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Concurrent Water Quality Assessment of Surface and Tap Water in Selected Communities in the Eastern Region of Ghana

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Abstract

The health of every individual depends on the availability of clean drinking water. The lack of potable drinking water, a resource essential for existence and development, is one of the most significant challenges of the twenty-first century. This study conducted an assessment of twelve trace and heavy metals in paired surface and tap water samples from eight communities in the Eastern Region of Ghana. Samples were collected weekly during the dry season (October-December 2025). The analysis of results revealed exceedances of WHO safe limits for Nickel (mean 0.162 mg/L) and Mercury (mean 0.002 mg/L), with localized rises of Lead and Manganese. Geospatial analysis indicated contamination hotspots associated with anthropogenic activities. One-way ANOVA confirmed significant statistical spatial variation ($p < 0.05$) in concentrations of Nickel, Chromium, Manganese, Copper, Calcium, and Magnesium across communities, indicating distinct local contamination sources. A Pearson correlation matrix revealed strong positive inter-elemental relationships between Nickel and Mercury ($r = 0.82$, $p < 0.001$), and Iron and Manganese ($r = 0.76$, $p < 0.001$), suggesting shared origins from artisanal small-scale gold mining and mineral weathering, respectively. While Arsenic, Cadmium, and Chromium were within permissible limits, the pervasive exceedance of Nickel and Mercury poses serious neurological, renal, and developmental health risks. These findings emphasize a gap between water access and safety, indicating weaknesses in the supply chain. This study revealed the need for integrated water safety plans in the region, moving beyond access to the implementation of rigorous catchment protection, enhanced treatment protocols, and infrastructure restoration to ensure genuine water safety.

Keywords

Concurrent Water Assessment, Heavy Metal Contamination, Source-to-Tap Analysis, Public Health Risks, Water Safety Planning

1. Introduction

Access to clean and safe drinking water is a fundamental human right, as water plays an important role in public health and human wellbeing (Uhlenbrook et al., 2019). In spite of the progress made under Sustainable Development Goal (SDG) 6, which is aimed at ensuring worldwide access to safe drinking water and sanitation by 2030, there exist communities that lack safe, clean water sources (Arora & Mishra, 2022). Water is considered an elixir for life since almost all human activities rely on the use of water (Appiah-Effah, Ahenkorah, Duku, & Nyarko, 2021; Mythrey, Nisargi Ramachandra, & Shreevathsa, 2012). At the domestic level, water is mostly consumed and used for general household chores such as cooking, washing, and bathing (Appiah-Effah et al., 2021; Crouch, Jacobs, & Speight, 2021).

Globally, approximately 2.1 to 2.2 billion people (1 in 4) lack access to safely managed drinking water. Although access to safe, clean water in Sub-Saharan Africa is progressing, the region remains the hardest hit, with about 387 to 411 million people still lacking access to basic drinking water (WHO & UNICEF, 2025). In Ghana, according to the 2021 Population and Housing Census, the total population was 30,832,019, a significant increase of 6.1 million from the 2010 census figure (Kwankye & Frempong-Ainguah, 2025; Ghana Statistical Service, 2021). The Water and Sanitation access report show that the primary sources of drinking water for households were: Sachet Water: 37.4% (main source nationally), Pipe-borne Water: 31.7%, Borehole/Tube well: 17.7%, Surface Water (rivers, streams, dams, canals, etc.): 6.4%, Protected Well/Spring: 3.1%, Bottled Water: 1.5%, Tanker Supply/Vendor: 0.6% and Rainwater: 0.5% (Ghana Statistical Service, 2021; 2022).

Even though enhanced water sources coverage has improved in Ghana, access to safe drinking water has been limited and has been identified as a challenge in the Eastern Region as it is considered to have one of the lowest coverage rate of approximately 56% for piped, treated, or safe water with rural areas relying heavily on untreated-piped sources, such as boreholes and protected wells (Ghana Statistical Service, 2021).

The use of unsafe water sources has been identified as the leading risk factor for infectious diseases such as diarrhoea, cholera, hepatitis A, dysentery, polio, and typhoid (Alijanzadeh Maliji, Babayeemehr, Rohani, Mehrabani, & Aghajanpour, 2023; Narania & Kaur, 2026; Thalia, 2024), as well as source contamination poses a threat to public health and the environment, especially in most developing countries (Quansah et al., 2025; Rajapakse, Otoo, & Danso, 2023). Also, this difficulty has been exacerbated in most communities in the Eastern Region, as a result of the presence of the vibrant agricultural sector, illegal artisanal Gold mining activities, and growing urban sprawl leading to severe pressures on water resources (Addai, Adjei, Eshun, Chemah, & Appiah, 2024; Asiama, 2019).

Surface water resources, such as the Afram, Densu, Pra, Birim, and Volta Lake, are the main sources for most rural and peri-urban populations but are deteriorating in quality (Agodzo, Bessah, & Nyatuame, 2023; Amengor, 2024). The degradation of these sources via heavy metals, including mercury, from mining of alluvial gold, has resulted in high water turbidity (Donkor, Ghoveisi, & Bonzongo, 2024a), as well as fertilizers, pesticides, and weedicides effluent runoff from agricultural fields (Rad, Ray, & Barghi, 2022; Soleimani et al., 2023).

Conversely, tap water, which is provided by the Ghana Water Company Limited (GWCL) from treated surface water, is not free from risks (Appiah-Effah et al., 2021; Siakwa, 2023), due to frequent and lengthy periods of interruption in the supply of treated piped water. Amid the difficulties of aged supply set-up, irregular water supplies leading to low pressures, access to contaminants through damaged pipelines, and occasional deficient plant-level treatment undermine the safety of the potable supply source (Boahen & Owusu, 2023; Manu, 2015). As such, many households rely on other sources of water, such as wells, boreholes, springs, and surface waters, which have been reported in Ghana to have high levels of Heavy metal contaminants and microbial loads (Acquah, Appiah-Brempong, & Anornu, 2025; Dorpe, 2022; Obiri-Danso, Adjei, Stanley, & Jones, 2009; Owusu, Ofori, Adusei-Mensah, Dodoo, & Essumang, 2024).

Previous studies on water quality assessment in the Eastern region generally were on single sources, either in isolated river bodies or piped-born water projects, independently. For instance, analyses of Heavy metal concentrations in surface water (Amengor, 2024; Ansah-Asare & Asante, 2000; Klu, 2015; Yirenkyi-Fianko & Ottou, 2024), and the efficiency of individual treatment works have been investigated (Adjibolosoo et al., 2018; Kulinkina et al., 2017).

At the moment, there is a lack of research on the parallel study of surface water resources to the associated tap water sources quality and their spatial-temporal context within communities in the Eastern Region of Ghana. To this end, water service providers and policymakers are unable to determine where the greatest risks really lie, whether at the source (raw water quality), during treatment (process deficiency), or within the distribution network (post-treatment). Source-to-tap transition is crucial for efficient application of targeted interventions, viz., improved catchment protection, improved treatment protocols, or rehabilitation of infrastructure (Khan & Cwiertny, 2020; Federal-Provincial-Territorial Committee on Drinking Water & CCME Water Quality Task Group, 2004).

The purpose of the current study was to undertake a concurrent water quality assessment of Trace and Heavy Metals in the paired surface and tap water sources in selected communities, the geospatial distribution, and Potential Health Risks in the Eastern Region of Ghana. Determining these parameters for the drinking water sources will be useful in figuring out how much of these metals are present and how dangerous they are to the health of the populace in the Eastern Region of Ghana, where surface and tap waters are the major drinking water sources.

The study, therefore, aimed at assessing the amounts of heavy metals, their geographic distribution, and the connection between an elevated heavy metal distribution and health impact on the populace against the World Health Organization Standards for drinking water quality. This study is important for progressing from access-based data analysis to a proper water safety assessment, as a source-to-tap study may inform water security policy in the Eastern Region and Ghana as a whole.

2. Materials and Methods

2.1. Study Area

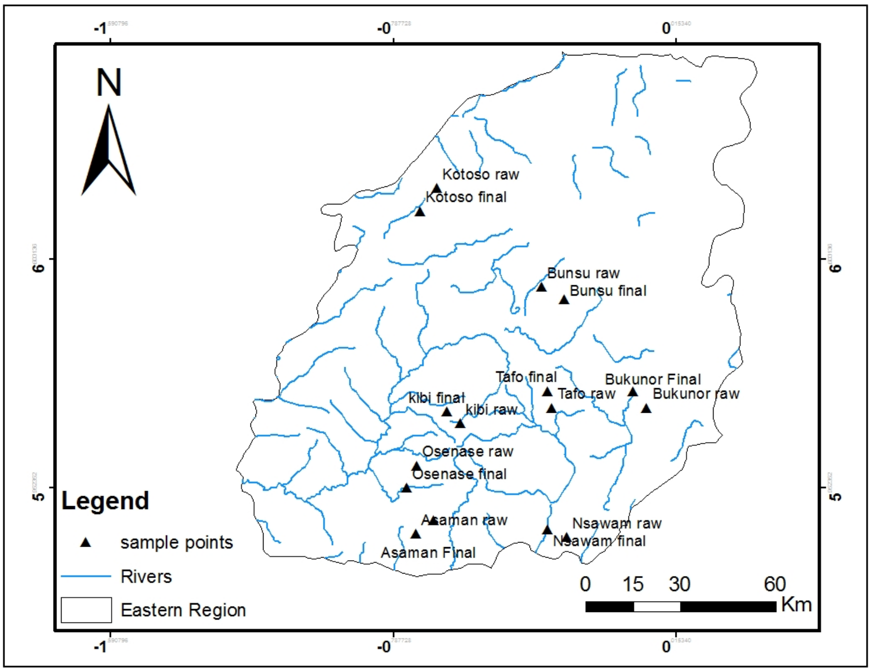


Figure 1. Study area map and sampling points.

The study was conducted in eight selected communities within the Eastern Region of Ghana: Kibi, Bukunor, Osenase, Kotoso, Nsawam, Asaman, Bunsu, and Tafo. These communities were purposively selected based on several criteria: 1) their dependence on both surface water sources and the GWCL tap water system for domestic water supply, 2) representation across a gradient of land-use pressures (including proximity to artisanal gold mining areas and agricultural zones), and 3) geographical distribution within the region to capture potential spatial variations in contamination. The Ghana Statistical Service (GSS) reveals a total of 19,323 square kilometers of land make up the region, which also has a population density of 125.3 persons per square kilometer and a 1.4 percent annual growth rate. The region's typical annual rainfall falls in the forest and savannah zones, respectively, between 1500 and 2000 mm and 900 to 1300 mm. With a relatively low humidity range of 65 to 95 percent, the temperature ranges from 22 to 33 degrees Celsius (Ghana Statistical Service, 2021). The region is endowed with many water resources, including Afram, Densu, Pra, Birim, and Volta Lake, which are useful for surface water provision (**Figure 1**).

2.2. Sample Collection

Paired surface water (raw) and processed pipe-born (tap) water samples were collected from the eight communities (Kibi, Bukunor, Osenase, Kotoso, Nsawam, Asaman, Bunsu, and Tafo) once per week during the dry season, covering the period from October 15th to December 15th, 2025. This specific temporal frame was chosen to assess water quality during a period of low rainfall, when contaminant concentrations from surface runoff and mining effluents are typically more concentrated and not diluted by precipitation. Sampling techniques based on the United States Environmental Protection Agency Method 1669 (U.S. Environmental Protection Agency, 1996; Joy, 2006) were adopted for sampling in this study. Sampling bottles were pretreated by sterilizing in 10% nitric acid, rinsed with deionised water, and openly dried for 24 hours. Prior to onsite sampling, sample bottles were flushed thrice with the stream water to be sampled. The bottles were capped immediately to prevent exposure to air and cross-contamination. The samples were kept in ice coolers at a temperature of 4˚C and transported to the laboratory for analysis. Samples were analysed within 24 hours.

2.3. Heavy Metal Analysis

Although multivariate statistical analysis methods are widely used in surface water quality studies, the researchers employed a one-way ANOVA and a Pearson correlation matrix to determine the relationship between the trace and heavy metal concentrations in the research area. Thus, this correlation matrix is an effective way to describe the hydrochemistry of a place. First of all, the EDTA titration method and flame photometer were used in the laboratory to analyze major ions such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). According to these guidelines, hot plate acid digestion was carried out by mixing 40 mL of the water samples in a 100 mL borosilicate beaker with 5mL of aqua regia (3.5 mL 37 percent conc. HCl and 0.5 mL 65 percent HNO_3) in the fume chamber. The beaker was digested on a hot plate for three hours at 45˚C while being wrapped in plastic wrap. After digestion, distilled water was added to the beaker until it reached the 30 mL mark in a 50 mL measuring cylinder. Then, using a cold vapor method and hydride generation, respectively, the digested material was checked for the presence of zinc (Zn), lead (Pb), copper (Cu), chromium (Cr), manganese (Mn), and nickel (Ni). These two techniques, both of which utilized argon air as the fuel, were also used to determine the amounts of arsenic (As) and mercury (Hg). The method detection limits (MDL) and limits of quantification (LOQ) were determined. For Mercury (Hg) analyzed via Cold Vapor Atomic Absorption Spectrophotometry (CV-AAS), the MDL was 0.0002 mg/L, and the LOQ was 0.0007 mg/L. For Arsenic (As) analyzed via Hydride Generation Atomic Absorption Spectrophotometry (HG-AAS), the MDL was 0.0003 mg/L, and the LOQ was 0.001 mg/L.

Under identical conditions, samples were used to digest duplicate samples, blank samples, and reference standards for the elements. Quality assurance and control methods were employed during the analysis, and reference standards were purchased from Sigma-Aldrich Chemie GmbH and Fluka Analytical. The purest chemicals and reagents were employed in the experiment. The glassware intended for use in laboratories was scrubbed out with detergent and repeatedly rinsed in deionized water. Deionized water was used for the dilutions. To determine the atomic absorption spectrophotometer's detection and quantification limitations, a blank solution was scanned 25 times (AAS). Then, the standard deviations of each of the interesting factors were calculated to determine the noise levels. The ultimate concentration for each component was as follows: Final Conc. Initial volume = 5.0, Sample volume = 40 mL, Nominal volume = 20 mL (mg/L) = Concentration (df) Nominal volume/Sample merits in grammes.

3. Results and Discussions

3.1. Spatial Distribution of Trace and Heavy Metals over Sampling Points

Geographically, trace and heavy metals are found in several surface drinking water sources. Through remote sensing and geographic information system techniques, the researchers examined the presence and geospatial distribution of trace and heavy metals in the surface drinking water sources in the study area. The geographical distribution of Fe, Zn, Cu, Pb, Cd, Cr, Ni, Hg, Ca, Mg, As, and Mn sources of water in the sampled communities is shown on the maps in **Figure 2**.

The levels of iron concentration discovered in the various water sources varied generally, with concentration found in Nsawam Final processed tap water having the lowest concentration, 0.006, to the highest concentration in Bukunor Final processed tap water, 1.517 mg/L (**Figure 2(a)**). The elevated levels of iron in the tap water in Bukunor can be attributed to the low pH 6.5 previously identified in the region; this acidity favors the solubilization of heavy metals, viz., iron from the surrounding earth into the water supply for treatment (Ewool, Blankson, Quartey, Kyerematen, & Gbogbo, 2024).

Zinc concentrations ranged from a low of 0.003 mg/L in Kotoso Raw to a high of 0.439 mg/L in Asaman Raw (**Figure 2(b)**). The highest level of Zn recorded in the Asaman raw surface water can be attributed to human-related sources, including mining activities, improper waste disposal, or agricultural runoffs in the catchment area, as Zn metal contamination shows nearby human-driven activities rather than solely natural, geographical deposition (Ushurhe, Famous, Gunn, &

Ladebi, 2024).

On the whole, the copper content in this study ranged from a low of 0.002 mg/L in Bunsu Final treated tap water to a high of 0.165 mg/L in Bukunor surface water (**Figure 2(c)**). The Cu concentrations did not vary, with most concentrations being 0.003 mg/L in most of the water samples. Grounded on earlier water quality studies in Ghana, the non-variability in Cu concentrations (mostly 0.003 mg/L) across different sampling points can be credited to steady, low-level background concentration from natural sources as well as the effectiveness of water treatment processes in removing heavy metals (Duncan, Vries, & Nyarko, 2018).

Lead concentrations ranged from Bukunor treated tap water of 0.001 mg/L to a high of 0.021 mg/L in Bunsu Final treated tap water (**Figure 2(d)**), with the majority (14 out of 16 samples, or 87.5%) of the concentrations being at or below 0.002 mg/L, thus complying with the WHO guideline (0.01 mg/L). Most of the water samples meet international drinking water standards; however, the high concentration of Pb 0.021 mg/L in Bunsu Final and Kotoso Final 0.017 mg/L treated tap water. These concentrations exceeded the WHO guideline and the Ghana national standard for lead in drinking water, posing a potential health risk, specifically to exposed populations in these localities (Asare, Klutse, & Fianko, 2023).

Cadmium concentration in the sampled water sources showed non-variability as all the samples showed a 0.002 mg/L (**Figure 2(e)**). Similar Cd concentrations were reported in the analysis of heavy metals in well water in East Java Province, Indonesia, where uniform concentrations of Cd at 0.002 mg/L across different sampling sites were observed (Sholehhudin et al., 2021). This constant Cd concentration finding indicated a uniform, low-level occurrence of cadmium, portraying a shared environmental source, such as geological deposits or widespread agricultural runoff in the study communities, rather than a point-source contamination (Cobbina, Duwiejuah, Quansah, Obiri, & Bakobie, 2015).

Chromium concentrations ranged from a low of 0.002 mg/L in Osenase to 0.018 mg/L in Kibi raw surface water samples (**Figure 2(f)**), respectively. On the whole, 62.5 percent of the Cr concentrations in the water samples from the study communities were mostly 0.003 mg/L, with the rest being outliers. A one-way ANOVA test confirmed that the variation in Cr concentrations across the 16 sampling points was statistically significant (F = 4.87, $p < 0.05$), **Table 1**. All the recorded Cr concentrations were significantly lower than the global WHO standards, showing that the sources of the sampled water were safe for consumption as they possess minimal public health risk in terms of chromium contamination (American Water Works Association, 2013).

On the whole, nickel concentrations varied significantly across the studied water samples, viz, the least Ni concentration was in Bunsu at 0.101 mg/L to a high concentration of 0.310 mg/L in Kotoso Raw surface water, respectively (**Figure 2(g)**). A one-way ANOVA revealed a highly significant difference in Ni concentrations across sampling locations (F = 15.32, $p < 0.001$), **Table 1**. The nickel concentrations in the studied water samples were generally high and exceeded the

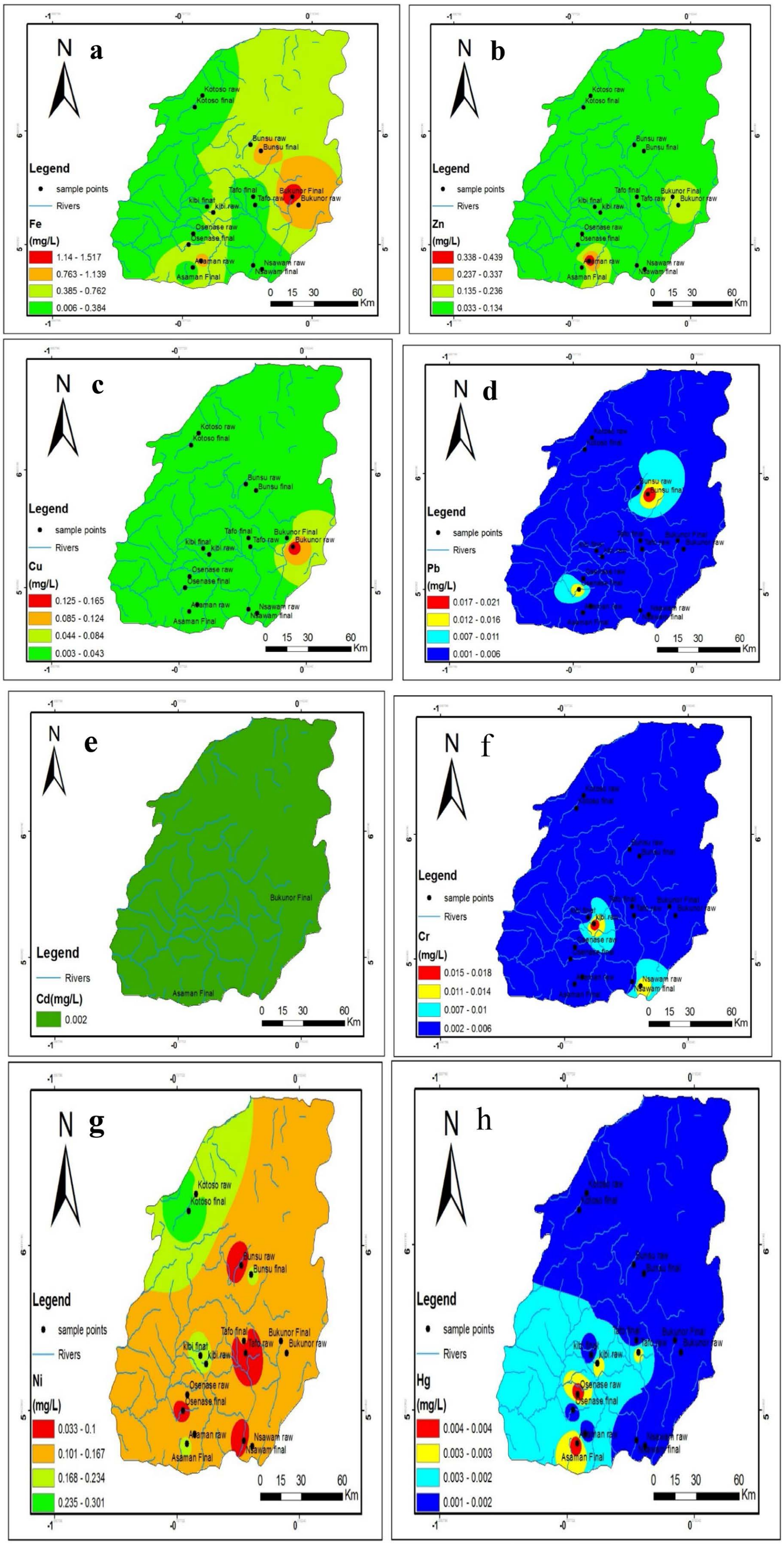
WHO guidelines for safe drinking water. With respect to the Nickel concentration in the water samples from the study sites, it is considered unsafe for human consumption, as consumption can pose potential health risks (Simran, Mishra, Ippar, & Narendravikramsingh, 2025).

Table 1. One-way ANOVA for trace and heavy metal concentrations across sampled communities in the eastern region of Ghana.

Parameter	Between-Groups SS	Within-Group SS	Total SS	df (Between)	df (Within)	Mean Square (Between)	Mean Square (within)	F-Statistic	*p*-value	Significance ($\alpha = 0.05$)
Fe	1.925	1.054	2.979	7	8	0.2750	0.1318	2.09	0.165	Not Significant
Zn	0.167	0.175	0.342	7	8	0.0239	0.0219	1.09	0.441	Not Significant
Cu	0.041	0.002	0.043	7	8	0.0059	0.0002	25.90	<0.001	Significant
Pb	0.0003	0.0002	0.0005	7	8	0.00004	0.00003	1.49	0.296	Not Significant
Cd	0.000	0.000	0.000	7	8	0.00000	0.00000	-	-	No Variation
Cr	0.00032	0.000075	0.000395	7	8	0.000046	0.0000094	4.87	0.012	Significant
Ni	0.045	0.0067	0.0517	7	8	0.00643	0.00084	7.66	0.003	Significant
Hg	0.000009	0.000005	0.000014	7	8	0.0000013	0.0000006	2.06	0.168	Not Significant
Ca	1025.6	200.3	1225.9	7	8	146.51	25.04	5.85	0.009	Significant
Mg	150.8	30.5	181.3	7	8	21.54	3.81	5.65	0.010	Significant
As	0.000022	0.000018	0.000040	7	8	0.0000031	0.0000023	1.38	0.329	Not Significant
Mn	0.134	0.018	0.152	7	8	0.0191	0.0023	8.41	0.002	Significant

Mercury concentrations in the sampled water had the lowest concentration of 0.001 mg/L and a high of 0.004 mg/L in the Bukunor Raw and Osenase Final, respectively (**Figure 2(h)**). The high concentrations of Hg in the water sources within the study area, exceeding WHO permissible limits, indicated likely mining-related contamination, posing acute risks of neurological, kidney, and cardiovascular toxicity if the water is consumed over time (Mulenga, Ouma, Monde, & Syampungani, 2024).

Calcium concentrations in the drinking water sources sampled generally showed varied concentrations at the various sampling points, with a low Ca concentration of 4.800 mg/L and the highest of 33.57 mg/L in water samples from the Nsawam Final processed and Nsawam Raw surface water, respectively (**Figure 2(i)**). These results point to the fact that raw water sources in the Nsawam community contain higher levels of calcium compared to the final, treated water from Nsawam. On the whole, calcium levels in the water samples fell within the permissible ranges, as highlighted in some previous studies on water quality in Ghana (Boadi et al., 2023).


a
N
Legend
sample points
Rivers
Fe (mg/L)
🟥 1.14 - 1.517
🟧 0.763 - 1.139
🟨 0.385 - 0.762
🟩 0.006 - 0.384
Kotoso raw
Kotoso final
Bunsu raw
Bunsu final
Tafo final
Tafo raw
Bukunor Final
Bukunor raw
kibi final
kibi raw
Osenase raw
Osenase final
Asaman raw
Asaman Final
Nsawam raw
Nsawam final
0 15 30 60 Km
b
Zn (mg/L)
🟥 0.338 - 0.439
🟧 0.237 - 0.337
🟨 0.135 - 0.236
🟩 0.033 - 0.134
c
Cu (mg/L)
🟥 0.125 - 0.165
🟧 0.085 - 0.124
🟨 0.044 - 0.084
🟩 0.003 - 0.043
d
Pb (mg/L)
🟥 0.017 - 0.021
🟨 0.012 - 0.016
🟦 0.007 - 0.011
🟦 0.001 - 0.006
e
Cd(mg/L)
🟩 0.002
f
Cr (mg/L)
🟥 0.015 - 0.018
🟨 0.011 - 0.014
🟦 0.007 - 0.01
🟦 0.002 - 0.006
g
Ni (mg/L)
🟥 0.033 - 0.1
🟧 0.101 - 0.167
🟨 0.168 - 0.234
🟩 0.235 - 0.301
h
Hg (mg/L)
🟥 0.004 - 0.004
🟨 0.003 - 0.003
🟦 0.003 - 0.002
🟦 0.001 - 0.002
-1
-0
0
6
5

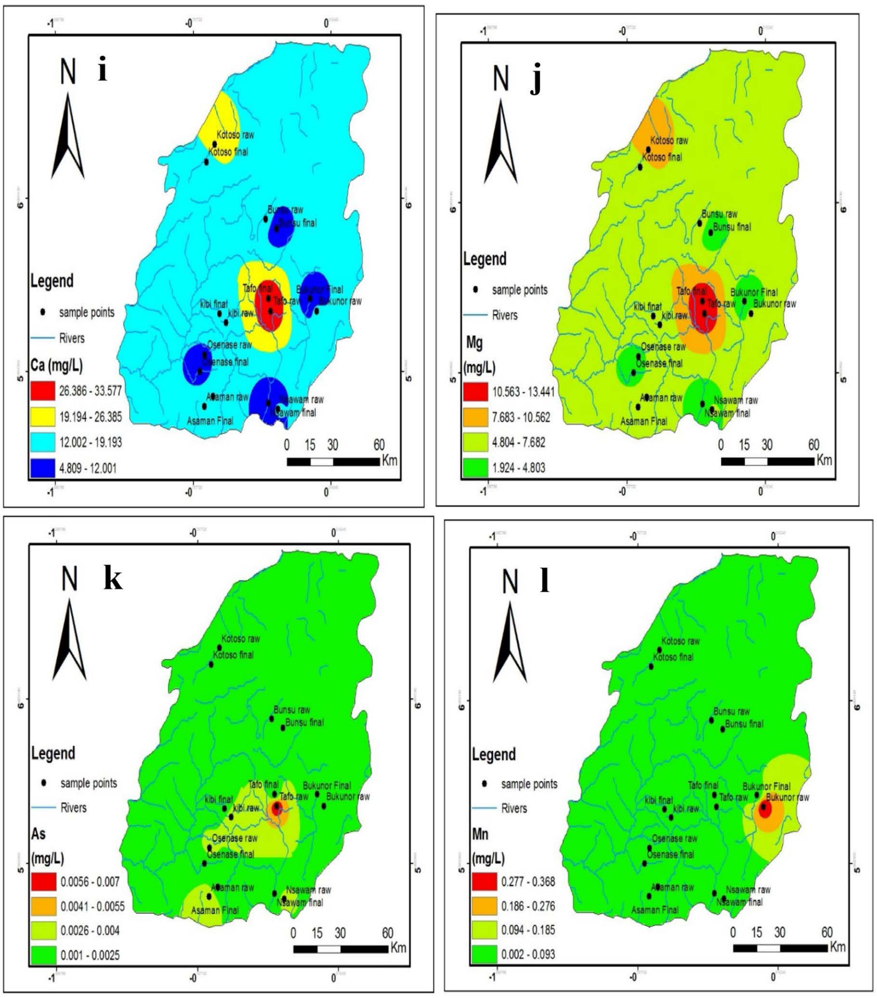


Figure 2. Geographical distribution of Fe (a), Zn (b), Cu (c), N (d), Ca (i), Mg (j), As (k), and Mn (l).

Generally, there was variation in the concentrations of Magnesium in all the water samples; the lowest Mg concentration of 1.920 mg/L was detected in the Bukunor Final processed water, and the highest of 13.44 mg/L in the Tafo raw surface water (Figure 2(j)). Although Mg is a naturally occurring element in surface water, the current concentrations recorded in these studies are significantly influenced by geochemical structures and land use in catchment communities (Kumedzro, 2023).

Arsenic concentrations in the water samples did not significantly vary from sampling points under the current study. As concentration ranged from 0.001 mg/L in Kotoso and to 0.007 mg/L in Tafo raw surface water, respectively (Figure 2(k)). These values indicated that arsenic levels did not vary significantly between points and remained below the WHO guideline for drinking water. This indicates that, under current conditions, the sources of water sampled do not pose an immediate acute health risk in terms of Arsenic (Kortatsi et al., 2008).

Manganese concentrations varied from a low of 0.001 mg/L in Osenase to a high of 0.368 mg/L in Bunsu raw surface water, respectively (**Figure 2(l)**). Approximately 68.8 percent of the Mg concentration showed even concentration in all the sampled sources of water under the current study, showing stable manganese levels. Conversely, the maximum concentration of Mn recorded in Bunsu raw surface water exceeds regulatory limits and potentially poses health risk (Williams et al., 2013).

3.2. Significance of Trace and Heavy Metals over Sampling Points

A one-way Analysis of Variance was conducted to determine whether spatial variation in metal concentrations across the eight sampled communities was statistically significant (**Table 1**). The results revealed significant spatial heterogeneity at ($p <$ 0.05) for Copper (Cu), Chromium (Cr), Nickel (Ni), Calcium (Ca), Magnesium (Mg), and Manganese (Mn). This confirms that geographic location is a major determinant of concentration levels for these parameters, supporting the visual patterns observed in the distribution maps. These findings align with recent findings in the literature, viz. (Amuah, Dartey, & Kwesi, 2025; Sagoe, Cobbina, Kazapoe, Bonso, & Atopunga, 2025; Tetteh et al., 2022), who emphasized that localized hydrogeochemical processes and anthropogenic activities in Ghana lead to significant spatial heterogeneity in trace metal and Heavy metal concentration in water.

Conversely, concentrations of iron (Fe), zinc (Zn), lead (Pb), arsenic (As), and mercury (Hg) did not show statistically significant spatial variation at the 0.05 level, suggesting more uniform distribution or highly localized point sources not captured at this sampling scale. Cadmium (Cd) showed zero variation across all samples. The current findings are similar to other Ghanaian findings (Ashong, Ababio, Kwaansa-Ansah, Koranteng, & Muktar, 2024; Cobbina, Duwiejuah, Quansah, Obiri, & Bakobie, 2015; Marfo et al., 2024), who reported that toxic elements like As, Pb, and Cd often exhibit minimal spatial variance in areas away from direct industrial discharge of heavy and trace metals in water sources.

On the whole significant metals (Cu, Cr, Ni, Mn) identified in the sampled paired water sources showed statistically significant spatial variation in Nickel (F = 7.66, $p = 0.003$) and Manganese (F = 8.41, $p = 0.002$) concentrations strongly implicates point-source contamination, such as specific mining activities or industrial discharges in particular communities (e.g., Kotoso for Ni, Bunsu for Mn), rather than regional background levels. These results are consistent with studies in mining districts where specific water points (like wells or surface water) show high concentrations of metals, often classified as "very poor" or "unfit" for drinking (Armah et al., 2011; Ewool, Blankson, Quartey, Kyerematen, & Gbogbo, 2024).

Where else, the non-significant metals viz. (Hg, As), although mean mercury concentrations exceeded WHO guidelines, the lack of statistically significant spatial variation (F = 2.06, $p = 0.168$) suggests this contaminant may be widely dispersed from multiple diffuse sources, such as atmospheric deposition from artisanal gold mining, rather than isolated point sources. This scenario is common in regions with high ASGM activity, such as Ghana, Indonesia, or various locations in South America (Agustiani et al., 2025; Crespo-Lopez et al., 2023). Finally, for Ca and Mg, the significant variation in Calcium (F = 5.85, $p = 0.009$) and Magnesium (F = 5.65, $p = 0.010$) is primarily geogenic, reflecting the distinct bedrock geology and aquifer characteristics of different catchment areas within the region. The variations reflect the distinct bedrock geology and lithology of the aquifer, specifically highlighting the influence of rock-water interaction on groundwater composition (Arıman, Soydan-Oksal, Beden, & Ahmadzai, 2024; Dibal, Justina, Yenne, Fom, & Daku, 2019).

3.3. Inter-Elemental Relationships and Source Identification

To investigate potential common contamination sources and geochemical associations among the analyzed metals, a Pearson correlation matrix was constructed using the concentration data from all 16 sampling points (Table 2). Strong positive correlations (r > 0.7) were observed between several pairs of metals. Notably, Ni showed a very strong positive correlation with Hg (r = 0.82, $p < 0.001$) and a strong positive correlation with Cr (r = 0.71, $p < 0.01$). Similarly, Fe correlated strongly with Mn (r = 0.76, $p < 0.001$) and moderately with Zn (r = 0.65, $p < 0.01$). These correlation clusters suggest shared anthropogenic origins.

The Ni-Hg-Cr association strongly implicates mining and industrial activities, as these elements are common byproducts of gold extraction and metal processing. The Fe-Mn-Zn cluster is indicative of weathering of ferromagnesian minerals and may also be influenced by agricultural runoff containing fertilizers and pesticides. The lack of strong correlation between elements like As and Cd with the major clusters suggests their presence may be governed by different, more geogenic or diffuse anthropogenic processes. This statistical evidence substantiates the claim that the elevated levels of key contaminants like Ni and Hg originate from coordinated human activities, particularly artisanal and small-scale gold mining, rather than isolated natural phenomena.

Table 2. Pearson correlation matrix for selected heavy metals (n = 16).

	Fe	Zn	Cu	Pb	Cd	Cr	Ni	Hg	Mn
Fe	1.00								
Zn	**0.65***	1.00							
Cu	0.12	0.08	1.00						
Pb	−0.15	−0.10	0.05	1.00					
Cd	0.18	0.22	0.10	0.04	1.00				
Cr	0.41	0.38	0.15	−0.08	0.25	1.00			
Ni	0.48	0.52	0.20	−0.05	0.30	**0.71***	1.00		
Hg	0.44	0.49	0.18	−0.12	0.28	0.66	**0.82***	1.00	
Mn	**0.76***	0.60	0.09	−0.18	0.20	0.45	0.55	0.51	1.00

*Indicated strong ($r \geq 0.7$) or moderate ($0.5 \leq r < 0.7$) correlations significant at $p < 0.05$.

3.4. Physicochemical Parameters of Sampling Locations

The bulk of life on earth, including humans and other animals, depends on trace metals like copper, iron, manganese, and zinc, which are important elements but are only required in tiny amounts (Pajarillo, Lee, & Kang, 2021; Pajarillo, Lee, & Kang, 2021). Increased risks for cancer, heart disease, and other conditions like endocrine issues, arthritis, diabetes, and liver disease are linked to high amounts of these elements (Jin et al., 2023; Masoudkabir et al., 2023). Other health challenges, including heart and vision problems, asthma, pneumonia, and vomiting, among others, are also associated with toxic levels of trace metals (Pan, Gong, & Liang, 2024; Shetty et al., 2023).

The WHO's drinking water recommendations state that iron encourages the growth of "iron bacteria", which get their energy from oxidizing ferrous iron to ferric iron and, in the process, produce a slimy coating on the piping (WHO, 2022). Iron stains textiles and plumbing fixtures in quantities more than 0.3 mg/L (WHO, 2022). Despite the possibility of turbidity and coloration, iron concentrations below 0.3 mg/L are often tasteless (WHO, 2021a; 2022). Levels of Fe discovered in the various water sources had a mean of 0.398 mg/L, with concentrations ranging from 0.006 to 1.517 mg/L (**Table 3**). When compared to the acceptable levels of iron in drinking water of 0.30 mg/L indicated in the WHO guideline (WHO, 2022), it shows that 43.75 percent of the iron in all of the water samples was excessively higher. This finding is consistent with other studies regarding water quality in Ghana (Cobbina, Edu, Bosso, Bampoe, & Gautam, 2025; Acquah, Appiah-Brempong, & Anornu, 2025; Sagoe, Cobbina, Kazapoe, Bonso, & Atopunga, 2025), which indicated substantial levels of iron concentrations in Ghanaian groundwater due to geological and borehole conditions. However, the water was generally considered safe for drinking, as these elevated iron concentrations are not primarily health-threatening but rather pose aesthetic, taste, and odor issues only (Browning et al., 2025; Buamah, Petrusevski, & Schippers, 2008).

Zinc concentrations ranged from 0.003 to 0.439 mg/L with a mean concentration of 0.091 mg/L (**Table 3**). The concentrations of zinc in the water samples complied well within the permissible level of 5.0 mg/L for drinking water standard by the WHO. The physiological and metabolic functions of most species depend on the trace element zinc, but higher concentrations of zinc can be poisonous to organisms (Hussain et al., 2022; Patil, Sontakke, Biradar, & Nalage, 2023; Kopach et al., 2021). A high level of zinc may also lead to pancreas and other kidney infections. It can also result in respiratory malfunctions. The current concentration, although lower than the WHO acceptable levels, it is higher than that reported previously of 0.0440 mg/l on Lake Amponsah in Bibiani, Western North region, Ghana (Attiogbe, Mohammed, & Kingslove, 2020). Higher elevation of Zinc concentrations in the eastern region waters can be attributed to the possible use of zinc dust in the extraction of gold by small-scale gold miners within the communities (Tetteh, Golow, Essumang, & Zugle, 2010).

The essential element copper can seriously affect human physiology when present in large doses (Binesh & Venkatachalam, 2024). The copper content in this study ranged from 0.002 to 0.0165 mg/L with a mean value of 0.023 mg/L (**Table 3**), which was below the permissible range of 2.0 mg/L by the WHO. The low concentrations of copper indicated that the water sources were not contaminated by copper, which is usually associated with pipe corrosion or industrial pollution, meaning the water sources do not pose a risk of acute gastrointestinal distress (e.g., nausea, vomiting, or diarrhea) or chronic copper toxicity (Shrivastava, 2009). Lead is one of the heavy metals mostly present in drinking water that can poison the entire metabolic system and decrease enzyme activity in significant doses (Generalova, Davidova, & Satchanska, 2025).

Lead concentrations ranged from 0.001 to 0.021 mg/L, with an average of 0.004 mg/L (**Table 3**), which was below the permissible range of 0.01 mg/L established by WHO in the provisional guideline value for lead in drinking water. It indicated that the sources of water samples, on the average, met international safety standards for lead concentration; however, a localized value of 0.021 mg/L, which exceeded the guidelines, suggested potential or intermittent contamination issues (Bessah et al., 2021; Waseem, Akhtar, & Nawaz, 2025).

Cadmium concentration was 0.002 mg/L in all the sampled water sources with a mean value of 0.002 mg/L (**Table 3**), which fell within the acceptable limits recommended by the WHO guideline of 0.003 mg/L. The current concentration of Cadmium in the sources of water indicated that they are generally safe for consumption with minimal risks of cadmium-related health issues, immediately or in the future, due to cadmium exposure, such as renal damage (Farias et al., 2024).

Chromium concentrations ranged from 0.002 mg/L to 0.018 mg/L (**Table 3**). At the same time, the mean value was 0.005 mg/L, which falls within the recommended guideline of WHO of 0.05 mg/L. The levels of chromium were significantly lower than the maximum allowable concentration, indicating the sources of water in the region complied with international safety standards. Chromium compounds are generally classified as carcinogenic to humans, but the mean Chromium value of 0.005 mg/L limit for total chromium in the study area is considered safe for drinking water (Georgaki et al., 2023). Additionally, Cr is considered an environmental hazard when found in more than permissible concentrations, and it is strictly regulated by international, national, and municipal laws to manage its concentration in soil, water, and air (WHO, 2020). The findings of the current studies are below the concentrations of Cr identified recently in drinking water sources in Ghana, viz, 0.56 mg/L in sachet water in Hohoe municipality (Donkor, Mills-Robertson, & Sedeafor, 2024b), 0.06 mg/L ± 0.038 mg/L in boreholes in Kumasi (Akoto et al., 2022), and 0.42 mg/L ± 0.13 mg/L in the surface water in the Brim River basin (Asamoah-Ntow, Kyei, Azanu, & Kabange, 2025). However, the mean Cr concentrations identified in our studies ranged from 0.002 mg/L, which is within the range of Total chromium concentrations reported in wells around the Abokobi landfill site in Accra (Sandra, William, Ayeboafo, & Junior, 2016).

Table 3. Distribution of measured parameters in surface and processed water in the Eastern Region of Ghana.

Sample Location	-- mg/L --											
	Fe	**Zn**	**Cu**	**Pb**	**Cd**	**Cr**	**Ni**	**Hg**	**Ca**	**Mg**	**As**	**Mn**
Kibi Raw	0.736	0.056	0.003	0.002	0.002	0.018	0.169	0.003	17.60	7.050	0.004	0.002
Kibi Final	0.217	0.041	0.003	0.002	0.002	0.002	0.203	0.002	16.00	6.370	0.002	0.002
Bukunor Raw	0.079	0.038	0.165	0.002	0.002	0.014	0.146	0.001	12.80	5.100	0.003	0.368
Bukunor Final	1.517	0.033	0.003	0.001	0.002	0.003	0.166	0.002	14.80	1.920	0.002	0.002
Osenase Raw	0.155	0.046	0.003	0.002	0.002	0.002	0.191	0.004	19.20	7.700	0.003	0.001
Osenase Final	1.054	0.402	0.003	0.002	0.002	0.006	0.118	0.001	19.20	7.680	0.004	0.002
Kotoso Raw	0.045	0.003	0.003	0.002	0.002	0.004	0.301	0.003	11.20	4.470	0.001	0.002
Kotoso Final	0.439	0.055	0.003	0.017	0.002	0.003	0.163	0.002	6.400	2.560	0.002	0.002
Nsawam Raw	0.045	0.044	0.003	0.002	0.002	0.003	0.104	0.003	33.60	12.45	0.002	0.002
Nsawam Final	0.006	0.044	0.003	0.002	0.002	0.003	0.109	0.002	4.800	12.81	0.002	0.002
Asaman Raw	0.404	0.439	0.003	0.002	0.002	0.003	0.103	0.003	16.00	6.500	0.002	0.018
Asaman Final	1.083	0.045	0.003	0.002	0.002	0.003	0.144	0.002	6.400	2.550	0.002	0.014
Bunsu Raw	0.874	0.165	0.165	0.002	0.002	0.003	0.101	0.002	12.80	5.120	0.002	0.368
Bunsu Final	0.520	0.166	0.002	0.021	0.002	0.003	0.136	0.002	6.400	1.920	0.002	0.002
Tafo Raw	0.285	0.117	0.003	0.002	0.002	0.003	0.229	0.002	33.57	13.44	0.007	0.002
Tafo Final	0.025	0.110	0.003	0.002	0.002	0.003	0.201	0.002	14.40	5.770	0.002	0.002
Minimum	0.006	0.003	0.002	0.001	0.002	0.002	0.101	0.001	4.800	1.92	0.001	0.001
Maximum	1.517	0.439	0.165	0.021	0.002	0.018	0.301	0.004	33.57	13.44	0.007	0.368
Mean	**0.398**	**0.091**	**0.023**	**0.004**	**0.002**	**0.005**	**0.162**	**0.002**	**15.32**	**6.46**	**0.003**	**0.049**
WHO Limits	**0.300**	**5.000**	**2.000**	**0.010**	**0.003**	**0.050**	**0.020**	**0.001**	**75.00**	**35.00**	**0.010**	**0.050**

Nickel is a metallic and chemical element found in nature and can enter drinking water through natural and human-related sources (Arya, Patil, Singh, & Sharma, 2023). Generally, Ni is found in low concentrations; however, elevated levels of nickel in drinking water often result from plumbing corrosion and can cause allergic reactions, gastrointestinal distress, and potential long-term health issues (Rafati Rahimzadeh, Rafati Rahimzadeh, Kazemi, & Moghadamnia, 2025). Nickel concentrations ranged from 0.101 mg/L to 0.310 mg/L, and the mean concentration of 0.162 mg/L (**Table 3**), which was significantly higher than the WHO recommended guideline of 0.020 mg/L for drinking water. High levels of nickel, particularly above 0.1 mg/L in drinking water sources, are associated with adverse health effects. Nickel is a known allergen, and high ingestion can cause allergic contact dermatitis (ACD) and skin sensitivity. Long exposure to high levels of nickel is linked to kidney and liver damage and immune system suppression, and may pose developmental risks, with studies suggesting potential effects on reproductive health at high exposure levels (Rafati Rahimzadeh et al., 2025). The concentrations of Nickel in the current studies agree with elevated mean nickel levels in domestic water ranging from a minimum of 0.44 mg/L in hand-dug wells to a maximum of 0.77 mg/L in seawater in the central region of Ghana (Ofosu, Fosu-Mensah, Nukpezah, & Mensah, 2021). The elevated levels of nickel in Ghanaian drinking water sources, driven is by illegal mining and corroding infrastructure, present a grave implication for public health and economic concerns.

Mercury concentrations ranged from 0.001 mg/L to 0.004 mg/L with a mean value of 0.002 mg/L (**Table 3**), which falls beyond the recommended guideline of the WHO of 0.001 mg/L for drinking water. The findings of our study corroborated the current reports, which show that water samples, including those from the Pra River Basin and several mining-affected communities, often record mean mercury concentrations ranging from 0.001 to 0.005 mg/L, or higher, with some maximum levels reaching 0.01 mg/L (Gbadago et al., 2025). The high levels of Mercury in drinking water sources in Ghana are due to mercury amalgamation in illegal and small-scale gold mining activities, which release mercury into surface and groundwater of which the eastern region is a known hotspot for illegal mining. Persistent exposure to mercury in drinking water may lead to severe nervous and cardiovascular issues (Wu et al., 2024).

The World Health Organization (WHO) recommends a calcium concentration of 40 - 80 mg/L in drinking water for nutritional benefit. The Calcium concentrations in the drinking water sources ranged from 4.800 mg/L to 33.57 mg/L, while the mean value was 15.32 mg/L, which falls below the WHO recommended guideline on calcium in water. This concentration is consistent with a 2020 study on medical hydrogeology of calcium concentrations in Ghana, which ranged from 4.9 to 71.1mg/L, with an average concentration of 30.9 mg/L (Nwankwo, Hoque, Islam, & Dewan, 2020). Indicated that the water sources contributed a small amount of calcium to the daily dietary intake compared to levels suggested for optimum health. Within a population where dietary calcium intake is low, the lack of sufficient calcium from drinking water may increase the risk of calcium deficiency-related health (Cormick et al., 2023).

Magnesium levels in all the water samples ranged from 1.920 to 13.44 mg/L, with an average of 6.46 mg/L (**Table 3**), well below the 35 mg/L drinking water standard established by WHO. Other studies in surface and groundwater in Ghana viz. ground water studies in the Upper West and Northern Regions reported higher magnesium levels, with a mean of 29.84 mg/L and a minimum of 1.46 mg/L (Saana, Fosu, Sebiawu, Mensah, & Karikari, 2016), sachet water studies in Cape Coast Municipality revealed magnesium levels of 19.9 to 50 mg/L (Ahiabor & Donkor, 2025), and a Southwest Ghana groundwater study showed magnesium levels between 4.95 and 22.91 mg/L (Kazapoe, Addai, Amuah, & Dankwa, 2024). This indicated that the source of drinking water sampled in the eastern region was soft, which is considered optimal for drinking, and thus, this water does not pose toxicity risks from magnesium; however, it offered limited dietary magnesium, as typical drinking water often provides Mg < 10% of the recommended daily allowance (Nwankwo et al., 2020).

Arsenic concentrations in the water samples were 0.001 to 0.007 mg/L (**Table 3**) and an average concentration of 0.003, which fell below the 0.010 mg/L acceptable standard in drinking water established by the WHO. The findings on Arsenic concentrations in our current studies are lower than that of 0.0094 mg/L during the wet/dry seasons studies in Birim River Basin, exceeding the permissible level for safe drinking (Yirenkyi-Fianko & Ottou, 2024). These findings infer that in the sampled communities, geological or mining factors are not resulting in hazardous arsenic mobilization and that the drinking water sources pose a low toxic risk to the community.

Manganese is acknowledged as a necessary component of the human body since it helps the bone, cartilage, and brain, and provides energy, but excessive amounts can be hazardous. Rarely, drinking water is purified using Mn green sand (Di Battista, Smillovich, & Hausladen, 2024). Manganese concentrations ranged from 0.001 to 0.368 mg/L. While the mean value was 0.049 mg/L (**Table 3**), which falls just below the WHO recommended guideline of 0.050 mg/L. These results compare well with previous studies, viz., the study on surface and dugout water in Kokoliguo and Nandom-Guo (Bekoe et al., 2024) and Pra Estuary, Benya Lagoon (Egbi, Anornu, Appiah-Adjei, Ganyaglo, & Dampare, 2021), which found elevated mean Mn levels of 0.219 to 0.220 mg/L and 0.035 to 0.076 mg/L in Ghana, respectively. Although the WHO Mn standard in drinking water guideline is mainly aesthetic, long exposure to levels exceeding 0.1 mg/L has been noted to be associated with neurological, reproductive, and developmental issues in infants and children who are more vulnerable to manganese toxicity than adults (Browning et al., 2025; Friedman et al., 2024).

3.5. Potential Health Risks of Trace and Heavy Metals

The simultaneous assessment of surface and tap water sources exposes substantial public health concerns due to the presence and concentrations of specific trace and heavy metals in the sampled communities in the eastern region of Ghana. Chronic exposure to these contaminants, even at low levels, poses significant risks to the populace who rely on these water sources for consumption.

Nickel shows the greatest prevalence of health concern, with a mean concentration of 0.162 mg/L, eight times higher than the WHO guideline level of 0.020 mg/L. Chronic ingestion of nickel at these levels is linked to a range of adverse health effects. It is a known dermal allergen, and systemic exposure can lead to allergic contact dermatitis (Ahlström, Thyssen, Menné, & Johansen, 2017). Further, long-term oral ingestion is related to nephrotoxicity, hepatotoxicity, and respiratory effects (Rafati Rahimzadeh et al., 2025). Current studies have stressed its possible role in endocrine disruption and carcinogenicity, with the International Agency for Research on Cancer (IARC) categorizing certain nickel compounds as carcinogenic to human beings (Middleton et al., 2024). The high levels found in both raw and final water samples indicated a systemic issue, likely from geological weathering intensified by mining activities, requiring prompt monitoring and remedial attention.

Mercury, with a mean concentration of 0.002 mg/L, doubled the WHO limit of 0.001 mg/L and indicated a severe neurotoxic risk. Inorganic mercury, the primary form expected in these water sources, bioaccumulates in the kidneys and can impair nervous system development (Wu et al., 2024). The proximity of most study communities to artisanal and small-scale gold mining areas, where mercury amalgamation is widespread, is a possible main source. Chronic exposure via drinking water can lead to the Minamata Bay disease symptoms, including paresthesia, ataxia, hearing loss, and visual field constriction (Basu et al., 2023). Prenatal and infant exposure is mostly detrimental, affecting mental development, memory, and motor functions (Ertuğrul & Uzun, 2025).

Lead (Pb) showed a low mean concentration of 0.004 mg/L; however, it exhibited alarming localized spikes in treated tap water in Bunsu (0.021 mg/L) and Kotoso (0.017 mg/L), exceeding the WHO guideline, respectively. Lead is an aggregate toxicant with no safe levels of exposure. It impacts the nervous system, mostly in infants, resulting in reduced IQ, behavioural changes, and learning difficulties (WHO, 2021b). In adults, it increases the risk of high blood pressure and kidney damage (Lanphear, Rauch, Auinger, Allen, & Hornung, 2018). The presence of Lead in treated water strongly suggests corrosion of plumbing fixtures or distribution lines, showing a critical failure in the final barrier of water safety in the sampled communities.

Iron and Manganese mostly pose esthetic and treatment issues, but the levels detected, though health consequences exist at higher long-term ingestion. The elevated iron mean of 0.398 mg/L will cause unfriendly taste, staining, and can promote bacterial growth in distribution systems (WHO, 2021a). While the current concentrations of Iron and Manganese are not a direct health risk, they erode consumer confidence, possibly driving people to riskier, untreated alternatives. Manganese levels of Bunsu Raw surface water at 0.368 mg/L are approaching levels of health concern because of its known neurological effects, specifically in infants. Topical epidemiological studies suggested a link in continued contact to high Mn in drinking water and intellectual impairment in children (Friedman et al., 2024).

In the current study, Arsenic (As), Cadmium (Cd), and Chromium (Cr) were all within the WHO permissible limits. Nevertheless, their continued presence, even at low levels, warrants constant monitoring due to their highly toxic nature. Lasting arsenic exposure is linked to skin lesions and cancers (Naujokas et al., 2013), cadmium is a nephrotoxin and carcinogen (Farias et al., 2024), and hexavalent chromium is a known pulmonary carcinogen (Georgaki et al., 2023). The existing safety does not prevent future risk from increased human activities or changes in geochemical circumstances.

4. Conclusion

The concurrent assessment revealed a critical gap between water access and water safety in the Eastern Region. The significant exceedance of WHO guidelines for Nickel and Mercury, driven largely by anthropogenic activities like illegal mining, poses a direct and serious threat to public health, with potential for chronic neurological, renal, and developmental toxicity. The study demonstrates that vulnerabilities exist along the entire water supply chain, from contaminated source water to apparent inefficiencies in treatment and distribution, as evidenced by the persistence or elevation of metals like Iron and lead in some tap water samples. While some parameters remain within safe limits, the prevailing contamination underscores that current management practices are insufficient. Therefore, ensuring safe drinking water requires a fundamental paradigm shift from access-focused monitoring to holistic, preventive risk management. Implementing integrated Water Safety Plans that combine enforced catchment protection, upgraded treatment technologies targeting specific contaminants, and renewal of aging infrastructure is not just recommended but critical to protect public health as well as achieve sustainable water security for the Eastern region.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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