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Analysis Of Environmental Health Risks from Exposure to Heavy Metals Cadmium and Manganese in Drinking Water for The Community in The Selayar Islands

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ABSTRACT

Background: Natural fault activity can lead to the contamination of water sources with heavy metals such as manganese (Mn) and cadmium (Cd). The fault movement that creates fractures opens pathways for groundwater to interact with metal-containing rocks, resulting in the dissolution and transportation of these metals into groundwater systems and surface water sources, potentially reaching concentrations that are harmful to human health and the environment.

Objective: This study aimed to determine the concentration levels of heavy metals Cd and Mn in well water and piped water, exposure duration, intake rate and frequency of Cd and Mn exposure through drinking water consumed by the residents of Pasimarannu District.

Method: This research is a quantitative descriptive study using the Environmental Health Risk Assessment (EHRA) method. Data analysis is conducted by calculating intake, Excess Cancer Risk (ECR), and risk management. If ECR > E-4, it indicates that the contaminant has carcinogenic risk and requires risk management.

Results: The study shows the environmental health risks from exposure to heavy metals Cd and Mn as follows The ECR value for Cd in independent well water is 2×10^{-4}, while in piped water, it is 4×10^{-4}. The ECR value for Mn in well water is 2 x 10, while in piped water, it is 1 x 10. The carcinogenic risk level (ECR) from Cd exposure increases every 10 years, with Cd intake from independent wells and piped water rising from 0.00057 mg/L and 0.001 mg/L (in the 10th year) to 0.004 mg/L and 0.0075 mg/L (in the 70th year), respectively. Risk management can be done by determining the safe consumption limit and the amount of safe consumption.

Conclusion: Risk management in Batu Bingkung, Bonea, dan Sambali Villages involves controlling variables like safe concentration limits and allowable consumption of Cd dan Mn to prevent health risks and protect community safety.

Keywords: *EHRA, cadmium, manganese, drinking water, risk management*

1. INTRODUCTION

Water is a vital element of life, the availability of clean water must always be maintained in terms of both quantity and quality (1). Clean water is that which is used in daily life and meets health standards, making it safe for consumption after being boiled (2). Ensuring that water quality complies with health requirements is essential to guarantee public health sustainably (3).

Water pollution in Indonesia is largely caused by human activities that result in residential waste, agricultural runoff, and industrial waste, including mining (4). The Asian Development Bank (2008) reported that water pollution in Indonesia incurs losses of IDR 45 trillion annually. The costs associated with water pollution include healthcare expenses, the costs of providing clean water, loss of productive time, a negative tourism image, and high infant mortality rates (5). Surface water pollution by heavy metals is a global health concern due to their toxic, non-biodegradable, and accumulative nature, while access to quality drinking water remains a challenge in many developing regions, making it essential to ensure water sources meet the quality standards set by Regulation of the Minister of Health No. 2 of 2023 (6).

One metal frequently found in drinking water is Cadmium (Cd), a toxic element that is not required by living organisms (7). The presence of Cd in the environment poses multiple threats, including damage to plants and various diseases in humans (8). The persistent nature of Cd allows this element to accumulate in various human body organs, potentially leading to harmful health effects (9). The accumulation of Cd in the human food chain increases the risk of various health problems, including carcinogenic potential, prompting the World Health Organization (WHO) to classify Cd as a human carcinogen (10).

Natural fault activities can also lead to water source contamination by heavy metals like manganese (Mn) and cadmium (Cd). Movements along faults can create fractures and geological changes, allowing groundwater to interact with rocks that contain these harmful metals (11). During this process, groundwater can leach Mn and Cd from minerals in the rocks, which subsequently enters groundwater systems and surface water sources. The accumulation of these heavy metals in water can reach concentrations hazardous to human health and the environment (12). Moreover, chemical and physical changes induced by fault activity can enhance the mobility and bioavailability of these heavy metals, exacerbating water contamination levels. Research indicates that areas with significant tectonic activity tend to have higher levels of heavy metal contamination in their water sources due to hydrogeochemical processes triggered by fault movements (13).

Research conducted by Angriana Anggriana (2011) revealed that the cadmium (Cd) content in three drinking water wells investigated was 0.11 mg/L, 0.08 mg/L, and 0.065 mg/L, respectively. These findings indicate that the levels of heavy metals exceed the maximum limits established by the Minister of Health of the Republic of Indonesia Regulation No. 416/MENKES/PER/1990, which sets the safe limit for cadmium at 0.005 mg/L. Based on these findings, it can be concluded that the water from these wells has been contaminated and is unsafe for consumption.

The study Awliahasanah Awliahasanah et al. (2021) reported a mean manganese concentration of 1.36 mg/L in the drinking water from wells in Depok City. The calculated risk quotient (RQ) was less than 1, indicating that the manganese content in residents' well water poses no risk for exposure over the next 30 years or under non-carcinogenic assessments; however, carcinogenic evaluations should be conducted to understand the risk of exposure over a 70-year period.

Based on interviews and the Drinking Water Quality Monitoring Report (PKAM) from the Pasimarannu Health Center, residents in eight villages use 24 drinking water sources, both piped and non-piped (e.g., dug and pump wells), serving a total population of 10,430 across 3,019 households. With cadmium (Cd) and manganese (Mn) detected in water sources per SKAMRT 2023, an Environmental Health Risk Analysis (EHRA) is essential to assess potential health impacts from environmental pollution. This analysis is used to assess the concentrations of heavy metals that can pose health risks, such as cadmium and manganese, thereby strengthening the research argument regarding environmental health risks associated with exposure to these heavy metals.

2. PARTICIPANTS & METHOD

The type of research is an analytical observational study with an Environmental Health Risk Analysis (EHRA) approach aimed at assessing or estimating the magnitude of human health risks caused by exposure to environmental hazards. The research procedures in the EHRA method include Hazard Identification, Dose-Response Assessment, Exposure Assessment, Risk Characterization, and Risk Management. The population in this study is the community at risk of exposure to Cadmium (Cd) and Manganese (Mn) from 3 villages, namely Batu Bingkung Village, Bonea Village, and Sambali Village (figure 1). The size of the sample objects in this study was determined using the Slovin formula, which included 43 drinking water samples (divided into 12 piped water samples and 31 independent water samples) and 98 human samples.

Questionnaires and interviews in this study are used to obtain data regarding the characteristics of respondents, consumption levels (consumption time, consumption frequency, consumption duration) in a day, body weight, and personal identity data such as name, age, and gender, how the water processing before consumption, as well as subjective health complaints experienced by the respondents. R*isk analysis and environmental health risk*

$$\boldsymbol{CDI\ Oral = \frac{CW\ x\ IR\ x\ EF\ x\ ED}{BW\ x\ AT}} \quad (1)$$

Description:

CW = Contaminant concentration in water (mg/liter)

IR = ingestion rate (Litres of water/day)

EF = exposure frequency (days/year)

ED = exposure duration (year)

BW = body weight (kg)

AT = average time (for carci AT=ED x 365 days)

$$ECR = I \times SF \quad (2)$$

Description:

ECR = Excess Cancer Risk

SF = Risk agent reference value (Slope Factor)

I = Intake (exposure)

$$RQ = \frac{CDI}{RfD} \quad (3)$$

Description:

RQ = Risk Quetient

CDI = Chronic Daily Intake

RfD = Reference dose

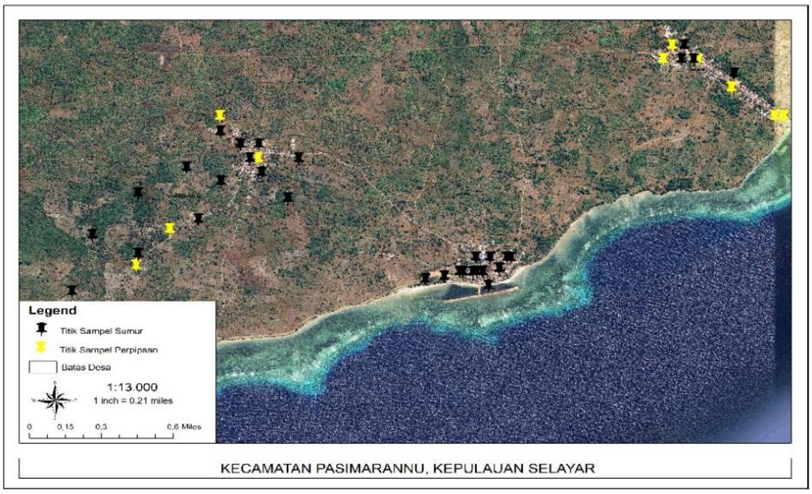
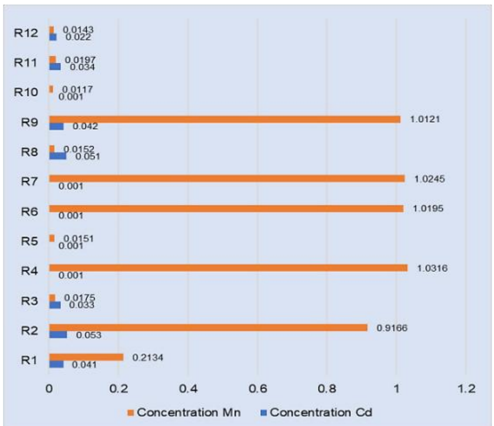


Figure 1. Research Location Map

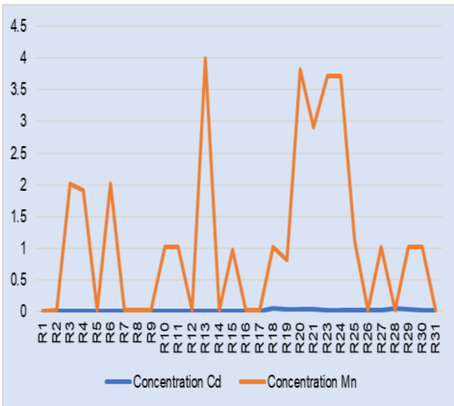
Findings

1. Concentration of cadmium and manganese



Source: Primary Data, 2024

Figure 2. Concentration of Cd and Mn (mg/L) in Piped Drinking Water



Source: Primary Data, 2024

Figure 3. Concentration of Cd and Mn (mg/L) in Independent Well Drinking Water

Figure 2 shows the measurement of Cadmium (Cd) and Manganese (Mn) concentrations in piped drinking water in Batu Bingkung Village, Bonea Village, and Sambali Village in 2024. Cd concentrations in households (R1 to R12) are relatively low, ranging from 0.001 to 0.053 mg/L, with the highest value at R1 being 0.053 mg/L. In contrast, Mn concentrations are higher, ranging from 0.9166 to 1.0361 mg/L, with R6 measuring the highest at 1.0361 mg/L and R3 the lowest at 0.9166 mg/L. Overall, Mn is more dominant than Cd, with Mn concentrations being more uniform, while Cd levels vary.

Figure 3 illustrates the differences in Cd and Mn concentrations in drinking water from wells in the same areas. Cd concentrations are mostly low (0.001 mg/L), although R19, R20, R27, and R28 show higher values. Mn concentrations vary widely, from 0.0034 mg/L (R1) to 3.9986 mg/L (R13), with some households, such as R20, R23, and R24, recording values above 3 mg/L. Many water samples exceed WHO standards, particularly for Mn (0.1 mg/L), indicating significant potential for heavy metal contamination due to geological factors or environmental pollution.

3. RISK ASSESSMENT

The identification of hazards in this study is the first step in EHRA to determine specific risk agents that could potentially cause health disturbances if exposed. Cadmium is toxic and can accumulate in the body. Whereas Manganese is an essential metal in the human body but can be toxic at high levels.

Figure 4. Pipe Source

Figure 5. Independent Well Source

Figure 4 illustrates that both piped water sources and Figure 5 indicates independent well sources can be contaminated with heavy metals like Manganese (Mn) and Cadmium (Cd) through natural mechanisms and human activities. Natural contamination occurs when groundwater flows through rock layers containing heavy metals, while island environments like Selayar can have geological characteristics that increase heavy metal content in the water.

Human activities, such as poor management of domestic waste and waste from small industries, also contribute to groundwater pollution. In piping systems, corrosion of pipes made from certain metals, like galvanized steel, or the use of piping materials that do not meet safety standards can lead to contamination. Furthermore, seawater intrusion in island areas can accelerate the leaching of heavy metals from soil layers.

Table 1. Characteristics of Respondents Based on Body Weight and Activity Patterns in 2024

Characteristicts	Min	Max
Age (year)	6	60
Weight (kg)	13.3	97.9
Intake Rate (L/day)	1.5	3
Exposure Frequency (day/year)	360	365

Based on Table 1, it shows that the age (years) of the respondents ranges from 6 to 60 years. The respondents' body weight ranged from 13.3 to 97.9 kg. The intake rate ranges from 1.5 to 3 (L/day), and the exposure frequency ranges from 360 to 365 (days/year).

Table 2. Carcinogenic and Non-Carcinogenic Intake Values of Respondents for Real-Time Exposure Duration in 2024

Heavy Metals	Intake (mg/day)						
	Independent wells			Piping			Information
	Min	Max	Mean	Min	Max	Mean	
Carcinogenic							
Cadmium	$2,4 \times 10^{-5}$	$5,9 \times 10^{-3}$	1×10^{-3}	$1,7 \times 10^{-5}$	$3,3 \times 10^{-3}$	$4,7 \times 10^{-4}$	not acceptable
Non- Carcinogenic							
Manganese	$1,1 \times 10^{-4}$	$2,7 \times 10^{-1}$	$5,1 \times 10^{-2}$	1×10^{-4}	$1,9 \times 10^{-1}$	$3,6 \times 10^{-2}$	acceptable

*Note: CSF Cd 15 mg/kg/day and RfD Mn 0.14 mg/kg/day

Table 2 shows the intake values of carcinogenic and non-carcinogenic heavy metals for respondents during the real-time exposure duration in 2024, indicating variations in independent well and piped water sources. For carcinogenic heavy metals, namely Cadmium (Cd), the intake from independent well water ranges from 2.4×10^{-5} mg/day (minimum) to 5.9×10^{-3} mg/day (maximum), with an average of 1×10^{-3} mg/day. In piped water, the minimum intake value of Cd is 1.7×10^{-5} mg/day, the maximum value is 3.3×10^{-3} mg/day, and the average is 4.7×10^{-4} mg/day.

For non-carcinogenic heavy metals, namely Manganese (Mn), the intake from independent well water varies from 1.1×10^{-4} mg/day (minimum) to 2.7×10^{-1} mg/day (maximum), with an average of 5.1×10^{-2} mg/day. Meanwhile, in piped water, the Mn intake has a minimum value of 1×10^{-4} mg/day, a maximum value of 1.9×10^{-1} mg/day, and an average of 3.6×10^{-2} mg/day. Generally, the intake of Manganese (Mn) is higher than that of Cadmium (Cd) in both water sources, whether from independent wells or piped water. This variation in intake indicates the potential risk of exposure to heavy metals differs based on the water source.

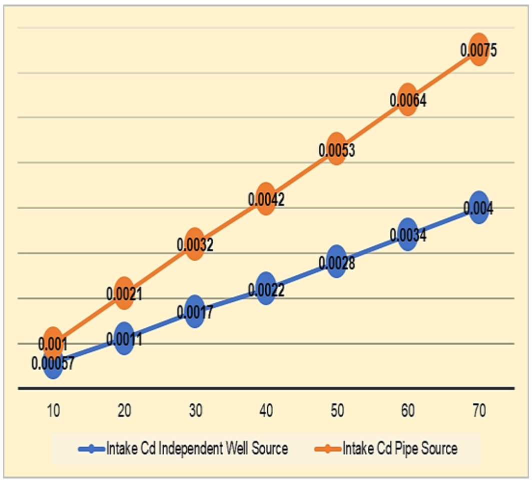


Figure 6. Projection of Mean Cd Intake Values Over 10-70 Years of Exposure Duration in Respondents 2024

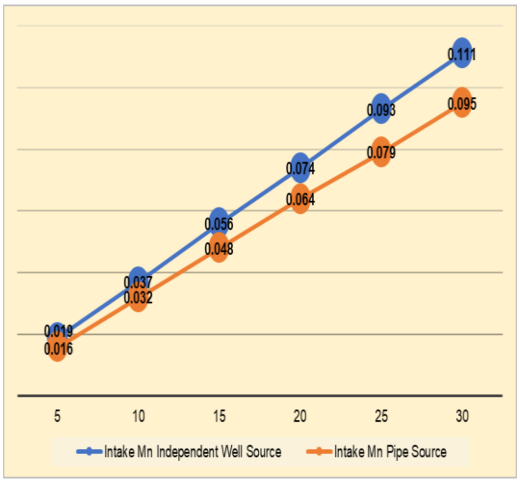


Figure 7. Projection of Mean Intake Mn Exposure Duration 5-30 Years in Respondents 2024

Figure 6 displays the projected mean intake values of cadmium (Cd) from two sources, independent wells and piped water, over an exposure duration of 10 to 70 years for respondents in 2024. The results indicate that Cd intake from piped water is consistently higher than from independent wells at all time points. For independent wells, the mean Cd intake rises from 0.00057 mg/L in the 10th year to 0.004 mg/L in the 70th year. In contrast, piped water intake shows a more significant increase, from 0.001 mg/L in the 10th year to 0.0075 mg/L in the 70th year, suggesting a higher long-term exposure risk to Cd from piped water compared to independent wells.

Figure 7 illustrates the projected mean intake values of manganese (Mn) from independent wells and piped water over a 5 to 30-year exposure period in 2024. Both sources show increasing Mn intake over time, though with different trends. In independent wells, the mean Mn intake starts low at 0.019 mg/L in the 5th year and rises to 0.111 mg/L by the 30th year. Conversely, Mn intake from piped sources increases steadily from 0.016 mg/L at the 5th year to 0.095 mg/L at the 30th year, without significant jumps.

This stage is used to understand the extent of health risks arising from exposure to hazardous substances such as heavy metals. This dose-response analysis does not have to be conducted through original experimental research but can be done by referring to the available literature. The Slope Factor (SF) values based on US-EPA (1998) obtained the SF (slope factor) value for Cd (15mg/kg/day) and RfD for Mn (0.14mg/kg/day). The Excess Cancer Risk (ECR) value of the risk agent from this ingestion exposure is then used to determine the magnitude of public health risk.

Risk characterization is carried out by combining exposure analysis and dose-response. Risk characterization is expressed in Excess Cancer Risk (ECR) for carcinogenic effects. The level of carcinogenic risk is expressed in a unitless exponent number. It is considered safe if the ECR value ≤ 1/10,000. The risk level is considered unsafe if the ECR value > E-4 (10-4) or expressed as > 1/10,000. Whereas for non-carcinogenic effects, it is expressed in Risk Question (RQ). It is considered safe if RQ < 1 and unsafe if RQ > 1.

Table 3. Min, Max, and Mean Excess Cancer Risk (ECR) and Risk Question (RQ) Realtime Values for Respondents in 2024

Heavy Metals	**Intake (mg/day)**						
	Independent wells			**Piping**			**Information**
	Min	Max	Mean	Min	Max	Mean	
Carcinogenic							
Cadmium (Cd)	1×10^{-6}	2×10^{-4}	3.1×10^{-5}	2×10^{-6}	4×10^{-4}	7×10^{-5}	acceptable
Non- Carcinogenic							
Manganese (Mn)	8×10^{-4}	2×10^{0}	4×10^{-1}	3×10^{-3}	1×10^{0}	3×10^{-1}	acceptable

Explanation: ECR Cd ≤ 10-4 (acceptable) and RQ Mn < 1 (acceptable)

*Note: CSF Cd 15 mg/kg/day and RfD Mn 0.14 mg/kg/day

Table 3 shows that the highest carcinogenic risk level or ECR of the heavy metal Cd in independent well water for real-time exposure duration is 2 x 10^-4, which means it can be concluded that there are 2 cases in 10,000 people at risk of cancer in a population of 10,000 people. Whereas the highest level in piped water is 4 x 10-4, it can be concluded that there are 4 cases per 10,000 people that could develop into cancer cases, or there are 4 people at risk of cancer in a population of 10,000. The real-time exposure duration of the heavy metal Cd is still considered acceptable or safe because the mean ECR value is < E-4 (10-4) or expressed as ECR < 1/10,000. The non-carcinogenic risk level or RQ value of the heavy metal Mn in independent well water is highest at 2 x 100, while in piped water it is highest at 1 x 100. The real-time exposure duration of heavy metal Mn is still considered acceptable or safe because the mean RQ value is < 1.

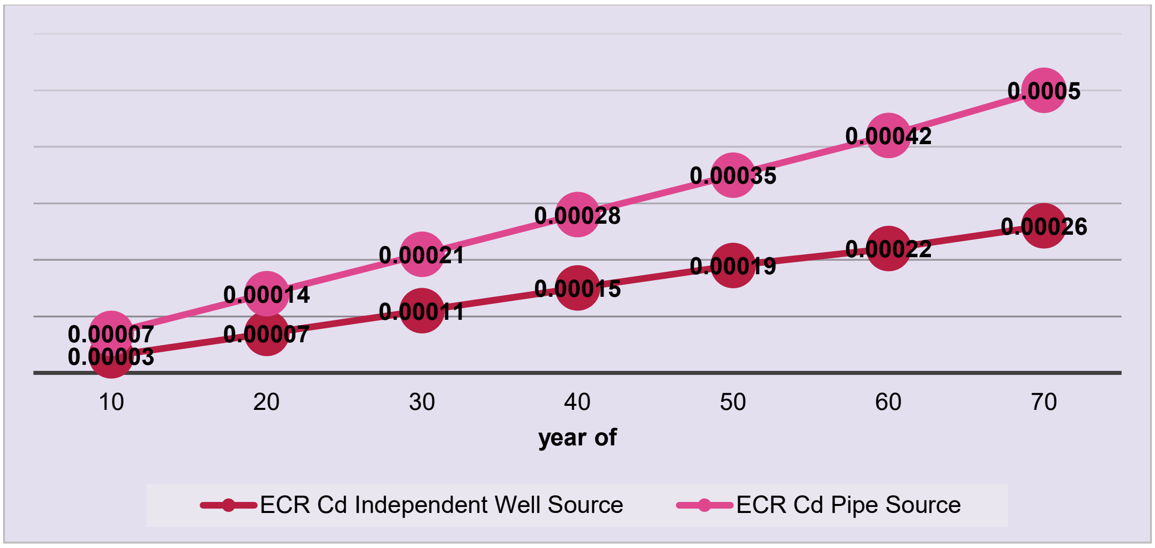


Figure 8. Projection of Mean RQ Mn Value for a 30-Year Exposure Duration

Figure 8 shows that the projection of ECR exposure to heavy metal Cd for exposure duration of 10-70 years in respondents who consume independent well water and piped water always increases. The mean ECR value obtained in respondents who consume independent well water is in the range of $7 \times 10^{-5} – 5 \times 10^{-4}$, while piped water ranges from $3 \times 10^{-5} – 3 \times 10^{-4}$. The mean ECR value of Cd exposure in independent wells increased every year and was categorized in the notation ECR > E^{-4} (10^{-4}) at a duration of 60-70 years While the mean ECR value at a duration of exposure of 30-70 years so that it has a carcinogenic risk due to Cd exposure and requires risk management. The average calculation of the carcinogenic Excess Cancer Risk (ECR) value is higher in respondents who consume piped water compared to consuming well water.

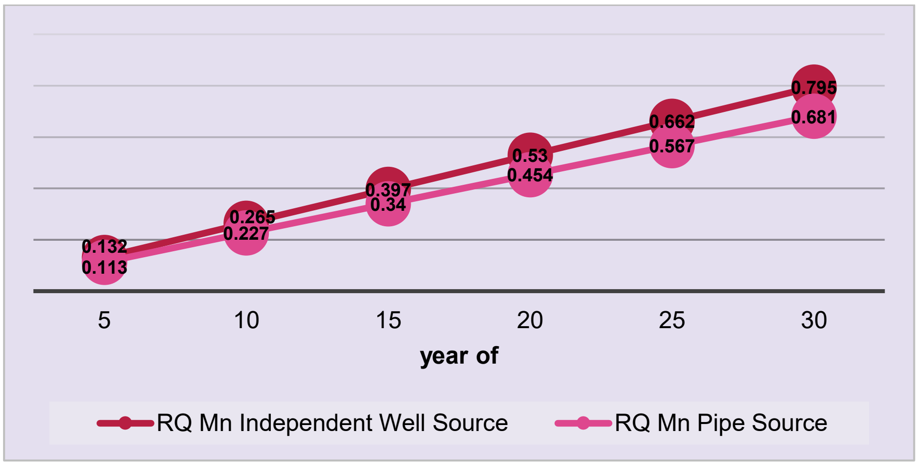


Figure 9. Projection of Mean RQ Mn Value for a 30-Year Exposure Duration

Figure 9 shows that the projected RQ for Mn heavy metal exposure over a duration of 5-30 years in respondents consuming independent well water and piped water always increases. The mean RQ value obtained for respondents consuming independent well water ranged from 1 x 10-1 to 8 x 10-1, while for piped water it ranged from 1 x 10-1 to 7 x 10-1. The mean RQ value for Mn exposure in independent wells and piped water increases each year and is categorized in the notation RQ < 1 over a duration of 5-30 years. The average calculation of non-carcinogenic RQ values is higher in respondents who consume well water compared to piped water.

Based on several literatures, it can be understood that heavy metals Cd and Mn can enter the human body through the ingestion/oral route and can pose a risk that is detrimental to humans. Carcinogenic risk is usually referred to as Excess Cancer Risk (ECR), which is obtained from the calculation of carcinogenic intake multiplied by the reference dose (Slope Factor), while non-carcinogenic risk or Risk Question (RQ) is obtained from the calculation of carcinogenic intake multiplied by the References Dose (RfD). The level of risk is presented based on the source of drinking water consumed by the respondents, namely independent well water and piped water.

Table 4. Distribution of Respondents Based on Real-Time Carcinogenic Risk Level Categories in the Drinking Water Sources of the Passimarannu Community in 2024

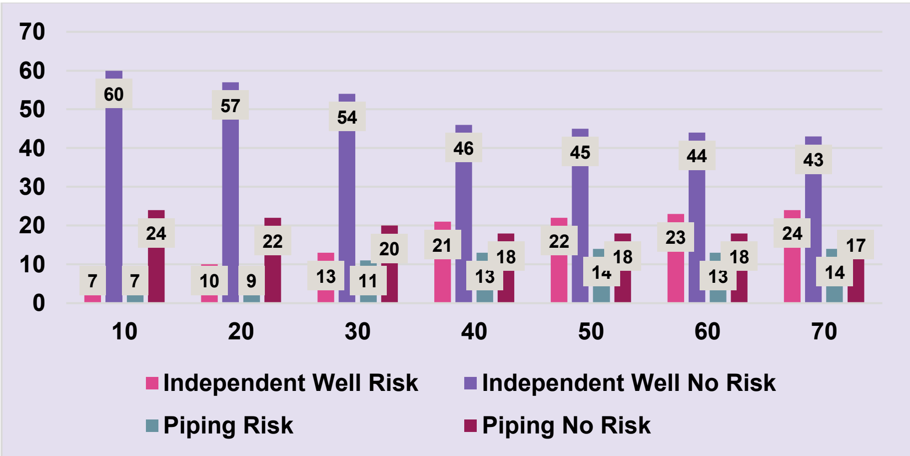
Drinking Water Source	High Risk	Excess Cancer Risk (ECR) Cadmium (Cd)	
		n	%
Independent wells (n-67)	> E-4	7	10.4%
	≤ E-4	60	89.6%
Piping (n-31)	> E-4	9	29%
	≤ E-4	22	71%

Table 4 shows that, for the carcinogenic risk due to Cadmium (Cd), out of 67 respondents using independent wells, 7 respondents (10.4%) showed a high carcinogenic risk (> E-4), while 60 respondents (89.6%) were in the safer category (≤ E-4). On the other hand, for piped water sources with 31 respondents, 9 respondents (29%) had a high risk, while 22 respondents (71%) showed a lower risk. Cd exposure with an ECR value > E-4 means the contaminant has a carcinogenic risk via the ingestion/oral route, while ≤ E-4 means the contaminant does not have a carcinogenic risk via the ingestion/oral route.

Table 5. Distribution of Respondents Based on Real-time Non-carcinogenic Risk Level Categories in Passimarannu Community Drinking Water Sources in 2024

Drinking Water Source	High Risk	Risk Question (RQ) Mangan (Mn)	
		n	%
Independent wells (n-67)	RQ ≥ 1	8	12%
	RQ < 1	59	88%%
Piping (n-31)	RQ ≥ 1	2	6.4%
	RQ < 1	29	93.6%

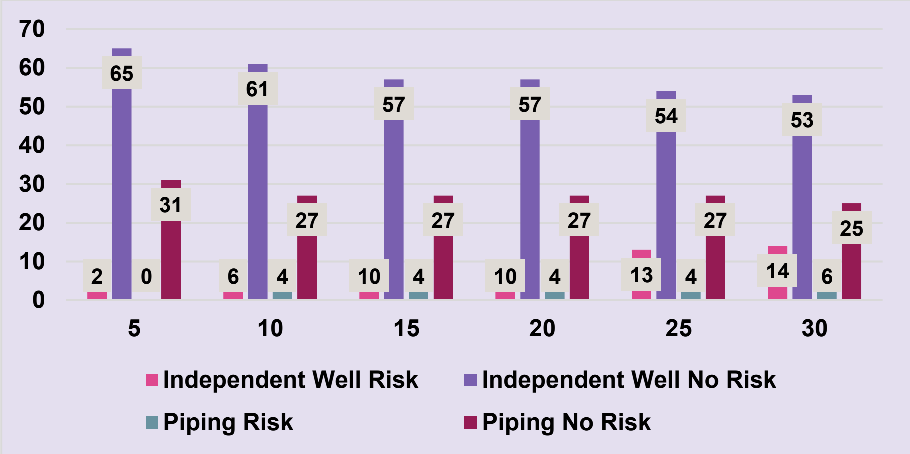
Table 5 shows that the non-carcinogenic risk assessment related to Manganese (Mn) indicates that 8 respondents (12%) from independent wells have a high risk (RQ ≥ 1), and 59 respondents (88%) are classified as safe (RQ < 1). However, out of the 31 respondents who used piped water sources, 2 respondents (6.4%) fell into the high-risk category, while 29 respondents (93.6%) showed safe risk levels.



Note: N Independent Wells = 67; N Piping = 31

Figure 10. Distribution of Respondents Based on Lifetime 10-70 Years Carcinogenic Risk Level Category in the Drinking Water Sources of the Passimarannu Community in 2024

Figure 10 shows the distribution of respondents based on carcinogenic risk for drinking water sources over a lifetime projection of 10-70 years. Independent wells have a higher number of "at-risk" respondents compared to piped sources. In the 10th year, 7 respondents from independent wells and piped sources were at risk. The number of at-risk respondents from independent wells gradually increased, reaching 24 people by the 70th year. On the other hand, the risk from piped water shows an increasing trend, reaching 14 people by the 70th year.



Note: N Independent Wells = 67; N Piping = 31

Figure 11. Distribution of Respondents based on Lifetime 5-30 years Non-carcinogenic Risk Level Category in the Drinking Water Source of the Passimarannu Community in 2024

Figure 11 shows the distribution of respondents based on non-carcinogenic risk for drinking water sources over a 5-30 years lifetime projection. Independent wells have a higher number of "at-risk" respondents compared to piped water sources. The number of at-risk respondents from independent wells gradually increased, reaching 14 people by the 30th year. On the other hand, the risk from piped water shows a stable trend from the 10th year to the 25th year, which is 4 people at risk. After conducting an environmental health risk analysis and obtaining an ECR value > E-4, follow-up actions are taken. In risk management, strategies are implemented that include determining safe concentration limits and consumption amounts of Cd and Mn.

Table 6. Determination of Safe Concentration Limits for Cadmium (Cd) Heavy Metal

Drinking Water Source	Heavy Metals	K	SF/RfD	Wb	tavg	IR	EF	Dt	Ck(mg/L)
Piping	Cd	10^{-4}	15	51	25550	2	365	70	2×10^{-3}
	Mn	10^{-4}	0,14	51	10950	2	365	30	2×10^{-2}
Independent Wells	Cd	10^{-4}	15	51	25550	2	365	70	2×10^{-3}
	Mn	10^{-4}	0,14	51	10950	2	365	30	2×10^{-2}

Based on Table 6, the concentration of the heavy metal Cd is considered unsafe in the respondents' drinking water sources, thus it is necessary to determine the safe concentration limit against carcinogenic risk. The safe limit for Cd in piped drinking water sources and independent wells is 2 x 10-3 (mg/L). Meanwhile, the concentration of the heavy metal Mn is considered unsafe in the respondents' drinking water sources, so it is necessary to determine the safe concentration limit against non-carcinogenic risk. The safe limit for Mn in piped drinking water sources and independent wells is 2 x 10-2 (mg/L).

Table 7. Determination of Safe Limits for Cadmium (Cd) Heavy Metal Consumption

Drinking Water Source	Heavy Metals	K	SF/RfD	Wb	tavg	IR	EF	Dt	Ck(mg/L)
Piping	Cd	10^{-4}	15	51	25550	0,022	365	70	1×10^{0}
	Mn	10^{-4}	0,14	51	10950	0,601	365	30	9×10^{-1}
Independent Wells	Cd	10^{-4}	15	51	25550	0,011	365	70	2×10^{0}
	Mn	10^{-4}	0,14	51	10950	1,135	365	30	1×10^{0}

Based on table 7, the concentration of the heavy metal Cd is considered unsafe in the respondents' drinking water sources, thus it is necessary to determine the safe consumption limits against carcinogenic risk. The safe limit for Cd in piped drinking water sources is 1 x 100 (mg/L) and for independent well water is 2 x 100 (mg/L). Meanwhile, the concentration of heavy metal Cd is considered unsafe in the respondents' drinking water sources, so it is necessary to determine the safe consumption limits against carcinogenic risk. The safe limit for Mn in piped drinking water sources is 9 x 10^-1 (mg/L) and for independent well water is 1 x 100 (mg/L).

4. CONCENTRATION OF CADMIUM AND MANGANESE

Cadmium is one type of heavy metal that is dangerous because it is non-degradable by living organisms (15). The accumulation of Cd in the body increases with age, with a half-life of 20-30 years in the body. In addition, Cd has also been classified as a carcinogenic agent by the International Agency for Research on Cancer (ICRP) (16).

The research results show that the cadmium (Cd) content in drinking water from the piped system ranges from 0.001-0.053 mg/l, while the cadmium content in drinking water from independent wells is within the range of 0.001-0.053 mg/l. The cadmium levels in the water do not meet the drinking water quality standards according to the Minister of Health Regulation Number 2 of 2023, which is below 0.003 mg/L. These results indicate that the majority of the analyzed water samples have cadmium levels exceeding the safe consumption limit. The study is consistent with the research conducted by Lan et al. (2024), which obtained a Cd result of (0.06 ug/L).

Inconsistent research has also been conducted by Azizah (2022) on the respondents' drinking water. The research results show that the heavy metal cadmium (Cd) is at 0.00019 mg/L. The concentration of the heavy metal is still below the permissible threshold. Cadmium exposure in drinking water is largely caused by leaching from galvanized steel used in household plumbing, pipes, and components or parts of wells and service lines (19). High levels of cadmium in drinking water from piped systems and independent wells can be caused by various factors, such as contamination from industrial activities, the use of phosphate fertilizers in agriculture, and natural erosion of rocks containing cadmium (20). The presence of cadmium in Pasimarannu District is linked to a past earthquake, which likely triggered the release of heavy metals like Cd and Mn from mineral-rich sediments through soil liquefaction, leading to groundwater contamination and posing risks to environmental and human health (21).

In the use of groundwater from dug wells as a drinking water source with a depth of 0-15 m, the problem often encountered is the manganese (Mn) content. Manganese is one of the metals commonly found in the Earth's crust and often occurs together with iron (14). Excessive exposure to manganese heavy metal can have serious impacts on human health (22). The research shows that manganese (Mn) levels in piped drinking water range from 0.9166-1.0361 mg/l, while in independent wells, it ranges from 0.0034-3.9986 mg/l. The manganese quality standard for clean and drinking water is 0.5 mg/l and 0.4 mg/l, respectively, according to Minister of Health Regulation No. 2 of 2023. Of the 11 dug wells, 55% exceed the standard for clean and drinking water, while all drilled wells meet the required quality standards.

Research by (23) shows that groundwater with manganese (Mn) levels meeting the standards is 61%, while 39% do not meet the standards, with 13 boreholes being non-compliant. For borehole water with high Manganese (Mn) levels, it is suspected that there is weathering of soil chemicals in the soil layer that will form Manganese (Mn) levels. Manganese compounds naturally exist in the environment as solids in the soil and small particles in the water. Manganese particles in the air are present in dust particles. Usually, these settle to the ground within a few days.

The results of the study conducted by (14) show that the univariate analysis results indicate an average Manganese content of 1.36 mg/l in the well water of residents in Depok City. Meanwhile, the risk quotient (RQ) calculation results in a value less than 1, which means that the Manganese content in the residents' well water is not at risk for exposure over the next 30 years or non-carcinogenic calculations. However, carcinogenic calculations need to be conducted to determine the exposure risk over the next 70 years. The chemical composition of groundwater is influenced by geological structure, hydrogeological conditions, and the hydrochemical evolution of water (24).

In certain amounts with the exposure to oxygen, manganese can form insoluble oxides and produce precipitates, causing problems in the physical appearance of the water. Although groundwater and surface water naturally contain manganese, additional concentrations of manganese can occur due to the presence of leachate (percolate), which is a liquid containing dissolved and very fine suspended substances as a result of microbial decomposition (23).

5. ENVIRONMENTAL HEALTH RISK ANALYSIS

Environmental Health Risk Analysis (EHRA) is an approach to calculate or estimate risks to human health, including the identification of uncertainty factors, tracing specific exposures, considering the inherent characteristics of the agent of concern, and the characteristics of the specific target (25). The level of risk that occurs can be estimated by conducting an EHRA study that refers to the technical guidelines of EHRA from the Director General of Disease Control and Environmental Health (P2PL) of the Indonesian Ministry of Health in 2012. Risk analysis can be used for predictive studies of future exposures (Basri et al., 2007).

The main variables that significantly affect the actual dose received by an individual from a risk agent are anthropometric characteristics and activity patterns. These anthropometric characteristics include body weight; the higher the individual's body weight, the lower the internal dose they receive (26). To obtain accurate data, the collection of information regarding the respondents' weight was conducted directly through weighing. The research results show that the respondents' body weight in Batu Bingkung Village, Bonea Village, and Sambali Village varies between 13.3 kg and 97.9 kg, with an average of 50 kg.

This average body weight is smaller compared to the standard adult body weight set by the US EPA, which is 70-80 kg, and the standard adult body weight for Asia/Indonesia, which is 55 kg (25). The results of this study are in line with Martini dan Wibowo (2020) , which show that individuals with normal body weight have a lower risk of exposure to heavy metals, including cadmium and manganese. In the Environmental Health Risk Analysis (EHRA) study, the smaller the body weight, the greater the intake received because body weight functions as the denominator in the intake formula; the larger the body weight of the population, the smaller the intake value received. Body weight will also affect the magnitude of the risk value, and theoretically, the larger a person's body weight, the smaller the likelihood of experiencing health issues (25).

In this study, the researchers measured the rate of drinking water intake from two main sources, namely piped water and well water, which are frequently used by the community. The measurement results show that the intake rate from piped water ranges from 1.5 to 3 liters/day with a median value of 2.5 liters/day.

Consumption of water contaminated with cadmium and manganese can increase health risks in individuals. The rate of intake or the amount of water consumed by an individual is directly proportional to exposure to those heavy metals (28). Research shows that the higher the rate of contaminated water intake, the greater the likelihood of individuals experiencing excessive exposure, which can lead to various health issues such as kidney dysfunction, poisoning, and neurological problems. This is in line with the research by Suhardi dan Anwar (2023) which shows that a high rate of water consumption positively correlates with cadmium and manganese levels in the blood, thereby increasing health risks.

Exposure frequency refers to the number of days in a year when respondents reside at the research location and use well water for drinking needs. In Batu Bingkung Village, Bonea Village, and Sambali Village, the average exposure frequency reaches 350 days/year. The research is consistent with the study in Jagalan Village, Banguntapan, Bantul, where the average exposure frequency reaches 350 days/year. The high frequency of exposure received by respondents in this study indicates that they are at greater risk of experiencing health disturbances. If respondents are exposed for a maximum of 350 days in a year, this can increase the likelihood of negative health impacts, considering that they are continuously exposed to well water contaminated with Cadmium (Cd) and Manganese (Mn) (30).

Based on the findings explained by Nasman (2024), the level of risk experienced by respondents is significantly influenced by the frequency of exposure received. The higher the frequency of individual exposure to hazardous substances within a one-year period, the greater the potential health risks that may arise. Therefore, a longer duration of exposure potentially increases the risk of health disorders associated with exposure to hazardous agents.

The duration of exposure is the length of time or the number of years the community has consumed drinking water, measured in years. The value of the exposure duration was obtained through direct interviews. From the research results, it was found that the maximum exposure duration is 60 years and the minimum is 6 years, with an average of 32.4 years.

The toxicity of heavy metals is closely related to the concentration and duration of exposure experienced. Generally, the higher the concentration of a metal and the longer the exposure lasts, the greater the toxic effects produced. The exposure duration in this study reflects the actual time respondents consume drinking water from piped and non-piped sources, while the lifetime exposure duration follows the default values for carcinogenic effects according to USEPA, which range from 10 to 70 years, used to estimate future exposure safety (31).

The intake of carcinogenic heavy metals for respondents during real-time exposure duration in independent well water averages 1×10^{-3} mg/day, while piped water averages 4.7×10^{-4} mg/day. The average calculation of the intake value of carcinogenic Cadmium (Cd) exposure during real-time exposure duration shows that respondents do not meet or exceed the reference dose Slope Factor (SF). This indicates that the intake rate value from Cd exposure is positively correlated with the concentration of the risk agent, intake rate, frequency of exposure, and duration of exposure. The higher the value of these variables, the greater the individual exposure intake. The intake of non-carcinogenic heavy metals for respondents during real-time exposure to independent well water averages 5.1×10^{-2} mg/day, while piped water averages 3.6×10^{-2} mg/day. The average calculation of non-carcinogenic Mn exposure intake values during real-time exposure duration shows that respondents meet the criteria or do not exceed the reference dose Slope Factor (SF).

The average calculation of the lifetime carcinogenic intake value in respondents shows a consistent increase from the 10th year to the 70th year. The increase in intake values reflects that the longer individuals are exposed, the higher the measured intake values in the respondents. Research by Wang et al., (2019) also found that long-term exposure to contaminants can increase health risks, especially in individuals who are consistently exposed. Additionally, research by Rahmawati & Setiawan (2021) emphasizes the importance of continuous monitoring of water quality to prevent potential health risks due to long-term exposure.

This is in line with Falahdina, (2017) where the value of intake is directly proportional to the concentration of heavy metals, duration of exposure, frequency of exposure, and rate of intake. This can be interpreted as the greater the value, the greater the intake of a person. Intake is inversely proportional to body weight, meaning that the greater a person's body weight, the lower their health risk.

Based on the research results regarding carcinogenic and non-carcinogenic risks in the drinking water sources of the Pasismarannu community in 2024, there is a quite striking pattern between the use of independent wells and piped water. In Figure 4.10, it is observed that among respondents who use independent wells, the number of individuals with carcinogenic risk tends to be lower, peaking in the 70-year age group, where only 24 individuals were identified as at risk. On the other hand, in the piped water system, 14 respondents showed carcinogenic risk, reflecting the influence of the water quality distributed through the pipes. These findings support the research by Hadi dan Kusuma (2020), which states that well-managed water sources can minimize health risks, particularly those related to exposure to hazardous chemicals such as Cadmium.

Next, in Figure 4.11, the non-carcinogenic risk analysis shows that independent wells have a higher number of "at-risk" respondents compared to piped sources. The number of respondents at risk from independent wells gradually increased, reaching 14 people by the 30th year. A similar study by Irianto et al. (2020) showed that the proportion of households based on the results of the IKL type of tap/piped drinking water source was 96.7%, which had a low pollution risk, and the pollution risk in urban areas was lower compared to rural areas.

6. HEALTH RISK

The absorption of cadmium through the human gastrointestinal tract is approximately 5% of the total ingested cadmium, depending on the dose and the proper nutritional composition (37). Low-level exposure to Cd can cause damage to the kidneys, liver, skeletal system, and cardiovascular system, as well as decreased vision and hearing. Along with the strong teratogenic and mutagenic effects associated with cadmium, it also shows adverse effects at low doses on human male and female reproduction and affects pregnancy or its outcomes (38).

Cadmium can interact with various hormonal signaling pathways and is considered an endocrine disruptor that can bind to alpha estrogen receptors and affect signal transduction along the estrogen and MAPK signaling pathways. Low doses of Cd affect the cardiovascular system (39). Epidemiological studies show that Cd exposure can increase the development of musculoskeletal diseases, such as osteoporosis, rheumatoid arthritis (RA), and osteoarthritis (OA) (40).

The disease burden caused by heavy metal exposure through drinking water according to risk factors, cancer types, and communities in the rural areas of Yazd County, the average value of health loss indicators due to heavy metal exposure through drinking water is as follows: 0.21 for cancer incidence, 0.57 for cancer incidence rate (per 100,000 people), 9.83×10^{-2} for mortality, 2.68×10^{-1} for mortality rate (24). Another study in the northern settlement area of Winder City shows that the area is located in a zone with excessive Cd levels. As many as 9% of kidney-related disease patients were reported in this settlement out of a total of 15% of respondents with kidney problems in the study area (41).

In water, most manganese tends to bind with particles and settle in sediments (42). Manganese (Mn) content causes obesity, glucose intolerance, blood clotting, skin diseases, bone diseases, lowers cholesterol levels, causes birth defects, changes in hair color, diseases of the nervous system, heart, liver, and blood vessels, birth defects, hypotension, and brain damage. damage and gastrointestinal disorders (43).

Well water can accumulate significant amounts of metals due to the weathering of nearby rock layers. Excess manganese (Mn) may come from anoxic groundwater, carbon-rich soil, agricultural fertilizers, and runoff from improperly disposed Mn-rich materials, such as batteries and mining waste. High levels of Mn in water sources have been associated with lower IQ scores, memory issues, reasoning problems, and reduced academic performance in children. Current US guidelines recommend that drinking water contain less than 400 micrograms of Mn per liter (44).

Manganese toxicity is a unique neurotoxicity that develops from early psychiatric disorders to symptoms reminiscent of Parkinson's disease, such as postural deficiency, bradykinesia, shuffling gait, mask-like face, micrographia, and speech difficulties. Neurons in the basal ganglia are particularly affected, leading to Parkinson's syndrome (45).

7. RISK MANAGEMENT

Environmental health risk analysis related to exposure to heavy metals cadmium (Cd) and manganese (Mn) in drinking water in Pasimarannu District, risk management becomes a crucial step after obtaining an ECR value indicating carcinogenic risk. Determination of safe concentration limits for both metals was carried out using a formula that considers factors such as body weight, consumption time, and intake rate. For cadmium, the safe concentration limit is set at 2×10^{-3} mg/L for piped drinking water sources and independent wells (Primary Data, 2024). Meanwhile, for manganese, the safe concentration limit is 2×10^{-2} mg/L, indicating that the concentration detected in the respondents' drinking water is not safe for consumption.

In addition, determining the safe consumption amount (R) is also important for managing exposure through food and drinking water. For cadmium, the safe consumption limit for piped drinking water sources is 1 x 10 mg/L, while for independent wells it is 2 x 10 mg/L. For manganese, the safe consumption limit is set at 9 x 10^{-1} mg/L for piped drinking water sources and 1 x 10 mg/L for independent wells. Appropriate mitigation measures must be taken to ensure the quality of drinking water and protect public health from the risks posed by exposure to these heavy metals.

Various efforts to control heavy metals are increasing, with a focus on finding new methods that are cheap, effective, and efficient. One way to reduce heavy metal concentration is by treating drinking water sources using various methods that leverage technological advancements, considering efficiency and the ability to remove heavy metals from water (46). Several methods that can be applied to remove heavy metals from contaminated water include ion exchange, chemical precipitation, adsorption, membrane filtration, reverse osmosis, solvent extraction, and electrochemical treatment (47). Although some of these methods require high operational costs, the adsorption method is considered the most suitable alternative due to its high efficiency, more affordable costs, and ease of use (48).

Several studies have been conducted to assess water quality and identify sources of heavy metal pollution, as done by Awliahasanah et al. (2021). his research shows the relationship between water quality and public health, providing a clearer vision of how to address pollution issues. Additionally, research by Chisholm (2020) evaluates the relationship between manganese exposure and neurological disorders, emphasizing the importance of attention to this heavy metal in water quality.

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