

Health risk assessment of metal exposure from Jengka Riverine system in Pahang, Malaysia

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ABSTRACT

The presence of metals in aquatic and soil ecosystems poses significant environmental and public health concerns, particularly in areas with increasing anthropogenic activities. This study evaluates the concentration of selected heavy metals, namely copper (Cu), chromium (Cr), lead (Pb), and zinc (Zn) in the water and soil of the Jengka Riverine system in Jengka, Pahang, Malaysia as this region is known for extensive agricultural activities. Samples were collected from multiple points along the river, and metal concentrations were analysed using inductively coupled plasma optical emission spectrometry (ICP-OES). Risk assessment models, including the hazard quotient (HQ) and lifetime cancer risk (LCR), were employed to evaluate both non-carcinogenic and carcinogenic risks associated with dermal contact, inhalation, and ingestion. For river water, the average heavy metal concentrations (\pm standard deviation) were in descending order of Zn (0.033 ± 0.023 mg/L) > Cu (0.013 ± 0.01 mg/L) > Pb (0.007 ± 0.005 mg/L). Cr was not detected in water samples. The average heavy metal concentrations (\pm standard deviation) in soil showed descending order of Zn (5.33 ± 1.15 mg/kg) > Cu (5.13 ± 2.31 mg/kg) > Cr (3.33 ± 0.305 mg/kg) > Pb (2.02 ± 0.001 mg/kg). The findings indicate slight elevated levels of certain metals indicating potential links to agricultural discharge and road surface runoff. Most HQ and LCR levels in the water and soil samples remained within permissible limits. However, some metal exposure specifically via dermal contact suggests potential long-term risk for local communities relying on the river for food and recreation, especially among children. The study highlights the need for regular monitoring and implementation of mitigation strategies to reduce health risks and preserve the ecology of the Jengka River.

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1. INTRODUCTION

The Jengka Riverine system, a tropical river located in the Pahang state of Malaysia, plays a crucial role in sustaining the livelihoods of surrounding rural communities, providing water for drinking, agriculture, and daily use. However, this vital water source faces significant environmental pressures, particularly from agricultural runoff, industrial discharges, and urbanization, which have led to concerns regarding its water quality. Pollutants such as heavy metals have increasingly been detected in the river, potentially posing serious health risks to the populations that rely on it. Heavy metals such as copper, chromium and lead are common pollutants contributing to the degradation of water quality and increased health risks in surrounding communities in rivers (Salam et al., 2019; Jesi et al., 2024; Mazilamani et al., 2024, Sulaiman et al., 2025).

Razali et al., (2021) conducted a study on the levels of heavy metals in a highland river in Pahang, Malaysia, with

a particular focus on areas near agricultural zones. Their findings revealed that rivers had elevated levels of cadmium and lead, which were linked to pesticide and fertilizer runoff from agricultural activities nearby. However, while that study highlighted the presence of contaminants, it did not explore the cumulative long-term health risks, rather focussing on ecological risk. Another recent study by Mazilamani et al., (2024) focused on river water in industrial areas in Johor, Malaysia. They found that river water experienced significant increases in metal levels due to domestic and industrial waste discharge. Moreover, several other studies on urban river water quality have also indicated elevated metal concentrations (Proshad et al., 2020; Razak et al., 2021; Jesi et al., 2024). Those findings describe the significant risks to human health from exposure to polluted river water.

Despite the socioeconomic importance of the Jengka Riverine system, research addressing the specific health risks arising from its contamination remains scarce. Studies on river health in Malaysia have predominantly focused on urban or

industrialized regions, leaving a significant gap in understanding the unique risks in rural river systems such as the Jengka River. This lack of localized data hinders effective policymaking and water management strategies that could safeguard the health of affected communities. The relevance of this study to the Jengka Riverine system is clear, as agricultural activities may introduce heavy metals into the river. This study provides one of the first integrated assessments of heavy metal contamination in both water and riverbank soils within the Jengka Riverine system, a predominantly agricultural landscape in central Pahang. By adopting the quantitative health risk assessment, this research establishes a baseline for understanding pollutant behaviour and exposure pathways in rural Malaysian river systems especially Jengka River. The findings contribute new evidence on the potential transfer of agricultural contaminants to local communities and offer data-driven recommendations for rural water safety management and public health protection.

This research aims to measure the concentration of metal pollutants in Jengka River water and soil near the riverbank. This study also evaluates the health risks associated with metal exposure from water and soil of the Jengka Riverine system. Additionally, this study seeks to provide evidence-based insights for public health interventions and propose recommendations for mitigating health risks and enhance community well-being for people living along the Jengka River.

2. MATERIALS AND METHODS

2.1. Study site

Fifteen water and soil samples were collected from five points (S1-S5) of Jengka River, Pahang, Malaysia (3°31'46" N, 102°33'14" E- 3°47'24" N, 102°32'0" E) (Figure 1). This river flows through reserved forests in the north part of Jengka region and agricultural areas of the Jengka region and is a tributary of Pahang River to the south. Table 1 provides details of the sampling locations.

2.2. Water sample collection

Samples were collected using grab sampling method (with 5 litres maximum volume) and from upstream to downstream of the river, with triplicate samples taken for each sampling location, considering the nearby agricultural cultivation area on both sides of the riverbanks. To avoid misrepresentation, samples were taken from the uppermost layer of the water at about 15 cm depth (as it has a shallow depth) and at least 1 meter from the riverbank. The samples were acquired and placed into 250 ml polyethylene (PE) bottles with caps that were pre-acid-washed with a 5% HNO₃ solution. The samples were acidified to pH<2, stored in an

icebox until transport to the laboratory, and kept at a temperature of 4°C before further analysis

Table 1: Sampling locations detail information.

Sampling point	River flow	GPS location	Location observation
S1 – Kg Bukit Lada, Maran	Downstream	3°31'46" N 102°33'14" E	Agricultural area, Primary school nearby
S2 – Felda Kg Awah	Downstream	3°31'17" N 102°30'44" E	Agricultural area, Main road
S3 – Felda Jengka 15	Middle	3°43'12" N 102°32'35" E	Agricultural area, Main road
S4 – Jambatan Sg Chenering	Middle	3°44'59" N 102°32'15" E	Agricultural area, Main road
S5 – Felda Jengka 11	Upstream	3°47'24" N 102°32'0" E	Main road, Car workshop

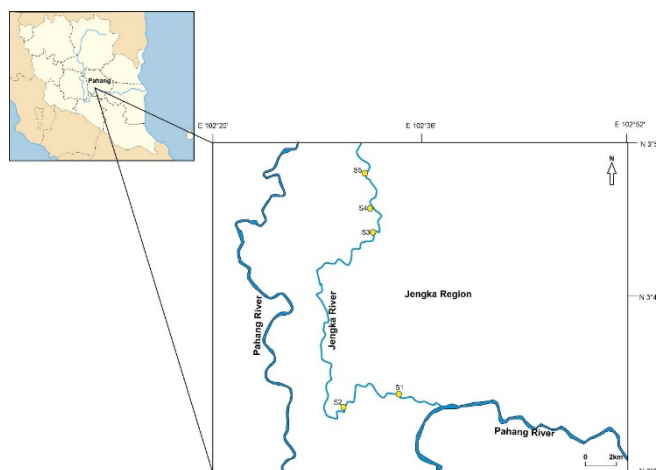


Figure 1: Sampling location of Jengka River in Pahang state, Malaysia.

2.3. Soil sample collection

Soil samples were taken at the same locations as each river water sample. For each location, triplicate samples were collected using a stainless-steel scope and put in the zip lock plastic with appropriate label. Samples were taken from the surface soil up to 15 cm depth at about 2 meters from the riverbank. This riparian soil chosen as it reflected the metal influence on river water (Sharma et al. 2020).

2.4. Sample preparation and analysis

Soil samples were dried in an oven at a temperature of 50 °C overnight avoiding certain compound volatilization. Each soil sample was sifted using a 2 mm sieve to separate any unwanted particles. Then, the samples were ground using a mortar and pestle to obtain homogenize sample. About 0.5 g of the soil sample was digested for 15 minutes at 80 °C in a mixture of 5 mL of HNO₃ and 15 mL of HCl (Abdullah et al., 2015). The digestion mixture was filtered by using Whatman 41 filter paper and distilled water was used to dilute in 100 mL in volumetric flask. Each diluted solution was placed in a

sample bottle and stored in a refrigerator (4°C) prior to sample analysis.

Prior to analysis, all samples (soil and water) underwent filtration using a membrane filter with a pore size of 0.45 µm. The concentrations of metals (copper (Cu), chromium (Cr), lead (Pb), and zinc (Zn)) were then determined using an inductively coupled plasma optical emission spectrometry (ICP-OES, model Agilent 5100) with RF power 1.2 kW, nebulizer flow 0.7 L/min, plasma flow 12 L/min, stabilization time 15 s and sample uptake time 25 s. Several other metals were tested. The data obtained for these are unsuitable for presentation due to exceedingly low concentrations, well below the ICP-OES standard established. Method detection limit was 0.009 ppm (Cu), 0.003 ppm (Cr), 0.002 ppm (Pb) and 0.011 ppm (Zn). Recovery tests were performed using certified reference material for soil (ERM CC141), with recovery rates ranging from 80% to 120%.

The Shapiro-Wilk test was utilised to assess the normality of the acquired data as the data is less than 50. Due to the data showing a non-normal distribution ($p < 0.05$) from Shapiro-Wilk test, the Kruskal-Wallis test was employed to assess the significant differences among the sampling points. All the statistical analysis test was performed using SPSS 20 (SPSS Inc., Chicago, IL, USA).

2.5. Health risk estimation

Empirical models can forecast the possible health impacts of ingesting, inhaling or dermal exposure, encompassing both non-cancer and cancer effects. The average daily dosage (ADD) functions as a quantitative metric to evaluate the potential health impact of metals in water and soil on humans (equation 1 - 3). For water, oral and dermal contact were considered as the exposure pathways. Meanwhile for soil, the exposure routes considered were inhalation and dermal contact. Table 2 shows the variable values used in calculating human health risk. Equation 4 was used to evaluate the health risks associated with non-cancer or hazard quotient (HQ). The calculation of the hazard index (HI) entails the aggregation of individual hazard quotients (HQs), as described in equation 5:

$$ADD_{oral} = (C \times IR \times ED \times EF \times CF) / (BW \times AT) \quad (1)$$

$$ADD_{dermal} = (C \times SA \times AF \times ABF \times CF \times ED \times EF) / (BW \times AT) \quad (2)$$

$$ADD_{inhale} = (C \times InhR \times EF \times ED) / (PEF \times BW \times AT) \quad (3)$$

$$HQ = ADD / RfD \quad (4)$$

$$HI = \sum HQ \quad (5)$$

The carcinogenic risk (CR) levels related to exposure to a likely carcinogen via oral, inhale and skin contact were estimated. These estimations allow for an assessment of a person's lifetime probability of developing cancer. The United

States Environmental Protection Agency defines a tolerable cancer risk range as between 1.0×10^{-6} and 1.0×10^{-4} (USEPA, 2011). The following equations (6-8) were used to determine the cancer risk in the current investigation, with equation 9 describing total cancer risk (TCR) (Proshad et al., 2020). Table 3 presents the reference dose and slope factor values used in calculating health risk.

$$CR_{oral} = ADD_{oral} \times SF \quad (6)$$

$$CR_{dermal} = ADD_{dermal} \times SF \quad (7)$$

$$CR_{inhale} = ADD_{inhale} \times IUR \quad (8)$$

$$TCR = \sum CR \quad (9)$$

Table 2: Variables used to estimate the health risk of heavy metals exposure in the Jengka River.

Parameter	Unit	Value	Reference
C- Concentration of metal in water or soil	mg/L or mg/kg	-	-
CF- conversion factor	kg/mg	1×10^{-6}	
SA – Exposed surface area of the skin	cm ² /event	5700 (adults) 2800 (child)	USEPA (2002)
AF - Skin adherence factor	mg/cm ²	7×10^{-2} (adults) 2×10^{-1} (child)	USEPA (2002)
ABF-Dermal absorption factor	mg/cm ²	1×10^{-3}	USEPA (2002)
EF-Exposure frequency	days/year	350	USEPA (2002)
ED -Exposure duration	years	70 (adults) 6 (child)	USEPA (2002)
BW-Average body weight	kg	62.65 (adults) 15 (child)	Malaysian Adult Nutrition Survey (2009)
AT-Averaging time	days	24500 (adults) 2100 (child)	USEPA (2002)
IR - Ingestion rate	L/day	2 (adults) 1 (child)	USEPA (2002)
InhR- Inhalation rate	m ³ /day	20	USEPA (2002)
PEF- Particle emission factor	m ³ /kg	1.36×10^9	USEPA (2002)

3. RESULTS AND DISCUSSION

3.1 Concentration of metals in soil

The concentrations of heavy metals (Cu, Cr, Pb, and Zn) in both soil and river water samples collected from five sites (S1–S5) along the Jengka Riverine system are presented in Table 4. Soil samples consistently revealed higher concentrations of heavy metals compared to water, which is expected due to the soil's role as a sink for metal accumulation over time (Ahmad et al. 2021). All metal concentrations in soil samples, however, were below the guidelines limit set by Department of Environment, Malaysia

(DOE 2009). Kruskal-Wallis analysis revealed no significant differences in metal concentrations in soil across the sampling sites. Among all sites, S1 and S3 exhibited the highest mean concentrations of Cu (5.33 ± 2.31 mg/kg and 3.33 ± 1.15 mg/kg, respectively), while S2 reported Cu levels below the detection limit (bdl). The elevated Cu levels in S1 may reflect local agricultural practices, including the use of copper-based fungicides (Razali et al., 2021). Cr levels ranged from 1.146 ± 0.393 mg/kg (S1) to 3.33 ± 0.305 mg/kg (S3), with the highest concentrations at S3, indicating possible contamination from agricultural practices such as the used of fertilizer. While Cr is naturally present in soils, elevated levels raise concerns due to its potential toxicity in hexavalent form (Cr^{6+}) (Dashtey 2024).

Table 3: Reference dose and slope factor values.

Parameter	Pathways	Unit	Value	Reference
RfD-reference dose	Oral	mg/kg/day	Cu: 4×10^{-2}	USDOE (2011)
			Pb: 3.5×10^{-3}	
			Zn: 3×10^{-1}	
SF-slope factor	Dermal	mg/kg/day	Cu: 1.2×10^{-4}	USDOE (2011)
			Pb: 5.25×10^{-3}	
			Zn: 6×10^{-2}	
IUR-inhalation unit risk	Inhale	mg/kg/day	Cu: 4×10^{-2}	USDOE (2011)
			Pb: 3.5×10^{-3}	
			Zn: 3×10^{-2}	
IUR-inhalation unit risk	Oral	mg/kg/day	Pb: 5.25×10^{-3}	USDOE (2011)
			Dermal	
IUR-inhalation unit risk	Inhale	mg/m ³	Pb: 1.2×10^{-8}	USDOE (2011)

Pb concentrations were relatively consistent across all sites at $2.00-2.03 \pm 0.001$ mg/kg, except for S2 (1.33 ± 1.15 mg/kg), suggesting uniform historical inputs, possibly from past use of leaded petrol residues. Lead's persistence in soil poses long-term ecological and health risks, especially in areas accessed by children or near agricultural zones (Eyenubo et al., 2023). Zn levels were highest at S5 (5.33 ± 1.15 mg/kg), a factor which is likely influenced by the accumulation of Zn-rich sediments or localized pollution sources (main road and car workshop). While Zn is essential for plant growth, excessive concentrations can inhibit microbial activity and soil health (Baran et al., 2018).

3.2 Concentration of metals in water

The water samples showed lower metal concentrations in comparison to soil (Table 4). The Kruskal-Wallis test indicated no significant differences in metal concentrations in water among the sampling sites. Cu levels ranged from 0.01 to 0.02 mg/L, with the highest at S1. These levels remain below the WHO guideline value of 2 mg/L for

drinking water (WHO 2022) and still acceptable according to DOE (2025). However, their presence, although low, indicates possible leaching from contaminated soils or direct runoff (Sulaiman et al. 2025). Pb was below detection limit (bdl) at S1 and S2 but was detected at low concentrations in S3–S5 ($0.003-0.007$ mg/L), indicating contamination events or recent inputs. However, the recorded levels remain within acceptable thresholds by WHO (2022) and DOE (2025). Zn concentrations in water ranged from 0.013 to 0.033 mg/L, with the highest mean concentration at S4. These values are far below the maximum limit, suggesting minimal ecological threat at present, although bioaccumulation through aquatic organisms could still pose risks (Ejaz et al., 2024).

Table 4: Metal concentrations from river water and soil in Jengka Riverine system (mean±SD).

Soils (mg/kg) (n=15)				
	Cu	Cr	Pb	Zn
S1	5.13 ± 2.31	1.146 ± 0.393	2.02 ± 0.001	4.67 ± 1.15
S2	bdl	2.67 ± 0.305	1.33 ± 1.15	4.00 ± 0.001
S3	3.33 ± 1.15	3.33 ± 0.305	2.01 ± 0.001	2.67 ± 1.15
S4	2.02 ± 0.001	2.00 ± 0.001	2.00 ± 0.001	2.01 ± 0.001
S5	2.00 ± 0.001	2.01 ± 0.001	2.03 ± 0.001	5.33 ± 1.15
DOE (2009)	13.80	6.00	10.37	21.90
Kruskal Wallis test				
χ^2	12.610	7.846	4.000	10.656
p-value	0.130	0.097	0.406	0.031
Shappiro-Wilk test				
p-value	0.013	0.000	0.000	0.006
Water (mg/L) (n=15)				
	Cu	Cr	Pb	Zn
S1	0.02 ± 0.01	bdl	bdl	0.030 ± 0.017
S2	0.013 ± 0.01	bdl	bdl	0.013 ± 0.011
S3	0.011 ± 0.001	bdl	0.007 ± 0.005	0.027 ± 0.005
S4	0.013 ± 0.005	bdl	0.003 ± 0.001	0.033 ± 0.003
S5	0.01 ± 0.01	bdl	0.003 ± 0.001	0.023 ± 0.015
DOE (2025)	0.02	0.05	0.05	5.00
Kruskal Wallis test				
χ^2	2.687	-	5.600	4.684
p-value	0.612	-	0.231	0.321
Shappiro-Wilk test				
p-value	0.037	-	0.000	0.093

bdl -below detection limit, Kruskal Wallis test p-value > 0.05 indicates no significant difference, Shappiro-Wilk p-value < 0.05 indicates non-normal distribution

The difference between soil and water concentrations suggests that while metal pollution may not currently pose a severe risk to aquatic life, there is potential for future contamination if soil-bound metals are mobilized during heavy rainfall or land-use changes (Razali et al. 2021). The Jengka Riverine system shows signs of localized metal contamination, particularly in soil. While water quality currently remains within safe limits for heavy metals, the elevated levels in soil emphasize the need for regular monitoring and health risks assessment.

3.3 Health risk assessment

3.3.1 Average daily dose of soil exposure

The average daily doses (ADD) of dermal and inhalation exposure to heavy metals in soil (Cu, Pb, Zn) for both adults and children across five locations (S1–S5) was indicated in Table 5. The health risk model proposed by USEPA (2002) accounted for Cr⁶⁺, hence this study does not provide any estimation for Cr exposure, as the data obtained only examined total Cr based on ICP OES analysis. Children are more susceptible to higher exposure levels compared to adults, a finding consistent with recent studies highlighting children's greater vulnerability, due to various physiological and behavioural factors (Rahman et al., 2021; Yu et al., 2021).

Children have significantly higher dermal doses across all metals, particularly at sites S1, S4, and S5. For instance, the ADD for Cu in children at S1 was 1.98×10⁻⁷ mg/kg/day, nearly six times higher than the adult dose at the same site (3.39×10⁻⁸ mg/kg/day). A similar pattern was observed for Zn and Pb, where the children's dermal doses were consistently higher. The elevated exposure at S5 may suggest localized contamination, possibly from anthropogenic activities such as waste runoff (Razali et al. 2021). This is aligned with the characteristics observed for S5, with car workshops located nearby.

Even though inhalation doses were lower than dermal contact across all sites, they remain non-negligible, specifically for children. For example, at S1, the inhalation dose for Zn in children (4.57×10⁻⁹ mg/kg/day) was more than four times higher than the corresponding adult dose (1.09×10⁻⁹ mg/kg/day). While the absolute values are relatively low, chronic exposure, especially in developing children, could contribute to cumulative toxicological effects (USEPA, 2004).

3.3.2 Average daily dose of water exposure

Table 6 shows the average daily doses (ADD) through dermal contact and ingestion from water exposure of metals in the Jengka Riverine water system. Across all

sampling sites (S1–S5), dermal ADD values were lower than ingestion values, reflecting the limited skin permeability of metals and shorter contact durations. However, children's dermal doses were consistently higher than adults. For instance, at S1, the dermal ADD of Cu for children was 7.46×10⁻¹⁰ mg/kg/day, compared to 1.27×10⁻¹⁰ mg/kg/day for adults. The highest dermal Zn exposure for children was recorded at S4 (1.24×10⁻⁹ mg/kg/day), which may indicate elevated Zn concentrations in water, consistent with findings from previous study in tropical river (Sulaiman et al., 2023). Pb levels were observed at S3 to S5 in very low doses (e.g., 2.48×10⁻¹⁰ mg/kg/day for children at S3). Although these values are below reference dermal exposure thresholds (USEPA, 2004), chronic exposure, especially in sensitive populations, may pose developmental concerns.

Table 5: Average daily dose of dermal contact and inhalation for adults and children of exposure to soil (mg/kg/day).

		Dermal contact		
Adults	Location	Cu	Pb	Zn
	S1	3.39×10 ⁻⁸	1.27×10 ⁻⁸	2.97×10 ⁻⁸
	S2	0	8.47×10 ⁻⁹	2.54×10 ⁻⁸
	S3	2.12×10 ⁻⁸	1.27×10 ⁻⁸	1.70×10 ⁻⁸
	S4	1.27×10 ⁻⁸	1.27×10 ⁻⁸	1.27×10 ⁻⁸
	S5	1.27×10 ⁻⁸	1.27×10 ⁻⁸	3.39×10 ⁻⁸
Child	Location	Cu	Pb	Zn
	S1	1.98×10 ⁻⁷	7.46×10 ⁻⁸	1.74×10 ⁻⁷
	S2	0	4.96×10 ⁻⁸	1.49×10 ⁻⁷
	S3	1.24×10 ⁻⁷	4.57×10 ⁻¹¹	6.10×10 ⁻¹¹
	S4	7.46×10 ⁻⁸	7.46×10 ⁻⁸	7.46×10 ⁻⁸
	S5	7.46×10 ⁻⁸	7.46×10 ⁻⁸	1.98×10 ⁻⁷
		Inhalation		
Adults	Location	Cu	Pb	Zn
	S1	1.25×10 ⁻⁹	4.69×10 ⁻¹⁰	1.09×10 ⁻⁹
	S2	0	3.12×10 ⁻¹⁰	9.38×10 ⁻¹⁰
	S3	7.81×10 ⁻¹⁰	4.69×10 ⁻¹⁰	6.26×10 ⁻¹⁰
	S4	4.69×10 ⁻¹⁰	4.69×10 ⁻¹⁰	4.69×10 ⁻¹⁰
	S5	4.69×10 ⁻¹⁰	4.69×10 ⁻¹⁰	1.25×10 ⁻⁹
Child	Location	Cu	Pb	Zn
	S1	5.22×10 ⁻⁹	1.96×10 ⁻⁹	4.57×10 ⁻⁹
	S2	0	1.30×10 ⁻⁹	3.92×10 ⁻⁹
	S3	3.26×10 ⁻⁹	1.96×10 ⁻⁹	2.61×10 ⁻⁹
	S4	1.96×10 ⁻⁹	1.96×10 ⁻⁹	1.96×10 ⁻⁹
	S5	1.96×10 ⁻⁹	1.96×10 ⁻⁹	5.22×10 ⁻⁹

Children once again showed substantially higher exposure via ingestion, particularly for Zn and Cu. For example, at S1, the ingestion ADD of Zn for children was 2.00×10⁻⁹ mg/kg/day, while for adults it was 9.57×10⁻¹⁰ mg/kg/day. Zn ingestion levels were highest at S4 for both age groups (1.06×10⁻⁹ mg/kg/day in adults, 2.22×10⁻⁹ mg/kg/day in children). While Zn is an essential micronutrient, excessive exposure may disrupt gastrointestinal and immune functions (Wan and Zhang, 2022).

Lead exposure through ingestion was most concerning. While Pb was undetectable at S1 and S2, it was

found at S3, S4, and S5, with the highest ingestion ADD for children at S3 (4.44×10^{-10} mg/kg/day). This is especially noteworthy as Pb exposure, even at low levels, has been linked to neurodevelopmental deficits and behavioural issues in children (WHO, 2022; Córdoba-Gamboa et al., 2023). Although these values remain below acute toxicity thresholds, they may still contribute to cumulative body burden over time, especially among communities with multiple exposure pathways.

Table 6: Average daily dose of dermal contact and ingestion for adults and children of exposure to water (mg/kg/day).

Dermal contact				
Adults	Location	Cu	Pb	Zn
	S1	1.27×10^{-10}	0	1.91×10^{-10}
	S2	8.49×10^{-11}	0	8.49×10^{-11}
	S3	6.36×10^{-11}	4.24×10^{-11}	1.69×10^{-10}
	S4	8.49×10^{-11}	2.12×10^{-11}	2.12×10^{-10}
	S5	6.36×10^{-11}	2.12×10^{-11}	1.48×10^{-10}
Child	Location	Cu	Pb	Zn
	S1	7.46×10^{-10}	0	1.12×10^{-9}
	S2	4.97×10^{-10}	0	4.97×10^{-10}
	S3	3.73×10^{-10}	2.48×10^{-10}	9.95×10^{-10}
	S4	4.97×10^{-10}	1.24×10^{-10}	1.24×10^{-9}
	S5	3.73×10^{-10}	1.24×10^{-10}	8.71×10^{-10}
Ingestion				
Adults	Location	Cu	Pb	Zn
	S1	6.38×10^{-10}	0	9.57×10^{-10}
	S2	4.25×10^{-10}	0	4.25×10^{-10}
	S3	3.19×10^{-10}	2.12×10^{-10}	8.51×10^{-10}
	S4	4.25×10^{-10}	1.06×10^{-10}	1.06×10^{-9}
	S5	3.19×10^{-10}	1.06×10^{-10}	7.44×10^{-10}
Child	Location	Cu	Pb	Zn
	S1	1.33×10^{-9}	0	2.00×10^{-9}
	S2	8.89×10^{-10}	0	8.89×10^{-10}
	S3	6.67×10^{-10}	4.44×10^{-10}	1.77×10^{-9}
	S4	8.89×10^{-10}	2.22×10^{-10}	2.22×10^{-9}
	S5	6.67×10^{-10}	2.22×10^{-10}	1.55×10^{-9}

3.4 Hazard quotients of dermal contact and inhalation exposure to soil contaminant

Table 7 outlines the hazard quotient (HQ) values for dermal contact and inhalation exposure to soil contaminant (Cu, Pb, and Zn) for both adults and children across five different locations (S1 to S5). These HQ values are essential in assessing the potential non-carcinogenic health risks associated with soil contamination. A comparison of dermal contact and inhalation exposure pathways reveals that for both adults and children, dermal contact generally poses a higher non-carcinogenic risk than inhalation.

For adults, the HQ values for dermal contact are generally low, indicating minimal non-carcinogenic risk. The highest HQ value is observed for Cu at location S1 (2.82×10^{-4}). This aligns with findings from a study in peninsular Malaysia in which Cu was identified as an

important contributor to health risks in soil exposure (Yap et al., 2021). In contrast, children have higher HQ values, particularly for Cu with the highest value of 1.65×10^{-3} . These values indicate a higher non-carcinogenic risk for children than adults, consistent with research indicating that children are more susceptible to soil-borne contaminants due to higher soil ingestion rates and greater dermal absorption (Yang et al., 2022).

Inhalation HQ values for adults are relatively low across all locations, with the highest value being 1.33×10^{-7} for Pb. This suggests that inhalation is a less significant exposure pathway for adults in the studied areas. For children, inhalation HQ values are higher than adults, where Pb showed an HQ of 5.57×10^{-7} . This elevated risk underscores the importance of considering inhalation exposure in children, as they are more vulnerable to airborne contaminants due to higher respiratory rates and developing respiratory systems (Behrooz et al., 2021).

Table 7: Hazard quotient of dermal contact and inhalation for adults and children of exposure to soil.

Dermal contact				
Adults	Location	Cu	Pb	Zn
	S1	2.82×10^{-4}	2.42×10^{-6}	4.95×10^{-7}
	S2	0	1.61×10^{-6}	4.24×10^{-7}
	S3	1.76×10^{-4}	2.46×10^{-6}	2.83×10^{-7}
	S4	1.06×10^{-4}	2.42×10^{-6}	2.12×10^{-7}
	S5	1.06×10^{-4}	2.42×10^{-6}	5.65×10^{-7}
Child	Location	Cu	Pb	Zn
	S1	1.65×10^{-3}	1.42×10^{-5}	2.96×10^{-6}
	S2	0	9.45×10^{-6}	2.48×10^{-6}
	S3	1.03×10^{-3}	8.70×10^{-9}	1.01×10^{-9}
	S4	6.22×10^{-4}	1.42×10^{-5}	1.24×10^{-6}
	S5	6.22×10^{-4}	1.42×10^{-5}	3.31×10^{-6}
Inhalation				
Adults	Location	Cu	Pb	Zn
	S1	3.12×10^{-8}	1.33×10^{-7}	3.65×10^{-8}
	S2	0	8.86×10^{-8}	3.12×10^{-8}
	S3	1.95×10^{-8}	1.33×10^{-7}	2.08×10^{-8}
	S4	1.17×10^{-8}	1.33×10^{-7}	1.56×10^{-8}
	S5	1.17×10^{-8}	1.33×10^{-7}	4.17×10^{-8}
Child	Location	Cu	Pb	Zn
	S1	1.30×10^{-7}	5.57×10^{-7}	1.52×10^{-7}
	S2	0	3.70×10^{-7}	1.30×10^{-7}
	S3	8.16×10^{-8}	5.57×10^{-7}	8.72×10^{-8}
	S4	4.90×10^{-8}	5.57×10^{-7}	6.53×10^{-8}
	S5	4.90×10^{-8}	5.57×10^{-7}	1.74×10^{-7}

3.5 Hazard quotients of dermal contact and ingestion exposure to water contaminant

Table 8 presents the hazard quotients (HQ) for dermal contact and ingestion exposure to Cu, Pb, and Zn in water for adults and children across five locations (S1 to S5). These HQs are essential for assessing the potential non-carcinogenic health risks associated with water

contamination. Dermal contact generally poses a higher non-carcinogenic risk than ingestion of the exposure pathways reveals for both adults and children. Children are at a particularly higher risk from Cu and Zn exposure through dermal contact.

The HQs for dermal contact exposure to Cu, Pb, and Zn are generally low across all locations, indicating minimal non-carcinogenic risk for adults. The high HQs are observed for Cu at location S1 (1.06×10^{-6}) and Pb at location S3 (8.08×10^{-9}), suggesting that these metals may pose a slightly higher risk through dermal exposure compared to Zn. Children have higher HQs for dermal contact exposure to Cu compared to those in adults. At location S1, the HQ for Cu for children is 6.22×10^{-6} , while for adults is 1.06×10^{-6} . These elevated HQs indicate a higher non-carcinogenic risk for children, consistent with studies highlighting that children are more susceptible to waterborne contaminants due to higher skin absorption rates and developing physiological systems (Xie et al., 2017).

For ingestion exposure in adults, the HQs for ingestion exposure to Cu, Pb, and Zn are lower compared to dermal contact exposure, indicating that dermal contact is a more significant route of exposure. The highest HQs are observed for Cu at location S3 (7.98×10^{-8}), suggesting that this metal may pose a slightly higher risk through ingestion. For children, the HQs for ingestion exposure are slightly lower than those for dermal contact, indicating that dermal contact is the predominant exposure route. The highest HQ value for children is at location S3 with 1.26×10^{-7} for Pb. Although the HQ values were below the unity value, these elevated HQs emphasise the importance of considering ingestion exposure in children, as they are more vulnerable to waterborne contaminants due to higher water intake relative to body weight (Eid et al., 2024).

3.6 Hazard index of metal exposure from soil and water

Figure 2 highlights notable variations in non-carcinogenic health risks associated with metal exposure via soil and water for both adults and children based on hazard index (HI). Children consistently have higher HI values across all exposure pathways dermal contact, ingestion, and inhalation especially from soil, aligning with earlier findings that children are more vulnerable to environmental contaminants, likely due to their lower body weight and frequent hand-to-mouth behaviour (Parlak et al., 2022).

The HI values not exceeding the safety threshold of 1, however, in the case of soil exposure, indicate potential health concerns. This is consistent with studies in similar agro-industrial regions where elevated levels of metals such as lead (Pb) and copper (Cu) in soil have been linked to agricultural runoff and atmospheric deposition from nearby industrial

activities (Proshad et al., 2020; Simatupang et al., 2024). Specifically, the HI values for Cu and Pb suggest potential exposure risks, especially for children, which may lead to developmental and neurological effects (Xie et al., 2017).

Table 8: Hazard quotient of dermal contact and ingestion for adults and children of exposure to water.

		Dermal contact		
Adults	Location	Cu	Pb	Zn
	S1	1.06×10^{-6}	0	3.18×10^{-9}
	S2	7.07×10^{-7}	0	1.41×10^{-9}
	S3	5.30×10^{-7}	8.08×10^{-9}	2.83×10^{-9}
	S4	7.07×10^{-7}	4.04×10^{-9}	3.53×10^{-9}
	S5	5.30×10^{-7}	4.04×10^{-9}	2.47×10^{-9}
Child	Location	Cu	Pb	Zn
	S1	6.22×10^{-6}	0	1.86×10^{-8}
	S2	4.18×10^{-6}	0	8.29×10^{-9}
	S3	3.11×10^{-6}	4.74×10^{-8}	1.65×10^{-8}
	S4	4.18×10^{-6}	2.37×10^{-8}	2.07×10^{-8}
	S5	3.11×10^{-6}	2.37×10^{-8}	1.45×10^{-8}
		Ingestion		
Adults	Location	Cu	Pb	Zn
	S1	1.59×10^{-8}	0	3.19×10^{-9}
	S2	1.06×10^{-8}	0	1.41×10^{-9}
	S3	7.98×10^{-8}	6.08×10^{-8}	2.38×10^{-9}
	S4	1.06×10^{-8}	3.04×10^{-8}	3.54×10^{-9}
	S5	7.98×10^{-9}	3.04×10^{-8}	2.48×10^{-9}
Child	Location	Cu	Pb	Zn
	S1	3.33×10^{-8}	0	6.67×10^{-9}
	S2	2.22×10^{-8}	0	2.96×10^{-9}
	S3	1.67×10^{-8}	1.26×10^{-7}	5.92×10^{-9}
	S4	2.22×10^{-8}	6.34×10^{-8}	7.40×10^{-9}
	S5	1.67×10^{-8}	6.34×10^{-8}	5.18×10^{-9}

The HI values for water exposure are significantly lower, which is likely due to dilution effects and possibly lower metal solubility or mobility in the aquatic medium. However, even these lower values must not be disregarded, particularly for communities relying heavily on river water for domestic and recreational use. As highlighted by Glicklich and Frishman (2021), even sub-threshold chronic exposures can lead to cumulative health effects over time, especially among metal-sensitive populations.

The spatial distribution of HI also implies site-specific risk variation, possibly influenced by point-source pollution such as industrial effluents and non-point sources like fertilizer application. This suggests the need for targeted risk management strategies and spatially resolved monitoring efforts. Moreover, given the observed differences in risk profiles between adults and children, public health advisories should prioritize vulnerable groups and emphasize preventive behaviours.

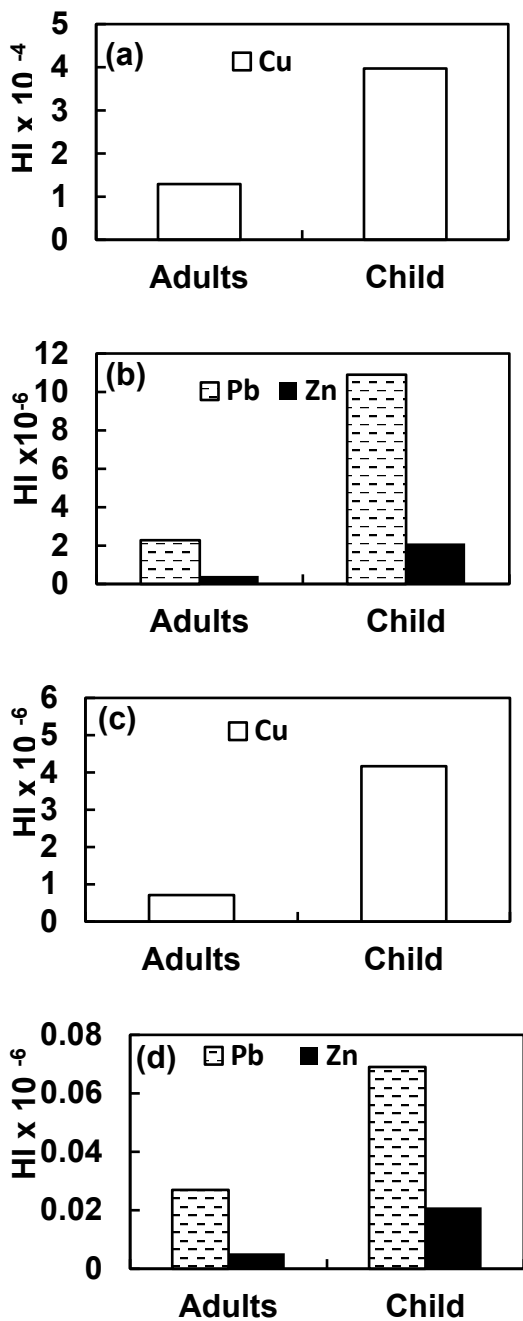


Figure 2: Hazard index for adults and children of metal exposure from (a-b) soil and (c-d) water.

3.7 Lifetime cancer risk of metal exposure from soil and water

Table 9 shows the estimated cancer risk levels associated with metal exposure through soil and water for both adults and children from Jengka Riverine system. The data highlight differences in risk magnitude between the two pathways and age groups, with children generally experiencing higher risk due to their lower body weight and higher intake rate relative to body mass (USEPA, 2004). Children showed elevated cancer risks compared to adults for soil exposure (Figure 3a). This aligns with findings from recent studies that highlight children's increased vulnerability to soil-

borne contaminants due to behaviours such as hand-to-mouth activity and prolonged outdoor play (Parlak et al., 2022). Notably, the total cancer risk consistent with previous environmental risk assessments in contaminated regions (Mahmoud et al., 2023).

Table 9: Cancer risk adults and children of metal exposure from soil and water.

Soil	CR dermal	CR inhale
	Pb	Pb
Adults	1.01×10^{-10}	5.25×10^{-18}
Children	4.65×10^{-10}	2.19×10^{-17}
Water	CR dermal	CR ingest
	Pb	Pb
Adults	8.91×10^{-14}	7.23×10^{-13}
Children	5.22×10^{-13}	1.51×10^{-12}

For the water exposure pathway (Figure 3b), although the overall cancer risks were lower than those from soil exposure, the total cancer risk is higher, especially among children. This observation confirms studies that emphasize the carcinogenic potential of metal even at low concentrations in drinking water (Latif et al., 2025). Furthermore, differences between adult and child exposure outcomes reaffirm the need for age-specific risk assessments in environmental health policies. This is particularly important for children, who are more susceptible not only due to exposure factors, but also their developing organs and systems (Xie et al., 2017).

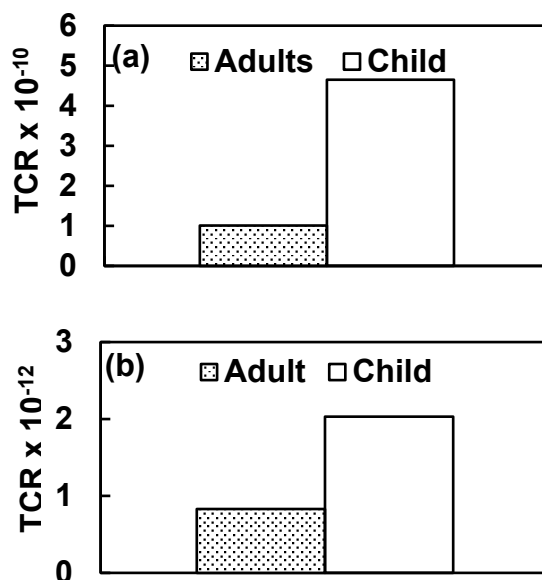


Figure 3: Lifetime cancer risk for adults and children of metal exposure from (a) soil and (b) water.

4. CONCLUSION

This study provides an assessment of the metal exposure risks in the Jengka Riverine system, revealing slight elevated concentrations observed downstream likely due to anthropogenic factors such as agricultural runoff and road

surface discharge. The presence of Cu, Cr, Pb, and Zn in environmental matrices highlights the relationship between land use practices and aquatic health. Hazard quotient (HQ) and lifetime cancer risk (LCR) values for both water and soil samples were within the acceptable limits. Nevertheless, the risk of non-carcinogenic and carcinogenic effects, especially in children via dermal contact, highlights the necessity for focused public health intervention. The presence of Pb warrants ongoing monitoring, given its long-term health effects even at low concentrations. Integrated continuous environmental monitoring, in conjunction with pollution mitigation strategies and public awareness initiatives, is important to reduce long-term health risks and ensure the sustainability of Jengka River for future generations. Future studies should focus on bioavailability assessment, seasonal variation analysis, and the cumulative impact of mixed metal exposure on susceptible populations.

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