Chapter

Occurrences of Cadmium, Arsenic, Lead, and Mercury in Potable Water in Greater Gaborone, Botswana: Implications for Public Health

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Abstract

Heavy metals, such as cadmium (Cd), arsenic (As), lead (Pb), and mercury (Hg), are often detected in water, causing detrimental effects to human health. This study assessed Cd, As, Pb, and Hg concentrations in drinking water from the greater Gaborone water distribution system supply area. The Inductively Coupled Plasma—Mass spectrometry was used to analyze 200 water samples from water treatment reservoirs, the distribution line, households, and bottled water. Heavy metal pollution was calculated using the heavy metal pollution index (HPI). Average heavy metal concentrations were in the order of Pb > Hg > As > Cd in the overall study, with lead exceeding the permissible limit set by the United States Environmental Protection Agency (US-EPA) in all the samples. Average lead concentrations from indoor taps were 15 times more than untreated raw water. HPI values were respectively 33.2 and 0.74 for the World Health Organization (WHO) and Botswana Bureau of Standards (BOBS). An increase in heavy metal concentrations post-water treatment suggests inadequate system maintenance and possible contamination of water during the distribution system from copper and lead soldered pipes. Further research on the treatment infrastructure and plumbing activities is suggested.

Keywords: drinking water, bottled water, lead, heavy metal leaching, Botswana, public health

1. Introduction

Heavy metals are defined as naturally occurring cations having atomic number (Z) greater than 20 g/cm^3 and an elemental density greater than 5 g/cm^3 [1]. Their

unintended use in industrial, domestic, agricultural, medical, and technological applications has led to their wide distribution in the environment, and this has generated concerns over their detrimental effects on human health and the environment [2]. International organizations, such as the World Health Organization (WHO) and the United States Environmental Protection Agency (U.S-EPA), have set regulatory standards on permissible concentration levels of heavy metals in dietary constituents, such as drinking water [2, 3]. Beside existing in elemental forms, toxic metals, such as cadmium (Cd), arsenic (As), lead (Pb), and mercury (Hg), are also found as mixtures in various parts of the ecosystem [4]. Drinking water and other dietary constituents are considered as the main entry points of heavy metals into the human food chain [5, 6]. Other sources, although negligible, include pharmaceuticals and human care products and their metabolites.

Even at low doses, these metals accumulate in the body, causing detrimental health effects [7]. Cd, As, Pb, and Hg, referred to as CALM in this chapter, are closely linked to hypertension, neurological disorders, cognitive impairments, cerebral palsy, blindness, dysarthria, cancers, cirrhosis, and hyperkeratosis [8–12]. These metals, albeit in excessive concentrations and exposure, have no known health benefits in human physiology and are thus considered toxicants [13, 14]. Further, accumulation of CALM in the body may lead to a steady reduction in intelligence quotient (I.Q.) an acute reduction in mental concentration span, and have been linked to behavioral delinquency and violence [15, 16].

Due to limited technical and economic capacities, the bulk of developing countries, especially in sub-Saharan Africa, are incapable of monitoring human exposure to heavy metals in drinking water [5]. Botswana, a middle-income country, is not spared from these technical challenges. Until now, water authorities have placed emphasis on the microbiological quality of drinking water [17].

The aim of this study was to determine concentrations of the CALM cations (As, Cd, Pb, and Hg) in drinking water in the greater Gaborone area (**Figure 1**). In addition, the study evaluated the contribution of household plumbing and piping systems to the overall concentrations of CALM cations in drinking water.

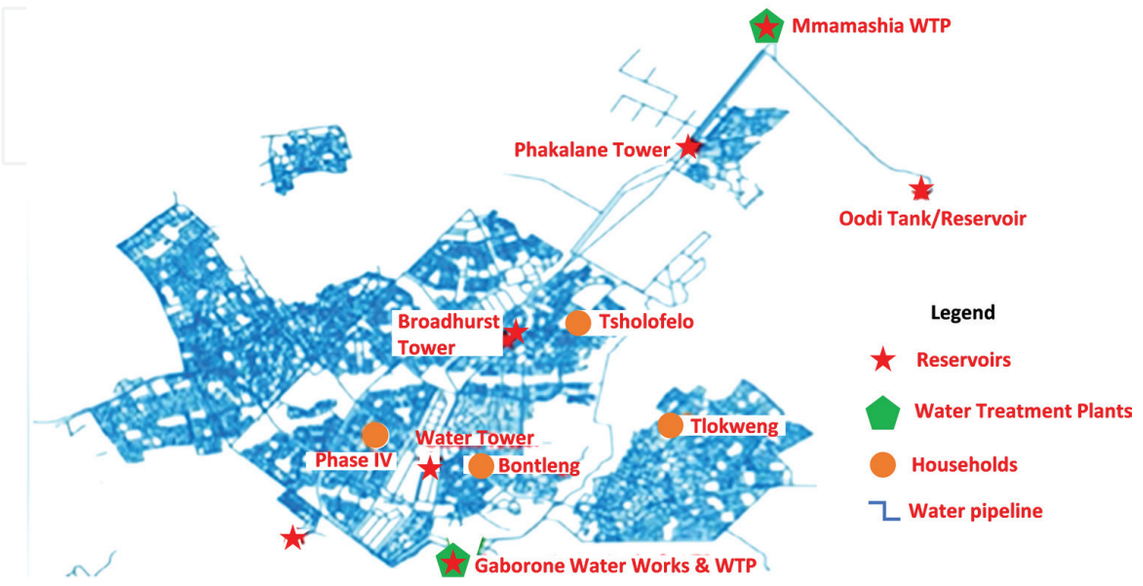

Figure 1.
Gaborone drinking water distribution system map showing sampling sites.

2. Occurrence, exposure to cadmium, arsenic, Lead, and mercury (CALM)

2.1 Heavy metals

Heavy metals, such as CALM, have received attention as both environmental contaminants and potential toxicological hazards due to their ubiquitous distribution in the environment. Although they are normally present in the environment at ultralow concentrations (e.g., ng/L–μg/L), they have the tendency to bio-accumulate in the different environmental compartments (e.g., soil, water, air), including body tissues and organs [18]. For instance, these toxicants affect the chemical synaptic transmission in the brain and the peripheral and central nervous system [19, 20]. CALM cations are known to disrupt the brain functioning system and may interfere with the cellular calcium (Ca) levels, leading to severe impairment of many body functions and metabolic pathways. Similarly, the interference with Ca levels in the brain often leads to the impairment of cognitive development and, in extreme cases, degenerative central nervous system (CNS) diseases [19, 20]. Toxic metals have also been found to affect cellular transfer and levels of other important minerals and nutrients that have significant neurological and health effects such as magnesium (Mg), lithium (Li), zinc (Zn), iron (Fe), and vitamins B-6 & B1-12 [19, 21]. Against this background, heavy metals, particularly the CALM species, must be monitored in dietary constituents, especially in drinking water.

2.2 Cadmium

Cadmium (Cd) occurs naturally in ores together with zinc (Zn), lead (Pb), and copper (Cu). Cd-containing products and waste are rarely recycled, but frequently dumped together with other household waste, contaminating the environment caused by leaching residual Cd, especially if the waste is incinerated [22]. Natural and anthropogenic sources of Cd, which may include industrial and landfill emissions, application of Cd-bearing fertilizers and Cd-containing sewage sludge and/or biosolids to farmland, may lead to contamination of soils and groundwater and, in severe instances, promote Cd uptake by farm crops intended for human consumption [23]. Food is, so far, the most identified route of exposure to humanity [24]. It is present in most foodstuffs, but concentrations vary considerably, and individual intake also varies considerably due to the differences in dietary habits [25]. For instance, women have lower daily Cd intakes because of comparatively lower energy consumption and/or requirements than men.

Gastrointestinal absorption of Cd may be influenced by nutritional factors, such as iron (Fe) levels in the body [26]. Therefore, exposure to Cd may cause kidney damage [25]. In contrast, long-term exposure may cause skeletal damage, as first reported in Japan, where the itai-itai (ouch-ouch) disease (i.e., a combination of osteomalacia and osteoporosis) was discovered in the 1950s [27]. In recent years, new data have emerged suggesting that even low Cd exposure may also result in skeletal damage as well. Such conditions are evidenced and characterized by low bone mineral density (osteoporosis) and vulnerability to fractures [28]. Until recently, the International Agency for Research on Cancer (IARC) classified and included Cd in a list of human carcinogens (group I) [10–12].

Although sources of Cd pollution in drinking water are widespread, several other pollution routes are emerging such as from corrosion of old-generation galvanized pipes, erosion of natural deposits, discharge from metal refineries, and from waste batteries and paints.

2.3 Arsenic

Arsenic (As) is a widely distributed metalloid occurring in rocks, soils, water, and air [29, 30]. It occurs naturally in three forms: organic, inorganic, and arsine gas. The inorganic form is highly soluble in water (i.e., hydrophilic), and this explains its presence and persistence in several water bodies, predominantly in groundwater as previously discovered in As-impacted terrains such as in Bangladesh, Canada, China, and Japan [31]. The main toxic As forms found in water are the tri- and pentavalent inorganic forms: arsenite (As^{3+}) and arsenate (As^{5+}), with As^{5+} being comparatively toxic. The implication is that overreliance on groundwater abstraction for potable water, as is the case in developing countries such as Botswana, may constitute a health risk unless otherwise cleared of As contamination.

Regarding organic As (i.e., organoarsenic species), several As-bearing organic compounds have been identified, such as trimethylarsine, arsenobetaine, arsenocholine, etc. and are of varying toxicity. For example, arsenobetaine and arsenocholine are found in most seafood and fish. They are of no known toxicologic relevance because they are not fully metabolized in the body but excreted as intact species [32]. Arsenic toxicity is related to its within-body metabolism and bioaccumulation in the blood and tissues [31]. This explains why the primary route of exposure is ingesting contaminated potable water and food [33]. Beside ingestion, other potential routes of exposure include inhalation of contaminated air (i.e., atmospheric pollution from gaseous As emissions), smelting of nonferrous metals, and producing energy from fossil fuel. So far, smelting activities are the largest single anthropogenic source of atmospheric pollution [34], as has been a health concern in Selibe Phikwe, Botswana, regarding the recently decommissioned Cu-Ni smelter.

As is undoubtedly a systemic toxicant known to cause cardiovascular diseases, neurological disorders, diabetes, gastrointestinal, and renal disorders. Moreover, chronic As exposure has been associated with various cancers (bladder, kidney, skin, and liver) [10–12]. The adverse health effects are related to the speciation of As, where inorganic arsenic is more toxic than organic arsenic. Inorganic arsenic is acutely toxic, and intake of large quantities leads to gastrointestinal symptoms, severe cardiovascular and central nervous system disturbances, and eventually death. In survivors, bone marrow depression, hemolysis, hepatomegaly, melanosis, polyneuropathy, and encephalopathy are widespread [33]. Populations exposed to As impacted drinking water are at risk of lung, bladder, and kidney cancer mortality, with risk directly proportional to exposure [35]. Skin cancer and other skin lesions, such as hyperkeratosis and pigmentation changes, are also a health concern [36, 37]. More recently, evaluations of as exposure from drinking water have been linked to cancer of the lungs, kidney, bladder, and skin, and in all these cases, there were observable and identifiable precancerous lesions [33].

2.4 Lead

Lead (Pb), occurring in various concentrations in rocks and soils, is one of the most pervasive and persistent heavy metals posing threats to the environment, soil quality, and human health [38, 39]. In the environment, Pb occurs naturally and from human activities such as mining, smelting, production, processing, recycling, waste disposal activities, and emissions from auto exhausts [40]. Six major environmental exposure sources of Pb include leaded paint, leaded petrol, stationary sources, dust/soil, food, and water [41]. In drinking water, the common contamination sources include corrosion of household plumbing systems and erosion of natural deposits [2, 42].

There is consensus in scientific and medical literature that the primary route of exposure to Pb in children is oral ingestion of Pb-based paint and Pb-contaminated dust and soil. For adults, the primary route of exposure is inhalation of Pb-containing dust and fumes from occupational settings. Pb-contaminated soils are a recognized exposure source for humans. Pb can enter the human body through inhalation [43], geophagia [44], and through skin lesions [45]. Pb in water is another important pathway for exposure, particularly in developing countries, where regulations on Pb containing plumbing materials are limited or nonexistent. At the household level, the sources of Pb contamination are corrosion of household plumbing systems and erosion of natural deposits. As a result, Pb levels in drinking water can vary from one homestead to another due to the variations in plumbing infrastructure [46, 47]. Pb in drinking water is efficiently absorbed by the body compared to other sources. This was confirmed by a study by Heard and others (1983), who found that 40–50% of radioactive Pb is retained and absorbed by the dermal tissues and/or skin [48].

Some short-term effects of exposure to Pb, either through drinking water or any other route of exposure, include persistent fatigue, irritability, temporary loss of appetite, stomach discomfort and/or constipation, reduced attention span, and insomnia [49]. Pb is a neurotoxin; therefore, its main target is the CNS, as observed in adults and children [50] and evidenced by the symptomatic loss of motor coordination, especially in fingers, wrists, and ankles. Other known health effects are that it promotes the onset of anemia due to its strong affinity for the hemoglobin protein in which it readily replaces Fe in the binding sites of the hemoglobin protein inside the red blood cells [51]. The resulting phenomenon of Fe replacement is the elevated levels of blood lead levels [51] and the onset of anemic conditions [49]. Its effects on the excretory system are evidenced by severe damage of the nephron functional units, resulting in renal and/or kidney failure. It also impedes the normal functioning of the reproductive system, as shown by high miscarriage cases among pregnant women. Similarly, it impairs the normal function of sperm production in males [50].

2.5 Mercury

Mercury is a ubiquitous heavy metal that exists in organic, inorganic, and elemental forms, and the general population is exposed through ingestion and inhalation of Hg-contaminated food, air, and water [14, 52]. Drinking water sources are contaminated by mercury through erosion of natural deposits, discharge from refineries and factories, and runoff from landfills and croplands [52].

Exposure to organic mercury (MeHg) is associated with adverse effects, particularly in children exposed in utero [53]. Other effects include mental retardation and cerebral palsy [54–56]. Acute mercury exposure may give rise to lung damage [57]. Chronic Hg poisoning is characterized by neurological and psychological symptoms, such as tremors, changes in personality, restlessness, anxiety, sleep disturbance, and depression [58]. Metallic mercury may cause kidney damage [59]. Methyl mercury poisoning has a latency of 1 month or longer after acute exposure, and the main symptoms relate to nervous system damage [60, 61].

3. Limits of CALM for drinking water by U.S-EPA, WHO, BOBS

To provide guidance in resolving the contamination of drinking water by microorganisms and heavy metals, WHO has developed guidelines and water safety plans

	Maximum contamination level (MCL) (μg/L)		
Heavy metal	**BOBS**	**WHO**	**US EPA**
Cd	3	3	5
As	10	10	10
Pb	10	10	0
Hg	1	6	2

Table 1.
Permissible limits of CALM in drinking water as prescribed by USEPA, WHO, and BOBS [2, 3, 62].

for drinking water quality [2]. The guidelines highlight that the proposed permissible threshold values are designated as provisional, given the practical difficulties of treating drinking water up to these required standards [2]. However, water authorities are encouraged to make an effort to maintain pollutants' concentrations below the guideline values.

Table 1 summarizes the maximum contamination level (MCL) for Cd, As, Pb, and Hg as proposed by BOBS, WHO, and the US EPA [2, 3, 63]. Control measures, such as pre-treatment, coagulation, flocculation, sedimentation, filtration, and disinfection, are highlighted as crucial steps during drinking water treatment processes [2, 64]. The piping system of the treatment plant and of the distribution network must be taken into consideration to avoid the unintended input of residual heavy metals through corrosion and leaching of plumbing networks. Proper maintenance and regulation or survey procedures of the treatment plant to prevent contamination help in determining the presence of unwanted HMs and the eventual removal of internal accumulation of deposits.

4. Materials and methods

4.1 Study area

Gaborone is Botswana's capital and largest city with a population of 231,626 based on the 2011 census, which is about 10% of the total population of Botswana. The city is supplied by raw water from Gaborone, Bokaa, Letsibogo, and Dikgatlhong dams. Raw water from the northern part of the country (Letsibogo and Dikgatlhong dams) is transported *via* the north-south carrier pipeline and undergoes treatment at different water treatment plants before it is eventually distributed to the existing distribution network.

4.2 Sampling

Figure 1 shows the Gaborone drinking water distribution system map and sampling sites. Sample collection and analysis procedures were performed in accordance with quality assurance measures prescribed by the Council for Scientific and Industrial Research (CSIR) Environmental Laboratory (Method No. CMP33).

The method was validated using conventional analytical parameters, such as linearity, limit of detections (LODs), and spike and recovery experimentation. In all instances, field and method blanks were assayed to assess potential cross-contamination.

Samples were collected in 50 mL precleaned polyethylene bottles and spiked with ~3 drops of 50% HNO_3 (1:1, HNO_3, v/v). Water samples were collected from the different stages of the drinking water supply chain, which included (i) raw untreated water reservoir tanks, (ii) treated water reservoir tanks, (iii) household outdoor taps representing the end of the distribution line (**Figure 2b**), and (iv) indoor drinking water taps (**Figure 2a**). In all instances, samples were collected in triplicates. Sample collection times were during the morning, peak usage, and midday to represent low to moderate usage. Temperature, pH, and total dissolved solids (TDS) were measured immediately after sampling using a pre-calibrated multimeter capable of measuring these parameters to the required accuracy. In each instance, samples were collected without flushing taps first [65]. The samples were preserved at ~4°C in an insulated cooler box and transported to the lab for processing. **Figure 2** exemplifies the sample collection process.

4.3 Sample preparation and instrumental analysis procedures

All reagents and chemicals used in this study were of analytical grade (Argon 99.999% purity, HNO_3 Analytical Grade). Samples were filtered to remove suspended solids and improve turbidity using glass membrane filters (Whatman™ 0.45 μm pore size), digested using microwave digestion method, and subsequently assayed using the inductively-coupled plasma mass spectrometer (ICP-MS, Agilent™ 7900). Microwave digestion entailed adding 2.5 mL of concentrated HNO_3 to 50 mL aliquots of samples and method blanks and digesting at 170°C for 30 min. The ICP-MS was optimized for the best sensitivity according to the standard operating procedure

Figure 2.
Drinking water sample collected from (a) indoor household tap and (b) outdoor tap.

detailed in the CMP33 method [66]. Calibration standards in the range 1 to 500 μg/L were prepared daily by appropriate dilution of the 1000 mg/L standards containing target analytes, and this includes quality control samples. To ensure accuracy and eliminate human error, a calibrated Hamilton auto-diluter was used for all dilutions.

4.4 Heavy metal pollution index

To determine the overall water quality of drinking water in the distribution system, a heavy metal pollution index (HPI) was determined using Eqs. (1) and (2) [67]. In this study, metals considered in the HPI index calculation included Cd, As, Pb, and Hg.

$$HPI = \sum_{i=1}^{n} W_i Q_i \tag{1}$$

Where W_i is the weighting factor of the ith metal and is a value ranging between zero and one, and Qi is the sub-index of ith parameter and is determined

$$Q_i = \sum_{i=1}^{n} \frac{M_i - I_i}{S_i - I_i} n \times 100 \tag{2}$$

Where;

M_i is the analyzed result of the ith parameter in μg/L, S_i is the permissible limit value given in the standard for the i^{th} parameter, and I_i is the ideal value of the ith parameter. The n in both equations denotes the number of heavy metal parameters considered in the study, $n = 4$.

5. Ethical considerations

Permission to conduct the study was sought from the University of Botswana Institutional Review Board and the Ministry of Health. Written Informed consent was obtained from all household owners and the Water Utilities Corporation.

6. Results and discussion

6.1 Water sample collection sources

A total of 200 water samples were collected from different water sources ranging from raw untreated water to indoor household tap water (**Figure 3**). The majority of water samples were from outdoor household tap water (48%) followed by indoor household tap water (43%). In contrast, raw water was collected from three reservoir tanks, accounting for 2% of the total samples collected; similarly, commercial bottled water comprised 4% of the total samples.

6.2 Evaluation of physicochemical parameters

The measured values of pH, temperature, and total dissolved solids (TDS) were all within the recommended limits in this study. Our results showed an overall mean pH of 7.93 ± 0.29, against a pH = 8 or less as recommended by WHO (2020). Similarly, the

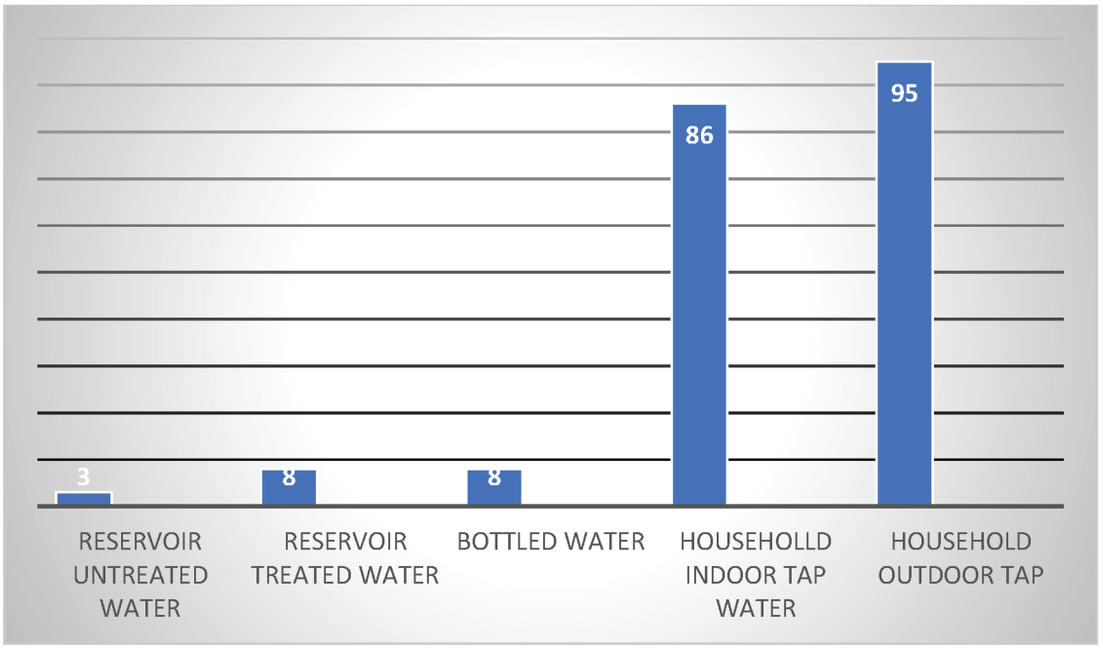

Figure 3.
A bar chart depicting sample collection sources. The numbers within each bar represent the actual individual samples collected at each point.

US EPA recommends a pH level of between 6.5 and 8.5 in drinking water for public consumption [3]. This is in agreement with the WHO [2]. A pH lower than 6.5 is considered acidic and likely to be corrosive. While pH generally has no direct impact on consumers health, it is among the most important water quality parameters for consideration at all stages of water treatment because low pH levels readily ionize cations and make them available and vice versa in that at high pH (basic conditions) cations are bound to organic complexes, and therefore unavailable. Therefore, pH is a necessary parameter during water treatment and plays a critical role in releasing heavy metals *via* oxidative processes such as corrosion [62].

A slight increase in pH was observed in samples collected in the afternoon (7.97 ± 0.17) compared to the morning (7.94 ± 0.20). This may be associated with the increase in water temperature from 27.0 (±2.2) in the morning to 29.5 (±2.1) in the afternoon. It has been shown that as water temperature increases and pH also increases [2, 68]. These values were within the permissible limits set by the US EPA, ranging from 6.5 to 10.5 [69]. Further, WHO (2022), advises close monitoring of the pH of water entering the distribution system to minimize the corrosion of water mains and pipes in household water distribution systems as nonadherence to such may result in the contamination of drinking water and the deterioration of taste, odor, and turbidity [2].

Similarly, TDS is among the most significant factors in giving water an acceptable taste, as well as in providing important elements such as calcium (Ca), magnesium (Mg), and potassium (K) [3]. The US EPA and WHO recommend a TDS of less than 500 and 600 mg/L, respectively. The overall mean TDS measured in this study complied with the threshold values above. For example, a mean TDS of 111.3 (±28.6) mg/L was measured for samples collected in the morning and 112.7 (±5.5) mg/L for samples collected in the afternoon. High TDS levels have been blamed for the accumulation of C.A. and Mg scales in water boilers and heaters.

Mittal et al. (2017) found that TDS in groundwater samples ranged from 535 to 2460 mg/L with a mean value of 1192.5 mg/L [70]. The study further showed that the

lower the TDS, the lower the radioactivity value, and this was proven by positive correlation of TDS with heavy metals. There was no direct impact of TDS on the human body except that it leads to hard water, salty taste, and films on fixtures leaving deposits, eventually leading to corrosiveness, which, in turn, results in the leaching of heavy metals in drinking water [70, 71].

6.3 Heavy metal concentrations

To the best of our knowledge, this is the first study to assess the HM concentrations (in particular the CALM cations) in drinking water in Botswana. For instance, Smith and others (1994) conducted a water quality study in Gantsi Township, Botswana, but overlooked to evaluate the occurrence of Cd, As, Pb, and Hg in drinking water [72]. The same concern is corroborated by the Botswana Water Statistics Report (2009), which observed that none of the water authorities in Botswana have tested or reported concentrations of CALM [17]. This is despite the national regulations governing drinking water quality specifications enforced by the BOBS [63]. It is, therefore, a pressing need to establish the concentrations of CALM in drinking water in Botswana.

The results obtained in the present study generally complied with the heavy metal (HM) standards set by WHO and BOBS [2, 63]. However, Pb concentrations exceeded the permissible limit set by US-EPA. Generally, the average concentrations showed the order of abundance as Pb > Hg > As>Cd. Furthermore, it was observed that raw water samples measured concentration levels lower than the after-treatment samples except for arsenic (As). In addition, the results showed an upward offset of ~93% in the concentration levels of lead (Pb), particularly in treated water (i.e., indoor household water) compared to untreated water (i.e., raw water) (**Table 2**), partially indicating a possibility of an input source after treatment. This could be ascribed to the residual leaching of HMs (especially lead) from household-level piping and plumbing.

Table 2 shows that while Cd was not detected in raw water, it was detected after water treatment, in outdoor household taps (representing input from the distribution line), and in indoor household taps. The concentrations were in the order of raw water < after treatment < distribution < households. The mean concentration of Cd in all the locations was less than the permissible limit set by US-EPA, WHO, and BOBS, with the overall mean (±SD) of 0.005 (±0.02) μg/L and 0.003 (±0.01) μg/L for indoor and outdoor concentration, respectively. The slightly higher concentrations

Parameter	Bottled water	Raw water	After treatment	Outdoor/ Distribution	Indoor/ Households
Cd	ND	ND	0.005 (±0.008)	0.003 (±0.01)	0.005 (±0.02)
As	0.16 ± 0.03	0.28 (±0.14)	0.18 (±0.03)	0.20 (±0.06)	0.23 (±0.05)
Pb	Nd	0.08 (±0.02)	0.57 (±0.47)	1.10 (±1.45)	1.19 (±1.25)
Hg	0.24 ± 0.06	0.24 (±0.9)	0.28 (±0.14)	0.19 (±0.17)	0.18 (±0.14)

Table 2.
Mean (±Standard Deviation) in μg/L of heavy metals in bottled, reservoirs, and households.

from indoor taps could be due to the reasons alluded to above, as well as impurities in the zinc of galvanized pipes and some metal fittings [73]. In comparison to other countries, such as Canada, concentrations in our study were lower compared to the mean of 0.044 μg/L [74]. Similarly, a survey carried out in Malaysia found Cd concentrations from household tap water was high, the contamination of which was associated with indoor plumbing material. This could also be a possible explanation in our study, where the concentrations of Cd and Pb are higher in indoor tap water than in raw water [75].

Whilst Cd levels in water were within acceptable water quality standards, recent environmental investigations on Cd have demonstrated that prolonged and low-level exposure to Cd is a risk factor for adverse effects to many organs and systems such as kidneys, liver failure, skeletal system, certain cancers, and the cardiovascular system including hearing loss [10–12, 76].

The levels of arsenic in raw water fell within the expected levels in natural waters at concentrations of less than 1–2 μg/L [3]. Arsenic concentrations were highest in raw water (0.28 ± SD:0.14) μg/L, with a reduction after treatment (0.18 ± SD:0.03 μg/L), during distribution (0.20 ± SD:0.06 μg/L) and indoor household taps (0.23 ± SD:0.05) μg/L. These levels fell within the current recommended limit of 10 μg/L in drinking water [3]. Contamination of drinking water from reservoirs by As might be due to paint, fertilizers, pesticide and pharmaceutical industries, and agricultural activities [77]. However, the indoor As concentration was still higher than the distribution line concentration at 0.23 ± 0.05 μg/L. A metalloid widely spread in rocks, soil, water, and air is usually ubiquitous in the environment, leading to high human exposure [78]. The contamination of drinking water from taps might be due to leaching from water distribution pipes and corrosion of plumbing systems 79).

Table 2 shows that Pb concentrations increased by 612.5% between raw water (0.08 ± [SD:0.02]) and after treatment (0.57 ± [SD:0.47]). This is indicative of contamination of water from the treatment plant. A 93% increase in lead concentration was detected between after-treatment and outdoor household tap water (distribution line) and an 8.2% increase between the outdoor and the indoor fixture. Among the heavy metals studied in New South Wales, Australia, almost 56% of 212 samples contained Pb, which exceeded the Australian Drinking Water Guidelines (ADWG) by 8% [79].

Our study showed that the mean concentration of Pb exceeded the set standards by U.S-Environmental Protection Agency of 0 μg/L. **Table 3** shows that the highest mean Pb concentrations were in Mogoditshane village (1.938 ± 1.587 μg/L) followed by Phase IV (1.874 ± 2.189 μg/L) and Tlokweng (1.802 ± 1.413 μg/L) with the lowest at Bontleng 0.445 ± 0.379 μg/L. The overall Pb mean concentration for indoor and outdoor water in all locations was 1.185 ± 1.254 μg/L and 1.096 ± 1.1451 μg/L, respectively.

The variability of lead concentrations from the different locations (**Table 2**) could be attributed to several factors, including the type of material used for plumbing, the age of the plumbing system, water flow rate, and standing time of the water at the time of sample collection [5, 80]. Investigations have shown that the newer the home, the greater the risk of lead contamination [81]. New homes fitted with soldered copper piping connections are estimated to release as much 210–390 μg/L of Pb that could cause intoxication, particularly in children [82]. Even though Pb can be leached from piping systems indefinitely, the leaching from soldered joints and brass taps may decrease with time. As buildings age, mineral deposits form a coating on the pipes' inside, reducing the leaching of Pb from soldered joints. These factors could have caused the variability on lead and other heavy metal concentrations from different locations. **Table 4** shows the different plumbing materials that households

Locations	Measured concentration levels in µg/L							
	Cd		As		Pb		Hg	
	Indoor	**Outdoor**	**Indoor**	**Outdoor**	**Indoor**	**Outdoor**	**Indoor**	**Outdoor**
Village	0.003 ± 0.01	0.003 ± 0.05	0.196 ± 0.02	0.182 ± 0.01	0.548 ± 0.52	0.965 ± 0.86	0.185 ± 0.14	0.267 ± 0.33
Naledi	0.00 ± 0.00	0.00 ± 0.00	0.235 ± 0.04	0.167 ± 0.05	0.805 ± 0.28	0.599 ± 1.35	0.285 ± 0.01	0.178 ± 0.19
Tsholofelo	0.00 ± 0.00	0.001 ± 0.01	0.187 ± 0.02	0.190 ± 0.07	0.894 ± 1.56	0.554 ± 0.35	0.149 ± 0.06	0.139 ± 0.04
Block 6	0.003 ± 0.06	0.001 ± 0.01	0.252 ± 0.03	0.268 ± 0.26	0.658 ± 0.75	0.897 ± 0.60	0.122 ± 0.04	0.154 ± 0.06
Mogodi	0.003 ± 0.01	0.002 ± 0.01	0.251 ± 0.30	0.262 ± 0.08	2.081 ± 1.64	1.478 ± 1.45	0.241 ± 0.25	0.334 ± 0.46
Maruapula	0.019 ± 0.05	0.018 ± 0.04	0.196 ± 0.07	0.247 ± 0.05	1.265 ± 1.15	1.629 ± 1.29	0.139 ± 0.053	0.116 ± 0.02
Bontleng	0.010 ± 0.05	0.001 ± 0.01	0.150 ± 0.01	0.158 ± 0.04	0.900 ± 0.01	0421 ± 0.37	0.240 ± 0.01	0.229 ± 0.15
Phase IV	0.001 ± 0.003	0.003 ± 0.005	0.246 ± 0.02	0.272 ± 0.08	0.916 ± 0.65	4.110 ± 2.92	0.203 ± 0.11	0.187 ± 0.03
Tlokweng	0.01 ± 0.010	0.005 ± 0.007	0.236 ± 0.76	0.221 ± 0.03	1.882 ± 1.64	1.730 ± 1.26	0.160 ± 0.80	0.209 ± 0.09
Total	0.005 ± 0.020	0.003 ± 0.012	0.226 ± 0.05	0.205 ± 0.06	1.185 ± 1.25	1.096 ± 1.45	0.181 ± 0.14	0.192 ± 0.17

Table 3.
Mean ± standard deviation of heavy metals by location.

Material	Cd (μg/L)	As (μg/L)	Pb (μg/L)	Hg (μg/L)
Chlorinated polyvinylchloride (CPVC)	0.01 ± 0.03	0.22 ± 0.55	1.14 ± 1.38	0.18 ± 0.19
Galvanized steel	0.01 ± 0.02	0.21 ± 0.05	1.18 ± 1.37	0.18 ± 0.11
Copper and copper-based alloys	0.01 ± 0.03	0.23 ± 0.07	1.40 ± 1.62	0.17 ± 0.15

Table 4.
Mean ± standard deviation of heavy metal concentrations by type of plumbing materials used in households.

use. Copper and copper-based alloys had the highest mean Pb concentrations (1.40 ± 1.62 μg/L) followed by and galvanized steel fittings (1.18 ± 1.37 μg/L).

Pb is a harmful metal that can affect the nervous system, weaken the fingers, wrists, and ankles and may lead to high blood pressure and mental illness due to brain damage. According to Mohod and Dhote (2013), Pb can lead to serious biochemical effects and interference with heme synthesis, leading to hemoglobin disorder [64]. According to WHO (2022), even though the set standard is 10 μg/L, this is no longer a health-based guideline value because Pb has no threshold for critical health effects [2]. WHO further emphasizes that the Pb concentrations should be maintained as low as reasonably practical since lead is highly toxic to the human body even at a deficient concentration.

Triantafyllidou and Edwards (2012) concluded that the alloys that contain lead and are used for plumbing, fittings, and soldering are a source of contamination in household taps [83]. This is corroborated by WHO (2022), emphasizing that Pb corrodes more rapidly when it is coupled to copper (Cu) and that the rate of galvanic corrosion is faster than that of simple oxidative corrosion [73]. The Cu lining may result in general corrosion, impingement attack, and pipping corrosion. Galvanized pipes are the significant sources of zinc that can leach Cd and Pb in drinking water. This corrosion typically occurs when galvanized steel or iron piping is connected to inappropriate materials, such as brass in taps and fittings [73].

In this study, only mercury was highest (0.24 ± 0.9 μg/L) in raw water compared to indoor household tap water (0.18 ± 0.14 μg/L). Mercury concentrations from the indoor households' taps had lower mean concentration as compared to the outdoor/distribution water line: 0.181 ± 0.138 and 0.192 ± 0.172 μg/L, respectively but lower than the permissible limit by US-EPA, WHO, and BOBS. Mogoditshane (0.263 ± 0.302 μg/L) had the highest mean concentration of Hg of any other location, with the lowest at Maruapula (0.129 ± 0.043 μg/L). A study evaluating the concentration of mercury, zinc, arsenic, lead, and cobalt in the Ilam city water supply network showed mercury levels ranging from 0.605 ± 0.1938 μg/L to 2.15 ± 0.0233 μg/L [84]. Global occurrence of potable water HM contamination has variably affected developed and developing countries [85].

None of the bottled water contained Pb and Cd. However, Hg (0.24 ± 0.06 μg/L) and As (0.15 ± 0.020 μg/L) were detected. These levels were less than the permissible limit by the US-EPA, WHO, and BOBS. Compared with research from elsewhere, the results obtained in Nigeria showed that in all the bottled water, Pb was found to be lower than the permissible limits by WHO and BOBs (10 μg/L) [86]. Whilst Pb was not detected in bottled water (**Table 2**) in our study, Hg was detected at slightly higher concentrations in bottled water than in tap water. Additionally, bottled water had slightly lower AS concentrations than indoor tap water. These findings are similar to other studies, which showed higher heavy metal concentrations in tap water compared to bottled water [87, 88]. A similar study carried out in Croatia showed that tap water contained higher levels of Cd, Cu, and Pb among others than bottled water [89].

The authors concluded that partial solubilization of the materials involved in the treatment, such as metal supply systems, tanks, pipes, valves, and pumps, were possible origins of the heavy metals. The low levels of heavy metals in bottled water could be due to filtration through multi-barrier filtration systems, reverse osmosis, and microfiltration. Other treatments may include exposure to ultraviolet light or ozonation. It is estimated that these methods remove up to 80% of H.M. [90]. This could explain bottled water's non-detection or low-level heavy metal content. Finally, the slight elevation of Hg in our bottled water results resembles those of other studies [87].

6.4 Analysis of the heavy metal pollution index

To determine the suitability of the drinking water, the heavy metal average concentration of outdoor and indoor tap water data obtained in **Table 3** were used to calculate the HPI index using Eq. (1) and (2). The WHO and BOBS standards were used to determine the appropriate HPI (**Tables 5** and **6**).

It is observed that the drinking water from the water distribution system has a heavy metal pollution index (HPI) of 0.74 (**Table 5**) according to the BOBS standards and 33.18 according to the WHO standards (**Table 6**). Therefore, the HPI of 0.74 indicates that the level of heavy metal pollution in the drinking water, as per the standards set by the Botswana Bureau of Standards (BOBS), is relatively low. BOBS might have established specific limits for heavy metal concentrations in drinking water. With an HPI of 0.74, the water appears to be within the acceptable range according to these

Water quality parameter	Maximum contamination level (MCL)	Monitored (M)	W_i	Q_i	W_iQ_i	HPI
Cd	3	0.004	0.333	−149.80	0.11	0.74
As	10	0.216	0.100	−24.47	0.01	
Pb	10	1.141	0.100	−9.85	0.01	
Hg	1	0.187	1.000	0.00	1	
Sum			0.333	−149.80	0.11	

Table 5.
Heavy metal pollution index (HPI) of drinking water from water distribution system (BOBS standards).

Water quality parameter	Maximum contamination level (MCL)	Monitored (M)	W_i	Q_i	W_iQ_i	HPI
Cd	3	0.004	0.333	−149.80	−49.93	33.18
As	10	0.216	0.020	−24.46	−0.489	
Pb	10	1.141	0.667	−9.85	−6.566	
Hg	6	0.187	0.167	105.69	17.614	
Sum			1.163	−78.43	−41.890	

Table 6.
Heavy metal pollution index (HPI) of drinking water from water distribution system (WHO Standards).

standards. However, the HPI of 33, as per the World Health Organization (WHO) standards, suggests a higher level of heavy metal pollution index. WHO has more stringent limits for heavy metal concentrations in drinking water, and the water in question seems to exceed these limits.

7. Conclusions

Our results show that drinking water from households, reservoirs, and bottled water was contaminated with heavy metals. The levels of heavy metals obtained were lower than the permissible limits set by the US-EPA, WHO, and BOBS, except for Pb, which has no safety threshold. Lead concentrations were higher than the US-EPA recommendations for households, treated, and untreated water, whereas bottled water contained no Pb. Whilst Pb is present in drinking water because of its dissolution from natural sources, the primary source at the household level is plumbing systems in which the pipes, solder, fittings, or service connections to homes contain lead. PVC pipes, largely used in Botswana, contain lead compounds that can be leached from them and result in high lead concentrations in drinking water. The pH values, temperature, and total dissolved solids (TDS) were all within the recommended limits in this study and, therefore, could not be attributed to the high Pb concentrations.

Whilst the levels of heavy metals were generally low in drinking water in this study, major concerns were observed on the increasing Pb concentrations after treatment and at the household level. Additionally, there is evidence from recent research that low-level mixtures of As + Pb and Cd + Pb can induce synergistic adverse effects [91]. These interactions could negatively affect public health and call for measures to reduce these contaminants.

The variability of heavy metals in drinking water from different locations, particularly Pb could be attributed to a combination of factors including the type of plumbing materials, age of fittings in the building, corrosion of these materials, specific water chemistry, galvanic corrosion between different metals, and the overall condition of the infrastructure. The amount of time the water was standing in the tap before use could have also facilitated Pb leaching. Low water pH can influence the extent of lead and increase corrosiveness; however, in this study, the pH was high enough not to influence piping corrosion. Cd and Pb were not detected in bottled water, suggesting bottled water is a safer drinking water alternative.

The water authorities should aim to reduce Pb in drinking water as it is harmful even if consumed at low concentrations. It is recommended that laws and policies guide industries, manufacturing companies, and other agricultural activities to discard waste accordingly to avoid water contamination. Monitoring the Greater Gaborone sources will also be necessary to ensure they follow lawful standards. The treatment plants should regularly monitor the plumbing materials as they contribute to heavy metals in drinking water through leaching and corrosion. The design of the plumbing system of new buildings should be approved and inspected by the regulatory body. Consumer awareness campaigns on safer plumbing materials and maintenance should be initiated.

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Conflict of interest

The authors declare no conflict of interest or delete this entire section.

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