Chapter

# Effects of Illegal Artisanal Gold Mining Operations on Groundwater Quality in Ghana: The Case of Ahafo-Ano South District

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## Abstract

The general properties and overall chemical quality for potability of groundwater in Ahafo-Ano South District of the Ashanti Region of Ghana have been evaluated. With respect to pH, about 92% of groundwaters were potable while 8% were acidic and not potable. Approximately 4%, 32%, 56% and 8% of sampled groundwater were soft, moderately soft, hard and very hard respectively. The overall chemical quality analysis of groundwaters showed that 20%, 28%, 40%, 4% and 8% had excellent, good, poor, very poor and unsuitable drinking water qualities respectively. Approximately 12%, 40% and 84% of As, Ni and Pb exceeded their respective WHO limits while 32% of Cd and Fe exceeded their respective limits for potable water. These higher concentrations of heavy metals were observed to have occurred in communities with intensive illegal gold mining operations. Inhabitants in these areas could potentially be more predisposed to potential health hazards including cancer, nervous system damage, low IQ in children, reduced growth of foetus and premature birth in pregnant women, and kidney damage. It is expected that illegal artisanal gold mining activities will be banned while policies aimed at providing alternative livelihood be instituted to minimize any potential health hazards on humans in the District.

**Keywords:** Illegal artisanal gold mining, groundwater, quality, Ahafo-Ano District, Ghana

## 1. Introduction

Water from surficial and underground sources is critical for the sustenance of all life forms on earth. Surface water is arguably the most easily available and well-harnessed drinking water source since creation. In tropical rainforest regions, surface water resources are the utilized and source of water supply to meet the demands of domestic, industrial and agricultural purposes. However, certain human activities and natural processes may alter the surface water quality, thereby limiting its ease and scope of reliability and usage. Such natural processes may include earthquakes, volcanic eruptions, landslides and hurricanes, and when such events are occurring at local and regional scales, they may alter the quality of surface water sources. Anthropogenically, the progressive industrialization and application of scientific methods in improving various livelihood demands by humans may result in the generation of varied amounts of wastes of varying toxicities, which when not properly handled may serve as potential sources of pollution to the environment including surface and groundwater resources.

One key activity of man that contributes to the pollution of drinking water sources is illegal artisanal gold mining activities. Globally, approximately 100 million people are considered to be directly or indirectly involved in such operations for their livelihood [1]. In Ghana, however, artisanal gold mining is estimated to have begun several decades ago with approximately one million people directly or indirectly involved [2]. The areas of operations are generally, rural settings with few peri-urban centers and a much fewer large urban centers that depend on both surface and groundwater resources for domestic, agricultural and industrial purposes. The rapid growth in urban and peri-urban population, coupled with the ever-increasing unemployment have resulted in the greater proportion of local and migrant youth (male and female) in Ghana, Burkina Faso, Mali Niger as well as Chinese nationals, getting in involved in illegal artisanal gold mining.

Despite the positivity of artisanal gold mining to the socio-economic development of societies, especially in most developing countries like Ghana [3], illegal artisanal gold mining activities utilizes crude and rudimentary techniques and environmentally unfriendly extractive processes. Examples may include but are not limited to the extraction of shallow alluvial gold deposits; diversion of streams and river courses to expose otherwise inundated beds for excavation; washing of alluvial ores at close proximities and many cases, inside river and stream channels. These may contribute to land degradation and water quality deterioration among others [4]. Furthermore, the utilization of mercury and cyanide to leach and/or amalgamate the gold during extraction, have been found to contribute to the release of harmful metals to the environment [5, 6]. These metals when found above permissible limits in drinking water and/or the food chain could be detrimental to human health and sustenance of the ecosystem [7].

According to [8], there is a great national concern with regards to the increasing activities of environmentally unfriendly mining activities in Ghana. The Ahafo-Ano South District in the Ashanti Region of Ghana is a predominantly rural area with few peri-urban and urban dwellings, where illegal artisanal gold mining activities occur. This has led to an influx of various people majority of which are youth from different parts of Ghana. Groundwater per the national water policy of Ghana [9] is the major source of potable water in rural Ghana. The observed rapid influx of people into the area to partake in the illegal artisanal gold mining requires that large quantities of groundwater must be exploited to meet the ever-increasing potable water demand. To this end, an evaluation of the quality groundwater in the area becomes essential. Poor drinking water quality, according to [7] can expose humans to potential health risks. Groundwater generally is considered to be of better quality, compared to surface water in terms of potability. Deterioration in quality, however, may occur over time due to certain natural processes and anthropogenic activities. According to [10], some of the natural processes may include hydrogeochemical processes such as water-rock-interaction, soil-water interaction, cationic exchange reactions, mixing of waters; certain biological processes including selective uptake by vegetation and evapotranspiration. Anthropogenic activities that may result in leachates into groundwater resources may come from agricultural fields that utilize especially, agro-chemicals and manures, municipal and urban wastewater sites, mining activities and mine waste disposal sites, domestic and industrial effluents, etc.

Consequently, this study is aimed at assessing the quality of groundwater resources for drinking purposes and to evaluate the potential risk(s) to human health in the Ahafo-Ano South District of Ghana, which is an artisanal gold mining area. In the authors' view, this will also provide a framework for any future groundwater quality monitoring and evaluation exercise to ensure sustainable utilization of the resources.

## 2. Materials and methods

### 2.1 The study area

#### *2.1.1 Location, climate and drainage*

The Ahafo-Ano South District (**Figure 1**), is located between longitude 1°45′ and 2°20'W and latitude 6°42′ and 7°10'N with an area of about 1190.7km$^2$ and an estimated population as at 2010 census to be approximately 121, 659. The district is bordered to the north-east by Tano-North District, north-west by Ahafo-Ano North District; south by Atwima Nwabiagya district and to the east by Offinso-North Municipal Topography is generally undulating with dominant hills being Aya, Kwamisa and Tinte hills, which run from the west towards the northeast. The highest elevation is about 763 meters above mean sea level [11]. According to [12], the area falls within the wet semi-equatorial climatic region of Ghana, which is characterized by the occurrence of two rainy seasons. The major season occurs normally between March and June while the minor season spans September to November. The average annual precipitation is about 1,700 mm - 1850 mm per year while the mean annual temperature is around 30°C with the lowest temperature being about 26.1°C. Relative humidity range is 70–75%. The area lies within the semi-deciduous forest belt with

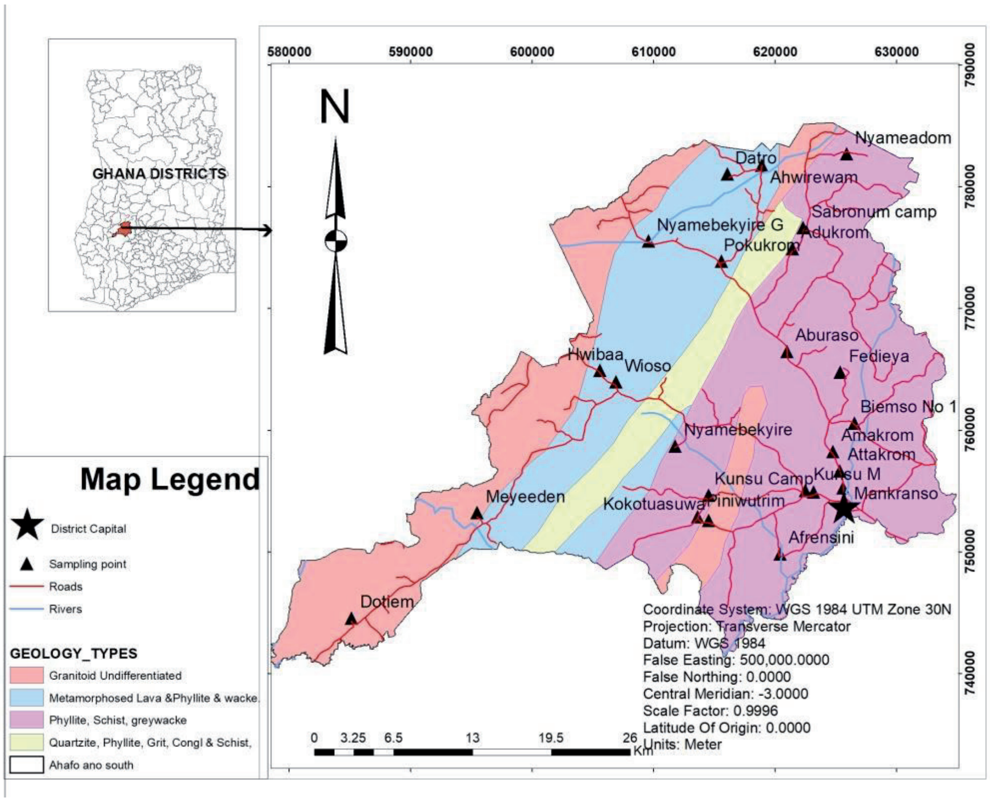

**Figure 1.**
*Geology map of the study area.*

vegetation types controlled by precipitation and groundwater. Prominent rivers draining the area include Mankran, Abu and Aboabo rivers and their tributaries.

### *2.1.2 Geology, soil and natural resources*

The area is underlain by the paleo-proterozoic Birimian metasediments subgroup. Common rock include phyllites and schist-intruded with their syngenetic basin-type granitoids [13]. The area lies within the Kumasi-Offin-Dwinyama-Bechemso belt [14], which contains extensive mineral deposits of great commercial significance such as gold, bauxite, manganese deposits as well as extensive granitic outcrop within which commercial quarrying operations occur. Gold-bearing rocks are very widespread and are commonly found and mined communities including Afrensini, Piniwutrim, Amakrom, Aburaso, Ahwirewam, Nyamebekyire, Kunsu, Mankranso, Sabronum, Barniekrom and many other parts of the District. The district is one the most important when it comes to natural resources in Ghana. It large forest reserves, namely, Tinte, Tano, Opuro River, Kwamisa forest reserves, parts of Asufufu Basin and Offin-North forest reserves. The study area is a major food basket in Ghana. About 80% of the land is arable, over 60% of which is used for agriculture. The cultivation of cash crops such as cocoa and cashew is very extensive with food crops such as corn, rice, bananas, cassava, as well as vegetables such as tomatoes, cabbage, lettuce. As briefly highlighted elsewhere, the district is known for extensive illegal artisanal gold mining operations due to the widespread gold deposits. Bauxite deposits are found at Aya Hills and Mpasaaso while manganese deposits can be found at Asirebuo Camp, close to the south of Mpasaaso. There are also clay deposits at Hwibaa, Wioso, Asuadei, Biemso II and Mankranso which have been tested by the Building and Road Research Institute (BRRI) as one of the richest clay deposits in the country [11].

The distribution of soils in the area is as shown in **Figure 2**. Three different soil types are commonly found in the area, namely Ferric Acrisols Rhodic Nitosols and

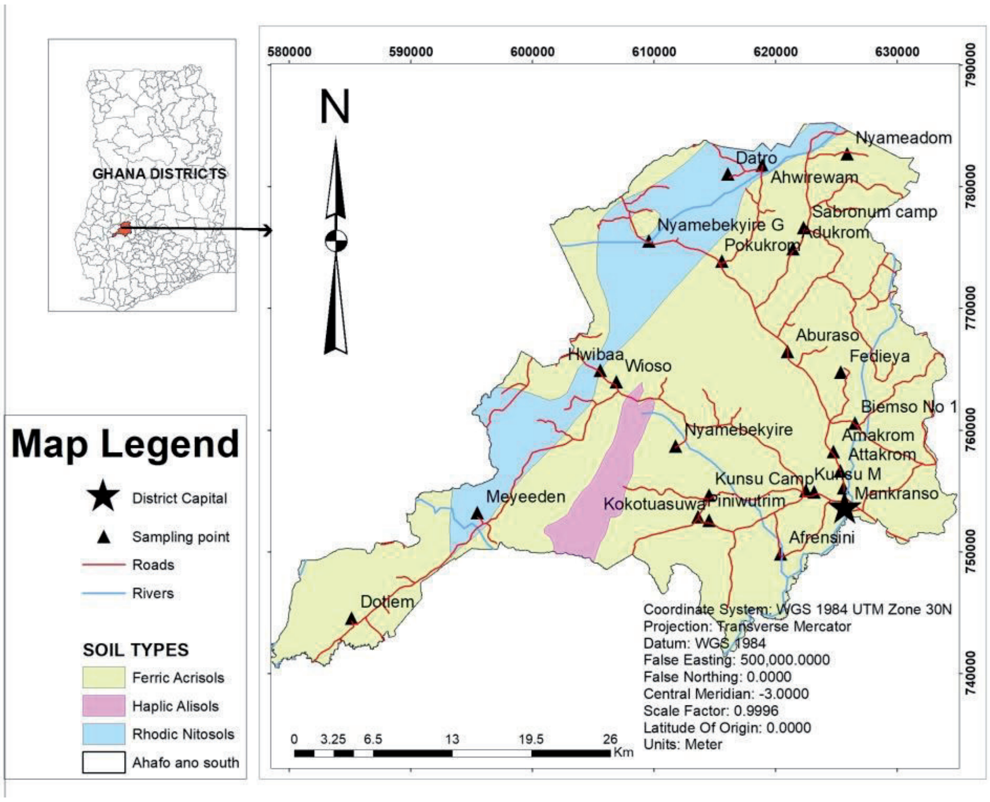

**Figure 2.**
*Soil map of the study area.*

Haplic Alisols [15] (**Figure 2**). Ferric acrisols are the dominant soil in the district follow by nitosols and then alisols. Ferric acrisols is a clay-rich soil and is associated with humid, tropical climates and it mostly supports forest areas. Limited cultivation occurs in areas underlain by acrisols due to their low fertility and the toxic amount of aluminum. Nitosols is a deep, red, well-drained soil with a clay content of more than 40% and dominantly from moderate to strong well-develop fine to mouth angular blocky structure [16].

## 2.2 Methods

### *2.2.1 Water sampling and analysis*

The selections of sampling sites (**Figure 3**) were based on a number of factors such as the ongoing land use activities (farming and illegal artisanal gold mining) and geological settings. Twenty-four (24) well-distributed groundwater point sources (boreholes) functioning hand pumps within the study area according to protocols developed by [17, 18] were sampled in 0.5 litre polythene containers. The containers were conditioned by thoroughly washing with detergent, rinsed several times with acidified water (2%) $HNO_3$ to prevent contamination. Boreholes were purged for over five (5) minutes so as to obtain fresh samples that were filtered through a 0.45-micron membrane. At each well-site, two (2) samples were obtained for the determination of heavy metals and major ions. To analyze for heavy metals in the laboratory, one sample is filtered and acidified with 2% v/v of $HNO_3$ to keep ions in solution while unacidified samples were used for major cation and anion analysis. Electrical conductivity (EC), pH and alkalinity were measured at point sampling in the field, using a calibrated WTW field conductivity meter model LFT 91, WTW

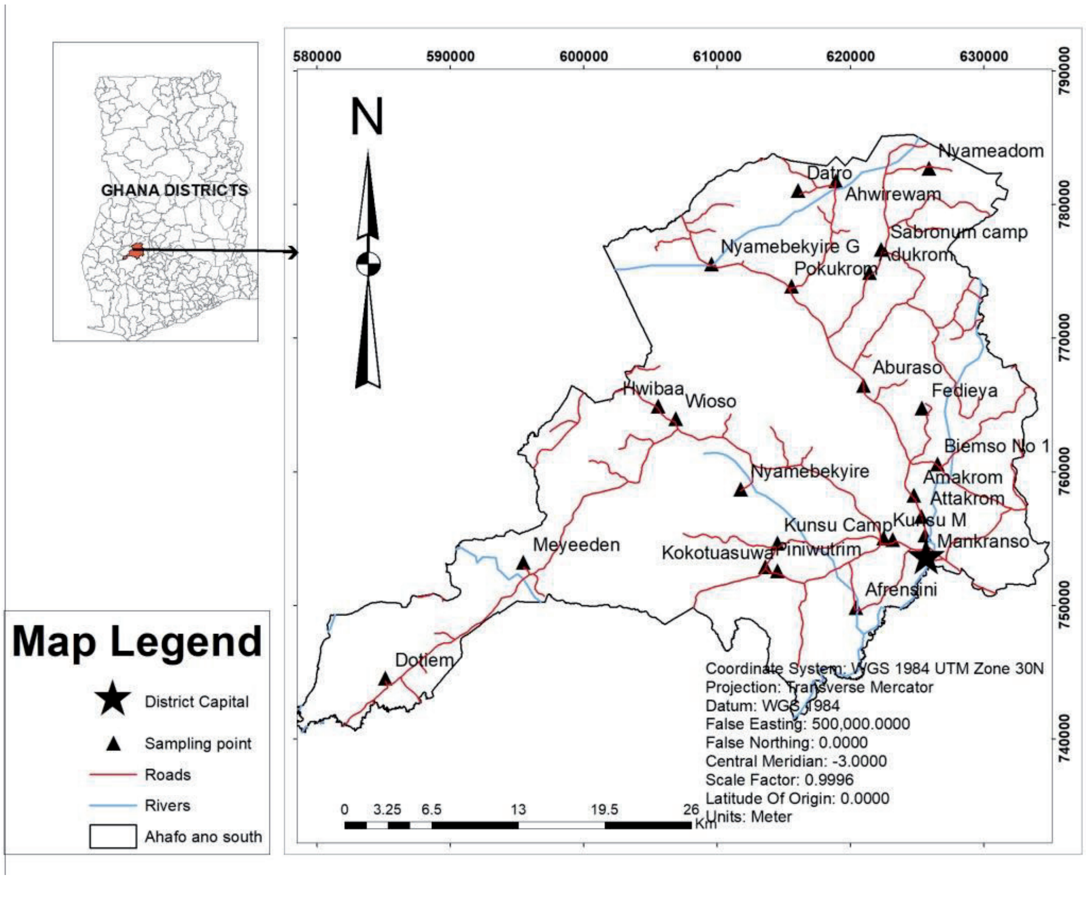

**Figure 3.**
*The study area showing water sampling points.*

field pH meter model pH 95 and a HACH digital titrator respectively. A multipurpose electronic DR/890 Colorimeter was used to measure the color, turbidity, total dissolved solids. Sodium and Potassium were analyzed in the laboratory using the flame photometer. Calcium and Magnesium were analyzed using the AA240FS the Fast Sequential Atomic Absorption Spectrometer whilst ICS-90 Ion Chromatograph (DIONEX ICS -90) was used for carrying out chloride (Cl), fluoride (F), nitrate ($NO_3$) and sulphate ($SO_4$) analyses. Phosphate was determined by the ascorbic acid method using the ultraviolet spectrophotometer (UV-1201). Five (5) ml of each acidified water sample was measured and 6 ml of nitric acid, 3 ml of HCl and 5 drops of hydrogen peroxide ($H_2O_2$) were added for acid digestion and placed in a milestone microwave lab station ETHOS 900. The digestate was then assayed for the presence of Zinc (Zn), lead (Pb), Copper (Cu), Chromium (Cr) and Cobalt (Co) using VARIAN AAS240FS Atomic Absorption Spectrum in an acetylene-air flame. Arsenic (As) and Mercury (Hg) were determined using argon-air flame.

### *2.2.2 Estimation of water quality index (WQI)*

To evaluate the general suitability of groundwater for drinking purposes, the water quality index (WQI), a rating and index concept, which was originally proposed by [19] as has been found to be a widely acceptable approach. According to [20], WQI is a rating that reflects the composite influence of different water quality parameters on a picture of the quality of groundwater for most domestic uses. The estimation of WQI requires the utilization of significant parameters that may influence the purpose to which the water is required. Major cations and anions as well as heavy metals that may impose health implications to human health selected are pH, Electrical Conductivity (EC), Sodium, and Calcium, Nitrate, Fluoride, Chloride, Sulphate, Zinc, Lead and Cadmium, and were used to calculate the WQI for this study. The highest weight of five (5) was assigned to lead, nitrate, and fluoride due to their health significance to human health. The water quality index (WQI) for each groundwater source (borehole) is estimated using the following series of relations (1, 2, 3 and 4), and the result was compared to the criteria defined by [20];

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

where, Wi is known as the relative weight; wi is the assigned weight to an influential parameter relative to its impact on the overall quality for drinking purpose and also health implications to humans; $\sum_{i=1}^{n} w_i$ is the summation of assigned weights of all the influential parameters

$$q_i = \frac{C_i}{S_i} \times 100 \tag{2}$$

where, $q_i$ is referred to as the water quality rating; $C_i$ and $S_i$ represent the measured concentration in sampled groundwater and the respective standard [7] of the $i^{th}$ influential parameter. The water quality sub-index for each of the influential parameter ($SI_i$) is estimated as

$$SI_i = q_i \times W_i \tag{3}$$

where, the symbols have their usual meanings.

$$WQI = \sum_{i=1}^{n} SI_{i} \tag{4}$$

Thus, the sum of all the water quality sub-indices is resulting in the estimated water quality index for i$^{th}$ influential parameter.

## 3. Results and discussion

The summarized results of the analyzed groundwater samples are shown in **Table 1**.

### 3.1 General properties of groundwater

With the exception of pH and TH, all the measured physical and chemical parameters (both cations and anions) of groundwater in the study area fell within their respective acceptable limits for drinking water for humans. The pH of

| Parameter | Unit | Min | Max | Mean | [7] |
|---|---|---|---|---|---|
| Temperature | °C | 27.9 | 29.700 | 28.728 | **N/A** |
| pH | pH units | **4.42** | 8.540 | 7.423 | **6.5–8.5** |
| Turbidity | NTU | 0.000 | 2.000 | 0.926 | **5** |
| TDS | mg/L | 25.000 | 573.000 | 175.185 | **1000** |
| Conductivity | uS/cm | 48.900 | 990.000 | 317.185 | **500** |
| TSS | mg/L | 0.000 | 3.000 | 0.481 | 5 |
| Hardness | mg/L | 48.000 | **348.000** | 186.222 | **150–300** |
| Salinity | mg/L | 0.000 | 0.500 | 0.104 | **n.a** |
| $Na^{+}$ | mg/L | 7.000 | 98.000 | 26.519 | **200** |
| $Ca^{2+}$ | mg/L | 8.000 | 59.200 | 32.000 | **200** |
| $Mg^{2+}$ | mg/L | 29.510 | 83.901 | 46.094 | **150** |
| $K^{+}$ | mg/l | 2.000 | **36.000** | 16.778 | **50** |
| $HCO_3^{-}$ | mg/L | 19.520 | 363.510 | 137.614 | **N/A** |
| $SO_4^{2-}$ | mg/L | 8.000 | 185.000 | 33.000 | **400** |
| $Cl^{-}$ | mg/L | 6.000 | 102.000 | 27.474 | **250** |
| $NO_3^{-}$ | mg/L | 0.080 | 0.520 | 0.143 | **50** |
| $PO_4^{3-}$ | mg/L | 0.042 | 3.573 | 1.900 | **30** |
| $F^{-}$ | mg/L | 0.680 | 1.450 | 1.165 | **0.5–1.5** |
| Pb | Mg/l | 0.000 | **0.280** | 0.048 | **0.01** |
| As | mg/L | 0.003 | **0.308** | 0.042 | **0.01** |
| Fe | mg/L | 0.070 | **1.050** | 0.298 | **0.3** |
| Ni | mg/L | 0.000 | **0.410** | 0.059 | **0.02** |
| Cd | mg/L | 0.000 | **0.030** | 0.059 | **0.003** |

**Table 1.**
*Summary of water quality analysis results.*

twenty-three (23) samples, representing about 92% of groundwater in the area fell within the [7] acceptable range of 6.5–8.5 for potable water while two communities (Sabronum Camp and Amakrom) representing 8% had values within the range of 4–6.5 with respective values of 4.42 and 4.48.

Thus, according to [21], 92% of groundwater was neutral while only 8% were moderately acidic. Hardness varied from 48 to 348 mg/l with a mean of 186.22 mg/l, with the exception of two (2) samples from Adukrom and Ahwirewan representing 8% exceeding the recommended limit of 300 mg/l [7] for drinking water. Water with hardness exceeding 300 mg/l, according to [22] may cause encrustation. Furthermore, [23] classified groundwater based on hardness as soft when hardness is less than 75 mg/l, moderately soft if hardness lies between 76 and 150 mg/l, hard when values fall between 150 to 300 mg/l and very hard groundwater if values are greater than 300 mg/l. In this study, 4%, 32%, 56% and 8% of groundwater in the area could be described as being soft, moderately soft hard and very hard respectively. Thus, groundwater could be generally considered to be predominantly moderately soft to hard water. TDS fell below the [7] limit of 1000 with values ranging from 25 to 573 mg/l with an estimated mean value of 175.185 mg/l. This according to [24], indicate that groundwater in the study area is fresh and young since TDS and conductivity values were generally within acceptable limits.

### 3.2 Chemical quality of groundwater as drinking water

The potability of sampled groundwaters in the Ahafo-Ano south District was evaluated using influential parameters (IPs). IPs is considered to be the drinking water quality parameters that have significant implications for the human health when ingested through water and food chain or by dermal contact [25]. By utilizing Eq. (1), the estimated relative weights ($W_i$) are presented in **Table 2**.

Eqs. (2)–(4) above, were utilized to estimate the respective WQI for each sampled groundwater was estimated and presented in **Table 2**. Based on the estimated WQI values, the potability of each sampled groundwater was appropriately classified by comparing to the scheme described in [20]. According to the scheme, groundwaters with WQI being less than 50 are 'Excellent' for drinking by humans, it 'Good water' when WQI range from 50 to 100; 'Poor water' if WQI range from 100 to 200; 'Very poor quality' if WQI range from 200 to 300 and 'Unsuitable as drinking water' when WQI exceeds 300 from **Table 2**,

The status of drinking water quality of sampled groundwater resources in the study area are shown in **Figure 4**.

Illegal artisanal gold mining is most intensive in Afrensini, Piniwutrim Amakrom with water quality described as unsuitable, unsuitable and very poor, respectively. It can be deduced that the anthropogenic activities in these three (3) communities might have rendered the groundwater qualities unsuitable for human consumption. Qualities of groundwater from ten (10) communities with lesser intensive

| IP | pH | Ca | Mg | Na | Cl | SO4 | Fe | As | Pb | Ni | Cd | $\sum w_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S_i$ | 8.5 | 200 | 150 | 200 | 250 | 400 | 0.3 | 0.01 | 0.01 | 0.02 | 0.003 | |
| $w_i$ | 4 | 1 | 2.00 | 2 | 3 | 3 | 3 | 5 | 5 | 3 | 4 | **39** |
| $W_i$ | 0.103 | 0.026 | 0.05 | 0.051 | 0.077 | 0.077 | 0.077 | 0.128 | 0.128 | 0.077 | 0.103 | |

**Table 2.**
*Assigned and estimated relative weights.*

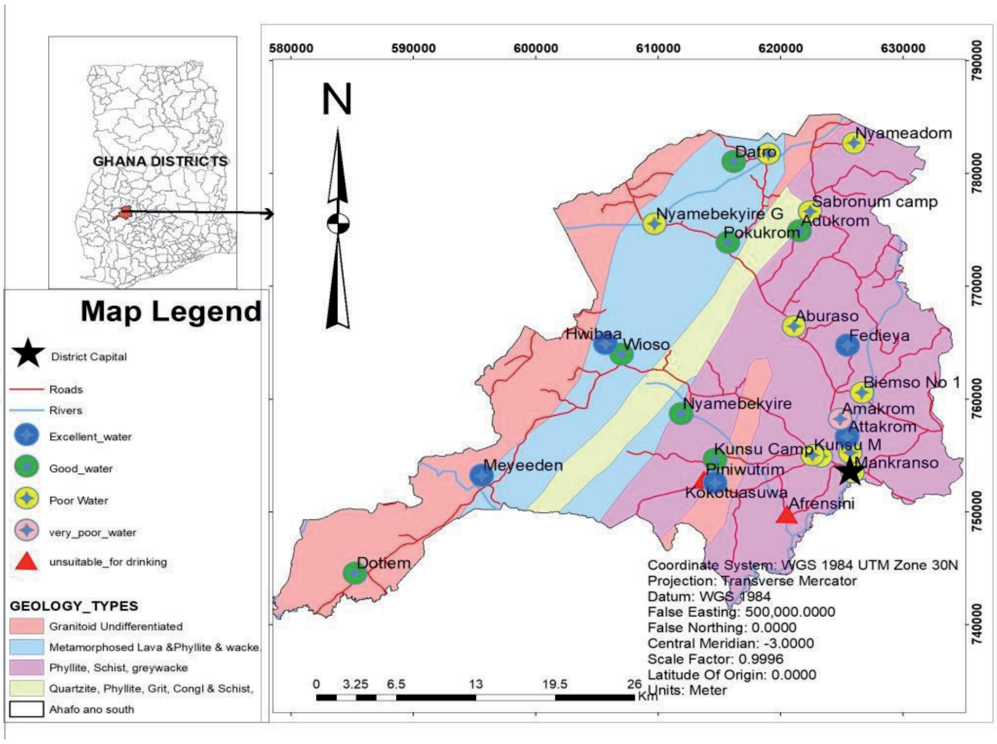

**Figure 4.**
*Spatial distribution of drinking water quality of sampled groundwater.*

illegal artisanal gold mining activities were described as poor. Conversely, sampled groundwaters from five (5) and seven (7) communities (representing 20% and 28% respectively) where illegal gold mining operations were non-existent had excellent and good drinking water qualities respectively. Areas with excellent drinking quality include Attakrom, Meyeeden, Kokotuaso, Fedieya and Hwibaa while areas with good groundwater drinking quality include areas include Wioso, Nyamebekyire, Adukrom, Pokukrom, Kunsu camp, Datro and Dotiem (**Table 3**).

### 3.3 Heavy metals and health implications

**Figure 5** presents the spatial distribution of analyzed heavy metals (Pb, As, Cd, Fe and Ni) in the study area. There was an observed elevated level of heavy metals above their respective permissible limits for drinking purposes as defined by [7]. For instance, eight (8) groundwater samples (representing 32% each) had levels of Fe and Cd exceeding their permissible limits of 0.3 mg/l and 0.003 mg/l respectively. The strong correlation between As-Pb (0.73) and As-Ni (0.5) as shown in **Table 4** could indicate a possible similar source. Twenty-one (21) samples out twenty-five had Pb concentrations exceeding [7] permissible limit of 0.01 mg/l while ten (10) and three (3) samples had Ni and As concentrations exceeding their permissible limits of 0.02 mg/l and 0.01 mg/l, respectively.

The observed unsuitable, very poor and poor groundwater drinking quality could therefore be due to the heavy metals such as Pb, Cd, Ni and As, which might have been released into surface waters and soils as a result of improper disposal of mined wastes by the illegal gold miners. Within the Piniwutrim, Afrensi, Amakrom and surrounding villages for instance, virtually, all streams and perennial rivers have been heavily polluted and their courses virtually blocked. In such situations, infiltration of surface waters laden with heavy metals may be enhanced, leading to the leaching of heavy metals infiltrating alongside the surface waters into the groundwater system.

| No | Community | N | E | WQI | Classification |
|---|---|---|---|---|---|
| 1 | Mankranso | 753517 | 625904 | 132.38 | Poor water |
| 2 | Kunsu Engineer | 754916 | 623278 | 192.25 | Poor water |
| 3 | Wioso | 763951 | 607010 | 66.95 | Good water |
| 4 | Hwibaa | 764903 | 605689 | 38.94 | Excellent water |
| 5 | Nyamebekyire | 758695 | 611902 | 77.15 | Good water |
| 6 | Fedieya | 764743 | 625492 | 47.90 | Excellent water |
| 7 | Aburaso | 766466 | 621102 | 134.52 | Poor water |
| 8 | Sabronum camp | 776640 | 622439 | 175.79 | Poor water |
| 9 | Nyameadom | 782722 | 626003 | 102.15 | Poor water |
| 10 | Adukrom | 774933 | 621565 | 67.39 | Good water |
| 11 | Ahwirewam | 781807 | 619012 | 112.44 | Poor water |
| 12 | Nyamebekyire | 775544 | 609697 | 174.66 | Poor water |
| 13 | Pokukrom | 773880 | 615706 | 77.38 | Good water |
| 14 | Afrensini | 749813 | 620545 | 363.56 | Unsuitable |
| 15 | Kokotuasuwa | 752580 | 614664 | 38.52 | Excellent water |
| 16 | Piniwutrim | 752848 | 613756 | 462.69 | Unsuitable |
| 17 | Kunsu Camp | 754657 | 614639 | 61.32 | Good water |
| 18 | Kunsu M | 755030 | 622626 | 108.26 | Poor water |
| 19 | Bronikrom Pt 1 | 755248 | 625714 | 158.90 | Poor water |
| 20 | Meyeeden | 753206 | 595590 | 39.13 | Excellent water |
| 21 | Biemso No 1 | 760573 | 626656 | 151.08 | Poor water |
| 22 | Datro | 781059 | 616186 | 87.21 | Good water |
| 23 | Attakrom | 756652 | 625429 | 47.23 | Excellent water |
| 24 | Dotiem | 744527 | 585245 | 83.67 | Good water |
| 25 | Amakrom | 758242 | 624895 | 286.82 | Very poor water |

**Table 3.**
*Estimated WQI and classification.*

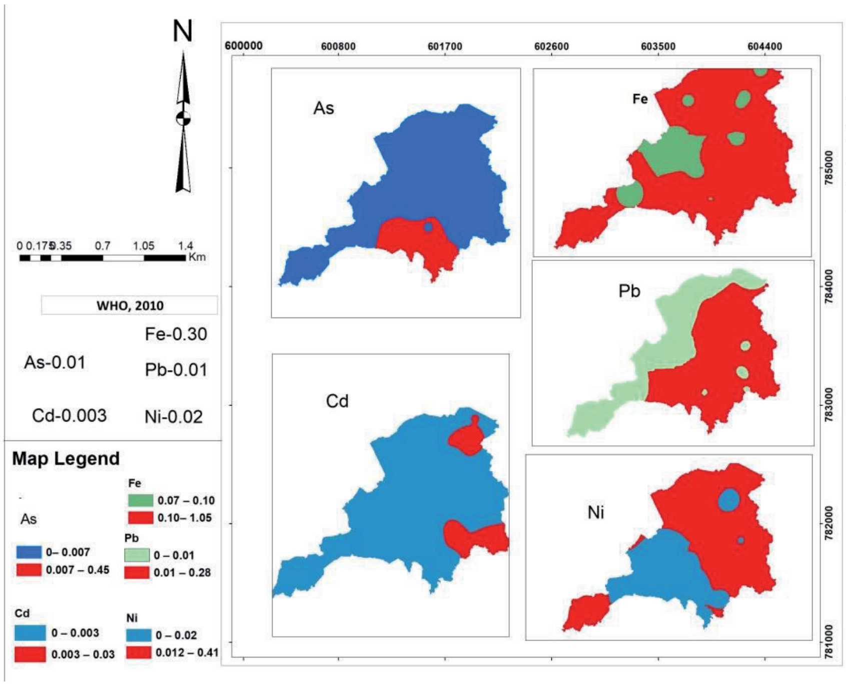

**Figure 5.**
*Distribution of heavy metals in the study area.*

| | **pH** | **Cond** | **Temp** | **TSS** | **Turb** | **TDS** | **Sal** | **TH** | **Alk** | **Fe** | **Cd** | **Ni** | **Pb** | **Cl** | **Na** | **K** | **$SO_4$** | **Ca** | **$HCO_3$** | **$CO_3$** | **Mg** | **As** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1 | | | | | | | | | | | | | | | | | | | | | |
| Cond | 0.37 | 1 | | | | | | | | | | | | | | | | | | | | |
| Temp | 0.14 | 0.04 | 1 | | | | | | | | | | | | | | | | | | | |
| TSS | 0.2 | 0.13 | 0.16 | 1 | | | | | | | | | | | | | | | | | | |
| Turb | 0.38 | 0.07 | −0.1 | −0.4 | 1 | | | | | | | | | | | | | | | | | |
| TDS | 0.42 | **0.89** | −0.1 | 0.19 | 0.15 | 1 | | | | | | | | | | | | | | | | |
| Sal | 0.33 | **0.75** | −0.1 | 0.03 | 0.13 | 0.9 | 1 | | | | | | | | | | | | | | | |
| TH | 0.4 | 0.35 | 0.59 | 0.17 | 0.13 | 0.35 | 0.36 | 1 | | | | | | | | | | | | | | |
| Alk | 0.61 | 0.46 | −0.3 | −0.1 | 0.3 | 0.56 | 0.48 | 0.14 | 1 | | | | | | | | | | | | | |
| Fe | 0.09 | −0.1 | −0.3 | 0.16 | 0.41 | 0.03 | 0.01 | −0.3 | 0.09 | 1 | | | | | | | | | | | | |
| Cd | −0.1 | 0.26 | 0.37 | −0.3 | 0.11 | 0.24 | 0.33 | 0.34 | 0.07 | −0.3 | 1 | | | | | | | | | | | |
| Ni | 0.19 | −0.1 | −.01 | 0.02 | 0.28 | −0.1 | 0.01 | −0.4 | 0.05 | **.494** | −0.2 | 1 | | | | | | | | | | |
| Pb | 0.04 | 0.21 | −0.1 | 0.12 | 0.13 | 0.11 | 0.12 | 0.25 | 0.09 | 0.22 | 0.07 | −0.3 | 1 | | | | | | | | | |
| Cl | 0.22 | **0.48** | −0.1 | 0.05 | 0.15 | **0.52** | 0.62 | 0.36 | 0.21 | 0.04 | 0.06 | −0.2 | 0.3 | 1 | | | | | | | | |
| Na | 0.34 | **0.48** | 0.05 | 0.18 | 0.29 | 0.48 | 0.52 | 0.37 | 0.2 | 0.13 | 0.08 | −0 | 0.21 | **0.91** | 1 | | | | | | | |
| K | 0.33 | 0.29 | 0.24 | 0.17 | 0.23 | 0.34 | 0.48 | 0.59 | 0.31 | −0.1 | 0.17 | −0 | 0.09 | 0.4 | 0.5 | 1 | | | | | | |
| $SO_4$ | 0.42 | **0.62** | 0.29 | 0.25 | 0.16 | 0.62 | 0.6 | 0.41 | 0.27 | 0.08 | 0.17 | 0.12 | −0.1 | 0.54 | **0.64** | 0.36 | 1 | | | | | |
| Ca | 0.29 | 0.13 | **0.58** | 0.27 | −0.2 | 0.07 | 0.14 | 0.69 | 0.2 | −0.4 | 0.16 | −0.3 | 0.17 | 0.07 | 0.12 | 0.51 | 0.23 | 1 | | | | |
| $HCO_3$ | **0.6** | 0.45 | −0.4 | −0.2 | 0.31 | 0.55 | 0.48 | 0.12 | 1 | 0.1 | 0.07 | 0.06 | 0.07 | 0.23 | 0.22 | 0.33 | 0.27 | −0.1 | 1 | | | |
| $CO_3$ | 0.6 | 0.45 | −0.4 | −0.2 | 0.31 | 0.55 | 0.48 | 0.12 | 1 | 0.1 | 0.07 | 0.06 | 0.07 | 0.23 | 0.22 | 0.33 | 0.27 | −0.1 | 1.0 | 1 | | |
| Mg | 0.4 | 0.34 | **0.59** | 0.16 | 0.14 | 0.34 | 0.36 | 1 | 0.14 | −0.3 | 0.34 | −0.4 | 0.24 | 0.38 | 0.39 | 0.61 | 0.42 | **0.69** | 0.12 | 0.12 | 1 | |
| As | −0.1 | 0.19 | 0.08 | 0.25 | −0.1 | 0.22 | 0.19 | **0.45** | 0.01 | 0.14 | 0.18 | **0.46** | **0.73** | 0.4 | 0.35 | 0.23 | 0.03 | 0.39 | −0.1 | −0.1 | 0.45 | 1 |

**Table 4.**
*Spearman correlation matrix of analyzed water quality parameters.*

### 3.4 Health effect due to elevated heavy metals in groundwater

The distribution of Pb in groundwater appears to be quite widespread. Twenty-one (21) representing about 84% of sampled groundwater elevated Pb levels exceeding [7] limit of 0.01 mg/l for potable water in the study area. This presents a potential health hazard to the inhabitants. According to [26], this is because, Pb normally accumulates in human body and builds up over a long period of exposure with no known documented usefulness to human health regardless of the pathway. But instead, exposure to different levels of Pb may predispose children, pregnant women and adults in general to serious health consequences [7]. According to [27], low levels of Pb ($Pb \leq 5$ μg/dl) may lead to hearing impairment, malfunctioning of blood cells in children, low IQ and damage to central and peripheral nervous systems. In pregnant women, it may lead to reduced growth of foetus and premature birth. This may put the lives of both the unborn baby and mother at risk. Pb may cause delayed puberty and reduction in IQ in children while there could be incidences of increased blood pressure when humans are exposed to Pb concentrations between 5 and 10 μg/dl. According to [26], exposure to Pb levels exceeding 15 μg/dl may predispose human to nervous disorders, reduced kidney function, low sperm count in men, and delayed conception in women. In this study, measured Pb concentrations fall within 'low Pb level' indicating that ingestion of groundwater by human may predispose especially children and pregnant women to potential health risks such as low IQ, damaged central and peripheral nervous system, impaired hearing and functioning of blood.

The concentration of Ni in sampled groundwaters ranged from 0 to 0.41 mg/l with a mean of 0.059 mg/l. Ten (10) out of the twenty-five (25) groundwater samples, representing about 40% had levels of Ni exceeding [7] permissible limit of 0.02 mg/l. According to [28], the commonest sources of Ni in mining areas may include effluent water generated from mining and smelting operations, runoff from tailing piles, or from utility water used for mine operations. Nickel has an extensive range of carcinogenic mechanisms which include regulation of transcription factors, controlled expression of certain genes and generation of free radicals. Nickel has been shown to be implicated in regulating the expression of specific long non-coding ribonucleic acids (RNA). It has also been demonstrated that nickel can generate free radicals, which contribute to carcinogenic processes. Common adverse health effects when Ni is ingested at high concentrations on humans include chronic bronchitis, lungs and nasal sinus cancer and reduced lung function. The exposure to nickel at high concentrations can be alarming as it causes chronic bronchitis, lungs and nasal sinus cancer and reduced lung function [29].

Cd concentration in the area varied from 0 to 0.03 mg/l with average value of 0.059 mg/l. In the current study, about 32% of groundwater had Cd levels above recommended limits for drinking water. High levels can be linked to the weathering and subsequent dissolution of chalcopyrite and pyrite ores in the area [30]. These minerals are common pathfinder minerals of gold within the meta-volcanics of Ghana [14]. The ingestion of Cd at levels exceeding the [7] permissible limits for drinking water can cause stomach irritation resulting to vomiting and diarrhea, and also lead to degenerate bone disease such as osteoporosis (skeletal damage). Short-term exposure to inhalation may lead to severe damages to the lungs and respiratory irritation while long-term exposure may lead to deposition in bones and lungs. Cd is highly toxic to the kidney and when accumulated in the proximal tubular cells at higher concentrations may predispose humans to renal dysfunction and kidney disease. Cd is also classified as group 1 carcinogens for humans by the International Agency for Research on Cancer [31].

Values of As in this study varied from 0.003 mg/l to 0.308 mg/l with an average concentration of 0.042 mg/l. Three samples out of twenty-five (25) sampled groundwater, representing about 12% had As values exceeding the recommended limit for potable water. Higher levels of As in groundwater may be due to anthropogenic activities such as mining and processing of gold ores, and naturally from water-rock interactions or soil-water interactions [7]. According to [32], As is commonly associated with ores containing metals, such as copper and lead. The strong positive correlation (0.73) between As and Pb concentration in this study supports this assertion and may indicate a common source. Exposure of As at lower levels can cause nausea and vomiting, reduced production of erythrocytes and leukocytes, abnormal heartbeat, pricking sensation in hands and legs, and damage to blood vessels. Long-term exposure may result in the occurrence of skin lesions, internal cancers, neurological problems, pulmonary disease, peripheral vascular disease, hypertension and cardiovascular diseases, and diabetes mellitus [33].

## 4. Conclusion

The activities of illegal artisanal gold mining have led to widespread degradation in the quality of groundwater in the study area as a result of indiscriminate dumping of mined wastes. Due to the potential interaction between contaminated surface waters and groundwater resources, it is anticipated that surficial waters with deteriorated quality arising from the contamination from the illegal small scale mining activities in the area may have compromised the otherwise generally better quality groundwaters in the area, which serve as the main source of potable water. This study has evaluated the quality of groundwaters to ascertain the potability and potential health risks associated with the consumption of groundwater resources in the Ahafo-Ano South District of Ghana. It was observed that areas with intensive illegal artisanal gold mining operations had much higher elevated levels of heavy metals such as Pb, As, Cd and Ni in sampled groundwaters and vice-versa. It is expected that the findings of this study will present a framework upon which, all stakeholders involved in the management of water resources and water supply for the inhabitants will develop an effective, efficient as well as preventive mechanisms to minimize groundwater quality deterioration, minimize potential health risks and to enhance the socio-economic development of the people.

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