

Integrated Assessment of Heavy Metal Contamination in Water, Sediments, and Fish Along the Ravi River, Lahore: Pollution Indicators, Bioaccumulation, and Human Health Risks

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Abstract

This study assessed heavy metal (HM) contamination in the Ravi River, evaluated environmental quality using contamination and bioaccumulation indices, and estimated human health risks from consuming *Labeo rohita* and *Cirrhinus mrigala* fish. As part of an environmental monitoring program, samples were collected from five locations (Siphon, Shahdara, M2, Park View, Head Balloki) and analyzed for HMs. Pollution and bioaccumulation indicators, including the geo-accumulation index (I_{geo}), contamination factor (CF), enrichment factor (EF), bioconcentration factor (BCF), and bio-sediment-accumulation factors (BSAF), were calculated to evaluate metal transfer pathways within the aquatic ecosystem. Non-carcinogenic (hazard index, HI) and carcinogenic (lifetime cancer risk, LCR) health risks associated with fish consumption were also assessed. Contamination indices showed moderate to high Cd values in both water and sediments, highlighting anthropogenic influence. Meanwhile, Cr and Pb values were in low-to-moderate ranges across sampling locations. The concentration of HMs in fish muscles (mg kg^{-1} dry weight) varied across sites and fish species, with ranges of 0.14 to 0.77 for Cd, 0.15 to 0.88 for Cr, and 0.06 to 0.24 for Pb. The non-carcinogenic risk associated with fish consumption remained below the safety threshold ($\text{HI} < 1$). Carcinogenic risks for Cd and Cr were either negligible ($\text{LCR} < 10^{-6}$) or within an acceptable risk range (10^{-6} to 10^{-4}). Overall, despite HM contamination, the estimated human-health risk associated with fish consumption remained within acceptable limits. These findings provide valuable information for environmental monitoring, ecological risk assessment, and sustainable management of riverine ecosystems in developing regions.

Keywords: Bioaccumulation, Chemical risk, Ecotoxicology, Food safety, One Health, Pollution monitoring

Introduction

Rivers are considered the lifelines of many urban cities and a source of economic growth. With rapid urbanization and anthropogenic activities, rivers have become polluted with microplastics, heavy metals (HMs), and various other toxic elements. The HMs are of particular concern due to their persistence in the environment, bioaccumulation, and toxicity to aquatic and terrestrial life (Ahamad, Rehman, et al. 2024). The main sources of these contaminants are sewage, agricultural residues (pesticides, fertilizers), and industrial effluents. Other sources of air pollution also settle on land and water (Ramish et al. 2024). In the U.S., a national assessment found that 100% of fish fillet samples contained detectable mercury (Hg) and Polychlorinated biphenyls, with 23.5–26.0% of river lengths exceeding protective health screening levels for Hg (Stahl et al. 2023).

Pakistani rivers (water and sediments) are among the most polluted in the world in terms of HMs (Afzaal et al. 2022; Samad et al. 2025). River water and sediments of major rivers, including the Ravi, the Chenab, the Indus, the Kabul, and the Jhelum, have been reported to contain toxic levels of HMs. In our previous investigation, we observed high contamination of the Tawi River water with chromium (Cr, 0.04 mg L⁻¹), cadmium (Cd, 0.07 mg L⁻¹), and lead (Pb, 0.09 mg L⁻¹) at 10 sampling sites. Yaqoob et al. (2020) reported HM concentrations in the Ravi River water (mg L⁻¹) collected from Ravi Siphon (Cr: 0.14, Co: 0.02, Cd: 0.12, and Zn: 0.14) and Head Balloki (Cr: 1.5, Co: 0.26, Cd: 0.32, and Zn: 0.36). Likewise, sediments in the Ravi River are also heavily contaminated with these HMs (Pb: 40 to 136, Zn: 129 to 396, Ni: 24.1 to 190, Cr: 50.4 to 57 mg kg⁻¹) (Javed 2005; Shakir et al. 2013; Tabinda et al. 2013).

Pollutants in river water and sediments are absorbed by fish and other organisms, potentially causing bioaccumulation that disrupts ecosystems and, through biomagnification, poses significant health risks across the entire food chain (Shafi et al. 2023). Rauf et al. (2019) reported that Ravi River water pollution was associated with HM contamination of the 13 phytoplankton species; further, the zooplankton were quasi-absent in this environment (Rauf et al. 2019). The fish are directly exposed to these pollutants through contact with water and sediments, and ingestion of contaminated water and food (zooplankton, phytoplankton, aquatic vegetation...) (Sultana et al. 2016). The muscles of main fish species (e.g., *Catla catla*, *Labeo rohita* and *Cirrhinus mrigala*) of Ravi River have been reported to be contaminated with zinc (Zn, 18.2 to 75.4 mg kg⁻¹), Pb (0.01 to 7.6 mg kg⁻¹), Ni (0.4 to 2.6 mg kg⁻¹), Cr (0.26 to 2.3 mg kg⁻¹), Cd (0.06 to 1.2 mg kg⁻¹), aluminum (Al, 80 to 93 mg kg⁻¹), arsenic (As, 1.8 to 2.7 mg kg⁻¹), and barium (Ba, 0.1 to 0.2 mg kg⁻¹) (Aiman et al. 2026; Jabeen et al. 2012; Javed 2005; Nawaz et al. 2010; Rauf et al. 2009; Shakir et al. 2013, 2015; Tabinda et al. 2013; Yaqoob et al. 2020). The concentrations of HMs in fish in these studies varied by species, body part (kidney, muscle, liver, gills, skin), geographical location, season, and proximity to an industrial zone.

Humans are exposed to these pollutants from the river through various routes. During water-related professional and recreational activities, such as fishing and swimming, humans accidentally ingest water, and their skin is exposed to contaminated water and sediments. The main exposure comes through consumption of contaminated aquatic (fish, aquatic vegetation) and terrestrial (where river water is used for irrigation) food (Hussain et al. 2022). Moreover, this contamination can also reach groundwater. Human health is affected based on the type, dose, and route of exposure to HMs. Non-carcinogenic and carcinogenic risk assessment studies have reported using the hazard quotient (HQ), hazard index (HI), and lifetime cancer risk (LCR) approaches to assess the risk of HMs. For example, various studies have reported these approaches to assess the risks from water and

sediments from the Ravi River (Ahamad, Rehman, et al. 2024; Ahamad, Yao, et al. 2024; Iqbal et al. 2024), the Indus drainage (Khan et al. 2022), the Korang River (Manan et al. 2026), the Indus River and its tributaries (Muhammad and Usman 2022), and Indus deltaic creek sediments (Ullah et al. 2026). Most of these studies assessed the risk of HM exposure through inhalation, ingestion/drinking, and contact.

Eating HM-contaminated fish can have significant adverse health effects on humans, depending upon the exposure dose and host-related factors. Fish are considered an important food source with vital nutrients. In Pakistan, however, per capita aquatic animal food consumption is only 1.9 kg year⁻¹ (or 5.2 g day⁻¹), which is very low compared to the global average of about 21 kg capita⁻¹ annum⁻¹ (FAO 2026). Although aquaculture is growing in the country, fish from rivers remain one of the main sources of aquatic animal protein. Some studies have evaluated the health risks in the Pakistani population associated with consumption of fish from the Tawi River (Ramish et al. 2024), Barandu River (Samad et al. 2025), Indus River (Habib et al. 2026; Rind et al. 2025; Ujan et al. 2026), Khanozai Dam in Balochistan (Nazeer et al. 2024), Chenab River (Aiman et al. 2026; Waheed et al. 2014), and Jhelum River (Ejaz et al. 2024; Zahid et al. 2025). However, the risk associated with fish from the Ravi River has not been widely documented. Some studies have documented human health risk from HM contamination of fish muscle based on comparison with WHO maximum limits (Shakir et al. 2015; Yaqoob et al. 2020); however, the ingestion-related risk was not assessed using the aforementioned tools. Aiman et al. (2026) reported contamination of multiple fish species in Balloki and Sidhnai headworks of the Ravi River. They estimated that the carcinogenic and non-carcinogenic risk of various HMs was within the acceptable limit. However, higher As levels in various fish species were responsible for higher HQ and LCR (Aiman et al. 2026).

Although several studies have reported HM contamination in individual environmental compartments of the River Ravi with varying degrees, a comprehensive assessment integrating ecological bioaccumulation and human health risks associated with the consumption of the main fish species throughout the Ravi River remains lacking (Figure 1). Therefore, the present study was designed to evaluate the distribution of HMs in river water, sediments, and fish muscle tissues along the Ravi River in Pakistan and to comprehensively assess the associated ecological and human health risks, thereby providing a holistic understanding of the environmental status of the River Ravi and its potential implications for ecosystem and public health.

collected in sterile bottles, and sediment samples were collected in sterile zipper bags. They were properly labelled for identification and transported respecting the cold chain ($<4^{\circ}\text{C}$) to the laboratory.

Table 1: Physicochemical study parameters of water, sediments, and fish

Sample	Parameters
Water	pH, chlorides, hardness, electrical conductivity (EC), total suspended solids (TSS), dissolved oxygen (DO), total dissolved solids (TDS), cadmium (Cd), chromium (Cr), and lead (Pb)
Sediment	pH, EC, Cd, Cr, Pb
Fish	Cd, Cr, Pb

Local fisherfolk, licensed to harvest in the study locations, supplied the cold-chain-maintained fish samples from each location. The *Labeo rohita* and *Cirrhinus mrigala* fish species were chosen because they are among the most commonly consumed and favored by residents around the sampling areas (FAO 2026). All fish were approximately two years old. After recording fish body parameters (weight, length, and size), the samples were thoroughly washed with deionized water, preserved in an icebox, and transported to the laboratory. Epaxial muscles of fish were dissected to obtain 10 g of sample and were stored at -20°C for heavy metal analysis (Ramish et al. 2024).

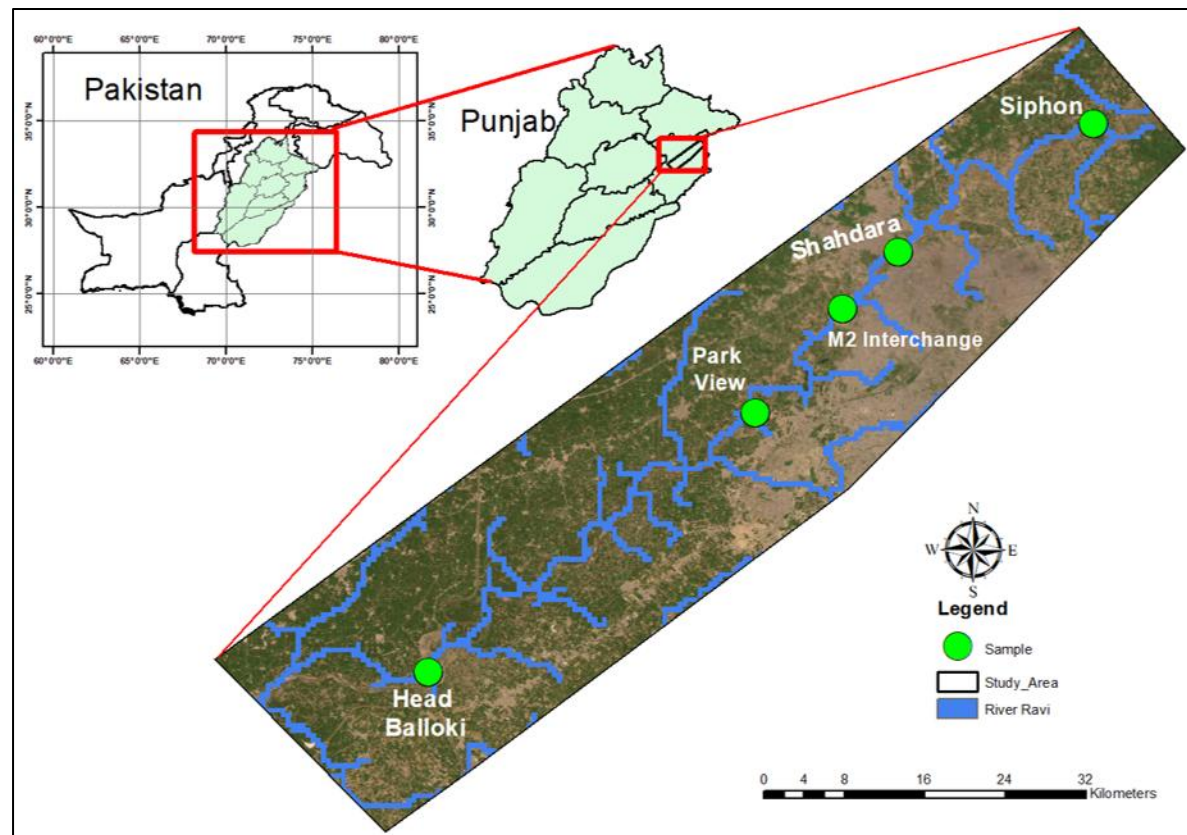


Figure 2. GIS location map of River Ravi, Pakistan. Lahore Siphon is located on the River Ravi, where it enters Pakistan. The Shahdara Bridge and M2 Bridge are on the western bank of the Ravi River in Lahore, Pakistan.

Park View sampling site is near the Park View Society, which is not directly on the River Ravi, but ends at the River Ravi. The Head Balloki is located in the district of Kasur.

Physicochemical parameters and HM analysis

An assessment of the contaminant status of the Ravi River ecosystem was conducted at the Environmental Analytical Laboratory of the University of Lahore, Pakistan. Physicochemical parameters and HM concentrations were analyzed in water samples, while HM contamination was examined in sediment and fish samples (Table 1). Atomic absorption spectroscopy was used to quantify HM concentrations in water, sediment, and fish samples following an appropriate sample digestion procedure (Ramish et al. 2024). Heavy metal concentrations in edible muscle tissues were determined using fish samples obtained from the Ravi River. The tissues were washed, oven-dried, and digested with a nitric acid-perchloric acid (2:1) mixture before being analyzed using atomic absorption spectrophotometry (AAS). Heavy metal concentrations were expressed as mg kg⁻¹ dry weight (DW), following conventional protocols (Ramish et al. 2024).

Assessment of contamination indicators for sediments and water

To evaluate the degree of HM (Cd, Cr, Pb) contamination in sediment and water samples collected along the Ravi River, three complementary and widely used pollution indices were calculated: the geo-accumulation index (I_{geo}), the contamination factor (CF), and the enrichment factor (EF). These indices quantify contamination by comparing the measured metal concentration in a sample against a geochemical background or a water-quality guideline value (Table 2).

Table 2. Background/reference and guideline values used for pollution-index calculation

Matrix	Metal	Background/guideline value	Source
Sediment	Cd	0.3 mg/kg	(Turekian and Wedepohl 1961)
	Cr	90 mg/kg	
	Pb	20 mg/kg	
	Fe (reference element)	47,200 mg/kg	
Water	Cd	0.003 mg/L	(World Health Organization 2022)
	Cr	0.05 mg/L	
	Pb	0.01 mg/L	
	Fe (reference element)	0.3 mg/L	

Geo-accumulation Index (I_{geo})

The geo-accumulation index, originally proposed for assessing metal contamination in river sediments, quantifies the enrichment of a metal in a sample relative to its pre-industrial (geochemical) background concentration (Muller 1969). It is calculated as:

$$I_{geo} = \log_2 \left[\frac{C_n}{(1.5 \times B_n)} \right] \dots \dots \dots \text{Equation I}$$

where C_n is the measured concentration of a metal n in the sediment or water sample, and B_n is the geochemical background (or guideline) concentration of the same metal. The constant 1.5 is a correction factor that accounts for natural lithogenic fluctuations in background metal concentrations in a given region. In this study, B_n for sediment was taken from the average documented shale values (Turekian and Wedepohl 1961), which remain the most widely cited background dataset used for I_{geo} calculation in recent contamination studies (Chai et al. 2026; Ramish et al. 2024). The values of I_{geo} were classified into seven contamination classes following the original scheme of Müller (1969), as summarized in Table 3.

Table 3. Classification of the geo-accumulation index (I_{geo}), contamination factor (CF) and enrichment factor (EF)

I_{geo}^*		EF**		CF***	
Value	Contamination	Value	Contamination	Value	Contamination
$I_{geo} \leq 0$	Uncontaminated	$EF < 1$	None	$CF < 1$	Low
$0 < I_{geo} \leq 1$	Uncontaminated to moderate	$1 \leq EF < 3$	Minor	$1 \leq CF < 3$	Moderate
$1 < I_{geo} \leq 2$	Moderate	$3 \leq EF < 5$	Moderate	$3 \leq CF < 6$	Considerable
$2 < I_{geo} \leq 3$	Moderate to strong	$5 \leq EF < 10$	Moderate to severe	$CF \geq 6$	Very high
$3 < I_{geo} \leq 4$	Strong	$10 \leq EF < 25$	Severe		
$4 < I_{geo} \leq 5$	Strongly to extreme	$25 \leq EF < 50$	Very severe		
$I_{geo} > 5$	Extreme	$EF \geq 50$	Extremely severe		

* Muller (1969), **Sutherland (2000), ***Håkanson (1980)

Contamination Factor (CF)

The contamination factor, developed by Håkanson (1980) as part of the potential ecological risk index, expresses the ratio of the measured metal concentration in a sample to its background/reference concentration (Eq. II):

$$CF = \frac{C_n}{B_n} \dots\dots\dots \text{Equation II}$$

where C_n and B_n retain the same meaning as in the I_{geo} equation above. For water samples, B_n corresponds to the permissible/guideline concentration of the metal specified in the WHO Guidelines for Drinking-water Quality (World Health Organization 2022). The guideline values used for Cd (0.003 mg/L), Cr (0.05 mg/L), and Pb (0.01 mg/L). The CF values were interpreted using the four-tier classification of Håkanson (1980), shown in Table 3.

Enrichment Factor (EF)

The enrichment factor normalizes the concentration of a metal against a conservative reference element to distinguish anthropogenic enrichment from natural geochemical variability (Sutherland 2000). It is calculated as:

$$EF = \frac{\left(\frac{C_n}{C_{ref}}\right)_{sample}}{\left(\frac{B_n}{B_{ref}}\right)_{background}} \dots\dots\dots \text{Equation III}$$

where C_n and C_{ref} are the concentrations of the target metal and the reference element, respectively, measured in the sample, and B_n and B_{ref} are their corresponding background/guideline concentrations. Iron (Fe) was used as the conservative reference element in this study, as it is predominantly of crustal/geogenic origin, generally shows limited anthropogenic input, and is one of the most commonly applied reference elements for EF calculation in both sediment and water matrices (Barbieri 2016; Sutherland 2000). EF values were classified using the seven-tier scheme proposed by Sutherland (2000), presented in Table 3.

Bioaccumulation factors

Bioconcentration (BCF) and Bio-sediment Accumulation Factors (BSAF) represent the tendencies of HM accumulation in fish muscles from water and sediment, respectively. The ratio between the HM concentration in fish and HM levels in water was referred to as BCF (Equation IV). Meanwhile, BSAF was the ratio between the HM concentrations in fish and sediment (Equation V).

$$BCF = \frac{C_{fish}}{C_{water}} \dots\dots\dots \text{Equation IV}$$

$$BSAF = \frac{C_{fish}}{C_{sediment}} \dots\dots\dots \text{Equation V}$$

Where the concentrations of HMs are C_{fish} in fish (mg kg⁻¹ DW), C_{water} in water (mg L⁻¹), and $C_{sediment}$ in the sediments (mg kg⁻¹ DW). A BCF>1 suggests that the metal concentration in fish exceeds that in the surrounding water, indicating high bioaccumulation potential. Meanwhile, BSAF >1 indicates the potential for HM accumulation from sediment into fish tissues.

Human health risks assessment associated with consumption of contaminated fish

Human health risks were assessed using the methodology described in our previous study with slight modifications (Ramish et al. 2024).

Measurement of Estimated Daily Intake (EDI)

The EDI was used to calculate the HM-associated health hazards (Equation IV).

$$EDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \dots\dots\dots \text{Equation IV}$$

The values used for this calculation are given in Table 4.

Table 4: Exposure parameters for calculating cancer and non-cancer health risks to humans

Risk exposure factors	Values	Symbol	Units
Heavy metal concentration in fish	Based on fresh weight	C	mg kg ⁻¹
Conversion factor*	0.20	C _f	--
Exposure duration	67 (adult), 6 (children)	ED	Years
Average ED (non-carcinogenic)	ED × 365; 67 × 365 (adult) = 24455 6 × 365 (children) = 2190	AT _{nc}	Days
Average ED (carcinogenic)	ED (life expectancy) × 365 = 24455	AT _c	Days
Fish ingestion Rate**	0.0052 (adult), 0.0025 (children)	IR	kg person ⁻¹ day ⁻¹
Body mass	62 (adult), 14 (children)	BW	kg
Exposure frequency	365	EF	Day year ⁻¹
Oral reference dose	Cd = 0.001 ^a , Cr = 1.5 ^a , Pb = 0.0036 ^b	RfD	mg kg ⁻¹ day ⁻¹
Oral carcinogenic slope factor	Cd = 0.38 ^c , Cr = 0.5 ^d , Pb = 0.0085 ^c	SF	(mg kg ⁻¹ day ⁻¹) ⁻¹

* Multiplication by dry weight converts to fresh weight, considering 80% moisture content of muscles (Shafi et al. 2023)

** Ingestion rate was calculated from FAO data reporting that per capita consumption of fish in Pakistan is 1.9 kg per year. For worst-case scenarios, ingestion of fish was considered equal to the global average, which is about 0.058 kg for adults and 0.029 kg per day for children (FAO 2026).

^a IRIS (U.S. Environmental Protection Agency (EPA) 2026)

^b Derived from (Health Canada 2010)

^c USEPA does not provide an oral dose (U.S. Environmental Protection Agency (EPA) 2026). This value has been reported by other studies (Aiman et al. 2026; Samad et al. 2025)

^d Oral SF is not available for Cr III (U.S. Environmental Protection Agency (EPA) 2026). This value has been reported by previous studies (Aiman et al. 2026; Samad et al. 2025)

^e Adapted from (OEHHA 2011)

Non-carcinogenic risk assessment

248 The non-carcinogenic risk of HMs (HQ) was determined as Equation VI;

249 $HQ = \frac{EDI}{RfD}$ Equation VI

250 where EDI is the estimated daily intake, and RfD is the oral reference dose of HMs ($\text{mg kg}^{-1} \text{ day}^{-1}$) (Table 4).

251 $HI = \sum HQ_i$ Equation VII

252 The sum of individual HQs is HI (Eq. VII). If HI is higher than 1, there is a potential non-cancer health risk.

253 *Lifetime carcinogenic risk*

254

255 The probability of an individual acquiring cancer over their lifetime is used to evaluate the possible cancer risk
256 linked to exposure to an HMs dose (Equation VIII).

257 $LCR = EDI \times SF$ Equation VIII

258 where EDI stands for the estimated daily intake. The SF is the oral cancer slope factor, which is a measure of the
259 incremental lifetime risk of cancer by oral intake of the HM (Table 4). Carcinogenic risk was deemed negligible
260 if it was less than 10^{-6} , acceptable risk if it was between 10^{-6} and 10^{-4} , and high risk if it was greater than 10^{-4} .

261 **Results and discussion**

262

263 The physicochemical characteristics and HM concentrations of water and sediment samples collected from five
264 locations along the Ravi River revealed considerable spatial variations in water quality and contamination levels
265 (Figure 3). Variations were also reflected in the accumulation of HMs in fish muscles, influencing human health
266 risks through the consumption of contaminated fish.

267 Water Quality Parameters

268

269 The water quality parameters, including pH, EC, Cd, Cr, and Pb, are illustrated in Figure 3A (a-e). The pH of
270 water was close to neutral, ranging from 6.7 to 7.6 across all sampling sites. The highest pH was recorded at
271 Siphon (7.65 ± 0.15), while the lowest was observed at Shahdara and Park View (6.8 ± 0.26). These values fall within
272 the acceptable limits for freshwater systems, suggesting that acidity was not a major concern during the study
273 period. Electrical conductivity (EC), on the other hand, is an indicator of dissolved salts and ionic content and
274 varied substantially among sites, ranging from 170 to $327 \mu\text{S cm}^{-1}$. The highest EC values were observed at M2
275 and Park View ($327 \mu\text{S cm}^{-1}$), indicating elevated concentrations of dissolved pollutants, whereas the lowest EC
276 was recorded at Head Balloki ($169.7 \pm 2.08 \mu\text{S cm}^{-1}$), suggesting comparatively better water quality.

277 The Cd concentrations in water samples ranged from 0.13 to 2.13 mg L^{-1} . The maximum Cd concentration
278 was detected at Shahdara ($2.13 \pm 0.15 \text{ mg L}^{-1}$), followed by Park View and M2 (both at 2.1 mg L^{-1}) and Head
279 Balloki ($1.16 \text{ mg} \pm 0.02 \text{ L}^{-1}$), and lowest at Siphon ($0.13 \pm 0.02 \text{ mg L}^{-1}$). These elevated values indicate substantial
280 Cd contamination, likely originating from industrial and municipal wastewater discharges. Lead concentrations
281 varied between 0.02 and 0.24 mg L^{-1} , with the highest at Head Balloki ($0.24 \pm 0.01 \text{ mg L}^{-1}$), followed by Park
282 View ($0.15 \pm 0.01 \text{ mg L}^{-1}$), while the lowest was at Siphon ($0.02 \pm 0.003 \text{ mg L}^{-1}$). The elevated Pb concentrations

may indicate anthropogenic inputs from industrial activities and urban runoff. Chromium concentrations in water ranged from 0.01 to 0.70 mg L⁻¹. The highest mean concentration was detected at Park View (0.70 mg L⁻¹), indicating a localized source of Cr pollution, whereas the lowest concentrations (0.01 mg L⁻¹) were observed at Siphon and Shahdara. The markedly elevated Cr concentration at Park View may be associated with industrial effluents, particularly from metal-processing and tanning industries (Ramish et al. 2024).

Sediment quality parameters

The spatial variations of parameters in sediment samples are described in Figure 3B (a-e). The sediments' pH was moderately to strongly alkaline (8.6 to 9.3) across the study area. The highest pH was recorded at Head Balloki (9.32±0.04), while the lowest was observed at M2 (8.64±0.03). Such alkaline conditions can influence the mobility and bioavailability of HMs in sediments (Shakir et al. 2013). The EC values of sediments ranged from 39 to 149 µS cm⁻¹. The maximum EC was recorded at M2 (149±1.15 µS cm⁻¹), followed by Park View (101±1.0 µS cm⁻¹), indicating greater salt accumulation and pollutant loading at these locations. The lowest EC was observed at Siphon (39±1.0 µS cm⁻¹). The high EC of M2 and Park View sites reflects a strong anthropogenic influence and greater ionic and pollutant loading, whereas the low EC at upstream sites indicates lower contamination and comparatively cleaner sediments (Shakir et al. 2015).

Sediment Cd concentration varied considerably from 1.22 to 16 mg kg⁻¹ across tested sites. Previous studies reported lower concentrations of Cd in the Ravi sediments. For example, Ahamad et al. (2024; 2024) reported it in the range of 0.25 to 2.98 mg kg⁻¹. Another study reported 0.23 to 2.34 mg kg⁻¹ during low-flow and 0.17 to 1.67 during high-flow seasons at Siphon, Shahdara, Sunder and Balloki sites (Shakir et al. 2013). In our study, the highest Cd mean concentration was detected at Park View (15.37±0.40 mg kg⁻¹), followed by Head Balloki (12.38 mg kg⁻¹) and Shahdara (7.27±0.08 mg kg⁻¹). The lowest mean concentration was recorded at Siphon (1.22±0.02 mg kg⁻¹). These findings indicate significant accumulation of Cd in riverine sediments, particularly at sites receiving wastewater inputs.

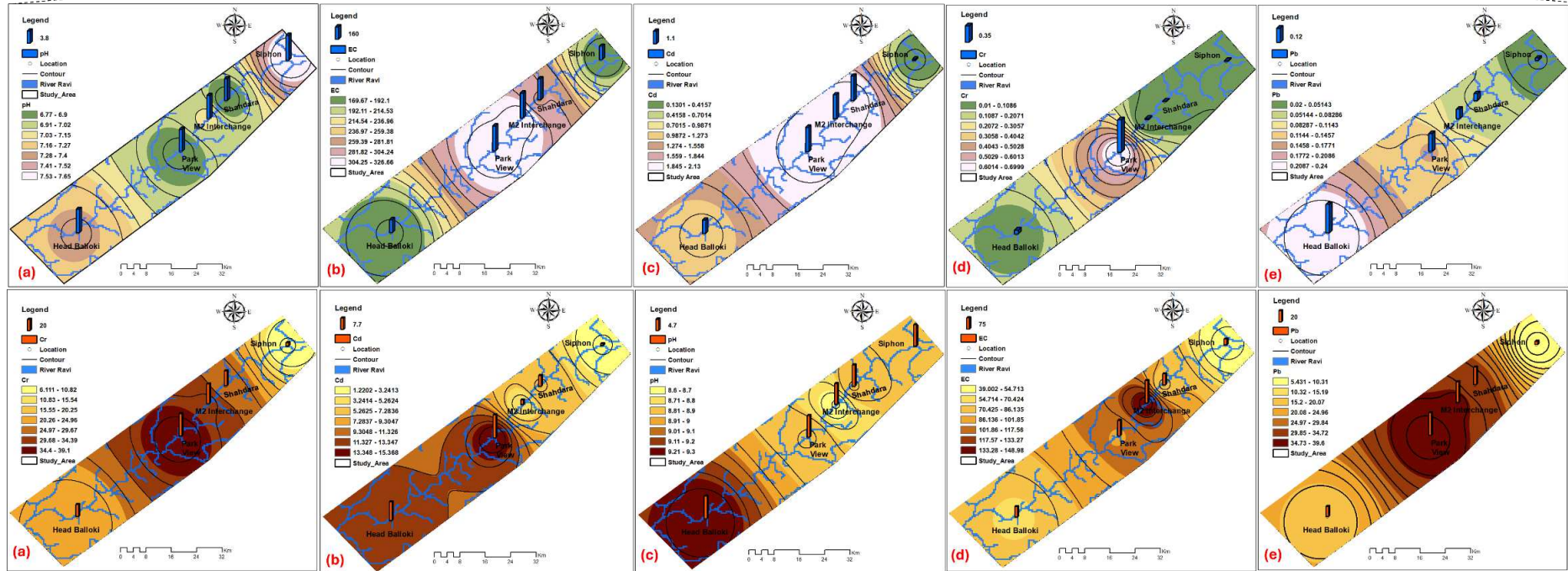
The Cr concentrations ranged from 6 to 39 mg kg⁻¹, with the following geographical order: Park View (39 mg kg⁻¹)> M2 (34.4 mg kg⁻¹)> Shahdara (26.44 mg kg⁻¹)> Head Balloki (21.1 mg kg⁻¹)> Siphon (6.1 mg kg⁻¹). The differences among geographical sites could be due to long-term accumulation of industrial contaminants in the surrounding soils of some sites such as M2 and Park View (Ahamad, Rehman, et al. 2024). Previous studies have also reported varying levels of Cr in the Ravi River bed sediments depending upon geographical location and season. Tabinda et al. (2013) reported higher Cr levels in sediments from Head Balloki during winter (50.4 mg kg⁻¹) and summer seasons (65 mg kg⁻¹). The study by Shakir et al. (2013) reported the ranges of 12.1 to 67.9 mg kg⁻¹ during the low flow and 9.7 to 41.6 mg kg⁻¹ during high flow seasons. Meanwhile, Ahamad et al. (2024; 2024) reported the highest levels, ranging from 60 to 200.4 mg kg⁻¹, from 32 sampling sites of the Ravi River.

Lead concentrations in sediments ranged from 5.4 to 39.6 mg kg⁻¹. The highest Pb mean concentration was observed at Park View (39.60 mg kg⁻¹), followed by M2 (36.3 mg kg⁻¹), Shahdara (31.1 mg kg⁻¹), Head Balloki (17.7 mg kg⁻¹) and Siphon (5.4 mg kg⁻¹). Clear spatial variation in HM concentrations was observed among sampling locations. The upstream Siphon had the lowest contamination, and the sites close to industries had the highest pollutant concentrations. As stated earlier, this could be due to different anthropogenic and

industrial activities happening near these sites. The variations in HM mean concentration among studies could be attributed to study site selection, methodology, season, and climatic factors, e.g., floods. For example, an old study reported higher concentrations of Pb in sediments at Head Balloki (136 mg kg⁻¹) and Sidhnai Barrage (40.8 mg kg⁻¹) sites on the Ravi River (Javed 2005). Later, Shakir et al. (2013) reported Pb contamination during the low-flow (1.03 to 5.8 mg kg⁻¹) and high-flow seasons (0.8 to 4.9 mg kg⁻¹). Recently, Ahamad et al. (2024; 2024) reported Pb in sediments of the Ravi River (8.7 to 100.8 mg kg⁻¹).

In total, the HM concentrations in sediments fell within the lower to intermediate range of previously documented values for the Ravi River; however, the significant site-specific variations highlight the ongoing influence of localized industrial inputs, underscoring the need for continued monitoring and targeted remediation efforts.

A. Water Parameters



B. Sediments Parameters

Figure 3: Physicochemical profile of water (A) and sediment (B) samples from Ravi River. Legends are overlaid on figures. Cadmium = Cd, chromium = Cr, lead = Pb.

Contamination indicators

Geoaccumulation Index

The I_{geo} , based on Müller's (1969) classification, provided further evidence of metal enrichment in the River Ravi system (Figure 4). Cadmium I_{geo} values indicated moderate contamination or higher at every site except for the Siphon sediment samples. Meanwhile, Cr and Pb generally remained below the uncontaminated limit in sediments and in the low-to-moderately contaminated range for water.

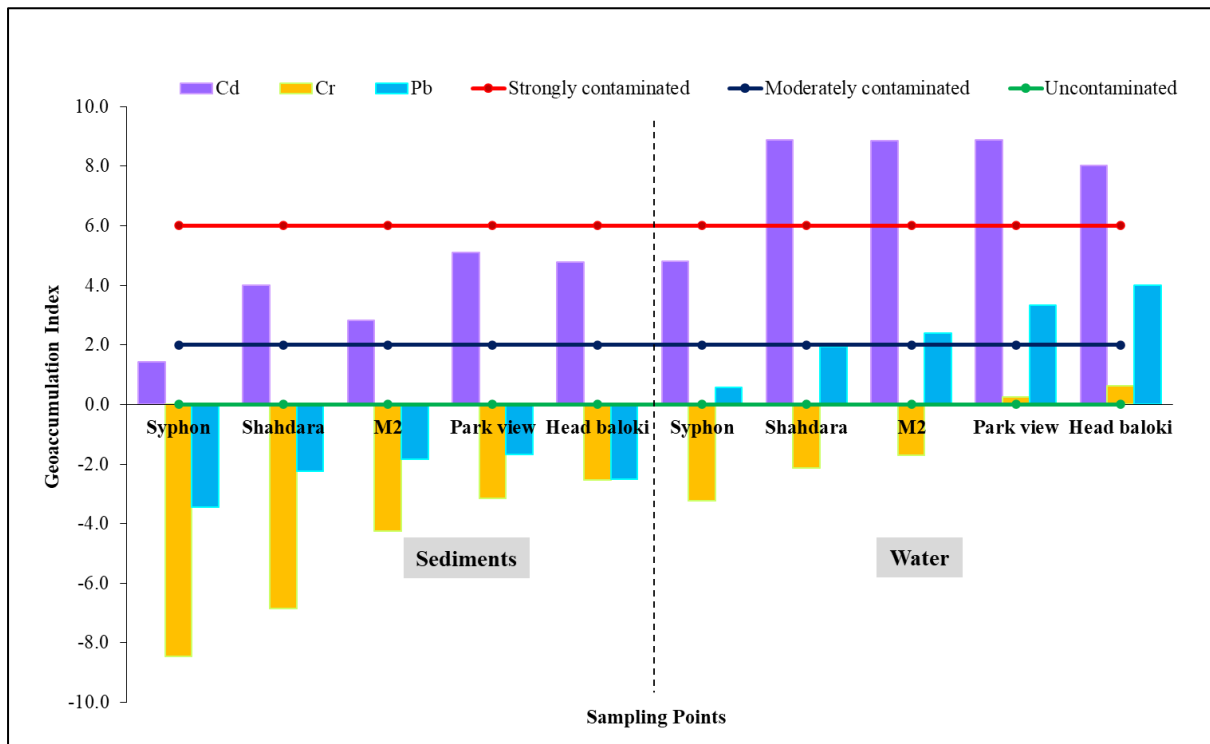


Figure 4: Geoaccumulation index (I_{geo}) of Cd, Cr, and Pb in sediment and water samples from River Ravi sampling sites, classified as uncontaminated (green), moderately contaminated (lighter red), and strongly contaminated (dark red).

These results are in line with the previous report of sediment I_{geo} , with the highest mean values for Cd (1.58), followed by Pb (0.47), and Cr (-0.13) (Ahamad, Yao, et al. 2024). Ahamad et al. (2024) also documented that Cd had high I_{geo} values around Lahore, indicating extremely polluted areas due to urban and industrial activities.

Contamination Factor

The CF, which expresses metal concentration relative to a regional geochemical background (Håkanson, 1980), followed a pattern broadly similar to the EF results (Figure 5). The highest CF values were associated with Cd for both the sediment and water, followed by Pb and Cr. Ahamad et al. (2024) also reported $CF \leq 1$ for Cr and Pb in the sediments in the Ravi River.

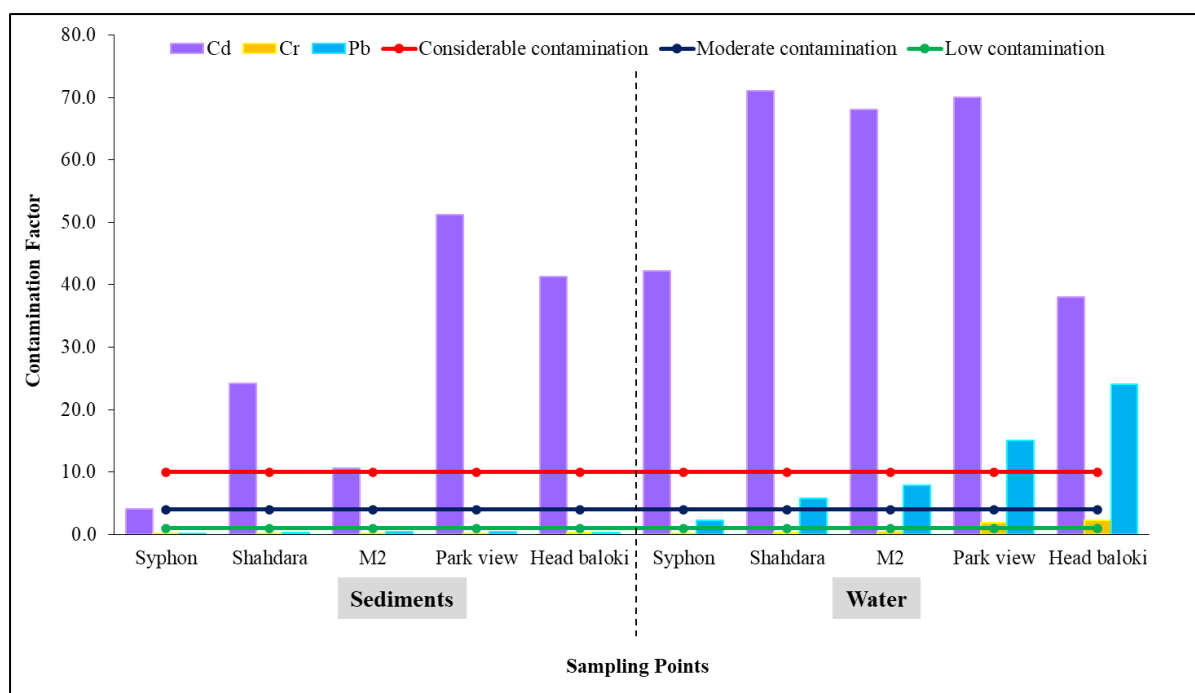


Figure 5: Contamination factor (CF) of heavy metals (Cd, Cr, and Pb) in sediment and water samples from the different sites along River Ravi. Reference lines denote the low (green), moderate (lighter red), and severe (dark red) contamination thresholds.

Overall, the elevated CF recorded for Cd corroborates findings from other Pakistani urban rivers, where untreated sewage and industrial discharges are the principal drivers of considerable Cd contamination in rivers (Ahamad, Rehman, et al. 2024; Ahamad, Yao, et al. 2024; Nasim et al. 2026).

Enrichment Factor

The enrichment factor was calculated for Cd, Cr and Pb in sediment and water samples collected from five representative sites along River Ravi, using iron (Fe) as the conservative reference element (Figure 6). Cadmium displayed the highest EF values among the three metals, exceeding the severe-enrichment threshold at most sediment sampling points and all water samples. The EF of Pb in river water from M2, Park View, and Head Balloki crossed the moderate enrichment limit. Meanwhile, Cr and Pb remained under the no-enrichment category for sediments. These results are in line with a previous study from the Ravi River reporting EF as highest for Cd, followed by Pb and Cr (Ahamad, Yao, et al. 2024). However, a previous study had reported higher enrichment around Lahore, with EF values greater than 5, suggesting substantial anthropogenic inputs (Ahamad, Rehman, et al. 2024). The spatial pattern, higher EF at Siphon, Shahdara and M2 relative to the downstream Park View and Head Balloki site, is consistent with the concentration of industrial and municipal effluent outfalls along the urban stretch of the river as it passes through Lahore (Ahamad, Rehman, et al. 2024).

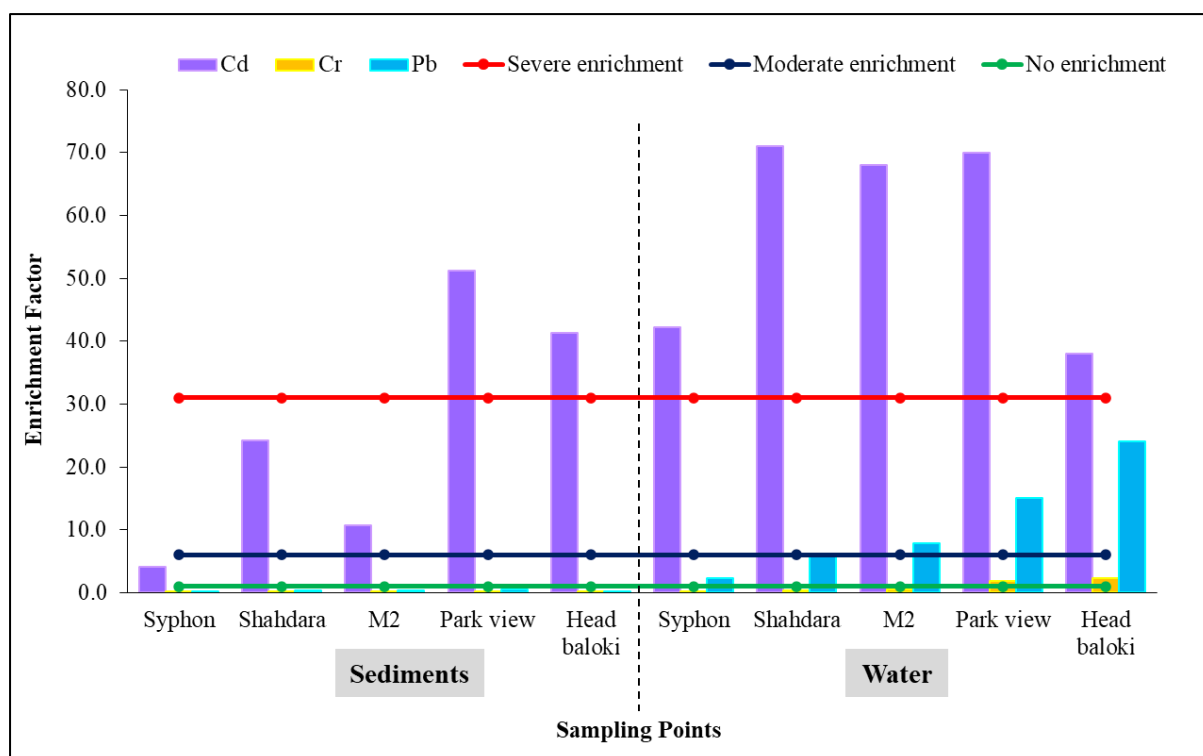


Figure 6: Enrichment factor (EF) of heavy metals (Cd, Cr, Pb) in sediment and water samples collected from five sites along River Ravi, Lahore. Horizontal reference lines indicate the no-enrichment (green), moderate-enrichment (lighter red), and severe-enrichment (dark red) thresholds.

Conclusively, the consistently higher pollution index values of Cd strongly indicate severe contamination from anthropogenic enrichment relative to background concentrations. Such heavy contamination is highly relevant for River Ravi given its role in irrigation, fisheries, and direct human contact (Ahamad, Rehman, et al. 2024). This poses significant ecological and human health risks, especially for vulnerable populations. In contrast, Cr and Pb indices indicated moderate pollution, with localized hotspots around Lahore (Ahamad, Rehman, et al. 2024).

Concentration of HMs (Cd, Cr, and Pb) in fish species

The concentrations of Cd, Cr, and Pb were determined in two fish species (*C. mrigala* and *L. rohita*) collected from five sampling locations along the Ravi River. The results in Figure 7 revealed considerable spatial variation in HM accumulation, reflecting differences in environmental contamination and metal bioavailability among selected locations and previously documented studies (Table 5).

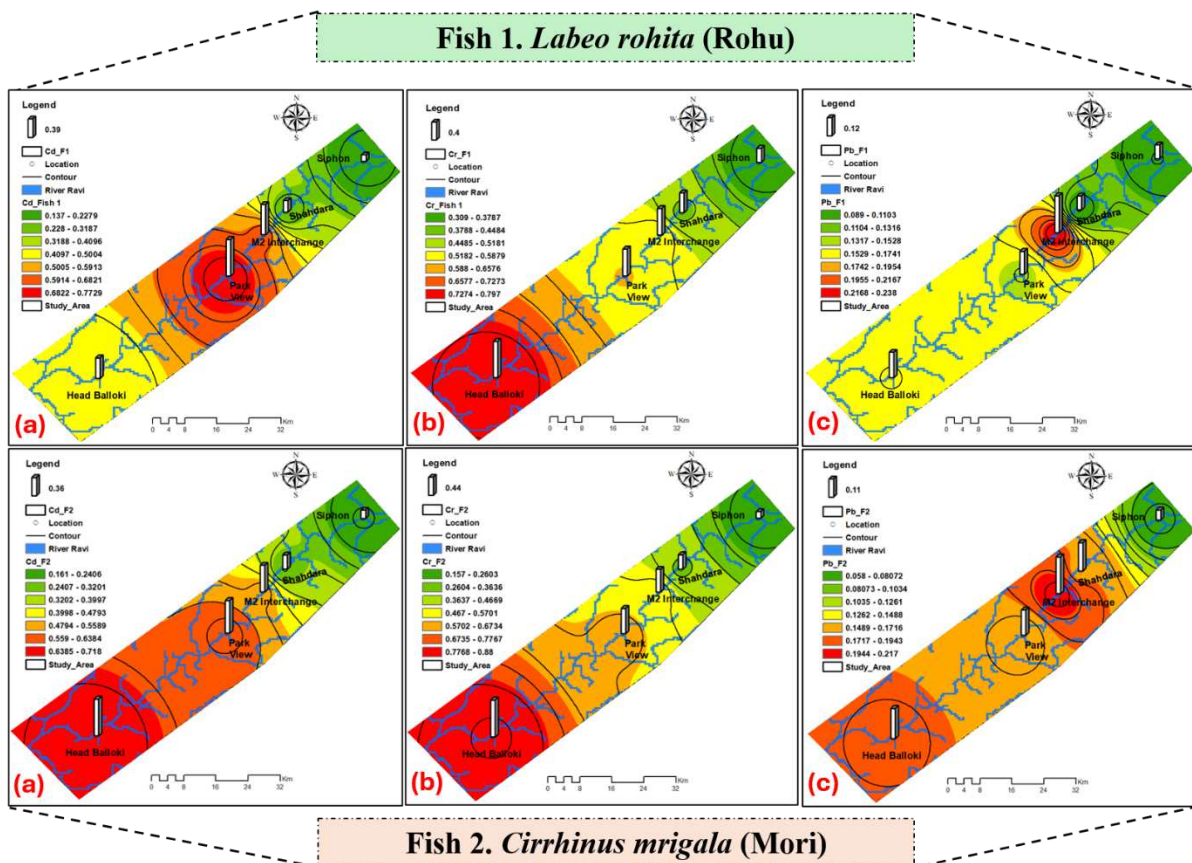


Figure 7: Heavy metal (Cd, Cr and Pb) contamination of fish samples from the Ravi River. Legends are overlaid on figures.

Concentration of Cd in fish

Cadmium concentrations in fish tissue ranged from 0.14 to 0.77 mg kg⁻¹, with the lowest mean concentration recorded at Siphon (0.15 mg kg⁻¹) and the highest at Park View (0.70 mg kg⁻¹). In the literature, Cd in these fish at Siphon has been reported to range from 0.03 to 1.2 mg kg⁻¹ (Rauf et al. 2009; Shakir et al. 2015). Only one study has reported substantially higher concentrations (11.8 to 13.8 mg kg⁻¹) of HM in these fish from the Ravi River (Yaqoob et al. 2020). The HM concentration also varied between fish species at some sites; for example, at Head Balloki, Cd in *C. mrigala* muscle was higher (0.72±0.08 mg kg⁻¹) compared to *L. rohita* (0.43±0.17 mg kg⁻¹). Previous studies have also reported variations of Cd in fish species based on location, season, and trophic levels of fish (Rauf et al. 2009; Shafi et al. 2023; Yaqoob et al. 2020). Overall, the elevated Cd concentration at Park View, M2, and Head Balloki indicates substantial Cd contamination in the downstream sites and efficient bioaccumulation by fish tissues (Rauf et al. 2009).

Table 5: Literature comparison on HM contamination of *L. rohita* and *C. mrigala* fish muscles across different sites of the Ravi River

Sites	Study period	HM (mg kg ⁻¹ DW)*			Reference
		Cd	Cr	Pb	

Siphon	April to May, 2025	0.14±0.08 R 0.16±0.08 M	0.31±0.09 R 0.16±0.05 M	0.09±0.01 R 0.06±0.03 M	Current study
Shahdara		0.24±0.07 R 0.28±0.04 M	0.44±0.10 R 0.35±0.10 M	0.09±0.06 R 0.17±0.05 M	
M2		0.64±0.03 R 0.52±0.07 M	0.58±0.22 R 0.54±0.11 M	0.24±0.05 R 0.22±0.06 M	
Park View		0.77±0.18 R 0.64±0.17 M	0.59±0.22 R 0.60±0.10 M	0.15±0.04 R 0.15±0.04 M	
Head Balloki		0.43±0.17 R 0.72±0.08 M	0.80±0.03 R 0.88±0.05 M	0.16±0.04 R 0.18±0.01 M	
Head Balloki	May to August 2022	NA	NA	0.07 R, 1.3 M	(Aiman et al. 2026)
Head Sidhnai			0.45 R	5.6 R, 0.4 M	
Village Kala Khatai	February 2016	0.24 R, 0.24 M	NA	1.48 M	(Shafi et al. 2023)
Head Balloki		0.28 R, 0.20 M	NA	1.7 M	
Head Balloki	November 2016 to March 2017	13.8 M	18.1 M	NA	(Yaqoob et al. 2020)
Siphon		11.8 R, 12.1 M	15.1 R, 13.7 M	NA	
Siphon	Low/high flow seasons	0.03 M	0.88-1.06 M	0.14-0.18 M	(Shakir et al. 2015)
Shahdara		0.07-0.08 M	1.96-2.13 M	0.94-1.03 M	
Sunder		0.11-0.16 M	2.54-4.48 M	2.64-3.16 M	
Head Balloki		0.04 M	1.33-1.54 M	1.36-2.0 M	
Head Balloki	Winter-summer	NA	1.2-1.6 R; 1.5-1.8 M;	NA	(Tabinda et al. 2013)
Shahdara	June, 2009 to May, 2010	NA	1.94** (R, M)	NA	(Jabeen et al. 2012)
Head Balloki,			2.62** (R, M)		
Sidhnai			3.07** (R, M)		
All locations			1.4±0.4 (R, M)		
Head Balloki	1999	0.4 (R, M)	NA	2.7 (R, M)	(Nawaz et al. 2010)
Siphon, Shahdara, Head Balloki	February 2006 to January 2007	1.2±0.8 (R, M)	1.5±0.5 (R, M)	NA	(Rauf et al. 2009)

Head Balloki, Syed wala, Marii pattan, Kamalia- Chichawatni (KC) bridge, Sidhnai	Sept 2003 to Aug 2004	NA	NA	1.9 (R, M) 2.7 R**, 2.1 M** Balloki 2.9> Sidhnai 2.2	(Javed 2005)
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* DW = dry weight. ** Whole fish (not specified for muscle mass). R= *Labeo rohita* or Rohu fish; M= *Cirrhinus mrigala* or Mori/Mrigal fish. NA = Not available or not studied

Concentration of Cr in fish

The Cr concentrations in *C. mrigala* varied from 0.16 to 0.88 mg kg⁻¹, with the maximum concentration detected at Head Balloki (0.88±0.05 mg kg⁻¹), followed by Park View (0.60±0.10 mg kg⁻¹) and M2 (0.54±0.11 mg kg⁻¹), whereas the minimum concentration was recorded at Siphon (0.16±0.09 mg kg⁻¹). Previous studies have reported these concentrations in the range of 0.95 to 2.54 mg kg⁻¹ (Aiman et al. 2026; Jabeen et al. 2012; Rauf et al. 2009; Shakir et al. 2015; Tabinda et al. 2013). Meanwhile, for *L. rohita*, Cr concentrations ranged from 0.31 to 0.80 mg kg⁻¹, whereas the literature reported 0.45 to 2.3 mg kg⁻¹ (Aiman et al. 2026; Jabeen et al. 2012; Rauf et al. 2009; Tabinda et al. 2013). The highest accumulation in this study was again observed at Head Balloki (0.80±0.03 mg kg⁻¹), followed by Park View (0.59±0.22 mg kg⁻¹) and M2 (0.58±0.22 mg kg⁻¹), and the lowest was recorded in samples from Siphon (0.31±0.09 mg kg⁻¹). These findings suggest that Cr is readily accumulated in fish tissues, particularly in downstream areas where industrial discharges and contaminated sediments contribute to increased metal availability.

Lead accumulation in fish

Lead concentrations in *C. mrigala* muscle ranged from 0.06 to 0.22 mg kg⁻¹, with the following order by site: M2 (0.22±0.01 mg kg⁻¹) > Head Balloki (0.18±0.01 mg kg⁻¹) > Park View (0.15±0.04 mg kg⁻¹) > Shahdara (0.17±0.05 mg kg⁻¹) > Siphon (0.06±0.03 mg kg⁻¹). In *L. rohita*, Pb concentrations were slightly higher, ranging from 0.09 to 0.24 mg kg⁻¹. Recently, Aiman et al. (2026) reported that Pb concentrations in *L. rohita* and *C. mrigala* fish from Head Balloki were 0.07 and 1.3 mg kg⁻¹, respectively. However, the mean concentration was higher in Rohu (5.6 mg kg⁻¹) compared to Mori (0.4 mg kg⁻¹) at the Head Sidhnai site of the Ravi River. These values remain within the literature-documented values, with variations attributed to environmental factors at the two sites, which could influence the trophic level ingestion by the fish (Aiman et al. 2026; Javed 2005; Nawaz et al. 2010; Shafi et al. 2023; Shakir et al. 2015). Overall, the higher Pb concentrations at M2 indicate the influence of local anthropogenic pollution sources, such as industrial effluents, urban runoff, and wastewater discharges.

Taken together, the results demonstrate that fish inhabiting the Ravi River are exposed to measureable HM contamination and are actively bioaccumulating Cd, Cr, and Pb from the aquatic environment. Among the sampling sites, Head Balloki, Park View, and M2 exhibited the highest levels of metal accumulation, whereas Siphon consistently showed the lowest concentrations. Contamination patterns were generally greater at

downstream locations, potentially reflecting cumulative wastewater inputs. The elevated concentrations of Cd, Cr, and Pb in fish tissues indicate potential ecological impacts and raise concerns regarding human health risks associated with the consumption of fish from contaminated sections of the Ravi River.

Bioaccumulation factors

The values of bioaccumulation factors varied among HMs and sampling locations (Table 6). The BCF of Cr was highest at upstream locations, ranging from 15.7 to 31.2 L kg⁻¹ for both fish. Aiman et al. (2026) reported a higher BCF for Cr in *L. rohita* (43.5 L kg⁻¹). Meanwhile, the lowest values were recorded for the Park View (0.8 L kg⁻¹), indicating reduced Cr bioaccumulation potential at this site. Overall, Cr showed greater accumulation from water compared with Cd and Pb in both fish species.

Table 6. Bioconcentration factor (BCF) and bio-sediment-accumulation factor (BSAF) of HMs for fish in the Ravi River sites

Parameters		Siphon		Shahdara		M2		Park view		Head Balloki	
		R	C	R	C	R	C	R	C	R	C
Cd	BCF	1.08	1.27	0.11	0.13	0.31	0.25	0.38	0.31	0.37	0.62
	BSAF	0.11	0.13	0.03	0.04	0.20	0.16	0.05	0.04	0.04	0.06
Cr	BCF	30.87	15.67	31.19	24.76	29.17	27.00	0.84	0.86	9.96	11.00
	BSAF	0.05	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.04	0.04
Pb	BCF	3.99	2.61	1.55	2.90	3.03	2.76	0.99	0.99	0.68	0.74
	BSAF	0.03	0.02	0.02	0.03	0.97	0.89	0.04	0.04	0.03	0.03

R and C as described in previous tables. The red cells with bold letters indicate values higher than 1.

The BSAF values were generally less than one, suggesting limited transfer of these HMs from sediments to fish. Cr had the lowest BSAF values (0.01-0.05), suggesting weak sediment-associated accumulation. Values for Cd were relatively higher, reaching 0.20 in *L. rohita* and 0.16 in *C. mrigala* at the M2 location. The highest BSAF values were for Pb, reaching 0.97 in *L. rohita* and 0.89 in *C. mrigala* at the M2 location. The Pb values at the remaining sites ranged from 0.02 to 0.04. Aiman et al. (2026) reported higher BSAF values for Cr (0.7) and Pb (2.2) in *L. rohita*. Overall, these results indicate that sediment-derived Pb was considerably more bioavailable at M2 than at the other sampling locations.

Human health risk analysis

The non-carcinogenic risk, assessed using the HQ, indicated that the consumption of HM-contaminated fish from the studied locations posed negligible non-carcinogenic health risks for both adults and children. All calculated HQ values were significantly lower than one, which is the generally accepted threshold for non-carcinogenic risk (Table 7). The HQ was highest for Cd, followed by Pb and Cr. Moreover, all the individual HQs of HMs were higher for children compared to adults. Moreover, the cumulative HQ of these heavy metals (HI) was less than one, which is an acceptable level of risk (Figure 8). Previously, Aiman et al. (2026) reported similar results where they showed that $HQ < 1$ for multiple HMs in fish from the Ravi River.

Table 7: Hazard quotients (HQ) linked to consumption of fish from different sites of the Ravi River

HMs	Locations	<i>Labeo rohita</i>		<i>Cirrhinus mrigala</i>	
		HQ Adult	HQ Children	HQ Adult	HQ Children
Pb	Siphon	0.00041	0.00089	0.00027	0.00058
	Shahdara	0.00041	0.00089	0.00078	0.00167
	M2	0.00111	0.00237	0.00101	0.00216
	Park View	0.00069	0.00148	0.00069	0.00148
	Head Balloki	0.00077	0.00164	0.00082	0.00176
Cd	Siphon	0.00229	0.00490	0.00271	0.00578
	Shahdara	0.00408	0.00873	0.00464	0.00992
	M2	0.01068	0.02283	0.00876	0.01872
	Park View	0.01296	0.02771	0.01068	0.02283
	Head Balloki	0.00727	0.01555	0.01204	0.02573
Cr	Siphon	0.00000	0.00001	0.00000	0.00000
	Shahdara	0.00000	0.00001	0.00000	0.00001
	M2	0.00001	0.00001	0.00001	0.00001
	Park View	0.00001	0.00001	0.00001	0.00001
	Head Balloki	0.00001	0.00002	0.00001	0.00002

In the worst-case scenario where an individual would eat fish equal to the global average (21 kg per capita per annum), the HI for children was still lower than one (Figure 8). In addition, the non-carcinogenic risk was higher downstream for both fish, except at the Head Balloki site, where HI values for *L. rohita* were lower than at the M2 and Park View sites, and also lower compared to that of *C. mrigala* across all three downstream sites. Here we considered only three heavy metals; including multiple heavy metals would also increase the HI values, as previously reported (Aiman et al. 2026). Therefore, these results should be considered only for screening-level studies for HM risks on these sites.

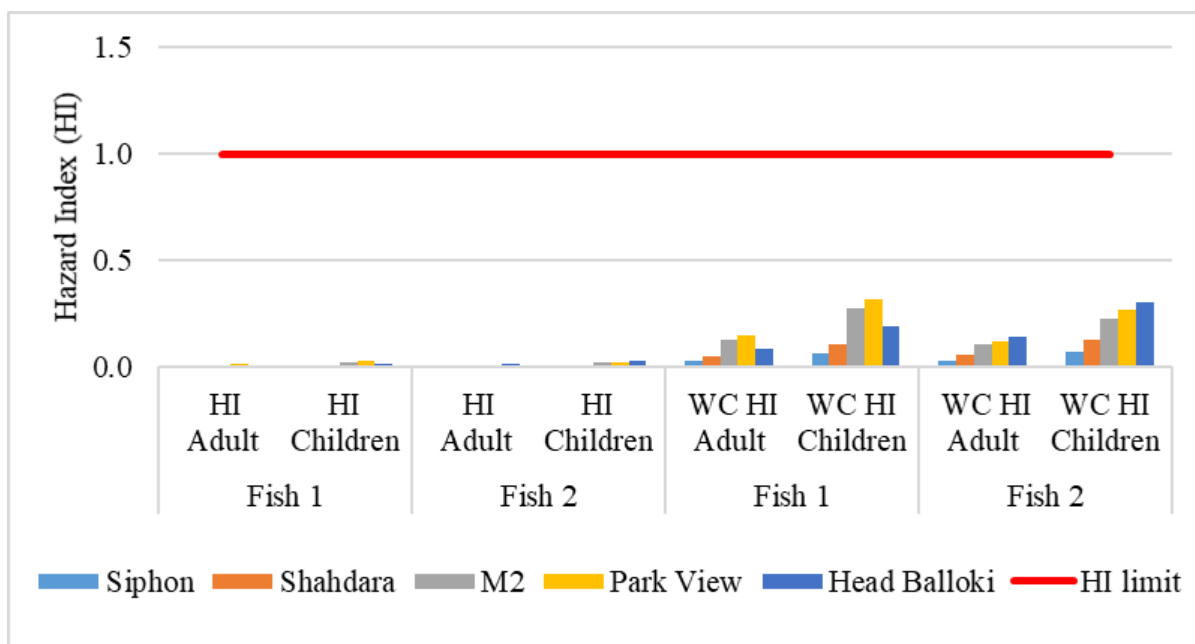


Figure 8: Hazard index (HI) linked to consumption of HMs (Cd, Cr, Pb) contaminated *L. rohita* (Fish 1) and *C. mrigala* (Fish 2) collected from different sites on Ravi River. WC represents the worst-case scenario where consumption is considered about 11 times higher. HI limit = 1.

The carcinogenic risk associated with Pb was negligible, and for Cd and Cr in both fish, it fell within the range of acceptable risk (10^{-6} to 10^{-4}) for adults (Figure 9). The estimated risk was below the de minimis risk threshold for children in all cases, except Cr in fish from Balloki, showing a slight jump over the risk of one in a million. The study of Aiman et al. (2026) reported the carcinogenic risk of As, Cr, and Pb for multiple fish species to be higher than the acceptable range (10^{-6} to 10^{-4}). This difference could be due to estimation differences and also the type of HM detected for fish specimens. In all cases, risk was higher in adults compared to children due to longer exposure time. The LCR was lowest for Siphon fish for all HMs; it was $<10^{-6}$ even for children consuming Cd- and Cr contaminated *C. mrigala* and Cd-contaminated *L. rohita*.

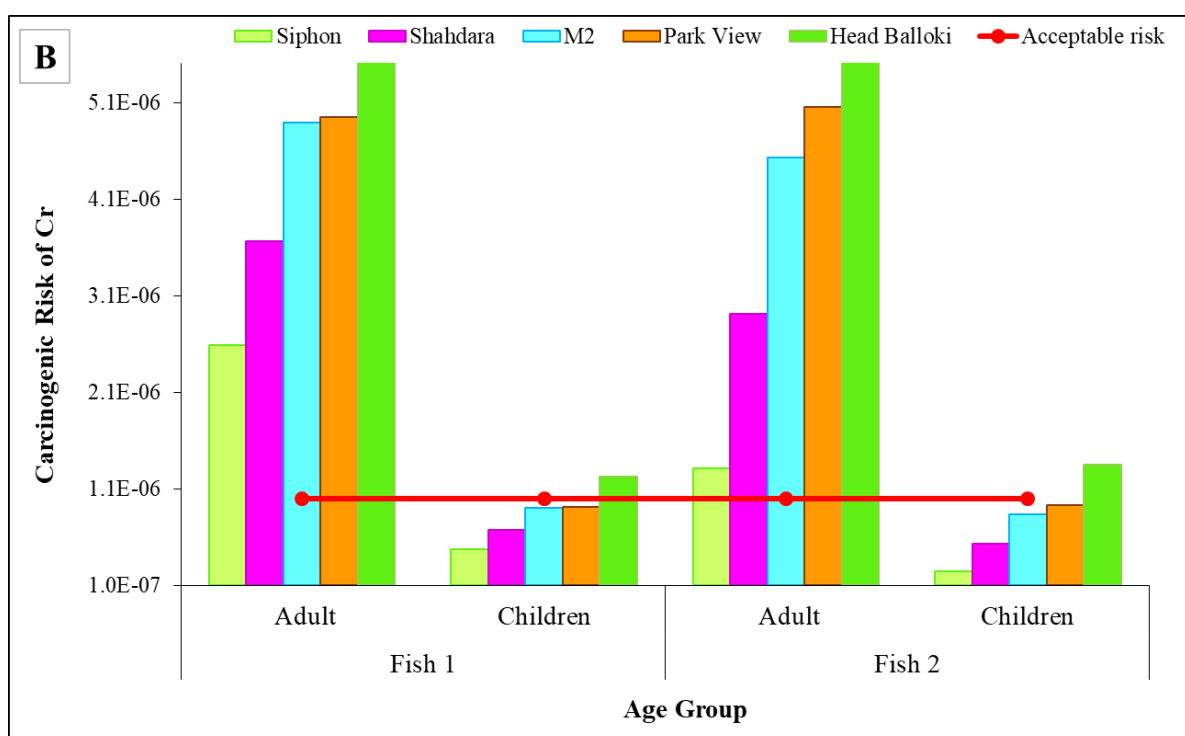
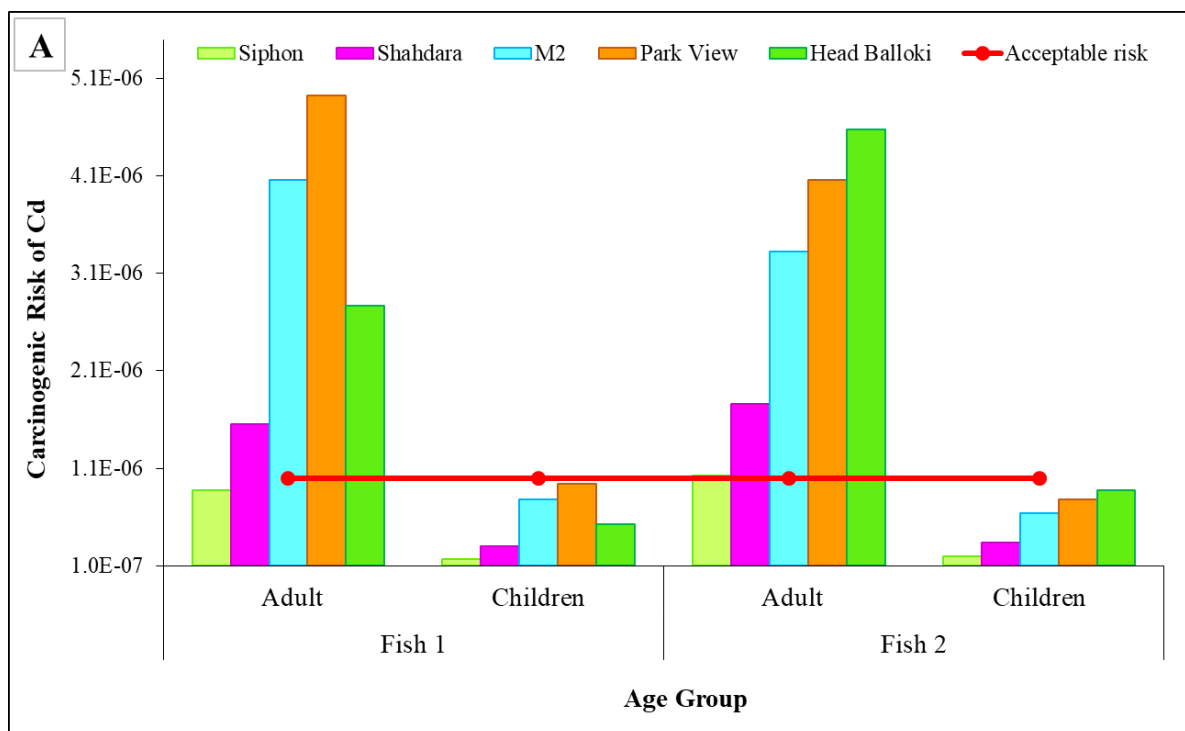


Figure 9. Lifetime Carcinogenic Risk (LCR) in adults and children consuming Cd (A) and Cr (B) contaminated *L. rohita* (Fish 1) and *C. mrigala* (Fish 2) from different sites in Ravi River. Red line indicates the lower-bound acceptable risk (1×10^{-6}).

From a management perspective, these findings support calls for stricter regulation and treatment of industrial and municipal effluents entering the river within the Lahore metropolitan stretch (Afzaal et al. 2022; Ahamad, Rehman, et al. 2024; Nasim et al. 2026). Further, periodic sediment monitoring using multiple, complementary pollution indices should be adopted rather than any single metric, since each index captures a

different facet of contamination: background normalization for EF, regional-baseline comparison for CF, and pre-industrial reference levels for I_{geo} . Continued multi-index surveillance of this kind will be essential for tracking the effectiveness of future pollution-control interventions along River Ravi.

This study has a few limitations which are either already published in the literature or should be considered when interpreting the results and planning future research. For risk assessments, some oral RfD and SF values were not formally recommended by the USEPA (e.g., oral RfD for Cd and SF for Cd III); instead, they were derived from published studies, which may influence the overall risk interpretation. Therefore, the current assessment should be considered at the screening level, and results should be interpreted with caution. We considered only two herbivorous fish species; including additional trophic groups would provide more wide-ranging, species-specific HM contamination and risk information (Aiman et al. 2026; Jabeen et al. 2012; Nawaz et al. 2010; Rauf et al. 2009). The fish samples were purchased from fisherfolk, relying on third-party information, which might not be precise because fishing was not actively supervised by the researchers. There are seasonal and flooding-related influences on the water quality, which could ultimately affect the River and fish contamination (Shakir et al. 2015; Tabinda et al. 2013; Yaqoob et al. 2020); such temporal dynamics were not evaluated and should be included in future monitoring programs. Addition of more trace HMs to the research question will provide a more comprehensive picture and a more complete risk assessment of HMs. Further, this study does not provide probabilistic risk assessment (Urban et al. 2009); however, the deterministic data presented in comparison with previous studies can serve as a foundation for such analysis.

Conclusions

The comprehensive study of different sites of the Ravi River integrated analyses of HMs in water, sediments, and fish (*C. mrigala* and *L. rohita*), and analyses with pollution indices and human-health risk evaluation. The highest site-specific contamination was observed for Cd, which had moderate to high I_{geo} , CF, and EF values in both sediments and water. Meanwhile, Cr and Pb remained within low to moderate contamination ranges.

Contamination of HMs in fish muscles, representing edible parts, varied across species and sites, indicating localized pollutant inputs and differential bioaccumulation. The non-carcinogenic and carcinogenic risk assessment results showed estimated risks were within internationally accepted regulatory thresholds ($HQ < 1$, $HI < 1$, and $LCR 10^{-6}$ to 10^{-4}).

Conclusively, the findings showed that while the Ravi River is contaminated by anthropogenic HM inputs, local fish consumption presently poses a low public-health risk. However, the presence of contamination hotspots highlights the need for regular monitoring, targeted pollution control, and strengthened river-management policies to protect ecological integrity and food safety.

Statements and Declarations

Ethics statement All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

Ethical approval No ethical approval was required, as all fish samples were purchased dead from local fisherfolk, and no other live animals were used in this study.

Competing interests The authors declare no competing interests.

Data availability The authors generated and analyzed original research data. All relevant data are provided within the manuscript.

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