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Assessment of Groundwater Quality in Agona East District, Ghana

James Kwame Kusi [1*] **,** ***Sam Arkoful*** [1] **,** ***Twumasi Ankrah Kwarteng*** [1] **,** ***Jacob Dadzie*** [2]

[1] *Department of Chemistry Education, University of Education, Winneba P.O. Box 25, Ghana*

[2] *Laboratory Department, Ghana Water Company Limited, Kwanyako P.O. Box KN 49, Ghana*

ABSTRACT

Groundwater also remains an important source of domestic water for rural areas in Agona East district, despite its quality being constantly endangered by natural and human-induced conditions. In this study, the physicochemical parameters and heavy metals present in hand-dug wells in eight rural communities in the Agona East District in Ghana were assessed. Water samples were collected and analyzed for tests that included pH, turbidity, colour, total dissolved solids (TDS), and levels of Fe, Pb, and As, and these were compared with standards outlined by the World Health Organization for clean drinking water. Results indicated that most physicochemical parameters were within World Health Organization (WHO) permissible limits. However, Fe concentrations in Asamoakwaa and Tawora exceed acceptable levels, likely due to geological sources such as Fe-rich parent bedrock. Trace levels of Pb were detected in Sakwa-kwa and Kokwaado. While the overall groundwater quality in the district is suitable for domestic use (Water Quality Index (WQI) = 38.99), site-specific contamination by heavy metals calls for targeted mitigation measures. The Hazard Index (HI) value was less than 1, indicating that the groundwater is likely not to pose a noncarcinogenic effect on consumers. Also, adults and children who depend on groundwater in Agona East district are not likely to suffer carcinogenic effects since the Carcinogenic Risk Index (CRI) for these groups was below their threshold value (1×10^{-4}). It is recommended that the Environmental Protection Agency (EPA) officers in Agona East district should frequently monitor the activities of people in the area to protect the groundwater resource.

Keywords: Groundwater Quality; Heavy Metal; Physicochemical Parameters; Hand-Dug Wells

*CORRESPONDING AUTHOR:

James Kwame Kusi, Department of Chemistry Education, University of Education, Winneba P.O. Box 25, Ghana; Email: jkkusi@uew.edu.gh

ARTICLE INFO

Received: 15 January 2026 | Revised: 4 March 2026 | Accepted: 10 March 2026 | Published Online: 7 April 2026
DOI: https://doi.org/10.30564/jees.v8i4.13021

CITATION

Kusi, J.K., Arkoful, S., Kwarteng, T.A., et al., 2026. Assessment of Groundwater Quality in Agona East District, Ghana. Journal of Environmental & Earth Sciences. 8(4): 34–45. DOI: https://doi.org/10.30564/jees.v8i4.13021

1. Introduction

All forms of life depend on water, which is one of the most important abiotic elements of the environment. Despite its richness, freshwater only makes up around 3% of the world's resources; the remaining 2.97% are kept in glaciers and ice caps. Surface water (0.025%) and groundwater (0.005%) that are suitable for human use make up the remaining 0.03%[1]. The proper use and preservation of freshwater resources are crucial for the entire world because of their finite supply. Access to flowing and clean drinking water is a fundamental right of every individual in the environment. It is fundamentally crucial for consumption, hygiene, food preparation, and sanitation[2]. Population growth, urbanization, and climate change have increasingly contributed to freshwater scarcity over the years, and the quality of existing groundwater reserves is degrading at a rapid rate[3].

Reduced groundwater quality arises due to the natural geology of the area, coupled with some artificial causes. Natural causes of the reduction in the quality of groundwater include the dissolution of As, F, and Fe-containing minerals in the aquifer[4]. Excess abstraction of groundwater in some areas, especially in coastal areas, results in saltwater intrusion, hence further reducing the quality of the groundwater[5]. Human activities such as agricultural intensification have increased the leaching of nitrates, phosphates, and pesticides into aquifers, posing risks like methemoglobinemia in infants[6]. Moreover, poor waste disposal methods, including badly managed landfills, leaking septic systems, and industrial discharges, substantially raise the risks of heavy metal and microbial contamination[7,8]. Heavy metals such as Pb, As, Cd and Hg are of particular importance. These elements can leach into aquifers from industrial waste, landfill seepage, and mining activities[9]. Chronic exposure to Pb-contaminated water has been linked to serious neurodevelopmental and renal effects, with the WHO permissible limits set at 0.3 mg/L[10]. Arsenic (As) exposure is associated with cancer, cardiovascular disease, and diabetes, and the WHO recommends a maximum level of 0.01 mg/L[10]. While Fe is not considered highly toxic, elevated levels (>0.3 mg/L) can cause operational issues such as pipe clogging, discolouration, and metallic taste, as well as promote bacterial growth[10]. In Ghana, Fe-rich laterite formations and over-extraction near coastal aquifers have been linked to high Fe and Cl ions levels in groundwater. This has resulted in the rejection or non-potable use of more than 49–60% of boreholes in affected areas[11].

The presence of pathogenic microorganisms, including *E. coli*, *Salmonella*, *Giardia*, and viruses, poses a significant health concern, often caused by inadequate sanitation, open defecation, or malfunctioning septic tanks[12]. Microbial quality is therefore a crucial factor in assessing water potability, as highlighted by the WHO and Ghana Standard Authority[10]. Alongside microbiological and chemical safety, the physical and aesthetic qualities of water, such as turbidity, taste, odour, and colour, affect consumer perception and acceptance[13]. High turbidity can hinder disinfection and suggest the possible presence of pathogens.

Expanding human settlements, rising demographic trends, and inadequate sanitation infrastructure have increased reliance on groundwater sources, particularly hand-dug wells in rural communities[14]. In the Agona East District, residents, especially in northern and middle rural communities, depend heavily on hand-dug wells due to an insufficient municipal supply. Observations indicate that these wells are often situated near pit latrines and waste disposal sites[15], raising contamination concerns. Previous studies in the southern part of the district[16] have reported faecal contamination and high levels of iron and chloride in hand-dug wells, linked to iron-rich geological formations and poor sanitation practices. Despite these findings, limited research exists on the groundwater quality in the northern and middle rural communities of Agona East. Therefore, this study aims to assess the physicochemical, heavy metal, and the health risk assessment of hand-dug well water in these understudied areas.

2. Materials and Methods

2.1. The Study Area

Groundwater samples were obtained from eight rural communities in the Agona East District, Ghana, as shown in **Figure 1**. Four sampling from the northern belt (Dua Bon, Ohenkwa, Asamoakwa, Tawora), and four from the middle belt (Saakwa-Kwa, Otwakwa, Kokwaado, Ansakwa). These communities rely mainly on hand-dug wells as their primary source of drinking water. Monthly sampling was conducted over four months (February–May), with two samples collected per site: one for physicochemical analysis and the other for heavy metal analysis.

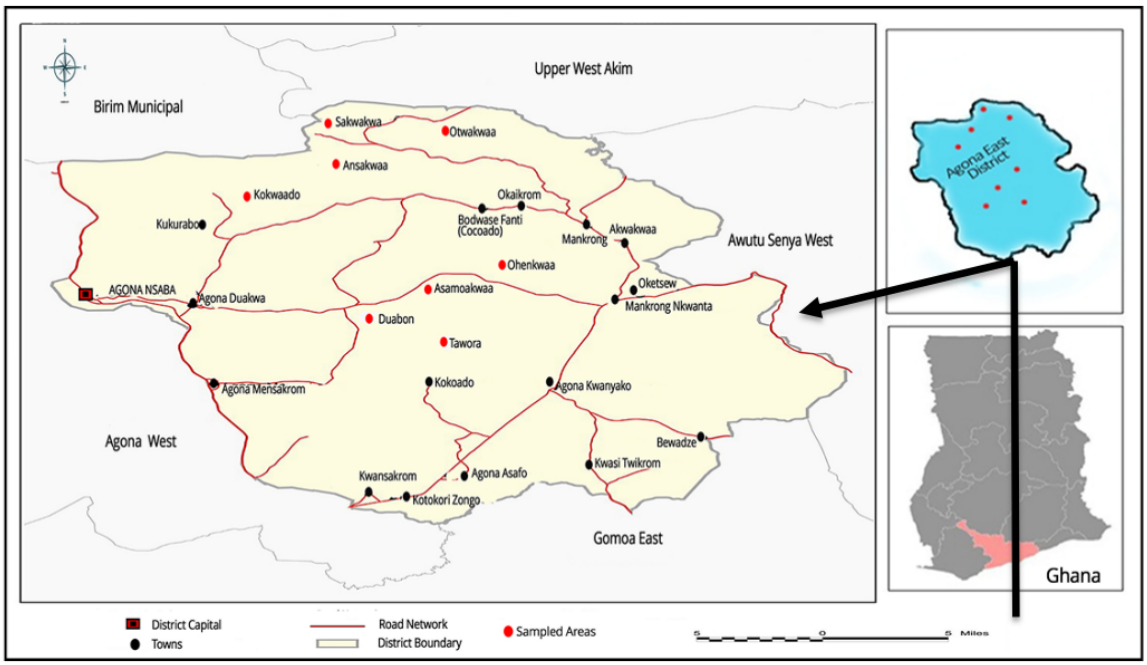

Figure 1. Map showing the study area and where water samples were collected.

2.2. Sample Collection and Preservation

Groundwater samples were collected from eight purposively selected sites in the Agona East District during the first week of each month from February to May 2024. Sample bottles for physicochemical and heavy metal analyses were pre-cleaned, sterilized, and appropriately labelled. A total of 32 samples were obtained from eight hand-dug wells to assess their physicochemical and heavy metal properties. Samples for physicochemical analyses were collected using 1.5 L plastic bottles, while 0.75 L plastic bottles were used for heavy metal samples. All sample bottles were labelled (W1–W8) corresponding to the sampling sites: Saakwa-Kwa, Otwakwa, Kokwaado, Ansakwa, Dua Bon, Ohenkwa, Asamoakwa, and Tawora. The samples were kept in an ice box immediately after collection to prevent parameter alteration. Also, concentrated nitric acid was added to the 0.75 L bottles to stabilize the heavy metals in the water samples. Some physicochemical parameters like temperature (temp), pH, electrical conductivity (EC), total dissolved salts (TDS), turbidity, and colour were measured on-site using calibrated meters in the field, after which samples were transported to the Ghana Water Company Limited (GWCL) Kwanyako Water Treatment Plant Laboratory and the GWCL Central Regional Laboratory, Cape Coast, for detailed analysis.

2.3. Physicochemical Analysis

Standard American Public Health Association (APHA) methods were employed to analyze parameters including pH, EC, alkalinity, total hardness (TH), Ca^{2+}, Mg^{2+}, NO_3^-, PO_4^-, F^-, Cl^-, NH_4^+, and TDS. Spectrophotometric methods—Ultraviolet/Visible Spectroscopy (UV-Vis) and Sodium 2-(parasulfophenylazo)-1,8-dihydroxy-3,6-naphthalene disulfonate (SPADNS) and titrimetry were used where appropriate.

2.4. Heavy Metal Analysis

2.4.1. Acid Digestion

Water samples were previously digested in order to conduct the Atomic Absorption Spectrophotometer (AAS) analysis through the use of concentrated aqua regia (HNO3 and HCl, in the ratio 1:3). The resulting solution was heated on a hot plate and allowed to cool to room temperature and filtered through Whatmann filter paper into a 100 mL volumetric flask. Distilled water was added to the flask to mark the top of the volumetric flask. Heavy metals (Pb, Fe, and Cd) determination was carried out through the use of r AAS (VARIAN SpectrAA 220), and the resulting metal, utilizing Air Acetylene flame, was carried out at a controlled temperature of 95–120 °C.

2.4.2. Instrumental Determination of Heavy Metals

Lead (Pb) and Fe concentrations were determined using AAS after nitric acid digestion. Arsenic (As) was analyzed using a hybrid generation system coupled with flow injection AAS, with argon gas as the carrier. Digestion ensured sample clarity and analyte release before analysis.

2.5. Quality Control and Assurance

Strict quality assurance/quality control measures were adhered to. All analytical instruments were calibrated with certified standards. Reagent blanks and reference materials were analyzed alongside samples. Sample containers were pre-cleaned, and digestion vessels were acid-washed to prevent gross contamination.

2.6. Water Quality Index (WQI)

The WQI was evaluated from all the measured parameters. The overall WQI from these key broad parameters was evaluated.

1. Each parameter was assigned a weight (w_i) based on its relative importance in the water quality assessment. The weights were normalized such that the sum of all weights equals 1 (one):

$$\sum_{i=1}^{n} w_i = 1 \tag{1}$$

2. Each water quality parameter was normalized to a scale of 0 to 100 using the following equation:

$$q_i = \left(\frac{C_i}{S_i}\right) \times 100 \tag{2}$$

Where:

q_i = Quality rating for the i^{th} parameter.

C_i = Measured concentration of the i^{th} parameter.

S_i = Standard permissible value for the i^{th} parameter (as per drinking water standards).

3. The sub-index (SI_i) for each parameter was calculated by multiplying the quality rating (q_i) by its corresponding weight (w_i):

$$SI_i = q_i \times w_i$$
$$WQI = \sum SI_i \tag{3}$$

4. Finally, the Water Quality Index (WQI) was computed by summing up all the sub-indices:

$$WQI = \sum_{i=1}^{n} SI_i = \sum_{i=1}^{n} (q_i \times w_i) \tag{4}$$

Hence, from Equation (4), the final WQI was computed as:

$$WQI = \frac{\sum (Q_i \times W_i)}{\sum W_i} \tag{5}$$

Where:

Q_i = Quality rating for each parameter.

W_i = Weight assigned to each parameter.

The WQI value was then interpreted based on the table provided by Tiwari and Mishra[17].

2.7. Health Risk Assessment

To establish the effect of taking the heavy metals orally, which were found in the water in the study area, a health risk assessment was carried out for both children and adults because of the differences in behavior and physiology between the two. This involved exposure assessment, non-carcinogen risk assessment, and carcinogen risk assessment.

2.7.1. Exposure Assessment

The estimated daily intake (EDI) was employed in calculating the exposure of the population to the heavy metals through oral exposure as per Equation (9), which was adapted from the United States Environmental Protection Agency (USEPA)[18] methods. This was done for the general population as well as the sensitive group of children. This is illustrated in Equation (6).

$$\text{EDI} = \frac{C \times IR \times EF \times ED}{BW \times AT} \tag{6}$$

Where EDI (mg/kg/day) is the estimated daily ingestion of the dosage, *C* is the concentration of the metal (mg/L) in the food, *IR* is the ingestion rate of food (L/day), *EF* is the Exposure frequency, *ED* is the exposure duration, *BW* (kg) is the standard body weight, and *AT* is the time duration of human exposure.

2.7.2. Non-Carcinogenic Risk

The Hazard quotient and Hazard index were used to assess noncarcinogenic health risk. Equation (7) was used to determine the Hazard Quotient (HQ). “A hazard quotient

is the ratio of the potential exposure to a substance and the level at which no adverse effects are expected"[19]. **Table 1** shows the specific reference doses (RfD) for each heavy metal and is adopted from USEPA[20].

$$HQ = \frac{EDI}{RfD} \quad (7)$$

Table 1. Reference dose and cancer slope factor (CSF) for heavy metals (HMs).

Parameter	RF Dose (mg/kg/day)	CSF (mg/kg/day)
As	0.0003	1.5
Fe	0.007	-
Pb	0.0035	0.0085

Source: USEPA (2012).

2.7.3. Hazard Index (HI)

The total potential for non-carcinogenic effects caused by many pollutants was evaluated using the Hazard Index (HI) technique. Equation (8) is used to determine HI[19].

$$HI = \sum HQ \quad (8)$$

"If the HI value is less than one, the exposed population is unlikely to experience obvious adverse health effects. If the HI value exceeds one, then adverse health effects may occur"[19].

2.7.4. Carcinogenic Risk Assessment

The calculation of carcinogenic hazards involves determining the probability that an individual will get cancer due to lifetime exposure to a carcinogen. Equation (9) shows how a cancer slope factor is used to calculate lifetime cancer risk (LCR)[19].

$$LCR = EDI \times CSF \quad (9)$$

Where LCR is the lifetime cancer risk and CSF is the cancer slope factor (mg/kg/day). LCR above 1×10^{-4} is considered unacceptable, risks below 1×10^{-6} are known to have significant health effects, and risks lying between 1×10^{-4} and 1×10^{-6} are said to be in an acceptable range[20].

2.8. Data Analysis

Results were compared to WHO drinking water standards (6th edition, 2020). Descriptive statistics—mean, variance, standard deviation (SD), were computed using SPSS version 10 and visualized with charts in Microsoft Excel.

3. Results and Discussion

3.1. Physicochemical Parameters

The results of the analysis on physicochemical parameters and heavy metals are presented in **Table 2**.

Table 2. Mean physicochemical parameters from hand-dug wells in Agona East District.

Location	Sample ID	pH	Colour (Hazen Units (HU))	Turbidity (Nephelometric Turbidity Units (NTU))	Alkalinity (mg/L)	Temp. (°C)	EC (µs/cm)	TDS (mg/L)	TH (mg/L)
Sakwakwa	W1	6.4	5	1.55	40	28.5	0.5	200	98
Otwakwa	W2	6.8	5	1.23	48	27.5	0.25	240	110
Kokwaado	W3	6.9	3	0.85	46	28.0	0.8	260	100
Ansakwaa	W4	6.5	3	0.98	40	27.8	0.4	220	96
Duabon	W5	7.1	2	0.45	68	28.0	1.25	380	250
Ohenekwaa	W6	6.9	2	0.59	64	29.0	1.0	300	220
Asamoakwaa	W7	7.2	2	0.53	74	28.5	1.5	415	280
Tawora	W8	6.9	2	0.33	60	29.5	2.5	350	200
Min		6.4	2	0.33	40	27.5	0.25	200	96
Max		7.2	5	1.55	74	29.5	2.5	415	280
Overall Mean		6.838	3.0	0.814	55	28.35	1.025	295.625	169.25
Standard Deviation		0.272	1.309	0.421	13.180	0.66	0.734	78.894	81.624
WHO Permissible Limit		6.5–8.5	0.0–15	0.0–5	No health guide	No health guide	1,000	1,000	0.0–500

Table 2 shows the average physicochemical parameters of the hand-dug well water samples collected from eight communities within the Agona East District. Overall, most of the measured parameters were within the recommended drinking water range of 6.5–8.5[21]. Which indicates that generally, the groundwater in the district is suitable for domestic use, though there is some spatial variation among the sample locations.

The pH values ranged from 6.4 in W1 to 7.2 in W7, with an overall mean of 6.84 ± 0.27, showing neutral to slightly alkaline conditions. This means that the groundwater was chemically stable and safe regarding the acidity-alkalinity

balance. Such pH values, according to Anim-Gyampo et al.[22], are typical for neutral to mildly alkaline groundwater systems. This agrees with earlier studies by Sunkari et al.[23], Annan et al.[24] and Tabi et al.[25] who recorded mean pHs of 6.7, 6.9, and 6.79, respectively, in comparable hydrogeological settings. However, the results contrast with the lower mean pH of 5.65 ± 0.39 reported by Akoto et al.[26], suggesting that groundwater in some regions may be more acidic due to local geochemical or anthropogenic influences. The near-neutral pH observed in this study may therefore be attributed to the buffering effects of carbonate and bicarbonate ions within the aquifer system[27] which help neutralize acidic inputs and stabilize groundwater chemistry.

According to WHO[10] standards, pH values below 6.5 are considered too acidic for consumption and may cause acidosis, while values above 8.5 can promote scale formation in pipes and reduce chlorine efficiency[28,29]. Thus, the slightly acidic to neutral pH recorded here suggests that the groundwater is generally suitable for domestic purposes. Moreover, as noted by Anim-Gyampo et al.[22], water with pH values below 7 is typically corrosive and capable of increasing metal leaching from geological or anthropogenic sources. Therefore, the near-neutral pH observed in this study likely limits the solubility and mobility of heavy metals, a conclusion that aligns with the low metal concentrations recorded.

Furthermore, assessing the colour of groundwater provides additional insight into its clarity and potential contamination from suspended particles or dissolved organic matter. In this study, colour values ranged from 2 to 5 Hazen, with a mean of 3 ± 1.31 Hazen. The highest values were recorded at Sakwa-Kwa and Otwa-Kwa, suggesting increased turbidity likely caused by organic matter or fine particulates. Although all values were within the WHO permissible limits, the relatively higher colour in these locations could reduce the aesthetic appeal of the water and discourage its domestic use[30].

Total dissolved solids (TDS) represent a key indicator of the ionic composition and salinity of groundwater, often reflecting both natural mineral dissolution and anthropogenic influence. In the present study, TDS values ranged from 200 to 415 mg/L, with a mean of 295.63 ± 78.89 mg/L, all below the WHO[10] permissible limit of 1,000 mg/L. These moderate values suggest that the groundwater remains fresh and suitable for domestic purposes. The relatively higher TDS recorded at site W7 may be attributed to geochemical weathering or leaching of soluble salts from surrounding agricultural soils. Similar patterns have been observed by Anang et al.[31], who reported that variations in TDS often result from the interaction between recharge water and aquifer minerals. Hence, the moderate TDS concentrations detected likely indicate that natural lithological processes, rather than pollution, control the overall ionic strength of the groundwater.

Similarly, turbidity serves as another important indicator of groundwater clarity and aesthetic quality. While colour reflects the presence of dissolved organic compounds, turbidity measures the presence of suspended particles. Turbidity values in this study ranged from 0.33 to 1.55 NTU, with a mean of 0.81 ± 0.42 NTU, all of which were within the WHO permissible limit of ≤5 NTU. The generally low turbidity complements the colour observations, suggesting that the groundwater is relatively free from particulate contamination. The reduced turbidity observed at Tawora and Asamoakwaa may result from stable well sidewalls that minimize soil infiltration[11]. Hence, the combined results of colour and turbidity indicate that groundwater in the study area is visually acceptable and suitable for household use.

In addition, alkalinity values ranged from 40 to 74 mg/L, with an average of 55 mg/L, all within acceptable limits for potable water. Alkalinity reflects the water's capacity to neutralize acids and maintain pH stability, primarily due to carbonate, bicarbonate, and hydroxide ions acting as natural buffers. The moderate alkalinity recorded suggests sufficient buffering capacity to resist sudden pH fluctuations, thereby supporting chemical stability within the aquifer[10].

Temperature also plays a crucial role in determining groundwater quality, as it influences electrical conductivity (EC), pH, and dissolved oxygen levels[32,33]. In this study, groundwater temperatures ranged from 27.5 to 29.5 ℃, with a mean of 28.35 ± 0.66 ℃. Lower temperatures observed at Otwa-Kwa and Ansakwaa may be attributed to greater well depths and shading, which limit solar heating, while the relatively higher temperatures at Tawora likely result from shallower wells and greater exposure to direct sunlight. These spatial variations underscore the influence of local environmental and structural factors on groundwater thermal dynamics.

Moreover, EC, a key indicator of the total dissolved

ions in groundwater, ranged from 0.25 to 2.5 µS/cm with a mean of 1.03 ± 0.73 µS/cm, signifying generally low mineralization within the aquifer system. Except for W8 (Tawora), where EC slightly exceeded the WHO limit, all samples remained within acceptable standards. The observed direct relationship between EC and temperature corroborates earlier findings by Akuo-ko et al.[34] which suggest that higher temperatures enhance ion mobility and consequently increase conductivity. In parallel, total dissolved solids (TDS) values ranged between 200 and 415 mg/L, averaging 295.6 mg/L, which is well below the WHO guideline value of 1,000 mg/L. This further indicates minimal ionic load in the groundwater and confirms its suitability for domestic use. The close relationship between EC and TDS supports the interpretation of low mineralization, implying limited rock-water interaction and minimal anthropogenic influence within the study area.

Closely related to TDS is total hardness, which provides insight into the concentration of divalent cations, mainly calcium and magnesium, in groundwater. The observed hardness values ranged between 96 and 280 mg/L, averaging 164.86 ± 81.62 mg/L, well within the WHO[10] limit of 500 mg/L. The moderate hardness levels suggest the dominance of Ca^{2+} and Mg^{2+} ions derived from carbonate and silicate rock weathering. The highest hardness recorded at W7 corresponds with its elevated TDS, implying that both parameters share a common geogenic source. Comparable findings by Ren et al.[35] linked hardness variations to aquifer lithology and the duration of water-rock interaction. Although the concentrations recorded are not harmful, they could contribute to scale formation in pipes and reduce soap lathering efficiency. Thus, the detected hardness mainly reflects natural mineral dissolution processes, underscoring the geological control on water chemistry within the study area.

3.2. Heavy Metals Concentrations

Monitoring heavy metals in groundwater is equally essential because even trace amounts can pose significant health and environmental risks. In this study, the concentration of iron (Fe) serves as another important indicator of aquifer geochemistry and redox status. Detected Fe values ranged from 0.10 to 0.35 mg/L, with a mean of 0.20 ± 0.10 mg/L (**Table 3**). Most samples were within the WHO[10] guideline limit of 0.3 mg/L, except for slight exceedances observed at W7 and W8. This pattern suggests localized enrichment of iron-bearing minerals or reducing conditions that enhance Fe solubility. A similar study by Ewool et al.[36] has attributed similar Fe enrichment in Ghanaian aquifers to lateritic soil weathering. Given the absence of major industrial activities in the district, these concentrations are more likely to be geogenic than anthropogenic. Therefore, the moderate Fe levels, with localized peaks, can be explained by natural mineral dissolution under mildly reducing aquifer conditions.

Table 3. Mean concentration of heavy metals from hand-dug wells in Agona East District.

Location	Sample ID	Fe (mg/L)	As (mg/L)	Pb (mg/L)
Sakwakwa	W1	0.1	0.0	0.001
Otwakwa	W2	0.12	0.0	0.0
Kokwaado	W3	0.16	0.0	0.001
Ansakwaa	W4	0.1	0.0	0.0
Duabon	W5	0.26	0.0	0.0
Ohenekwaa	W6	0.2	0.0	0.0
Asamoakwaa	W7	0.32	0.0	0.0
Tawora	W8	0.35	0.0	0.0
min		0.1	0.0	0.0
max		0.35	0.0	0.001
Overall Mean		0.201	0.00	0.0003
Standard Deviation		0.099	0.00	0.0005
WHO Permissible Limit		0.0–0.30	0.0–0.01	0.01

Arsenic (As), a toxic metalloid commonly associated with mining, geothermal, or volcanic sources, was not detected in any groundwater sample, indicating concentrations below the WHO[10] limit of 0.01 mg/L. The absence of As reflects the non-arseniferous lithology of the area and the lack of industrial or mining inputs. Shankar et al.[37] similarly noted that arsenic mobilization tends to occur in sulfide-rich sediments or under strong anthropogenic influence conditions, not evident in this study area. Consequently, the non-detectable arsenic confirms the geochemical safety of

groundwater regarding this contaminant.

Lead (Pb) concentrations ranged from 0.00 to 0.001 mg/L, with a mean of 0.0003 ± 0.0005 mg/L, far below the WHO[10] limit of 0.01 mg/L. The low level of Pb can be attributed to geogenic release of Pb through weathering of Pb-containing rocks. Anim-Gyampo et al.[22] reported similar findings, linking minor Pb enrichment to breakdown of rocks. Although the observed concentrations are low, they point to possible localized contamination. The detection of Pb, albeit in trace amounts, therefore, indicates that groundwater chemistry may be influenced mainly by geogenic and minor anthropogenic factors.

3.3. Cations and Anions Concentrations

Table 4 displays the findings of the analysis of the cation and anion concentrations from the manually hand-dug wells.

Table 4. Mean cations and anions concentration in water samples from hand-dug wells in Agona East District.

Location	Sample ID	Parameters (mg/L)						
		Calcium	Magnesium	Phosphate	Nitrates	Chloride	Fluoride	Ammonia
Sakwakwa	W1	24.0	9.2	0.05	2.0	15.0	1.1	0.2
Otwakwa	W2	30.4	8.3	0.02	2.2	18.0	0.6	0.5
Kokwaado	W3	24.0	9.7	0.04	2.5	20.0	1.7	0.8
Ansakwaa	W4	24.8	8.3	0.06	2.1	16.0	0.5	0.4
Duabon	W5	80.0	12.2	0.20	4.8	45.0	0.1	1.0
Ohenekwaa	W6	64.0	14.6	0.15	3.5	35.0	0.3	0.6
Asamoakwaa	W7	79.2	19.9	0.50	5.0	30.0	0.5	1.2
Tawora	W8	53.6	16.0	0.54	5.3	30.0	0.5	1.4
min		24.0	8.3	0.02	2.0	15.0	0.1	0.2
max		80.0	19.9	0.54	5.3	45.0	1.7	1.4
Overall Mean		47.5	12.275	0.195	3.425	26.125	0.663	0.763
Standard Deviation		24.735	4.228	0.209	1.416	10.656	0.507	0.414
WHO Permissible Limit		0.00–200	0.00–150	0.0–2.5	10	0.0–200	0.0–1.5	0.0–0.5

Note: The value was given as mean ± standard deviation of four replications (n = 32) from eight sampling sites in Agona East District.

Calcium (Ca^{2+}) was detected at concentrations ranging from 24 to 80 mg/L, with an average of 47.50 ± 24.74 mg/L, which falls well below the WHO[10] limit of 200 mg/L. The uniform distribution of Ca^{2+} across sites suggests its origin from carbonate and gypsum dissolution, with slightly higher values observed in areas near limestone formations, consistent with the findings of Ram et al.[21]. The strong correlation between Ca^{2+} and total hardness supports the conclusion that water chemistry is largely governed by natural lithological composition.

Magnesium (Mg^{2+}), which contributes to both water hardness and ionic equilibrium, ranged from 8.30 to 19.90 mg/L, averaging 12.28 ± 4.12 mg/L, well below the WHO[10] guideline value of 150 mg/L. The consistent presence of Mg^{2+} across the sampling points indicates leaching from dolomitic and mafic rock formations. The relatively higher concentrations observed at W8 may result from prolonged groundwater residence time, which facilitates enhanced mineral dissolution. Thus, the safe Mg^{2+} concentrations confirm the geogenic origin of these ions with minimal anthropogenic intrusion.

Nitrate (NO_3^-) concentrations varied from 2.0 to 5.3 mg/L, with a mean of 3.43 ± 1.42 mg/L, all below the WHO[10] limit of 10 mg/L. These low concentrations indicate minimal agricultural or sewage influence on groundwater quality. Slightly elevated nitrate levels at W7 and W8, however, may be linked to localized fertilizer use or domestic waste infiltration. Boateng et al.[38] similarly observed increased nitrate concentrations near farmlands, emphasizing agricultural influence. Therefore, the generally low nitrate levels detected suggest that groundwater remains largely unpolluted, with only minor anthropogenic inputs in specific localities.

Phosphate (PO_4^{3-}) was detected in concentrations ranging from 0.02 to 0.54 mg/L, with an average of 0.20 ± 0.21 mg/L, which is below the USEPA threshold of 2.5 mg/L. The detection of phosphate in all samples indicates a mild organic or agricultural influence, possibly arising from detergent residues or fertilizer leaching. Elevated values at W8 suggest proximity to farming or household waste disposal sites. Although phosphate is not directly toxic to humans, its enrichment can promote eutrophication in connected surface

waters[31]. Hence, the detected phosphate concentrations imply mild anthropogenic interference with limited ecological impact.

Fluoride (F^-) concentrations ranged from 0.10 to 1.70 mg/L, with a mean of 0.66 ± 0.51 mg/L, mostly within the WHO[10] limit of 1.5 mg/L. Only site W3 exceeded the limit slightly, which can be attributed to the dissolution of fluoride-bearing minerals such as fluorite and apatite under favorable pH and temperature conditions. While moderate fluoride levels are beneficial for dental health, chronic exposure can cause fluorosis[34]. Therefore, the fluoride concentrations recorded here indicate primarily geogenic origin, with isolated enrichment zones that require continued monitoring.

Chloride (Cl^-), a major anion used to assess both natural and anthropogenic inputs, ranged between 15 and 45 mg/L, with an average of 26.13 ± 10.66 mg/L far below the WHO[10] permissible limit of 250 mg/L. The widespread but low detection of Cl^- suggests that groundwater is derived mainly from natural mineral dissolution rather than saline intrusion or industrial pollution. Similar chloride ranges were reported by Boateng et al.[38] in non-coastal aquifers, reinforcing the conclusion that the groundwater in the district remains fresh and geogenically controlled.

The quantities of ammonium ions (NH_4^+) varied from 0.20 to 1.40 mg/L, with a mean of 0.76 ± 0.41 mg/L. Approximately half of the samples were higher than the 0.5 mg/L WHO[10] limit. Elevated levels, particularly at W7 and W8, point to organic waste infiltration or fertilizer runoff. Annan et al.[24] similarly observed ammonium enrichment in groundwater affected by domestic waste leachates. Excess NH_4^+ can enhance microbial nitrification and disrupt oxygen balance in groundwater systems. Therefore, the elevated ammonium concentrations in certain locations indicate localized anthropogenic contamination, likely due to poor sanitation practices or agricultural inputs.

3.4. Groundwater Quality Classification Based on WQI

Based on Tiwari and Mishra[17], the computation of WQI values for physicochemical and heavy metals and cations and anions analysis was 34.89 and 32.08, respectively. Based on the values obtained for physicochemical and heavy metals and cations and anions, the groundwater was classified as good (25 < WQI < 50).

3.5. Health Risk Assessment of Heavy Metals

In **Table 5**, the HQ values for adults and children for all the heavy metals were below one. The overall hazard indices for adults and children were 0.0203 and 0.0013, respectively. These estimated values below one suggest that consumers of groundwater in the study area are not at risk of non-carcinogenic effects. Also, the CRI values for children and adults were far below the upper threshold of 1×10^{-4} and indicated no likely of consumers suffering from cancer when the water is used for a period.

Table 5. Health risk assessment of heavy metals found in groundwater.

		Adult	Children	Adult	Children
Parameter	**Mean**	**HQ**	**HQ**	**CRI**	**CRI**
Fe	2.01×10^{-1}	2.03×10^{-2}	1.30×10^{-3}	0	0
As	0	0	0	0	0
Pb	3.00×10^{-4}	6.03×10^{-5}	1.97×10^{-6}	1.80×10^{-9}	1.68×10^{-8}
HI		2.03×10^{-2}	1.30×10^{-3}		

4. Conclusion

This study provides a comprehensive evaluation of the physicochemical properties and heavy metal levels in hand-dug well water from Agona East District, revealing clear spatial differences in groundwater quality. Elevated turbidity observed in Saakwa-Kwa, Otwakwa, Kokwaado, and Ansakwa was mainly caused by sediment-rich agricultural runoff, while trace amounts of lead in Otwakwa and Kokwaado likely stemmed from leaching influenced by illegal mining along the Birim River. Slight exceedances of Fe, Pb, F^-, and NH_4^+ observed in some wells indicate subtle but significant geogenic and anthropogenic interactions affecting groundwater chemistry. Elevated Fe concentrations may originate from mineral dissolution and corrosion of well casings, Pb from mining-related leaching, F^- from weathering of fluoride-bearing rocks, and NH_4^+ from infiltration of agricultural or domestic effluent. Despite these localized

issues, the calculated Water Quality Index (WQI = 38.99) classifies the groundwater as good and generally suitable for human consumption, in accordance with WHO standards. This investigation offers new baseline data, crucial for understanding the hydrochemical behaviour of groundwater within the district. The findings highlight the importance of managing agricultural and mining activities to protect groundwater quality. Future research should include long-term seasonal monitoring, microbial risk assessment, and advanced hydrogeochemical modelling to trace contaminant pathways and predict emerging threats. Such comprehensive approaches are vital for guiding sustainable water resource management and ensuring the long-term safety of rural groundwater sources in Ghana.

Author Contributions

Conceptualization, J.K.K. and S.A.; methodology, T.A.K.; software, T.A.K.; validation, S.A., J.K.K. and T.A.K.; formal analysis, J.D.; investigation, J.D.; resources, J.D.; data curation, J.K.K.; writing—original draft preparation, J.D.; writing—review and editing, J.K.K.; visualization, J.K.K.; supervision, S.A.; project administration, S.A.; funding acquisition, J.K.K., S.A., T.A.K. and J.D. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All relevant data generated or analyzed are included in the article.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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