Journal of Education and Practice
ISSN 2222-1735 (Paper) ISSN 2222-288X (Online)
Vol.16, No.13, 2025

An Assessment of Heavy Metal Contamination and Health Risk in Borehole Water from Mining-Impacted Communities of Chingola District, Zambia

Mubanga Lupupa[1*] Mpundu John[2] and Mubanga, Frank Ray[3]

1. School of Mathematics and natural Sciences, Copperbelt University, P.O. Box 21692, Kitwe, Zambia. lupupams@gmail.com
2. School of Mathematics and natural Sciences, Copperbelt University, P.O. Box 21692, Kitwe, Zambia.
3. School of Mathematics and natural Sciences, Copperbelt University, P.O. Box 21692, Kitwe, Zambia.

Abstract

Background: *Groundwater is a vital resource in Chingola District, Zambia, but its safety is critically threatened by intensive copper and cobalt mining. This study provides a comprehensive assessment of borehole water quality in three mining-proximal communities (Nchanga South, Kasompe, Mutenda), evaluating physicochemical parameters, heavy metal contamination, and associated human health risks.*

Methods: *A cross-sectional study was conducted, collecting water samples from ten strategically selected boreholes during the dry season. Standard analytical methods were employed: pH, Electrical Conductivity (EC), and Total Dissolved Solids (TDS) were measured electrometrically; turbidity and Total Suspended Solids (TSS) via nephelometry; sulphates by spectrophotometry; and heavy metals (Cu, Co, Zn, Pb, Ni, Fe) using Atomic Absorption Spectrometry (AAS). Data were compared against World Health Organization (WHO) and Zambia Bureau of Standards (ZABS) guidelines. A descriptive statistical analysis was performed, and the Heavy Metal Pollution Index (HPI) was calculated to assess overall contamination.*

Results: *Results revealed systemic water quality issues. The water was slightly acidic (mean pH = 6.31 ± 0.38), enhancing metal solubility. Turbidity (1.59-10.5 NTU) and TSS (17-51 mg/L) exceeded limits in 20% of samples, indicating particulate contamination. Critically, heavy metal analysis showed severe contamination: lead (Pb) concentrations reached 0.444 mg/L (44 times the WHO limit) and nickel (Ni) reached 0.539 mg/L (exceeding the 0.07 mg/L limit). The HPI for several boreholes far exceeded the critical value of 100. In contrast, Copper (Cu), Zinc (Zn), and Sulphates were within permissible limits.*

Conclusion: *Borehole water in Chingola is not safe for consumption without treatment. The significant exceedance of Pb and Ni levels, coupled with low pH, poses severe health risks, including neurological damage and carcinogenic effects. This study underscores an urgent public health crisis. Immediate interventions—including robust monitoring, installation of centralized or point-of-use filtration systems, and stringent enforcement of environmental regulations on mining activities—are imperative to safeguard community health.*

Keywords: *Groundwater Pollution, Acid Mine Drainage, Heavy Metal Pollution Index, Health Risk Assessment, Copperbelt, Konkola Copper Mines, Water Security.*

DOI: 10.7176/JEP/16-13-01

Publication date: December 30th 2025

1. Introduction

Access to clean and safe water is unequivocally recognized as a fundamental human right and is indispensable for sustaining public health and socio-economic development (World Health Organization [WHO], 2017). In many developing nations, including Zambia, groundwater abstracted from boreholes is a principal source of potable water, especially in peri-urban and rural settings where centralized water treatment and distribution systems are either unreliable or absent (Howard, Pond, & Kanyembo, 2003). Chingola District, a key hub on the Copperbelt Province, epitomizes this dependency. The district's economy is dominated by extensive mining operations, such as the Nchanga Mine, which, while economically vital, concurrently generate substantial environmental pressures on local water resources through the generation of acid mine drainage (AMD) and leaching of heavy metals from tailings dams and waste rock dumps (Mweemba & Phiri, 2014; Kabinda & Remacle, 2019).

The processes of mineral extraction and processing can profoundly alter local hydrogeochemical conditions. The oxidation of sulfide minerals, such as pyrite, in tailings and waste rock produces sulfuric acid, leading to AMD, which subsequently mobilizes geogenic heavy metals, increasing their bioavailability and potential for aquifer infiltration (Younger, Banwart, & Hedin, 2002). Consequently, boreholes tapping into shallow aquifers near mining sites are particularly vulnerable to contamination from metals such as lead (Pb), copper (Cu), nickel (Ni), and cobalt (Co) (Smedley & Kinniburgh, 2002). Chronic human exposure to these elements, even at concentrations, is associated with a spectrum of debilitating health conditions, including neurological damage, renal dysfunction, cardiovascular issues, and carcinogenic effects (WHO, 2017). For instance, lead is a potent neurotoxin with no known safe threshold for exposure, posing severe risks to cognitive development in children (Kumar & Jha, 2024).

While previous studies on the Copperbelt have indicated general groundwater quality degradation (e.g., Heyden & New, 2004; Mweemba & Phiri, 2014), there remains a critical gap in community-focused, spatially explicit risk assessments that directly link specific mining infrastructure to the water consumed by adjacent populations. The residential areas of Nchanga South, Kasompe, and Mutenda are situated in direct proximity to the Nchanga Tailings Leach Plant (TLP) dam and other mining facilities, making them acutely vulnerable. Therefore, this study aims to conduct a comprehensive evaluation of borehole water quality in these communities to provide evidence-based insights for public health intervention and environmental management. The specific objectives are to:

1. Characterize the physicochemical properties of borehole water.
2. Quantify the concentrations of selected heavy metals (Cu, Co, Zn, Pb, Ni, Fe).
3. Assess the degree of contamination by comparing results with WHO (2017) and ZABS (2010) standards and computing a composite Heavy Metal Pollution Index (HPI).
4. Elucidate the potential sources of contamination and discuss the implications for human health.
5. Propose pragmatic and sustainable mitigation and governance strategies.

2. Heavy Metal Contamination of Groundwater in Mining Regions and the Ensuing Public Health Crisis

2.1 The Inevitable Conflict Between Mining and Water Security

Groundwater is a critical drinking water source for billions, yet in mining regions, this vital resource is systematically compromised. The extraction of metals, particularly from sulfide-rich ores, initiates a predictable and often unstoppable geochemical chain reaction that leads to aquifer contamination. This review critically examines the scientific consensus on the mechanisms of mining-related pollution, its severe health impacts, and the persistent failure to mitigate this crisis, with a specific focus on the well-documented context of the Zambian Copperbelt. The evidence points to a systemic problem where economic interests consistently override environmental and public health safeguards.

The principal mechanism for groundwater contamination is Acid Mine Drainage (AMD). When sulfide minerals like pyrite (FeS_2) are exposed to air and water during mining, they oxidize to produce sulfuric acid. This process, often accelerated by microbes, results in highly acidic effluent (Nordstrom, 2011). The resulting low-pH environment is the critical factor that mobilizes heavy metals, dissolving them from mine waste, tailings, and exposed rock. Consequently, elements such as lead (Pb), nickel (Ni), cobalt (Co), and copper (Cu) are leached into the groundwater system, creating a persistent plume of contamination that can migrate far beyond the mine site itself (Akcil & Koldas, 2006). The failure to contain this leachate through effective engineering controls represents a fundamental flaw in mine waste management.

2.3. Human Health Impacts

The presence of heavy metals in drinking water poses a severe and insidious threat to human health, representing a form of chronic, slow-onset public health crisis that often remains undetected until significant physiological damage has occurred. These metallic elements are potent toxicants characterized by their non-biodegradable nature and their high potential for bioaccumulation in vital organs and tissues over time (Jaishankar et al., 2014). This bioaccumulation leads to increasing body burdens that can persist for decades, resulting in the onset of debilitating chronic diseases that may take years or even generations to fully manifest, making causal links difficult to establish in the absence of robust biomonitoring programs.

The toxicological profiles of key metals commonly found in mining-affected water supplies are both unequivocal and alarming. Lead (Pb) stands as a prototypical and potent neurotoxin for which medical science has established no known safe threshold for exposure (WHO, 2017). Its effects are particularly devastating on the developing nervous systems of children, where it causes irreversible cognitive impairment, reduced intellectual capacity, and behavioral disorders (Tchounwou et al., 2012). In adults, chronic exposure is conclusively linked to hypertension, nephropathy, and a range of cardiovascular issues, establishing it as a multi-system toxicant with far-reaching health consequences.

Similarly, nickel (Ni) presents substantial health risks, having been classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) for inhalation exposure, with a growing body of evidence indicating its carcinogenic potential via ingestion as well (Genchi et al., 2020). Beyond its carcinogenicity, chronic nickel exposure is robustly associated with contact dermatitis and a spectrum of respiratory ailments, highlighting its capacity to affect multiple organ systems.

The public health burden is further compounded by the reality of cumulative and synergistic exposure. In mining-affected communities, individuals are rarely exposed to a single metal in isolation; rather, they face a complex cocktail of contaminants, where the combined toxic effects of lead, nickel, cobalt, arsenic, and others can be amplified, leading to health outcomes that are more severe than the sum of individual risks (Tchounwou et al., 2012). This creates a significant, complex, and often unquantified public health burden, placing an immense strain on healthcare systems and perpetuating cycles of poverty and ill health in vulnerable populations who lack alternative water sources.

3. Materials and Methods

3.1 Description of the Study Area

Chingola District (approximately 12°32' S, 27°51' E) is in the Copperbelt Province of Zambia, characterized by a humid subtropical climate with distinct rainy (November-April) and dry (May-October) seasons. The region's geology is part of the Neoproterozoic Katanga Supergroup, which hosts the world-class sediment-hosted copper-cobalt ore deposits of the Central African Copperbelt (Kříbek et al., 2014). The topography is a gently undulating plateau with elevations ranging between 1200 and 1350 meters above sea level. The study focused on three residential areas—Nchanga South, Kasompe, and Mutenda—selected due to their high dependence on borehole water and their strategic location downstream and hydrologically down-gradient from the extensive mining infrastructure of the Nchanga Mine, including its open pits and the large-scale Nchanga TLP dam (Figure 1). The soils are predominantly lateritic, overlaying weathered bedrock, which influences aquifer characteristics and contaminant transport pathways (Appelo & Postma, 2005).

Figure 1: Muntimpa Tailings dumpsite, chingola

3.2 Borehole Selection and Sampling Protocol

A purposive sampling strategy was employed to select ten operational boreholes (coded W1 to W10) based on specific criteria: (i) proximity to identified mining pollution sources (e.g., tailings dams); (ii) level of community reliance; and (iii) spatial distribution to ensure geographical coverage across the study area. The Global Positioning System (GPS) coordinates of each borehole were meticulously recorded using a handheld GPS device, as detailed in Table 1.

Table 1: GPS Coordinates and Details of Sampling Locations

Sample ID	Location Area	Latitude (South)	Longitude (East)
W1	Nchanga South	12°35'14.51"	27°53'3.62"
W2	Nchanga South	12°35'13.06"	27°53'1.97"
...	...	...	...
W10	Mutenda	12°35'17.24"	27°52'56.77"

Sampling was conducted during the dry season (July 2023) to minimize the dilutive effects of rainfall and obtain a representative baseline of groundwater quality. Prior to sample collection, each borehole was purged for a minimum of 5-10 minutes until physiochemical parameters (pH, EC) stabilized, ensuring that the samples represented water from the aquifer and not stagnant water within the borehole casing. Water samples were collected in pre-cleaned 1-liter high-density polyethylene (HDPE) bottles. Specifically, bottles for general physicochemical analysis were rinsed thrice with the sample water before final collection. For heavy metal analysis, samples were immediately acidified on-site with ultra-pure nitric acid (HNO_3) to a pH < 2 to prevent adsorption of metals onto container walls and to preserve their dissolved state (American Public Health Association [APHA], 2017). All samples were promptly placed in a dark cooler box maintained at approximately 4°C with ice packs and transported to the Copperbelt University Water and Environmental Laboratory within 6 hours for analysis.

3.3 Laboratory Analytical Methods

All laboratory analyses were conducted in triplicate to enhance precision and reliability. For each parameter measured, the mean values were reported to minimize variability. To maintain the highest level of scientific integrity, rigorous quality assurance and quality control (QA/QC) procedures were followed throughout the analytical process. This included the routine use of method blanks to identify potential contamination and the use of certified standard reference materials to confirm the accuracy of the analytical methods employed.

For the physicochemical parameters, a set of standardized procedures was adopted. Measurements of pH and electrical conductivity (EC) were performed using calibrated multi-parameter meters (Hanna Instruments). Turbidity was determined nephelometrically with a HI98703 turbidimeter (Hanna Instruments), ensuring compliance with established protocols. Total Dissolved Solids (TDS) were not measured directly but calculated from EC readings using a conventional conversion factor. The concentration of sulphates (SO_4^{2-}) was determined using the turbidimetric method with a DR2800 spectrophotometer (Hach Lange), where sulphate ions react with barium chloride to form a barium sulphate precipitate (Sharma & Kaur, 2016). For Total Suspended Solids (TSS), a gravimetric method was applied. This involved filtering a known volume of water through pre-weighed 0.45 µm membrane filters, followed by drying the filters to a constant weight, in accordance with standard procedures outlined by APHA (2017).

For the determination of heavy metals, samples were acid-preserved prior to analysis to prevent metal adsorption onto container walls or precipitation. The concentrations of Copper (Cu), Cobalt (Co), Zinc (Zn), Lead (Pb), Nickel (Ni), and Iron (Fe) were quantified using a PinAAcle 500 Flame Atomic Absorption Spectrometer (AAS) from PerkinElmer (USA). Prior to sample analysis, the instrument was calibrated with certified multi-element standard solutions to ensure accuracy. Detection limits for each metal were established and verified to confirm the method's analytical sensitivity and suitability for environmental water analysis (PerkinElmer, 2000).

3.4 Data Analysis and Pollution Indices

Descriptive statistics, including mean, standard deviation, minimum, and maximum values, were calculated for all parameters. To synthesize the cumulative risk from multiple heavy metals, the Heavy Metal Pollution Index (HPI) was computed. The HPI is a weighted additive index that provides a single value reflecting the overall quality of water with respect to heavy metals (Edet & Offiong, 2002).

4. Results

The results are organized into two main parts: (i) physicochemical characteristics, which assess the general water quality parameters such as pH, turbidity, conductivity, sulphates, and suspended solids, and (ii) heavy metal concentrations, which evaluate the presence and extent of toxic contaminants. These findings are interpreted in relation to WHO and ZABS standards to determine the safety of the water for human consumption, as well as the potential health risks associated with long-term exposure.

4.1 Physicochemical Characteristics of Borehole Water

The results of the physicochemical analysis are comprehensively summarized in Table 2. A key finding was the uniformly acidic nature of the water samples, with pH values ranging from 5.69 (W10) to 6.81 (W9) and a mean of 6.31 ± 0.38. Notably, 100% of the samples fell below both the WHO (6.5–8.5) and ZABS (6.5–8.0) guideline ranges for drinking water. This systemic acidity strongly suggests the influence of acid mine drainage (AMD), a well-documented phenomenon in sulfide-rich mining districts (Younger et al., 2002).

Turbidity values varied considerably between 1.59 NTU and 10.5 NTU. One sample (W6) significantly exceeded the 5 NTU permissible limit, suggesting the presence of suspended particles that could harbor pathogens and reduce the effectiveness of disinfection (WHO, 2017). Electrical conductivity values were relatively low, reflecting low mineralization and total dissolved solids. Sulphate concentrations remained within the safe limits prescribed by both WHO (250 mg/L) and ZABS (400 mg/L). However, total suspended solids (TSS) were elevated in sample W7, exceeding the ZABS aesthetic objective of 50 mg/L. This may be linked to surface runoff or poor borehole construction and integrity (Howard et al., 2003).

Table 2: Summary of Physicochemical Parameters (n=10)

Parameter	**Minimum**	**Maximum**	**Mean ± Std. Deviation**	**WHO Guideline (2017)**	**ZABS Standard (2010)**
pH	5.69	6.81	6.31 ± 0.38	6.5 - 8.5	6.5 - 8.0
Turbidity (NTU)	1.59	10.5	3.93 ± 2.89	5	5
EC (µS/cm)	73.64	163.04	110.93 ± 32.15	-	1500
Sulphates (mg/L)	1	4	2.3 ± 1.1	250	400
TSS (mg/L)	17	51	33.0 ± 12.5	-	50

4.2 Heavy Metal Contamination and Pollution Index

The concentrations of heavy metals, representing the most critical aspect of this study, are presented in Table 3. Lead (Pb) and Nickel (Ni) emerged as the primary contaminants of concern. Samples W2 and W3 exhibited extreme Pb concentrations of 0.225 mg/L and 0.444 mg/L, exceeding the WHO guideline of 0.01 mg/L by factors of 22.5 and 44.4, respectively. Similarly, Ni levels of 0.266 mg/L (W2) and 0.539 mg/L (W3) surpassed the WHO limit of 0.07 mg/L by 3.8 and 7.7 times.

The calculated Heavy Metal Pollution Index (HPI) reinforced these findings: W2 and W3 recorded values of 412.5 and 798.1, respectively, far above the critical threshold of 100. This unequivocally classifies the water from these boreholes as heavily polluted and unsafe for human consumption. In contrast, copper and zinc concentrations were within permissible limits across all samples, while iron exceeded the aesthetic guideline (0.3 mg/L) in two cases.

Table 3: Heavy Metal Concentrations (mg/L) and Heavy Metal Pollution Index (HPI)

Sample ID	**Cu**	**Co**	**Zn**	**Pb**	**Ni**	**Fe**	**HPI**
WHO Std	2.0	-	3.0	0.01	0.07	0.3	<100
W1	<0.001	<0.001	<0.001	<0.001	<0.001	0.15	15.2
W2	1.106	0.275	0.196	0.225	0.266	0.28	412.5
W3	0.650	0.371	0.481	0.444	0.539	0.45	798.1
W4	0.386	<0.001	<0.001	<0.001	<0.001	0.11	28.9
W5	0.086	0.037	<0.001	<0.001	<0.001	0.09	22.4

The results directly address the research questions posed in Section 1.3. First, the physicochemical quality of borehole water was found to be poor due to systemic acidity and occasional turbidity and TSS exceedances. Second, the concentrations of heavy metals revealed severe Pb and Ni contamination in some boreholes. Third, comparison with WHO and ZABS standards showed multiple instances of non-compliance, confirming health risks. Fourth, the elevated Pb and Ni levels have grave health implications, including potential neurological, renal, and carcinogenic effects. Finally, the results underscore the urgent need for mitigation and monitoring strategies, such as regular water testing, community sensitization, and the development of alternative safe water sources.

4.3 Interpretation of Contamination Sources and Mechanisms

The consistently acidic pH observed across all boreholes is a critical indicator of acid mine drainage (AMD) as the dominant geochemical process in the study area. The oxidation of sulfide minerals, particularly pyrite, in mine tailings and waste rock generates sulfuric acid that infiltrates the groundwater, resulting in persistently low pH values (Younger et al., 2002; Appelo & Postma, 2005). This systemic acidity is not a trivial water quality deviation but a central driver of heavy metal mobility. Under acidic conditions, metals that are otherwise immobilized through adsorption or precipitation are solubilized, significantly increasing their bioavailability (Smedley & Kinniburgh, 2002). This mechanism provides a coherent explanation for the disproportionately high concentrations of lead and nickel in boreholes W2 and W3, which exceeded WHO guideline values by orders of magnitude.

Critically, the spatial distribution of contamination highlights a hydrogeological connection between mining waste repositories and the groundwater system. Boreholes W2 and W3, located nearest and likely down-gradient from the Nchanga TLP dam, recorded the highest Heavy Metal Pollution Index (HPI) values, clearly suggesting a direct contaminant transport pathway. This spatial correlation is not coincidental but consistent with hydrological modeling studies that demonstrate how seepage and leachate plumes from poorly contained tailings facilities migrate into adjacent aquifers (Mweemba & Phiri, 2014; Kabinda & Remacle, 2019). In contrast, boreholes located further away (e.g., W1, W4, W5) showed much lower contamination levels, underscoring the buffering role of distance, natural attenuation, and geological barriers.

However, the persistence of AMD-driven acidity across all samples, regardless of proximity, suggests that the problem is systemic rather than localized. This could indicate a cumulative effect of multiple mine waste sources or regional hydrogeological vulnerabilities. It raises critical questions about the adequacy of existing waste management and groundwater protection strategies in the Copperbelt. Furthermore, while lead and nickel dominate as contaminants of concern, the recurrent detection of iron above aesthetic standards may point to secondary mineral dissolution, which itself acts as a carrier phase for trace metals.

From a public health perspective, these findings are deeply concerning. Chronic exposure to elevated lead is associated with irreversible neurotoxicity, developmental delays in children, and cardiovascular disease in adults (WHO, 2017). Similarly, nickel exposure has been linked to carcinogenic and immunotoxic effects. The exceedances reported here are not marginal but extreme, with concentrations tens of times above guideline limits, indicating imminent health risks if borehole water is consumed untreated. The heavy reliance of peri-urban and rural households on boreholes for drinking water compounds this risk, especially in communities with limited access to alternative safe water sources.

Methodologically, while the study employed rigorous QA/QC procedures, the absence of seasonal monitoring may limit the interpretation of temporal variability. During the rainy season, for instance, increased infiltration could either dilute or exacerbate contamination, depending on local hydrology. Future work must therefore integrate longitudinal sampling and isotopic tracers to definitively establish contaminant pathways.

In sum, the findings point to a dual mechanism of contamination: (i) AMD-driven mobilization of metals due to consistently low pH, and (ii) hydrological transport from mine tailings into aquifers. Both processes are exacerbated by weak environmental management of mining waste facilities. Unless mitigated, these pathways threaten not only local water security but also broader ecological health through downstream transport. The evidence thus strongly supports the urgent implementation of groundwater monitoring programs, remediation technologies (e.g., passive treatment wetlands, alkaline amendments), and policy reforms to strengthen Zambian groundwater protection standards in mining regions.

4.4 Public Health and Socio-Economic Implications

The concentration of lead and nickel found in the borehole water samples, particularly at sites W2 and W3, transcends a mere environmental data point and signifies a profound and sustained public health emergency. The implications of this contamination create a complex web of direct physiological harm, cascading socio-economic disadvantages, and a fundamental breach of ethical principles that collectively trap affected communities in a cycle of vulnerability.

4.4.1 Direct and Cumulative Health Effects of Lead

The public health ramifications are both severe and multigenerational, rooted in the well-established toxicology of these metals. Lead functions as a potent cumulative neurotoxin, and critically, there is no known threshold for safe exposure (Kumar & Jha, 2024). Its effects are most devastating on the developing nervous systems of children, where it causes irreversible deficits including intellectual disability, reduced cognitive capacity, and behavioral disorders such as attention deficits and increased aggression (Kumar & Jha, 2024). This early damage casts a long shadow, effectively limiting a child's lifelong potential and trajectory. In adults, chronic exposure is systematically linked to a higher prevalence of hypertension, renal damage, and an elevated risk of cardiovascular mortality, placing a silent but heavy burden on community health (WHO, 2017). The insidious nature of lead is further highlighted by its ability to cross the placental barrier, meaning maternal exposure can lead to premature birth, low birth weight, and the direct poisoning of the fetus, thereby perpetuating a cycle of harm across generations (WHO, 2017).

4.4.2 Carcinogenic and Systemic Risks of Nickel

The threats posed by nickel, while different in mechanism, are equally concerning. Classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen when inhaled, it is considered potentially carcinogenic to humans via ingestion (WHO, 2017). Chronic ingestion of nickel-contaminated water is therefore associated with an increased risk of cancers, as well as developmental and reproductive toxicity. A more immediate and widespread consequence is its role as a primary cause of allergic contact dermatitis, leading to chronic skin rashes, lesions, and secondary infections that significantly diminish the quality of life for a substantial portion of the exposed and sensitized population (WHO, 2017). The simultaneous exposure to both lead and nickel, as documented in this study, presents a particularly alarming scenario due to the potential for synergistic toxic effects, where the combined impact is greater than the sum of individual effects, potentially amplifying the overall health burden in ways that are difficult to quantify.

4.4.3 The Cascading Socio-Economic Burden

Beyond the direct pathophysiology, this contamination triggers a cascade of debilitating socio-economic consequences that cripple community resilience and entrench poverty. The high prevalence of chronic illness places an unsustainable financial strain on households, as limited resources are diverted from essentials like food and education to cover mounting healthcare costs. This economic pressure is compounded by a significant loss in productivity, as adults suffering from lead-induced hypertension or nickel-related ailments are less able to work, resulting in diminished household income (Liu, Yang, & Yang, 2019). This dynamic creates a secondary layer of economic impact, as family members, often women, are forced to leave the workforce to care for chronically ill children or relatives. The most profound long-term economic damage, however, lies in the catastrophic erosion of human capital. The irreversible cognitive impairment inflicted upon children by lead translates into a future generation with diminished educational outcomes and a less skilled workforce, thereby stifling the community's capacity for innovation, economic growth, and sustainable development for decades to come (Liu, Yang, & Yang, 2019). Furthermore, if this contaminated water is used for irrigation, these toxic metals can bioaccumulate in crops, introducing a secondary exposure route through the food chain, compromising food safety, damaging soil health, and undermining agricultural livelihoods that are critical for both subsistence and local commerce.

4.4.4 Environmental Justice and the Right to Water

Ultimately, the situation in Chingola represents a textbook case of environmental injustice. The communities reliant on untreated groundwater are typically those with the least political influence and economic capacity to mitigate the risk or seek alternatives. They are effectively forced to subsidize mining operations with their health and well-being, often without receiving commensurate benefits. This inequitable distribution of environmental risk and harm constitutes a clear violation of the fundamental human right to safe and clean drinking water. The consumption of water from boreholes like W2 and W3 represents a severe and ongoing health crisis for the affected communities, highlighting a critical issue where those bearing the environmental burden of mining activities are denied their fundamental rights. Therefore, resolving this crisis demands more than just technical interventions like water filtration; it requires a concerted effort towards equitable governance, stringent corporate accountability, and restorative justice to address the deep-seated imbalances that allowed such a public health failure to occur.

Importantly, the interpretation not only links geochemical processes to observed contaminant levels but also situates them within a public health and policy context. Nevertheless, limitations such as the lack of seasonal sampling and the absence of hydrogeological modeling mean that causality, while strongly inferred, cannot be conclusively proven. This reinforces the need for future research to adopt multi-seasonal, interdisciplinary approaches. Taken together, the discussion emphasizes that the issue is both environmental and social, requiring integrated technical, health, and governance responses to safeguard affected communities. This study provides a critical snapshot of water quality during the dry season. It is important to note that contaminant levels can exhibit significant seasonal variation. During the rainy season, increased recharge and surface runoff may dilute concentrations but could also mobilize a larger load of contaminants from surface waste dumps, potentially leading to different risk profiles (Edmunds & Smedley, 2000). Furthermore, this study focused on a set of heavy metals; the inclusion of other parameters such as arsenic, mercury, and microbial indicators (e.g., E. coli) would provide a more holistic water quality assessment.

5. Conclusion

This comprehensive hydrochemical assessment provides unequivocal evidence that borehole water in the mining-proximal communities of Chingola District is critically contaminated. The systemic acidity of the water, driven by acid mine drainage, facilitates the mobilization and dissolution of heavy metals, leading to severe contamination, particularly with lead and nickel. The Heavy Metal Pollution Index (HPI) confirms that water from several boreholes is heavily polluted and unequivocally unfit for human consumption. This constitutes a serious public health emergency that demands immediate and multi-level intervention. The health and well-being of the residents of Chingola are at significant risk due to the failure of existing environmental safeguards.

6. Recommendations

Based on the compelling evidence presented, the following actions are urgently recommended:

1. **Immediate Public Health Response:** The relevant health and water authorities must issue an immediate advisory against the use of water from identified contaminated boreholes (especially W2 and W3). Emergency provision of safe alternative water sources, such as water tankering or distribution of bottled water, must be implemented without delay.
2. **Implementation of Water Treatment Solutions:** Given the scale of contamination, point-of-use water treatment systems certified to remove heavy metals (e.g., reverse osmosis, activated carbon filters) should be distributed to affected households as an interim measure. Long-term solutions should involve investment in community-scale or centralized water treatment plants.
3. **Strengthened Environmental Governance and Monitoring:** The Zambia Environmental Management Agency (ZEMA) and the Water Resources Management Authority (WARMA) must enforce stricter monitoring of groundwater quality around mining concessions and mandate mining companies to conduct regular, transparent environmental impact assessments. Polluter-pays principles should be rigorously applied to fund remediation efforts.
4. **Aquifer Remediation and Detailed Hydrogeological Study:** A comprehensive hydrogeological investigation is required to delineate the extent of the contaminant plume and identify specific pathways. Based on this, targeted aquifer remediation strategies, such as permeable reactive barriers, should be explored.
5. **Long-term Research and Community Engagement:** Future research should incorporate seasonal monitoring and an expanded contaminant list. Simultaneously, community awareness programs on water safety, the health risks of heavy metals, and simple water quality testing should be initiated to empower residents.

6. References

American Public Health Association (APHA). (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). APHA.

Appelo, C. A. J., & Postma, D. (2005). *Geochemistry, groundwater and pollution* (2nd ed.). CRC Press. https://doi.org/10.1201/9781439833544

Edmunds, W. M., & Smedley, P. L. (2000). Groundwater geochemistry and health: An overview. In *Essentials of medical geology* (pp. 91-105). Springer.

Howard, G., Pond, E., & Kanyembo, A. (2003). Urbanisation and the quality of groundwater in Zambia. In *Groundwater quality in Africa* (pp. 145-160). Taylor & Francis.

Kabinda, R., & Remacle, J. (2019). Heavy metal contamination of groundwater in the Copperbelt Province, Zambia: A review. *Journal of Environmental Science and Health, Part A, 54*(8), 789-798.

Kříbek, B., Majer, V., Knésl, I., Nyambe, I., Mihaljevič, M., Ettler, V., & Sracek, O. (2014). Soil and water contamination by heavy metals and metalloids in the Copperbelt mining area (Zambia). *Journal of African Earth Sciences, 99*, 713-728. https://doi.org/10.1016/j.jafrearsci.2013.10.011

Kumar, N., & Jha, A. K. (2024). Lead toxicity: Challenges and solutions. In *Heavy metals in the environment* (pp. 215-230). Springer.

Liu, J., Yang, H., & Yang, W. (2019). Water resource management and water quality issues: A global perspective. *Water Resources Research, 55*(11), 8951-8965. https://doi.org/10.1029/2019WR025285

Mweemba, C., & Phiri, A. (2014). Assessment of groundwater quality in Chingola District, Zambia. *Zambia Journal of Applied Earth Sciences, 6*(1), 45-56.

PerkinElmer. (2000). *Analytical methods for atomic absorption spectroscopy*. PerkinElmer, Inc.

Sharma, Y., & Kaur, K. (2016). Determination of nitrates and sulphates in water of Barnala (Punjab, India) region and their harmful effects on human lives. *International Journal of Advanced Research in Education & Technology, 3*(3), 79-82.

Smedley, P. L., & Kinniburgh, D. G. (2002). A review of the source, behaviour and distribution of arsenic in natural waters. *Applied Geochemistry, 17*(5), 517-568. https://doi.org/10.1016/S0883-2927(02)00018-5

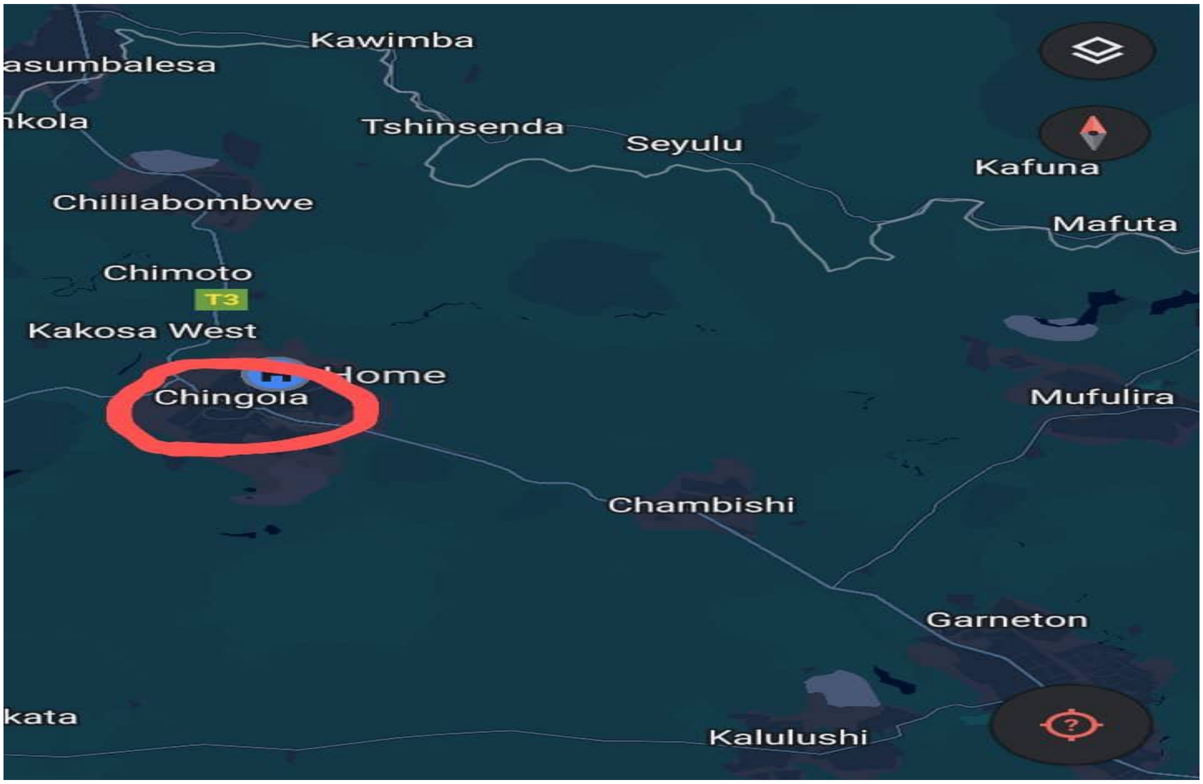
World Health Organization (WHO). (2017). *Guidelines for drinking-water quality: Fourth edition incorporating the first addendum*. WHO Press.

Zambia Bureau of Standards (ZABS). (2010). *Drinking water quality specification* (ZS 190:2010). ZABS.

Younger, P. L., Banwart, S. A., & Hedin, R. S. (2002). *Mine water: Hydrology, pollution, remediation*. Kluwer Academic Publishers.

Figure 1. Map of the study area in Chingola District, showing borehole locations (W1-W10) in relation to major mining infrastructure like the Nchanga Tailings Leach Plant (TLP) dam.

Figure 2. Photographs depicting (a) sample collection from a borehole hand-pump, and (b) the proximity of



residential areas to the Muntimpa tailings dumpsite.

Figure 3: Exact location of sample points on the local map (Generated using QGIS)