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Research article

Groundwater quality and associated health risks in the Eastern Region of Ghana

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A B S T R A C T

In the Eastern Region of Ghana, 95 % of residents have access to boreholes. However, approximately 30 % of these boreholes are characterized by unpleasurable taste, odour, oily scum and particulate matter. Thus, this study aimed to assess water quality, predict the sources of groundwater contaminants, evaluate the human health risk and to generate spatial distribution and health risk maps. In achieving this, the water quality of 136 boreholes in the region was evaluated through Water Quality Index (WQI) and Groundwater Pollution Index (GPI) analyses. Multivariate statistical procedures, namely, principal component and correlation analyses were employed to define the major groundwater pollutants and their possible sources. Non-carcinogenic health risk to infants, children and adults through nitrates, iron, manganese and fluorides ingestion was also assessed. The results revealed that groundwater in the region is generally slightly acidic with a mean pH of 6.30. WQI analysis grouped 68 % of the groundwater samples under the 'excellent' and 'good' water types with the remaining percent categorized under 'poor', 'very poor' and 'unsafe' drinking water types. GPI analysis classified 95 %, 2.21 % and 2.79 % of the boreholes as 'insignificant', 'low' and 'highly' polluted zones. From the multivariate analyses, the dominant pollutants were iron, manganese, chlorides, sodium, fluorides, potassium, turbidity, total suspended and dissolved solids, hardness, alkalinity, sulphates, nitrates and phosphates. The sources of these contaminants are primarily from rock-water interactions and fertilizers. Health risk assessment for nitrates, fluorides, iron and manganese ingestion revealed that 23, 17 and 15 boreholes in the region are likely to pose non-carcinogenic health risk to infants, children and adults respectively. Health risk maps indicated that the most vulnerable districts were Atiwa East, Fanteakwa North, Achiase, Birim South, Akwapim, Suhum and Ayensuano. From these findings, it is imperative that appropriate groundwater remediation measures are implemented in the region to protect public health.

1. Introduction

Constituting approximately 99 % of the total liquid freshwater resource on the planet Earth, groundwater serves as drinking water source for an estimated 50 % of the world's population [1]. Groundwater has become the most reliable source of water due to its potability and dependence on it is anticipated to rise following the hikes in population growth, industrialization, economic development, urbanization and the unpredictable patterns in rainfall [1]. Around the world, groundwater constitutes approximately 38 % of

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the drinking water demand in the United States of America [2] and about 28.6 % of the demand in China [3]. In India, the dependency on groundwater as a drinking water source is about 85 % [2] and it goes beyond 95 % in countries such as Austria, Denmark and Hungary [4]. In Ghana and most developing countries, erratic supply of water from distribution networks have heightened the reliance on groundwater. As a result, about 95 % of water meant for domestic purposes in Ghana is extracted from groundwater sources [5]. Being the primary source of water for irrigation, industrial and domestic activities, groundwater plays a salient role in attainment of the sustainable development goals, precisely, in food security, poverty alleviation, good sanitation and hygiene, socio-economic growth, good health and education, climate change resilience, ecosystem services, and development of sustainable cities [6].

This important resource is, however, prone to pollution from several sources such as, geogenic factors, salt-water intrusion, runoffs from agricultural fields, illegal mining activities, landfills and indiscriminate discharge of domestic and industrial wastewater [7]. Variety of contaminants including microbial organisms, heavy metals, pesticides, nitrates, fluorides, arsenic, microplastics and hydrocarbons have been identified in groundwater bodies across the world [8]. In countries such as Germany, high levels of 1,4-dioxane (0.15–152 μg/L), a carcinogenic chemical which is applied as pesticides on agricultural farms has been detected in groundwater bodies [9]. Different types of microplastics including polystyrene and polyethylene with concentrations ranging between 17 and 44 n/L have also been identified in groundwater bodies in Northern China [10]. Additionally, poly-aromatic hydrocarbons such as naphthalene and benzo(a)pyrene have been found at levels between 5.0 and 48.72 ng/mL in groundwater bodies located in Brahmaputra Valley in India [11]. In Ghana, high levels of *E-coli* from on-site sanitation facilities [12], cadmium from landfill sites [13], arsenic from illegal mining activities [14] and fluorides from geogenic sources [15] have been identified in various boreholes and hand-dug wells. The deterioration of groundwater quality adversely affects the health of humans, ecosystem balance and availability of potable water [8].

In the Eastern Region of Ghana where close to 95 % of the residents have access to borehole water [16], research has shown that a significant number of these boreholes within the range of 20–30 % is characterized by excessive loads of manganese (Mn) and iron (Fe) with concentrations above the WHO stipulated limits [17]. Increased crop production and urban sprawl in the region has also heightened the susceptibility of the groundwater resource to pollution from agricultural runoffs and municipal wastes [18], imparting an obnoxious taste to the water [19]. This has compelled some residents in the region to fall on water from unimproved sources such as unprotected wells and rivers for drinking purposes [20]. As a result, previous research works conducted in the study area has sought to determine the physicochemical characteristics of borehole water in the region, predict water quality parameters linked to the complaints made by the inhabitants on their borehole water quality [19], assess the spatio-temporal patterns of water consumption from piped systems in the region [21] and also to evaluate the potential health risk upon exposure to nitrate and fluoride in the borehole water in the region [22].

Even though this present study also encompasses the physicochemical characteristics of borehole water as well the health risks associated with the consumption of groundwater in the region, the study further goes on to evaluate and compare water quality information on different boreholes sited in the same communities, most essentially, rural communities in the region. Additionally, water quality spatial distribution maps revealing boreholes that would require treatment prior to usage have also been included in this present study. Furthermore, this study goes beyond assessment of health risk based on nitrates and fluoride ingestion by adults only to include evaluation of health risk of the vulnerable age group, specifically, infants and children upon ingestion of iron, manganese, nitrates and fluorides and additionally, provides health risk spatial distribution maps indicating the most affected rural communities in the region. Thus, this present study essentially provides a comprehensive water quality data on the boreholes in the rural communities in the Eastern region of Ghana, evaluates the potability of groundwater in these communities including the potential health risks to infants, children and adults and finally provides spatial distribution maps based on the outcome of the water quality and health risk assessments. This appraisal study provides significant information to water providers on the most vulnerable communities with poor water quality problems. This will aid in the selection of appropriate methods of treatment required to improve the quality of contaminated borehole water. Ultimately, the useability of groundwater in the region will be enhanced to preserve human health. Succinctly, this study was carved out to (i) elucidate the physicochemical characteristics of the groundwater, (ii) assess the quality of the groundwater for drinking purposes using water quality index and pollution indices, (iii) identify the probable pollution sources of the physicochemical contaminants in the groundwater through multivariate statistical analyses and finally (iv) evaluate the non-carcinogenic health risk that inhabitants including infants, children and adults in the region might be prone to upon ingestion of nitrates, manganese, fluorides and iron in the groundwater.

The combination of analytical techniques employed in this study including water quality index, ground water pollution index, health hazard index and the multivariate statistical methods (Principal Component Analysis and correlation analysis) are ubiquitous tools applied by many researchers [23,24] in appraising the quality of groundwater for drinking purposes, assessing the degree of pollution of groundwater bodies, determining the relationships among water quality parameters, identifying the sources of pollutants in groundwater and also for evaluating the possible risks to human health [25,26].

2. Materials and methods

2.1. Description of study area

The Eastern region of Ghana with an estimated population of 3,377,593 people as at 2021 is the third largest region (19323 km^2) among the sixteen (16) administrative regions in Ghana. It is surrounded by other regions, namely, the Ashanti and Bono-East Regions to the north, Ashanti region to the west and the Greater Accra and Central Regions on the south. The Volta Lake is located on the eastern side of the region [7,16]. Geographically, Eastern Region is located on longitude $0^\circ\ 30'$ E and $1^\circ\ 30'$ W and on latitude $5^\circ\ 30'$ N and $7^\circ 22'$ N [27]. The region is characterized by two climatic seasons: the dry period which occurs within the months of November and

February and the rainy periods which occur within the months of March and July and also within September and November. The mean annual precipitation in the region falls between 1500 and 2000 mm [27]. The primary vegetation in the area is the semi-deciduous rain forest with some areas characterized by savanna zones. Major crops cultivated in the region include cocoa, maize and cassava [28]. Late Proterozoic-Paleozoic Voltaian Group sandstones, Precambrian Togo Formation schists, and intrusive granites of the Cape Coast Complex constitute the region's geological formation [18]. The rocks in this region comprise quartzite, schist, sandstone, talc mica, phyllites and shale [18]. The map of the study area is shown in Fig. 1.

2.2. Collection and analyses of groundwater samples

A total of 136 groundwater samples were taken from boreholes and hand-dug wells in the study area during the dry season, in the months of January and February 2023. The coordinates of the exact sampling points indicated in Fig. 1 were noted using a portable Global Positioning System (Handy GPS: Garmin eTrex 10J). The methods of sampling, transportation, preservation and analyses of the water samples as prescribed in the standards methods [29] were adhered to. Physicochemical parameters including pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), turbidity, Total Suspended Solids (TSS), alkalinity, Total Hardness (TH), colour, fluoride (F^-), chloride (Cl^-), carbonate ($C\,O_3^-$), iron (Fe), manganese (Mn), nitrite (NO_2^-), nitrate (NO_3^-), sodium (Na^+), potassium (K^+), phosphate ($P\,O_4^-$) and sulphate (SO_4^{2+}) were tested for in all the water samples. pH, TDS and EC were measured in-situ using a multipurpose pH/TDS/EC meter (HI 9813-6N). Turbidity was determined using a turbidimeter (HI 93414). Total Hardness (TH) of the samples was analyzed using EDTA titrimetric procedure. Samples designated for determination of ions were initially filtered through 0.45 μm cellulose filter before being analyzed. Concentrations of K^+, Na^+, F^-, Fe, Mn, $P\,O_4^-$ and Cl^- were evaluated using ion chromatography. Alkalinity and carbonate ion concentration were determined through titrimetric methods. Colour, NO_2^-, NO_3^- and SO_4^{2+} were analyzed using the HACH methods and the HACH DR 3900 spectrophotometer.

2.3. Water quality index

The suitability of water from the boreholes and hand-dug wells in the region for drinking purposes was rated using the Water Quality Index (WQI) method as presented in Equations (1)–(4) [25]. In the computation of the WQI, the following parameters were considered: pH, colour, turbidity, TH, alkalinity, TDS, EC, K^+, Na^+, Fe, Mn, $P\,O_4^-$, Cl^-, F^-, SO_4^{2+}, NO_2^- and NO_3^-.

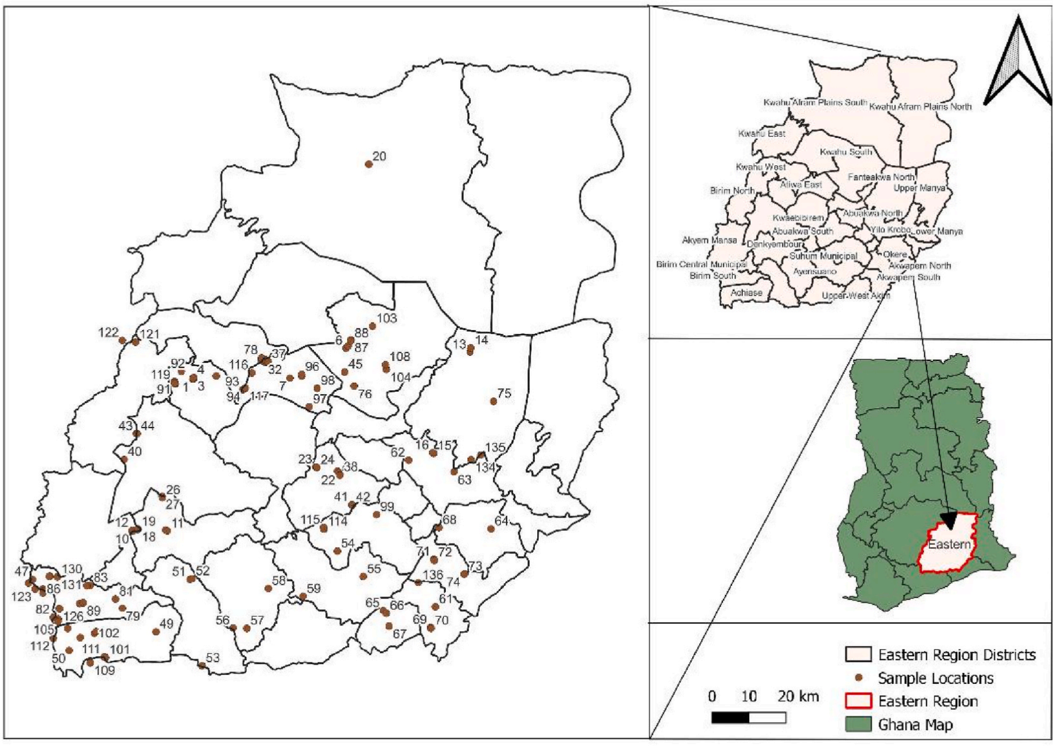


Fig. 1. Map of the Eastern Region of Ghana showing the groundwater sampling sites.

$$WQI = \frac{\sum_{i=1}^{n} R_n W_n}{\sum_{i=1}^{n} W_n} \tag{1}$$

$$W_n = k/S_n \tag{2}$$

$$k = \frac{1}{\frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \frac{1}{S_4} + \ldots + \frac{1}{S_n}} = \frac{1}{\sum_{i=1}^{n} 1/S_n} \tag{3}$$

$$R_n = 100 \times \frac{C_n - C_i}{S_n - C_i} \tag{4}$$

Where:

W_n = unit weight of the nth parameter
S_n = recommended standard concentration or value of the nth water quality parameter
k = numerical constant
R_n = quality rating of the nth water quality parameter
C_n = actual concentration or value of the nth parameter at a particular sampling point
C_i = ideal concentration or value of the nth parameter in pure water. $C_s = 0$ for all parameters in pure water except for pH = 7 and DO = 14 mg/L.

2.4. Multivariate statistical analyses

Multivariate statistical analyses, precisely, correlation and principal component analyses were applied in this study. Correlation analysis aids in identifying the clusters of water quality parameters with significant inter-relations. It also reveals sources of contaminants identified in groundwater [25]. The analysis was carried out by computing the Pearson's correlation coefficients for all pairwise combinations of the 19 water quality parameters considered in this study.

Principal Component Analysis (PCA) on the hand, pinpoints the predominant water quality parameters which characterize groundwater sources. The aptness of the data for the computation of the principal components was adjudged by conducting the Kaiser-Meyer-Olkin Measure (KMO) of sampling adequacy and the Bartlett's tests [30]. Generally, values of KMO ranging from 0.8 to 1 are considered good, those ranging from 0.5 to 0.79 are moderately acceptable whiles those lesser than 0.5 are inadequate [30]. The KMO value obtained for the water quality dataset was 0.852 which is higher than the threshold value of 0.5. Based on the KMO value obtained, the data was considered suitable for PCA. The Bartlett's test of sphericity yielded a *p-value* < 0.000 indicating that the PCA can be executed on the water quality data. PCA was conducted using the correlation matrix. Based on the Kaiser criterion, components with Eigen values greater than or equal to 1 were extracted as the principal components. The principal components were then rotated using varimax rotation. Multivariate analyses were performed with the aid of IBM SPSS Statistics 22.

2.5. Groundwater pollution index

Groundwater Pollution Index (GPI) was used to evaluate the quality of the groundwater samples. The initial step in its computation was the assignment of relative weight (R_p) to each water quality parameter using a scale of one (1) to five (5) [24] depending on the relevance of that parameter in determining the quality of the groundwater and its health implication on humans. The next step was to compute the weight parameter (W_p) for each water quality parameter as shown in Equation (5). Then came the calculation of the status of concentration (C_s) (Equation (6)) which depended on the concentration of the parameter in groundwater (C_n) and the threshold limits for drinking water stipulated by the Ghana Standards Authority (S_n). The groundwater pollution index for each parameter (I_p) was determined by multiplying the status concentration by the weight parameters (Equation (7)). The overall Groundwater Pollution Index (GPI) was obtained by summing up all the individual pollution indices for each parameter (Equation (8)).

$$W_p = R_p \Big/ \sum R_p \tag{5}$$

$$C_s = C_n/S_n \tag{6}$$

$$I_p = W_p \times C_s \tag{7}$$

$$GPI = \sum I_p \tag{8}$$

2.6. Non-carcinogenic human health risk assessment

The human health risk associated with drinking water from the boreholes and the hand-dug wells were also assessed. Four water quality parameters: iron, nitrate, fluoride and manganese were considered in analyzing the non-carcinogenic health risk in infants, children and adults. In the computations, the Average Daily Dose (ADD) measured in mg/kg/day was determined using Equation (9). Next, the hazard quotient which relates to the probability of health risk when an individual is exposed to dosages of the contaminant above the reference dose was computed for each contaminant according to Equation (10). The Reference Dose (RfD) which varies for each chemical contaminant is the safe daily intake level set by the US Environmental Protection Agency (USEPA). The reference dose for nitrate, fluoride, iron and manganese are 1.6, 0.06, 0.7 and 0.14 mg/kg/day respectively.

$$ADD_{oral} = \frac{C_w \times I \times Ex \times F}{BW \times ET} \tag{9}$$

Where: C_w = concentration of the contaminant in groundwater (mg/L)

I = Ingestion Rate (2.5 L/day for adults, 0.78 L/day for children and 0.3 L/day for infants) [26].

Ex = E xposure Duration (connoting how long a person drinks the water; 70 years for adults, 6 years for children and 1 year for infants)".

F = Exposure Frequency (referring to the number of days a person drinks the water; 365 days/year for adults, children and infants).

BW = Average Body Weight (65 kg for adults, 18.7 kg for children and 6.9 kg for infants) [26]

ET = Exposure Time (estimated as 25,550 days for adults, 2190 days for children and 365 days for infants)

$$HQ_{oral} = \frac{ADD_{oral}}{RfD} \tag{10}$$

Lastly, the Total Hazard Index (THI) which is the measure of the overall non-carcinogenic health risk was computed following Equation (11). Values of THI <1 connotes no risk whilst values ≥ 1 is an indication of a non-carcinogenic health risk.

$$THI = \Sigma\, HQ_{NO_3^- - oral} + HQ_{F^- - oral} + HQ_{Fe^{2+} - oral} + HQ_{Mn^{2+} - oral} \tag{11}$$

3. Results and discussion

3.1. Groundwater characteristics

The descriptive statistics on the physicochemical parameters of the 136 groundwater samples are presented in Table 1 and Fig. 2. The pH of the water samples ranged between 5.7 and 7.8 with a mean value of 6.30. This mean value is below the guideline value of 6.5–8.5 set by the Ghana Standards Authority [31]. Approximately 74 % of the water samples exhibited a pH value below the desirable limit of 6.5 (Fig. 2a) which tallies with the results obtained by Kulinkina et al. [19]. Boreholes in other regions in Ghana such as the coastal cities including Accra and Winneba exhibited much lower pH values of 3.11 and 4.08 [32]. The low pH indicates a slight acidity of these water samples. This could be stemming from the dissolution of CO_2 in the groundwater resulting in the production of H_2CO_3. Dissociation of H_2CO_3 into HCO_3^- and H^+ ions consequently lead to an acidic groundwater [33]. Low pH of groundwater bodies is known to favour the solubilization of heavy metals such as iron and manganese [34,35]. Thus, ingestion of acidic water is likely to result in heavy metal accumulation in body tissues and its related diseases [36]. Additionally, acidic drinking water can cause acidosis

Table 1
Descriptive statistics on the levels of physicochemical water quality parameters of groundwater samples in the region.

Parameter	S.I. Units	Min	Median	Max	Mean	Std Dev	Ghana Standards Authority [31]
pH		5.70	6.30	7.80	6.30	0.33	6.50–8.50
Turbidity	NTU	0.00	0.20	358	7.63	36.9	5.00
Colour	HU	0.00	1.00	450	12.7	56.9	5.00
Electrical conductivity	mS/m	24.3	42.4	197	48.6	24.5	100
TDS	mg/L	122	212	985	243	122	1000
TSS	mg/L	0.00	0.00	358	7.00	36.1	0.00
Alkalinity	mg/L	4.00	34.0	266	43.5	32.6	400
Hardness	mg $CaCO_3$/L	14.0	102	660	121	93.4	500
Fluoride	mg/L	0.00	0.34	2.36	0.43	0.49	1.50
Iron	mg/L	0.00	0.05	13.7	0.45	1.41	0.30
Manganese	mg/L	0.00	0.08	8.23	0.27	0.78	0.40
Nitrite	mg/L	0.00	0.01	0.50	0.03	0.07	3.00
Nitrate	mg/L	0.00	1.40	28.6	2.90	4.86	50.0
Chloride	mg/L	7.00	28.0	297	39.7	41.5	250
Phosphate	mg/L	0.60	2.95	33.6	4.77	5.46	30.0
Carbonate	mg/L	2.40	20.4	160	26.6	21.6	–
Sodium	mg/L	4.54	17.5	193	27.3	17.5	200
Potassium	mg/L	0.76	2.97	32.1	4.25	4.25	30.0
Sulphate	mg/L	0.00	100	152	9.09	24.0	250

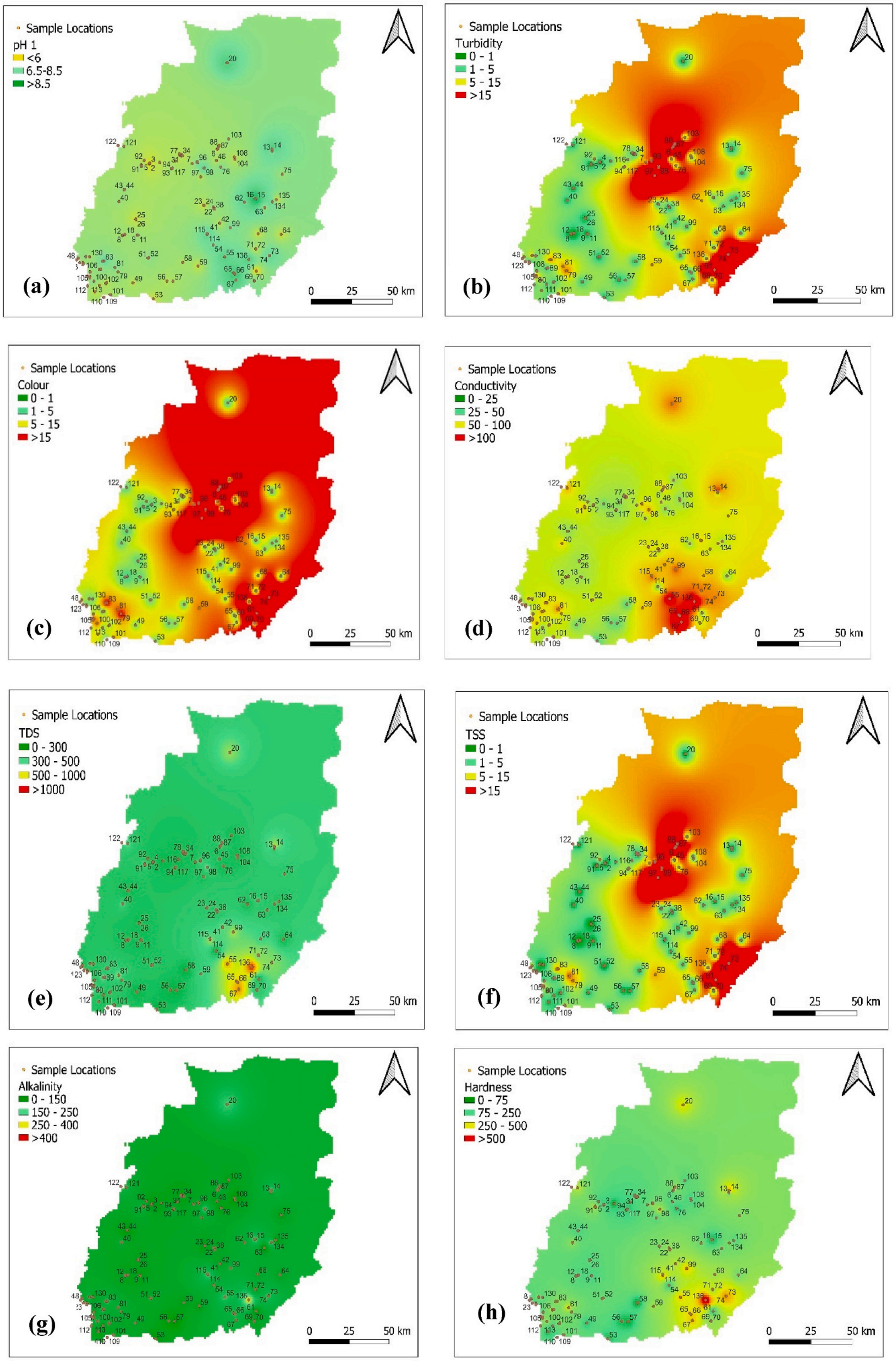
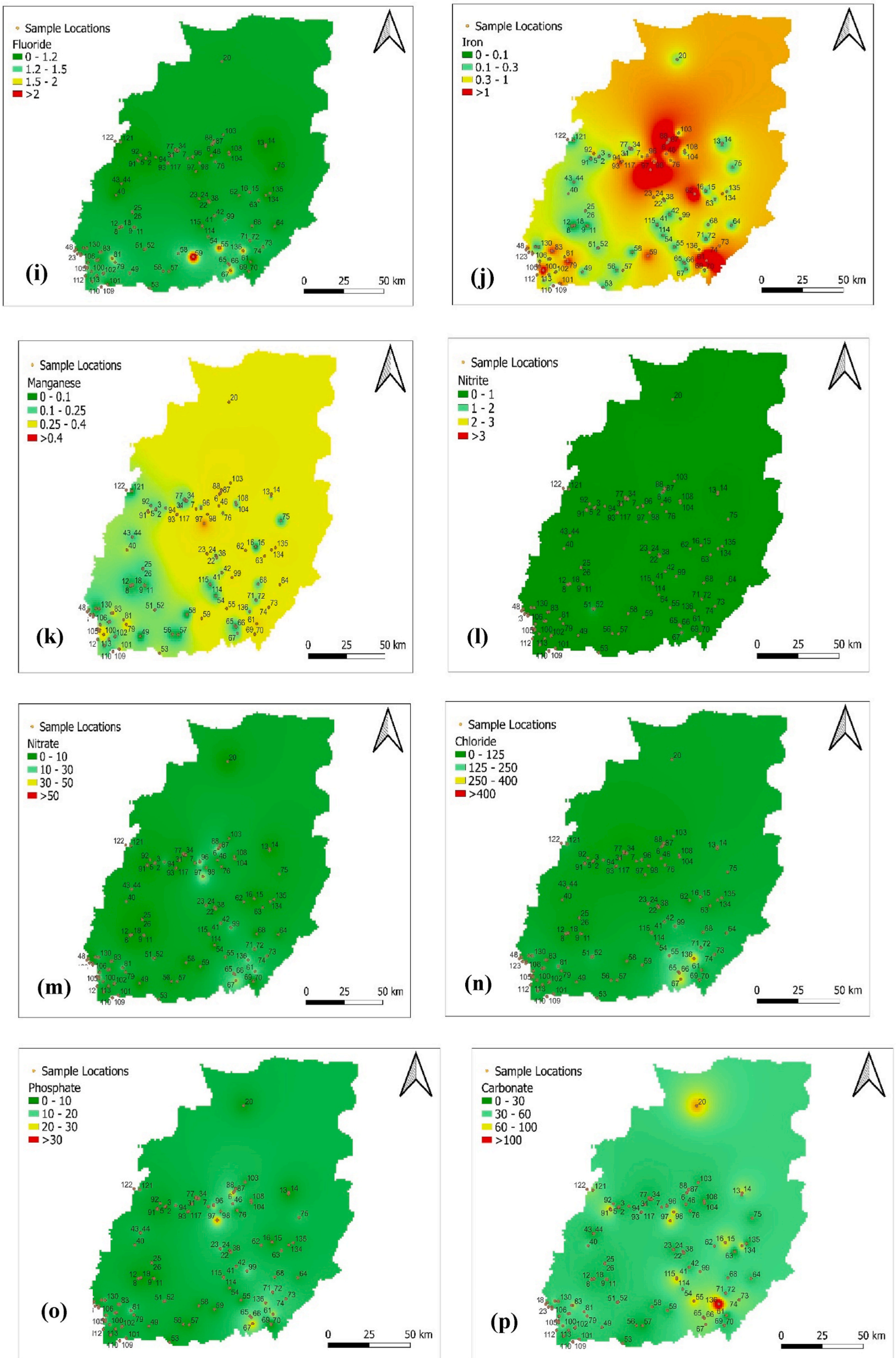


Fig. 2. Spatial variation maps for **(a)** pH; **(b)** Turbidity; **(c)** Colour; **(d)** Electrical conductivity; **(e)** TDS; **(f)** TSS; **(g)** Alkalinity **(h)** Hardness; **(i)** Fluoride; **(j)** Iron; **(k)** Manganese; **(l)** Nitrite; **(m)** Nitrate; **(n)** Chloride; **(o)** Phosphate; **(p)** Carbonate; **(q)** Sodium**;** **(r)** Potassium; **(s)** Sulphate.



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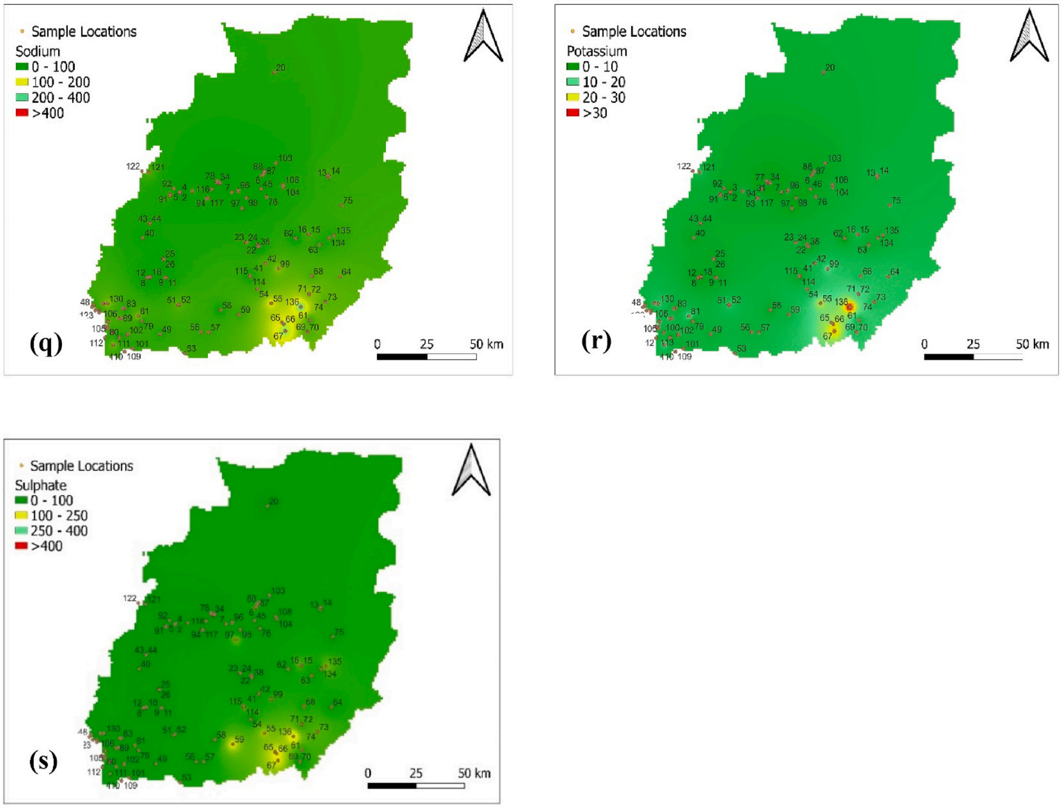

Fig. 2. (*continued*).

in humans [37] and corrosion in water distribution pipes [36].

Turbidity of the water samples ranged within 0 and 358 NTU with the average value of 7.63 being higher than the permissible limit of 5 NTU [31]. The values obtained in this study are higher than that reported in other works [38,39]. Approximately, 14 % signifying 19 of the groundwater sources primarily located in the northern, central and south-eastern part of the region had turbidity levels higher than the threshold value of 5 NTU (Fig. 2b). Turbidity in groundwater is generally related to the existence of microbes, suspended matter, clay particles and decomposing parts of living organisms. Enhanced rock weathering induced in acidic aquifers increases turbidity of the groundwater [40]. The source of turbidity in the groundwater could be associated with soil particles as well as the presence of iron and manganese ions in the water.

The colour of the water samples ranged between 0.00 and 450 HU with an average value of 12.67. Other works like [19,23] has

Table 2
Categorization of groundwater samples based on Electrical Conductivity (EC), Total Dissolved Solids (TDS) and Total Hardness (TH).

Parameter	Range	Category	No. of samples	% of samples
EC (μS cm^{-1}) [44]	0–333	Excellent	28	20.59
	333–500	Good	68	50.00
	500–1100	Permissible	36	26.57
	1100–1500	Brackish	4	2.94
	1500–10,000	Saline	–	–
TDS (mg L^{-1}) [48]	<500	Desirable for drinking	131	96.32
	500–1000	Permissible for drinking	5	3.68
	1000–3000	Useful for irrigation	–	–
	>3000	Unfit for drinking and irrigation	–	–
TDS (mg L^{-1}) [47]	<1000	Fresh	136	100
	1000–10,000	Brackish	–	–
	10,000–100,000	Saline	–	–
	>100,000	Brine	–	–
TH (mg L^{-1}) [53]	<75	Soft	47	34.56
	75–150	Moderately hard	56	41.17
	150–300	Hard	28	20.59
	>300	Very hard	5	3.68

reported similar results. HU which is above the stipulated limit of 5 HU according to the Ghana Standard Authority guidelines [31]. Boreholes sited at the central, northern and south-eastern portions of the region were negatively affected (Fig. 2c) as was observed with the turbidity of the groundwater samples. Colouration of groundwater may result from the presence of iron and manganese in the water. Seepage of dissolved organic matter primarily from vegetative parts into groundwater is also known to impart a yellowish hue to the groundwater bodies. Complexes of transition metals and sulphur compound can also give groundwater a yellowish colour. The accompanying health impact of these compounds in drinking water are kidney disorders and cancers [41].

The mean electrical conductivity of the water samples was 48.58 mS/m which is well below the permissible limit of 100 mS/m. However, some water samples located at the south-eastern part of the region (Akuapim District) had exceedingly high electrical conductivity values ranging between 101 and 197 mS/m (Fig. 2d) which may be explained by the intense agricultural production in the area [18]. Values of EC obtained in this study is higher than that reported for groundwater in the Western [42], Greater Accra and Central Regions [32] of Ghana as well as some areas in India [43]. According to Langenegger classification of electrical conductivity [44] shown in Table 2, approximately, 21 % and 50 % of the water samples were classified as excellent and good respectively while 26 % and 3 % fell under the permissible and brackish water types respectively.

The concentrations of the total dissolved solids ranged from 121.60 to 985 mg/L with a mean value of 242.91 mg/L. All the water samples fell below the standard value of 1000 mg/L (Fig. 2e). The mean value obtained are comparable to those reported for boreholes in Essiama (290 mg/L) a coastal community in Ghana [32] but lower than that reported for Winneba (1570 mg/L), another coastal town in Ghana [32] and also for some boreholes sited in Algeria (1498 mg/L) [45]. Fisher et al. [46] averred that drinking water with TDS concentrations beyond the permissible limit has an undesirable taste and can result in tinting of clothes. Applying the TDS classification according to Freeze and Cherry [47], all the water samples are categorized under the freshwater type. Similarly, under the Davis and De Wiest's classification [48], approximately 96.32 % of the groundwater sources were classified as the desirable drinking water type with only about 3.68 % being classified under the permissible drinking water type (Table 2).

With about 85 % of the water samples having a TSS concentration of zero tallying with the desirable limit set by GSA, 15 % of the boreholes precisely those found in the central and south-eastern section of the region had higher TSS concentrations ranging from 3 to 358 mg/L (Fig. 2f). The mean TSS concentration was 7 mg/L. The range of TSS values in this study is higher that reported for other boreholes in India [49,50]. The occurrence of suspended solids in water may indicate the occurrence of soil particles. Metals and pesticides may be adsorbed onto these soil matrices which can have a negative implication on the health of consumers. Moreover, suspended particles in the water can obstruct piping networks and discolour raiment and water containing vessels [46].

The alkalinity values of all the water samples were under the desirable limit of 400 mg/L with the mean alkalinity value being 43.5 mg/L. This value is lower than those documented in other works [41,48]. High levels of alkalinity in water does not only impart a disagreeable taste to drinking water but also result in the formation of scales in pipe networks and in cookware [51]. The spatial map showing the levels of alkalinity in groundwater samples is illustrated in Fig. 2g.

Regarding the hardness of the water samples, a mean value of 120.50 mg $CaCO_3$/L which is below the standard limit of 500 mg$CaCO_3$/L was recorded. Only two samples (from boreholes located in the south-eastern area) had levels of hardness specifically, 530 and 660 mgCaCO3/L (Fig. 2h) exceeding the standard value. The results in this study is in agreement to that documented by Ref. [50] but lower than reported by Wekesa and Otieno [52]. With reference to the Sawyer and McCarty's classification of water hardness [53], about 34 % and 41 % of the water samples fell under the 'soft' and 'moderately hard' water types respectively indicating their suitability for domestic and industrial applications. However, 21 % and 4 % of the samples were identified as 'hard' and 'very hard' water types respectively pointing to potential scaling issues in water systems and appliances [54]. Hard water is also linked to eczema, irritation of skin, odd taste in drinking water, wastage of soap and staining of clothes during washing [55].

Fluoride concentrations ranged between 0 and 2.36 mg/L with a mean value of 0.43 mg/L. Similar results were documented by other authors [25,48,56]. Approximately, 95 % of the water samples had fluoride concentrations below the desirable limit of 1.5 mg/L. Such levels do not spark any reason for concern. However, 7 of the groundwater sources located in Ayensuano and Akuapim districts had concentrations above the desirable limit (Fig. 2i). Fluoride content in water is crucial. While, deficiency in fluoride can lead to dental caries, alterations in bone mineral density and risk of osteoporosis, high fluoride intake on the other hand can result in dental and crippling fluorosis [57].

Iron levels fell within 0 and 13.70 mg/L with a mean concentration of 0.45 mg/L. These results are in close agreement with that stated for groundwaters in Ashanti Region of Ghana [58] and other regions in India [50]. Approximately, 44 % of the groundwater sources were within the permissible limit (0.3 mg/L) designated for iron. Boreholes located in the central and south-eastern portions of the region were characterized by high iron content (Fig. 2j). With regards to manganese, about 9.5 % of the groundwater sources specifically those sited in the central part of the region (Atiwa District) had concentrations above the permissible limit of 0.4 mg/L (Fig. 2k). The Atiwa District is well-known for mining of precious metals including gold, bauxite and manganese [59]. On the whole, manganese concentrations in the region varied between 0.08 and 8.23 mg/L with the average being 0.27 mg/L. Other works such as [41,53] also reported similar results for manganese levels in groundwater. Iron and manganese are widely spread within the earth crust. Essentially, the functions of iron in the human body include transport of oxygen to various body tissues, brain development and synthesis of hormones [60]. Manganese, on the other hand is required in the body for bone and tissue formation as well as metabolism of carbohydrates, fats and amino acids [61]. Excess iron may results in cancer and cirrhosis of the liver [62]. Exposure to high levels of manganese may also result in neurotoxicity, poor development of the skeletal system and damage of DNA [63]. Oxidation of iron and manganese in water does not only impart a foul odour, a metallic taste and colour to water but also stains clothes and utensils. Whiles oxidized iron yields a reddish brown colouration, oxidized manganese ions produce a blackish colouration in water [64]. Furthermore, a reddish-brown slime in water is an indication of the existence of iron and manganese-oxidizing bacteria [64] which might explain the odour, oily scum and the change in food colour that was observed in the region by Kulinkina et al. [19].

For the nitrogenous compounds, namely, nitrite and nitrate, the mean levels observed were 0.03 and 2.9 mg/L respectively, with none of the groundwater sources having concentrations above the desirable limits of 3 and 50 mg/L respectively. Similar observations were reported by other authors [41,55]. The low levels indicate that the consumers have decreased susceptibility to thyroid diseases and methaemoglobinaemia. Common sources of nitrates are from seepage of inorganic fertilizer used on farmlands, indiscriminate discharge of wastewater and excreta [65]. The spatial maps for nitrite and nitrate are illustrated in Fig. 2 l and Fig. 2 m respectively.

With the permissible limits of chloride and sodium pegged at 200 and 250 mg/L respectively, the average concentrations (39.74 mg Cl^{-}/L and 27.33 mg Na/L) observed were within these specified limits. Other works including [18,41] reported similar results. None of the borehole water had sodium concentrations above the acceptable limits (Fig. 2q). However, three (3) samples notably from the Akim District, Ayensuano District and Suhum Municipal Assemblies had chloride concentrations exceeding the standard limit (Fig. 2n). Overall, the mean sodium and chloride concentrations in the Eastern Region were lesser than that observed in the Effutu Municipality (96.91 mg Na/L and 223.61 mg Cl^{-}/L) [23] which is located in the coastal region of Ghana. This is due to the probable saltwater intrusion into the groundwater in the Effutu Municipality which is located in the coastal region of Ghana. Sodium and chloride ions are required in humans for relaying nerve impulses and balancing blood pressure and fluid volume in the body. However, excessive intake of sodium chloride may lead to hypertension, dehydration, convulsion, kidney and heart diseases [66,67]. High levels of sodium (>200 mg/L) and chloride (>250 mg/L) ions have been linked to unpleasurable taste of water [66,68].

Carbonate concentrations ranged from 2.4 to 159.6 mg/l, with the mean level occurring at 26.64 mg/l. Very low carbonate levels have been reported in another study [69]. The very high levels were identified in the south-eastern part of the region (Fig. 2p). Their presence is associated with hardness and alkalinity in water [55]. Carbonate hardness can simply be eliminated from water through boiling [70]. There is no guideline value set by GSA for carbonate concentrations in drinking water.

The average levels of phosphates and potassium were 4.77 and 4.25 mg/L respectively which were below the standard limit of 30 mg/L. Similar results were obtained in other studies [18,25,43]. However, one sample had phosphate concentrations (33.60 mg PO_4^{-}/L) in the central part of the region exceeding the threshold limit and another in the south-eastern part of the region had potassium concentration (32.13 mg K/L) also exceeding the desired limit as portrayed in the spatial maps (Fig. 2o and Fig. 2r). Potassium is required in the right amount for regulation of osmotic pressure and release of insulins in the body [65]. Phosphates are pivotal for the production and storage of energy in the human body. It is an essential component of nucleic acids, teeth and bones. Excessive amount of phosphates is however, linked to diseases of the heart, bones and kidneys [71]. Appropriate levels of potassium are necessary for the regulation of osmotic balance in the body as well as the normal functioning of nerves and muscles. High concentrations of potassium can heighten the risk of cardiac arrythmia and hypertension [72].

Sulphate concentrations occurred within the range of 0 and 152 mg/L with the mean concentration of 9.09 mg/L satisfying the permissible limit (250 mg/L) set by GSA. The spatial map has been presented in Fig. 2s. Such results were also reported by Refs. [70,73]. In the human body, sulphates play a critical role in cell development even though excessive intake is known to result in dehydration and laxative effect [74].

3.2. *Water quality index*

To further evaluate the suitability of the groundwater samples in the region for human consumption, the Water Quality Index (WQI) method was employed. WQI comprises five different classifications, namely, 'excellent water type' for WQI <25, 'good water type' for WQI within 26 and 50, 'poor water type' for WQI within 51 and 75, 'very poor water type' for WQI within 76 and 100 and lastly, 'unsuitable for drinking water type' for WQI >100. Computations for Water Quality Index were done based on the wide array of information gathered on the different water quality parameters for the 136 groundwater samples. The values obtained for the Water Quality Index ranged from 3.39 to 3162.99, with an average value of 104.41. Based on the WQI classification, approximately 54 % representing 74 groundwater samples fell within the excellent water type category. 14 % (19 water samples) were deemed to be good water type. However, 8 % and 4 % representing 11 and 5 water samples respectively were categorized as being poor and very poor water types respectively. 20 % being 27 of the groundwater samples were classified as unsuitable for drinking water type. Table 3 summarizes the water quality types of the 136 groundwater samples based on the WQI classification.

3.3. *Pollution index of groundwater*

The Pollution Index of Groundwater (GPI) was adopted in this study to estimate the extent of pollution of the groundwater sources in the region. Each parameter's Overall Water quality value (Ow) was calculated by multiplying its concentration with a pre-assigned weight reflecting its relative importance in water quality assessment. An Ow value exceeding 0.1 gives an indication that the specific

Table 3
Groundwater type based on Water Quality Index classification.

WQI range	Water quality type	Number of samples	Number of samples in percentages
0–25	Excellent	74	54
26–50	Good	19	16
51–75	Poor water	11	8
76–100	Very poor water	5	4
>100	Unsuitable	27	20

parameter contributes significantly (10 %) to the overall GPI [24]. GPI has five (5) classes of pollution based on the degree of groundwater contamination. These five divisions are: insignificant pollution zone for GPI <1.0, low pollution zone for GPI between 1.0 and 1.5, moderate pollution zone for GPI between 1.5 and 2, high pollution zone for GPI between 2 and 2.5 and finally, very high pollution zone for GPI >2.5. GPI values obtained in this study ranged from 0.08 to 13.50 with an average value of 0.49.

Based on the GPI classification, the insignificant pollution zone with a GPI value less than one covered over 95 % (129) of the groundwater samples in the study region. The mean value of the GPI for the insignificant pollution zone was 0.25 which is lower than 1.0. The Ow values of all the parameters within the insignificant pollution zone ranging from turbidity (0.022), colour (0.025), pH (0.022), EC (0.029), TDS (0.014), F^- (0.022), Fe (0.047), Mn (0.025), NO_2^- (0.00), NO_3^- (0.003), Cl^- (0.009), hardness (0.011), alkalinity (0.005), PO_4^- (0.008), Na^+ (0.006), K^+ (0.004) to SO_4^{2-} (0.002) were below 0.1 (Table 4). The corresponding mean concentrations of each of these parameters within the insignificant pollution zone, namely, turbidity (1.44 NTU), colour (2.81 HU), EC (48.33 mS/m), TDS (241.66 mg/L), F^- (0.45 mg/L), Fe (0.23 mg/L), Mn (0.17 mg/L), NO_2^- (0.02 mg/L), NO_3^- (2.30 mg/L), Cl^- (39.20 mg/L), hardness (117.53 mgCaCO3/L), alkalinity (43.30 mgCaCO3/L), PO_4^- (4.12 mg/L), Na^+ (25.44 mg/L), K^+ (4.18 mg/L) and SO_4^{2-} (8.55 mg/L) were all within the threshold limits designated for drinking water (Table 4) with the exception of pH (6.30) which was slightly lower than the desirable limit of 6.5 set by GSA. The slight acidity of the groundwater may be linked to the dissolution of CO_2 in the groundwater resulting in the formation of weak carbonic acid (H_2CO_3) which further breaks down into HCO_3^- and H^+ ions [33]. The release of the hydrogen ions explains the slightly low pH of the groundwater in this region. The results of the GPI and the corresponding concentrations of the water quality parameters obtained in this zone evidently portrays that the groundwater exist in its natural state with insignificant contamination from external sources.

The low pollution zone with GPI values within 1 and 1.5 covered 2.21 % of the entire region and this originated from three (3) groundwater sources out of the total of 136. The GPI values spanned from 1.13 to 1.14 with an average value of 1.23. The overall water quality (Ow) values of the parameters contributing to this zone were: 0.02 (pH), 0.04 (EC), 0.02 (TDS), 0.02 (F^-), 0.08 (Mn), 0.002 (NO_2^-), 0.02 (NO_3^-), 0.006 (Cl^-), 0.02 (Hardness), 0.006 (alkalinity), 0.02 (PO_4^-), 0.003 (Na^+), 0.003 (K^+) and 0.001 (SO_4^{2-}). All Ow values within the zone were below 0.1. However, the Ow values of turbidity (0.353), colour (0.299) and iron (0.326) were above 0.1. Observing from Table 4, all average values of the water quality parameters within the low polluted zone were within the specified permissible limit for drinking water except colour (7.26 HU), pH (6.27) and Fe (0.75 mg/L). In aerobic groundwaters, at pH > 5, Fe^{2+} ions released into water from weathered rocks are oxidized to Fe^{3+} ions. Fe^{3+} ions occur as insoluble precipitates in water and impart a reddish-brown hue to the groundwater [75]. This may explain the high concentrations of iron and colour found this zone. This implies that the low polluted zone within the study region may be resulting from geogenic contamination.

There are no moderate and high pollution zones within the study region based on the GPI values obtained. However, GPI values > 2.5 within the range of 3.44 and 13.50 with an average value of 7.70 indicated the occurrence of a highly polluted zone within the region. Water quality parameters including pH, EC, TDS, F^-, NO_3^-, Cl^-, hardness, alkalinity, PO_4^-, Na^+, K^+ and SO_4^{2-} had Ow values less than 0.1 (Table 4). The remaining parameters, namely, turbidity, colour, iron and manganese had Ow values of 2.91, 2.82, 1.30 and 0.50 respectively. Clearly, their average concentrations; turbidity (195 mg/L), colour (315 HU), pH (6.13), Fe (6.5 mg/L) and Mn (3.34 mg/L) fell beyond the permissible threshold limits set by the Ghana Standard Authority. According to Usman et al. [76], iron and manganese can leach from rock minerals bearing Fe^{2+} and Mn^{2+} within their crystal lattices. These divalent cations are oxidized into insoluble precipitates of ferric oxide and manganese (IV) oxides which impart reddish-brown and blackish colouration respectively to water. This may explain the poor water quality in the highly polluted zone. The spatial map shown in Fig. 3 defines the specific areas within the region which are categorized under insignificant, low and highly polluted zones. From Fig. 3, the highly polluted zones correspond to Fanteakwa North, Atiwa East, Akwapim North and Akuapim South Districts.

3.4. Multivariate statistical analyses

3.4.1. Principal component analysis

Principal Component Analysis (PCA) was conducted to reveal the primary physicochemical parameters dictating the groundwater quality in the region. The results of the PCA are presented in Table 5, in Fig. 4 and Fig. 5. The scree plot shown in Fig. 4 displays the eigen value for each of the components developed. From the plot, it is evident that out of the 19 components developed, three (3) components had eigen values greater than 1. Applying the criterion developed by Chatfield and Collins [77], the three components were adjudged significant and were subsequently maintained. The results obtained for the eigen values, percentage variance and cumulative variances are depicted in Table 5. The cumulative variance of the three components was 80.225 % indicating that the PC retained expounded 80.225 % of the variance in the water quality data. With reference to Liu et al. [78] values of component loading higher than 0.75 should be classified under 'strong', values between 0.75 and 0.50 are signified as 'moderate' and those within 0.50 and 0.30 are described as 'weak'.

Component 1 which gives the predominant description of the groundwater quality in the region explained 40.62 % of the total variance. The strong positive loadings were ascribed to EC (0.945), TDS (0.945), Cl^- (0.877), Na^+ (0.869), K^+ (0.876) and SO_4^{2-} (0.8371) whiles F^- (0.48) was associated with weak loadings. Electrical conductivity and total dissolved solids are directly proportional to each other as they are both dependent on the concentrations of ionized compounds present in water [79]. The occurrence of these anions (Cl^-,SO_4^{2-}) and cations (Na^+, K^+) in water elevate the electrical conductivity and the total dissolved solids concentrations in groundwater. These ions may be originating from rock weathering or infiltration of sewage or agrochemicals applied on farmlands [80]. High levels of dissolved solids has been reported to occur in some parts of the mountain ranges in Atiwa [19]. Still under Component 1, strong positive loadings on hardness (0.825) and moderate loadings on alkalinity (0.741), carbonate (0.695) and pH

Table 4
Descriptive statistics of Groundwater Pollution Index (GPI) values.

Description	GPI	pH	Turbidity	Colour	EC	TDS	Alkalinity	Hardness	F^-	Fe	Mn	NO_2^-	NO_3^-	Cl^-	PO_4^-	Na	K	SO_4^{2-}
		Overall water quality values (Ow) for each parameter																
Minimum	0.08	0	0	0	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	13.50	0.03	5.34	4.03	0.01	0.59	0.03	0.06	0.12	2.73	1.22	0.01	0.04	0.07	0.07	0.04	0.03	0.03
Mean	0.49	0.02	0.11	0.11	0.03	0.01	0.00	0.01	0.02	0.09	0.04	0.00	0.00	0.01	0.01	0.01	0.00	0.00
Mean values of Overall water quality values (Ow) for each GPI zone																		
Insignificant pollution zone (GPI < 1.0)	0.25	0.02	0.02	0.03	0.03	0.01	0.005	0.011	0.02	0.05	0.03	0.00	0.003	0.01	0.008	0.001	0.00	0.00
Low pollution zone (1< GPI<1.5)	1.23	0.02	0.35	0.30	0.04	0.02	0.01	0.02	0.02	0.33	0.08	0.002	0.02	0.006	0.02	0.003	0.003	0.001
Moderate pollution zone (1.5< GPI<2)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
High pollution zone (2< GPI<2.5)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Very high pollution zone (GPI > 2.5)	7.70	0.02	2.91	2.82	0.03	0.00	0.004	0.015	0.000	1.30	0.50	0.005	0.03	0.01	0.043	0.005	0.004	0.005
Mean values of water quality parameters for each GPI zone																		
Insignificant pollution zone (GPI < 1.0)		6.30	1.44	2.81	48.33	241.66	43.30	117.53	0.45	0.23	0.17	0.02	2.30	39.20	4.12	25.44	4.18	8.55
Low pollution zone (1< GPI<1.5)		6.27	4.73	7.67	39.89	199.43	46.00	83.33	0.41	0.75	0.13	0.01	1.43	35.67	3.10	22.62	3.72	0.33
Moderate pollution zone (1.5< GPI<2)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
High pollution zone (2< GPI<2.5)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Very high pollution zone (GPI > 2.5)		6.13	195.00	315.00	45.31	226.53	40.00	166.00	0.00	6.52	3.34	0.19	16.50	35.00	21.83	24.20	3.79	28.25

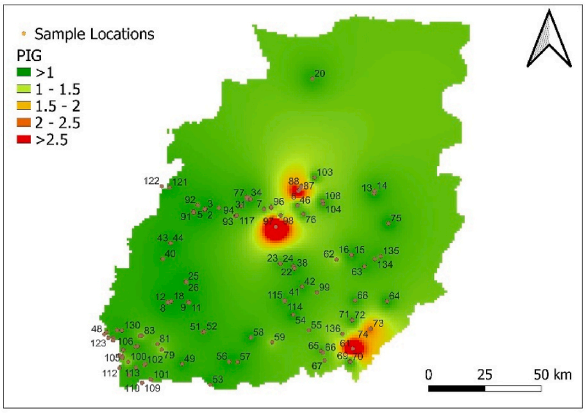

Fig. 3. Spatial distribution map of pollution zones within the region based on GPI classification.

Table 5
Rotated component matrix showing the eigen values for each water quality parameter, total and cumulative variance.

Parameter	Component		
	1	2	3
Turbidity	0.167	**0.955**	0.133
TSS	0.177	**0.940**	0.148
Colour	0.144	**0.948**	0.046
Iron	0.128	**0.927**	0.187
Manganese	0.157	**0.898**	0.219
Phosphate	0.479	**0.630**	−0.303
Nitrate	0.477	**0.594**	−0.371
Nitrite	0.235	0.471	−0.400
Chloride	**0.877**	−0.195	−0.319
Sodium	**0.869**	−0.190	−0.327
Potassium	**0.876**	−0.198	−0.306
Sulphate	**0.837**	0.031	−0.194
TDS	**0.945**	−0.194	0.062
Conductivity	**0.945**	−0.194	0.062
Fluoride	0.480	−0.217	−0.233
Alkalinity	**0.741**	−0.195	**0.571**
Carbonate	**0.695**	−0.075	**0.614**
pH	**0.603**	−0.230	0.397
Hardness	**0.825**	−0.153	0.245
Total	7.718	5.689	1.836
% of Variance	40.622	29.940	9.664
Cumulative %	40.622	70.562	80.225

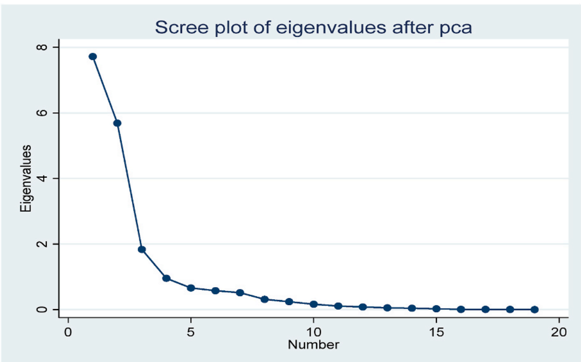

Fig. 4. Scree plot of Eigen values.

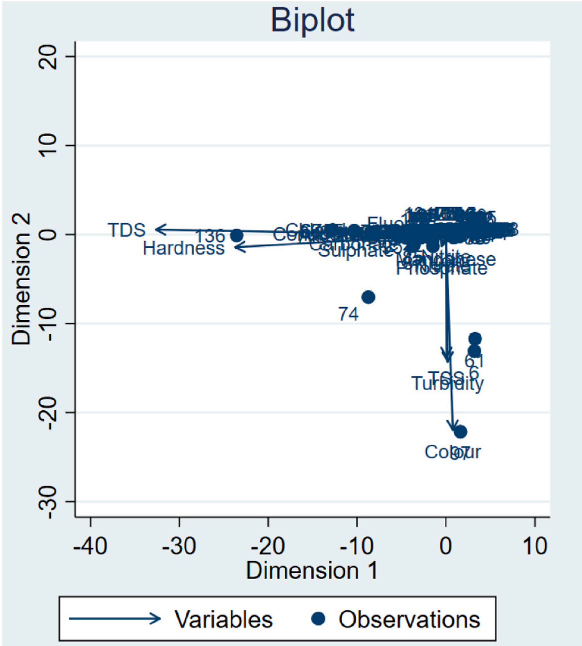

Fig. 5. A PCA biplot of water quality variables.

(0.603) were observed. Carbonate ions is among the list of compounds, including CO_2 and HCO_3^- which directly influence alkalinity and hardness levels in water. pH of water plays an essential role in determining which species, either CO_2, HCO_3^- or CO_3^{2-} will be dominant in groundwater. The occurrence of carbonate ions in groundwater may originate from the dissolution of carbonate rocks such as limestones and dolomite found in aquifers [81]. These results align with those obtained by Kyeremeh [23].

The second principal components described 29.94 % of the total variance. Among the parameters, turbidity (0.955), TSS (0.940), colour (0.948), Fe (0.927) and Mn (0.898) had strong positive coefficients. The presence of suspended solids, iron and manganese in the water could signify pollution from geological sources. Iron and manganese form part of the mineralogy of most rock aquifers. In the study area, the Upper Birim Watershed in the Atiwa District of the Region is noted for its high iron load [19]. Water infiltrating through the aquifers dissolves these minerals into groundwater [64]. In acidic groundwater, iron and manganese exist in their reduced forms as ferrous (Fe^{2+}) and manganous (Mn^{2+}) ions. In the presence of oxygen, Fe^{2+} and Mn^{2+} are oxidized to precipitates of ferric (Fe^{3+}) and manganic (Mn^{4+}) ions. Fe^{3+} and Mn^{4+} ions impart reddish-brown and brownish-black hues to the water respectively [82] making the water look turbid. Moderate loadings of 0.594 and 0.630 were observed for NO_3^- and PO_4^- respectively under Component 2. The occurrence of nitrate and phosphate ions in the water may be stemming from anthropogenic sources specifically, the leaching of fertilizer applied on agricultural farms as well as seepage of sewage and septic wastes into the groundwater [83]. Similar results were obtained by Khanoranga [56].

The third component which revealed moderate positive loadings on alkalinity (0.571) and carbonate (0.614) explained 9.664 % of the total variance. Similar groupings of Components 1, 2 and 3 were observed in the biplot shown in Fig. 5.

3.4.2. Correlation analysis

The Pearson's correlation matrix for the water quality parameters specifying the values of the correlation coefficient (r) is presented in Table 6. Values of r below ±0.05 is an indication of a weak relationship between parameters. Correlation coefficient (r) values within ±0.5 and ± 0.8 portray a moderate correlation between parameters and those above ±0.8 signifies a strong correlation between parameters.

From the correlation matrix, turbidity had a strong positive correlation with TSS (0.991), Fe (0.929), Mn (0.913) and colour (0.959). Colour, also had a strong positive correlation with TSS (0.935), Fe (0.905) and Mn (0.847). Furthermore, TSS had a positive correlation with Fe (0.919) and Mn (0.912). Fe also strongly correlated with Mn (0.949) emphasizing their frequent co-occurrence in natural water bodies [84]. Turbidity, a measure of water clarity, may result from the presence of suspended solids in water. High levels of suspended particles in water leads to scattering of light making the water appear turbid and this often alters the colour of water [85]. Fe and Mn are known to originate from the same source, usually, from soils and rocks. They also exhibit some similarities in their transportation mechanisms in groundwater. With their high tendency to bind to the same types of sediments, water containing these sediments (suspended solids) are also highly likely to be contaminated with Fe and Mn [84]. Oxidation of iron and manganese ions results in a change in colour of the water giving it a turbid appearance [82]. Hence, the strong correlation observed among these water quality parameters (colour, TSS, Fe, Mn and turbidity). The result here is in agreement with that obtained for Principal Component 1.

From Table 6, conductivity had a strong positive correlation with TDS (1.000), Cl^- (0.813), hardness (0.896), Na^+ (0.801), K^+

Table 6
Pearson's correlation coefficient matrix of groundwater quality parameters in the Eastern Region of Ghana.

Parameter	Turbidity	Colour	pH	EC	TDS	TSS	F^-	Fe	Mn	NO_2^-	NO_3^-	Cl^-	Hardness	Alkalinity	PO_4^-	CO_3^{2-}	Na^+	K^+	SO_4^{2-}
Turbidity	1																		
Colour	**0.959**	1																	
pH	−0.081	−0.127	1																
EC	−0.034	−0.056	0.596	1															
TDS	−0.034	−0.056	0.596	**1.000**	1														
TSS	**0.991**	**0.935**	−0.069	−0.020	−0.020	1													
F^-	−0.129	−0.132	0.206	0.446	0.446	−0.105	1												
Fe	**0.929**	**0.905**	−0.088	−0.051	−0.051	**0.919**	−0.111	1											
Mn	**0.913**	**0.847**	−0.071	−0.011	−0.011	**0.912**	−0.099	**0.949**	1										
NO_2^-	0.395	0.454	−0.028	0.113	0.113	0.364	0.018	0.302	0.314	1									
NO_3^-	0.542	0.562	0.092	0.322	0.322	0.530	0.122	0.489	0.447	0.515	1								
Cl^-	−0.052	−0.052	0.427	**0.814**	**0.814**	−0.046	0.469	−0.097	−0.077	0.170	0.347	1							
Hardness	0.022	−0.026	0.517	**0.896**	**0.896**	0.039	0.302	−0.039	0.007	0.069	0.249	0.616	1						
Alkalinity	−0.006	−0.045	0.690	**0.751**	**0.751**	0.009	0.277	0.001	0.031	−0.059	0.061	0.489	**0.758**	1					
PO_4^-	0.578	0.607	0.089	0.341	0.341	0.563	0.051	0.529	0.494	0.507	**0.888**	0.317	0.273	0.090	1				
CO_3^{2-}	0.110	0.051	0.610	0.675	0.675	0.117	0.212	0.111	0.160	−0.040	0.092	0.433	0.687	**0.924**	0.119	1			
Na^+	−0.046	−0.048	0.422	**0.801**	**0.801**	−0.040	0.466	−0.095	−0.074	0.168	0.348	**0.992**	0.606	0.477	0.316	0.421	1		
K^+	−0.052	−0.052	0.420	**0.811**	**0.811**	−0.046	0.469	−0.097	−0.074	0.162	0.336	**0.994**	0.621	0.501	0.305	0.443	**0.993**	1	
SO_4^{2-}	0.157	0.149	0.404	**0.753**	**0.753**	0.172	0.517	0.134	0.170	0.213	0.388	**0.784**	0.566	0.477	0.393	0.434	**0.771**	0.778	1

(0.811) and alkalinity (0.751). The ionic parameters (dissolved solids, Cl^-, Na^+ and K^+) especially, Cl^- increases the concentration of dissolved ions in water which significantly enhances the electrical conductivity of water [79]. Water hardness which is greatly dependent on the occurrence of calcium and magnesium ions as well as anions such as Cl^- in water [86], also influences electrical conductivity of water [51]. Chloride, on the other hand, correlated positively with sodium (0.992) and potassium (0.994), just as sodium also had a strong positive correlation with potassium (0.993). These three ions, Cl^-, K^+ and Na^+ usually occur together in aqueous media in the form of KCl and NaCl. Their high solubility in water and similar chemical properties contribute to the close association [65] observed in this study.

Nitrate also showed a strong positive correlation with phosphate (0.888). This might imply a common source of these nutrients. Agricultural runoffs containing fertilizer may be the most likely source of these contaminants as agriculture is the primary occupation in the study area. Other possible sources of these nutrients might be indiscriminate wastewater discharge and leachates from improperly constructed landfills or dumpsites [87].

Alkalinity had a strong positive correlation with carbonate ions (0.924) obviously because carbonate ions are a major contributor to alkalinity in water. Carbonate ions (CO_3^{2-}) have the capacity to accept two hydroxonium ions (H^+) and hence, their presence in water enhances the buffering capacity (alkalinity) of the water [88]. Alkalinity also exhibited a moderate correlation with water hardness (0.758) largely because the carbonate ions which influence alkalinity of water also enhance water hardness [86].

3.5. Non-carcinogenic health risk assessment

From the water quality index, 43 (32 %) groundwater samples were classified as being 'poor', 'very poor' and 'unsafe water' for drinking purposes. Analytical tests conducted on the 136 groundwater samples in the study region have proven that most of the boreholes and hand-dug wells are contaminated with iron, manganese, fluoride and nitrates from both geological and anthropogenic sources. As a result of high iron and manganese content in the groundwater, most residents in the region resort to surface water due to the unpleasurable taste of the groundwater, discolouration of clothes and food, scaling of cooking pans, occurrence of suspended particles and oily scum in the groundwater [19]. Additionally, excess fluorides and nitrates in drinking water is reported to cause fluorosis and 'blue baby' syndrome respectively. Due to these observations and consumer complaints in the region, it is imperative to evaluate the health risk associated with drinking water from these boreholes polluted with varying levels of nitrates, fluorides, manganese and iron. The health risk that ingestion of groundwater in the region is likely to pose to infants, children and adults were assessed in this study.

The minimum, maximum and mean values of the Average Daily Dose (ADD), Hazard Quotient (HQ) and the Total Health Index (THI) are displayed in Table 7.The total health index ranged from 0.02 to 4.02 for infants, 0.01 to 3.86 for children and 0.01 to 3.56 for adults. The corresponding means were 0.51, 0.48 and 0.45 for infants, children and adults respectively. Values of THI greater than the permissible value of 1 implies that the non-carcinogenic elements considered would pose health risk to an individual. Values lesser than 1 suggest that an individual exposed to a non-carcinogenic element is not prone to any health risk. Out of the 136 water samples, the hazard quotient for fluoride was above 1 in 11, 11, and 7 samples representing 8.09 %, 8.09 % and 5.15 % for infants, children and adults respectively. For manganese, a hazard quotient of one (1) was observed in one sample for infants, children and adults. On the contrary, the hazard quotients for both iron and nitrate were zero (0) for infants, children and adults. This value complies with the threshold limit ($HQ < 1$). Thus, ingestion of only nitrate or iron polluted water will not pose any health risk to the consumers. These results implies that the risk posed by the non-carcinogenic elements are in the decreasing order of $F > Mn > Fe = NO_3^-$.

On the other hand, the total hazard index which is the summation of all the hazard quotients for F, NO_3^-, Fe and Mn, was found to be greater than 1 in 23 (16.91 %), 17 (12.50 %) and 15 (11.03 %) groundwater samples for infants, children and adults respectively. This connotes that consumption of a single non-carcinogenic element poses a lesser health risk to an individual than ingestion of all four chemicals. Moreover, it can be inferred from the THI values that infants are more vulnerable to non-carcinogenic health risks than children and adults as was also observed by Adimalla and Qian [26]. The health risk maps for infants, children and adults are displayed in Fig. 6a and b and c respectively. Based on the Total Health Index (THI), the most vulnerable districts liable to non-carcinogenic health risk are Atiwa East, Fanteakwa North, Achiase, Birim South, Akwapim, Suhum and Ayensuano. It is therefore imperative that groundwater remediation measures be put in place to ensure provision of safe drinking water. Even though the installation, operation and maintenance of such remediation technologies will come at a cost, such interventions will not only protect the health of consumers but also improve the economic status of different economic actors such water utility providers, farmers who may depend on groundwater for irrigation and industries who may also utilize groundwater for manufacturing purposes [89].

4. Conclusion

This study assessed the groundwater water quality in the Eastern Region of Ghana through Water Quality Index, Groundwater Pollution Index (GPI), multivariate statistical methods (principal component analysis and correlational analysis) and Health Risk Assessment (HRA). Laboratory analyses were carried out on 136 groundwater samples from the study region. Nineteen (19) physicochemical parameters including, pH, TDS, EC, turbidity, TSS, alkalinity, total hardness, colour, Cl^-, CO_3^-, F^-, Fe, Mn, NO_2^-, NO_3^-, Na^+, K^+, PO_4^- and SO_4^{2+}.

The following findings were made from this study.

Table 7
ADD, HQ and THI values for F^-, NO_3^-, Fe and Mn.

Individual	Health risk index	Parameter	Minimum	Maximum	Mean	No. of samples with HQ > 1 or THI >1
Infants	ADD	F^-	0.00	0.10	0.02	–
		NO_3^-	0.00	1.24	0.13	–
		Fe	0.00	0.60	0.02	–
		Mn	0.00	0.36	0.01	–
	HQ	F^-	0.00	1.71	0.32	11 (8.09 %)
		NO_3^-	0.00	0.78	0.08	0
		Fe	0.00	0.85	0.03	0
		Mn	0.00	2.56	0.08	1 (0.74 %)
	THI	–	0.02	4.02	0.51	23 (16.91 %)
Children	ADD	F^-	0.00	0.10	0.02	–
		NO_3^-	0.00	1.19	0.12	–
		Fe	0.00	0.57	0.02	–
		Mn	0.00	0.34	0.01	–
	HQ	F^-	0.00	1.64	0.30	11 (8.09 %)
		NO_3^-	0.00	0.75	0.08	0
		Fe	0.00	0.82	0.03	0
		Mn	0.00	2.45	0.08	1 (0.74 %)
	THI	–	0.01	3.86	0.48	17 (12.50 %)
Adults	ADD	F^-	0.00	0.09	0.02	–
		NO_3^-	0.00	1.10	0.11	–
		Fe	0.00	0.53	0.02	–
		Mn	0.00	0.32	0.01	–
	HQ	F^-	0.00	1.51	0.28	7 (5.15 %)
		NO_3^-	0.00	0.69	0.07	0
		Fe	0.00	0.75	0.02	0
		Mn	0.00	2.26	0.07	1 (0.74 %)
	THI	–	0.01	3.56	0.45	15 (11.03 %)

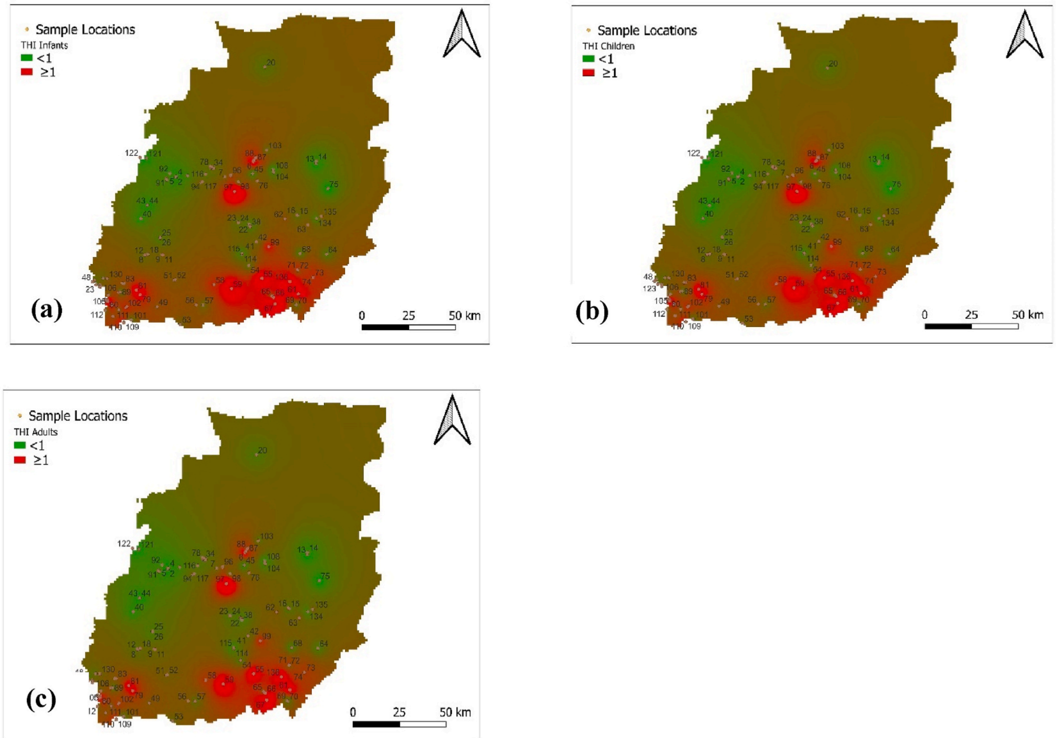

Fig. 6. Health risk maps based on Total Health Index for **(a)** Infants; **(b)** Children; **(c)** Adults.

- Approximately 74 % of the groundwater samples were slightly acidic with the pH falling below the permissible range of 6.50–7.50 as is stipulated by Ghana Standards Authority (GSA).
- The levels of pH, EC, turbidity, TSS, colour, Cl^-, F^-, Fe and Mn in some of the boreholes and hand-dug wells exceeded the threshold limits set by GSA.
- Based on the WQI classification, approximately 32 % of the groundwater samples were classified as 'poor', 'very poor' and 'unsuitable for drinking' water types.
- From the GPI analysis, 95 % of the groundwater samples were categorized as being 'insignificantly polluted'. 2.21 % and 2.79 % fell within the 'low pollution zone' and the 'highly polluted zone' respectively.
- Multivariate statistical analysis based on the PCA and correlational analysis indicated that the dominant pollutants in the groundwater are turbidity, TSS, Fe, Mn, NO_3^-, Cl^-, Na, F^-, SO_4^{2-}, PO_4^-, TDS, K^+, alkalinity, total hardness, and turbidity. The dominant sources of these pollutants are from the dissolution of rock minerals into groundwater, seepage of fertilizer applied on agricultural farms and also from mining activities in the region.
- Non-carcinogenic health risk assessment based on the total health index for the ingestion of F^-, Fe, Mn and NO_3^- showed that infants (0.02–4.02) are at the highest risk compared to children (0.01–3.86) and adults (0.01–3.56).
- Although the primary aim of this study in evaluating the potability of groundwater in the Eastern Region was achieved, the impact of seasonal variation on the water quality was not considered and this could be a possible limitation of this study. Since the quality of water is likely to vary during different seasons, it is recommended that the study should be repeated using water samples collected during the wet season. Furthermore, remediation technologies targeted at improving groundwater quality in the rural areas in the region should be put in place to safeguard human health.

CRediT authorship contribution statement

Thomas Acquah: Writing – original draft, Visualization, Software, Resources, Formal analysis, Data curation, Conceptualization. **Miriam Appiah-Brempong:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Geophrey Kwame Anornu:** Writing – review & editing, Supervision, Conceptualization.

Data availability statement

The data used to support the findings of this study are included in this article.

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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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