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Original Research

Carcinogenic and Non-Carcinogenic Health Risk Assessment of Heavy Metals in Drinking Water near the Batang Masumai River, Indonesia

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Abstract

Contamination of drinking water by heavy metals poses a serious public health concern due to their persistence, bioaccumulation, and potential toxic effects on human health. This study evaluated both carcinogenic and non-carcinogenic health risks associated with seven heavy metals (Hg, Cd, Ni, Fe, Cu, Mn, and Pb) in drinking water sources surrounding the Batang Masumai River, Indonesia. A total of 30 water samples were collected from municipal water supplies (PDAM), refill drinking water depots (AMIU), and groundwater wells, and analyzed using Atomic Absorption Spectrometry (AAS). Health risk assessment was conducted based on the United States Environmental Protection Agency (USEPA) model, including Chronic Daily Intake (CDI), Hazard Quotient (HQ), Hazard Index (HI), and Total Cancer Risk (CR_{total}). The results showed that all PDAM samples had HI values below the acceptable limit (HI<1), indicating negligible non-carcinogenic risk. However, HI values exceeding the acceptable threshold were observed in one AMIU sample and one groundwater sample (HI = 1.4), suggesting potential health concerns. In contrast, carcinogenic risk was found to be significantly higher across all water sources, with 90% of PDAM samples and 100% of AMIU and groundwater samples exceeding the acceptable limit ($CR_{total}>1\times10^{-4}$). The highest carcinogenic risk was detected in groundwater, reaching 4.6×10^{-3}, which is substantially above the recommended safety threshold. The findings reveal that while non-carcinogenic risks are generally within acceptable limits, carcinogenic risks are widespread and pose serious long-term health threats. This study highlights the urgent need for stricter water quality control, continuous monitoring, and targeted mitigation strategies to reduce heavy metal exposure in the study area.

Keywords: human health risk assessment, heavy metals, drinking water, carcinogenic risk, non-carcinogenic risk

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Introduction

Heavy metal contamination in drinking water has become a major global public health concern due to its persistence, bioaccumulation potential, and long-term toxicity. Chronic exposure to hazardous metals such as cadmium (Cd), nickel (Ni), and lead (Pb) has been widely associated with kidney dysfunction, neurotoxicity, metabolic disorders, and increased cancer risk [1-3]. Numerous studies have reported elevated concentrations of heavy metals in groundwater and surface water, originating from both natural geological processes and anthropogenic activities, including mining, agriculture, and domestic waste discharge [4-6]. These conditions are particularly critical in developing regions, where limited water treatment and monitoring systems may increase population vulnerability to long-term exposure.

In Indonesia, heavy metal contamination has been documented in several watersheds, particularly in regions affected by mining activities and domestic wastewater discharge [7]. Exposure to heavy metals has been linked to both carcinogenic and non-carcinogenic health risks in local populations [8]. Previous studies conducted in developing countries such as Iran, Egypt, and India have reported Hazard Index (HI) and Cancer Risk (CR) values exceeding acceptable thresholds, indicating significant long-term health risks associated with contaminated drinking water [9-11]. These findings highlight the importance of comprehensive health risk assessment, particularly in areas where communities rely on multiple drinking water sources with varying levels of treatment and quality.

Recent studies have applied various approaches, including pollution indices and geospatial analysis, to assess heavy metal contamination in drinking water systems. For instance, Latif et al. [2] employed a GIS-based heavy metal pollution index to evaluate drinking water quality in urban environments, highlighting significant spatial variability in contamination levels. However, comprehensive health risk assessment using USEPA-based carcinogenic and non-carcinogenic models remains essential to accurately quantify potential health impacts and support risk-based decision-making.

Despite extensive global research, studies focusing on the integrated assessment of carcinogenic and non-carcinogenic health risks across multiple drinking water sources remain limited, particularly in small-scale watersheds in Indonesia. In the Batang Masumai River area (Merangin District), previous investigations have primarily reported heavy metal contamination in sediments and aquatic organisms, including Hg and Pb [12]. However, systematic evaluation of human exposure through different drinking water sources, such as municipal water (PDAM), refill drinking water depots (AMIU), and groundwater wells, has not been comprehensively addressed. This gap is critical, as differences in water treatment and source characteristics may lead to substantial variation in health risk levels, particularly for carcinogenic exposure. Furthermore, the relative contribution of individual metals, especially nickel (Ni), to total carcinogenic risk remains insufficiently explored, despite increasing evidence of its dominant role in water-related cancer risk [13-15]. It is hypothesized that heavy metal contamination in drinking water sources around the Batang Masumai River poses significant carcinogenic and non-carcinogenic health risks, with higher carcinogenic risk potentially occurring in less regulated water sources such as groundwater and refill drinking water sources. Therefore, this study aims to: (i) determine the concentrations of heavy metals (Hg, Cd, Ni, Fe, Cu, Mn, and Pb) in different drinking water sources, (ii) evaluate non-carcinogenic and carcinogenic health risks using the United States Environmental Protection Agency (USEPA) framework through parameters including chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), and total cancer risk (CR_{total}), and (iii) compare the relative risk levels among water sources and identify dominant metal contributors.

This study provides novel insights into the distribution and magnitude of health risks in a small watershed context and highlights critical public health implications associated with drinking water safety in Indonesia.

Materials and Methods

Materials and Laboratory Standards

This study utilized analytical-grade materials, including ultrapure distilled water, concentrated nitric acid (HNO_3) for preservation, and 1000 mg/L multi-element standard solutions for calibration. All analytical procedures were performed at the Instrument Chemistry Laboratory, Universitas Negeri Padang, following the Indonesian National Standard (SNI) protocols to minimize contamination and ensure analytical reliability. Sampling bottles, filtration tools, and glassware were cleaned using 10% HNO_3 to remove trace-metal residues before use, consistent with established trace metal analytical practices [5, 13]. The heavy metals analyzed in this study (Hg, Cd, Ni, Pb, Cu, Fe, and Mn) were selected due to their toxicological relevance and regulatory importance in global drinking-water guidelines [2, 3].

Study Area and Sample Distribution

The research was conducted between February and April 2025 in communities surrounding the Batang Masumai River, Merangin District, Jambi Province. This area is known to be influenced by domestic runoff, agricultural activities, and artisanal mining, which may elevate heavy metal concentrations in local water sources [7, 12]. A total of 30 drinking-water samples were collected from PDAM (n=10), refill depots (AMIU, n=10), and household wells (n=10). Sampling locations

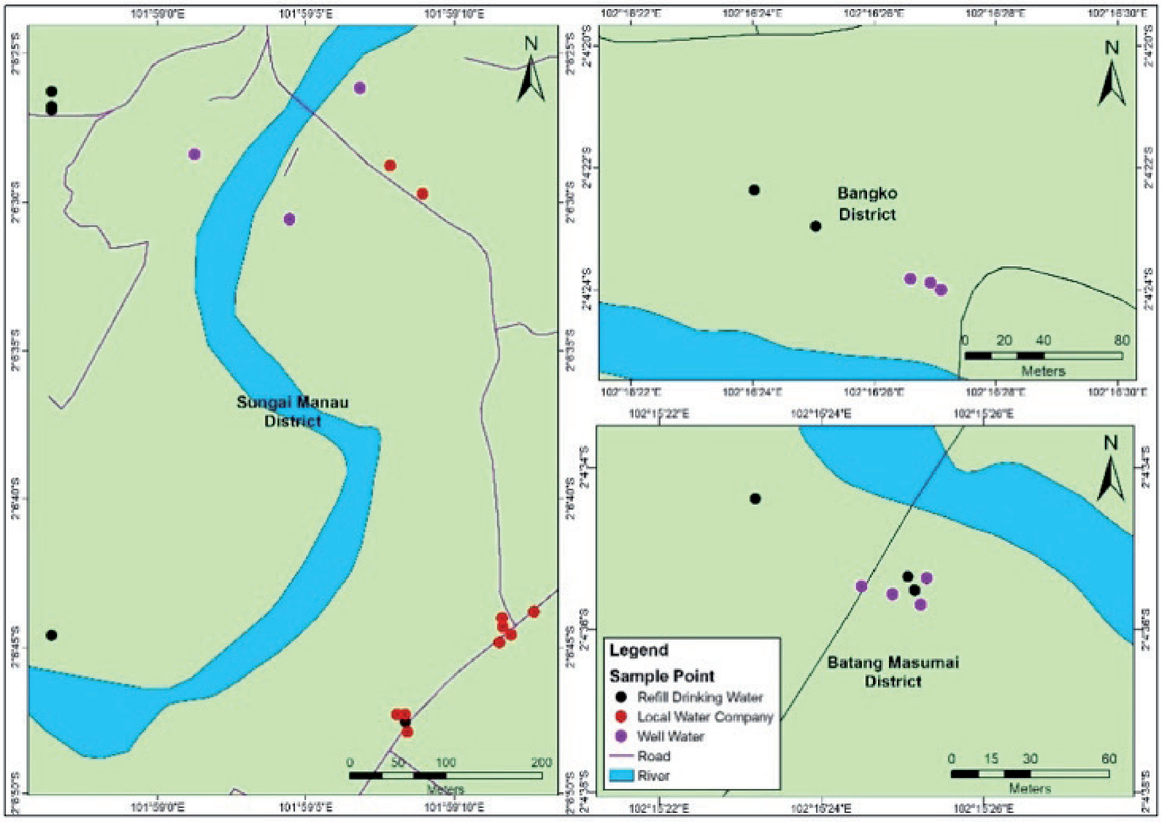

Fig. 1. Spatial distribution of sampling points for refill drinking water depots (AMIU), local water company (PDAM), and household wells in the Sungai Manau, Bangko, and Batang Masumai districts.

across the Sungai Manau, Bangko, and Batang Masumai districts were selected to capture spatial variations in contamination influenced by river proximity and land-use intensity. Fig. 1 presents the spatial distribution of sampling points.

Sampling Design and Population

Samples were collected using acid-washed polyethylene containers and transported under cold-chain conditions to prevent chemical alteration. Households located within <10 m and >10 m from the riverbank were included to reflect hydrological influence on contamination. The study population consisted of adults aged 20-80 years who routinely consumed PDAM, AMIU, or well water, reflecting realistic exposure scenarios comparable to international health-risk assessments [9-11]. A total of 30 samples were collected during February-April 2025, representing typical seasonal water-use conditions. All samples were filtered and immediately acidified with concentrated HNO_3 to stabilize metal concentrations.

Analytical Methods and QA/QC Procedures

Heavy metal concentrations were measured using Atomic Absorption Spectrophotometry (AAS), following widely accepted trace metal analytical guidelines [5, 13]. Calibration curves were established using multi-point standard solutions (0.1-2.0 mg/L), yielding coefficients of determination (R^2) greater than 0.995. Quality assurance and control procedures included the use of reagent blanks, duplicate samples, and certified reference materials to ensure accuracy and precision, consistent with international QA/QC protocols for metal analysis [6, 16]. Limits of detection ranged from 0.001-0.005 mg/L, and analytical errors were maintained below 5%, ensuring high reliability of the data used in risk assessment.

Exposure Assessment and CDI Calculation

Human exposure to heavy metals was estimated using the Chronic Daily Intake (CDI) method recommended by the U.S. EPA. CDI quantifies long-term ingestion exposure using physiological and behavioral parameters widely adopted in global health risk assessments [8, 9, 17]. The CDI for each metal was computed using:

$$CDI = \frac{C \times IR \times EF \times ED}{RW \times AT} \quad (1)$$

where C is metal concentration (mg/L), IR is ingestion rate (L/day), EF is exposure frequency (days/year), ED is exposure duration (years), BW is body weight (kg), and AT is averaging time (days). EPA-standard assumptions were applied to ensure comparability with international studies.

Reference Dose (RfD) and Cancer Slope Factor (CSF)

Toxicological benchmarks for non-carcinogenic (RfD) and carcinogenic (CSF) assessments were obtained from the U.S. EPA IRIS database [18]. The RfD reflects the daily exposure level unlikely to cause adverse effects, while the CSF quantifies the probability of cancer from lifetime exposure. These toxicological values were consistently applied in calculating HQ, HI, and CR, as commonly practiced in regional and international water risk studies [19]. Table 1 summarizes the RfD and CSF values used.

Non-carcinogenic Risk Assessment (HQ and HI)

Non-carcinogenic risks were quantified using the Hazard Quotient (HQ), defined as the ratio of estimated exposure to the reference dose. HQ>1 indicates potential non-carcinogenic effects. The cumulative impact of multiple metals was evaluated using the Hazard Index (HI), which represents the sum of all HQ values. The formulas used are:

$$HQ = \frac{CDI}{RfD} \quad (2)$$

$$HI = \sum HQi \quad (3)$$

Table 1. Reference Doses (RfD) and Cancer Slope Factors (CSF) for heavy metals used in the health risk assessment.

Element	RfD (Oral) (mg/kg/day)	CSF ((mg/kg/day)$^{-1}$)
Hg (Mercury)	3.0×10^{-4}	NAD
Fe (Iron)	7.0×10^{-1}	NAD
Pb (Lead)	3.5×0^{-3}	8.5×10^{-4}
Cd (Cadmium)	5.0×10^{-4}	3.8×10^{-1}
Cu (Copper)	4.0×10^{-2}	NAD
Cr (Chromium)	3.0×10^{-3}	0.5
Ni (Nickel)	4.0×10^{-2}	1.7
Mn (Manganese)	2.4×10^{-2}	NAD

Note: RfD (reference dose) and CSF (cancer slope factor) values were obtained from the United States Environmental Protection Agency (USEPA) Integrated Risk Information System (IRIS) and supported by relevant literature [20, 21]. NAD indicates that carcinogenic slope factor data are not available; therefore, carcinogenic risk was not calculated for these elements.

This approach follows established heavy metal risk assessment methods and is widely applied in recent studies using the USEPA framework [5, 9, 22-24].

Carcinogenic Risk Assessment (CR)

Carcinogenic risks were assessed for metals with available cancer slope factors (Cd, Pb, Ni). Individual cancer risk was calculated using CDI multiplied by the CSF, while the total cancer risk (CR_{total}) represents the sum of all individual CR values:

$$CR = CDI \times CSF \quad (4)$$

$$CR_{total} = \sum CRi \quad (5)$$

CR values above 1×10^{-4} indicate unacceptable lifetime cancer risk. This method is consistent with recent studies evaluating carcinogenic risks of heavy metals in environmental media [19, 21-24].

Results and Discussion

The results and discussion section presents the concentrations and health risk evaluation of seven heavy metals: manganese (Mn), cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), iron (Fe), and mercury (Hg) in drinking water sources collected from the Batang Masumai River basin, Merangin Regency, Jambi Province, Indonesia. The investigated water sources include municipal drinking water supplied by the Regional Drinking Water Company (PDAM), refill drinking water depots (AMIU), and groundwater wells.

Non-Carcinogenic Risks

Carcinogenic risk assessment using the assessment basis HQ (Hazard Quotient) → compares exposure with a reference threshold. Reference Doses (RfD) and Cancer Slope Factor (CSF) USEPA IRIS 2011. HI (Hazard Index) + Total HQ of all metals in one individual.
HI < 1 → no non-carcinogenic risk
HI ≥ 1 → potential non-carcinogenic risk

The analysis in Table 2 shows that the concentrations of the heavy metals manganese (Mn), lead (Pb), and mercury (Hg) were at very low to undetectable levels (value of 0.0) in almost all samples. This indicates that these three metals do not contribute significantly to health risks in the context of the PDAM water samples analyzed. However, the presence of cadmium (Cd) is a serious concern even though its concentration is relatively low (10^{-5}-10^{-4}), due to the toxic, bioaccumulative, and potentially carcinogenic nature of Cd, which can cause long-term health impacts even at low exposures.

Table 2. Chronic Daily Intake (CDI) of PDAM water.

ID	AT	BW	IR	EF	Mn	Cd	Cu	Pb	Ni	Fe	Hg
P1	26	63	2	26	0.0	2.2×10^{-4}	4.3×10^{-4}	0.0	9.6×10^{-4}	9.6×10^{-4}	0.0
P2	59	49	2	25	0.0	1.8×10^{-4}	6.2×10^{-4}	0.0	6.2×10^{-4}	0.0	0.0
P3	60	73	2	2	0.0	1.0×10^{-5}	2.8×10^{-5}	0.0	4.8×10^{-5}	3.8×10^{-5}	0.0
P4	45	57	3	45	0.0	3.9×10^{-4}	1.3×10^{-3}	0.0	1.9×10^{-3}	8.3×10^{-4}	0.0
P5	62	80	2	35	2.3×10^{-4}	2.4×10^{-4}	5.2×10^{-4}	0.0	9.2×10^{-4}	6.7×10^{-4}	0.0
P6	54	72	2	54	0.0	9.4×10^{-5}	0.0	0.0	1.5×10^{-3}	0.0	0.0
P7	80	70	1	80	0.0	0.0	0.0	0.0	9.8×10^{-4}	0.0	0.0
P8	25	45	2	25	0.0	6.5×10^{-5}	0.0	0.0	1.0×10^{-3}	0.0	0.0
P9	60	60	2	60	0.0	3.1×10^{-5}	0.0	0.0	1.3×10^{-3}	0.0	0.0
P10	49	85	2	49	0.0	5.6×10^{-5}	0.0	0.0	5.7×10^{-4}	8.3×10^{-4}	0.0

Copper (Cu) exposure was found in several samples at relatively moderate levels, with P4 recording the highest concentration (1.3×10^{-3}). This condition reflects the possibility of a local or specific source of pollution, which, if continued, could increase the risk of subchronic toxic effects. Nickel (Ni) was consistently identified in the majority of samples with a concentration range of 10^{-4}-10^{-3}, and several samples, such as P4 and P9, showed relatively high values, indicating a potential carcinogenic risk that requires priority attention. Iron (Fe), although toxicologically considered less hazardous than Cd or Ni, still needs to be monitored because concentrations approaching the threshold can trigger iron metabolism disorders if consumed over the long term. Meanwhile, mercury (Hg) was not detected in any samples, which is a positive finding because Hg is known to have high neurotoxic potential even at low doses.

Table 3 shows the pattern of heavy metal exposure in refill drinking water (AMIU) samples with varying concentrations that require serious attention. Manganese (Mn) was detected in four samples (A1, A2, A4, A5), with the highest concentration in A2 (5.8×10^{-3}), indicating significant Mn exposure and the potential for neurotoxic effects if consumed continuously. This is important because Mn in high doses is known to affect the central nervous system, especially in vulnerable groups such as children. Cadmium (Cd) was present in almost all samples, and despite the low range (10^{-5}-10^{-4}), it remains dangerous due to its bioaccumulative, nephrotoxic, and potentially carcinogenic properties. These findings underscore that even relatively small Cd levels can increase chronic health risks.

Copper (Cu) exposure was quite high in A2 (1.0×10^{-3}) and A4 (1.2×10^{-3}), which may indicate the presence of specific pollution sources such as pipes or water treatment materials. High Cu concentrations can trigger gastrointestinal disorders if they exceed the daily threshold. Lead (Pb) was not detected in any samples (0.0), which is a positive finding considering that Pb has serious toxic impacts on cognitive development. Nickel

Table 3. Chronic Daily Intake (CDI) of AMIU Water.

ID	AT	BW	IR	ED	Mn	Cd	Cu	Pb	Ni	Fe	Hg
A1	25	60	2	25	1.1×10^{-3}	2.3×10^{-4}	4.1×10^{-4}	0.0	8.4×10^{-4}	4.7×10^{-4}	0.0
A2	54	55	2	54	5.8×10^{-3}	5.4×10^{-4}	1.0×10^{-3}	0.0	2.2×10^{-3}	2.2×10^{-3}	0.0
A3	31	61	2	10	0	6.1×10^{-5}	1.8×10^{-4}	0.0	2.6×10^{-4}	5.2×10^{-4}	0.0
A4	55	48	2	55	2.6×10^{-3}	4.1×10^{-4}	1.2×10^{-3}	0.0	1.9×10^{-3}	6.9×10^{-4}	0.0
A5	30	70	2	30	2.4×10^{-3}	1.5×10^{-4}	5.2×10^{-4}	0.0	7.0×10^{-4}	1.0×10^{-4}	0.0
A6	41	50	3	40	0	0	0.0	0.0	1.5×10^{-3}	0.0	0.0
A7	46	50	2	25	0	3.1×10^{-5}	0.0	0.0	6.8×10^{-4}	0.0	0.0
A8	44	68	2	44	0	1.3×10^{-5}	0.0	0.0	5.1×10^{-4}	9.3×10^{-4}	0.0
A9	26	65	2	26	0	2.6×10^{-5}	0.0	0.0	4.1×10^{-4}	0.0	0.0
A10	55	50	2	55	0	0	0.0	0.0	1.1×10^{-3}	0.0	0.0

Table 4. Chronic Daily Intake (CDI) of Well water.

No	AT	BW	IR	ED	CDI						
					Mn	Cd	Cu	Pb	Ni	Fe	Hg
S1	64	53	2	64	1.4×10^{-2}	4.0×10^{-4}	4.0×10^{-4}	0.0	1.5×10^{-3}	6.9×10^{-3}	0.0
S2	63	60	2	63	0.0	3.4×10^{-4}	1.4×10^{-3}	0.0	1.4×10^{-3}	3.1×10^{-3}	0.0
S3	46	60	2	46	2.2×10^{-3}	2.6×10^{-4}	9.3×10^{-4}	0.0	1.3×10^{-3}	1.0×10^{-2}	0.0
S4	59	70	2	59	0.0	3.4×10^{-4}	1.0×10^{-3}	0.0	1.4×10^{-3}	3.4×10^{-3}	0.0
S5	52	75	3	27	1.9×10^{-4}	2.6×10^{-4}	5.1×10^{-4}	0.0	1.0×10^{-3}	3.8×10^{-4}	0.0
S6	41	72	3	17	0.0	0.0	0.0	0.0	5.9×10^{-4}	0.0	0.0
S7	46	68	2	35	3.1×10^{-5}	6.5×10^{-5}	0.0	0.0	1.1×10^{-3}	0.0	0.0
S8	51	58	3	51	0.0	1.1×10^{-4}	0.0	0.0	1.2×10^{-3}	0.0	0.0
S9	60	45	2	60	0.0	1.4×10^{-4}	0.0	0.0	2.7×10^{-3}	0.0	0.0
S10	48	51	2	48	0.0	0.0	0.0	0.0	1.3×10^{-3}	0.0	0.0

(Ni) appeared in almost all samples with a concentration range of 10^{-4}-10^{-3}, with the highest concentrations in A2 (2.2×10^{-3}) and A4 (1.9×10^{-3}). The consistent presence of Ni at relatively high levels strengthens the suspicion that Ni is one of the main contributors to carcinogenic risk in this population. Iron (Fe) was detected in six samples, with the highest value at A2 (2.2×10^{-3}), which, although not the most dangerous heavy metal, still requires monitoring because it can trigger metabolic disorders if consumed in excess. Meanwhile, mercury (Hg) was not detected in any samples, indicating that the risk of Hg exposure from AMIU sources is relatively negligible.

Table 4 revealed that the pattern of heavy metal exposure in well water showed more extreme concentration variations compared to PDAM and AMIU. Manganese (Mn) recorded the highest concentration in S1 (1.4×10^{-2}), far exceeding other samples, indicating significant exposure and the potential to cause neurotoxic effects and motor disorders if consumed continuously. Mn exposure was also detected in S3 (2.2×10^{-3}), S5 (1.9×10^{-4}), and S7 (3.1×10^{-5}), but the values were much lower, so the relative risk was more moderate. These findings indicate the presence of a local source of contamination at the S1 location that should be a priority for mitigation.

Cadmium (Cd) was found in almost all samples with a range of 10^{-4}, and relatively high concentrations in S1 (4.0×10^{-4}), S2 (3.4×10^{-4}), and S4 (3.4×10^{-4}). Given that Cd is carcinogenic and accumulative in kidney tissue, its presence in significant amounts indicates a long-term health risk that cannot be ignored. Copper (Cu) was highest in S2 (1.4×10^{-3}) and S3 (9.3×10^{-4}), with lower contributions in S1, S4, and S5. Although Cu is an essential element, excessive exposure can trigger gastrointestinal disorders and hepatotoxicity. Lead (Pb) was not detected in any samples (0.0), which is a positive result because Pb is a potent neurotoxin that is harmful to children's development.

Nickel (Ni) was detected in almost all samples with a range of 5.9×10^{-4}-2.7×10^{-3}, and the highest concentration was found in S9 (2.7×10^{-3}), indicating the most serious potential carcinogenic risk at that location. Relatively high concentrations of Ni were also found in S1, S2, S3, and S4, so the concentration of this metal needs to be closely monitored. Iron (Fe) showed relatively high values in several samples, especially S3 (1.0×10^{-2}), S1 (6.9×10^{-3}), and S2 (3.1×10^{-3}). Although Fe is not a dangerous heavy metal, excessive exposure can cause hemochromatosis or iron metabolism disorders in susceptible individuals. Mercury (Hg) was not detected in any samples, meaning the risk of neurotoxicity due to Hg is negligible for this population.

The results of this study clearly demonstrate that heavy metal exposure in drinking water sources around the Batang Masumai River remains a serious public health threat. A comprehensive analysis in Tables 2-4 reveals variations in heavy metal exposure patterns both among samples and among water sources (PDAM, AMIU, and wells), indicating that contamination is not uniform but tends to follow environmental characteristics and possibly different sources of contamination. Manganese (Mn), lead (Pb), and mercury (Hg) were generally detected at very low levels or even undetectable, so their contribution to health risks can be categorized as minimal. This finding is a positive sign, given that Pb and Hg are known to have high neurotoxic potential even at low doses [1-4]. However, these results should not be interpreted as completely risk-free, as intermittent exposure or fluctuations in metal levels due to industrial or domestic activities can still suddenly increase the risk [5-8].

The most striking finding is the consistent presence of cadmium (Cd) in almost all samples, albeit at low levels (10^{-5}-10^{-4}). Toxicologically, Cd is a bioaccumulative heavy metal that can accumulate in the kidney and bone tissues, causing chronic kidney dysfunction and long-term carcinogenic risks [9-12]. Thus, although Cd exposure values appear small, the implications remain serious if consumption continues throughout life. In addition to Cd, the presence of nickel (Ni) at relatively high levels (10^{-4}-10^{-3}) in almost all samples, especially in samples P4, A2, and S9, which showed the highest values, confirms that Ni is a dominant contributor to carcinogenic risk in this region. This is very important because Ni is scientifically recognized as a carcinogenic metal with a mechanism that induces oxidative stress and DNA damage with the potential to trigger cancer [13, 14].

In addition to Cd and Ni, copper (Cu) and iron (Fe) were also found at moderate to high levels in several samples. Although Cu and Fe are essential metals required by the body in limited amounts, excess levels can trigger metabolic disorders, liver damage, and certain degenerative diseases if exposure exceeds safe thresholds [15, 16]. Therefore, although the risks posed by Cu and Fe are relatively lower than those of Cd and Ni, their presence still requires monitoring, particularly in locations with concentrations approaching the maximum permissible limits according to WHO standards.

Table 5 shows that all samples had a Hazard Index (HI) value <1, which quantitatively indicates no significant non-carcinogenic risk from heavy metal exposure through PDAM water consumption. However, sample P4 recorded the highest HI value (0.86), approaching the risk threshold (HI = 1). This fact emphasizes the need for vigilance because values approaching this limit can potentially cause health impacts if metal concentrations increase in the future or if exposure continues over the long term.

Analysis of metal contributions to HI values indicates that cadmium (Cd) and nickel (Ni) are the main contributors to risk, in line with their toxicological properties, which are bioaccumulative and can trigger kidney disorders and carcinogenic effects. The dominance of Cd and Ni in the HI composition reinforces the urgency of routine monitoring of PDAM water quality, especially for these heavy metal parameters, to prevent the accumulation of chronic exposure. Mitigation strategies that include increasing the efficiency of water treatment systems and regular monitoring are needed to ensure HI values remain below the safe threshold as recommended by the USEPA and WHO.

Table 6 indicates that the majority of samples had a Hazard Index (HI) <1, meaning that exposure to heavy metals in refilled drinking water (AMIU) generally does not pose a significant non-carcinogenic risk. However, two samples were of particular concern: A2, with an HI = 1.4, clearly exceeding the safe threshold, and A4 with an HI = 1.0, right on the risk threshold. Both findings indicate potential health impacts for individuals consuming water from these sources, especially if exposure continues.

The main contribution to the high HI value comes from cadmium (Cd), which at A2 even has a Hazard Quotient (HQ) > 1 (HQ = 1.1), so it is toxicologically categorized as high risk. In addition to Cd, manganese (Mn) and nickel (Ni) also make additional contributions in some individuals, exacerbating the potential cumulative impact. These findings reinforce the urgency of water quality monitoring at AMIU depots, especially since the consumption of refilled drinking water is generally the main choice for urban communities. Mitigation approaches that can be implemented include improving filtration standards and heavy metal adsorption in the water treatment process, as well as implementing regular water quality audits to prevent chronic exposure that poses a risk to public health.

Table 7 shows that among the 10 samples, only S1 had a Hazard Index (HI) of 1.4, exceeding the safe

Table 5. Hazard Quotient (HQ) and Hazard Index (HI) of heavy metals in PDAM water.

ID	HQ							HI_	Risk level
	Mn	Cd	Cu	Pb	Ni	Fe	Hg		
P1	0.0	4.4×10^{-1}	1.0×10^{-2}	0.0	2.4×10^{-2}	1.4×10^{-3}	0.0	4.8×10^{-1}	Acceptable
P2	0.0	3.6×10^{-1}	1.5×10^{-2}	0.0	1.5×10^{-2}	0.0	0.0	3.9×10^{-1}	Acceptable
P3	0.0	2×10^{-2}	7.0×10^{-4}	0.0	1.2×10^{-3}	5.4×10^{-5}	0.0	2.2×10^{-2}	Acceptable
P4	0.0	7.8×10^{-1}	3.2×10^{-2}	0.0	4.7×10^{-2}	1.2×10^{-3}	0.0	8.6×10^{-1}	Acceptable
P5	9.6×10^{-3}	4.8×10^{-1}	1.3×10^{-2}	0.0	2.3×10^{-2}	9.6×10^{-4}	0.0	5.3×10^{-1}	Acceptable
P6	0.0	1.9×10^{-1}	0.0	0.0	3.7×10^{-2}	0.0	0.0	2.3×10^{-1}	Acceptable
P7	0.0	0.0	0.0	0.0	2.4×10^{-2}	0.0	0.0	2.4×10^{-2}	Acceptable
P8	0.0	1.3×10^{-1}	0.0	0.0	2.5×10^{-2}	0.0	0.0	1.5×10^{-1}	Acceptable
P9	0.0	6.2×10^{-2}	0.0	0.0	3.2×10^{-2}	0.0	0.0	9.4×10^{-2}	Acceptable
P10	0.0	1.1×10^{-1}	0.0	0.0	1.4×10^{-2}	1.19×10^{-3}	0.0	1.3×10^{-1}	Acceptable

Note: HQ represents the non-carcinogenic risk of individual metals, while HI is the cumulative hazard index calculated as the sum of HQ values. HI<1 indicates an acceptable non-carcinogenic risk.

Table 6. Hazard Quotient (HQ) and Hazard Index (HI) of heavy metals in AMIU drinking water.

ID	HQ							HI	Risk level
	Mn	Cc	Cu	Pb	Ni	Fe	Hg		
A1	4.6×10^{-2}	4.6×10^{-1}	1.0×10^{-2}	0.0	2.1×10^{-2}	6.7×10^{-4}	0.0	5.4×10^{-1}	Acceptable
A2	2.4×10^{-1}	1.1×10^{0}	2.5×10^{-2}	0.0	5.5×10^{-2}	3.1×10^{-3}	0.0	1.4×10^{0}	Potential risk
A3	0.0	1.2×10^{-1}	4.5×10^{-3}	0.0	6.5×10^{-3}	7.4×10^{-4}	0.0	1.3×10^{-1}	Acceptable
A4	1.1×10^{-1}	8.2×10^{-1}	3×10^{-2}	0.0	4.7×10^{-2}	9.9×10^{-4}	0.0	1×10^{0}	Acceptable
A5	1×10^{-1}	3×10^{-1}	1.3×10^{-2}	0.0	1.7×10^{-2}	1.4×10^{-4}	0.0	4.3×10^{-1}	Acceptable
A6	0.0	0.0	0.0	0.0	3.7×10^{-2}	0.0	0.0	3.7×10^{-2}	Acceptable
A7	0.0	6.2×10^{-2}	0.0	0.0	1.7×10^{-2}	0.0	0.0	7.9×10^{-2}	Acceptable
A8	0.0	2.60×10^{-2}	0.0	0.0	1.28×10^{-2}	1.33×10^{-3}	0.0	4.01×10^{-2}	Acceptable
A9	0.0	5.20×10^{-2}	0.0	0.0	1.03×10^{-2}	0.0	0.0	6.23×10^{-2}	Acceptable
A10	0.0	0.0	0.0	0.0	2.75×10^{-2}	0.0	0.0	2.75×10^{-2}	Acceptable

Note: HQ represents the non-carcinogenic risk of individual metals, while HI is the cumulative hazard index calculated as the sum of HQ values. HI<1 indicates an acceptable non-carcinogenic risk, whereas HI>1 indicates a potential health concern.

Table 7. Hazard Quotient (HQ) and Hazard Index (HI) of heavy metals in well water.

ID	HQ							HI_{total}	Risk level
	Mn	Cd	Cu	Pb	Ni	Fe	Hg		
S1	5.8×10^{-1}	8.0×10^{-1}	1.0×10^{-2}	0.0	3.7×10^{-2}	9.9×10^{-3}	0.0	1.4×10^{0}	Potential risk
S2	0.0	6.8×10^{-1}	3.5×10^{-2}	0.0	3.5×10^{-2}	4.4×10^{-3}	0.0	7.5×10^{-1}	Acceptable
S3	$9.2.0\times10^{-2}$	5.2×10^{-1}	2.3×10^{-2}	0.0	3.2×10^{-2}	1.4×10^{-2}	0.0	6.8×10^{-1}	Acceptable
S4	0.0	6.8×10^{-1}	2.5×10^{-2}	0.0	3.5×10^{-2}	4.8×10^{-3}	0.0	7.4×10^{-1}	Acceptable
S5	7.9×10^{-3}	5.2×10^{-1}	1.3×10^{-2}	0.0	2.5×10^{-2}	5.4×10^{-4}	0.0	5.6×10^{-1}	Acceptable
S6	0.0	0.0	0.0	0.0	1.9×10^{-2}	0.0	0.0	1.9×10^{-2}	Acceptable
S7	1.3×10^{-3}	1.3×10^{-1}	0.0	0.0	2.7×10^{-2}	0.0	0.0	1.6×10^{-1}	Acceptable
S8	0.0	2.2×10^{-1}	0.0	0.0	3.0×10^{-2}	0.0	0.0	2.5×10^{-1}	Acceptable
S9	0.0	2.8×10^{-1}	0.0	0.0	6.7×10^{-2}	0.0	0.0	3.5×10^{-1}	Acceptable
S10	0.0	0.0	0.0	0.0	3.2×10^{-2}	0.0	0.0	3.2×10^{-2}	Acceptable

Note: HQ represents the non-carcinogenic risk of individual metals, while HI is the cumulative hazard index calculated as the sum of HQ values. HI<1 indicates an acceptable non-carcinogenic risk, whereas HI>1 indicates a potential health concern.

threshold and clearly indicating a non-carcinogenic risk that needs to be addressed immediately. The other samples (S2-S10) remained below the threshold (HI<1) and were thus categorized as safe, although several samples, such as S2 (0.75), S3 (0.68), and S4 (0.74), recorded values close to the threshold, indicating potential risk if exposure increases in the future. Analysis of metal contributions revealed that cadmium (Cd) was the dominant risk contributing factor, followed by manganese (Mn), which was significant in S1, and nickel (Ni), which increased the risk burden for several samples. These findings emphasize the need for regular well water quality control, especially in locations with HI approaching or exceeding the threshold, to minimize long-term exposure accumulation and protect public health.

The non-carcinogenic risk analysis based on Tables 5-7 confirms that the majority of samples had a Hazard Index (HI)<1, indicating that overall heavy metal exposure does not pose a significant non-carcinogenic health risk. However, there were notable exceptions in samples A2 (HI = 1.4), A4 (HI = 1.0), and S1 (HI = 1.4), whose levels exceeded or approached the risk threshold. This indicates that chronic exposure risks are present in a portion of the samples, with Cd as the primary risk contributor, followed by Mn and Ni in some samples. It shows that while the majority of samples appear safe, there are pockets of the population that face a higher risk and should be prioritized for public health intervention. Regular monitoring is important because the cumulative impacts of Cd and Ni exposure can increase over time [17-19, 22, 25, 26].

Carcinogenic Risk

Carcinogenic risk assessment was conducted to estimate the potential lifetime probability of cancer development associated with chronic exposure to heavy metals through drinking water consumption. This assessment follows the United States Environmental Protection Agency (USEPA) framework and is expressed as cancer risk (CR), which quantifies the incremental probability of an individual developing cancer over a lifetime due to exposure to carcinogenic contaminants. The carcinogenic risk (CR) was calculated using the following equation:

$$CR = CDI \times CSF$$

where CDI (Chronic Daily Intake) represents the average daily exposure dose of a contaminant through ingestion, consistent with the intake parameter used in non-carcinogenic risk assessment. CSF (Cancer Slope Factor) is a toxicity parameter that describes the quantitative relationship between chronic exposure to a carcinogenic substance and the probability of cancer occurrence. CSF values are derived from toxicological studies and regulated by the United States Environmental Protection Agency (USEPA).

CR_{total} data with EPA reference (1999):

1×10^{-6} - 1×10^{-4} no cancer risk (still acceptable)

$> 1\times10^{-4}$ cancer risk (unacceptable)

Table 8 shows that of the 10 PDAM drinking water samples, only P3 was categorized as having no cancer risk, while the other nine samples (90%) were identified as having a Cancer Risk (CR) $> 1\times10^{-4}$, thus falling into the unacceptable carcinogenic risk category according to EPA standards (1999). These findings indicate that exposure to heavy metals, especially nickel (Ni) as the main contributor, has reached levels that may affect public health in the long term. The dominance of Ni as a risk contributor strengthens the hypothesis that the contamination pathway may originate from industrial sources or distribution pipe corrosion processes, thus requiring a comprehensive evaluation of the PDAM distribution system. The fact that only 10% of samples were safe emphasizes the need for immediate intervention through improving the water treatment system, implementing specific heavy metal adsorption or filtration technologies, and regular monitoring to ensure PDAM water quality meets WHO health standards and to prevent cancer risks due to chronic exposure.

Table 9 reveals that all refill drinking water (AMIU) samples (A1-A10) have a Cancer Risk (CR_{total})$>1\times10^{-4}$, meaning 100% of the samples are classified as having unacceptable cancer risk, and none of them meet the safe category. This finding indicates that heavy metal exposure from AMIU sources consistently exceeds the acceptable threshold according to the EPA (1999), thus becoming a critical public health issue. Nickel (Ni) was identified as the dominant contributor to carcinogenic risk, while cadmium (Cd) made a smaller additional contribution, and lead (Pb) was not detected at all. This fact reinforces the urgency of tightening quality standards and routine inspections of AMIU depots, implementing more effective filtration technology for heavy metals, and educating the public to be more selective in choosing drinking water sources, considering that chronic Ni exposure can trigger cumulative carcinogenic effects and increase the burden of disease at the population level.

Table 8. Carcinogenic risk (CR) of heavy metals in PDAM drinking water.

ID	Cd	Pb	Ni	Σ CR	Risk category
P1	8.36×10^{-5}	0.0	1.63×10^{-3}	1.72×10^{-3}	Unacceptable
P2	6.84×10^{-5}	0.0	1.05×10^{-3}	1.12×10^{-3}	Unacceptable
P3	3.80×10^{-6}	0.0	8.16×10^{-5}	8.54×10^{-5}	Acceptable
P4	1.48×10^{-4}	0.0	3.23×10^{-3}	3.38×10^{-3}	Unacceptable
P5	9.12×10^{-5}	0.0	1.56×10^{-3}	1.66×10^{-3}	Unacceptable
P6	3.57×10^{-5}	0.0	2.55×10^{-3}	2.59×10^{-3}	Unacceptable
P7	0.0	0.0	1.67×10^{-3}	1.67×10^{-3}	Unacceptable
P8	2.47×10^{-5}	0.0	1.70×10^{-3}	1.72×10^{-3}	Unacceptable
P9	1.18×10^{-5}	0.0	2.21×10^{-3}	2.22×10^{-3}	Unacceptable
P10	2.13×10^{-5}	0.0	9.69×10^{-4}	9.90×10^{-4}	Unacceptable

Note: CR represents the lifetime carcinogenic risk associated with exposure to individual metals through drinking water ingestion. ΣCR is the total carcinogenic risk calculated as the sum of individual CR values. According to USEPA guidelines, $CR\leq1\times10^{-4}$ is considered acceptable, whereas $CR>1\times10^{-4}$ indicates an unacceptable carcinogenic risk.

Table 9. Cancer Risk (CR) of Refilled Drinking water (AMIU).

ID	Cd	Pb	Ni	Σ CR	Risk category
A1	8.7×10^{-5}	0.0	1.4×10^{-3}	1.5×10^{-3}	Unacceptable
A2	2.0×10^{-4}	0.0	3.7×10^{-3}	3.9×10^{-3}	Unacceptable
A3	2.3×10^{-5}	0.0	4.4×10^{-4}	4.6×10^{-4}	Unacceptable
A4	1.6×10^{-4}	0.0	3.2×10^{-3}	3.4×10^{-3}	Unacceptable
A5	5.7×10^{-5}	0.0	1.2×10^{-3}	1.2×10^{-3}	Unacceptable
A6	0.0	0.0	2.5×10^{-3}	2.5×10^{-3}	Unacceptable
A7	1.2×10^{-5}	0.0	1.2×10^{-3}	1.2×10^{-3}	Unacceptable
A8	4.4×10^{-6}	0.0	8.7×10^{-4}	8.7×10^{-4}	Unacceptable
A9	9.9×10^{-6}	0.0	6.97×10^{-4}	7.1×10^{-4}	Unacceptable
A10	0.0	0.0	1.9×10^{-3}	1.9×10^{-3}	Unacceptable

Note: CR represents the lifetime carcinogenic risk associated with heavy metal exposure through drinking water ingestion. ΣCR is the total carcinogenic risk calculated as the sum of individual CR values. According to USEPA guidelines, $CR>1\times10^{-4}$ indicates an unacceptable carcinogenic risk.

Table 10. Cancer Risk (CR) of Well water.

ID	Cd	Pb	Ni	Σ CR	Risk category
S1	1.5×10^{-4}	0.0	2.55×10^{-3}	2.7×10^{-3}	Unacceptable
S2	1.3×10^{-4}	0.0	2.38×10^{-3}	2.5×10^{-3}	Unacceptable
S3	9.9×10^{-5}	0.0	2.21×10^{-3}	2.3×10^{-3}	Unacceptable
S4	1.3×10^{-4}	0.0	2.38×10^{-3}	2.5×10^{-3}	Unacceptable
S5	9.9×10^{-5}	0.0	1.70×10^{-3}	1.8×10^{-3}	Unacceptable
S6	0.0	0.0	1.00×10^{-3}	1.0×10^{-3}	Unacceptable
S7	2.5×10^{-5}	0.0	1.87×10^{-3}	1.9×10^{-3}	Unacceptable
S8	4.2×10^{-5}	0.0	2.04×10^{-3}	2.1×10^{-3}	Unacceptable
S9	5.3×10^{-5}	0.0	4.59×10^{-3}	4.6×10^{-3}	Unacceptable
S10	0.0	0.0	2.21×10^{-3}	2.2×10^{-3}	Unacceptable

Note: CR represents the lifetime carcinogenic risk associated with heavy metal exposure through drinking water ingestion. ΣCR is the total carcinogenic risk calculated as the sum of individual CR values. According to USEPA guidelines, $CR>1\times10^{-4}$ indicates an unacceptable carcinogenic risk.

Table 10 shows that all well water samples (S1-S10) had a Cancer Risk (CR_{total})$>1\times10^{-4}$, so 100% were categorized as having unacceptable cancer risk and none met the safe criteria. This finding is very concerning because it indicates that heavy metal exposure from well water has exceeded the acceptable carcinogenic risk limit according to the EPA (1999). Nickel (Ni) was again the main contributor to risk, strengthening a pattern consistent with the results from PDAM and AMIU, while cadmium (Cd) only contributed slightly, and lead (Pb) was not detected at all. The most critical case was found in S9 with the highest CR value (4.6×10^{-3}), indicating the potential for serious health impacts for the population consuming water from this source. These results emphasize the urgency of immediate intervention through improving groundwater quality, implementing effective domestic treatment technologies for heavy metals, and public health education programs to reduce dependence on contaminated well water sources.

The carcinogenic risks analyzed in Tables 8-10 paint a much more alarming picture. Nearly all samples from the three water sources showed CR_{total} values$>1\times10^{-4}$, exceeding the acceptable cancer risk threshold according to EPA standards (1999). Of the ten PDAM samples, nine (90%) were categorized as high risk, all AMIU samples (100%) were high risk, with Ni as the primary contributor, and all well samples were also in the high-risk category, with the most extreme value found in S9 (4.6×10^{-3}). These findings strengthen the evidence that

Ni is the primary determinant of carcinogenic risk in this area, with Cd contributing only a small amount and Pb being barely detectable. This pattern also implies that well water poses the most critical risk compared to other water sources, so mitigation interventions should be prioritized in areas dependent on groundwater.

When compared with previous studies, these results align with those of [27-32], who reported significant contributions of Cr, Cd, and Pb to non-carcinogenic risk in Saraven, Iran, [33] and a study in Neyshabur, Iran, which documented heavy metal exposure in groundwater despite a lower contaminant index. However, this study makes a novel contribution by demonstrating that nickel (Ni) is the dominant factor determining carcinogenic risk, a finding rarely reported in similar studies. This difference enriches the scientific literature and suggests the presence of local factors such as geological characteristics or industrial activities that trigger high Ni levels in the study area [34-40].

These findings confirm that although not all heavy metals are present in high concentrations, the presence of certain metals, such as nickel (Ni) and cadmium (Cd), still poses significant health impacts, both through non-carcinogenic and carcinogenic mechanisms. Therefore, strategic measures such as regular water quality monitoring, controlling pollution sources from industrial and domestic activities, and improving water treatment systems are crucial to reduce public health risks [41-50]. Evidence-based policy interventions, including the implementation of stricter water quality standards and public education on the dangers of contaminated water, are expected to minimize future exposure to heavy metals and protect public health in the long term [51-55].

From a broader perspective, the observed distribution of heavy metals suggests a combination of natural and anthropogenic sources, including domestic activities and possible upstream inputs. The dominance of certain metals, particularly Ni, in contributing to carcinogenic risk indicates that specific elements may play a disproportionate role in determining overall health risk. Recent studies have emphasized that integrating pollution assessment with source identification is essential for understanding contamination pathways and associated health impacts, especially in complex environmental systems [56, 57].

Conclusions

This study evaluated heavy metal concentrations in drinking water sources around the Batang Masumai River and assessed associated non-carcinogenic and carcinogenic health risks using the USEPA framework. The results indicate that non-carcinogenic risks were generally within acceptable limits, with all PDAM samples showing HI < 1, although an elevated risk (HI = 1.4) was observed in one AMIU and one groundwater sample, primarily influenced by Cd and Mn. In contrast, carcinogenic risks were found to be significant across all water sources. A high proportion of PDAM samples (90%) and all AMIU and groundwater samples (100%) exceeded the acceptable cancer risk threshold ($CR_{total}>1\times10^{-4}$), with the highest risk recorded in groundwater (4.6×10^{-3}). Nickel (Ni) was identified as the dominant contributor to carcinogenic risk, while Cd and Pb contributed to a lesser extent. Overall, this study highlights that drinking water sources in the study area pose unacceptable carcinogenic risks, emphasizing the need for targeted mitigation strategies. These include improved water treatment, regular monitoring of priority heavy metals, and stricter regulation of pollution sources. The findings provide important scientific evidence to support water quality management and public health protection in small watershed regions.

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Declaration of AI Use

ChatGPT (OpenAI) and Grammarly were used solely to improve the grammar, language quality, and readability of the manuscript. No AI tools were used for data collection, data analysis, interpretation of results, or generation of scientific conclusions. All content was reviewed and verified by the authors, who take full responsibility for the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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