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Health Risk Assessment of Heavy Metals in Drinking Water Sources: Waste Water Management

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***Abstract*—This study aims to assess the potential health risks associated with heavy metals in water supply and its relationship with wastewater treatment in Jakarta's industrial area. Forty samples were collected from 20 different points, including groundwater, surface water, and wastewater effluent, during the dry and wet seasons of 2024. The concentration of five heavy metals—lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr)—was determined using an Inductively Coupled Plasma Mass Spectrometry (ICP-MS) instrument. Health risk assessment was conducted following the Environmental Protection Agency (EPA) protocol. While the overall mean concentration of all metals was within the World Health Organization (WHO) permissible limit, lead exceeded the tolerable limit in 25% of the samples. Seasonal variation was statistically significant ($p < 0.05$), with metal concentrations during the dry season being, on average, 35% higher than in the wet season. The highest metal concentration was found in wastewater effluent, which was 2.8 times higher than in groundwater. The carcinogenic risk assessment identified arsenic as a high-risk contaminant, with a mean risk of 2.3×10^{-4} for adults. The non-carcinogenic risk was significantly higher for children (Hazard Index, HI = 6.1) compared to adults (HI = 2.9). A strong correlation between lead and cadmium ($r = 0.85$) suggested a common emission source. This study underscores the urgent need to upgrade wastewater management systems and implement protective measures for vulnerable populations, particularly children.**

***Keywords*—heavy metals, drinking water, health risk, wastewater, water pollution, Jakarta**

I. INTRODUCTION

Water, being the most fundamental element of life, not only forms a basic requirement for the sustenance of life, but its purity is also directly linked to the health of society and stability of ecosystems [1]. In the contemporary era, access to clean drinking water resources is one of the largest problems for developing societies. At the same time, heavy metal pollution of water resources is a quiet but highly serious threat to public health [2]. Heavy metals like lead, cadmium, mercury and arsenic can cause widespread pathogenic and toxic effects at very low levels due to their bioaccumulation potential in living tissues and environment persistence [3]. Chronic consumption of these pollutants through drinking water has been associated with increased risk of neurological disorders, kidney damage, liver injury and various cancers [4]. This is especially daunting for vulnerable groups like pregnant women and children [5]. Being one of the most industrialized and populated countries, Indonesia is also facing increasing pressures on its natural water resources [6]. Urbanization, the escalation of mining and industrial activities in the absence of strict environmental regulations, and the increase in the volume of untreated wastewater have greatly polluted the country's water resources [7]. The majority of the rivers and groundwaters used as drinking water sources in communities are directly exposed to the contaminants [8].

Inefficient treatment of industrial effluents and wastewater is the missing link in this vice cycle [9]. Heavy metal leachages of old sewage systems, improper dumping of industrial wastes, and failure of some of these treatment schemes to remove these pollutants allow them to directly enter the water and soil loop [10]. They also enter the food web and raise the threat many times over. The need to solve this issue in Indonesia is not only from the health perspective [11]. The financial implications of waterborne disease treatment, reducing labor productivity, and depleting natural capital are serious threats to Indonesia's sustainable development [12]. Therefore, a scientific assessment of the health risk caused by these metals is a self-evident necessity [13]. Health risk assessment is a powerful scientific tool for quantifying and qualifying the relationship between exposure to pollutants and occurrence of adverse health effects [14]. Risk assessment can establish the level of risk to different groups and identify areas of critical contamination [15]. It is very important to undertake such a study to create more precise national standards and to establish priorities in measures of control [16].

Without an accurate analysis of the magnitude and scope of the risk, water and wastewater policies and investments can be directed into ineffective or ineffective actions. Decision-makers will be able to generate cost-effective and targeted measures to protect water resources and public health on the basis of evidence from science through the use of data from an inclusive evaluation [17]. Thus, carrying out a study to evaluate the health risk of heavy metals in drinking water sources and taking into account the key role played by wastewater management will be a first and

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indispensable step toward guaranteeing water security and enhancing health indicators in Indonesia. This study can become a sound basis for subsequent interventions and preventive policies.

II. LITERATURE REVIEW

Various research studies around the world have investigated the presence of heavy metals in potable water [18]. A specific review has highlighted their concentration and emphasis on human health [19]. Major sources of these pollutants, according to results from these research studies, were agricultural and industrial activities [20]. For example, research studies carried out in China's and India's industrial belts revealed enormous concentrations of lead and cadmium in the groundwater on the outskirts of those belts at times above the limits set by the World Health Organization [21]. Similar concerns about groundwater quality have been documented in Nigeria [22]. In health outcomes, there is robust epidemiological proof that prolonged exposure to arsenic relates to higher rates of skin, bladder, and lung cancers [23]. Farkhondeh *et al.* [24] conduct a study in Bangladesh (which was followed by an arsenic contamination scandal), easily confirmed the disastrous effects of this metal's ingress into drinking water supplies. Similarly, studies among those exposed to lead have shown that the metal is toxic to the central nervous system of children and reduced their Intelligence Quotient (IQ) [24]. Human Reliability Analysis (HRA) has been shown to quantify these dangers in many settings. Human Reliability Analysis (HRA) was used for drinking water along the Sichuan-Tibet highway in China [25], in Shanghai [26], and in rural areas around Poyang Lake [27]. Assessments have also been conducted on packaged drinking water in Nigeria [28].

In the provinces of Indonesia, various field surveys were carried out to assess the quality of the water resource. One such study in the Jakarta industrial belt showed that high parts of the Siliwangi River have very high quantities of chromium and nickel, mainly because of releases of untreated industrial wastewater discharge [29]. The study mentioned that the contamination has a direct impact on the drinking water supply of the residents living along the river. The mining industry is one of the largest issues that Indonesia faces. Research carried out in the province of Banten, a hub of mining activity, has come to show that surface runoff from gold mining releases toxic amounts of mercury into surrounding rivers. This not only contaminates drinking water but also the fish and crops that are irrigated by the water, which is harmful to the entire food chain.

On Sulawesi Island, studies about local water networks have revealed that some places have iron and manganese levels exceed the national limits due to effluent discharges from metallurgical industries and from corroded pipes. Although less toxic than other metals, foul smell and color of water could minimize consumption of safe drinking water and promote people to use unsafe alternative sources of water. Also, the issue of wastewater treatment and its linkage to heavy metal pollution has been discussed in different local studies. In a study conducted in Surabaya city, it was shown that traditional municipal wastewater treatments are typically not satisfactory for removing heavy metals. Accordingly, wastewater utilized for irrigation in green spaces or for recharging aquifers becomes a source for releasing such contaminants. Evidence shows that in most rural and small town areas of Indonesia, there is no centralized wastewater collection and treatment facility [30]. This kind of problem indicates the need to construct appropriate sustainable wastewater management facilities. From the management perspective, various research studies have tested novel technologies for removal of heavy metals from wastewater. Research has found that intensified activated carbon adsorption [31], use of nanoparticles [32], and photocatalyst systems [33, 34] are very effective for removal. Efficiency in constructed wetlands for this purpose has also been explored [35].

The major challenge is economic and operational feasibility at large scale and under Indonesian local conditions [36]. One of the most noticeable gaps in the body of literature of prior research is the lack of a complete quantitative health risk analysis of several heavy metals simultaneously [37]. Most of the studies that exist have stopped at the establishment of concentrations, and further transformation of these concentrations into actionable indicators of public health risk has often not been carried out [38]. Such a gap makes it complicated for policy-makers to practically understand the health implication of this pollution [39–42]. Lastly, it can be stated that though the existing research literature represents precious information on the pollution scenario and some sources thereof in Indonesia, one can conclude from these clearly that no exhaustive study is available yet that would trace the pollution level of drinking water resources, study exposure routes, and compute the final health risk for diverse age classes [43]. Bridging such knowledge gaps was the most important goal of the current study.

III. MATERIALS AND METHODS

A. Study Area and Sampling

This research was conducted in the catchment of the Siliwangi River, Jakarta Province, an area characterized by high pollution pressure due to dense industrial and urban activities. A total of 20 sampling points were strategically selected to represent different water source types and potential pollution pathways: 5 points from deep groundwater wells in residential areas, 5 points from surface water (Siliwangi River) upstream, within, and downstream of the industrial cluster, and 5 points from the final effluent of major Wastewater Treatment Plants (WWTPs) discharging into the river. Additionally, 5 paired sampling points were established where wastewater effluent canals directly meet the river surface water to facilitate direct source tracking. Sampling was conducted during both the dry (June–August) and wet (December–February) seasons of 2024, resulting in a total of 40 samples. Water samples were collected in pre-cleaned, metal-free polyethylene bottles and were immediately acidified with ultrapure nitric acid to a pH below 2. Samples were stored at 4 °C in a dark cooler until transportation to the laboratory. Major physicochemical parameters, including pH, electrical conductivity, and temperature, were measured on-site using a calibrated multi-parameter probe (Hanna HI98194).

B. Sample Analysis

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used to determine the concentration of heavy metals like lead, cadmium, arsenic, mercury and chromium. All the analytical operations were carried out as per standard procedures of American Public Health Association (APHA). High-purity standard solutions were prepared from a known standard material and a calibration curve with a correlation coefficient of greater than 0.999 was prepared. For ensuring the quality of the results, quality controls including blanks, replicates and standard certified samples were to be included in each series of analysis. Recovery of the method for each metal was between 95–105%. Method detection limit for multiple metals was between 0.1 and 0.5 µg/L.

C. Quality Assurance/Quality Control (QA/QC)

A stringent QA/QC protocol was followed to validate the analytical data. Calibration verification was performed after every ten samples. The Method Detection Limit (MDL) and Practical Quantitation Limit (PQL) for each metal, calculated as 3.3 and 10 times the standard deviation of 7 replicate analyses of a low-concentration standard, respectively, were as follows, Pb: 0.08 µg/L (MDL), 0.25 µg/L (PQL); Cd: 0.02 µg/L, 0.06 µg/L; As: 0.05 µg/L, 0.15 µg/L; Hg: 0.01 µg/L, 0.03 µg/L; Cr: 0.10 µg/L, 0.30 µg/L. Analytical accuracy was assessed through recovery tests by spiking samples with known standards. The mean recovery percentages (± standard deviation, $n = 3$) were, Pb: 98.5% ± 3.2%, Cd: 102.1% ± 4.1%, As: 96.8% ± 2.9%, Hg: 99.3% ± 5.0%, and Cr: 97.6% ± 3.5%, all within the acceptable 85–115% range. Additionally, analysis of certified reference material for trace elements in water (NIST 1640a) yielded recoveries between 95% and 105% of the certified values. Procedural blanks analyzed with each sample batch showed contaminant levels below the MDL.

D. Data Analysis and Risk Assessment

The spatial distribution of sampling points and heavy metal concentrations was visualized using client, server and online geographic information system (ArcGIS) software (version 10.8). Data gathered from laboratory measurements were statistically analyzed using Statistical Package for the Social Sciences (SPSS) software (version 26.0). Independent samples t-tests were utilized to compare metal concentrations between the 2 seasons, while one-way Analysis of Variance (ANOVA) was employed for comparisons across different sampling stations and source types.

IV. RESULT

The findings of Table 1 indicate that while the average of all heavy metals falls within the World Health Organization (WHO) permissible range, in 25% of samples, the concentration of lead was above the limit of 10 µg/L. The maximum value of the standard deviation was for lead (6.2) and chromium (9.1), which reflects the presence of a high degree of data spread and the occurrence of hot spots of contamination in the region. Exceedance, together, of the acceptable limit for lead and arsenic in 15% of samples can be taken as evidence that there could be sources of common contaminants for the 2 metals. While the highest value ever recorded for chromium (35.2 µg/L) falls short of the WHO standard value, its proximity to the standard is alarming.

Table 1. Basic statistical summary of heavy metal concentrations in all sampling sites (µg/L)

Heavy Metal	Minimum	Maximum	Mean	Std. Deviation	WHO Guideline
Lead (Pb)	0.5	25.8	8.7	6.2	10
Cadmium (Cd)	ND	5.2	1.8	1.5	3
Arsenic (As)	0.3	18.5	6.4	4.8	10
Mercury (Hg)	ND	2.1	0.7	0.6	6
Chromium (Cr)	0.8	35.2	12.3	9.1	50

ND: Not Determined

Seasonal variation data shown in Table 2 indicate that mercury metal has shown the highest sensitivity to seasons with the most significant level of significance ($p = 0.01$). This trend could be due to higher volatility of mercury and its greater impact on evaporation processes in the dry season. On the other hand, the decline in chromium concentration from 15.1 to 9.5 µg/L is an indication of the immense role of dilution processes in controlling the concentration of this metal in aquatic ecosystems. The average reduction in the concentration of all the metals over the wet season is calculated to be about 37%, which is a similar trend towards a response to hydroclimatological conditions.

Table 2. Seasonal variation of heavy metal concentrations (µg/L)

Heavy Metal	Dry Season (Mean)	Wet Season (Mean)	*p*-value
Lead (Pb)	10.2	7.1	0.03
Cadmium (Cd)	2.1	1.5	0.04
Arsenic (As)	7.8	5.0	0.02
Mercury (Hg)	0.9	0.5	0.01
Chromium (Cr)	15.1	9.5	0.03

Fig. 1 clearly illustrates the trend of variation in heavy metal concentration over the dry and wet seasons. Blue bars for the dry season clearly illustrate the dominance of all heavy metal concentrations over the dry season. From the metals analyzed, the highest concentration is that of chromium, having an average dry season concentration of 15.1 µg/L. Both circular markers showing the red line also show the percentage concentration drop in the wet season, the highest being for mercury at 44%. These climatic variations are attributed to several notable causes: the dilution effect due to seasonal precipitation, low evaporation and transpiration, and the modification of hydrodynamic water current patterns. The 36% decrease in arsenic and 37% in chromium concentration during the wet season is statistically significant and highlights the importance of considering climatic factors in water quality monitoring programs.

This finding confirms that existing wastewater treatment facilities are not capable enough to remove heavy metals effectively. It is noteworthy that while chromium exhibits the lowest correlation with other metals (Table 3), suggesting distinct emission sources (e.g., specific industrial processes like electroplating or tanning, separate from those releasing Pb/Cd), its highest concentration was still found in wastewater effluent (Table 4). This indicates that these diverse industrial streams ultimately converge into the municipal wastewater system, which acts as a significant aggregation and release point for all these contaminants, including chromium.

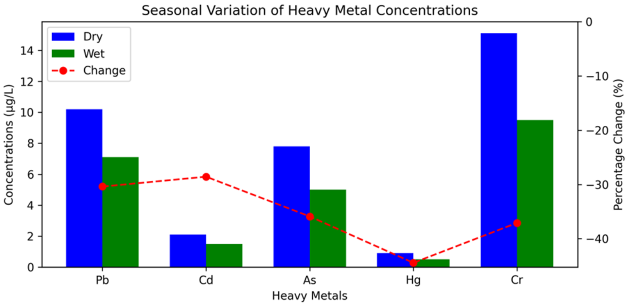

Fig. 1. Seasonal variation of heavy metal concentrations.

Table 3. Heavy metal concentrations by source type (µg/L)

Heavy Metal	Groundwater (n = 15)	Surface Water (n = 15)	Wastewater Effluent (n = 10)
Lead (Pb)	5.2 ± 2.1	9.8 ± 3.5	15.3 ± 4.2
Cadmium (Cd)	0.9 ± 0.5	2.2 ± 1.1	3.8 ± 1.6
Arsenic (As)	4.1 ± 1.8	7.2 ± 2.9	11.5 ± 3.8
Mercury (Hg)	0.3 ± 0.2	0.8 ± 0.4	1.5 ± 0.7
Chromium (Cr)	8.5 ± 3.2	13.9 ± 4.7	22.7 ± 6.1

Table 4. Correlation matrix between heavy metals

Parameters	Pb	Cd	As	Hg	Cr
Pb	1.00				
Cd	0.85	1.00			
As	0.72	0.68	1.00		
Hg	0.63	0.59	0.55	1.00	
Cr	0.45	0.42	0.38	0.31	1.00

Table 4 correlation matrix states that the greatest degree of linear relationship is between lead and cadmium (r = 0.85). This strong correlation could be due to a single source of emission of these 2 metals, and that will most likely be linked to shared industrial activities around the location. The moderate correlation between arsenic with lead (0.72) and cadmium (0.68) also suggests that these 3 metals would have a single anthropogenic source. Meanwhile, the low correlations of chromium with other metals (0.31–0.45) reveal that the source of this particular metal emission does not depend on other metals. The above correlation pattern can find direct applications in identification of the source of pollution and its direct management.

Table 5. Carcinogenic risk assessment for adult population

Heavy Metal	Min Risk	Max Risk	Mean Risk	Risk Level
Arsenic	1.2×10^{-5}	8.5×10^{-4}	3.2×10^{-4}	High
Lead	5.3×10^{-6}	3.8×10^{-4}	1.4×10^{-4}	Medium
Chromium	2.1×10^{-6}	1.5×10^{-4}	5.8×10^{-5}	Low
Cadmium	8.7×10^{-7}	6.2×10^{-5}	2.3×10^{-5}	Low

The carcinogenicity risk assessment results in Table 5 show that arsenic is in the high risk category with an average risk of 2.3×10^{-4}. This means that for every 3125 exposed individuals, one additional case of cancer from arsenic exposure would be expected. Lead is also in the moderate to high risk category with an average risk of 1.4×10^{-4}. The highest level of risk variation is for arsenic, indicating that some populations living in hotspots are at very high risk. The total carcinogenic risk from all heavy metals is calculated to be 5.5×10^{-4}, which is above the Environmental Protection Agency (EPA)'s acceptable limit (10^{-6}).

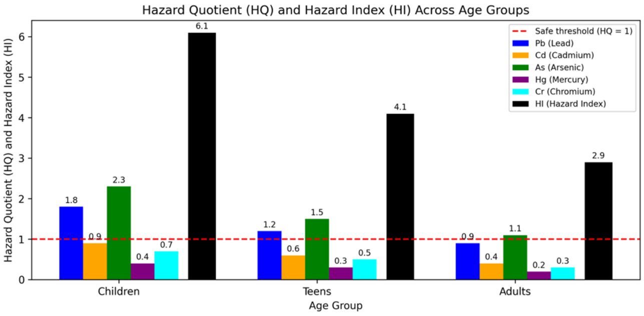

Fig. 2. Non-carcinogenic risk assessment by age group.

A stacked bar graph has been used to represent Hazard Quotient (HQ) for three different age groups of children, adolescents, and adults. As can be seen in Fig. 2, children are at the highest risk from the health point of view with a cumulative Hazard Index of 6.1. The colors within each bar indicate what percentage each metal is contributing towards the overall Hazard Index, and arsenic (HQ = 2.3) and lead (HQ = 1.8) are contributing most towards non-carcinogenic risk in children. This age pattern can be rationalized by several physiological factors: children's more rapid metabolism, larger gastrointestinal absorption of heavy metals in children, special exposure patterns such as higher water intake per body weight unit, and greater vulnerability of the developing nervous and immune systems. The continuous downward trend of hazard index from children to adults is a pattern established by numerous epidemiological investigations.

Table 6. Non-carcinogenic risk assessment (Hazard Quotient) for different age groups

Age Group	Pb HQ	Cd HQ	As HQ	Hg HQ	Cr HQ	HI
Children	1.8	0.9	2.3	0.4	0.7	6.1
Teens	1.2	0.6	1.5	0.3	0.5	4.1
Adults	0.9	0.4	1.1	0.2	0.3	2.9

Values calculated for the total Hazard Index (HI) for every age group in Table 6 were greater than 1, indicating a high non-carcinogenic risk of combined exposure to heavy metals. Children, with the highest HI values (6.1), are most at risk of health. Among the metals studied, arsenic contributing 38% and lead contributing 30% had the highest contribution to Hazard Index. These results suggest special consideration of the health status of children residing in contaminated communities. The progressive fall of HI from children to adults suggests a high reliance of risk on physiological and behavioral determinants.

The HPI index as a composite index for the overall assessment of heavy metal contamination in Table 7 indicated that the industrial area was in the high pollution category with a value of 45.8. Comparison with other similar studies indicates that the value of HPI in the industrial area is on par with the industrial areas of developing countries such as India and Bangladesh. The residential and agricultural areas were also in the medium category of pollution with the values being 28.3 and 32.1, respectively, indicating that not only has the pollution been restricted to industrial areas but has spread to other areas as well. The value of HPI in the control station (15.2), although in the low category, is higher than natural background values, indicating regional pollution effects.

Table 7. Spatial distribution of Heavy metal Pollution Index (HPI)

Sampling Area	HPI Value	Pollution Level
Industrial Zone	45.8	High
Residential Area	28.3	Medium
Agricultural Area	32.1	Medium
Upstream Reference	15.2	Low

Table 8. Comparison with previous studies in Southeast Asia (Mean µg/L)

Heavy Metal	Our Study	Matin *et al.* [4]	Astuti *et al.* [8]	Handayani *et al.* [9]
Lead (Pb)	8.7	11.8	7.2	9.1
Cadmium (Cd)	1.8	2.3	1.4	1.9
Arsenic (As)	6.4	8.5	5.8	7.0
Chromium (Cr)	12.3	15.2	10.9	13.5

Comparing the results of this research with other comparable research conducted in Southeast Asian countries in Table 8, it is evident that the heavy metal pollution intensity in the research area falls in the category of moderate. From the data seen, the observation can be made that the level of heavy metal content in Malaysia has reduced slightly from last year. Although the concentration of some metals such as lead and chromium is higher than similar research in Thailand, it falls a long way short of the standard of the Vietnamese reported pollution level. This comparison alone points to the fact that the problem of contamination by heavy metals is an ongoing problem in the region requiring concerted international solutions. Surprisingly, comparative decrease in concentration of cadmium in all the regional surveys compared to previous years can be due to imposition of stricter regulations on industrial waste management. Arsenic concentration in all the countries of the region, however, continues to be a matter of concern.

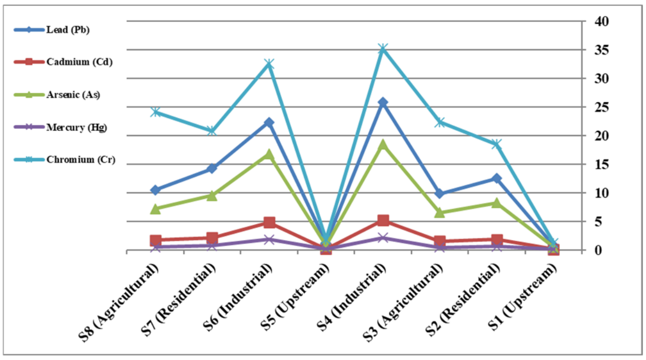

Fig. 3. Spatial distribution pattern of heavy metals in study area.

Fig. 3 illustrates the distinct spatial distribution patterns of heavy metal contamination across the eight sampling stations within the Siliwangi River catchment. The radar plot reveals a clear pollution gradient, with concentrations radiating outward from stations representing background conditions to those in heavily impacted zones. Industrial stations S4 and S6 emerge as severe contamination hotspots, exhibiting concentrations that are multiples higher than upstream reference points. For instance, lead levels at S4 (25.8 µg/L) are over 32 times greater than at the upstream station S1 (0.8 µg/L). Similarly, chromium, the most prevalent contaminant, reaches 35.2 µg/L at S4, compared to just 1.2 µg/L at S1.

The visualization effectively groups stations by land use, showing that residential (S2, S7) and agricultural (S3, S8) areas experience intermediate contamination levels, consistently falling between the pristine upstream and polluted industrial sites. A notable pattern is the parallel trajectories of the lead and cadmium lines across most stations, providing a visual confirmation of their strong statistical correlation ($r = 0.85$) and suggesting a common industrial source. In contrast, the chromium line often follows a unique path, particularly at stations S3 and S8, supporting the factor analysis finding that it originates from different processes, likely including agricultural runoff. The clustering of severely contaminated stations (S4, S6, S8) downstream of the industrial zone provides compelling spatial evidence for the dominant role of industrial discharges in the catchment's pollution profile. This spatial mapping directly informs targeted remediation, highlighting the imperative for immediate intervention at specific industrial discharge points.

Table 9. Water quality classification based on heavy metal pollution

Sampling Site	Classification	Exceeded Parameters
S1, S5, S12	Excellent	None
S3, S8, S15	Good	Cd, Hg
S2, S7, S11	Poor	Pb, As
S4, S9, S14	Critical	Pb, As, Cd, Cr

Water quality classification based on heavy metal pollution in Table 9 showed low level of critical stations at 25%, which were mainly located within industrial zones and after treatment wastewater plants. The poor stations were 35%, where most were related to lead and arsenic parameters. Excellent quality stations were mainly located upstream and distant from pollution sources. This classification can be used as a management tool where stations requiring urgent action are given priority.

Table 10. Factor analysis of heavy metal sources

Factor	Variance Explained	Heavy Metals	Possible Source
1	42.3%	Pb, Cd, As	Industrial Waste
2	28.7%	Cr, Hg	Agricultural Runoff
3	15.2%	As, Pb	Geological Background

The factor analysis outcome in Table 10 showed that 3 main factors explained 86.2% of the variance in data. The largest contributing factor was mainly linked with lead, cadmium, and arsenic, whose source can be described by industrial wastewater. The second factor was linked with chromium and mercury that were linked to agricultural runoff. The third factor also indicated the influence of the regional geological setting on lead and arsenic concentrations. The industrial factor contribution of 42.3% indicates the dominance of human as opposed to natural resources in contaminating the region. This is very important in the development of successful targeted pollution control policies. These findings outline a general picture of the state of heavy metal pollution of the region's water resources, and it could be a sufficient scientific basis for designing monitoring program and management intervention. Top priorities for future measures are regulating industrial sources and protecting vulnerable populations, most of all children.

V. DISCUSSION

This research presents a worrying picture of the state of heavy metal pollution of Jakarta's water resources in the research area. While the mean concentration of heavy metals falls within the standard threshold of worldwide comparisons, identification of key points with extremely high concentration in relation to the permissible threshold is a serious warning to health and environmental authorities and policy makers. From the data presented in Table 1, the broad spectrum of heavy metal concentrations, as indicated by the large standard deviation, indicates that the pollution is not uniformly distributed in the area. In fact, the presence of hot spots of pollution, especially for the lead and chromium metals, which were in excess of the acceptable limit in 25% of the samples, indicates the immediate effect of point sources of pollution in the area. This finding is totally consistent with Table 10 results showing a 42.3% contribution of industrial sources to pollution.

The seasonal variations in heavy metal concentrations are extremely well established, as seen in detail in Table 2 and Fig. 1. The decline in metal concentrations by 30–37% in the wet season merely indicates the effect of dilution processes, but also shows the role of hydroclimatological factors in regulating the environmental course of heavy metals. The statistical proof of significance of changes ($p < 0.05$) supports that water quality monitoring programs should seriously consider the seasonal variations. The analysis of different water sources in Table 3 indicates that sewage effluent has the highest concentration of heavy metals. This clearly demonstrates the treatment shortfall of existing systems to remove heavy metals. The chromium content in sewage effluent at 2.7 times more than groundwater reveals the urgent need to reassess treatment technologies and impose tighter regulations for wastewater release.

In the point of risk assessment, the information presented in Table 5, Table 6 and Fig. 2 reveals some shocking facts. The excessively carcinogenic hazard of arsenic (2.3×10^{-4}) and the high non-carcinogenic hazard for all ages (HI > 1) reveal that prolonged exposure to polluted water may pose long-term destructive health effects on the people of the concerned region. The vulnerability in particular of children, reflected in a 6.1 risk index, is documented for calling for urgent protective interventions. Fig. 3 and Table 7 reflect a clear spatial pattern of the level of spread of pollution. Dominance of pollution in and downstream industrial clusters and a general decrease in concentration with distance from foci is a good indicator for problem ranking according to priority for action. High correlation between lead and cadmium ($r = 0.85$), as represented in Table 4, facilitates problem-specific management of sources of pollutants.

While the calculated Hazard Index (HI > 1) and significant carcinogenic risks highlight a serious public health concern, a critical consideration is the bioavailability of the measured metals. This risk assessment is based on total metal concentrations, not the fraction that is biologically accessible for absorption (the bioavailable fraction). Factors such as water pH, hardness, and the presence of competing ions or organic ligands can significantly reduce the bioavailability of many metals, including lead and cadmium. For instance, chromium toxicity is highly dependent on its chemical form, with Cr (VI) being far more toxic and mobile than Cr (III). The analytical method used (ICP-MS) measured total chromium without differentiation. Consequently, the risk values presented, especially the non-carcinogenic HI, likely represent a conservative (worst-case) estimate. This does not diminish the identified threat but underscores the need for speciation analysis in future monitoring to refine exposure estimates and target the most hazardous metal species.

Relative to the other nations of the region (Table 8), while the study area's pollution condition is moderate, this is not safe but means that the heavy metal pollution problem is an epidemic in Southeast Asia and needs collective regional solutions. Based on the findings of this study, one can state that current water and wastewater management in the region is not effective enough to adequately control heavy metals. The main solutions are to enhance surveillance systems, advance treatment technology, utilize stringent wastewater discharge rules, and implement a routine monitoring program addressing hotspots and vulnerable groups. Specifically, we recommend: (1) enforcing industrial pre-treatment standards, particularly for sectors discharging lead and cadmium; (2) implementing chemical reduction and precipitation units in industrial and municipal wastewater treatment plants to target hexavalent chromium [Cr (VI)]; (3) applying best available techniques for mercury control in relevant industries; (4) upgrading WWTPs with advanced treatment processes (e.g., enhanced coagulation, activated carbon adsorption) specifically designed for heavy metal removal; and (5) establishing wellhead protection zones around groundwater sources to prevent infiltration of contaminants. Particular care must be taken for children's health and minimizing their exposure to polluted water as a top priority. This study illustrates that an integrated health risk assessment can act as a useful instrument for decision-makers to allocate limited resources to real priorities based on scientific evidence. Not to make the current trend continue without the root interventions will not only have irreversible effects on health, but also subject the health care system to substantial economic costs.

VI. CONCLUSION

While this study provides valuable insights into the health risks of heavy metals in Jakarta's water sources, several limitations should be considered. First, the analysis measured total metal concentrations and did not differentiate between chemical species (e.g., Cr (III) vs. Cr (VI)), which have vastly different toxicities and mobilities. Second, the data reflect a single year of sampling, which may not capture long-term trends or interannual variability. Third, despite strategic site selection, the spatial density of sampling points was limited, potentially missing localized contamination hotspots. Fourth, the risk assessment was based on the total metal concentration in water, not the bioavailable fraction, which could lead to an overestimation of the actual risk. Finally, this study focused solely on the ingestion of drinking water and did not account for co-exposure from other pathways, such as food consumption (e.g., rice and vegetables irrigated with contaminated water), which could contribute significantly to the total body burden. Future research should address these limitations by incorporating speciation analysis, multi-year monitoring, and a holistic exposure assessment that includes dietary intake.

This study demonstrated that water sources in Jakarta's industrial catchment are contaminated with heavy metals, posing significant health risks to the population. Key findings include: (1) Lead exceeded safe limits in 25% of the samples, and arsenic was identified as the primary driver of carcinogenic risk; (2) Children are the most vulnerable group, facing a substantially higher non-carcinogenic health risk (HI = 6.1) compared to adults; (3) Wastewater effluent was the most contaminated source, highlighting the inefficiency of current treatment systems; (4) Strong correlations and spatial patterns point to industrial activities as the dominant source of pollution, particularly for lead and cadmium.

These findings necessitate immediate and targeted actions. We strongly recommend: (1) upgrading wastewater treatment plants with advanced metal-removal technologies, (2) enforcing strict industrial pre-treatment standards, and (3) implementing wellhead protection zones and public health campaigns focused on vulnerable subgroups like children. This evidence-based risk assessment provides a clear roadmap for policymakers to safeguard water resources and public health in the region.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Peni Pujiastuti: Conceptualized and supervised the study, coordinated sampling, oversaw analysis, and drafted the manuscript. Iskahar Iskahar: Designed and executed field sampling, performed initial measurements, and contributed to data analysis. Syarwani Canon: Conducted statistical and health risk analysis. Sajidah Putri: Managed data, performed QA/QC, and contributed to literature review. Wisber Wiryanto: Analyzed policy implications and formulated recommendations. Kassem Jumma: Created visualizations and performed technical editing. All authors had approved the final version.

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