

Original Research Article

Comparative determination of human health risks associated with consumption of groundwater contaminated with lead in selected areas surrounding the former lead mine in Kabwe and non-mining areas in Lusaka, Zambia

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ABSTRACT

Background: This study focused on addressing health risks attributed to lead (Pb) contamination in groundwater, prompted by its known connection to negative health outcomes. It investigated the extent of Pb exposure through groundwater consumption near areas surrounding the former lead mine in Kabwe and non-mining areas in Lusaka, Zambia. The study compared the health risks of consuming Pb-contaminated groundwater in Kabwe's mining vicinity and Lusaka's non-mining areas.

Methods: A comparative cross-sectional study collected 61 borehole samples from both areas and analyzed Pb levels using atomic absorption spectrometry. Health risks were evaluated via estimated daily intakes (EDI), target hazard quotient (THQ), and target cancer risk (TCR) assessments. Statistical analysis employed the Mann-Whitney U test due to non-normal data distribution.

Results: Pb concentrations were significantly higher ($p < 0.05$) in mining areas (median = 0.131 mg/l) than in non-mining areas (median = 0.071 mg/l). Alarming, 91% of mining and 74% of non-mining samples exceeded world health organization limits. Particularly, EDIs for adults and children from mining areas exceeded recommended intakes. However, THQs were < 1 , indicating no immediate adverse health effects. Equally important, TCRs fell within USEPA's acceptable range, suggesting negligible cancer risk associated with Pb exposure.

Conclusions: The elevated EDIs in both mining and certain non-mining areas suggest potentially toxic health effects. Notably, the THQ values below 1 imply no immediate health risks. TCRs within acceptable limits underscore a minimal cancer risk. As a result, addressing elevated Pb levels in groundwater is critical in both study areas to mitigate potential health effects associated with Pb exposure.

Keywords: Groundwater, Lead, Health risks, Kabwe, Lusaka, Zambia

INTRODUCTION

Groundwater is crucial for the environment and plays a significant role in biotic development.¹ However, insufficient regulation of industrial development, particularly in developing countries, has led to the

contamination of groundwater by heavy metals, such as Pb.² According to WHO's 2015 data, Pb exposure resulted in 494,550 deaths and 9.3 million disability-adjusted life years (DALYs) due to its long-term health effects.³ Human exposure to Pb through untreated groundwater and tap water in cities with Pb installations is a growing concern.⁴ Lead can enter the body through ingestion,

inhalation, or skin contact, with ingestion being the most common route.⁵

Pb is a silvery metal found in the Earth's crust at a concentration of 13 mg/kg with four stable isotopes ²⁰⁸Pb, ²⁰⁷Pb, ²⁰⁶Pb, and ²⁰⁴Pb, listed in order of abundance.⁶ Human exposure to Pb can cause mental retardation, behavioral disorders in children, renal impairment, hypertension, immunotoxicity, and toxicity to the reproductive organs.³

In Kabwe, approximately 70% of the distributed water is sourced from groundwater obtained from deep boreholes, as reported by the Zambia national water supply and sanitation council.⁷ Similarly, in Lusaka, about 55% of the distributed water comes from groundwater.⁸ However, the contribution of groundwater to the overall burden of Pb-related diseases in Kabwe has not been evaluated adequately.

To address this concern, a study conducted in Zambia specifically analyzed water sources near the Pb mine in Kabwe. The study encompassed seventeen shallow wells, five deep wells, three ponds, and three borehole wells. The study revealed low dissolved Pb levels ($<4 \times 10^{-5}$ mg/L), but high particulate Pb concentrations (0.002-0.1 mg/L) in the seventeen shallow groundwater and five shallow wells, exceeding the WHO guideline of 0.01 mg/L for total Pb concentration.⁹

Therefore, the study aimed to analyze and compare Pb levels in groundwater from boreholes and assess the health risks of Pb exposure through groundwater consumption in specific areas around the former Pb mine in Kabwe and non-mining areas in Lusaka.

METHODS

Study area

The research investigation was conducted in two distinct locations within the Central and Lusaka province of Zambia. One of the study sites was Kabwe, which is a mining town positioned at approximately 14.4285° S latitude and 28.4514° E longitude.

In Kabwe, simple random sampling, specifically the lottery method, was used to select Chowa and Makululu townships, both of which are situated close to the former Pb mine, a significant landmark in the region. The second location of interest was Lusaka, a non-mining town situated at approximately 15.3875° S latitude and 28.3228° E longitude within the Lusaka province (Figure 1).

In Lusaka, purposeful sampling was used to select Kanyama and Chelstone-Obama, which were chosen based on the presence of boreholes aligning with the research objectives.

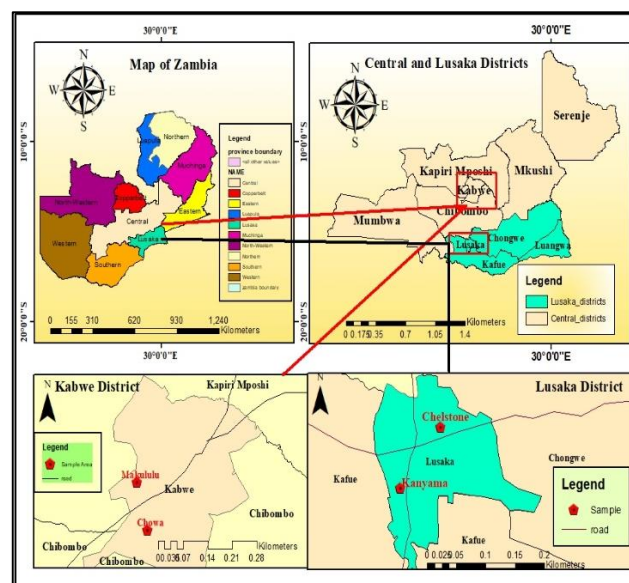


Figure 1: Location map of mining areas in Kabwe and non-mining areas in Lusaka (ArcGIS, version 10.4).

Study sample

A total of 61 drinking groundwater samples were collected from boreholes for Pb analysis and assessment of associated human health risks. The sample sizes for both mining areas and non-mining areas were determined using the non-infinite formula, taking into account the known number of boreholes.¹⁰ However, out of the total samples collected, 34 were from mining areas, specifically 21 samples from Makululu and 13 samples from Chowa. On the other hand, 27 samples were obtained from non-mining areas, comprising of 13 samples from Kanyama and 14 samples from Chelstone-Obama.

Sampling

The groundwater sample collection took place from May to June 2022, when the water table had risen and stabilized. The hand pump boreholes were used for drawing the groundwater samples, and sterile high-density polyethylene (HDPE) tubes with a capacity of 100 ml were utilized for collection. Following collection, the bottles were labelled, placed in a cooler box containing ice packs, and transported to the laboratory for filtration and preservation.¹¹ To prevent Pb absorption onto the bottle walls, approximately 1 ml of 60% nitric acid (HNO₃) was added to 100 ml of groundwater, maintaining a pH of around 2.¹² The prepared groundwater samples were then kept at a temperature of 4°C until laboratory analysis.

Sample preparation

Before conducting the analysis, all laboratory materials were thoroughly cleaned by washing and soaking them in a 2% diluted solution of nitric acid (HNO₃) for 24 hours.

They were then rinsed using distilled water obtained from a Milli-Q-Element system (18 MΩ.cm, Millipore®, Milford, MA, USA) and subsequently dried in an oven.¹³ To enhance the sensitivity of metal detection using atomic absorption spectrometry (AAS), a metal extraction process was performed using a microwave digester (Berghof, SpeedWave®ENTRY, Eningen, Germany). During the digestion process, 5 ml of 69% HNO₃ (Kanto Chemical Co, Japan) and 2 ml of 30% HNO₃ (Wako Chemical Co, Japan) were utilized. The measured samples were subsequently placed into a Teflon vessel (DAP-60K, Berghof, Germany) along with the digestion reagents. After completion of the digestion process, the samples were transferred into a Teflon beaker and the total volume was adjusted to 25 ml using Milli-Q water.¹⁴ The digester utilized an automated controlled temperature of approximately 190 °C for a duration of 30 minutes. The mixture was then allowed to cool for 20 minutes before analysis.¹⁵

Metal analysis and quality control

The groundwater samples were analyzed for total Pb levels using atomic absorption spectrometry (AAS, Perkin Elmer, A-analyst 400 series, USA) with a lowest detection limit of <0.001 mg/l at the school of agricultural sciences laboratory, university of Zambia. For the analysis, a direct measurement approach was employed, and a calibration curve was prepared using known standard levels of Pb (0, 5, and 10 mg/l) prepared from Pb (II) nitrate (Pb (NO₃)₂) with a concentration of 1000 mg/L. A standard Pb concentration of 1 mg/l (Pb (NO₃)₂) was used to check the accuracy of the machine at regular interval of the first, thirtieth and last three samples. Additionally, analytical duplicates were performed for each groundwater sample to ensure accuracy.^{13,14}

Health risk assessment

The study involved aggregating EDIs to calculate cumulative THQs and TCRs for conducting comprehensive health risk assessments. An overview of the parameters and corresponding input values used to compute EDIs, THQs, and TCRs is provided in Table 1.

Estimated daily intake of Pb through groundwater consumption

The EDI of Pb through groundwater consumption was determined by considering the approximate daily water ingestion rates (IngR), the median concentration of Pb in drinking water (CW) from the study sites, and the person's body weight (BW). According to the Zambia demographic and health survey report 2019, the average body weight of an adult is 60 kg and a child is 16 kg.²⁰ The average ingestion rates of water were 2L/day for adults and 1L/day for children.¹⁶ The EDI values were determined using equation (1).

$$EDI = (IngR \times CW) / BW \quad (1)$$

Risk characterization

The risk characterization analysis, employing assessments of both carcinogenic and non-carcinogenic risks through ingestion, was recognized as a pivotal instrument for detecting the potential health risks on humans and furnishing evidential support for informed decision-making.

Non-carcinogenic health risk

The risk of non-carcinogenic effects caused by Pb was determined using the THQ. The THQ is calculated as the ratio of potential exposure to a substance to the level at which no adverse effects are expected. The health risk assessment using THQs was conducted based on the USEPA Region III risk-based concentration table, as presented below.²²

$$THQ = (EF \times ED \times EDI) / (RfD \times AT) \times 10^{-3} \quad (2)$$

In this study, EF represents 365 days in a year, while ED corresponds to 64 years, equivalent to the life expectancy in Zambia.²⁰ The EDI was determined using equation (1). The RfD was estimated to be 0.0035 mg/kg/day, derived from the provisional weekly tolerable intake (PWTI) of 0.025 mg of Pb per kg of body weight, as recognized by the joint FAO/WHO expert committee.²¹ AT accounts for Pb toxicity based on the average lifetime exposure (365 days × 64 years), with 10⁻³ as the unit conversion factor. According to the rule of thumb, a THQ>1 indicates a potential for non-carcinogenic health effects. Conversely, if THQ≤1, it indicates no risk of adverse health effects resulting from the consumption of Pb-contaminated groundwater.

Carcinogenic health risk

The equation outlined in the USEPA region III risk-based concentration table was utilized to ascertain the lifetime cancer risk associated with Pb resulting from consuming groundwater from boreholes.

$$TCR = (EF \times ED \times EDI \times CSF) / (AT) \times 10^{-3} \quad (3)$$

The determination of the CSF in this study relied on the intake dose conversion factor of 0.008 mg/kg/day, as mandated by the USEPA.¹⁹

Statistical analysis

Data were subjected to quantitative statistical analysis using Microsoft excel and STATA 21 to test hypotheses. Before analysis, the normality of data distribution was assessed using the Shapiro-Wilk test, which revealed a departure from normality. Statistical comparison analysis, specifically the Mann-Whitney U test, was conducted to identify differences in EDIs and median Pb concentrations in groundwater samples between mining

areas in Kabwe and non-mining areas in the Lusaka. A $p < 0.05$ was deemed statistically significant.

RESULTS

Lead concentrations in groundwater

The Mann-Whitney U test revealed that Pb levels in mining areas of Kabwe were significantly higher ($p < 0.05$) compared to non-mining areas in Lusaka. Mining area samples had Pb levels ranging from 0 to 0.379 mg/l with a median of 0.130 mg/l, while non-mining area samples ranged from 0 to 0.197 mg/l with a median of 0.071 mg/l. In Kabwe, only 9% of the collected groundwater samples met the WHO permissible limit of 0.010 mg/l, while 91% exceeded the limit.²³ In Lusaka, 26% of the samples were within the limit, while 74% exceeded it (Figure 2).

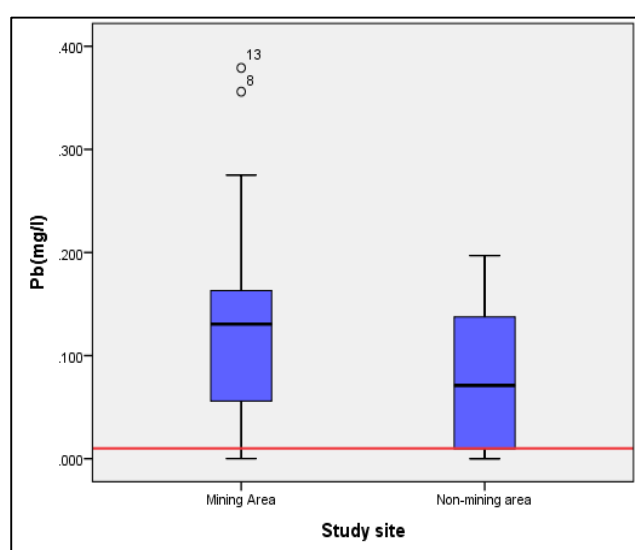


Figure 2: Lead levels in groundwater samples of mining and non-mining areas.

Key: Redline denotes WHO safe limit of Pb in drinking water.

Health risk assessment

EDI of Pb through groundwater consumption

The EDIs of Pb through the consumption of contaminated groundwater exhibited significant variations ($p < 0.05$) between mining areas in Kabwe and non-mining areas in Lusaka. The EDIs followed a specific order, with the highest levels observed in children from mining areas in Kabwe, followed by children from non-mining areas, adults from mining areas, and finally adults from non-mining areas (Table 2).

Non-carcinogenic and carcinogenic health risks

The study found significant variations ($p < 0.05$) in THQs and TCRs associated with the consumption of groundwater contaminated with Pb between adults and children from mining areas in Kabwe and non-mining

areas in Lusaka. The THQs followed the order of highest to lowest: children from mining areas in Kabwe, children from non-mining areas, adults from mining areas, and adults from non-mining areas. All the THQs values from both areas were < 1 , indicating no potential health risks (Table 3).

However, all TCR values were below the USEPA's protective range (1×10^{-6} to 1×10^{-4}), with the highest TCR observed in children from mining areas (6.4×10^{-8}). These findings highlight the significant contribution of ingesting groundwater from boreholes to THQ and TCR values in residents from both mining and non-mining areas in Kabwe and Lusaka.

Table 1: Parameters of the human health risk assessment.

Parameters	Unit	Value	References
Averaging time	Days	365 days $\times$ 64 years	16
Bodyweight	kg	Adults=60, children=16	17, 18
Cancer slope factor	mg/ kg/ day	0.008	19
Median Pb conc.	mg/l	Ranged from 0-0.379 mg/L	
Lifetime exposure duration	years	64	20
Exposure frequency	Days/ year	365	19
Ingestion rate	Liters/ day	Adult=2L, children=1L	16
Oral reference dose	mg/ kg/ day	0.0035	21

Table 2: EDI in adults and children.

Variables	Median Pb (mg/L) levels	EDI (mg/kg/day)	
		Adult	Children
Kabwe (mining area)	0.131*	0.004*	0.008*
Lusaka (non-mining area)	0.071*	0.002*	0.004*
MAC	0.010 ^a (WHO)	0.003 ^b (FAO/WHO)	

*Statistically significant at $p < 0.05$, MAC signifies maximum acceptable concentration, ^a WHO's Pb (mg/L) MAC per day for drinking water, and ^b Maximum Pb (mg/L) concentration for drinking water.²¹

Table 3: Target hazard quotient and target cancer risk from consumption of groundwater.

Variables	THQ		TCR	
	Adult	Children	Adult	Children
Kabwe (mining area)	0.001*	0.002*	3.2×10^{-8} *	6.4×10^{-8} *
Lusaka (non-mining area)	0.001*	0.001*	1.6×10^{-8} *	3.2×10^{-8} *
MAC (USEPA)	<1.00		1×10^{-6} - 1×10^{-4}	

*Statistically significant at $p < 0.05$, MAC signifies Maximum acceptable concentration.²²

DISCUSSION

The study revealed that Pb levels from the mining area were significantly higher ($p < 0.05$) than levels from the non-mining area. From the findings, the proximity of the former Pb mine to the study mining areas in Kabwe contributed to the high concentrations of Pb in groundwater collected from boreholes. The findings aligns with a recent study on the geochemical identification of particulate Pb pollution in groundwater of mining areas in Kabwe detected high particulate Pb concentrations (0.002-0.1 mg/L) in shallow groundwater samples and some wells exceeded the WHO guideline of (0.010 mg/L) as the safe limit.⁹

Similarly, a study conducted in India also suggested that proximity near the open-cast chromium mine was playing a major role in the heavy metal contamination in the groundwater of Sukinda Valley in Orissa due to the possibility of leaching contaminants from the ore material wastages and degraded material produced during the mining process.²⁴ Another similar study conducted in Nigeria supports the notion that proximity to mines contributes to high levels of Pb contamination. That study specifically found that water resources in lead-zinc mining communities of Abakaliki exceeded the WHO guidelines for Pb.²⁵

This study further revealed that a significant proportion of groundwater samples, 91% from mining areas and 74% from non-mining areas, exceeded the maximum acceptable concentration of 0.010 mg/l of Pb in drinking water as recommended by the WHO. The fact that even non-mining areas in Lusaka recorded a high percentage of groundwater samples surpassing the WHO limit is particularly alarming. This suggests that the contaminants may be entering the aquifer system through various sources such as the seepage of bottom automobile exhaust during road traffic and waste from manufacturing industries.²⁶

Previous research conducted in Zambia and Ethiopia supports the notion that anthropogenic activities,

including nearby manufacturing industries and chemical and metallurgic activities, contribute to heavy metal contamination in groundwater due to the flow direction of groundwater.^{27,28}

These findings underscore the potentially widespread nature of the issue and raise concerns about the quality and safety of drinking water in the affected areas. It implies that contamination may not be limited to mining areas alone but can also originate from other human activities such as waste disposal, agricultural practices and manufacturing processes impacting non-mining regions as well. The presence of high levels of Pb in drinking water is of great concern because Pb is a toxic heavy metal that can have detrimental effects on human health, particularly on the neurological development of children and the overall well-being of individuals.

The current study revealed significant differences in EDIs of Pb through the consumption of groundwater between mining areas in Kabwe and non-mining areas in Lusaka. The EDIs for adults and children in mining areas were higher than the MAC (0.003 mg/kg/day) recommended by the WHO unlike the EDIs for adults and children in non-mining areas.²¹ These findings suggest that individuals in mining areas, particularly children, may be at a higher risk of Pb-related health complications due to their elevated exposure levels.

The study also compared the findings with other research conducted in different regions. For instance, in two townships near a proposed mining area in India, the EDIs from contaminated groundwater with Pb were 0.026 and 0.028 mg/l which exceeded the MAC.²⁹ A similar study conducted in America also reported higher EDIs of Pb in groundwater, ranging from 0.22 to 4.4 mg/kg/day in groundwater for adults and children thus indicating potential health risks.³⁰ These results serve to highlight the significance and widespread nature of the issue, with similar concerns arising in various parts of the world.

The THQ values recorded in the study for adults and children from mining areas, as well as children from non-mining areas, were less than the safe limit of one (1). This implies that individuals exposed to Pb through groundwater consumption may not experience non-carcinogenic health risks. The mentioned health complications, such as mental retardation, behavioural disorders in children, renal impairment, hypertension, immunotoxicity, and reproductive organ toxicity, have been documented in previous studies due to exposure to Pb.^{3,31,32} Additionally, a study conducted in Kerman, Iran, revealed that children who consume water contaminated with lead (Pb) and other heavy metals face the possibility of experiencing adverse health effects that are not related to cancer.³³ This finding provides further evidence and reinforces the potential risks connected to Pb exposure.

However, it is important to note that the study did not find potential carcinogenic risks from consuming groundwater

from either mining areas in Kabwe or non-mining areas in Lusaka. The cancer risk values, as determined by the TCR assessment, were within acceptable levels set by the USEPA. Similar findings from previous studies in Ethiopia and China further support the notion that the risk of developing cancer from Pb contamination in groundwater may not be a significant concern in these areas.^{27,34}

The current study limited scope focused on specific mining areas in Kabwe and non-mining areas in Lusaka, making it difficult to generalize the findings to other regions. The sample size and selection process may introduce bias and fail to capture the full range of Pb levels and associated risks. Other potential sources of contamination and confounding factors were not accounted for, such as anthropogenic activities or natural processes that can influence contamination levels.

Additionally, the current study cross-sectional design and lack of long-term follow-up limit the assessment of long-term health effects and temporal variations in Pb levels. Overall, caution is needed when applying the findings to different populations or regions due to variations in geological characteristics, industrial activities, and regulatory frameworks.

CONCLUSION

In conclusion, the study found that the Pb concentration in groundwater differed significantly between mining areas in Kabwe and non-mining areas in Lusaka, but both areas exceeded the WHO's maximum acceptable concentration for drinking water. The EDIs of Pb exceeded the WHO limit, indicating potential health risks, even though the THQs were within the safe limit. Although the TCRs were within acceptable limits and no potential cancer risk, ingesting groundwater from both areas remains a significant source of Pb exposure. Therefore, it is crucial to avoid consuming borehole groundwater in these areas and implement appropriate control measures such as implementing remediation strategies, promoting safe alternative water sources, improving waste disposal practices, and enhancing regulatory measures to minimize Pb contamination risks.

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