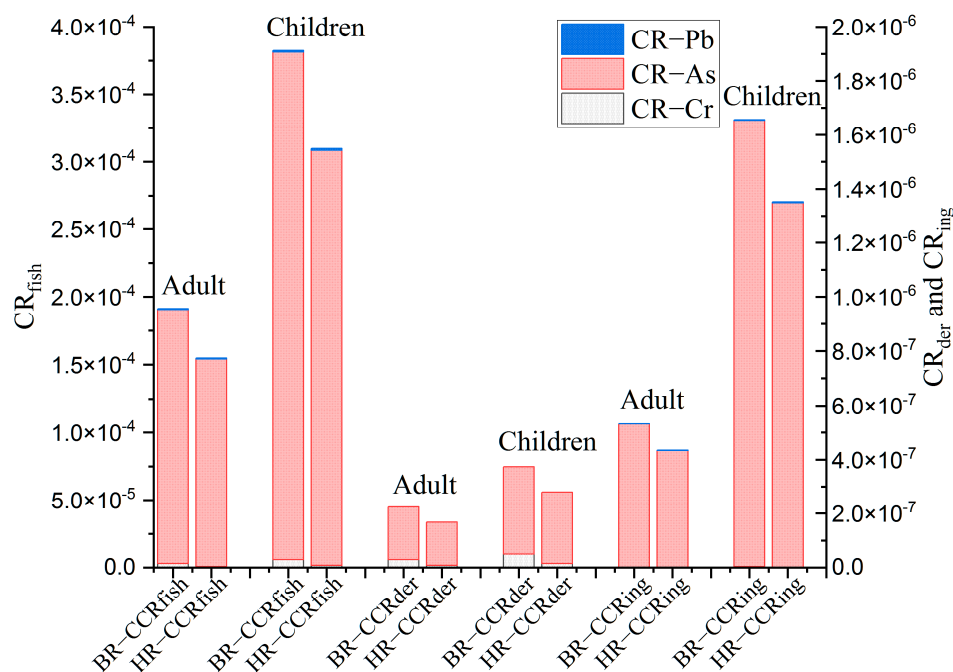


Figure 4. Lifetime cancer incidence risk values of different exposure scenarios of BR and HR.

4. Discussion

The heavy metals in the aquatic system are mainly from natural and anthropogenic activities, and the main pollution pathways are surface runoff and atmospheric deposition, such as weathering of minerals, soil leaching, urban runoff, agricultural runoff, and industrial emissions [31,42–44]. In the current study, the contents of As and Hg in the surface water of some sampling sites exceeded the standard values, especially for the sampling position of B9, which had the highest contents of As and Hg. The site of B9 is located in Yanji City near the Industrial Park, which may be the main reason for the higher As and Hg concentrations in the rivers. According to the results of different studies, there are significant differences in the degree of heavy metal pollution in rivers in different study areas (Table 3). Compared with relevant studies at home and abroad, the concentrations of Cr, Cu, Cd, Hg, and Pb in the two studied rivers are lower, while the contents of As are higher, but they are still lower than the river in the Pearl River Delta of China and the Hazar River of Iran [21,45], and it also shows that rivers are polluted by heavy metals in different degrees under different interference of human activities.

A lot of studies have shown that heavy metal pollution in rivers is closely related to pollutant discharge from industrial and agricultural activities [33,46,47], so the intensity of human activities is the main factor affecting river water quality [13,15]. In the current study, the average coefficient of variation (CV) of the BR (0.64) was significantly higher than the HR (0.37), indicating that the BR was more severely disturbed by human activities. As two

tributaries in the Tumen River basin, there are obvious differences in land use status. The proportion of agricultural land area in the BR basin is 23.33%, which is significantly higher than that in the HR (13.05%), while the proportion of woodland and grassland distribution area was 11.74% lower than the HR. In addition, the area proportions of cities and towns (2.34% for the BR, 0.85% for the HR) and wetland (0.21% for BR, 0.49% for the HR) were also different [48]. In general, the contents of heavy metals in the river water from the upstream of the BR and HR were relatively small, except for Cu in the HR, which had a high concentration at the source location (Figure 2). The HR originates from the north side of the Panling Mountains in Jilin Province, so the source of Cu should mainly come from the weathering of minerals and soil leaching. However, with the increase in villages and towns in the downstream, As and Pb in the HR river water showed a significant increasing trend. Moreover, the average content of the heavy metals of Cr, Cu, As, Cd, and Hg in the BR was also higher than that in the HR, except for Pb, and the concentrations of Cr, Cu, and Hg in the BR water body were significantly higher than that in the HR ($p < 0.05$), which further indicated that the BR, with greater interference from human activities, was more polluted by heavy metals. The previous studies had shown that the anthropogenic activities were associated with higher concentrations of heavy metals in the river [49–51]. In addition to agricultural activities and domestic sewage discharge, mining is one of the important sources of heavy metal pollutants [52,53], and the dumps located around abandoned mining sites are also potential sources of contamination [54–56]. In the BR basin, a variety of mineral resources such as copper, nickel, and polymetal are distributed, which may be one of the main reasons for the prominent heavy metal pollution in the river water of the basin under the runoff action.

Table 3. Heavy metal concentrations in the surface water of different rivers.

River Metal ($\mu\text{g L}^{-1}$)	Cr	Cu	As	Cd	Hg	Pb	Reference
Beiyun River	0.77	1.34	2.98	0.01	-	0.07	[16]
Han River	8.00	14.00	-	2.00	-	9.00	[23]
Liuyang River	0.73	2.90	2.41	0.07	-	1.20	[19]
Wen-Rui Tang River	5.32	20.90	-	0.98	0.03	4.23	[18]
Pearl River Delta	12.20	28.40	39.00	0.70	0.90	31.80	[21]
Yangtze River	-	2.86	-	0.96	-	4.69	[17]
Yangtze River	1.30	2.80	0.97	0.40	0.04	2.00	[22]
Yongding River	9.90	1.50	-	-	-	0.20	[20]
Houjing River	10.50	105.40	3.20	1.50	2.80	51.30	[13]
Gomti River	-	20.00	-	100.00	-	20.00	[57]
Beas River	31.00	4.00	-	5.00	-	81.00	[58]
Kali River	60.00	-	-	60.00	-	130.00	[24]
Brahmani River	24.70	7.60	-	5.60	-	10.80	[59]
Buriganga River	114.00	239.00	-	59.00	-	119.00	[25]
Korotoa River	73.00	61.00	-	8.00	-	27.00	[60]
Pardo River	1.88	3.28	2.14	0.05	-	1.80	[61]
Guadaira River	20.00	10.00	-	1.00	-	8.00	[62]
Tigris River	5.00	32.00	-	0.10	-	0.30	[63]
Soan River	10.00	20.00	-	-	-	650.00	[26]
Mississippi River	0.20	2.10	-	0.57	-	0.31	[64]
To Lich River	2.90	4.50	-	-	-	8.10	[65]
Ismailia Canal	-	7.00	-	0.45	-	18.00	[66]
Ajay River	-	80.00	-	30.00	-	50.00	[31]
Bogacayi	3.20	0.92	0.43	0.23	-	0.48	[67]
Coruh River	1.68	670.90	-	1.87	-	67.38	[68]
Upper Ganga River	33.00	-	-	-	-	5.00	[69]
Hazar River	-	13.50	55.35	2.65	-	4.40	[45]
Sirsa	35.50	27.00	5.50	2.60	-	17.90	[70]
Euphrates	0.07	2.48	-	2.14	-	0.10	[71]
Mashavera River	0.80	210.00	0.10	4.60	-	2.80	[72]
Mean	18.63	56.98	11.21	11.17	0.94	44.23	
Mean value of BR and HR	3.23	10.48	34.73	1.46	0.59	9.86	In this study

In the current study, the 95th percentile was used to estimate the ADD values of heavy metals and assess the human health risks to protect the upper-bound consumers [13,73].

Heavy metals in the BR and HR rivers posed exposure risks to human health in three pathways of freshwater fish ingestion, dermal contact, and incidental water ingestion during swimming, and there were significant differences in exposure doses and risks between children and adults, and the average daily exposure doses of heavy metals for children were higher than adults through the three pathways. The highest exposure doses of heavy metals for the ADD_{fish} , ADD_{der} , and ADD_{ing} were Cu, As, and As, respectively. Although Cu is an essential trace element for the human body, the excessive intake of Cu can still cause harm to human health [74]. Among the three exposure pathways, freshwater fish ingestion was the main exposure pathway of heavy metals in the rivers to human health risks and the result was consistent with the study of the Houjing River [13]. The health risk of heavy metals in the BR was higher than that in the HR, mainly due to the higher content of heavy metals in the water affected by human activities, especially for Cr, Cu, and Hg, indicating that the health exposure risk of the river to the resident population would increase with the increase in human activities in the river basin [1,13,51]. The cumulative risk value of the BR for children was higher than 1, indicating adverse effects on human health. Consistent with the non-carcinogenic risks, the carcinogenic risks for children under different exposure scenarios were higher than adults [75,76], so children are more vulnerable to health hazards from exposure to heavy metal pollution in rivers [75–77]. Because children's bodies are still developing and their immune systems are weaker, it is necessary for governments, businesses, schools, and all sectors of society to take measures to protect children from environmental pollution and ensure that they can grow up in a clean and healthy environment [78].

5. Conclusions

The surface water of the Buerhatong River and Hunchun River has been found to be contaminated with heavy metals, exceeding the set pollution standard values. As and Hg are the primary pollutants that require attention and control due to the high levels of contamination, particularly in the Buerhatong River, which was more severely disturbed by human activities.

The comprehensive risk analysis indicates that heavy metal contamination in the BR poses a threat to children, with the carcinogenic risks of Cr and As being higher than the HR in various exposure scenarios. Fish ingestion is the most concerning exposure pathway, having significantly higher non-carcinogenic and carcinogenic risks than other pathways. Under this pathway, the As levels in the BR and HR are considered carcinogenic, while the Cr levels in the BR for adults and the Cr and Pb levels in both the BR and HR for children are deemed acceptable. Additionally, the As levels in the BR and HR for children under incidental water ingestion also present an acceptable carcinogenic risk. This study highlights the heightened vulnerability of children to non-carcinogenic and carcinogenic risks caused by heavy metal pollution in rivers. The risks were found to be particularly high in the Buerhatong River, emphasizing the need for measures to control the risks from this river. These measures should include strict monitoring and control of the heavy metal content in aquatic products and domestic water in the river basins. Additionally, it is crucial to manage the emission sources of Cr, As, Hg, and Pb.

Furthermore, conducting an in-depth exploration of the sources and pathways of heavy metal pollutants in rivers, as well as their temporal distribution patterns, is of profound significance in formulating targeted pollution prevention and control measures.

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