Physico-Chemical Quality and Heavy Metal Assessment of Surface Water Sources in Artisanal Mining Communities in Mpohor Wassa East District, Ghana

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Abstract

This study evaluated the physico-chemical characteristics and concentrations of heavy metals present in the surface water sources that were affected by artisanal mining activities within the Mpohor Wassa East District in Ghana. To determine the key factors that most significantly affect the variability of water quality, multivariate statistical methods, such as the Principal Component Analysis (PCA), were used. Except for turbidity, all measured physico-chemical parameters complied with World Health Organization (WHO) guidelines for drinking water. PCA revealed six principal components, with the first component (PC1) accounting for 22.5% of the total variance. PC1 was strongly associated with cobalt (Co), chromium (Cr), copper (Cu), arsenic (As), and cadmium (Cd), and moderately associated with nickel (Ni), zinc (Zn), mercury (Hg), magnesium (Mg), lead (Pb), and iron (Fe). These results are important in the informative design of both location-specific surface water monitoring and management plans in Ghana's artisanal mines.

Keywords: Artisanal mining; Physicochemical; Water Quality; Surface Water; Hydrochemistry; Heavy metals; Ghana

Introduction

Water holds the key to the survival and socio-economic growth of human beings. It is critical to human health, agriculture, industry and the health of ecosystems. The growing demand of water resources in Ghana due to the rapid growth of the population, urbanization, industrialization, and other factors has put a significant burden on both surface and groundwater resources (Sumarga & Hein, 2020). Rivers and streams have been utilized in rural and peri-urban communities as domestic, irrigation, and industrial resources. Nevertheless, modern anthropogenic disruptions, predominantly mining, have led to a great decline in the quality of these water sources and increased contamination of aquatic ecosystems in many developing countries (Attua et al., 2014; Akabzaa et al., 2007; Akoto et al., 2021; Abu et al., 2024).

Artisanal and small-scale gold mining (ASGM) has been widely reported as a major contributor to surface water deterioration in many developing countries, particularly in sub-Saharan Africa. Previous studies in Ghana have shown that mining-related activities significantly increase sediment loads, turbidity, dissolved solids and concentrations of potentially toxic heavy metals in rivers and streams located near mining communities (Akabzaa et al., 2007; Armah et al., 2013; Attua et al., 2014, Annan et al., 2018; Woananu et al., 2024). Similar findings have also been reported in other mining regions globally, where artisanal mining activities contribute to ecological degradation contamination of aquatic systems and long-term risks to human health through the release of mervury, arsenic, cadmium and lead into water bodies (Wongsasuluk et al., 2013, Liang etm al., 2014).

Artisanal and small-scale gold mining (ASGM), also known locally as galamsey, exerting pressure on surface water pollution in the southwestern part of Ghana, has recently become a significant problem in the Mpohor Wassa East District (Armah et al., 2013). ASGM has a significant impact on the development of the national economy and offers livelihood to many unskilled young people; however, the environmental cost is significant. The mining activities, particularly on the riverbanks and stream bed, cause high quantities of sediments and heavy metals into the water bodies, causing discoloration, turbidity, and pollution by toxic elements such as mercury (Hg), arsenic (As), and cadmium (Cd) (Durkin and Hermann, 2008; Annan et al., 2018; Amegbey and Eshun, 2003). Similar ecological and toxicological impacts associated with galamsey activities have recently been reported in other mining communities in Ghana (Ofori et al., 2024). Such factors make the surface water sources unsuitable to be used both as drinking tap and as farm water (Obiri, 2007; Wongsasuluk et al., 2013).

Illegal small-scale mining activities have become widespread in the Wassa region, which traditionally relies on agriculture and mining, and many of these activities are carried out using mechanized equipment (excavators and dredgers) (Akabzaa et al., 2007). This has also contributed to the extensive destruction of freshwater ecosystems and the apparent deterioration of the quality of surface water. As a reaction, communities in Mpohor Wassa East and other adjacent districts are increasingly resorting to groundwater sources including boreholes and hand-dug wells as alternatives to domestic and irrigation needs (Annan et al., 2022; Simon et al., 2004). More than 70% of Ghanaians are estimated to rely on groundwater in their domestic chores and the number increases to 90% in the rural regions (Akurugu et al., 2020; Ghana Statistical Service [GSS], 2014). Although this has changed the way people depend on water, ground water is not resistant to contamination, particularly where mining is being carried out. Research has demonstrated that mining processes may release heavy metal into the aquifer with long-term environmental and human health implications (Kazapoe and Arhin, 2019; Obiri, 2007; Erdiaw-Kwasie et al., 2014; Abu et al., 2024). Using contaminated water to drink or irrigate is dangerous to human health and the stability of the ecosystem. Hence, the quality of surface and groundwater needs to be continuously monitored, especially in the mining-based areas such as Mpohor Wassa East. The use of multi-dimensional methods is necessary to evaluate the water quality of this kind of complex environmental setting. The multi-variable statistical methods (i.e., Principal Component Analysis (PCA) and Cluster Analysis (CA)) are useful in determining the most influential factors contributing to water chemistry and the classification of natural and anthropogenic sources of contamination (Attua et al., 2014; Liang et al., 2014; Winkler et al., 2013). These techniques enable the interpretation of large environmental data and create a solid basis on which water management plans can be created. Recent hydrogeochemical studies in Ghana have successfully applied multivariate statistical techniques to identify the dominant geogenic and antropogenci controls influencing groundwater and surface water chemistry in mining environments (Kazapoe et al., 2023; Addai, 2025). Although several studies have examined the environmental and hydrochemical impacts of artisanal and small scale gold mining in major mining districts such as Tarkwa, Obuasi and Prestea in Ghana (Akabzaa et al., 2007; Armah et al., 2013; Attua et al., 2014), limited studies have specifically investigated the combined physicochemical characteristics and heavy metal contamination of surface water systems within the Mpohor Wassa East District using multivariate statistical techniques (Kazapoe et al., 2023; Addai, 2025). Existing studies in southeastern Ghana have largely focused on groundwater systems, general environmental degradation or socio-economic impacts of mining activities without detailed hydrochemical assessment and pollution source identification of surface water bodies in the district (Obiri, 2007; Annan et al., 2022; Abu et al., 2024). Consequently, there remains insufficient information regarding the dominant factors controlling surface water quality and the extent of mining-related contamination in Mpohor Wassa East. Addressing this gap in important for developing effective water quality monitoring and environmental management strategies for mining-affected communities in the district. Such information is essential for sustainable water resource management, pollution mitigation and protection of public health in mining-affected communities (Egbueri et al.., 2023; Tabi et al., 2024). The broad objective of the study was to assess the physicochemical quality and heavy metal concentrations of surface water sources in artisanal mining communities within the Mpohor Wassa East District of Ghana. Specifically, the study sought to:

1. Determine the physicochemical characteristics of surface water in selected artisanal mining communities;
2. Assess the concentration and spatial distribution of heavy metals in surface water sources;
3. Evaluate the relationships among physicochemical parameters and heavy metals using correlation analysis; and
4. Identify the major facts influencing surface water quality using multivariate statistics techniques, particularly Principal Component Analysis (PCA).

Materials and methods

Study Area

The Mpohor Wassa East District was selected for this study because of the increasing intensity of artisanal and small-scale gold mining (ASGM) activities and the dependence of local communities on surface water resources for domestic and agricultural purposes. The district has experienced increasing environmental pressure from mining operations, including land degradation, vegetation loss and environmental assessment.

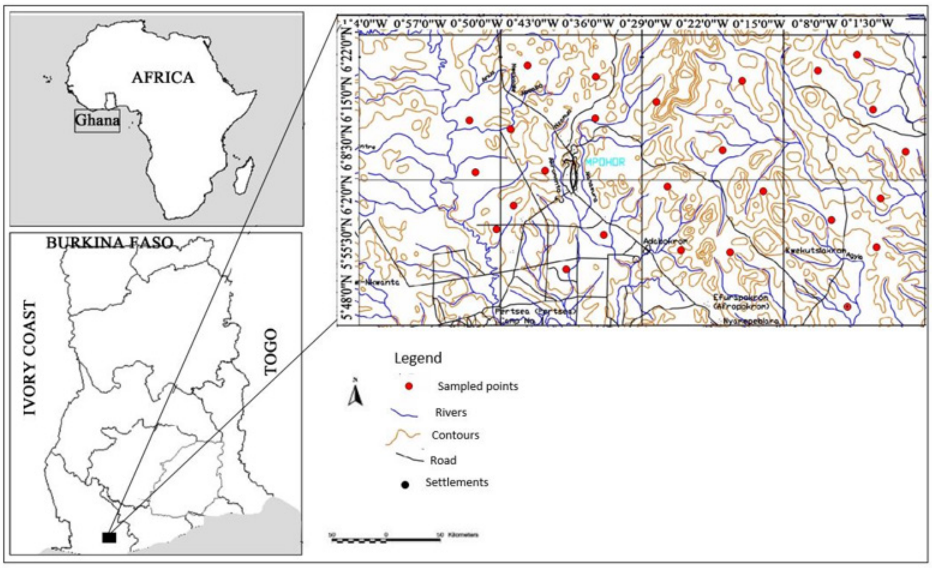

Figure 1 Study Area and Sampling Point Map of Mpohor Wassa East District

Geographically, Mpohor Wassa East District is in the southeastern part of Ghana's Western Region. It shares boundaries to the northeast and southeast with Twifo Hemang Lower Denkyira and Komenda Edina Edina Abrem Districts in the Central Region. To the west and northwest, it borders the Tarkwa Nsuaem Municipality and Prestea Huni-Valley District, while to the south, it is flanked by the Sekondi-Tarkoradi Metropolis, Shama and Ahanta West Districts (Ghana Statistical Services, 20214).

Sample Collection

Surface water samples were collected in triplicate from four artisanal mining communities within the Mpohor Wassa East District, where active small-scale mining activities were observed during field investigations: Asowuo Ayipa (ASA), Adum Tokoro (ADT), Mpohor Motorway (MM), and Mpohor Adawotwe (ADW). The selection of sampling locations was based on the presence of active artisanal mining activities, accessibility of surface water sources and community dependence on these water bodies for domestic and agricultural purposes. A control sample was also collected for comparison. The control sample was collected from a surface water source located in a relatively less disturbed area within the Mpohor Wassa East District, where no active artisanal mining activities were observed during field sampling. The site was selected to provide background physicochemical conditions for comparison with mining-influenced sampling locations. Basic stream morphometric parameters, including channel width and water depth, were measured on-site in meters. Sampling procedures followed the United States Environmental Protection Agency (USEPA) Method 1669 protocol for trace metal sampling. Polyethylene sampling bottles were pre-treated by soaking in 10% nitric acid, rinsing thoroughly with deionized water, and drying in open air for 24 hours. Prior to collecting each sample, the bottles were rinsed three times with stream water to minimize contamination. Samples were capped immediately after collection to prevent exposure to air and cross-contamination. Field parameters, including temperature, pH, dissolved oxygen (DO), and electrical conductivity (EC), were measured in situ using a pre-calibrated HORIBA U-51 multiparameter water quality meter. To validate DO values, confirmatory tests were conducted using the Azide modification of the Winkler method. Turbidity was assessed using a 2100Q Portable Turbidimeter (HACH, USA), while colour measurements were carried out using a HACH DR/2010 portable spectrophotometer. For heavy metal analysis, samples were preserved in ice-cooled containers at 4°C and transported to the laboratory within 24 hours. A dual atomizer and hydride generation Atomic Absorption Spectrophotometer (AAS; model ASC-7000, Shimadzu, Japan) was used to quantify nine heavy metals: arsenic (As), total chromium (Cr), cadmium (Cd), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni), zinc (Zn), and iron (Fe). Mercury and arsenic were determined using specialized hydride generation techniques. All reagents were of analytical grade and supplied by MES Equipment Ghana. Ultrapure deionized water (metal-free) was used throughout the procedures, and all glassware and plasticware were rigorously cleaned by soaking in 5% nitric acid for 6–7 hours followed by rinsing with ultrapure water. Nitric and hydrochloric acids used for digestion were of the highest analytical quality.

Statistical Analysis

Quantitative data were initially entered and cleaned in Microsoft Excel and subsequently exported to STATA version 16 for statistical analysis. Descriptive statistics including mean ± standard deviation (SD), range, and 95% confidence intervals were used to summarize water quality data. To assess spatial differences among the sampling sites, a one-way analysis of variance (ANOVA) at a 95% confidence level was performed. Where statistically significant differences were observed. Pearson's product moment correlation coefficient (r) was calculated to examine linear relationships between physico-chemical parameters and metal concentrations. Principal Component Analysis (PCA) was employed to identify underlying factors influencing water quality, using eigenvalues greater than 1 as the criterion for component extraction. The suitability of the dataset for factor analysis was evaluated using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity.

Results

Physical Parameters

Physico-Chemical Characteristics of Surface Water

The physico-chemical properties of surface water samples from four mining-impacted communities in the Mpohor Wassa East District, along with a control site, are summarized in Table 1. The pH values of the surface water samples ranged from 6.5 at Asowuo Ayipa (ASA) and Mpohor Motorway (MM) to 7.1 at the control site, with standard deviations of 0.32 and 0.17, respectively. These values fall within the acceptable range for natural waters. One-way ANOVA revealed no statistically significant differences in pH among the sampling sites ($p > 0.05$). Similarly, water temperature varied modestly, ranging from 24.6°C at Adum Tokoro (ADT) to 25.4°C at Mpohor Adawotwe (ADW). These differences were also not statistically significant ($p > 0.05$). The highest mean EC value was observed at MM (152.3 ± 24.4 µS/cm), while the lowest was at the control site (58.7 ± 3.4 µS/cm) (Figure 3). ANOVA indicated significant variation among sites ($p < 0.05$), and Tukey's HSD post-hoc test revealed significant differences between

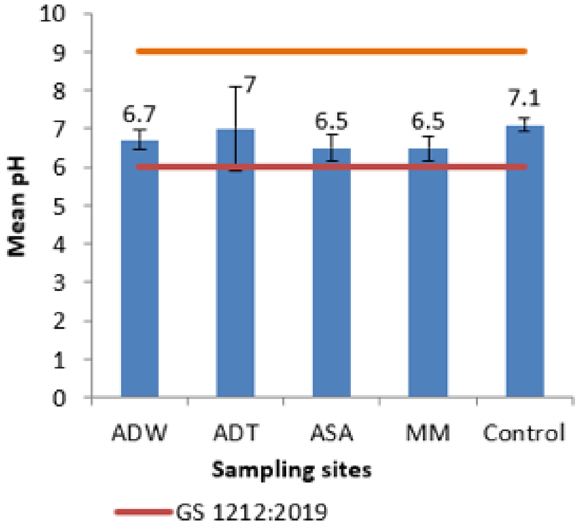

Figure 2 pH Variations across surface water locations

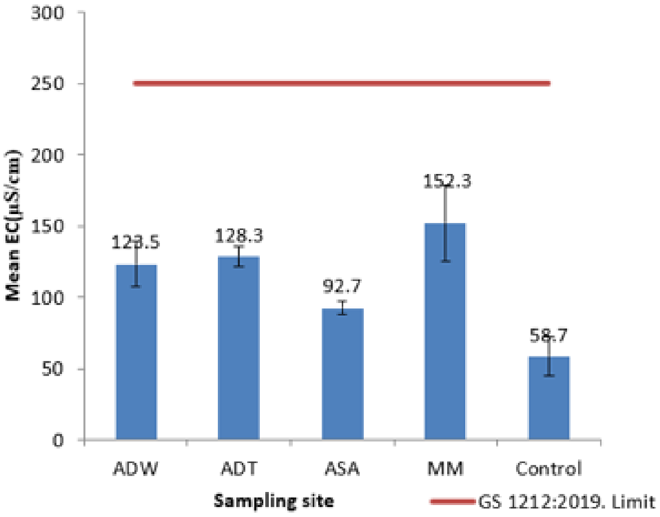

Figure 3 Conductivity Variations across surface water locations

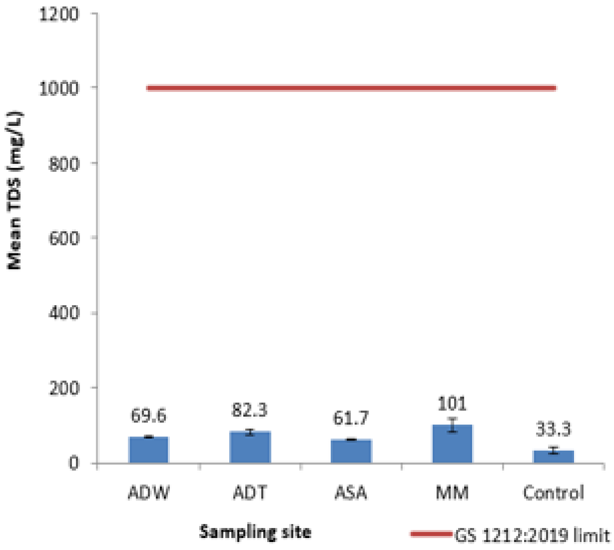

Figure 4 TDS Variations across surface water locations

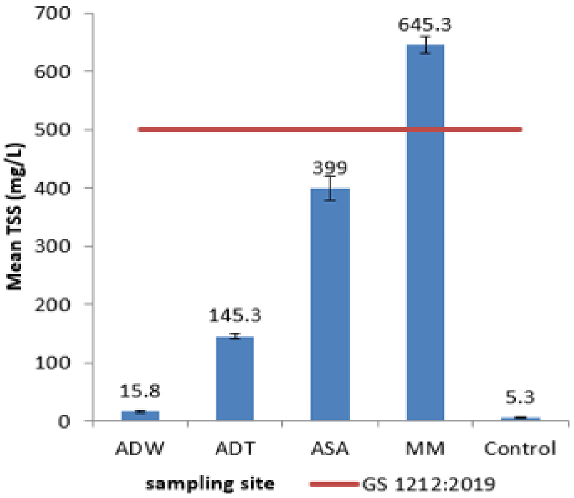

Figure 5 TSS Variations across surface water locations

MM and the control (p = 0.004), ADT and control (p = 0.002), and ADW and control (p = 0.001). Correspondingly, TDS values followed a similar pattern, with MM recording the highest mean (101 ± 17.2 mg/L) and the control site the lowest (33.3 ± 9.1 mg/L). These differences were statistically significant (F = 21.8; p = 0.0001).

TSS concentrations were highest at MM (645.3 ± 14.8 mg/L) and lowest at the control site (5.3 ± 0.5 mg/L) (Figure 5). Statistical analysis revealed significant differences among sites (F = 178; p = 0.0001). Turbidity also showed marked variation, ranging from 2.5 ± 0.7 NTU at the control site to 299.2 ± 12.2 NTU at MM. The differences in turbidity across sites were statistically significant (p = 0.001), indicating elevated sediment loads likely associated with nearby artisanal mining activities. Total alkalinity was highest at the control site (64.3 ± 8.0 mg/L) and lowest at ASA (9.0 ± 2.6 mg/L), with significant differences across sites (F = 160.4; p = 0.0001). For total hardness, ADT recorded the highest mean value (72.6 ± 0.67 mg/L), while the control site exhibited the lowest (11.7 ± 2.8 mg/L). ANOVA confirmed significant variation among sites (p = 0.001), reflecting differences in ionic concentrations likely linked to mining-related geochemical inputs. Dissolved oxygen levels varied from 5.4 ± 0.91 mg/L at ASA to 12.9 ± 3.7 mg/L at the control site. These differences were statistically significant (p = 0.02), suggesting reduced oxygenation in mining-impacted waters. In contrast, BOD values ranged from 1.0 ± 0.42 mg/L at the control site to 1.7 ± 0.60 mg/L at ADW, although no significant differences were observed among sites (p = 0.349). Salinity was highest at ADT (2.0 ± 0.06 mg/L) and lowest at the control site (0.00 mg/L). The differences were statistically significant (p = 0.013), indicating possible ion influx from surrounding geological and anthropogenic sources.

Heavy metals

The concentrations of heavy metals in surface water samples from the Mpohor Wassa East District are summarized in Table 1. The data reveals distinct spatial variability in metal concentrations across the four sampling sites and the control location. Iron (Fe) concentrations ranged from 0.41 to 0.49 mg/L at Asowuo Ayipa (ASA), with a mean of 0.46 ± 0.04 mg/L, the lowest among all sites. In contrast, the highest Fe concentrations were observed at the control site, ranging from 1.28 to 3.17 mg/L and yielding a mean value of 2.40 ± 0.97 mg/L. This anomaly may reflect natural geogenic input or redox variations at the control location. Cobalt (Co) was not detected in control samples. The highest Co concentration was recorded at Adum Tokoro (ADT), ranging from 0.01 to 0.04 mg/L, with a mean of 0.03 ± 0.00 mg/L. Copper (Cu) was also absent from control samples and reached

TABLE 1

Heavy Metals in Surface Water Samples from the Mpohor Wassa East District

Parameter	ADW	ADT	ASA	MM	Control	WHO Standard	Ghana Standard (GS 1212:2019)
Physicochemical Parameters							
pH	6.6	6.5	6.5	6.5	7.1	6.5–8.5	6.5–8.5
Temperature (°C)	25.4	24.6	25.1	25.2	24	22–27	22–27
EC (µS/cm)	90.2	60.4	82.5	152.3	58.7	1500	1500
TDS (mg/L)	91	88	94	101	85	1000	1000
TSS (mg/L)	432.1	332.8	523.1	645.3	5.3	500	500
Turbidity (NTU)	204.6	257.8	154.3	299.2	2.5	5	5
DO (mg/L)	7.6	6.3	5.4	8.3	12.9	≥7.5	≥5
Alkalinity (mg/L)	24	20	9	28	64.3	400	500
Total Hardness (mg/L)	62.4	72.6	66.2	56.3	11.7	500	500
BOD (mg/L)	1.7	1.4	1.3	1.5	1	6	6
Salinity (mg/L)	1.4	2	1.6	1.8	0	200	200
Heavy Metals (mg/L)							
Fe	1.44	0.75	0.46	1.8	2.4	0.3	0.3
Co	0.01	0.03	0.02	0.01	ND	ND	ND
Cu	0.0002	0.32	0.0002	0.0001	ND	2	2
Cr	ND	0.006	0.001	0.003	ND	0.05	0.05
Ni	0.02	0.31	0.29	0.21	0.02	0.07	0.07
Zn	0.08	0.49	0.04	0.002	0.003	3	3
As	0.00006	0.0003	0.0002	0.00001	ND	0.01	0.01
Hg	0.0002	0.0003	0.0002	ND	ND	0.002	0.002
Mn	0.4	0.41	0.38	0.43	0.2	0.4	0.4
Cd	0.3	0.2	0.1	0.2	0.06	0.003	0.003
Pb	0.006	0.005	0.02	0.003	0.0003	0.01	0.01

Mean ± SD (Range) ADW: Adawotwe; ADT: Adum Tokoro; ASA: Asowuo Ayipa
MM: Mpohor Motorway
Source: Field Data, Annan (2021) N.D = No Detection

its maximum at ADT, where concentrations ranged from 0.20 to 0.38 mg/L, with a mean of 0.32 ± 0.01 mg/L. Chromium (Cr) was not detected at either Mpohor Adawotwe (ADW) or the control site. The highest Cr levels were found at ADT, with values ranging from 0.004 to 0.008 mg/L and a mean concentration of 0.006 ± 0.00 mg/L. Nickel (Ni) concentrations were highest at ADT, ranging from 0.22 to 0.39 mg/L, with a mean of 0.31 ± 0.08 mg/L. This elevated concentration suggests a significant anthropogenic or lithogenic influence at this location. Zinc (Zn) recorded its lowest concentrations at the control site, ranging from non-detectable levels to 0.01 mg/L (mean = 0.003 ± 0.001 mg/L). The highest Zn levels were found at ADT, ranging from 0.27 to 0.93 mg/L, with a mean of 0.49 ± 0.01 mg/L. Mercury (Hg) and arsenic (As) were not detected in control site samples. However, both elements were found at trace levels in impacted sites, with mean concentrations of 0.0003 ± 0.00 mg/L for each. While these values appear low, even trace levels of Hg and As can be of toxicological concern in aquatic environments. Cadmium (Cd) concentrations were lowest at the control site (0.05–0.07 mg/L; mean = 0.06 ± 0.01 mg/L) and highest at ADW, where concentrations ranged from 0.11 to 0.54 mg/L (mean = 0.30 ± 0.02 mg/L). These values exceed typical background levels and suggest direct contamination from ASGM activities. Lead (Pb) levels were lowest at the control site (mean = 0.0003 ± 0.00 mg/L) and highest at ASA, with a mean concentration of 0.02 ± 0.0001 mg/L.

Statistics

Factor Analysis

To identify the underlying factors influencing water quality variation and pollution sources in surface water samples from Mpohor Wassa East District, Principal Component Analysis (PCA) with Varimax rotation and Kaiser Normalization was performed. The analysis included all measured physico-chemical and heavy metal parameters. Factors with eigenvalues greater than one (≥1) were retained in accordance with established criteria (Liang et al., 2014; Bhat et al., 2014; Winkler et al., 2013; Kose et al., 2016). A total of 25 components were initially extracted, of which the first six accounted for 88.611% of the total variance and were deemed sufficient for further interpretation (Table 2). PC-1, which explained 22.501% of the total variance, was strongly loaded with turbidity, cobalt (Co), chromium (Cr), copper (Cu), arsenic (As), and cadmium (Cd). Moderate loadings were observed for total hardness, nickel (Ni), zinc (Zn), mercury (Hg), magnesium (Mg), lead (Pb), and iron (Fe). This component likely reflects the influence of anthropogenic pollution from artisanal gold mining activities, particularly those involving metal processing and sediment disturbance. PC-2 accounted for 21.490% of the total variance and was strongly associated with electrical conductivity (EC), total dissolved solids (TDS), salinity, manganese (Mn), and sodium (Na), while showing moderate loadings for total alkalinity, As, Mg, Pb, and Cd. This factor appears to represent the contribution of dissolved ions and salinity-driven inputs, possibly from mineral weathering or runoff enriched by mining operations. PC-3, which explained 20.185% of the variance, was heavily loaded by total alkalinity, bicarbonates (HCO_3^-), calcium (Ca), and Pb, with moderate contributions from Fe and Zn. This factor may reflect geogenic controls, especially carbonate dissolution and cation exchange processes. PC-4 accounted for 9.273% of the total variance and was predominantly influenced by pH, with Zn moderately loading. This factor suggests the buffering capacity of the water and the influence of pH on trace metal solubility and speciation. PC-5, contributing 7.830% of the variance, was strongly loaded by total suspended solids (TSS), indicating the role of sediment load and erosion in shaping surface water quality—likely a direct consequence of soil disturbance from mining. PC-6 explained 7.330% of the total variance and was strongly associated with Hg and potassium (K), suggesting discrete

TABLE 2

Rotated Component Matrix of physico-Chemical Parameters, Mpohor Wassa East

Variable	Components						communalities
	PC1	PC2	PC3	PC4	PC5	PC6	
Temperature	-0.169	0.149	-0.119	0.409	-0.205	0.142	0.782
EC	0.135	0.912*	-0.117	0.134	0.211	0.147	0.947
TDS	0.255	0.720*	-0.076	-0.037	0.507	0.049	0.85
pH	0.395	-0.188	0.278	0.742*	-0.004	-0.161	0.846
Salinity	0.286	0.855*	0.188	-0.26	-0.065	-0.023	0.921
TSS	-0.14	0.327	-0.11	-0.041	0.875*	0.242	0.965
Alkalinity	0.063	-0.005	0.970*	-0.011	0.046	-0.055	0.95
Bicarbonates	0.098	0.023	0.965*	-0.069	0.085	0.046	0.956
Turbidity	0.894*	0.111	0.042	0.342	0.154	-0.026	0.954
Total Hardness	0.609**	0.694**	0.2	-0.15	0.142	0.12	0.95
Fe	-0.553**	-0.001	0.689**	0.164	-0.157	-0.105	0.842
Co	0.750*	0.04	-0.436	-0.301	0.032	0.309	0.941
Cu	0.910*	0.223	0.176	-0.216	-0.16	0.018	0.981
Cr	0.961*	0.18	0.143	0.051	-0.054	-0.005	0.982
Ni	0.553**	0.227	-0.315	-0.254	0.458	0.214	0.777
Zn	0.566**	0.305	0.052**	-0.661**	-0.338	0.068	0.971
As	0.723*	0.585**	0.033	0.347	0.087	0.393	0.692
Hg	0.624**	0.197	-0.531	0.121	0.005	0.715**	0.917
Mg	0.669**	0.656**	0.174	-0.081	0.059	0.111	0.93
Mn	0.107	0.732*	-0.552	-0.141	0.057	0.15	0.898
Ca	0.254	-0.157	0.903*	-0.071	-0.113	-0.018	0.923
K	0.075	0.064	0.254	-0.065	0.267	0.776*	0.751
Na	0.399	0.760*	-0.001	-0.039	0.461	0.175	0.982
Pb	0.603**	-0.540**	-0.721*	-0.173	0.288	0.321	0.737
Cd	0.757*	0.670**	-0.37	0.095	-0.138	-0.301	0.708
Eigenvalue	8.53	5.218	3.308	2.082	1.806	1.209	
% of variance	22.501	21.49	20.185	9.273	7.83	7.33	
% Cumulative	22.501	43.992	64.177	73.45	81.281	88.611	

*Strong (factor score>0.75); **Moderate (0.5≤score≤0.75), Weak (Score<0.5)

geochemical or contamination sources, such as mercury amalgamation practices commonly observed in artisanal mining. Variables with factor loadings ≥ 0.5 were considered significant for interpretation, with loadings between 0.5 and 0.7 classified as moderate and ≥0.7 as strong. Communalities analysis revealed that most parameters contributed substantially to the total explained variance, with all but arsenic (As; 69.2%) contributing more than 70%. This confirms the robustness of the retained components and the reliability of the underlying structure identified by the PCA model. These six components jointly describe the complex interplay between geogenic processes and anthropogenic activities, particularly mining that influence the hydrochemical characteristics of surface water in Mpohor Wassa East. The dominance of heavy metals and TSS among the leading components underscores the need for targeted monitoring of these parameters in environmental management efforts.

A scree plot was used to determine the optimal number of factors or principal components to retain for further analysis. The eigenvalues of each factor were organized in descending order, allowing the researchers to identify the point at which the marginal gain in explained variance begins to level off, a pattern commonly referred to as the "elbow" effect (Cartell, 1997). Using this rule of thumb, all components that appeared above the elbow were considered significant and were retained. In the current study, six components had eigenvalues greater than 1. The scree plot revealed a distinct elbow at the fourth factor, indicating that four components should be retained for subsequent analysis (Figure 6).

Correlation of Physico-Chemical Parameters

To examine the relationship, directions, and strengths among the physico-chemical parameters of surface water samples collected from the Mpohor Wassa East sampling sites, Karl Pearson's correlation coefficient was employed. The results of the correlation matrix are presented in Table 3.

Several significant positive correlations were observed among key parameters. Electrical conductivity (EC) showed strong positive correlations with total dissolved solids (TDS) (r=0.82), salinity (r=0.72), total hardness (r=0.727), manganese (r=0.737), magnesium (r=0.708), and sodium (Na) (r=0.870). Alkalinity exhibited a very strong correlation with bicarbonates (r=0.708), while TDS also correlated positively with total suspended solids (TSS) (r=0.632). Salinity was positively associated with both total hardness (r=0.884) and bicarbonates (r=0.888). Sodium (Na) also correlates with TDS (r=0.910).

In contrast, pH showed a weak negative correlation with all the heavy metals analysed in the surface water samples from the Mpohor Wassa East area, suggesting a potential inverse relationship between acidity and metal concentration in the study area.

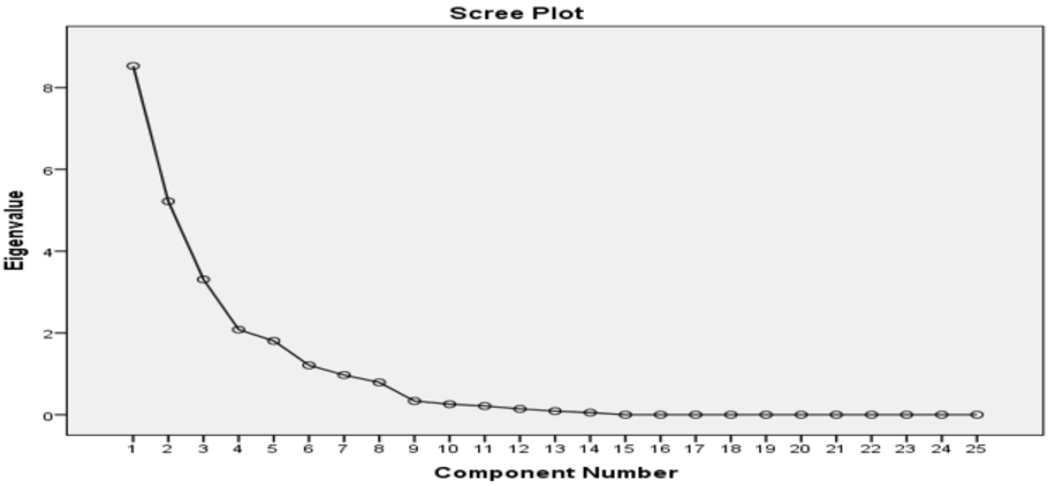

Figure 6 Screen plot of physico-chemical parameters, Mpohor Wassa East

TABLE 3

Correlation between Physicochemical Parameters in Water Samples, Mpohor Wassa East District

Parameter	EC	TDS	TSS	Sal	Na	Mg	Ca	Alkal	Bicarbonates	Hardness
EC	1									
TDS	0.820**	1								
TSS	0.487	0.632*	1							
Sal	0.720*	0.646*	0.195	1						
Na	0.870**	0.940**	0.631*	0.711*	1					
Mg	0.708	0.700*	0.171	0.754*	0.837*	1				
Ca	-0.28	0.228	-0.285	0.122	0.07	0.232	1			
Alkalinity	-0.112	0.078	-0.091	0.202	0.016	0.166	0.884*	1		
Bicarbonates	-0.049	-0.022	-0.039	0.232	0.096	0.235	0.888*	0.983**	1	
Hardness	0.727	0.775	-0.265	0.790*	0.248	0.977*	0.211	0.21	0.21	1

**Correlation is significant at $p < 0.01$ level (2-tailed).
*Correlation is significant at $p < 0.05$ level (2-tailed)

Discussion

Physico-Chemical Quality of Surface Water

Surface water samples collected from Mpohor Wassa sampling sites were found to be neutral to slightly alkaline, with pH values falling within the acceptable range of 6.0 to 9.0, as prescribed by both WHO (2010) and the Ghana Standards Authority (GS 1212:2019) for drinking water. These pH values indicate generally good water quality. Maintaining pH within this range is important, as lower pH levels can increase the solubility of heavy metals in water, potentially resulting in elevated concentrations of toxic metals. Such conditions pose significant health risks to consumers and can adversely affect aquatic life (Asante Ababio and Boadu, 2017). Surface water samples at Asowuo Ayipa (ASA) and Mpohor Motorway (MM) were slightly acidic (6.5), while the water at Mpohor Anomabo control site registered neutral pH (7.1). The buffering mechanisms of carbonate and silicate substances leached from geological layers appear to regulate the pH equilibrium between all monitoring points, as indicated by statistical comparisons ($p > 0.05$), which show no significant variations. Kesse (1985) explains how the Birimian Supergroup lateritic and phyllitic terrain of Mpohor Wassa East District produces moderate water alkalinity. The lower pH measurements at ASA and MM seem to indicate acid-producing processes, which often occur due to sulfide mineral oxidation from artisanal gold extraction (Donkor et al., 2006). Similar pH trends have been reported in mining-affected surface waters in Tarkwa and Obuasi, Ghana, where sulfide mineral oxidation and mine drainage influenced the acidity of nearby streams (Akabzaa et al., 2007; Attua et al., 2014).

There was no significant difference in temperature between the surface water in the different sampling locations in the Mpohor Wassa District. Every value obtained was in the range of natural background 22 to 27°C as required by the World Health Organization (WHO) (WHO, 2010). These steady measurements indicate that there are steady thermal conditions in the study region at the time of sampling.

Temperature is a critical parameter in aquatic ecosystems, as it directly influences both aquatic life and the physico-chemical characteristics of water, including solubility, chemical reaction rates, and biological activity (Armah et al., 2013; Annan et al., 2018).

The results for the Electrical Conductivity (EC) revealed a noticeable distinction in measurements ($p < 0.05$), where MM registered 152.3 ± 24.4 µS/cm as the highest reading and the control area exhibited 58.7 ± 3.4 µS/cm as the lowest value. The presence of elevated EC values indicates increased amounts of ions because of mineral dissolution along with human-induced inputs (Appelo & Postma, 2005). EC levels reached high values in MM ADT and ADW, probably because dissolved ions entered the system through mining-affected runoff and potential agrochemical residue accumulation, which results from both mining and farming operations in the area. The measured concentrations fall under WHO's safe drinking water standards at 1,500 µS/cm, but the marked difference between these sites shows that clear human-induced activity has significantly increased the water ionic content. Similar elevated electrical conductivity values have been reported in mining-affected surface water systems in Ghana and other artisanal mining regions, where increased dissolved ion originated from mineral weathering, mine tailings and runoff from mining activities (Armah et al., 2013; Wongssauluk et al., 2013; Akoto et al., 2021; Abu et al., 2024).

At the Mpohor Wassa East District sampling sites, the highest concentration of dissolved oxygen (DO) was recorded at the control site, with a mean value of 12.9 mg/L, while the lowest DO level was observed at site ASA, with a mean value of 5.4 mg/L. Mining activities likely contributed to the reduced dissolved oxygen (DO) levels observed at the impacted sampling sites through increase sedimentation, organic loading and oxidation of sulfide-bearing minerals. Artisanal mining disturbs streambeds and surrounding soils, increasing suspended particles and reducing light penetration and oxygen transfer within the aquatic system (Armah et al., 2013; Anann et al., 2018). In addition, the decomposition of organic matter and oxidation of mining-related waste materials may further deplete dissolved oxygen concentrations in surface water (Younger, 2001). Similar reduction in DO have been reported in mining-affected water bodies in Tarkwa and Obuasi, Ghana, where artisanal mining activities significantly altered stream ecological conditions (Attua et al., 2014; Donkor et al., 2006)

Low dissolved oxygen (DO) in mining-affected areas may result from microbial decomposition of organic matter or chemical oxidation of sulfide minerals, both of which are common in disturbed mining catchments (Younger, 2001). Water with a dissolved oxygen (DO) level below 6.0 mg/L may be stressful for aquatic life, and levels below 4.0 mg/L may be inadequate for sensitive species (USEPA, 2000). DO depletion at ASA, therefore, suggests ecological stress and reduced self-purification capacity. However, a provisional health-based guideline value of at least 7.5 mg/l was indicated for the purpose of public health protection (WHO, 2010). Throughout the study period, dissolved oxygen (DO) levels in nearly all surface water samples from the Mpohor Wassa East District fell below the recommended guideline value. DO is a critical indicator of water quality, with a minimum threshold of 5 mg/L required to sustain most forms of aquatic life (WHO, 2010). The observed low DO levels are likely due to the presence of high concentrations of oxidizable substances, particularly organic matter. When organic matter builds up, aerobic microorganisms use up huge quantities of oxygen to decompose it, and thus the oxygen is lost (Annan et al., 2018; Hutchinson and Meema, 2017).

Such poor oxygenation can cause conditions conducive to anaerobic microbial growth, which could lead to offensive smell and make the water unfit to be consumed by humans (Lenn, 2017). DO is generally considered to be one of the most significant parameters in lakes and other freshwater systems estimation (Amegbey and Eshun, 2003). Even though aquatic biodiversity is best supported in higher DO environments, low levels of less than 3 mg/L can have a devastating impact on aquatic life and the quality of overall water (Fondriest Environmental Inc., 2014).

Biological Oxygen Demand (BOD) is a method of determining the amount of organic pollution present in water by the amount of oxygen needed by microbes to decompose organic matter. The World Health Organization states that water which is considered safe to drink must be free of organic matter (WHO, 2010). In this experiment, even though the values of BOD in the control sites were somewhat lower, all the obtained values were above the WHO recommended limit of zero per 100mL, meaning that the water cannot be directly consumed. High levels of BOD can be caused by insufficient mixing of oxygen in the atmosphere with the water and increased levels of organic pollution, probably caused by anthropogenic sources, specifically artisanal mining. Such untreated water also presents a serious health risk to a community (Winkler et al., 2013; Annan et al., 2018).

WHO (2014) recommends that the limit of total alkalinity in drinking water should not exceed 400 mg/L, and during the study, the alkalinity of all samples of surface water did not exceed this level, indicating that the water is not too sensitive to the rapid changes in pH. The control site contained the highest level of alkalinity (64.3 +- 8.0 mg/L and the lowest ASA (9.0 +- 2.6 mg/L). The statistical analysis showed that the difference observed was significant with an effect size of F = 160.4 (p = 0.0001), and the impacts of acidification or dilution by mining activities at the sites. The small concentrations of alkalinity in ASA may predispose the site to acid mine drainage since the chemical constituent serves as a shield against changes in PH (Sahoo et al., 2013). Similar low alkalinity conditions have been reported in mining-affected streams in southwestern Ghana, where acid-generating sulfide minerals reduced the buffering capacity of surface waters (Akabzaa et al., 2007; Attua et al., 2014). The fact that the sites of mining affected by the ASA are characterized by low alkalinity values could be evidence that the buffering capacity was used up by acidic sulfate compounds (Attua et al., 2014). The alkalinity content of the water samples was kept within reasonable thresholds during research time. Whereas the maximum allowed level is 400 mg/L (World Health Organization (WHO, 2014), the United States Environmental Protection Agency (USEPA) and the Ghana Water Company (GWC) tolerate 500 mg/L (WHO, 2014). Even though alkalinity does not relate directly to the public health issue, it is an important factor in buffering capacity and pH regulation. Carbonates, bicarbonates, hydroxides, phosphates, borates, and organic acids are the major sources of alkalinity in water. The low alkalinity levels noted in this study could also be explained by the immediate geology which is sedimentary and composed of limestone and sandstone that are abundant in carbonate and bicarbonate ions (Akabzaa et al., 2007).

The salinity (the sum of all the dissolved salts in water) is often determined by total dissolved solids (TDS) or electrical conductivity (EC). WHO regulations state that the salinity level must not exceed 200 mg/L lest it causes salty taste to drinking water (Akabzaa et al., 2007). Any water sample that was studied during the study was found below this threshold. These findings are similar to those of the social survey where 85 percent of the respondents indicated that the water was not salty.

Electrical conductivity or the overall ionic content of water also did not exceed the allowable limit of 250 uS/cm as recommended by WHO and Ghana Standards Authority. EC positively relates with TDS, which can be calculated by multiplying EC value by a conversion factor that is usually equal to half or three quarters (Yadav et al., 2015). TDS is used to determine the level of dissolved organic and inorganic stuff in water (Agyeman et al., 2012). The values of TDS in all the sampling sites in this study were lower in comparison with the WHO guideline value of 1000 mg/L. It should be mentioned that water that contains more TDS than this amount could be regarded as distasteful by consumers (WHO, 2010).

The concentration of the particulate matter in the water is measured as total suspended solids (TSS), which determine the visual clarity of surface water and the overall quality of water. WHO guideline states that TSS must not be more than 500 mg/L to be regarded as safe to consume (WHO, 2014). Even though most of the sites satisfied this criterion, the maximum TSS was obtained at the Mpohor Motoway (MMW) site in the Mpohor Wassa District, with the mean value of 645.3 mg/L, which is higher than the recommended limit and indicates the possibility of particulate contamination at the site. This is due to the presence of higher EC values which reflect higher levels of ions due to mineral dissolution and anthropogenic inputs (Appelo and Postma, 2005). The high EC of MM, ADT and ADW is likely to be due to dissolved ions being introduced via runoff and potential accumulation of agrochemical residues, both associated with mining and agricultural activity in the region. The measured values are lower than the WHO safe drinking water standard of 1,500 mS/cm but the significant difference between the two locations indicates that human-generated activity has had a significant impact on increasing the ionic content of water.

The World Health Organisation (WHO) states that the guideline value of turbidity in drinking water is 5 NTU (Nephelometric Turbidity Units). In this research, the turbidity of most of the sampling sites is very high compared to this limit. The maximum turbidity of 299.2 NTU was observed in one of the sites in the Mpohor Wassa District. All the sampled communities except the control site had turbidity levels above the allowable WHO and Ghana Standards Authority levels.

This high turbidity is a cause of concern and can probably be attributed to soil disruptions caused by artisanal mining in the region. The elevated turbidity observed in this study is consistent with findings from other artisanal mining regions in Ghana, particularly Tarkwa and Obuasi, where mining-related land disturbance and sediment mobilization significantly increased suspended particulate matter in nearby rivers and streams (Armah et al., 20011; Annan et al., 2018; Woananu et al., 2024). As the rainfall occurs, silt, clay, organic body, and other particulates on the disturbed mining landscapes are transported by surface runoff into the adjacent water bodies, contributing to turbidity. Lasting intensities of turbidity when not managed, may cause the surface water sources to become sedimented and silted (Armah et al., 2011). Such circumstances impair aquatic habitats, lower water quality and can adversely affect fish populations and aquatic biodiversity, inhibiting light penetration, smothering eggs and benthic organisms and reducing total productivity.

Heavy Metals in Surface Water

A significant source of heavy metal contamination in surface water includes artisanal mining that can add toxic elements to the water (arsenic (As), mercury (Hg), lead (Pb), copper (Cu), and cadmium (Cd)) (Creek, 2016). These are the top ten of the most important public health issues in the world (WHO, 2014). One of the major contributors to heavy metal pollution of rivers and streams is mining-related activity, especially in developing countries where artisanal mining is widespread and environmental regulations are weak (Akabzaa et al., Armah et al., 2013; Queensland DEHP, 2019). Recent hydrogeochemical assessments in mining catchments across Ghana have similarly identified artisanal mining activities as major drivers of elevated concentrations of potentially toxic elements in water resources (Abu et al., 2024; Ofori et al., 2024). Several studies in Ghana have reported elevated concentrations of arsenic, mercury, cadmium and lead in mining-affected water bodies due to ore processing, tailings discharge and mercury amalgamation practices associated with ASGM activities (Donkor et al., Annan et al., 2018).

World Health Organisation (WHO) guidelines state that the acceptable amounts of heavy metals in drinking water are mercury 0.002 mg/L, arsenic 0.01 mg/L, lead 0.01 mg/L, cadmium 0.005 mg/L and copper 1.3 mg/L. The mercury content in water samples obtained in the Mpohor Wassa District in this study was higher than the WHO and Ghana Environmental Protection Authority (EPA) content limit, which serves as an indication of a strong anthropogenic influence, probably because of artisanal mining. The control site, however, registered mercury levels within acceptable limits (USEPA, 2002).

Surface water samples also contained arsenic levels that were reported to exceed 0.01 mg/L (WHO recommended concentration) throughout the district. High levels of arsenic are probably related to runoff of the artisanal mining activity and to weathering of arsenopyrite-enriched rocks, typical of the Birimian geological terrane (Rambaud et al., 2016; Simon et al., 2004; Serfor-Armarh et al., 2006). This is very clear at the Mpohor Motorway, where the maximum as concentration was measured and the locals use the polluted water source to serve as domestic use.

Arsenic also might be explained by the treatment of gold ores, especially the roasting process, which emits arsenic trioxide gas into the atmosphere. It is possible to deposit this gas on soil and then be washed into surface and groundwater (Amasa, 1975; Osei et al., 2010; Smedley, 2003). WHO (2017) indicates that arsenic enters the water body due to erosion, dissolution and weathering of geological formations which contain arsenic. These results indicate that the arsenic pollution in the area of study is both natural and manmade. Arsenic exposure has been associated with acute and chronic health outcomes, such as death, growth retardation, reproductive toxicity, retarded photosynthesis in aquatic vegetation, and cognitive retardation in humans (Wetzel, 2001).

Cadmium and lead concentrations also exceeded the WHO permissible limits of 0.005 mg/L and 0.01 mg/L, respectively. This suggests a strong anthropogenic source most likely linked to artisanal mining activities. Principal Component Analysis (PCA) further supports this, showing that both elements shared a common source. Nickel levels were notably high at several Mpohor Wassa sampling sites, aligning with findings from similar mining contexts in Jharkhand, India (Donkor et al., 2006), although higher than values reported in Turkey (Yavuz et al., 2010) and lower than those observed in Tarkwa, Ghana (Donkor et al., 2006).

Although Pb concentration (0.02 mg/L) was observed at site ASA, it still exceeded WHO's recommended threshold. Even trace levels of lead pose significant health risks, especially for children, as recognized by the United States Environmental Protection Agency (USEPA, 2014).

Overall, the observed heavy metal concentrations in this study are consistent with those reported in other artisanal mining communities, such as Obuasi (Donkor et al., 2006; Yidana et al., 2012). PCA revealed that Principal Component 1 (PC-1) accounted for 22.5% of total variance and was strongly loaded by Co, Cr, Cu, As, and Cd, and moderately by Ni, Zn, Hg, Mg, Pb, and Fe. This suggests that these metals are the primary contributors to water-quality variation in the Mpohor Wassa District. Similar applications of Principal Component Analysis in hydrochemical studies have successfully identified mining-related and geogenic sources of contamination in surface water systems within Ghana and other developing mining regions (Helena et al., 2000; Varol et al., 2012; Kazapoe et al., 2023; Addai, 2025).

These findings underscore the need for district-level water quality monitoring strategies that prioritise heavy metals based on local mining impacts. Monitoring efforts must be tailored to each district's specific contamination profile to manage and mitigate pollution risks effectively. The transport of trace metals in streams is guided by both the form of the trace metal and its oxidation properties and its ability to complex organic matter and mineral elements. The measured high concentrations of Fe, Mn and Cd within the stream water support partial oxidation conditions, which lead to metal oxide dissolution and surface colloidal desorption (Stumm & Morgan, 1996). The dynamic flow regime sustains metals in the dissolved phase due to reduced residence times and lower adsorption onto sediments compared to stagnant systems (Younger et al., 2002).

Both Fe and Mn show elevated concentrations, which indicates that co-precipitation mechanisms alongside scavenging processes take place due to the well-known role of these elements as hydroxide floc carriers (Appelo & Postma, 2005). Trace metal buildup in the Mpohor Wassa area derives mainly from mining processes, which include ore washing along with mercury amalgamation and tailings discharge, possibly at ADT and ADW. The mining signature featuring high Zn/Cd ratios and enhanced Ni levels stands clearly at these sites because of the recurring Cd, Zn, and Ni elevations (Adjei et al., 2020). The measurements of Co alongside Cr strengthen the evidence for local ultramafic rocks being exposed to the surface through waste rock debris or acidic drainage from tailings accumulations.

Long-term exposure to heavy metal-contaminated water may pose serious health risks to communities that depend on these surface water sources for domestic activities. Although zinc and copper are essential trace elements, prolonged exposure to elevated concentrations may result in adverse effects. More importantly, cadmium, lead, mercury and arsenic are toxic even at relatively low concentrations and may cause neurological, renal, developmental and carcinogenic effects following chronic exposure (WHO, 2017; USEPA, 2014). The elevated concentrations observed in some sampling sites therefore indicated potential public health concerns and highlighted the need for regular monitoring and appropriate remediation measures in mining-affected communities. Comparable public health concerns associated with mining-related water contamination have been reported in other Ghanaian mining communities and similar developing-country environments (Egbueri et al., 2023; Ofori et al., 2024.

Conclusion

This study evaluated the surface water quality in the Mpohor Wassa District in Ghana using multivariate statistical methods. The findings revealed that although most physicochemical parameters were within the permissible limits recommended by the World Health Organization (WHO) and the Ghana Standards Authority for drinking water, turbidity levels at several sampling sites exceeded recommended limits, indicating significant sediment contamination likely associated with artisanal mining activities. Elevated concentrations of iron, cadmium, nickel and lead were also observed at some sampling locations, suggesting potential environmental and public health concerns in the district.

Principal Component Analysis (PCA) and Factor Analysis identified cobalt, chromium, copper, arsenic and cadmium as the major contributors influencing surface water quality in the district. Other metals, including nickel, zinc, mercury, manganese, lead and iron, were moderately associated with water quality deterioration, indicating both anthropogenic and geogenic influences. These findings underscore the need for continuous monitoring and strengthened regulatory control of mining-related pollution to safeguard public health and aquatic ecosystems in mining-impacted areas.

The findings of this study provide important baseline information for understanding the impact of artisanal and small-scale gold mining on surface water resources within the Mpohor Wassa District. The study will benefit local communities, environmental management agencies and policymakers by supporting evidence-based decision-making, water quality monitoring, pollution mitigation and sustainable water resource management strategies aimed at protecting both human health and the surrounding environment.

Data availability statement

Data included in article/supp. Material/ referenced in article.

Credit authorship contribution statement

Stephen Twumasi Annan: Writing, Investigation, Data curation, Conceptualization, Funding acquisition. Kwabina Ibrahim: Writing– original draft, Writing–review & editing, Data curation, Methodology, Conceptualization. Raymond Webrah Kazapoe: Writing– original draft, Writing–review & editing. Bright Frimpong: Data curation, Validation, Methodology, Investigation. Frank K. Nyame: Supervision, Investigation, Methodology, Validation. Alfred A. Yankson: Writing – review & editing. Roland Asare: Writing – review & editing. Adwoba Edjah:Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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