Heliyon 10 (2024) e27554

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Investigation of fluoride concentrations, water quality, and non-carcinogenic health risks of borehole water in bongo district, northern Ghana

Gerheart Winfred Ashong *, Boansi Adu Ababio, Edward Ebow Kwaansa-Ansah, Simon Konadu Koranteng, Gwalley Diyawul-Haqq Muktar

Department of Chemistry, Kwame Nkrumah University of Science and Technology. Kumasi, Ghana

ARTICLE INFO

Keywords:
Fluoride
Physicochemical parameters
Health risk assessment
Groundwater
Bongo district

ABSTRACT

Access to potable water is a significant concern due to the increasing global threat posed by fluoride contamination in groundwater sources. This study investigated the concentrations of fluoride (F^{-}), the suitability of groundwater for human consumption, the physicochemical characteristics affecting the water quality, and non-carcinogenic adverse health risks to both children and adults in the Bongo district in Northern Ghana. The findings revealed that the groundwater had a mean pH, salinity, TDS, conductivity, and turbidity below the WHO guideline values with a mean fluoride concentration of 1.76 mg/L above the guideline limit of 1.5 mg/L. The study also found that there was no strong relationship between fluoride and the measured water parameters, which may be attributed to poor control of distribution, transport mechanisms, and sources. The WQI scores ranged from 42.62% to 70.72%, indicating that all borehole water samples were of good and excellent quality. The average chronic daily intake showed that children are often more exposed to the harmful impact of fluoride than adults. The average HQ $>$ 1 indicates the probability of dental and skeletal fluorosis after continuous exposure over time in adults and children. The study recommends taking immediate action to mitigate high groundwater fluoride concentrations, implementing appropriate water management strategies, and raising public awareness of the health risks. These measures can guide future groundwater management practices and help policymakers address contamination and protect local communities.

1. Introduction

Water, a crucial resource for humanity and the environment, has long been regarded as abundant and a gift of nature, with various sources and forms of consumption. In traditional Ghanaian communities, where the most dependable water supply is underground water, numerous sources such as hand-dug wells, boreholes, and hand pumps are generally utilized to meet the demand for drinking water. However, the quality of these sources can be adversely impacted by a combination of both human and natural processes [1]. For water to be considered appropriate for drinking, its physicochemical attributes such as pH, total dissolved solids (TDS), electrical

* Corresponding author.
E-mail addresses: gerheart33@gmail.com (G.W. Ashong), boansiaduababio@gmail.com (B.A. Ababio), eekwaansa-ansah.cos@knust.edu.gh (E.E. Kwaansa-Ansah), s.konadu@gmail.com (S.K. Koranteng), haqqgwalley@gmail.com (G.D.-H. Muktar).

https://doi.org/10.1016/j.heliyon.2024.e27554
Received 20 June 2023; Received in revised form 8 February 2024; Accepted 1 March 2024

conductivity (EC), and fluoride concentration must fall within acceptable standards [2]. The Water Quality Index is a numerical representation or scoring system that combines various water quality parameters to give an overall assessment of the suitability of the water for human consumption. Researchers have employed various water quality indices over the years, such as the National Sanitation Foundation Water Quality Index (NSFWQI), the Canadian Council of Ministers of Environment Water Quality Index (CCMEWQI), the Oregon Water Quality Index (OWQI), and the Weight Arithmetic Water Quality Index (WAWQI) [3]. Among these, the use of weights and relative weights in the weight arithmetic water quality index allows it to prioritize the importance of different parameters based on their significance on human health and recommended standards. This offers WAWQI, the distinct advantage of comprehensively reflecting the varying impacts of different parameters on the overall assessment of water quality. This has led to its wide application in numerous groundwater quality studies across the globe and the country such as [4–11].

Fluoride is one of the pollutants detected in the groundwater of semi-urban and rural regions in the 21st century. Groundwater contamination by geogenic fluoride is a significant concern that poses a challenge to the availability of safe drinking water. It can cause dental fluorosis, bone strength reduction, and osteosarcoma, among other adverse effects [1,12]. Fluoride is a critical element for facilitating bone growth and development, and its presence in potable water has attracted considerable attention globally [13–17]. The prevalence of fluoride in water supplies beyond the 1.5 mg/L recommended by the WHO is a global challenge. Approximately 250 million individuals across several nations are at risk of severe illness due to its accumulation in groundwater [18,19]. Long-term exposure to high fluoride concentrations in fluoride-endemic areas can interfere with the body's processes of calcium and phosphorus, leading to calcium deficiency, hormonal imbalance, cognitive decline, and dental cavities [18,19].

Anthropogenic causes of fluoride contamination in groundwater include fly ash deposition and the application of phosphate fertilizers. Basic pH, low Ca^{2+} concentrations, and high bicarbonates are among the geochemical factors, that can create favorable conditions for fluoride enrichment in groundwater [18,20,21]. Ghana is a country in the world with numerous groundwater fluoride hotspots. The northern parts of the country are highly fluoridated because they have volcanic and sedimentary rocks belonging to the Voltaian and Birimian Supergroups that are intruded by granitoids [22,23]. The high water rock relationship, ion exchange processes, and mineral breakdown of Bongo phosphorite, granite, and gneisses rocks with the two main naturally occurring fluoride minerals being biotite and muscovite and Voltaian deposits such as silicates and alkalis have been identified as the causes of increased groundwater fluoride concentrations in the district [20,24,25]. The water types identified in the region exhibit hydrochemical facies comprising primarily of $Ca–Na–HCO_3$ (70%) and secondarily of $Ca–Mg–HCO_3$ (30%). The $Ca–Na–HCO_3$ water types originate from fractured bedrocks of the Upper Birimian metavolcanic and the K-feldspar-enriched Bongo granitoid. Conversely, the $Ca–Mg–HCO_3$ water types are found within the Upper Birimian volcanic/metavolcanic sequences [26].

In fluoride-endemic locations such as the northern sector of Ghana, access to potable water remains a challenge [27]. Borehole water in these communities contains high concentrations of fluoride, leading to dental fluorosis [28]. Over the past decades, previous research on groundwater quality in the country has reported excessive fluoride concentrations above 10 mg/L in the Northern and Savannah Regions of Ghana [20,24,27–35]. Based on the elevated levels of fluoride reported, fluoride exposure from groundwater poses serious long-term health risks to children and the younger generation [23,25]. Few authors have reported the health consequences of drinking water with high fluoride concentrations in the Upper East Region of Ghana [32,36]. Increasing attention is required to assess the quality of drinking water in these areas [37]. Therefore, to fill the research gap, a comprehensive assessment of the adverse consequences of fluoride contamination in the groundwater of localities in this region must be conducted. WAWQI was employed in this study because of its wide usage and ability to provide a comprehensive assessment of water quality which is based on the impact of parameters on human health. The findings of this study will provide valuable information that could enhance the quality of drinking water in the community. It would expand the scope of the existing literature on the negative effect of fluoride in drinking water on human health and provide information on the potential health consequences associated with high concentrations of fluoride in drinking water in the district. The objectives of the study are as follows.

1. To investigate fluoride concentrations in borehole water in the Bongo district of the Upper East Region of Ghana.
2. To assess the suitability of the borehole water for human consumption.
3. To evaluate the critical physicochemical characteristics that affect the quality of drinking water in the Bongo district.
4. To assess the non-carcinogenic adverse health risks to both children and adults associated with the consumption of fluoride-contaminated water in the Bongo district.

2. Materials and methods

2.1. Description of the study area

The Upper East Region of Ghana consists of nine districts, including Bongo. The study area's latitude and longitude are 10° 54′ 28″ north and 0° 48′ 29″ west. The map of Bongo district is illustrated in Fig. 1. With a total area of 459 square kilometers, the district shares borders with Burkina Faso to the east and north, the Bolgatanga municipal district to the south, the Kassena-Nanka district to the west, and the Bolgatanga district. The Bongo district is situated in the Birimian Supergroup with the Bongo granitoids as its predominant rocks.

The Bongo district is one of the driest locations, and its topography is mainly flat and low-lying, with outcrops of granite rocks. In addition to protruding throughout the landscape, granite rocks are a source of materials used in the building industry. The study area is mostly covered by monzonite and granitoids that are rich in K-feldspar (Bongo granite). In the study area, granitoids predominate as rock types. The study area is in both the Guinea Savannah agroecological zone and Ghana's semi-arid climate zone. Wet

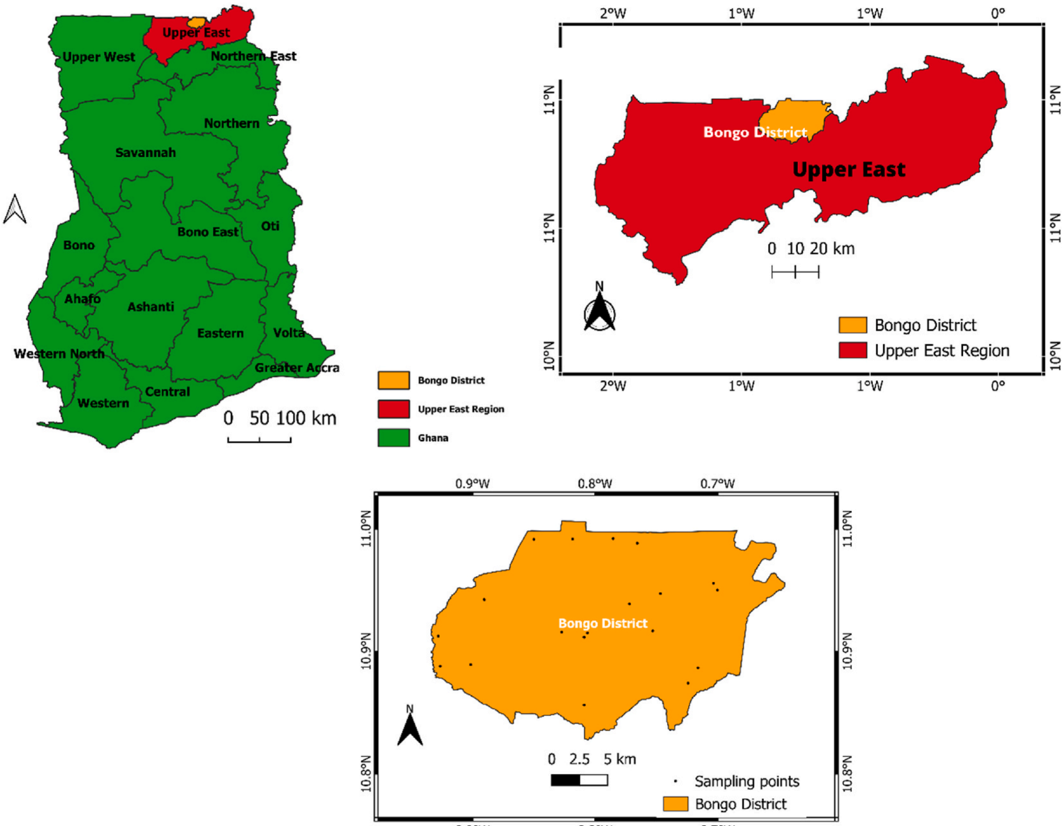

Fig. 1. Map of the Bongo district.

(June–October) and dry (November–February) seasons are experienced in the study's area. In general, the dry season in Ghana is cold or locally known as harmattan and laced by northeast trade winds. The area experiences a single-season precipitation pattern that begins in May/June and finishes in October/November. Between June and September is when the most rainfall occurs. With an annual mean of 935 mm, the yearly rainfall ranges from 600 to 1400 mm. Groundwater within the Bongo area is extracted from bedrock fragments, often at drilling depths of 40–60 m. The aquifer flows from north to south and is limited by the amount of mica and clay it contains. It has high static water levels (2–16 m below ground level, m b.g.l.). The geography and thickness of the weathered mantle affects the aquifer's supply.

2.2. Groundwater sampling and techniques

Twenty (20) samples were collected from various boreholes in the Upper East district of Bongo, Ghana. The borehole water valve was opened, water was allowed to flow to the ground for some time, and then a clean polyethylene sample bottle was uncovered and placed directly under the tap for sample collection. It was rinsed with the borehole water before being filled and immediately covered with a cap. The borehole water samples were collected in polyethylene bottles that had been prewashed (with mild soap and water, dilute HNO_3, as well as distilled water, respectively). The sample bottles were labeled B1–B20 to represent the study area. The samples were then dispatched to the KNUST Chemistry laboratory in a cold storage box and kept in a freezer at a temperature of 4 °C until analysis.

The pH was measured using a pH meter of model 209 (Mettler Toledo). The electrode was then washed with distilled water after the pH meter had been placed in buffer solutions with pH values of (4, 7, and 9). The electrode was placed in a beaker containing 50 ml of the water sample.

The turbidity meter 2100 N was used to measure the cloudiness in each sample. A Nessler with 10 ml of each sample was filled, then covered and inserted into the instrument's cell compartment. The RATIO configuration was chosen by pressing the corresponding key, and then the NTU measurement unit was chosen by holding down the UNITS EXT key. The displayed value on the device screen was determined and noted in the nephelometric turbidity unit after a short period (NTU).

All groundwater samples were measured for conductivity, total dissolved solids, and salinity using a multipurpose conductivity meter, the HANNA HI 9032.

A Palintest photometer was used to measure the fluoride concentration. Two tablets' reagents were added to the borehole water samples for the Palintest fluoride measurement to cause the color to develop, which is a criterion of the fluoride concentration using a

Palintest photometer. Twenty (20) test tubes were filled with water samples to the 10 ml mark. The two reagent fluoride tablets were ground and added one at a time until they were dissolved. Five minutes were allocated for full-color formation before reading with a fully automated wavelength and comparing the concentration of fluoride to the calibration graph.

2.3. Water quality index analysis (WQI)

The weight arithmetic water quality index was employed in this study. The WQI was calculated using Equations (1) and (2), to determine whether underground water samples from the Bongo district were suitable for a particular use based on the assigned weight (w_i) and relative weight (wi) in Equation (3). This approach assessed WQI according to the purity rating scale by evaluating the maximum calculated water quality indicators. From Equation (3), the relative weight (Wi) was calculated based on the maximum recommended limits reported [38–40]. Each component received an assigned weightage ranging from 1 to 5, depending on the extent of the threat to human health (Table S1) [41]. The five (5) categorized sections that make up the water quality index are excellent water (<50), good water (50–100), poor water (100–200), extremely poor water (200–300), and groundwater that is unfit for human consumption (>300) [38,41].

$$\mathrm{WQI} = \sum\nolimits_i^n (W_i \times q_i) \tag{1}$$

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

$$W_i = \frac{w_i}{\sum w_i} \tag{3}$$

Where.

WQI = Water quality index

q_i = quality rating.

W_i = relative weight

w_i = assigned weight of each parameter.

C_i = concentration of each parameter.

S_i = drinking water standards for each parameter,

n = number of parameters.

Table 1
Physicochemical parameters of groundwater water from Bongo district.

Sample ID	F^- (mg/L)	pH	Turbidity (NTU)	TDS (mg/L)	Conductivity (μs/cm)	Salinity (mg/L)
B1	0.75	6.97	0.77	48.10	46.60	0.00
B2	1.70	6.69	0.56	106.70	103.80	0.30
B3	1.90	6.95	0.27	36.00	35.00	0.00
B4	2.00	6.72	0.45	71.60	69.70	0.10
B5	1.80	7.04	0.60	66.10	64.40	0.10
B6	1.47	6.67	0.10	43.60	42.20	0.00
B7	1.50	6.71	0.32	53.70	52.70	0.00
B8	1.07	7.05	0.86	89.50	87.00	0.20
B9	2.00	6.75	0.00	50.00	48.60	0.00
B10	1.90	6.75	0.23	46.10	44.60	0.00
B11	1.70	7.08	0.17	33.30	32.40	0.30
B12	1.75	6.87	0.50	38.20	37.20	0.00
B13	1.95	6.93	0.84	84.50	59.00	0.00
B14	2.20	6.71	0.70	69.30	54.00	0.00
B15	1.45	7.03	0.23	64.21	47.60	0.10
B16	1.65	6.88	0.22	60.70	58.80	0.00
B17	2.50	6.98	0.76	49.50	64.60	0.20
B18	1.85	7.07	0.10	97.60	43.80	0.00
B19	2.10	7.02	0.48	79.30	52.90	0.00
B20	1.90	6.98	0.58	85.70	57.60	0.20
Mean	1.76	6.89	0.44	63.69	55.13	0.08
Min	0.75	6.67	0.00	33.30	32.40	0.00
Max.	2.50	7.08	0.86	106.70	103.80	0.30
StDev	0.39	0.15	0.27	21.42	17.23	0.11
UCL	1.94	6.96	0.56	73.71	63.19	0.13
LCL	1.58	6.82	0.31	53.66	47.06	0.02
MRL	1.50	6.5–8.5	1	500	400	600

StDev = standard deviation, UCL = 95% upper confidence limits, LCL = 95% lower confidence limits, and MRL = maximum residual guideline levels.

2.4. Health risk assessment (HRA)

Evaluating the likelihood of adverse non-cancer effects in humans exposed to groundwater physicochemical characteristics is useful for assessing health risks [18]. This evaluation was characterized as non-carcinogenic risk (NCR), which was based on assessing the level of fluoride exposure [16,38]. Ingestion was considered to be the most prominent route of fluoride exposure in this study [36]. The chronic daily intake (CDI) through the oral route was revised for children and adults based on equation (4) [16,18,32,36,38].

$$\mathrm{CDI} = \frac{C \times \mathrm{DI} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \tag{4}$$

Where,

$C = F^-$ concentration.

DI = Daily water intake.

EF = Exposure frequency.

ED = Exposure duration.

AT = Average time.

BW = Body weight.

RfD = Oral reference dose.

A modified overview of the parameters and units of C, DI, EF, ED, BW, and *AT* used in equation (1) for children and adults can be found in Table S2.

The hazard quotient (HQ) was also estimated to determine the possible non-carcinogenic risk (NCR) [16,32]. If HQ > 1, it indicates harmful non-carcinogenic health risks, while HQ < 1 is within the allowable threshold [42]. Equation (5) was used to assess the HQ.

$$\mathrm{HQ} = \frac{CDI}{RfD} \tag{5}$$

where *RfD is the oral reference dose*. *RfD* values in mg/kg/day for fluoride are shown in Table S2.

2.5. Data analysis

Microsoft Excel 2019 was used to compute the descriptive statistics and a single parametric *t*-test was used for the statistical analysis of data. Minitab statistical software 20 was used to compute the Pearson correlation and the principal component analysis (PCA). Descriptive analysis, such as 95% confidence intervals (UCL, LCL), mean, maximum, minimum, mean, and standard deviation, were used to summarize data from the physicochemical parameters. The upper and lower confidence limits provide a range of values that are likely to contain the standard limit value at an error rate of 5%. Pearson correlation was used to determine the association between fluoride concentration and other physicochemical parameters, as well as whether they are interdependent. The PCA tool was used to estimate the source of groundwater pollution, whether it is from anthropogenic sources, or natural sources by compressing a large dataset into components.

Table 2
Water quality index (WQI) of groundwater samples.

Sample ID	WQI	Water Condition
B1	44.86	Excellent water
B2	57.66	Good water
B3	52.09	Good water
B4	58.14	Good water
B5	58.35	Good water
B6	42.62	Excellent water
B7	47.58	Excellent water
B8	53.67	Good water
B9	49.14	Excellent water
B10	51.46	Good water
B11	47.63	Excellent water
B12	53.84	Good water
B13	64.65	Good water
B14	64.85	Good water
B15	46.25	Excellent water
B16	48.76	Excellent water
B17	70.72	Good water
B18	50.65	Good water
B19	60.53	Good water
B20	59.67	Good water
Min	42.62	Excellent water
Max	70.72	Good water
Mean	54.16	Good water

3. Results and discussion

3.1. Assessment of fluoride and physicochemical characteristics of groundwater

The quality of groundwater in the Bongo district was assessed by correlating the mean values of each physicochemical parameter with WHO standards, amongst others. The mean, maximum residual guideline levels (MRL), minimum, and maximum fluoride concentrations, and physical and chemical properties are given in Table 1. The fluoride concentration range was within 0.75–2.50 mg/L in the borehole water samples. The average fluoride, F^- concentration in Bongo was 1.76 ± 0.39 mg/L mg/L, which was higher than the WHO recommended threshold of 1.5 mg/L. Also, the 95% UCL and LCL was 1.94, and 1.58 mg/L obtained was higher than the maximum residual guideline level of 1.5 mg/L for fluoride. The variation in F^- levels in the study could be attributed to differences in geological factors, such as the weathering of fluoride-bearing minerals, and anthropogenic activities, such as industrial discharges and agricultural practices that release fluoride into groundwater. A relatively higher range of F^- concentrations as reported in comparative studies in India (0.2–6.9 mg/L) [18,43], Ethiopia (1.1–18 mg/L) [44], China (0.44–2.06) [45], and Sri-Lanka (0.02–2.50) [18,44–46].

The minimum and maximum pH values in this study were 6.67 and 7.08, respectively. The average pH was 6.89 ± 0.15 which was within the WHO range of 6.5–8.5 [40]. The upper and lower confidence limits of 6.97 and 6.82 lie within the WHO guideline value. The variation in pH might be due to differences in the industrial discharge of acidic effluents, the presence of carbonates and bicarbonates, and the buffering capacity of the soil and rocks in the study area. Similar average pH values were reported in the groundwater of endemic regions such as Bihar, India (7.8) [13], Central Guizhou, China (7.90) [47], and Vea catchment, Northern Ghana (7.31) [48]. Low or acidic pH conditions have been reported to influence the overload of F^- in borehole water [47,49]. Turbidity shows the aesthetic appearance and acceptability (colorless and transparent) of drinking water supplies. Borehole turbidity varied from 0.00 to 0.86 NTU, with a mean of 0.44 ± 0.27 NTU. The 95% UCL and LCL of turbidity values of 0.56 and 0.31 NTU fall with turbidity values below the guideline value of 1 NTU, indicating that all analyzed samples were clear. Differences in the rates of runoff, soil erosion, or human activities such as construction and mining, which can introduce suspended particles into the groundwater to cause cloudiness or haziness, might have accounted for the variation in turbidity of groundwater in the study. High turbidity values of 7.2 NTU were reported for groundwater in Chitral, Northern Pakistan [50]. A minimum value of 0.13 NTU was disclosed in Ghana's Upper West region [51]. Low turbidity below 1.0 NTU indicates the absence of organic and inorganic particles such as dissolved dyes from clays of the earth, and algae [52]. Water-related diseases can occur because turbid water serves as a breeding ground for harmful microorganisms [53]. Maximum (106.7 mg/L), minimum (33.30 mg/L), and average (63.69 ± 21.42 mg/L) TDS levels were below the WHO limit of 500 mg/L [40,54]. The 95% UCL and LCL were 73.71 and 53.66 mg/L, respectively. The TDS values obtained were lower than the maximum permissible limit of 500 mg/L. Differences in weathering processes and human activities such as agricultural practices in the Bongo district could have contributed to the variation in the levels of TDS during this study. Recently, lower mean TDS values of 0.15 and 1.53 mg/L were observed in the Upper East Region of Ghana [36]. High TDS in groundwater is frequently associated with higher concentrations of bacteria, nutrients, pesticide residues, and toxic metals in the water [53]. The borehole samples' electrical conductivity (EC) ranged from 32.40 to 103.80 μs/cm with an average EC of 55.13 ± 17.23 μs/cm. The 95% UCL and LCL 63.19 and 47.06 μs/cm obtained for the EC values were lower than the WHO MRL of 400 μs/cm. The variation in

Table 3
Chronic daily intake (CDI) and non-carcinogenic risks via ingestion exposure of groundwater in Bongo district for adults and children.

Sample ID	CDI (mg/kg/day)		HQ	
	Children	Adults	Children	Adults
B1	0.08	0.03	1.25	0.54
B2	0.17	0.07	2.83	1.21
B3	0.19	0.08	3.17	1.36
B4	0.20	0.09	3.33	1.43
B5	0.18	0.08	3.00	1.29
B6	0.15	0.06	2.45	1.05
B7	0.15	0.06	2.50	1.07
B8	0.11	0.05	1.78	0.76
B9	0.20	0.09	3.33	1.43
B10	0.19	0.08	3.17	1.36
B11	0.17	0.07	2.83	1.21
B12	0.18	0.08	2.92	1.25
B13	0.20	0.08	3.25	1.39
B14	0.22	0.09	3.67	1.57
B15	0.15	0.06	2.42	1.04
B16	0.17	0.07	2.75	1.18
B17	0.25	0.11	4.17	1.79
B18	0.19	0.08	3.08	1.32
B19	0.21	0.09	3.50	1.50
B20	0.19	0.08	3.17	1.36
Mean	0.18	0.08	2.93	1.26
Minimum	0.08	0.03	1.25	0.54
Maximum	0.25	0.11	4.17	1.79

conductivity could be linked to differences in the dissolved mineral content. Groundwater from the Vea catchment in northeastern Ghana had an average EC value of 26.00 μs/cm [48]. Electrical conductivity is affected by the availability of inorganic elements, such as chlorine byproducts, alkaline substances, bicarbonate, and sulphur materials, in addition to dissolved salts. Total dissolved solids and conductivity are directly correlated, indicating that EC increases with an increase in TDS [53]. Groundwater salinity in this study ranged from 0.00 to 0.30 mg/L, with an overall mean of 0.08 ± 0.11 mg/L. The 95% UCL and LCL salinity values of 0.13 and 0.02 mg/L obtained were lower than the WHO MRL of 600 mg/L [40]. In comparison to our study, Northeastern Ghana groundwater has an average concentration of dissolved salt of 0.15 mg/L [48].

3.2. Water quality index (WQI)

The quality status for the groundwater samples ranged from excellent water at 42.62 to a good water quality of 70.72 in Table 2. The mean water quality status of the Bongo district was 54.16, indicating good quality. The **WQI** showed that 35 % of the borehole samples had an excellent quality status, whereas 65 % had a good water quality status. The good and excellent quality status of water in this study indicates that it is suitable for consumption, irrigation, and industrial applications [55]. In comparison, groundwater samples from the Aksu River Basin, Southeast Turkey [41] were also reported to have good and excellent water quality status. Furthermore, comparative studies of groundwater samples from Gilgit Baltistan, Northern Pakistan [56], and Kahk City, Iran [16] reported poor water quality.

3.3. Health risk evaluation of fluoride

The level of chronic daily intake (CDI) for the borehole samples in the Bongo district was calculated for exposure assessment. Fluoride CDI levels in children ranged from 0.08 to 0.25 mg/kg/day (mean 0.18 mg/kg/day) and in adults from 0.03 to 0.11 mg/kg/day (mean 0.08 mg/kg/day). The acceptable upper consumption level (UL) of fluoridated water associated with the detrimental consequences of dental and skeletal fluorosis was established at 0.12 mg/kg/bw/day for children and adults [57,58]. Children mean CDI levels were higher than the safe limit of 0.05 mg/kg/day, whereas adults mean CDI levels were lower than the safe limit of 0.13 mg/kg/day [32]. In comparison to our study, the Kahk community in Iran reported relatively high fluoride exposure levels for both adults and children (0.008 and 0.023 respectively) [16] and Tunisia (0.08 and 0.24) [59].

Table 3 displays the non-carcinogenic risk (HQ) values considering the groundwater oral pathway for adults and children. The table shows that the HQ estimated range of fluoride exposure by consumption of water in the Bongo district was 1.25–4.17 (average 2.93) for children and 0.54–1.79 for adults, respectively (average 1.26). Children had higher CDI and HQ exposure than adults, which may be attributed to differences in body weights [16,18]. This study's findings are in agreement with previous research [13,16,18,32,36,59,60]. According to Table 3, all borehole water samples consumed by children and adults in the Bongo district had mean HQs that exceeded one. This suggests that after long periods of exposure, both children and adults may develop non-carcinogenic adverse effects of fluoride, such as dental and skeletal fluorosis, in the oral consumption of drinking water from boreholes in the Bongo district. In agreement with the current study, similar HQ findings have been reported in other studies [13,16,32,45,54,61]. Because children are more vulnerable to fluoride non-cancer risks than adults, special precautions should be taken to protect them.

3.4. Pearson's correlation

The pearson correlation shows the relationship between fluoride concentrations and the physical and chemical properties shown in Table S3 is revealed by Pearson correlation. F^- has a weak negative correlation with pH, turbidity, TDS, conductivity, and salinity, as shown in Table S3. High fluoride concentrations does not correlate with an increase or decrease in turbidity, TDS, salinity, and conductivity. The negative relationship could be that the presence of F^- is associated with an increasing trend in groundwater's alkaline pH [62]. The pH of the water samples was positively and weakly correlated with turbidity, TDS, and salinity and negatively and weakly correlated with conductivity. Turbidity showed a moderate positive correlation with TDS, conductivity, and salinity. TDS was positively correlated with conductivity and salinity, whereas conductivity was positively correlated with salinity. The weak significant negative correlation among fluoride, turbidity, conductivity, pH, TDS, and salinity signifies an inverse relationship, which implies the possibility that ion exchange and redox reactions did not occur in groundwater samples [38].

The positive significant association among the physicochemical parameters indicates similar sources of enrichment, the same transportation behaviors, and mutual reliance. Negatively correlated components could come from a different or unrelated source and be independent [63]. The lack of a strong relationship with measured parameters may be attributed to poor distribution, transport mechanism, and non-point sources.

3.5. One sample t-test and confidence level

The one-sample *t*-test is a statistical hypothesis tool used to evaluate the statistical significance of whether the average fluoride concentration and measured physicochemical parameters of borehole water samples differ from their maximum guideline levels (MRL), as shown in Table S4. The confidence interval in Table S4 is a statistical evaluation test that shows that the reported water sample parameters are 95% certain to include estimated (higher or lower) intervals of the mean within the guideline values. The statistical decision to accept or reject a sample mean population compared with the MRL can be best determined by the p-value, mean, t-stat, t-critical values, and upper and lower confidence intervals.

The negative t-stat for pH, turbidity, TDS, conductivity, and salinity shows that the mean population of these parameters is significantly less than their standard values. A positive t-stat of 2.97 for fluoride showed that the mean of the borehole samples in the Bongo district was significantly greater than the standard value of 1.5. Because the negative t-stat values are lower than the t-critical values, it shows the mean of pH, turbidity, TDS, conductivity, and salinity are significantly less than their specific standards. The low p-value in the pH, turbidity, TDS, conductivity, and salinity parameters is less than the significance level of 0.05, which means that the mean of the measured parameters is significantly less than their guideline values. The upper and lower confidence intervals for fluoride confirm that the mean water samples contain fluoride levels significantly greater than the MRL of 1.5 mg/L. The one-sample *t*-test and the confidence intervals show a clear significant difference between the means of the measured parameters and their MRL. Based on this evaluation, there is sufficient statistical evidence to show that the mean physicochemical parameters were below their reference values, whereas the mean fluoride parameter was above their safe limit for human consumption.

3.6. Principal component analysis (PCA)

Principal component analysis (PCA) using varimax rotation under the Kaiser normalization principle and varimax rotation was used on the water quality properties to condense the number of dimensions from six (6) water quality parameters revealed in twenty (20) water samples as large data sets based on significant eigenvalues greater than one by condensing a large collection of water quality parameters into two (2) significant principal components (PC1 and PC2) that cumulatively retained 39.42 % of the proportion of the data. Table S5 displays PCs, factor loadings, percentages of variance, and cumulative percentages for each variable and component. Interpreting the factor loadings involves finding variables that are highly (>0.75), moderately (0.50–0.75), and weakly (0.50) associated with each component [64].

By examining the factor loadings of the physicochemical parameters on each PC, it is possible to understand PCs in terms of hydrogeochemical processes, such as water rock interaction. The first PC with the highest eigenvalue and maximum proportion frequently represents the most important process or set of processes influencing the hydrogeochemistry of borehole water samples in the Bongo district [28] (see Table S5).

The first principal component factor (PC1) showed 39.42% of the total variation. Highly positive-loaded variables included salinity, TDS, and conductivity, while weakly loaded variables included pH, TDS, and F^- ion. The strength and direction of conductivity and TDS loadings in PC1 were associated with urban runoffs, especially subsurface runoff that eroded road boundaries during rainfall, which may account for the presence of dissolved mineral content and solids. The weak loading of the F^- anion appears to be inactive in borehole water under a neutral pH region because of its weak solubility, and it is absorbed into exchangeable minerals such as kaolinite clay or the earth. The hydroxyl group does not, however, favor the desorption of the F^- exchange process in clay particles made of illite, kaolinite, chlorite, and smectites in this study due to the neutral pH [28,32,38,65]. As a result, the low pH loading may also be due to the mineral dissolution reactions' lack of exchangeable protons, which could cause the pH to drop. In addition to the dryness of the climate, the decreased pH may also be caused by a lack of precipitation and evapotranspiration processes. Although the levels of all the parameters under investigation varied, no relationship was found between them (Fig. 2A and B).

The second component confirms a weakly negative association with F^-, pH, and turbidity, and a weak correlation with TDS, and conductivity with a variable proportion of 20.17 % and a cumulative percentage of 59.59 %. The cumulative percentage indicates that the F^- has a moderate influence on the safety of groundwater samples collected. The weak load of F^- could be attributed to the unfavorable natural solubilization and distribution of alkaline earth fluoride in groundwater and minor anthropogenic activities (fertilizer and pesticide application) or natural activities that contribute to the quality of borehole water [66]. Weak and negative factor loadings of TDS, F^- anion, conductivity, salinity, pH, and turbidity are non-point sources of pollution that could be linked to agricultural activities, rainfall, runoff, and organic contaminants.

3.7. Limitations of this study

Heavy metals and some emerging contaminants such as pharmaceutical residues and antibiotics could be studied to draw a proper pollution profile for the area. Bioaccessibility and bioavailability studies should be evaluated to explain the synergistic effects of risk assessment models. Plants, animals, and soil around the study area should be monitored for the presence of high levels of fluoride in drinking water sources to identify the mass accumulation of fluoride and to emphasize that water is the only channel of transport for fluoride transport. The small sampling points for the study area are due to the availability of few groundwater samples coupled with factors such as water scarcity, malfunctioning boreholes with no maintenance, and a low population density over the 459 square kilometers, which is also a rural area. Consequently, we recommend the utilization of the Gibbs and Chadha diagrams respectively, to explore geochemical phases for a greater understanding of fluoride geochemistry within the study area. These limitations must be acknowledged because they present an opportunity for future research to fill research gaps and improve the understanding of groundwater quality in the studied area.

4. Conclusion

- This study successfully assessed the quality of water in boreholes in Bongo, with a focus on fluoride concentrations, and evaluated the potential adverse health impacts on both children and adults.
- According to the study's findings, fluoride concentrations in 80 % of the groundwater samples exceeded the WHO standard of 1.5 mg/L, while TDS, conductivity, salinity, turbidity, and pH were within their respective standard limits.

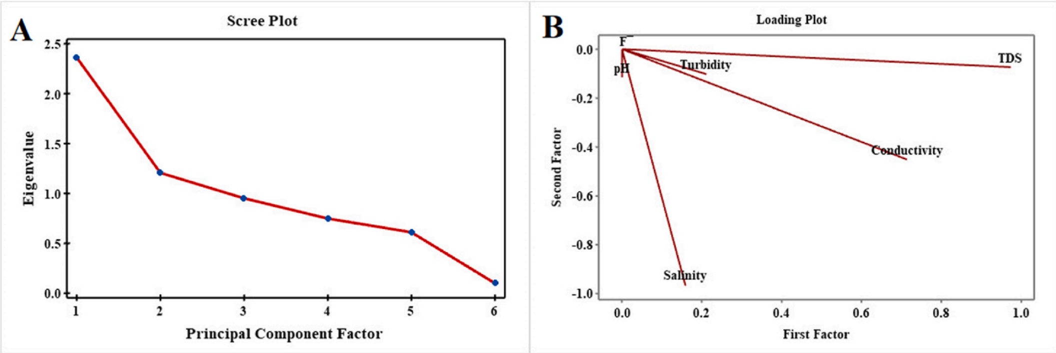

Fig. 2. (A) Scree plot of PCs and (B) loading plot of PC1 and PC2.

- The borehole water contamination was mainly caused by geogenic processes, primarily the breakdown of bongo rocks such as quartzite, dolomite, and mudrock into the underground water supplies of the study area based on water rock interactions at the water table, with an insignificant impact due to human activities, according to the multivariate statistical data.
- The one-sample *t*-test and confidence interval show that the mean fluoride and water parameters population is statistically different from the guideline values.
- The borehole water quality index (WQI) varied from good to excellent status, making it suitable for household, agricultural, and industrial use.
- Children and adults are more likely to experience negative health effects from consuming fluoride-contaminated water, according to the exposure assessment for fluoride pollution of borehole water samples in the Bongo district.
- According to the CDI and HQ values, children are more susceptible than adults to the negative effects of high fluoride levels in water. The average non-carcinogenic exposure was alarming and greater than the USEPA limit ($HQ > 1$) in children and adults at Bongo.
- With a focus on fluoride pollution and its associated harmful health effects on both adults and children, the study findings provide benchmark statistics and knowledge on the quality criteria and suitability of groundwater in the Bongo district.
- This research recommends that groundwater supplies in the Bongo district and other areas experiencing fluoride prevalence should be exposed to economical and practical techniques for water treatment before intake.

Funding

This study received no specific support from public, commercial, or non-profit funding bodies.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Gerheart Winfred Ashong: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Boansi Adu Ababio:** Writing – review & editing, Visualization, Validation, Resources, Formal analysis. **Edward Ebow Kwaansa-Ansah:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. **Simon Konadu Koranteng:** Writing – original draft, Resources, Investigation. **Gwalley Diyawul-Haqq Muktar:** Writing – original draft, Resources, Investigation.

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.

Acknowledgment

The authors would like to express their gratitude to the locals of the study geographical area for their assistance during the field investigation. The authors would like to thank the Chemistry department for the use of its facilities.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e27554.

References

[1] N. Akhtar, M.I. Syakir Ishak, S.A. Bhawani, K. Umar, Various natural and anthropogenic factors responsible for water quality degradation: a review, Water (Switzerland) 13 (2021) 2660, https://doi.org/10.3390/w13192660.

[2] J.C. Agbasi, J.C. Egbueri, Assessment of PTEs in water resources by integrating HHRISK code, water quality indices, multivariate statistics, and ANNs, Geocarto Int. 37 (2022) 10407–10433.

[3] S. Chidiac, P. El Najjar, N. Ouaini, Y. El Rayess, D. El Azzi, A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives, Rev. Environ. Sci. Bio/Technology. 22 (2023) 349–395.

[4] E.M. Radouane, A. Chahlaoui, A. Maliki, A. Boudellah, Assessment and modeling of groundwater quality by using water quality index (WQI) and GIS technique in meknes aquifer (Morocco), Geol. Ecol. Landscapes. 7 (2023) 126–138.

[5] A. Tesema, M. Jothimani, A. Abebe, J. Gunalan, E. Getahun, S. Karuppannan, Hydrochemical characterization and water quality assessment for drinking and irrigation purposes using WQI and GIS techniques in the upper omo River Basin, southern Ethiopia, J. Chem. 2023 (2023).

[6] A. Kumar, V.N. Mishra, R. Ratnam, C.B. Pande, A.P. Krishna, Assessment of groundwater quality in south karanpura coalfield region, Jharkhand, India using WQI and geospatial approach, in: River Conserv. Water Resour. Manag., Springer, 2023, pp. 27–52.

[7] J. Osei-Owusu, W.K. Heve, R.Q. Duker, O.F. Aidoo, L. Larbi, G. Edusei, M.J. Opoku, R.A. Akolaa, F. Eshun, J. Apau, Assessments of microbial and heavy metal contaminations in water supply systems at the University of Environment and Sustainable Development in Ghana, Sustain. Chem. Environ. 2 (2023) 100015.

[8] F. Obiri-Nyarko, A.A. Duah, A.Y. Karikari, R. Tagoe, Characterization of leachate, groundwater quality analysis, and evaluation of hydrogeochemical processes at the Kpone engineered landfill site, Ghana, Sustain. Water Resour. Manag. 9 (2023) 15.

[9] R.A. Myers, E. Gyimah, K. Gbemadu, B. Osei, O. Akoto, Appraising groundwater quality and the associated health risks of heavy metal contamination at Suame magazine, Sci. African. 21 (2023) e01794.

[10] E. Manu, M. De Lucia, M. Kühn, Hydrochemical characterization of surface water and groundwater in the crystalline basement aquifer system in the pra basin (Ghana), Water 15 (2023) 1325.

[11] G. Krishan, M. Kumar, M.S. Rao, R. Garg, B.K. Yadav, M.L. Kansal, S. Singh, A. Bradley, M. Muste, L.M. Sharma, Integrated approach for the investigation of groundwater quality through hydrochemistry and water quality index (WQI), Urban Clim. 47 (2023) 101383.

[12] J. Podgorski, M. Berg, Global analysis and prediction of fluoride in groundwater, Nat. Commun. 13 (2022) 4232, https://doi.org/10.1038/s41467-022-31940-x.

[13] D. Mridha, P. Priyadarshni, K. Bhaskar, A. Gaurav, A. De, A. Das, M. Joardar, N.R. Chowdhury, T. Roychowdhury, Fluoride exposure and its potential health risk assessment in drinking water and staple food in the population from fluoride endemic regions of Bihar, India, Groundw. Sustain. Dev. 13 (2021) 100558, https://doi.org/10.1016/j.gsd.2021.100558.

[14] D. Araya, J. Podgorski, M. Kumi, P.A. Mainoo, M. Berg, Fluoride contamination of groundwater resources in Ghana: country-wide hazard modeling and estimated population at risk, Water Res. 212 (2022) 118083, https://doi.org/10.1016/j.watres.2022.118083.

[15] M. Golaki, A. Azhdarpoor, A. Mohamadpour, Z. Derakhshan, G.O. Conti, Health risk assessment and spatial distribution of nitrate, nitrite, fluoride, and coliform contaminants in drinking water resources of kazerun, Iran, Environ. Res. 203 (2022) 111850, https://doi.org/10.1016/j.envres.2021.111850.

[16] M. Qasemi, M. Darvishian, H. Nadimi, M. Gholamzadeh, M. Afsharnia, M. Farhang, M. Allahdadi, M. Darvishian, A. Zarei, Characteristics, water quality index and human health risk from nitrate and fluoride in Kakhk city and its rural areas, Iran, J. Food Compos. Anal. 115 (2023) 104870, https://doi.org/10.1016/j.jfca.2022.104870.

[17] I.A. Revelo, M. Robinson, G. Idrobo, V.A. López, Fluoride levels in river water from the volcanic regions of Cauca (Colombia), Environ. Monit. Assess. (2022), https://doi.org/10.1007/s10661-022-09999-2.

[18] L. Kaur, M.S. Rishi, A.U. Siddiqui, Deterministic and probabilistic health risk assessment techniques to evaluate non-carcinogenic human health risk (NHHR) due to fluoride and nitrate in groundwater of Panipat, Haryana, India, Environ. Pollut. 259 (2020) 113711, https://doi.org/10.1016/j.envpol.2019.113711.

[19] J. Bazeli, S. Ghalehaskar, M. Morovati, H. Soleimani, S. Masoumi, A. Rahmani Sani, M.H. Saghi, A. Rastegar, Health risk assessment techniques to evaluate non-carcinogenic human health risk due to fluoride, nitrite and nitrate using Monte Carlo simulation and sensitivity analysis in Groundwater of Khaf County, Iran, Int. J. Environ. Anal. Chem. 102 (2022) 1793–1813, https://doi.org/10.1080/03067319.2020.1743280.

[20] E.D. Sunkari, S.J. Adams, M.B. Okyere, P. Bhattacharya, Groundwater fluoride contamination in Ghana and the associated human health risks: any sustainable mitigation measures to curtail the long term hazards? Groundw. Sustain. Dev. 16 (2022) 100715 https://doi.org/10.1016/J.GSD.2021.100715.

[21] S. Srivastava, S.J.S. Flora, Fluoride in drinking water and skeletal fluorosis: a review of the global impact, Curr. Environ. Heal. Reports. 7 (2020) 140–146, https://doi.org/10.1007/S40572-020-00270-9/METRICS.

[22] E.D. Sunkari, S.J. Adams, M.B. Okyere, P. Bhattacharya, Groundwater fluoride contamination in Ghana and the associated human health risks: any sustainable mitigation measures to curtail the long term hazards? Groundw. Sustain. Dev. 16 (2022) 100715 https://doi.org/10.1016/j.gsd.2021.100715.

[23] N.F. Mwiathi, X. Gao, C. Li, A. Rashid, The occurrence of geogenic fluoride in shallow aquifers of Kenya Rift Valley and its implications in groundwater management, Ecotoxicol. Environ. Saf. 229 (2022) 113046, https://doi.org/10.1016/j.ecoenv.2021.113046.

[24] S.J. Cobbina, A.B. Duwiejuah, R. Quansah, S. Obiri, N. Bakobie, Comparative assessment of heavy metals in drinking water sources in two small-scale mining communities in Northern Ghana, Int. J. Environ. Res. Public Health 12 (2015) 10620–10634, https://doi.org/10.3390/ijerph120910620.

[25] A. Rashid, D.X. Guan, A. Farooqi, S. Khan, S. Zahir, S. Jehan, S.A. Khattak, M.S. Khan, R. Khan, Fluoride prevalence in groundwater around a fluorite mining area in the flood plain of the River Swat, Pakistan, Sci. Total Environ. 635 (2018) 203–215, https://doi.org/10.1016/j.scitotenv.2018.04.064.

[26] E.D. Sunkari, M. Abu, Hydrochemistry with special reference to fluoride contamination in groundwater of the bongo district, Upper East Region, Ghana, Sustain. Water Resour. Manag. 5 (2019) 1803–1814.

[27] L. Craig, A. Lutz, K.A. Berry, W. Yang, Recommendations for fluoride limits in drinking water based on estimated daily fluoride intake in the Upper East Region, Ghana, Sci. Total Environ. 532 (2015) 127–137, https://doi.org/10.1016/J.SCITOTENV.2015.05.126.

[28] A. Salifu, B. Petrusevski, K. Ghebremichael, R. Buamah, G. Amy, Multivariate statistical analysis for fluoride occurrence in groundwater in the Northern region of Ghana, J. Contam. Hydrol. 140–141 (2012) 34–44, https://doi.org/10.1016/J.JCONHYD.2012.08.002.

[29] K.A. Alfredo, D.F. Lawler, L.E. Katz, Fluoride contamination in the Bongo District of Ghana, West Africa: geogenic contamination and cultural complexities, Water Int. 39 (2014) 486–503, https://doi.org/10.1080/02508060.2014.926234.

[30] C.K. Firempong, K. Nsiah, D. Awunyo-Vitor, J. Dongsogo, Soluble fluoride levels in drinking water-a major risk factor of dental fluorosis among children in Bongo community of Ghana, Ghana Med. J. 47 (2013) 16–23.

[31] E.D. Sunkari, M.S. Zango, H.M. Korboe, Comparative analysis of fluoride concentrations in groundwaters in northern and southern Ghana: implications for the contaminant sources, Earth Syst. Environ. 2 (2018) 103–117.

[32] M.S. Zango, E.D. Sunkari, M. Abu, A. Lermi, Hydrogeochemical controls and human health risk assessment of groundwater fluoride and boron in the semi-arid North East region of Ghana, J. Geochemical Explor. 207 (2019) 106363, https://doi.org/10.1016/j.gexplo.2019.106363.

[33] S.M. Yidana, D. Ophori, B. Banoeng-Yakubo, A.A. Samed, A factor model to explain the hydrochemistry and causes of fluoride enrichment in groundwater from the middle Voltaian sedimentary aquifers in the northern region, Ghana, ARPN J. Eng. Appl. Sci. 7 (2012) 50–68.

[34] S.K. Abanyie, E.D. Sunkari, O.B. Apea, S. Abagale, H.M. Korboe, Assessment of the quality of water resources in the Upper East Region, Ghana: a review, Sustain. Water Resour. Manag. 6 (2020) 1–18.
[35] F.A. Atipoka, Water supply challenges in rural Ghana, Desalination 248 (2009) 212–217.
[36] S.Y. Ganyaglo, A. Gibrilla, E.M. Teye, E.D.G.J. Owusu-Ansah, S. Tettey, P.Y. Diabene, S. Asimah, Groundwater fluoride contamination and probabilistic health risk assessment in fluoride endemic areas of the Upper East Region, Ghana, Chemosphere 233 (2019) 862–872, https://doi.org/10.1016/J.CHEMOSPHERE.2019.05.276.
[37] N. Chai, X. Yi, J. Xiao, T. Liu, Y. Liu, L. Deng, Z. Jin, Spatiotemporal variations, sources, water quality and health risk assessment of trace elements in the Fen River, Sci. Total Environ. 757 (2021) 143882.
[38] O. Akoto, A. Adopler, H.E. Tepkor, F. Opoku, A comprehensive evaluation of surface water quality and potential health risk assessments of Sisa river, Kumasi, Groundw. Sustain. Dev. 15 (2021) 100654, https://doi.org/10.1016/j.gsd.2021.100654.
[39] C.K. Tay, M. Dorleku, L.K. Doamekpor, Human exposure risks assessment of heavy metals in groundwater within the amansie and adansi districts in Ghana using pollution evaluation indices, West African J. Appl. Ecol. 27 (2019) 23–41.
[40] Who, Guidelines for Drinking-Water Quality, Incorporating the 1st Addendum (Chapters), fourth ed., 2017. https://www.who.int/publications/m/item/guidelines-for-drinking-water-quality-4th-ed.-incorporating-the-1st-addendum-(chapters. (Accessed 3 January 2023).
[41] Ş. Şener, E. Şener, A. Davraz, Evaluation of water quality using water quality index (WQI) method and GIS in Aksu River (SW-Turkey), Sci. Total Environ. 584–585 (2017) 131–144, https://doi.org/10.1016/j.scitotenv.2017.01.102.
[42] USEPA IRIS, Integrated Risk Information System IRIS Assessments | IRIS, Environmental Protection Agency Region I. United State Environmental Protection Agency | US EPA, Washington DC 20460, 2011. https://iris.epa.gov/AtoZ/?list_type=alpha. (Accessed 28 January 2023).
[43] V. Duggal, S. Sharma, Fluoride contamination in drinking water and associated health risk assessment in the Malwa Belt of Punjab , India, Environ. Adv. 8 (2022) 100242, https://doi.org/10.1016/j.envadv.2022.100242.
[44] T. Rango, A. Vengosh, M. Jeuland, R. Tekle-Haimanot, E. Weinthal, J. Kravchenko, C. Paul, P. McCornick, Fluoride exposure from groundwater as reflected by urinary fluoride and children's dental fluorosis in the Main Ethiopian Rift Valley, Sci. Total Environ. 496 (2014) 188–197, https://doi.org/10.1016/J.SCITOTENV.2014.07.048.
[45] H. Qiu, H. Gui, H. Xu, L. Cui, H. Yu, Occurrence, controlling factors and noncarcinogenic risk assessment based on Monte Carlo simulation of fluoride in mid-layer groundwater of Huaibei mining area, North China, Sci. Total Environ. 856 (2023) 159112, https://doi.org/10.1016/j.scitotenv.2022.159112.
[46] S. Wickramarathna, S. Balasooriya, S. Diyabalanage, R. Chandrajith, Tracing environmental aetiological factors of chronic kidney diseases in the dry zone of Sri Lanka—a hydrogeochemical and isotope approach, J. Trace Elem. Med. Biol. 44 (2017) 298–306, https://doi.org/10.1016/J.JTEMB.2017.08.013.
[47] X. Li, P. Wu, Z. Han, J. Shi, Sources, distributions of fluoride in waters and its influencing factors from an endemic fluorosis region in central Guizhou, China, Environ, Earth Sci. 75 (2016) 1–14, https://doi.org/10.1007/s12665-016-5779-y.
[48] K.V. Koffi, E. Obuobie, A. Banning, S. Wohnlich, Hydrochemical characteristics of groundwater and surface water for domestic and irrigation purposes in Vea catchment, Northern Ghana, Environ. Earth Sci. 76 (2017) 1–19, https://doi.org/10.1007/S12665-017-6490-3/METRICS.
[49] R. Sharma, M. Tsuchiya, Z. Skobe, B.A. Tannous, J.D. Bartlett, The acid test of fluoride: how pH modulates toxicity, PLoS One 5 (2010), https://doi.org/10.1371/JOURNAL.PONE.0010895.
[50] A. Rashid, S.A. Khattak, L. Ali, M. Zaib, S. Jehan, M. Ayub, S. Ullah, Geochemical profile and source identification of surface and groundwater pollution of District Chitral, Northern Pakistan, Microchem. J. 145 (2019) 1058–1065, https://doi.org/10.1016/J.MICROC.2018.12.025.
[51] S.B.B.M. Saana, S.A. Fosu, G.E. Sebiawu, N. Jackson, T. Karikari, Assessment of the quality of groundwater for drinking purposes in the Upper West and Northern regions of Ghana, SpringerPlus 5 (2016) 2001, https://doi.org/10.1186/s40064-016-3676-1.
[52] J. Tomperi, A. Isokangas, T. Tuuttila, M. Paavola, Functionality of turbidity measurement under changing water quality and environmental conditions, Environ. Technol. 43 (2022) 1093–1101.
[53] N.O. Boadi, S.A. Saah, F. Baa-Poku, E.A. Mensah, M. Addo, Safety of borehole water as an alternative drinking water source, Sci. African. 10 (2020) e00657, https://doi.org/10.1016/j.sciaf.2020.e00657.
[54] S. Nizam, H.S. Virk, I.S. Sen, High levels of fluoride in groundwater from Northern parts of Indo-Gangetic plains reveals detrimental fluorosis health risks, Environ. Adv. 8 (2022) 100200.
[55] M. Chedadi, H. Amakdouf, A. El Barnossi, A. El Moussaoui, M. Kara, H. El Asmi, M. Merzouki, A. Bari, Impact of anthropogenic activities on the physicochemical and bacteriological quality of water along Oued Fez River (Morocco), Sci. African. 19 (2023) e01549, https://doi.org/10.1016/J.SCIAF.2023.E01549.
[56] S.U. Fatima, M.A. Khan, F. Siddiqui, N. Mahmood, N. Salman, A. Alamgir, S.S. Shaukat, Geospatial assessment of water quality using principal components analysis (PCA) and water quality index (WQI) in Basho Valley, Gilgit Baltistan (Northern Areas of Pakistan), Environ. Monit. Assess. 194 (2022) 1–22, https://doi.org/10.1007/S10661-022-09845-5/METRICS.
[57] German Federal Institute for Risk Assessment (BfR), Proposed Maximum Levels for the Addition of Fluoride to Foods Including Food Supplements, 2015.
[58] N. Efsa, Panel on Dietetic Products and Allergies (NDA), Scientific opinion on dietary reference values for fluoride, EFSA J. 11 (2013) 3332.
[59] W. Guissouma, O. Hakami, A.J. Al-Rajab, J. Tarhouni, Risk assessment of fluoride exposure in drinking water of Tunisia, Chemosphere 177 (2017) 102–108, https://doi.org/10.1016/j.chemosphere.2017.03.011.
[60] R.A. Fallahzadeh, M. Miri, M. Taghavi, A. Gholizadeh, R. Anbarani, A. Hosseini-Bandegharaei, M. Ferrante, G. Oliveri Conti, Spatial variation and probabilistic risk assessment of exposure to fluoride in drinking water, Food Chem. Toxicol. 113 (2018) 314–321, https://doi.org/10.1016/j.fct.2018.02.001.
[61] M. Yousefi, S. Ghalehaskar, F.B. Asghari, A. Ghaderpoury, M.H. Dehghani, M. Ghaderpoori, A.A. Mohammadi, Distribution of fluoride contamination in drinking water resources and health risk assessment using geographic information system, northwest Iran, Regul. Toxicol. Pharmacol. 107 (2019) 104408, https://doi.org/10.1016/j.yrtph.2019.104408.
[62] Y. Wang, R. Yu, G. Zhu, Evaluation of physicochemical characteristics in drinking water sources emphasized on fluoride: a case study of yancheng, China, Int. J. Environ. Res. Public Health. 16 (2019), https://doi.org/10.3390/IJERPH16061030.
[63] V.A. Makokha, Y. Qi, Y. Shen, J. Wang, Concentrations, distribution, and ecological risk assessment of heavy metals in the east dongting and honghu lake, China, expo, Heal 8 (2016) 31–41, https://doi.org/10.1007/s12403-015-0180-8.
[64] R. Rajesh, L. Elango, K. Brindha, Methods for Assessing the Groundwater Quality, Elsevier Inc., 2019, https://doi.org/10.1016/B978-0-12-815413-7.00006-7.
[65] K.D. Brahman, T.G. Kazi, H.I. Afridi, S. Naseem, S.S. Arain, N. Ullah, Evaluation of high levels of fluoride, arsenic species and other physicochemical parameters in underground water of two sub districts of Tharparkar, Pakistan: a multivariate study, Water Res. 47 (2013) 1005–1020, https://doi.org/10.1016/j.watres.2012.10.042.
[66] R.T. Iwar, K. Ogedengbe, K.K. Katibi, J.N. Jabbo, Fluoride levels in deep aquifers of Makurdi, North-central, Nigeria: an appraisal based on multivariate statistics and human health risk analysis, Environ. Monit. Assess. 193 (2021), https://doi.org/10.1007/s10661-021-09230-8.