Jurnal Kesehatan Lingkungan
Journal of Environmental Health
Journal Home Page:
https://e-journal.unair.ac.id/JKL
Vol. 17 No. 2
DOI: 10.20473/jkl.v17i2.2025.110-119
ISSN: 1829 - 7285 | E-ISSN: 2040 - 881X

ORIGINAL RESEARCH Open Access

HUMAN HEALTH RISK ASSESSMENT OF HEAVY METALS IN THE SERAYU RIVER WATER, CENTRAL JAVA-INDONESIA

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Article Info

Submitted	: 31 January 2025
In reviewed	: 3 March 2025
Accepted	: 18 April 2025
Available Online	: 30 April 2025

Keywords : *Hazard index, Hazard quotient, Health risk, Heavy metal, River*

Published by *Faculty of Public Health Universitas Airlangga*

Abstract

Introduction: *Pollution is a major factor contributing to the decline in river water quality, which serves as a source of clean water for residents. This study examines the pollution degrees of heavy metals, including lead, cadmium, chromium, nickel, arsenic, cobalt, and manganese, in surface water, as well as the associated public health risks for adults and children.* ***Methods:*** *Water samples were obtained from 18 unique sites along the Serayu River in Central Java Province. The concentrations of heavy metals were measured utilizing an Atomic Absorption Spectrophotometer. The heavy metal pollution index was employed to evaluate the Serayu River's suitability as drinking water. Public health risks were evaluated by employing the hazard quotient (HQ), hazard index (HI), and carcinogenic risk estimation.* ***Results and Discussion:*** *The heavy metal pollution index exceeded 100 at several sampling sites (W1, W2, W3, W4, W6, W7), indicating that the water is unsafe for drinking. However, non-carcinogenic risks from metal ingestion are negligible, as the HI and HQ values for both adults and children remain below one. The estimated carcinogenic risk is within the acceptable threshold (1E-4), with values of 1.109E-6 for adults and 4.199E-6 for children, suggesting no significant carcinogenic risk to the population.* ***Conclusion:*** *The results indicate that the Serayu River does not pose a significant carcinogenic or non-carcinogenic for illness to adults and children. However, owing to their heightened susceptibility to toxic effects, monitoring strategies to address the elevated vulnerability of children to heavy metal exposure.*

INTRODUCTION

Water quality has declined in many countries worldwide, particularly in developing nations (1). This deterioration is primarily driven by increasing anthropogenic activities such as industrialization, urbanization, and agriculture (2). Rapid industrialization, population growth, and unregulated agricultural activities have led to significant concerns about clean water availability, prompting extensive research on water quality and scarcity (3).

Indonesia, like other developing countries, faces substantial water quality challenges due to human activities (4). These activities introduce pollutants such as heavy metals, pesticides, and industrial waste into water sources. As a result, ensuring safe drinking water for the population becomes increasingly difficult and requires significant intervention and regulation. Rivers, as crucial sources of surface water, play a vital role in providing clean water and supporting local communities. However, several major rivers in Indonesia, such as the Brantas River in East Java, the Bengawan Solo River in Central Java, and the Citarum River in West Java, have been significantly impacted by anthropogenic activities (5–7).

River water in fact suffers from heavy metal pollution. Even small amounts of these poisonous metals could damage the ecology, and pollution from their exposure to humans is too costly (8). Toxic metals

Cite this as :
Handayani CO, Zu'amah H, Sukarjo S. Human Health Risk Assessment of Heavy Metals in the Serayu River Water, Central Java-Indonesia. *Jurnal Kesehatan Lingkungan*. 2025;17(2):110-119. https://doi.org/10.20473/jkl.v17i2.2025.110-119

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in water are directly related to public health since their ill effects can pass through our aliment (including what food we eat and our drinking-water) into our bodies (9). Metallic elements can come into people in several ways: through eating, breathing, or contact with the skin. The most common paths of contaminant invasion are ingestion and skin contact (10). The primary route for human exposure to heavy metals is to drink water that contains these poisonous substances (11). If a person drinks water with a high content of toxic metals for a long period, these poisons will accumulate in the body and produce a variety of health problems (12). Exposure to heavy metals raises a number of health hazards, including diseases both non-cancerous and cancerous. It can result in such things as diseases of the respiratory and digestive systems (13). Non-cancerous disorders of the nervous system, breathing difficulties, and dyspepsia are all symptoms of heavy metal poisoning, while cancers derive from malignancy (14–16). Children are particularly vulnerable to the harmful effects of heavy metals because their growing bodies consume more food and water relative to their weight. Contaminated river water doesn't just impact humans and harms aquatic life, disrupting ecosystems and increasing health risks for people as toxins move up the food chain. The Serayu River, a major river in Central Java Province, serves multiple communities across Wonosobo, Banjarnegara, Purbalingga, Banyumas, and Cilacap (17). Previous studies have documented environmental degradation in the Serayu Watershed due to human activities, including intensive crop cultivation in Wonosobo, sand mining in Cilacap, and industrial pollution (18–20). Although previous studies have documented environmental degradation in the Serayu River, limited research exists on the specific human health risks assessment with heavy metal contamination.

Human Health Risk Assessment (HHRA) is an established approach to predict how exposure to pollution could affect human health (21). Human Health Risk Assessment (HHRA) looks at individual exposures brought about by various environmental contaminants through different routes, including drinking water, dermal absorption and inhalation. The Serayu River, under sustained human activity such as industry and agriculture, needs an overall health assessment. The river is a vital water source for communities nearby, but such activities have introduced toxic pollutants, including lead, mercury and arsenic, into the water, posing serious health risks. HHRA helps monitor these contaminants' amounts for researchers and identifies how people become vectors of risk. Findings from HHRA will permit policymakers and local leaders to come up with successful strategies. The new system allows communities to maintain ongoing surveillance. Any swings in pollution levels can be addressed immediately, ensuring the safety and health of an entire town.

Considering the critical role of river water as a safe water supply for communities, it is imperative to assess its quality, particularly with regard to heavy metal contamination. This study aims to evaluate the pollution index of heavy metals (Pb, Cd, Cr, Ni, As, Co, Mn) in the Serayu River and assess the associated non-carcinogenic and carcinogenic health risks for adults and children through consumption and dermal exposure.

METHODS

Research Location and Water Sampling

The Serayu River is located in Central Java Province at 7.03111°-7.53167° South Latitude and 108.83778°-110.07222° East Longitude. It flows through the districts of Wonosobo, Banjarnegara, Purbalingga, Banyumas, and Cilacap in Central Java Province. The Serayu River has an inflow rate of 6.56 dal/s and an outflow rate of 28.66 dal/s, with a total length of 181 kilometers.

Table 1. Location of Water Sampling in the Serayu River

Sample	Location	Coordinates	Sources that Caused Pollution
W1	Wonosobo	7° 40' 6.13" S 109° 7' 5.56" E	Paddy field, settlement, dryland agriculture
W2	Wonosobo	7° 39' 1.82" S 109° 7' 13.08" E	Paddy field, settlement, dryland agriculture
W3	Wonosobo	7° 38' 12.04" S 109° 6' 54.80" E	Paddy field, settlement, dryland agriculture
W4	Banjarnegara	7° 35' 49.27" S 109° 7' 27.53" E	Paddy field, settlement, dryland agriculture
W5	Banjarnegara	7° 35' 18.94" S 109° 8' 28.82" E	Paddy field, settlement
W6	Banjarnegara, Purbalingga	7° 32' 29.25" S 109° 10' 45.13" E	Paddy field, settlement
W7	Banjarnegara, Purbalingga	7° 29' 29.33" S 109° 13' 26.60" E	Paddy field, settlement, industry
W8	Banjarnegara, Purbalingga	7° 28' 39.99" S 109° 23'11.76"E	Paddy field, settlement, industry
W9	Banjarnegara, Purbalingga	7° 28' 17.05" S 109° 24' 35.93" E	Paddy field, settlement
W10	Banjarnegara, Purbalingga	7° 28' 31.97" S 109° 25' 13.78" E	Paddy field, settlement
W11	Banjarnegara, Purbalingga	7° 27' 2.22" S 109° 26' 26.76" E	Paddy field, settlement
W12	Banyumas	7° 26' 51.23" S 109° 27' 45.08" E	Paddy field, industry, forest, dryland agriculture
W13	Banyumas	7° 26' 31.79" S 109° 29' 19.36" E	Paddy field, settlement
W14	Cilacap	7° 26' 51.58" S 109° 31' 3.34" E	Paddy field, settlement, dryland agriculture
W15	Cilacap	7° 26' 6.35" S 109° 32' 39.12" E	Paddy field, settlement, dryland agriculture
W16	Cilacap	7° 23' 10.84" S 109° 37' 33.13" E	Paddy field, settlement
W17	Cilacap	7° 22' 58.02" S 109° 39' 14.01" E	Paddy field, settlement
W18	Cilacap	7° 23' 30.74" S 109° 41' 0.71" E	Paddy field, settlement

Water samples were collected from 18 different locations (Table 1). The selection of sampling sites by stratified random sampling considered various water sources, including natural freshwater sources, contaminated water sources, and water utilized for consumption. Water samples were collected throughout the rainy season to evaluate the impact of runoff from various pollution sources. Table 1 presents the locations of water collection sites. The sampling method at each station was adapted to the water flow conditions and followed the established procedures outlined in SNI 6989.57:2008 Part 57 for surface water sampling. Water specimens were taken using a common water sampler with a weighted base.

Analysis of Heavy Metals

The water samples were filtered through filter paper. The supernatant liquid was analyzed immediately using an atomic absorption Spectropotometer. Heavy metal levels for Pb, Cd, Cr, Ni, As, Co, and Mn were measured within this study. The analysis was performed at the IAERI testing laboratory, a reliable laboratory operating under SNI ISO 17025:2017 (License: LP-556-IDN).

Quality assurance and quality control of heavy metal data obtained through measurements were validated using standard control samples from the series analysis. The accuracy of the data was further verified by reanalyzing the specimens and comparing the results with the control samples. The detection limits for Pb, Cd, Cr, Ni, As, Co, and Mn were 0.008, 0.0038, 0.002, 0.0034, 0.0005, 0.003, and 0.004 mg/L, respectively.

Heavy Metal Contamination Index (HCI)

The Heavy Metal Contamination Index (HCI) is a trusted method for checking water quality by analyzing the levels of harmful substances. Water is deemed safe for drinking when the HCI value is less than 100, calculated using a specific formula (22):

$$\mathrm{HCI} = \frac{\sum Wi \left(\frac{\sum (Mi - Ii)}{\sum (Si - Ii)} x\ 100 \right)}{\sum Wi}$$

where Wi is the weighting factor for the ith component, Mi is the observed concentration of the ith toxic metal, Ii is the ideal concentration of the ith variable, and Si is the recommended concentration of the ith component.

Health Risk Assessment Tools

The hazard quotient (HQ) estimates the risk of non-carcinogenic health effects related to receiving heavy metals from water consumption. HQ is calculated using the following equation (11):

$$HQi = \frac{CDI}{RfD}$$

$$CDI_{ingestion} = \frac{CM\ x\ EF\ x\ ED\ x\ IRW}{BW\ x\ AT\ x\ 10^6}$$

$$CDI_{dermal} = \frac{CM\ x\ SA\ x\ KC\ x\ EF\ X\ ET\ x\ ED\ x\ ABS}{BW\ x\ AT\ x\ 10^6}$$

where CDI represents the chronic daily intake, CM is the concentration of heavy metals in water, EF is the exposure frequency (365 days/year), and IRW is the ingestion rate (35 L/day). ED denotes the exposure duration, while BW represents body weight (70 kg for adults and 15 kg for children). AT is the averaging time for non-carcinogenic substances (365 × ED days) and for carcinogens (365 × 70 years). SA represents the exposed skin surface area (5700 cm²/day for adults, 2800 cm²/day for children), KC is the skin permeability factor (0.001 cm/hour), ET is the exposure time (24 hours/day), 10^6 is the conversion factor from kg to mg, and ABS is the skin absorption fraction (0.03 for As and 0.001 for other metals). RfD is the reference dose set by the US EPA for ingestion and dermal exposure. An HQ value below 1 indicates that the population is not at risk of health issues. If HQ is equal to or greater than 1, non-carcinogenic health effects may occur, with the risk increasing as the HQ value rises (23).

The total Hazard Index (HI) is determined by adding the HQ values for all exposure routes (24):

$$\mathrm{HI} = \sum_{i=1}^{n} \mathrm{HQ_s} = \mathrm{HQ_{dermal}} + \mathrm{HQ_{ingestion}}$$

An HI value greater than 1 suggests the likelihood of non-carcinogenic health effects, while an HI value below 1 indicates no significant non-carcinogenic risk (25).

Carcinogenic risk is calculated based on lifetime exposure to individual metals and their corresponding cancer slope factors. The carcinogenic risk (CR) is determined using the following formula (11):

$$\mathrm{CR} = \sum_{i=1}^{n} CSF_i\ x\ CDI_i$$

where CRi represents the cancer risk for each metal, CDIi is the CDI of every metal, and CSFi is the cancer slope factor for inorganic metals. The acceptable lifetime carcinogenic risk range is between 10^{-6} and 10^{-4}. If CR exceeds 10^{-4}, a potential cancer risk exists for the population (26).

RESULTS

Heavy Metal Concentration of Serayu River Water

Based on the analysis that has been carried out, the following levels of heavy metals were obtained; lead (Pb) levels of 0.0610 mg/L, cadmium (Cd) 0.0003 mg/L, chromium (Cr) 0.0120 mg/L, nickel (Ni) 0.0122 mg/L, arsenic (As) 0.0012 mg/L, cobalt (Co) 0.0087 mg/L, and manganese (Mn) 0.0392 mg/L, with standard deviations of lead (Pb) 0.0434, cadmium (Cd) 0.0014, chromium (Cr) 0.0010, nickel (Ni) 0.0020, arsenic (As) 0.0006, cobalt (Co) 0.0023 and for manganese (Mn) 0.0088. For the metals, the minimum levels reported were zero, indicating that some samples did not contain these substances. Over all of the locations tested, the average concentration of lead was 0.061 mg/L, which is outside of the safety limit of 0.030 mg/L for drinking water (27). At least the amounts of other metals (Cd, Cr, Ni, As, Co, and Mn) also fall below the limits for water quality.

At all water sampling stations along the Serayu River, heavy metals Pb, Cr, and Ni exceeded drinking water quality standards in certain locations, such as W1 and W3. In contrast, in 11 other locations (W2, W4, W5, W6, W7, W8, W9, W10, W11, W13, and W15), only Pb concentrations exceeded the quality limits. Pb concentrations surpassing the permissible limit were observed in 13 sampling locations, whereas Cr and Ni concentrations exceeded the standards in only two locations each. The concentrations of Cd, As, Co, and Mn remained below the quality standards at all sampling locations.

Table 2. Summary Statistics of Metallic Elements for River Water Samples

Descriptive statistics	Pb (mg/L)	Cd (mg/L)	Cr (mg/L)	Ni (mg/L)	As (mg/L)	Co (mg/L)	Mn (mg/L)
Mean	0.0610	0.0003	0.0120	0.0122	0.0012	0.0087	0.0392
SD	0.0434	0.0014	0.0222	0.0221	0.0033	0.0085	0.0021
Min	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0350
Max	0.1250	0.0060	0.0740	0.0740	0.0140	0.0240	0.0420
Quality standards (51)	0.03	0.01	0.05	0.05	0.05	0.2	0.4

Heavy Metal Contamination Index (HCI)

The HCI value serves as an indicator of river water quality by assessing contamination from toxic metals. The HCI value is derived based on the average concentrations of heavy metals. As shown in Table 3, the overall HCI value is 39.773 (<100), indicating that, on average, the river water quality remains within acceptable limits. However, specific locations, including W1, W2, W3, W4, W6, and W7, exhibit HCI values exceeding 100 (Figure 1), suggesting localized contamination concerns.

Table 3. Heavy Metal Contamination Index (HCI) Value of Serayu River Water

Parameters	Mean Value mgl/L (Mi)	Standard Tolerable Level (Si)	Highest Acceptable Level (Ii)	Unit Weighting Factor (wi)	Qi	Qi*Wi	HCI
Pb	0.061	0.030	0.000	10.000	203.056	2030.556	
Cd	0.000	0.010	0.000	33.330	3.500	116.655	
Cr	0.012	0.050	0.000	2.000	23.978	47.956	
Ni	0.012	0.050	0.000	0.500	24.444	12.222	39.773
As	0.001	0.050	0.000	10.000	2.267	22.667	
Co	0.009	0.200	0.000	0.100	4.328	0.433	
Mn	0.039	0.400	0.000	0.200	9.735	1.947	

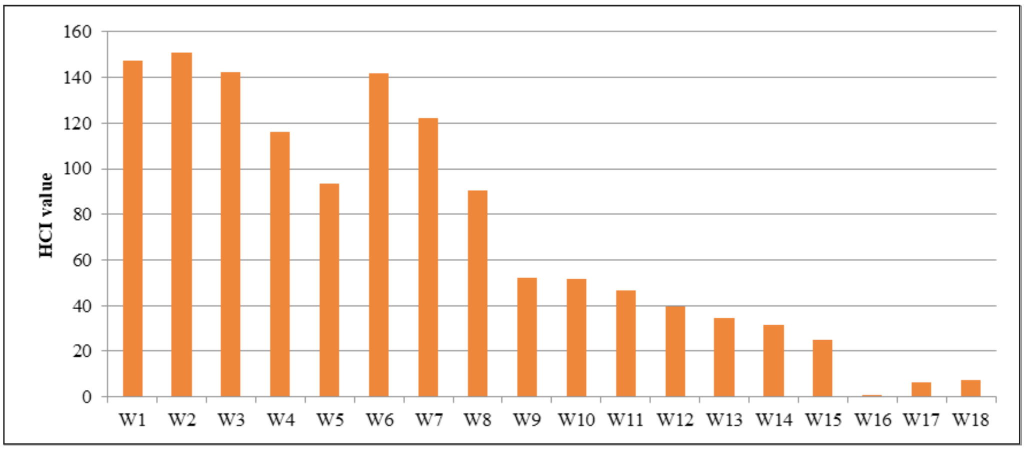

Figure 1. The HCI Level at Every Water Station

Health Risk Measurement

Non-Carcinogenic Risk

The non-carcinogenic risk was evaluated based on HQ and HI values for different exposure routes in both adults and children (Table 4). The average HQ values for all age groups follow the order: As > Cr > Pb > Co > Mn > Cd > Ni, for both ingestion and dermal absorption pathways (Table 4). The maximum HQ value for arsenic via the ingestion route is 2.21E-3 for adults and 8.82E-3 for children. For the dermal absorption route, the highest HQ value for arsenic is 2.59E-4 for adults and 5.08E-4 for children. The cumulative HQ values for all exposure routes remain within the permissible limit (HQ < 1), with ingestion posing a higher risk than dermal absorption.

Table 4. Hazard Quotient Value (HQ)

Trace Element	Adults		Children	
	Ingestion	Dermal	Ingestion	Dermal
Pb	8.88E-06	3.47E-08	3.55E-05	6.82E-08
Cd	6.81E-07	2.66E-09	2.72E-06	5.23E-09
Cr	2.33E-05	9.11E-08	9.32E-05	1.79E-07
Ni	1.78E-07	6.97E-10	7.13E-07	1.37E-09
As	2.21E.-03	2.59E-04	8.82E-03	5.08E-04
Co	5.05E-06	1.97E-08	2.02E-05	3.88E-08
Mn	9.46E-07	3.7E-09	3.79E-06	7.27E-09
HI	**0.00225**	**0.00026**	**0.00898**	**0.00051**

The HI values for children and adults were determined by summing the HQ values from ingestion and dermal absorption pathways. The HI value via ingestion for adults has a mean of 2.24E-4, whereas for children, the mean is 8.98E-4. The HI value via dermal absorption has an average of 0.26E-4 for adults and 0.51E-4 for children.

Carcinogenic Risk (CR)

Carcinogenic Risk (CR) Figure 2 presents the carcinogenic risk values for children and adults. The calculated CR values are 4.199E-6 for children and 1.109E-6 for adults, indicating a low but non-negligible lifetime cancer risk related to toxic metal exposure in the Serayu River.

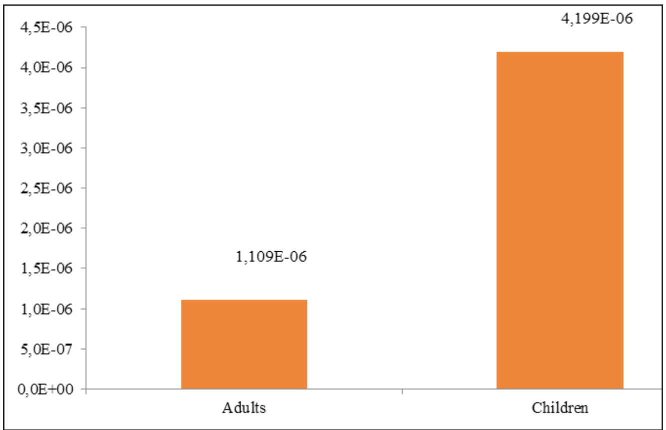

Figure 2. The Carcinogenic Risk Values for Both Children and Adults

DISCUSSION

Heavy Metal Concentration of Serayu River Water

The concentrations of heavy metals investigated were found in nearly all water sampling locations. Based on the mean degrees of several toxic metals, such as Pb, Cd, Cr, Ni, As, Co, and Mn, only Pb (0.061 mg/L) exceeded the quality standard for drinking water (0.030 mg/L). The presence of Pb in river water beyond the permissible limits poses significant health risks to communities that rely on this water source. Lead is a hazardous substance that can lead to severe health effects, particularly with prolonged exposure. It can accumulate in the human body, primarily in the teeth, bones, and soft tissues (28–30). Exposure to lead through contaminated water can result in neurological damage, especially in children, leading to developmental delays, behavioral issues, and impaired cognitive function (31). In adults, lead exposure can cause cardiovascular problems, reproductive health issues, and other complications (32–33). The majority of lead sources in rivers are anthropogenic, including industrial waste, domestic waste, mining runoff, and atmospheric deposition from industrial emissions and vehicle exhaust (34).

The average concentrations of lead (Pb) are much higher than the permissible limit (0.05 mg/L) for that of drinking water, which is further confirmed by data from individual sampling sites. Among all the sites studied, lead at 13 (W1, W2, W3, W4, W5, W6, W7, W8, W9, W10, W11, W13, and W15) locations exceeded the threshold of drinking water quality standard.

The levels of toxic metals Pb, Cr and Ni were detected at W1, W2 and W3 with concentrations that were above the quality standards at W1 and W3. These locations (W1, W2, and W3) are situated in Wonosobo Regency. Heavy metals in river water can originate from both natural sources (source rocks) and anthropogenic activities (35). The primary anthropogenic activity responsible for heavy metal deposition in Wonosobo Regency is intensive agriculture on the Dieng Plateau, which lies upstream of the Serayu River (36). In the Dieng highlands, Wonosobo Regency, potato farmers use manure and chemical fertilizers, as well as chemical pesticides, often in quantities that exceed recommended limits. Over time, the manure applied to agricultural land can lead to a build-up of toxic metals in the soil and agricultural products (37). In addition to agricultural activities, other anthropogenic sources contributing to elevated levels of metallic elements in the Serayu River include mining operations in Wonosobo and Banjarnegara Regencies. These mining activities, which involve C-type mining (stone and sand) and geothermal operations (38–39), generate heavy metal waste through excavation, material washing, or the inherent presence of heavy metals in the mining materials.

Heavy Metal Contamination Index (HCI)

The Heavy Metal Contamination Index (HCI) is an important tool to assess the presence of pollution from heavy metals in the environment, whether in soil, water, or sediment, providing a quantitative evaluation of the pollution's impact. The HCI value for Serayu River water is 39.773 (<100), indicating that, based on the mean content of all contaminants, the water is still safe for use as clean water. Lead (Pb) is the primary contributor to the overall contamination index. Its mean concentration

(0.061 mg/L) exceeds the standard tolerable level (0.030 mg/L) by more than double, making it the most critical contaminant in the river. Cadmium also contributes significantly to the HCI with a Qi value of 33.330 due to its toxicity; however, its mean concentration (0.000 mg/L) is below detectable levels, which results in a relatively smaller contribution (116.655). Despite this, the dominant roles of lead and cadmium in the HCI highlight the need for proactive management to prevent future risks to water quality. Lead, as the main contributor to the HCI, showed results consistent with those discussed previously regarding the concentration of heavy metals found in all water sampling locations, where values exceeded the quality limits for drinking water.

A more extensive HCI assessment for each water sampling point is still ongoing to provide more precise information regarding the suitability of Serayu River water as clean water. Locations W1, W2, W3, W4, W6, and W7 exhibit an HCI value above 100, indicating that these water samples are no longer acceptable for consumption (40). The water samples with HCI levels >100 are located in Wonosobo Regency and Banjarnegara Regency, while those with HCI values <100 are found in Purbalingga Regency, Banyumas Regency, and Cilacap Regency. Based on the overall HCI data, six points (33.33%) had an HCI value >100, while 12 locations (66.67%) had an HCI value <100.

A more comprehensive evaluation of Serayu River water as a potential drinking water source would benefit from a feasibility study conducted over two seasons: the rainy and dry periods (41). This research was conducted at the end of the rainy season, when precipitation is still frequent at the study site. The results of the HCI analysis align with the previous discussion regarding the higher level of heavy metals in the upstream areas of the Serayu River compared to the downstream areas. The upstream areas observed are located in Wonosobo Regency and Banjarnegara Regency. Wonosobo Regency, situated in the higher regions of the Serayu River, is known for large-scale potato production that utilizes fertilizers and pesticides (42). The heavy metals deposited from fertilizers and pesticides in these potato-producing areas are carried by rainwater into the neighboring rivers and the upstream regions of the Serayu River. Furthermore, mining activities, such as Class C mining and geothermal operations in Wonosobo and Banjarnegara Regencies, contribute to the heavy metal contamination in the Serayu River.

Future studies should also consider seasonal variations in contamination levels, as fluctuations in water flow during the rainy and dry periods can influence the distribution and concentration of heavy metals. A comprehensive assessment that incorporates broader seasonal and geographic sampling will offer a more detailed understanding of the risks and help develop more effective mitigation strategies.

Health Risk Measurement

Non-Carcinogenic Risk

Non-carcinogenic health risks from contact with heavy metals can arise when humans are exposed to these metals for a certain period at levels exceeding the safety threshold. This exposure can affect various body systems without causing cancer, primarily by disrupting organ function, the nervous system, and metabolism. In the analysis of non-carcinogenic health risks, arsenic (As) is the dominant trace element contributing to potential health problems from both oral and skin pathways for both adults and children. The dominance of arsenic in contributing to non-carcinogenic health risks is concerning due to its ability to bioaccumulate in the body over time. Whenever any kind of trace amounts of arsenic are exposed for any length of time, this can cause the build-up of arsenic within major organs such as the liver, kidney, and skin that may not become apparent early but instead pose major health hazards over the long term (43–45). Some arsenic in the body can interrupt its cellular functions; when cascades of oxidative stress hit, people will cease to respond to immune stimuli while also suffering damage deep down at a quantum level--Dna strands turn into double strand brakes Scaled up over time Like leading lines from an epic poem leading Toward floodtides, this contributing towards severe health problems such AT neurotoxicity, heart diseases or developmental delays in children (46). Arsenic can also interfere with enzymes and hormonal systems, thereby exacerbating its deleterious effects.

The Hazard Quotient (HQ) analysis shows that arsenic poses a greater health risk than lead, despite lead being more abundant in the Serayu River and contributing more to the Heavy Metal Contamination Index (HCI). This is because HQ values consider not only the concentration of a metal but also factors like its toxicity reference value and how people are exposed to it. Arsenic has higher inherent toxicity, stricter safety limits, and possibly greater bioavailability, making it a bigger threat. These findings highlight the need to focus on managing arsenic contamination in environmental and health risk assessments.

Children are much more vulnerable to the effects of trace element exposure compared to adults. The Hazard Quotient (HQ) value for oral exposure in children is four times higher than in adults, and for skin absorption, it is about twice as high. This increased risk in children can be attributed to their lower body weight, faster metabolism, and developmental stages, which make them more sensitive to toxic substances. These findings highlight the greater health risks children face and underscore the importance of implementing focused measures to protect this vulnerable group.

The aggregate HQ values for all exposure pathways were within permissible limits (HQ < 1), with consumption-related values exceeding skin absorption-related values. This research suggests that people are unlikely to face health concerns from drinking Serayu River water. However, while current HQ values indicate minimal non-carcinogenic risk, it is important to consider the potential for long-term changes in air quality and contamination sources. Continued anthropogenic activities, such as agricultural intensification, mining operations, and household waste disposal, may pose ongoing threats to air quality. Over time, these activities can lead to increased concentrations of heavy metals, potentially raising HQ values above safe thresholds.

The fact that HQ ingestion values are greater than HQ skin absorption values underscore the urgent need for pollution control measures in upstream areas where ingestion remains the predominant route of exposure to contaminants. Heavy metal runoffs to the river come from agricultural activities, with the use of fertilizers and pesticides, and from mining upstream. For the long-term preservation of water quality and public health, we must follow implemented measures like stricter environmental laws and regulations, improved waste management, and education for the public on sustainable practices. For ingestion, the HI values range for adults is 2.24E-4 (average value), while a much higher average level of HI values (8.98E-4) is observed for children. The average HI levels of 0.26E-4 for adults and 0.51E-4 for skin absorption illustrated that children's exposure to these risks was more vulnerable. These values indicate higher exposure levels for children than adults via ingestion and skin absorption. The difference can probably be attributed to their smaller body size and different behaviors and physiological characteristics that make them more vulnerable to contaminants.

The HI levels for both adults and children through the intake and skin absorption routes are within the safe limit (HI < 1), suggesting that non-carcinogenic harm to public health is unlikely, as the exposure levels remain within safe limits. The analysis underscores the importance of evaluating multiple exposure routes and age-specific risks to ensure comprehensive public health safety assessments. If the HI exceeds 1 (HI > 1), it indicates a potential risk of non-carcinogenic health effects from exposure to the assessed metal. This suggests that the exposure level surpasses the established safe reference dose, thereby increasing the probability of experiencing negative health effects. For instance, exposure to lead (Pb) is linked to neurological damage, particularly in children, whereas cadmium (Cd) exposure is associated with kidney and bone damage (47–48). Some populations, including children, pregnant women, and individuals with existing health conditions, are particularly vulnerable to the adverse effects of contamination. In addition, a higher body burden can exacerbate health risks with acute exposure, and some contaminants with Hazard Index (HI) values over one may have cumulative or combined effects. However, when HI values exceed a threshold of safety, immediate action is warranted, targeting and reducing contamination sources, intensifying existing environmental controls, and providing public guidance on mitigating exposure.

Carcinogenic Risk (CR)

The risk of developing cancer from heavy metal exposure increases with long-term exposure, even at low levels, as it can lead to genetic mutations, DNA damage, or uncontrolled cell growth. In the case of the Serayu River, the carcinogenic risk (CR) is estimated to be about 4 in 10 million for children and 1 in 10 million for adults over their lifetime. These values reveal that children are significantly more vulnerable to the cancer-causing effects of heavy metals compared to adults. This difference underscores how much more vulnerable children are to environmental contaminants. Factors such as their smaller body size, greater intake relative to their weight, and the fact that their biological systems are still developing all contribute to this heightened sensitivity (49).

The CR values for both children and adults remain below the acceptable tolerance limit of 1.E-4. These findings indicate that the carcinogenic risk for both groups is within tolerable thresholds. A CR value exceeding 1.E-4 would indicate a significant probability of developing various types of cancer from consuming river water (50). However, continuous monitoring of CR values and carcinogenic heavy metal concentrations is crucial to ensure that risks remain within acceptable limits, particularly for children, who are more susceptible to environmental pollutants.

ACKNOWLEDGMENTS

The authors are pleased to provide appreciation to the field technicians and laboratory analysts from IAERI, particularly Fitra Purnariyanto and Slamet Rianto, for their dedicated efforts in collecting and analyzing the heavy metal data.

AUTHORS' CONTRIBUTION

COH: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. HZ: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. S: Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

CONCLUSION

The concentrations of heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), cobalt (Co), and manganese (Mn) were found to vary across different sampling points in the Serayu River water, Central Java, Indonesia. Some of these concentrations approached or exceeded the thresholds set by water quality standards, particularly for Pb, Cr, and Ni. Thirteen water sampling locations showed Pb concentrations above the drinking water quality limit, and two locations exhibited concentrations of Pb, Cr, and Ni that exceeded the quality standards for drinking water. While most heavy metal concentrations remain within acceptable limits, the elevated Pb levels at certain locations suggest that the Serayu River is not uniformly safe for consumption.

HCI values exceeding 100 at several sampling locations (W1, W2, W3, W4, W6, W7) in Wonosobo Regency and Banjarnegara Regency (upper Serayu watershed) rendered the water unsuitable for community consumption. The source of these heavy metals is most likely linked to anthropogenic activities, including agriculture and mining practices conducted by communities around the Serayu River.

Health risk analysis indicates that exposure via water consumption and skin contact pathways results in higher HQ, HI, and CR values for children compared to adults. Non-carcinogenic and carcinogenic health hazards that affect children and adults remain within safe limits (HI < 1 and CR < 1.E-4). Although exposure to contaminants in Serayu River water does not present carcinogenic or non-carcinogenic risks for either adults or children, special attention should be given to the children's group due to their heightened vulnerability to toxic effects. Additional treatment is required to reduce the concentration of toxic substances (Pb) in the Serayu River water to make it suitable for consumption.

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