Scientific Publishing House
Trends in Ecological and Indoor Environmental Engineering
Norman Gumbo & Cleopas Kapenge
TEIEE 3(2) 2025
RESEARCH ARTICLE
https://doi.org/10.62622/TEIEE.025.3.2.37-45
OPEN ACCESS
ISSN 2956-9761

GROUNDWATER CONTAMINATED WITH HEAVY METALS AS A THREAT TO POPULATION SAFETY AND HEALTH IN DEVELOPING COUNTRIES: A SCOPING REVIEW

Norman Gumbo[1*], Cleopas Kapenge[2]
[1]National University of Science and Technology, Bulawayo, Zimbabwe
[2]Ministry of Health and Child Care, Harare, Zimbabwe
*Corresponding email: norman.gumbo@nust.ac.zw

Received: 08.04.2025; ***Accepted:*** 08.05.2025; ***Available online:*** 30.06.2025; ***Published:*** 30.06.2025

Cite this article: Gumbo, N., & Kapenge, C. (2025). Groundwater Contaminated with Heavy Metals as a Threat to Population Safety and Health in Developing Countries: a Scoping Review. *Trends in Ecological and Indoor Environmental Engineering*, 3(2), 37–45.

Background: Gold mining is a distinct and complex process, involving extraction techniques that use toxic chemicals like cyanide, that pose critical environmental concerns as compared to the mining of other minerals like copper. Most communities in developing countries (especially those in rural areas), rely much on ground water sources for their domestic needs. The studies established high contamination levels of the water by heavy metals from the mining activities. However, there is paucity of information on the impact of artisanal gold mining on ground water sources and associated human health outcomes in the exposed populations. **Objectives:** The current review aims to identify the most common heavy metals contaminating groundwater from industrial activities in African developing countries and the associated safety and health implications to exposed populations from both peer reviewed and grey literature sources. The study is expected to find that due to the low (or non-existent) funding for environmental protection in developing countries, there is a strong correlation between industrial activity and heavy metal pollution, and this may be particularly evident for mining activities as the most environmentally unfriendly activity. **Methods:** The research methodology is based on PRISMA 2020. How keywords were used: heavy metal pollution; water pollution; water sources; human health risks; environmental impact. PubMed, Scopus, Web of Science, EBSCOhost, ResearchGate, and the Internet were used to search for literature sources. **Results:** All of the twenty-three included studies pointed out that heavy metals pose significant ecotoxicological risks to ecosystems, contaminating soil, water sources, plants, and animals. Mining activities contribute to the pollution of ecosystems with heavy metals Pb, As, Cd, Hg, Pb, Zn, which are transported by rivers and other water bodies and contribute to high concentrations of Cu and moderate levels of Pb in sediments, even in national parks where there is no anthropogenic activity. Sediments in polluted water systems have been identified as the best absorbent, reservoir and potential future source of pollutants. Heavy metals like mercury (Hg), cadmium (Cd), and copper (Cu) are known to be highly toxic to aquatic organisms as they are known to interfere with physiological processes such as respiration, enzyme function, and reproduction in fish, amphibians, and invertebrates. All included studies stated that long-term exposure to heavy metals can lead to serious health problems, including cancer, neurological damage, kidney failure, and developmental delays in children. Lead exposure is known to cause cognitive impairment and developmental problems in children. Pregnant women exposed to heavy metals may suffer from complications such as preeclampsia, a condition characterized by high blood pressure and organ damage. Exposure to lead and mercury can lead to kidney damage and the risk of miscarriage and premature birth. Arsenic exposure is considered a risk factor for cancer in pregnant women. **Conclusion:** Several literature sources have indicated that mining activities appear to be the largest contributor to groundwater contamination with heavy metals. Artisanal mining typically thrives in the lowest income countries, worsening environmental conditions due to the lack of even minimal environmental protection measures.

Keywords: heavy metals; water pollution; water sources; health risks; environmental impacts; mining.

INTRODUCTION

Gold mining is a distinct and complex process, involving extraction techniques that use toxic chemicals like cyanide, that pose critical environmental concerns as compared to the mining of other minerals like copper. Small-scale gold mining operations have their own unique challenges that include labour intensity, and the potential environmental damage from mercury and cyanide. Pollution of water sources from mining activities remains a cause for concern in developing countries (Pltonykova et al., 2020). Pollution from gold mining in particular continues un-abated, causing very high pollution levels of water sources. According to WHO (2017), the degradation and contamination of the bio-physical environment from gold mining was found to be rampant in most developing countries with economies relying more on extraction of natural resources. Most developing countries has challenges in carrying out industrial gold mining that pay cognizance to safe mining practices due to poor technological advancement.

Most communities in developing countries (especially those in rural areas), rely much on ground water sources for their domestic needs. Several studies have been conducted to assess the effect of mining on surface water bodies. The studies established high contamination levels of the water by heavy metals from the mining activities. However, there is paucity of information on the impact of artisanal gold mining (AGM) on ground water sources and associated human health outcomes in the exposed populations. Some of these ground water sources will be very close to AGM activities.

Ground water has been considered as one of the reliable water sources (Nnoli et al., 2021) the world over since time immemorial. Globally, there seem to have been great concern in the cases of heavy metal poisoning (Oyewale et al., 2019). Most of the cases have been successfully linked to water contamination, especially in well-developed countries like those in America and Europe, where diagnostic facilities are readily available. Studies on environmental pollution in Africa indicate that toxic metal pollution has reached unprecedented levels over the past decade (WHO, 2023). Human exposure to toxic metals has become a major health risk on the continent and is the subject of increasing attention from national and international environmentalists (Korish & Attia, 2020). An assessment of environmental risk factors from industrial facilities such as oil production, mining, metallurgy, and even automobile repair shops in various economically weak African countries reveals high levels of pollution of ecosystem components and high susceptibility of the population to respiratory diseases, skin diseases, and other associated health risks (Ana et al., 2009; Sawadogo et al., 2023; Sable et al., 2024).

Heavy metals are released into the environment through natural processes and anthropogenic activities. Their multiple industrial, domestic, agricultural, medical and technological applications have led to their widespread distribution in the environment, raising concerns over their potential effects on human health and the environment (Mbongwe et al., 2023). Because of their high degree of toxicity, arsenic, cadmium, chromium, lead, and mercury rank among some of the priority metals that are of public health significance. These metallic elements are considered systemic toxicants that are known to induce multiple organ damage, even at lower levels of exposure. They are also classified as known or probable carcinogens according to the U.S. Environmental Protection Agency, and the International Agency for Research on Cancer.

Given that mining activities rely heavily on water resources and are associated with the pollution of these same water bodies, it was imperative that a scoping review be conducted to gain a deeper insight into the available literature. The aim of the review was to identify the most common heavy metals contaminating groundwater from industrial activities in African developing countries and the associated safety and health implications to exposed populations from both peer reviewed and grey literature sources. The study is expected to find that due to the low (or non-existent) funding for environmental protection in developing countries, there is a strong correlation between industrial activity and heavy metal pollution, and this may be particularly evident for mining activities as the most environmentally unfriendly activity.

METHODOLOGY

The research methodology is based on PRISMA 2020 (Page et al., 2021).

Keywords

Heavy metal contamination; Water pollution; Water sources; Human health risks; Environmental impacts.

Literature search

Databases – PubMed, Scopus, Web of Science, EBSCOhost, ResearchGate, internet.

Search strings

Specific search queries and filters that were applied to each database, the records found in each database and the last day of search per each database are presented in Table 1.

Screening flow chart

A total of 342 studies were found from database searches. After duplicate removal as well as inclusion and exclusion assessment, 228 studies were excluded for various reasons and 114 studies passed through to the titles and abstracts screening stage; 74 out of 97 studies were excluded during full text eligibility assessment, thus a total of 23 studies were passed for inclusion in the scoping review, as presented in Figure 1.

RESULTS

Three major themes were identified during the inquiry, and these were further broken down into eleven sub-themes, together with the authors of the studies that reported on each specific theme as presented in Table 2. These themes helped the reviewers to organize the data and maintain a clear focus on the most important aspects of the data to gain deeper understanding of ground water contamination by heavy metals in developing countries and the accompanying safety and health outcomes to exposed populations. These themes were used to answer the scoping review questions, thus allowing easier thematic analysis of the data.

Table 1. Literature search strategies

Database	Search query	Filters applied	Records found
EBSCO Host	(heavy AND metal AND contamination) AND (groundwater AND pollution AND developing AND countries OR low AND income AND countries) AND (health AND impacts OR environmental AND effects))	– Online full text and peer reviewed – Date range 01/2019 to 12/2023 – Language: English	1324 records 02/07/24
PubMed/Research Gate	Heavy metal contamination OR groundwater pollution AND developing countries OR low-income countries AND health impacts OR environmental effects	– Refined by period: 2019 to 2023 – Review articles and research articles	693 records 17/08/24
Web of Science/Scopus	((((ALL=(heavy metal contamination)) AND ALL=(groundwater pollution)) AND ALL=(health impacts)) OR ALL=(developing countries)) OR ALL=(low-income countries))))	– Publication years: 2019 to 2023 – Document types: article; review article; open access	1529 records 23/10/24

Anthropogenic activities and heavy metal contamination of ground water sources

Industrial activities and heavy metals

Industrial activities are significant sources of heavy metal pollution (Mbongwe et al., 2023). These metals, such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), and nickel (Ni), can be released into the environment through emissions, effluents, and waste disposal. A total of eight included studies (Cairncross, 1992; Jarawaza, 1997; Nnoli et al., 2021; Oyewale et al., 2019), pointed out that industrial processes like metalworking, battery manufacturing, and electronics production release heavy metals such as lead, mercury, and cadmium into the environment, either through air emissions, wastewater discharges, or solid waste. According to Adeyemi & Ojekunle (2021), electronics manufacturing involves materials like cadmium, mercury, and lead. If these items are improperly disposed of, electronics can leach these toxic substances into the environment. In a manner, the production of vehicle batteries involves the use of metals like lead, zinc, and chromium. As such, the disposal of car batteries can contribute to heavy metal contamination if not properly managed (WHO, 2023).

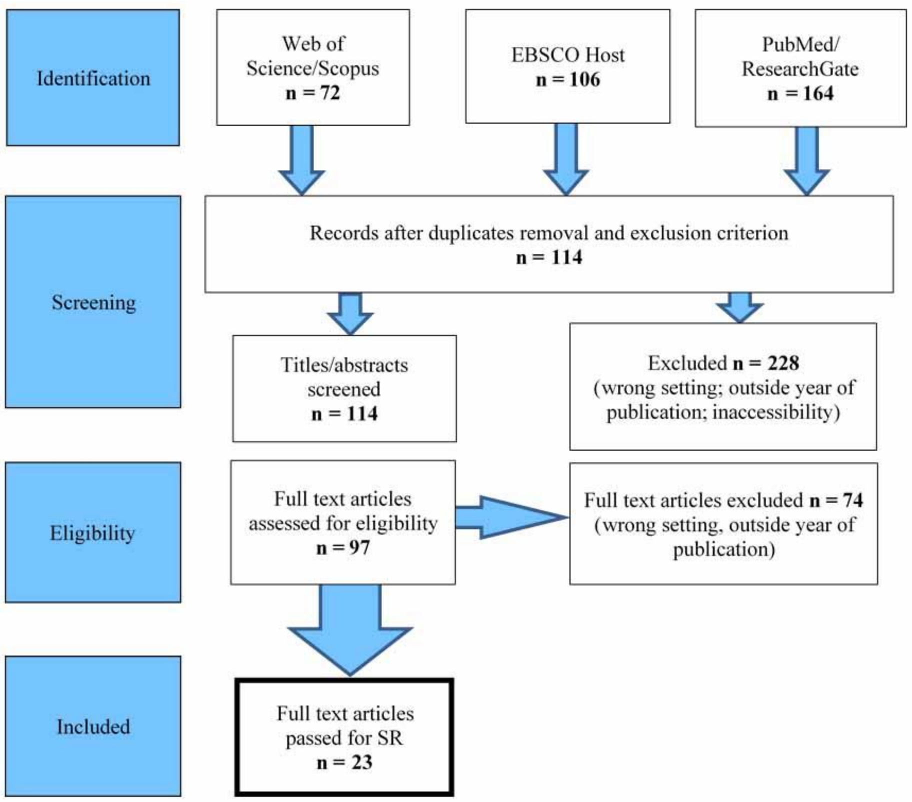

Figure 1. Literature screening flow chart

Table 2. Literature search findings

Theme	Sub-theme	Source
1. Anthropogenic activities and heavy metal contamination of ground water sources.	1. Industrial activities and heavy metals 2. Mining activities and heavy metals 3. Agricultural activities and fertilizers	Nnoli et al., 2021; Oyewale, 2019; Panda, 2020; WHO, 2023; Ruppen, 2023; Nhapi & Tirivarombo, 2004
2. Heavy metal contamination global burden	1. Ecotoxicological effects of heavy metals on ecosystems 2. Sources and pathways of heavy metal contamination 3. International agreements and conventions	Ismael, 2022; Korish & Attia, 2020; Ujah et al., 2020; Hasimuna et al., 2020; Mbongwe, 2023; Akosa et al., 2002
3. Safety and health implications of heavy metal contamination of ground water	1. Health effects to pregnant women and the unborn baby 2. Health effects to immune-compromised individuals 3. Health effects to the general populace	Adeyemi & Ojekunle, 2021; Ravindra & Mor, 2019; Mbongwe, 2023; WHO, 2023; EPA, 2020; Helmer & Hespanhol, 1997

Mining activities and heavy metals

All the included studies indicated that mining operations for minerals like gold, copper, and zinc often release heavy metals into the environment through direct runoff or the use of toxic chemicals in ore extraction for example cyanide or mercury. Smelting processes also release metals like lead, zinc, and copper into the air or water, further contaminating the environment (Cairncross, 1992; Jarawaza, 1997; Ruppen et al., 2023).

Agricultural activities and fertilizers

All the included studies highlighted that certain industrial fertilizers, pesticides, and herbicides were known to contain heavy metals like cadmium and lead. They argued that over time, the accumulation of these substances in soil have the potential to lead to contamination of the environment and ultimately, water systems.

Heavy metal contamination global burden

Ecotoxicological effects of heavy metals on ecosystems

All of the twenty-three included studies pointed out that heavy metals pose significant ecotoxicological risks to ecosystems, contaminating soil, water sources, plants, and animals. According to Ruppen (2023), heavy metals are persistent, meaning they do not easily degrade and can accumulate over time, leading to long-term environmental pollution. Lead (Pb), cadmium (Cd), and arsenic (As) has the potential to affect plant root systems, impairing nutrient uptake and leading to stunted growth, chlorosis (yellowing of leaves), or even plant death (Hasimuna et al., Ujah et al., 2020).

Heavy metals like mercury (Hg), cadmium (Cd), and copper (Cu) are known to be highly toxic to aquatic organisms as they are known to interfere with physiological processes such as respiration, enzyme function, and reproduction in fish, amphibians, and invertebrates (Akosa et al., 2002; Ruppen et al., 2023). A good example is that of mercury which has the ability to bioaccumulate in aquatic organisms, leading to biomagnification up the food chain (Akosa et al., 2002; Ruppen et al., 2023). Cadmium interferes with gill function in fish, leading to impaired oxygen exchange and potential death (Ismael et al., 2022).

Was found that when animals, especially herbivores, ingest plants or drink water contaminated with heavy metals, bioaccumulation of heavy metals occur, leading to physiological damage such as organ failure, reproductive problems, and increased mortality rates. Mercury in particular is known to cause neurological damage in animals (Akosa et al., 2002; Ismael et al., 2022; Korish, & Attia, 2020; Mbongwe et al., 2023; Ujah et al., 2020).

Sources and pathways of heavy metal contamination

Figure 2 is a graphic representation of the various sources of heavy metals and pathways leading to contamination of water sources.

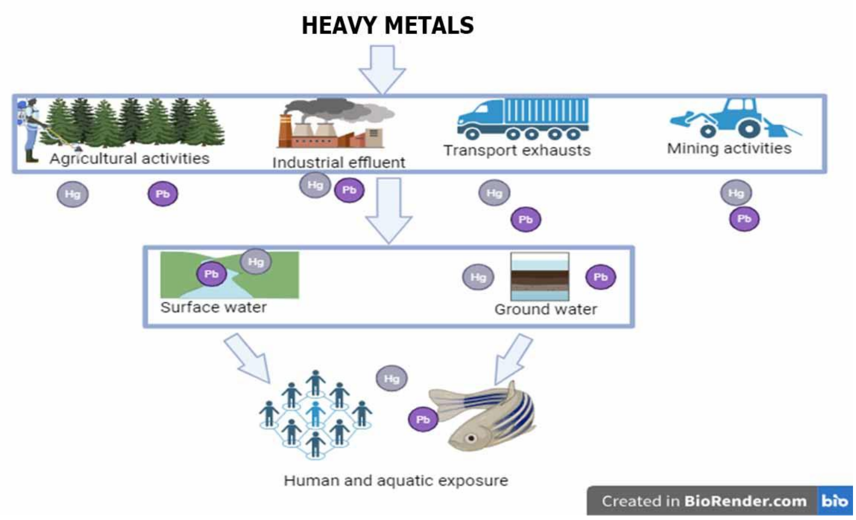

Figure 2. Sources of heavy metals in water sources and human/aquatic exposure pathway

All the included studies highlighted that heavy metal contamination in the environment do come from a variety of sources, and these metals can enter ecosystems through several pathways. Industrial activities such as the manufacture of electronics, batteries, pigments, and chemicals have the potential to release heavy metals like mercury, lead, cadmium, and chromium through waste disposal or emissions (Hasimuna et al., 2020; Mbongwe et al., 2023). Electronic waste is considered a significant source of these metals (Ruppen et al., 2023).

Mining and ore processing operations, for such metals as gold, copper, and zinc are known release heavy metals like arsenic, lead, mercury, and cadmium into the environment, ending up in water sources (MMMD, 2021). Pesticides and fertilizers from agricultural activities contain heavy metals like cadmium and lead and these have the ability to accumulate in soil and enter the food chain through crops (Hasimuna et al., 2020; Ujah et al., 2020). Irrigation using water contaminated with heavy metals from industrial waste, sewage, or runoff can lead to the accumulation of these metals in the soil, affecting crop health and safety (Ismael et al., 2022; Korish, & Attia, 2020).

According to Ruppen (2023), when waste such as slag, ash, and sludge from industries is improperly disposed of, heavy metals can leach into the surrounding soil and groundwater, leading to long-term contamination. Poorly designed landfills or refuse dumping areas are known to be common sources of lead, cadmium, and mercury contamination of soil and water bodies (Akosa et al., 2002; Mbongwe et al., 2023).

Emissions from vehicles using leaded fuels are to contain trace amounts of heavy metals, such as lead, zinc, and nickel, into the atmosphere (Akosa et al., 2002; Ismael et al., 2022; Korish, & Attia, 2020; Mbongwe et al., 2023). Worn out and discarded tyres and brake pads release heavy metals like zinc, copper, and cadmium into the environment (Ruppen et al., 2023). Once heavy metals are introduced into the environment, they can follow different pathways that can lead to contamination of soil, water, air, plants, and animals (Akosa et al., 2002).

International agreements and conventions

Seven of the twenty-three included studies (Akosa et al., 2002; Hasimuna et al., 2020; Ismael et al., 2022; Korish, & Attia, 2020; Mbongwe et al., 2023; Ujah et al., 2020), highlighted that there are several international agreements and conventions established to address the global challenge of heavy metal contamination and its environmental and health impacts. They argued that these agreements are aimed at reducing the release of heavy metals into the environment and protect human health and ecosystems from toxic exposure. These agreements include:
– the Stockholm Convention on Persistent Organic Pollutants (POPs) of 2001, which called for the phasing out of mercury and lead from certain products;
– the Minamata Convention on Mercury of 2013, aimed at eliminating mercury emissions and releases into the environment;
– the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal of 1989, which sought to control the release of lead, cadmium and mercury into the environment;
– the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade of 1998, which is aimed at controlling movement of chemicals that may contain cadmium, lead and mercury from one country to another.

Safety and health implications of heavy metal contamination

Health effects to pregnant women and the unborn baby

Authors of the research (Adeyemi & Ojekunle, 2021; Ravindra & Mor, 2019), pointed out that exposure to heavy metals does

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have serious health effects, to pregnant women and their unborn babies. According to WHO (2017), pregnant women exposed to heavy metals can suffer from complications such as preeclampsia, a condition characterized by high blood pressure and damage to organs. Exposure to lead and mercury can cause kidney damage and the risk of miscarriage and premature birth. Arsenic exposure is considered to be a cancer risk factor in pregnant women (Adeyemi & Ojekunle, 2021; Ravindra & Mor, 2019; WHO, 2023).

Unborn babies may suffer neurodevelopmental damage due to exposure to arsenic, lead and cadmium (Adeyemi & Ojekunle, 2021; WHO, 2017). They can also be born with low birth weight, which can lead to developmental delays and other health complications. According to WHO (2017), babies exposed to mercury may have cerebral palsy, which is a neurological disorder, including memory impairment.

Health effects to immune-compromised individuals

The following from the included studies (Adeyemi & Ojekunle, 2021; EPA US, 1996), pointed out that immune-compromised individuals were particularly vulnerable to the health effects of heavy metal exposure due to their already weakened immune systems. They argued that heavy metals such as lead, mercury, cadmium, arsenic, and nickel can exacerbate health conditions in individuals with compromised immune systems, making them more susceptible to infections, chronic diseases, and other adverse health outcomes, including the risk of cancer.

Health effects to the general populace

All of the included studies argued that prolonged exposure to heavy metals can lead to severe health problems, including cancer, neurological damage, kidney failure, and developmental delays in children. Exposure to lead is known to can cause cognitive impairments and developmental issues in children (EPA US, 1996). Exposure to mercury can damage the nervous system, whilst exposure to cadmium can cause kidney and bone damage (EPA US, 1996; WHO, 2023).

DISCUSSIONS

The scoping review observed the central theme of the study as well as the broad and specific objectives of the study. Issues discussed include various sources of heavy metals, how they end up contaminating water, how they exert their toxic effects on specific immune compromised individuals as well as the safety and health concerns to the general populace.

The effects of lead were extensively studied and are well documented as indicated in all the twenty-three included studies. These effects led to the reduction and banning of the use of lead in some products. One of the major products banned was leaded petrol, among others. Mercury is another well documented heavy metal which was studied ever since the 1956 Minamata methyl mercury poisoning in Japan. The findings of this scoping review agreed with those of the WHO (2017) that heavy metals' effects on humans and the environment are well documented. Adeyemi & Ojekunle (2021) pointed out that artisanal miners extensively use mercury and batteries with cadmium during their activities. These batteries are then haphazardly/indiscriminately disposed of once they are spent promoting the release of cadmium into the environment.

Heavy metals have got a high degree of toxicity and are known or believed to be potentially carcinogenic (Adeyemi & Ojekunle, 2021; WHO, 2023). This means that they have the potential to cause cancer in exposed populations. According to WHO (2017), they have the ability to seep/leach through the soil as ions to contaminate water sources. Furthermore, these heavy metals are not biodegradable and tend to accumulate in living organisms (Ruppen et al., 2023). Even though cadmium is the most soluble in water, some compounds of lead and mercury are slightly soluble (EPA US, 1996).

Anthropogenic activities and heavy metal contamination of ground water sources.

A variety of anthropogenic sources of pollution contribute to surface or deep groundwater pollution (WHO, 2017). The main factors affecting the vulnerability of aquifers to pollution are the amount of precipitation, the permeability of the material between the surface and the aquifer, the slope of the surface, and the depth of the groundwater table (Helmer & Hespanhol, 1997). Unconfined and shallow aquifers are more vulnerable, while confined aquifers are much less vulnerable, as are deeper ones (Jarawaza, 1997). The risk of pollution will be lower with steeper slopes since the likelihood of infiltration is reduced due to the existing tendency of pollutants to runoff. Similarly, in arid areas the risk of pollution is lower compared to areas with heavy rainfall. The study by Helmer & Hespanhol (1997) highlights the following most important sources of anthropogenic groundwater pollution:

– agriculture through animal waste and plant protection chemicals;
– waste disposal and accumulation sites through emissions and leachate;
– various levels of industrial enterprises;
– mineral extraction and processing facilities;
– underground fuel product pipeline systems and storage tanks;
– septic systems;
– road drainage systems that collect road runoff and spills.

Industrial activities and heavy metals

Researchers have proven that Arsenic, Chromium, Cadmium, Mercury, and Lead are some of the most significant metals that increase public health risks because they are recognized carcinogens and the main route of entry of these metals into the human body is drinking water. People with high concentrations of these heavy metals in the body are at risk of diabetes, kidney damage, cardiovascular diseases, neurotoxicity, and infertility (Sable et al., 2024). The characteristics of heavy metal pollution in Africa have been described as having major sources of pollution in the different regions. Dabiré & Sako (2024) found that the presence of Cr, Ni and Zn in agricultural soils is predominantly due to natural factors, in contrast to Ag, As, Hg, Co, Cu and Mn, the presence of which is predominantly associated with industrial activities. Dusengemungu et al. (2022) report a low environmental risk for all heavy metals in the immediate vicinity of the studied waste dumps, while contaminated soils around steel plants and mine tailings dumps are susceptible to dispersal by wind and water. In fact, sediments in contaminated aquatic systems have been recognized as the best sink, reservoir and possible future source of pollutants (Ikenaka et al., 2010; Hasimuna et al., 2021). That is, natural water bodies are actively involved in the accumulation and transport of pollutants, including heavy metals. Thus, Umeoguaju et al. (2021) found that Ni, Cd, Cr and Pb levels in most natural water bodies in the Niger Delta of Nigeria exceed the WHO safe drinking water limit due to oil production facilities, which urgently requires stricter enforcement of environmental management practices. Owamah et al. (2023) reported the impact of automobile workshop leachate on groundwater, which resulted in high concentrations of heavy metals, namely Cd – 0.0315, Cr – 0.0772, Cu – 0.0701, Fe – 0.3645, and Pb – 0.1602 (average). It was also found that heavy metal-containing waste discharged into the upstream of a river in a mining area was transported and retained in a lake located more than 450 km downstream (Ikenaka et al., 2010). In Zambia, the Kabwe and Copperbelt mining areas contribute to the pollution of ecosystems with heavy metals Pb, As, Cd, Hg, Pb, Zn, which are transported within each area by rivers and contribute to high concentrations of Cu and moderate levels of Pb in sediments in national parks (Ikenaka et al., 2010). In some tributaries of the Kafue River, especially those located near major mining centres, concentrations of dissolved Cu and Co are high (up to 14.752 μg/L and 1.917 μg/L), which is mainly due to dust fallout from tailings dams and smelter emissions, leaks of solutions from tailings dams due to poor pipeline quality, and failures in pipelines transporting slurry from treatment plants to tailings dams (Kříbek et al., 2023).

Mining activities and heavy metals

Mineral exploration in Zimbabwe dates to the pre-colonial era. It is believed that the presence of such minerals like gold was also a factor contributing to the eventual colonization by Britain in 1890. The discovery of the Great Dyke belt resulted in the concentration of gold mines along it (Mbongwe et al., 2023). During the colonial era and a few years post colonization, gold mining was a well-regulated economic activity. The available literature suggests that there was a downturn from around the year 2000 when there was the land reform program. Coupled with the economic meltdown that followed, AGM activities begun to escalate to the unprecedented levels they are currently at (Mbongwe et al., 2023). These prevailing economic challenges and the good gold prices both on the formal and informal market are believed to be fuelling AGM activities (Appelo & Postma, 2004).

The abundant deposit of mineral resources in sub-Saharan Africa has attracted high mining activity with its negative environmental effects (WHO, 2023). Poor regulatory mechanisms have led to environmental contamination from mining activities by pollutants like heavy metals. Thus, in BISSA Village, Burkina Faso, the risk index (RI) values in the mining area ranged from moderate 167.935 to extremely high 707.056. The average values of environmental risk factors were ranked in the following order: Hg (382.750) > As (38.211) > Cu (6.347) > Pb (4.486) > Ni (2.858) > Cr (2.273) > Zn (0.616) (Sawadogo et al., 2023). As the largest coal and gold producer, South Africa is a significant source of Hg pollution in the world, with an estimated 46.4 tonnes of Hg contamination in 2018 alone (Van Rooyen et al., 2023). Ali et al. (2018) reported the extent of Hg contamination of river sediments in Sudan in areas with active gold mining, namely low levels in eastern Nile State (0.001 mg/kg) and elevated levels in northern (0.002 mg/kg), southern (0.004 mg/kg) and western (0.005 mg/kg) Nile State (Sudan).

Dabiré & Sako (2024) found the prevalence of artisanal gold mining due to the significant Hg content found in agricultural and control soils and the absence of this metal in industrial waste. Artisanal gold mining is a global activity, mainly in developing countries (Akosa et al., 2002). It is the use of simple, primitive technology to extract gold from soil, river sands and disused gold mines. The gold ore is taken to a processing area usually not registered. Some put the ore in sacks and carry it to the processing area, some use wheel barrows whilst some use trucks and tractors. The ore is then ground or crushed to produce a concentrate. The concentrate is then mixed with mercury which will bind to the gold to form an amalgam. Mercury is then separated from the amalgam by roasting it in the open air (Cairncross, 1992). Pure gold produced contains up to 5% of mercury (Hg) (Korish, & Attia, 2020). Most of the mercury will escape into air. The remaining soil from the gold ore is left on the land as dumps.

Up to 15 million miners are estimated to be working with mercury, and about 80 – 100 million people depend on gold mining as the main source of family income (Akosa et al., 2002). With favourable local and international gold prices, artisanal gold mining has gained increasing importance. Concerns over the impact of artisanal gold mining practices on the environment, occupational health of the miners, health of the local communities, and social dimensions have been investigated (Akosa et al., 2002). A lot of potential pollution sources have been associated with these AGM activities. These include dust particles, chemical reagents used in the gold extraction, gaseous emissions and tailing materials from the dumps. Major AGM related environmental problems include air pollution, water pollution, noise and land degradation.

Thus, the environmental risk and toxicity to the population increases significantly when mercury is included in the index calculation, indicating the cumulative impact of industrial and artisanal gold mining on agricultural soil quality (Dabiré & Sako, 2024).

Mining in general causes various environmental concerns. The major concerns observed in this area include land degradation which results from removal of vegetative cover and destruction of flora and fauna (Akosa et al., 2002). Another concern is the contamination of water sources and soil resulting from the release of cyanide, arsenic, sulphates, and heavy metals such as Cu and Fe during ore processing (Akosa et al., 2002). Roasting of ore containing pyrite gives rise to the production of SO_2 in the atmosphere which produces acid rain (Akosa et al., 2002). The acid water then releases high levels of toxic ions from the rock matrix in the groundwater. Other impacts associated with mining includes noise, vibration and dust from blasting operations.

Heavy metal contamination global burden

Ecotoxicological effects of heavy metals on ecosystems

There are various sources of water on earth which include ground water, which constitute about 30.1%; surface and atmospheric water, which constitutes about 0.4% and glaciers, which constitutes the bulk of 68.7% (Pltonykova et al., 2020). According to the report, few countries measure the quality of groundwater or the rate at which it is being exploited, and this makes it difficult to manage. Ground water is often overexploited and polluted (WHO, 2023). Pollution can harm water resources and aquatic ecosystems. Major pollutants include organic matter and disease-causing organisms from waste water discharges, fertilizers and pesticides running off from agricultural lands, acid rain resulting from air pollution, and heavy metals released from mining and industrial activities (Nhapi & Tirivarombo, 2004). Groundwater has the advantage that it is not as easily contaminated as surface water. However, groundwater can become naturally contaminated because of its very close connection to the materials of its aquifer and once contaminated, groundwater is very difficult to clean up (Nhapi & Tirivarombo, 2004).

Sources and pathways of heavy metal contamination

Groundwater moves slowly through an aquifer, and unlike the surface water of a stream, it has a lot of contact with the surrounding rock or sediment. In most aquifers, the geological materials that make up the aquifer are relatively inert or are made up of minerals that dissolve very slowly into the groundwater. Over time, however, all groundwater gradually has more and more material dissolved within it as it remains in contact with the aquifer. In some areas, that rock or sediment includes some minerals that could potentially contaminate the water with elements that might make the water less ideal for human consumption or agricultural use. Examples include copper, arsenic, mercury, fluorine, sodium, and boron (Helmer &

Hespanhol, 1997). In some cases, contamination may occur because the aquifer material has particularly high levels of the element in question. In other cases, the aquifer material is just normal rock or sediment, but some features of the water or the aquifer allows the contaminant to build up to significant levels.

Health implications of heavy metal contamination of water

These are naturally occurring substances which are often present in the environment at low levels. In larger amounts, it was demonstrated through various studies that they can be dangerous. Some of the heavy metals of no nutritional value to humans include Arsenic, Cadmium, Lead, Chromium, Copper, Mercury and Nickel. These are regarded to be of major public health concern, mainly due to their presence at relatively high concentrations in drinking water because of human activities and their effects on human health (Oyewale et al., 2019).

Several studies have shown that exposure to toxic metals causes long term health problems in human populations. Although the acute and chronic effects are known for some metals, little is known about the health impact of mixtures of toxic elements. Recent reports have pointed out that these toxic elements may interfere metabolically with nutritionally essential metals such as iron, calcium, copper, and zinc (Panda et al., 2020).

Health effects to pregnant women and the unborn baby

Lead competes with calcium to be absorbed by the body. Adults absorb 35 to 50% of lead through drinking water and the absorption rate for children may be greater than 50%. It sticks to red blood cells and then moves into soft tissues, like the liver and lungs (Nnoli et al., 2021). If lead is absorbed into bones, it can stay there for decades and re-circulate in the person's blood if a bone is broken or when a woman is pregnant, potentially poisoning both the mother and the foetus (WHO, 2023).

Prenatal exposure to lead was successfully linked with reduced birth weight and preterm delivery, and with neuro-developmental abnormalities in infants (EPA US, 1996). In children, these studies have shown an association between blood level poisoning and diminished intelligence, lower intelligence quotient-IQ, delayed or impaired neuro-behavioural development, decreased hearing acuity, speech and language handicaps, growth retardation, poor attention span, and anti-social and delinquent behaviours (Panda et al., 2020). In the adult population, reproductive effects, such as decreased sperm count in men and spontaneous abortions in women have been associated with high lead exposure (Panda et al., 2020).

Health effects to immune-compromised individuals

EPA (2020) has found cadmium to potentially cause a variety of effects from acute exposures, including: nausea, vomiting, diarrhoea, muscle cramps, salivation, sensory disturbances, liver injury, convulsions, shock and renal failure.

According to EPA (2020), the no-observed-adverse-effect level (NOAEL) for Cadmium for humans is 0.01 mg/kg/day. Cadmium has chronic potential to cause kidney, liver, bone and blood damage from long- term exposures (EPA US, 1996).

Health effects to the general populace

Mercury is a widespread environmental toxicant and pollutant which induces severe alterations in body tissues and causes a wide range of adverse health effects (Hasimuna et al., 2020). All forms of mercury are toxic, and their effects include gastro-intestinal toxicity, neurotoxicity, and nephrotoxicity (Cairncross, 1992).

Both humans and animals are exposed to various chemical forms of mercury in the environment. These include elemental mercury vapor (Hg^0), inorganic mercurous (Hg^{+1}), mercuric (Hg^{+2}), and the organic mercury compounds (Helmer & Hespanhol, 1997). The elemental vapor is highly lipophilic and is effectively absorbed through the lungs and tissues lining the mouth. After Hg^0 enters the blood, it rapidly passes through cell membranes, which include both the blood-brain barrier and the placental barrier (Appelo & Postma, 2004). Once it enters the cell, Hg^0 is oxidized and becomes highly reactive Hg^{2+}. Methyl mercury derived from eating fish is readily absorbed in the gastrointestinal tract and because of its lipid solubility, can easily cross both the placental and blood-brain barriers. Once mercury is absorbed it has a very low excretion rate. A major proportion of what is absorbed accumulates in the kidneys, neurological tissue and the liver (Pltonykova et al., 2020).

Both organic and inorganic mercury have been shown to alter calcium homeostasis but through different mechanisms (Cairncross, 1992). Organic mercury compounds (methylmercury (MeHg)) are believed to increase intracellular calcium by accelerating the influx of calcium from the extracellular medium and mobilizing intracellular stores, while inorganic mercury (Hg^{2+}) compounds increase intracellular calcium stores only through the influx of calcium from the extracellular medium (Pltonykova et al., 2020). Studies have shown that mercury and other toxic metals affect cellular organelles and adversely affect their biological functions (Cairncross, 1992).

Although mercury-containing compounds are not mutagenic in bacterial assays, inorganic mercury has been shown to induce mutational events in eukaryotic cell lines with doses as low as 0.5 μM (Pltonykova et al., 2020). The EPA (2020) has determined that mercuric chloride and methylmercury are possible human carcinogens. Exposure to high levels can permanently damage the brain, kidneys, and developing foetuses.

Effects on brain functioning may result in irritability, shyness, tremors, changes in vision or hearing, and memory problems. Short-term exposure to high levels of metallic mercury vapours may cause lung damage, nausea, vomiting, diarrhoea, increase in blood pressure or heart rate and skin rashes.

Epidemiological studies on heavy metal exposures and diseases

Lead is a naturally occurring bluish-grey corrosion-resistant metal present in small amounts in the earth's crust. While it has some beneficial uses, it can be toxic to humans and animals causing some health problems, associated with calcium-dependent release of several neurotransmitters (Korish & Attia, 2020). Experimental studies have indicated that lead is potentially carcinogenic, inducing renal tumours in rats and mice (Pltonykova et al., 2020) and is therefore considered a probable human carcinogen.

Lead has been used for pipes, pewter and paint for a long time. It has also been used in lead glazes for pottery, insecticides, hair dyes and as an anti-knocking additive for petrol. Some of these uses have now been banned (Pltonykova et al., 2020), replaced or discouraged as lead is known to be detrimental to health, particularly that of children.

Lead is still widely used for car batteries, pigments, ammunition, cable sheathing, weights for lifting, weight belts for diving, lead crystal glass, radiation protection and in some solders (Ujah et al., 2020). It is often used to store corrosive liquids.

Mercury is a heavy metal belonging to the transition element series of the periodic table. It is unique in that it exists or is found in nature in three forms (elemental, inorganic, and organic), with each having its own profile of toxicity (EPA US, 1996).

Methylmercury is the most frequently encountered compound of the organic form found in the environment and is formed because of the methylation of inorganic (mercuric) forms of mercury by microorganisms found in soil and water (Jarawaza, 1997).

Mercury is utilized in the electrical industry (switches, thermostats, batteries), dentistry (dental amalgams), and numerous industrial processes including the production of caustic soda, in nuclear reactors, as antifungal agents for wood processing, as a solvent for reactive and precious metal, and as a preservative of pharmaceutical products (Jarawaza, 1997).

Cadmium is a rare but widely dispersed element found naturally in the environment (Oyewale et al., 2019), and most cadmium ore (greenockite) exists as cadmium sulphide, is refined during zinc production, and occurs in association with zinc.

It is mostly released into the environment through mining, smelting and its use in various industrial processes (Pltonykova et al., 2020). It enters the food chain from uptake by plants from contaminated soil or water.

CONCLUSION

A number of both published and unpublished articles on heavy metals and their potential to contaminate water sources were identified. Several literature sources pointed out that mining activities seemed to contribute most to the contamination of ground water sources with heavy metals. Several of the studies also laid bare the effects of heavy metals on both aquatic and human health. Artisanal mining typically thrives in the lowest income countries, worsening environmental conditions due to the lack of even minimal environmental protection measures.

Author's statements

Contributions

All authors contributed equally to all aspects of the research and writing of the manuscript.

Declaration of conflicting interest

The authors declare no competing interests.

Financial interests

The authors declare they have no financial interests.

Funding

Not applicable.

Data availability statement

No data were used for the current study.

AI Disclosure

The authors declare that generative AI was not used to assist in writing this manuscript.

Ethical approval declarations

Not applicable.

Additional information

Publisher's note

Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

Adeyemi, A. A., & Ojekunle, Z. O. (2021). Concentrations and health risk assessment of industrial heavy metals pollution in groundwater in Ogun state, Nigeria. *Scientific African*, 11, e00666. https://doi.org/10.1016/j.sciaf.2020.e00666.

Akosa, A. B., Adimado, A. A., Amegbey, N. A., Nignpense, B. E., Carboo, D., & Gyasi, S. (2002). Report submitted by Cyanide investigate committee. *Ministry of Environment and Science*. June.

Ali, M., Elhagwa, A., & Elfaki, J. (2018). An investigation of mercury distribution in the soils around gold mining area at Dar-Mali locality, river Nile State, Sudan. *Eurasian Journal of Soil Science*, 7(4), 365–372. https://doi.org/10.18393/ejss.467595.

Ana, G. R., Sridhar, M. K., & Bamgboye, E. A. (2009). Environmental risk factors and health outcomes in selected communities of the Niger delta area, Nigeria. *Perspectives in Public Health*, 129(4), 183–191. https://doi.org/10.1177/1466424008094803.

Appelo, C. A. J., & Postma, D. (2004). Geochemistry, groundwater and pollution. CRC press. https://doi.org/10.1201/9781439833544.

Cairncross, S., 1992. UNDP-World Bank Water and Sanitation Program. Sanitation and Water Supply: Practical Lessons from the Decade. International Bank for Reconstruction and Development, *World Bank*, 63 pp. Available: https://documents1.worldbank.org/curated/en/488891493776777098/pdf/multi-page.pdf.

Dabiré, B. A. M., & Sako, A. (2024). Comprehensive assessment of heavy metal pollution of agricultural soils impacted by the Kalsaka abandoned gold mine and artisanal gold mining in northern Burkina Faso. *Environmental Monitoring and Assessment*, 196(8), 755. https://doi.org/10.1007/s10661-024-12894-7.

Dusengemungu, L., Mubemba, B., & Gwanama, C. (2022). Evaluation of heavy metal contamination in copper mine tailing soils of Kitwe and Mufulira, Zambia, for reclamation prospects. *Scientific Reports*, 12(1), 11283. https://doi.org/10.1038/s41598-022-15458-2.

Hasimuna, O. J., Chibesa, M., Ellender, B. R., & Maulu, S. (2021). Variability of selected heavy metals in surface sediments and ecological risks in the Solwezi and Kifubwa Rivers, Northwestern province, Zambia. *Scientific African*, 12, e00822. https://doi.org/10.1016/j.sciaf.2021.e00822.

Hasimuna, O. J., Maulu, S., & Chibesa, M. (2022). Assessment of heavy metal contamination in water and largescale yellowfish (Labeobarbus marequensis, Smith 1841) from Solwezi River, North-Western Zambia. *Cogent Food & Agriculture*, 8(1), 2121198. https://doi.org/10.1080/23311932.2022.2121198.

Helmer, R., & Hespanhol, I. (1997). Water pollution control: a guide to the use of water quality management principles. *CRC Press.*

Ikenaka, Y., Nakayama, S. M., Muzandu, K., Choongo, K., Teraoka, H., Mizuno, N., & Ishizuka, M. (2010). Heavy metal contamination of soil and sediment in Zambia. *African Journal of Environmental Science and Technology*, 4(11), 729–739.

Ismael, M., Mokhtar, A., Adil, H., Li, X., & Lü, X. (2022). Appraisal of heavy metals exposure risks via water pathway by using a combination pollution indices approaches, and the associated potential health hazards on population, Red Sea State, Sudan. *Physics and Chemistry of the Earth*, Parts a/b/c, 127, 103153. https://doi.org/10.1016/j.pce.2022.103153.

Jarawaza, M. (1997). Water quality monitoring in Harare. Lake Chivero–A Polluted Lake. *Univ. of Zimbabwe Publications*, 27–34.

Korish, M. A., & Attia, Y. A. (2020). Evaluation of heavy metal content in feed, litter, meat, meat products, liver, and table eggs of chickens. *Animals*, 10(4), 727. https://doi.org/10.3390/ani10040727.

Kříbek, B., Nyambe, I., Sracek, O., Mihaljevič, M., & Knésl, I. (2023). Impact of mining and ore processing on soil, drainage and vegetation in the Zambian copperbelt mining districts: a review. *Minerals*, 13(3), 384. https://doi.org/10.3390/min13030384.

Mbongwe, B., Odirile, P. T., Letsholo, B., Lesetedi, B., Tapera, R., Mmualefe, L., ... & Zetola, N. (2023). Occurrences of Cadmium, Arsenic, Lead, and Mercury in Potable Water in Greater Gaborone, Botswana: Implications for Public Health. In Poisoning-Prevention, Diagnosis, Treatment and Poison Repurposing. *IntechOpen*. https://doi.org/10.5772/intechopen.113716.

Ministry of Mining and Mining Development (MMMD). Yearly report (2021). Zimbabwe

Nhapi, I., & Tirivarombo, S. (2004). Sewage discharges and nutrient levels in Marimba River, Zimbabwe. *Water*, 30(1), 107–113. https://doi.org/10.4314/wsa.v30i1.5033.

Nnoli, N. G., Olomukoro, J. O., Odii, E. C., Ubrei-Joe, M. M., & Ezenwa, I. M. (2021). Another insight into the contamination levels at Ogoniland in Niger Delta, Nigeria, with focus on Goi Creek. *Environmental Science and Pollution Research*, 28(26), 34776–34792. https://doi.org/10.1007/s11356-021-13117-z.

Owamah, H. I., Akpoedafe, T. O., Ikpeseni, S. C., Atikpo, E., Orugba, H. O., & Oyebisi, S. (2023). Spatial distribution of heavy metals in groundwater around automobile workshops in a popular Niger-Delta University town, Nigeria. *Journal of Engineering and Applied Science*, 70(1), 79. https://doi.org/10.1186/s44147-023-00249-x.

Oyewale, A. T., Adesakin, T. A., & Aduwo, A. I. (2019). Environmental impact of heavy metals from poultry waste discharged into the Olosuru stream, Ikire, southwestern Nigeria. *Journal of Health and Pollution*, 9(22), 190607. https://doi.org/10.5696/2156-9614-9.22.190607.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. bmj, 372. https://doi.org/10.1136/bmj.n71.

Panda, B., Chidambaram, S., Thilagavathi, R., Ganesh, N., Prasanna, M. V., & Vasudevan, U. (2020). Source governed trace metal anomalies in groundwater of foothill aquifer and its health effect. *Applied Water Science*, 10(7), 173. https://doi.org/10.1007/s13201-020-01253-9.

Pltonykova, H., Koeppel, S., Bernardini, F., Tiefenauer-Linardon, S., de Strasser, L., & Connor, R. (2020). The United Nations World Water Development Report 2020: Water and Climate Change. *UNESCO for UN-Water 2020*, 235 pp. Available: http://hdl.handle.net/1834/42227.

Ravindra, K., & Mor, S. (2019). Distribution and health risk assessment of arsenic and selected heavy metals in Groundwater of Chandigarh, India. *Environmental Pollution*, 250, 820–830. https://doi.org/10.1016/j.envpol.2019.03.080.

Ruppen, D., Runnalls, J., Tshimanga, R. M., Wehrli, B., & Odermatt, D. (2023). Optical remote sensing of large-scale water pollution in Angola and DR Congo caused by the Catoca mine tailings spill. *International Journal of Applied Earth Observation and Geoinformation*, 118, 103237. https://doi.org/10.1016/j.jag.2023.103237.

Sable, H., Singh, V., Kumar, V., Roy, A., Pandit, S., Kaur, K., ... & Malik, S. (2024). Toxicological and bioremediation profiling of nonessential heavy metals (mercury, chromium, cadmium, aluminium) and their impact on human health: A review. *Toxicologie Analytique et Clinique*, 36(3), 205–234. https://doi.org/10.1016/j.toxac.2024.03.096.

Sawadogo, Y. Z., Bambara, T. L., Zongo, I., Kaboré, K., & Zougmoré, F. (2023). Pollution and ecological risk assessment of heavy metals in the agricultural soils around a gold mine in BISSA Village, Burkina-Faso. *Journal of Environment Pollution and Human Health*, 11(3), 51–59. https://doi.org/10.12691/jephh-11-3-1.

Ujah, I. I., Achikanu, C. E., Nsude, C. A., & Okpako, I. O. (2020). Bioaccumulation of Lead, Copper and Antimony in Freshwater Fishes Caught from Onitsha Segment of the River Niger, Anambra State, Nigeria. J Public Health Dis Prev, 2, 205. Available: https://www.scholarena.com/article/Bioaccumulation-of-Lead-Copper-and-Antimony-in-Freshwater-Fishes-Caught-from-Onitsha-Segment-of-the-River-Niger-%20Anambra-State-Nigeria.pdf.

Umeoguaju, F. U., Akaninwor, J. O., Essien, E. B., & Amadi, B. A. (2022). Heavy metal profile of surface and ground water samples from the Niger Delta region of Nigeria: a systematic review and meta-analysis. *Environmental Monitoring and Assessment*, 194(1), 46. https://doi.org/10.1007/s10661-021-09688-6.

US Environmental Protection Agency (EPA US). (1996). Method 1669: Sampling ambient water for trace metals at EPA water quality criteria levels.

Van Rooyen, D., Erasmus, J. H., Gerber, R., Nachev, M., Sures, B., Wepener, V., & Smit, N. J. (2023). Bioaccumulation and trophic transfer of total mercury through the aquatic food webs of an African sub-tropical wetland system. *Science of the Total Environment*, 889, 164210. https://doi.org/10.1016/j.scitotenv.2023.164210.

WHO. (2017). Guidelines for drinking-water quality, 4th edition, incorporating the 1st addendum. ISBN: 978-92-4-154995-0. 631 p. Available: https://www.who.int/publications/i/item/9789241549950.

WHO. (2023). Global water, sanitation and hygiene: Annual report 2022. Available: https://www.who.int/publications/i/item/9789240076297.