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Assessing groundwater quality: a case study in Ghana Talensi district

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ABSTRACT

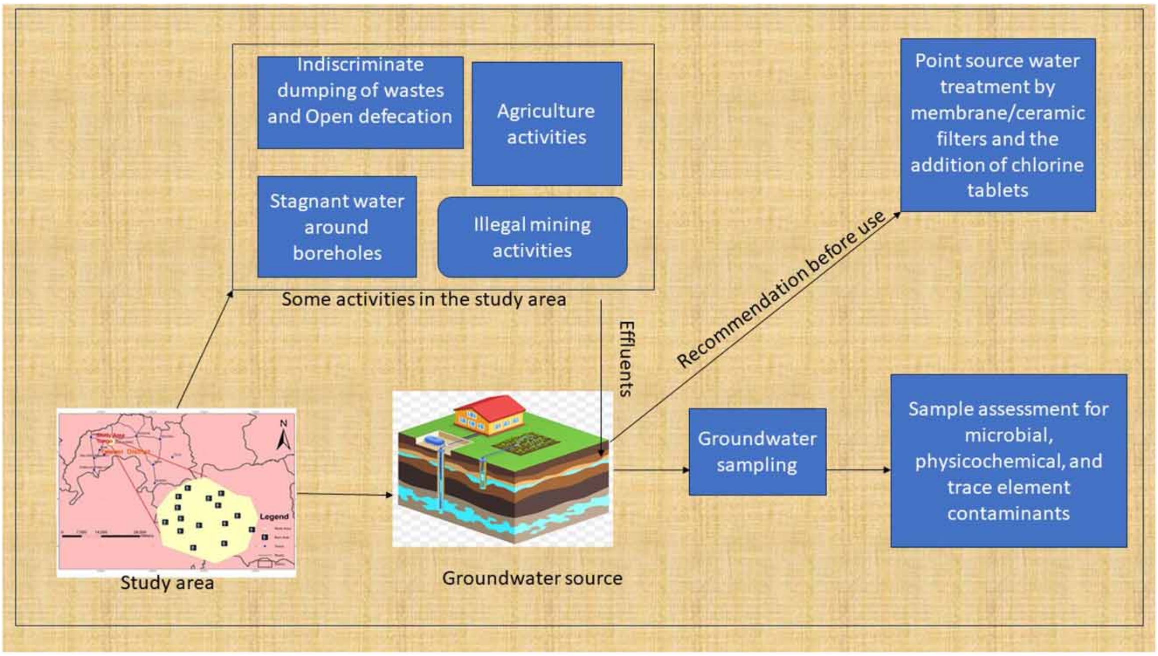
Because most life processes are directly or indirectly related to water, people are investigating on the various sources of drinking water supply. Surface water and groundwater are the most common sources of water for domestic and other uses. The availability of safe and sufficient drinking water in developing countries' rural and many urban areas is critical. Groundwater has become the primary source of drinking water supply in northern Ghana, particularly in rural areas. Tongo, in northern Ghana, is entirely dependent on groundwater for its drinking water supply. The quality of groundwater from 15 boreholes and open well samples was assessed in this study. The primary goals of the research are to assess the quality of groundwater for drinking and to determine the distribution of major ions in groundwater and the factors that control them. Groundwater physicochemical parameters were within the WHO guidelines limit. However, coliform bacteria were found in some groundwater sources. Anthropogenic, natural, and ion exchange processes were also identified as controlling groundwater major ion distribution. Insanitary conditions were identified as potential sources of contamination during field observations. As a result, the regular monitoring of groundwater resources could reveal more about the area's groundwater quality status.

Key words: geochemical processes, groundwater, microbial, physicochemical, Tongo town

HIGHLIGHTS

- Microbial contamination and health risks.
- Targeted water treatment strategies.
- Hydrochemical facies and anthropogenic impact.
- Evidence of ion exchange and interplay of ions.
- Holistic approach to management and future research.

GRAPHICAL ABSTRACT



1. INTRODUCTION

An estimated 1.1 billion people, constituting a significant portion of the world's population, lack access to safe drinking water, despite its fundamental necessity (Hossain *et al.* 2020). This inadequate drinking water supply poses a substantial challenge, particularly for developing nations. As a result, many communities in these countries resort to utilizing untreated sources such as rivers, streams, wells, and boreholes for both domestic and drinking purposes (Oyelude *et al.* 2013). Although groundwater is generally considered safe for consumption due to its subterranean location and reduced exposure to the atmosphere in comparison to surface water, the pollution of potable groundwater is on the rise due to various human and natural influences (Oyelude *et al.* 2013). The consumption of contaminated water is linked to several diseases, especially prevalent in developing nations, underscoring the alarming mismanagement of this crucial resource (Oyelude *et al.* 2013). Groundwater emerges as the primary and dependable source of fresh water in semi-arid climates such as northern Ghana, supporting domestic, agricultural, and industrial activities, as reported by the Community Water and Sanitation Agency (CWSA), as well as substantiated by Chegbeleh *et al.* (2020). Similarly, Singh *et al.* (2020) highlight groundwater's vital role in sustaining both fauna and flora in India.

Nonetheless, human activities and natural factors impact the quality of groundwater. Anthropogenic practices like open defecation, agriculture, improper waste disposal, and burial sites adversely affect groundwater quality. Therefore, regular monitoring and testing are essential to ensure safe water for consumption and industrial purposes. In many rural and semi-urban areas of northern Ghana, access to the Ghana Water Company Limited's treated drinking water remains limited. Tongo, situated in the Talensi District of the Upper East Region, exemplifies such a community. Boreholes and open wells serve as the primary sources of drinking water for Tongo, yet information concerning the quality of groundwater in the region is notably inadequate. To address this research gap, this study evaluates the quality of groundwater from selected boreholes and open wells within the district capital, Tongo Town. The evaluation encompasses various aspects including physicochemical properties, heavy metal concentrations, and microbial quality parameters. The study's findings are subsequently compared against the World Health Organization's (WHO) drinking water guidelines to assess the suitability of water from these sources for consumption.

1.1. Study area

1.2. Location and accessibility

Tongo is the capital of Ghana's Talensi District in the country's Upper East Region (Figure 1). The municipality of Bolgatanga borders Talensi to the north, the districts of West and East Mamprusi (both in the Northern Region), the district of Kassena-Nankana to the west, and the municipalities of Bawku West and Nabdam to the east (Ghana Statistical Service 2014). Tongo areas are distinguished geomorphologically by scattered rock outcrops and upland slopes with relatively undulating lowlands with gentle slopes ranging from 10 to 50 gradients (Ghana Statistical Service 2014). Because of the drainage pattern, most Tongo township households rely on hand-dug wells and boreholes for water.

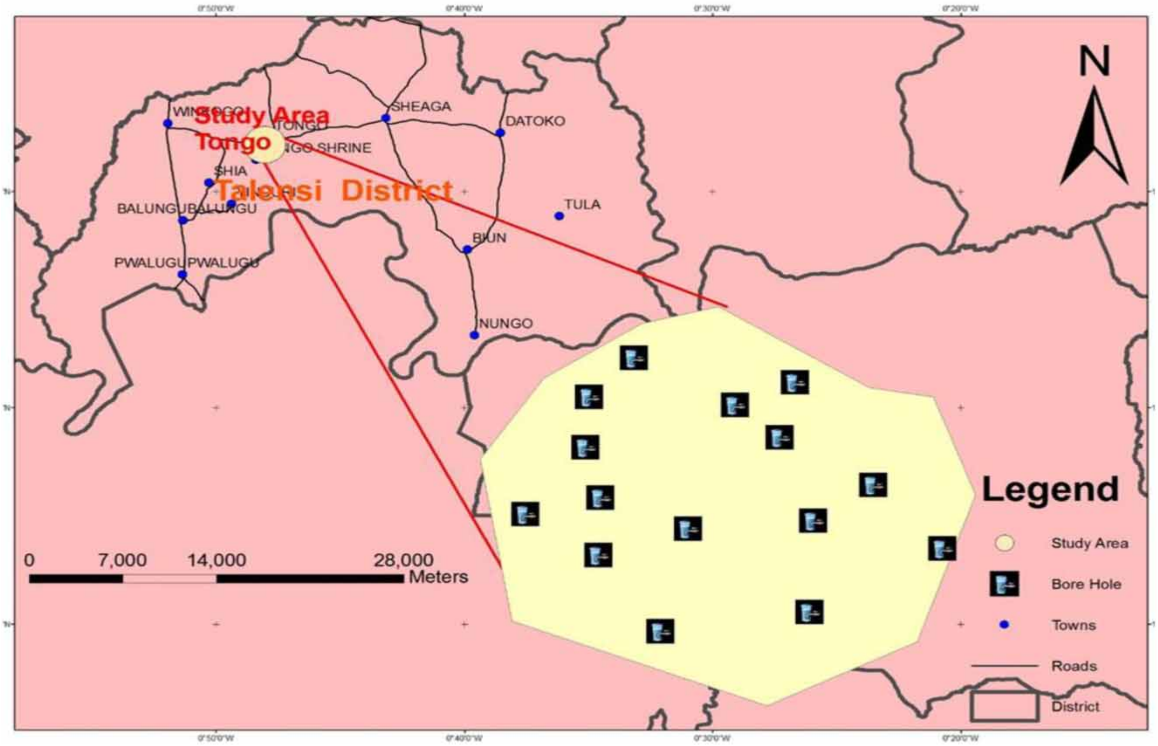


Figure 1 | Talensi district map showing the study area and sampling stations.

1.3. Population and size

As per the 2010 National Population and Housing Census, the district's total population stood at 81,194, comprising 50.3% males and 49.7% females, with an average household size of 5.2 people (Ghana Statistical Service 2014). These data highlight a pronounced public demand for both water and land resources. The local assembly encountered significant challenges due to the scarcity of potable water supply within the district. Notably, 64.8% of households rely on water sourced from drilled pumps, tubular wells, or pumps, while 10.6% use protected wells, 6.5% rely on unprotected wells, 6.1% draw from rivers or streams, 4.0% use sources like shelters, ponds, lakes, dams, or canals, and 3.4% access water from pipes located outside their dwellings. In terms of water sources, unimproved wells constitute 6.5% of all well sources, while rivers or streams account for 6.1%. Similarly, excavations, ponds, lakes, dams, and canals collectively contribute 4.0%, and unimproved sources represent 4.0% of the total.

1.4. Climate and vegetation

The study region experiences a tropical climate characterized by two distinct seasons: an erratic wet rainy period spanning from May to October and an extended dry season prevailing from October to April, featuring minimal rainfall. On a monthly scale, the average precipitation ranges from 88 to 110 mm, summing up to an annual mean of 950 mm. During March and April, temperature extremes are observed, reaching up to 45 °C at the maximum and dropping to 12 °C at the minimum (Ghana Statistical Service 2013). Throughout the extended dry season, the study area's landscape is dominated by Guinea Savannah Forest vegetation. This landscape comprises short, widely spread deciduous trees accompanied by grasses forming a ground cover. These grasses are susceptible to both fire and the intense rays of the sun. The prevailing extreme temperatures and the lengthy dry period encourage the occurrence of bushfires, which hinder the growth and survival of trees and contribute to the deterioration of land quality (Ghana Statistical Service 2013).

1.5. Soil and drainage

The district's landscape comprises scattered rock outcrops and elevated slopes, alongside gently undulating lowlands found in the Tongo areas, where the slopes range from 10 to 50 degrees. The prevalent soil composition is primarily composed of granite rocks, leading to shallow soil fertility, a deficiency in organic matter, and a coarse texture. Erosion emerges as a significant issue within the district. In the valleys, the soil composition varies from sandy loams to saline clays. These soils possess inherent high fertility, yet their cultivation proves more demanding due to their susceptibility to flooding and waterlogging during the growth season. The primary rivers flowing through the district encompass the White Volta and its tributaries (Ghana Statistical Service 2014).

1.6. Water supply and sanitation system

The study found that potable water supply was a major challenge in the municipality, particularly because the assembly had no direct control over the urban water supply. Boreholes and wells are used in areas such as Gbeogo, Seok, Korig, Gurig, Puhig, and others that have limited or no access to piped water. In addition, many people have access to public or private sanitation facilities. Others defecate in gutters, open spaces, and public garbage dumps without regard. Furthermore, approximately 15.7% of the town's population dumps solid waste indiscriminately, while 73.8% throw liquid onto the street/outside (Ghana Statistical Service 2014). This causes a significant backlog, resulting in a variety of inconveniences, including heat hazards for those in the area.

2. MATERIALS AND METHODS

2.1. Sampling site and field measurements

Tongo was divided into seven communities: Korig, Seok, Gurig, Gbeogo, Puhig, Zubeong, and Tongo, where the samples were collected. These towns were then divided into five clusters. A total of 15 water samples were collected by employing a random selection method, which involved choosing (3 boreholes or wells from each of the 5 clusters. This collection encompassed water obtained from both boreholes and a well. The clusters were later labeled SB, KW/PU, TO, ZB, and GB, and the corresponding boreholes/wells were similarly labeled. Distances between the boreholes and the nearest pollution sources (farms and pit latrines) were measured using steel tape. The recorded measurements fell within the range of 21–61 m. Coordinates of sample stations were also recorded using the GPS waypoints Android application version 3.10. Additionally, a visual assessment of the immediate surroundings of the boreholes was conducted. The assessment revealed that sanitary conditions around boreholes/wells were not in good standing.

2.2. Sample collection

Fifteen 1-liter preconditioned polyethylene bottles were utilized to gather groundwater samples from five distinct areas within Tongo Town. Thirteen of these samples originated from boreholes, while two were sourced from wells. The entirety of the 15 samples was acquired for the analysis of physicochemical parameters, encompassing trace elements, alongside bacteriological analysis. The collection of samples commenced from early morning until noon, following a 15-min purging process designed to eliminate all stagnant water, thereby facilitating the collection of genuinely representative samples.

Each collected sample was placed in a light-proof, insulated container alongside ice packs. This precautionary measure was undertaken to prevent potential light-induced changes to the parameters and to ensure the viability, albeit dormancy, of the microorganisms. Subsequently, the samples were transported to the laboratory for both physicochemical and bacteriological assessments. Throughout the sample collection process, adherence to the sampling protocols adopted by Iddrisu *et al.* (2023) and described by Barcelona *et al.* (1985) was rigorously followed.

2.3. Laboratory analysis

The disk comparator was used to determine the color of the water samples. The HACH 2100P turbidimeter, Hach Sension1, and Hach Sension5 were used to measure conductivity, pH, turbidity, temperature, and total dissolved solids (TDS). To ascertain parameters such as total alkalinity (TA), total hardness (TH), magnesium, calcium, and chloride, the 'Classical EDTA titrimetric' method (Cl^-) was utilized. The 'SPADNS colorimetric method' was employed to determine fluoride concentrations in water samples using the HACH DR6000. The HACH DR6000 was used for other chemical parameters and trace elements analyses, namely, nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3^-), sulfate, and phosphate, along with trace elements iron (Fe), zinc (Zn), chromium (Cr), copper (Cu), manganese (Mn), cyanide (CN^-), and arsenic (As). The Jenway PFP7 photometer was used to analyze sodium and potassium. The determined bacteriological parameters are as follows: total coliform (TC), fecal coliform (FC), *Escherichia coli*, and salmonella.

2.4. Color

First, the colorimetric method was used to determine the color of the water samples. The sample was poured into a Nessler tube until it reached 50 mL. Similarly, distilled water was used as a color standard in a tube. The color of the sample is visually compared to that of the standard by viewing vertically downwards, and the color index is determined using a color comparator stand (APHA 2012).

2.5. Conductivity

The conductivity cell potentiometric method was used to determine electrical conductivity. This method involves the use of a conductivity meter capable of measuring conductivity with an error of no more than 1% or 0.1 mS/m. The conductivity cell was rinsed three times with 0.01 M KCl solution. The probe is immersed in the standard KCl solution and the meter is set to 141.2 mS/m. The probe was dipped into the water samples to read the conductivity and the values were recorded along with the temperature (APHA 2012).

2.6. pH

pH was obtained by rinsing the electrode of the Hach Sension1 pH meter with distilled water, blot dried, and immersed in the sample, stirring gently while measuring pH to ensure homogeneity (APHA 2012).

2.7. Total hardness

TH was determined using the EDTA (ethylenediaminetetraacetate) titrimetric method. A conical flask was used to transfer a 25 mL sample. To achieve a pH of 10, 1.5 mL of ammonium chloride buffer solution was added. This resulted in the formation of an initial violet color in the sample. A few drops of Eri chrome black T indicator were then added. The solution was continuously stirred while titrating with 0.01 M EDTA until blue color indicating the endpoint was reached. The volume of EDTA used, denoted as $V1$, was recorded. The provided equation (APHA 2012) was used to calculate the value of $V1$.

$$\text{Calculation: total hardness as mgCaCO}_3/\text{L} = (V1 \times S)/(\text{Sample volume}) \times 1,000$$

where S is mgCaCO_3 equivalent to 1.0 mL EDTA titrant.

2.8. Calcium

Calcium levels were also determined using the EDTA titrimetric method. A conical flask was filled with a 50 mL sample of water. An aliquot was mixed with 2.5 mL of 1 M NaOH, and a small amount of murexide indicator was added, causing the solution to exhibit an initial violet color. It was then titrated from the burette to a purple endpoint against disodium EDTA. The titer values were read and recorded. The results were given in milligrams per liter of Ca (APHA 2012).

$$\text{Calculation: Ca(mg/l)} = (A \times B \times 400.8)/(\text{Volume of sample}).$$

where A is the amount of EDTA titrant used in milliliters and B = (mL of standard calcium solution)/(mL of EDTA titrant).

2.9. Magnesium

The amount of magnesium was calculated using a method based on TH and calcium level. This was accomplished by multiplying the TH and calcium values by 0.243, where

$$\text{TH as mgCaCO}_3/\text{L} - \text{Calcium Hardness as }(\text{mgCaCO}_3/\text{L}) = \text{Mg(mg/l)}.$$

$$\text{Total Hardness (TH)} = \text{mgCaCO}_3/\text{L}.$$

2.10. Total alkalinity

The titrimetric method with phenolphthalein as an indicator was used to determine carbonate, bicarbonate, and TA. To begin with, 50 mL of the sample was poured into a conical flask, and subsequently, 2–3 drops of phenolphthalein indicator were added. Next, the sample was titrated with 0.02 N H_2SO_4 until the pink color vanished, indicating the endpoint. The corresponding titer values (TV) were recorded according to the guidelines provided by APHA (2012). The calculation of phenolphthalein alkalinity was performed using the formula:

$$\text{The phenolphthalein alkalinity expressed in milligrams of calcium carbonate per unit volume} \\ = (\text{TV})/(\text{Sample volume}) \times 1,000.$$

2.11. Chloride

The argentometric method with potassium chromate K_2CrO_7 as an indicator was utilized to determine the chloride content in the water sample. Each water sample was carefully transferred into a 25 mL conical flask using a pipette. Next, two drops of potassium chromate solution were added, resulting in an initial yellow color. The sample was titrated against 0.1 M silver nitrate ($AgNO_3$) using a burette until a reddish yellow endpoint was observed. The titer values were carefully recorded in accordance with the APHA guidelines (2012). A control experiment was also conducted using distilled water. The calculation of the chloride content was carried out using the given formula:

$$\text{Chloride mg/L} = ((x - y) \times N \times 35.45)/(\text{Sample volume}) \times 1,000.$$

where x is mL $AgNO_3$ required for the sample; y is mL $AgNO_3$ required for the blank; and N is normality of the $AgNO_3$ used.

2.12. Nitrite

The spectrophotometric method of sulfanilamide was used to determine nitrite. Two milliliters of the color reagent were mixed into 50 mL of the sample. The mixture was transferred to a cuvette, wiped with a dry tissue, and measured with a spectrophotometer at 543 nm. The calibration blank was distilled water (APHA 2012).

2.13. Nitrate

Nitrate was measured using an ultraviolet spectrophotometer. To 50 mL of the sample, 1 mL of HCl was added. At a wavelength of 220 nm, the absorbance was measured against distilled water.

The standard solution curve was used to calculate sample concentrations (APHA 2012).

2.14. Sulfate

The measurement of sulfate levels in the water was conducted using the turbidimetric method. In this method, a test tube was filled with 10 mL of water, and then 0.5 mL of the conditioning reagent (containing glycerol) and a small amount of barium chloride ($BaCl_2$) were added. The contents of the test tube were shaken for 1 min and allowed to settle for 5 min. The absorbance of the prepared sample at a wavelength of 420 nm was measured and recorded using a UV spectrophotometer, following the guidelines provided by APHA (2012).

2.15. Fluoride

The SPADNS method was employed to determine the fluoride concentration. In this procedure, a test tube was used to mix 10 mL of the water sample with 2 mL of the SPADNS reagent (sodium 2-(parasulfophenylazo)-1,8-dihydroxy-3,6-naphthalene disulfate). The resulting mixture was then transferred to a cuvette, ensuring that the exterior of the cuvette was wiped clean with a tissue. The absorbance of the sample was measured at a wavelength of 570 nm using a UV spectrometer. Additionally, a blank SPADNS record was read as a reference for comparison, following the guidelines provided by APHA (2012).

2.16. Sodium

In order to standardize and calibrate the flame photometer, a solution consisting of 5 mL of distilled water and 2 mL of a 20 mg/l lithium standard was prepared and transferred to the photometer's tube using a 10 mL graduated cylinder. Similarly, a solution containing 5 mL of a 20 mg/l sodium standard was mixed in the graduated cylinder, shaken, and added to the tube for result reading. This procedure ensured an accurate operation of the flame photometer. To perform the actual measurement, 5 mL of the water sample was mixed with 2 mL of the lithium solution and then introduced into the flame photometer's tube for result reading and recording (APHA 2012).

2.17. Potassium

To calibrate and standardize the flame photometer, a 10 mL graduated cylinder was utilized. Initially, a mixture of 5 mL of distilled water and 2 mL of lithium standard solution (20 mg/l) were prepared in the cylinder. This mixture was then transferred to the tube of the flame photometer for the analysis. In a separate measuring cylinder, 5 mL of potassium standards (20 mg/l) were measured, shaken, and the results were read after adding them to the tube. This process ensured the accurate calibration of the flame photometer. For the actual measurement of the water sample, 5 mL of the sample was mixed with 2 mL of the lithium standard solution. The resulting mixture was carefully added to the tube of the flame photometer, and the readings were taken and recorded. Using the appropriately calibrated flame photometer (APHA 2012), the concentrations of potassium in the samples were determined.

2.18. Microbiological analysis

The 'membrane filtration method' was used for microbiological analysis of TC, FC, *E. coli*, and salmonella. The media were prepared by utilizing appropriate amounts of chromocult agar and then heating them. The working area in the laboratory was cleaned with methylated spirit and duplicate petri plates clearly labeled. Ten milliliters of the prepared agar was pipetted into each well-labeled sterile Petri dish plate, swirled gently, and allowed to solidify for 15 min. Plates were incubated for 24–48 h at 37 °C ± 1. The colony counter was used to quickly count colonies after the incubation period (APHA 2012).

3. RESULTS AND DISCUSSION

3.1. Water quality

As stated by Bani (2015), the quality of groundwater frequently relies on factors such as the makeup of recharge water, the interplay between water and the soil, the interaction of soil gas and rock in the unsaturated zone, as well as the duration water spends in the aquifer and the ensuing reactions. The physicochemical characteristics of the water samples are provided in Table 1 and discussed.

Physical examination of the samples revealed that they are odorless and colorless. Tongo Town's groundwater pH ranged from 6.80 to 7.30. The pH of the water was generally within the WHO recommended range of 6.5–8.5. Boreholes with low pH levels can cause pump parts to corrode, but they may not affect the water quality for domestic use. According to Chegbeleh *et al.* (2020), the pH of water influences the dissolution of rock minerals in groundwater which affects its quality. Additionally, low pH values may cause the water to taste sour. Since the recorded pH values in the current study are within the WHO guideline, it implies that the groundwater is safe for drinking with respect to pH.

TDS ranged from 217 to 357.5 mg/l and electrical conductivity ranged from 434 to 715 μS/cm. Seok had the lowest conductivity (434 μS/cm), while Zubeong had the highest (715 μS/cm). Tongo Town's groundwater has low conductivities in general, indicating minimal mineralization. The concentrations of TDS and EC were consistently less than 1,000 mg/l, indicating that the water was fresh. Tongo Town's water may be odorless and colorless due to its low TDS, as high TDS in water can cause poor esthetic value, undesirable taste, odor, and color. Furthermore, it has the potential to cause unfavorable physiological reactions in consumers (WHO 2011).

Salifu *et al.* (2017) reported that TH is an important factor for ascertaining the calcium and magnesium levels in water as well as salts of other minerals. In this report, hardness is only used to determine the suitability of

Table 1 | Physicochemical parameters of groundwater samples

Source	Borehole No	T (°C)	pH (SU)	Color (HU)	TB (NTU)	EC (μS/cm)	TDS	TA	TH	Na^+	K^+	Mg^{2+}	Ca^{2+}	HCO_3^-	SO_4^{2-}	Cl^-
Seok-1	558	20.90	6.80	0.00	1.17	434.00	217.00	66.00	34.00	25.20	2.70	1.70	10.80	46.00	11.70	29.00
Seok-2	453-C15	24.30	6.90	0.00	1.27	561.00	280.50	92.00	63.00	37.30	2.50	5.10	16.80	48.00	15.00	55.00
Seok-3	WELL	22.60	7.00	0.00	0.48	504.00	252.00	68.00	49.00	44.00	2.10	4.13	12.80	48.00	8.30	48.00
Gbeogo1	1347	21.60	7.00	0.00	0.44	577.00	288.50	156.00	68.00	38.60	4.70	4.37	20.00	128.00	15.00	25.00
Gbeogo2	WELL	25.90	7.30	0.00	2.77	466.00	233.00	93.00	42.00	4.90	3.20	17.01	14.80	69.00	8.30	39.00
Gbeogo3	GWSC/CID	23.80	6.90	0.00	0.19	524.00	262.00	106.00	56.00	32.00	2.50	6.32	12.00	78.00	8.30	39.00
Korig1	3256	23.10	6.80	0.00	0.21	617.00	308.00	77.00	71.00	34.60	3.00	8.75	14.00	37.00	9.20	77.00
Korig2	1295	22.60	6.80	0.00	0.22	523.00	261.50	127.00	48.00	42.30	2.50	4.13	12.40	101.00	10.00	35.00
Korig3	453C-8	24.60	6.90	0.00	0.13	506.00	253.00	58.00	42.00	23.30	1.60	1.22	14.80	30.00	8.30	43.00
Puhig1		25.10	6.90	0.00	0.39	478.00	239.00	90.00	40.00	35.00	2.40	2.43	12.00	66.00	8.20	40.00
Tongo1	C-7	21.70	7.00	0.00	0.41	530.00	265.00	82.00	105.00	25.10	3.50	8.99	14.80	62.00	8.30	51.00
Tongo2	AFD199	23.90	6.90	0.00	0.54	506.00	253.00	72.00	53.00	29.30	2.50	2.43	15.20	48.00	11.60	44.00
Zubeong1	10512	23.00	7.20	0.00	0.81	715.00	357.50	198.00	121.00	44.00	2.10	15.31	23.20	160.00	8.30	58.00
Zubeong2	453-C24	23.90	7.00	0.00	0.27	469.00	234.50	92.00	43.00	31.60	2.50	4.13	10.40	68.00	12.50	33.00
Zubeong3	2225	24.50	7.10	0.00	0.34	657.00	328.50	143.00	105.00	20.10	2.10	17.63	25.60	121.00	8.30	53.00
WHO Guidelines (2011)														–	400	250

Units are in mg/l unless otherwise stated.

groundwater for domestic and drinking purposes. The assessment of water's suitability for household purposes mainly relies on its response to soap. Given that soap's reaction is chiefly influenced by Ca^{2+} and Mg^{2+} ions, water hardness is characterized as the combined concentration of these ions, expressed in terms of milligrams per liter (mg/l) of $CaCO_3$. According to Bani (2015), water with hardness in the range 0–75 mg/l, 75–150 mg/l, 150–300 mg/l, and >300 mg/l are regarded as soft, moderately hard, hard, and very hard, respectively (Table 2). Groundwater from Tongo Town varies in TH from 34 to 121 mg/l. Generally, the waters are soft to moderately hard with 80% of the boreholes having soft water. This estimation implies that the majority of the boreholes in Tongo Town may be used for domestic purposes since they are soft and can lather with soap. In contrast to the favorable view of using softened water for household purposes, Knezović *et al.* (2014) reported that cardiovascular diseases are less common in areas of hard water than in areas of soft water.

Table 2 | Classification of water based on total hardness

Total hardness as $CaCO_3$ mg/l	**Water class**	**Number of samples**
0–75	Soft	12 (80%)
75–150	Moderately hard	3 (20%)
150–300	Hard	N/A
>300	Very hard	N/A

Source: Bani (2015).

3.2. Major ions chemistry

Figure 2 illustrates the relative concentration of major ions found in the groundwater from various boreholes within Tongo Town.

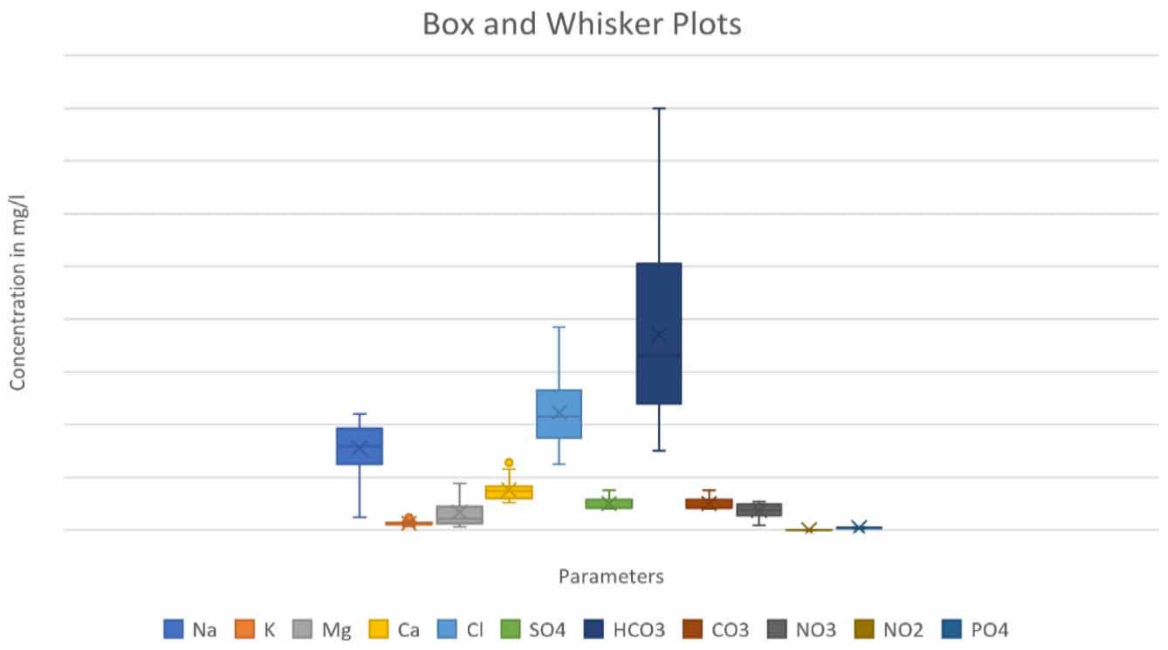


Figure 2 | Major ion box and whisker plots in the study area.

The overall ionic dominance pattern observed in this study is in the order of $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, for the cations and $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > CO_3^{2-} > PO_4^{2-} > NO_2$ for anions. As a result, the dominant ions in these areas' groundwaters are Na^+ and HCO_3^-.

3.2.1. The geochemical processes of groundwaters in Tongo Town

The graphs (Figure 3) show the interrelationship among dissolved species.

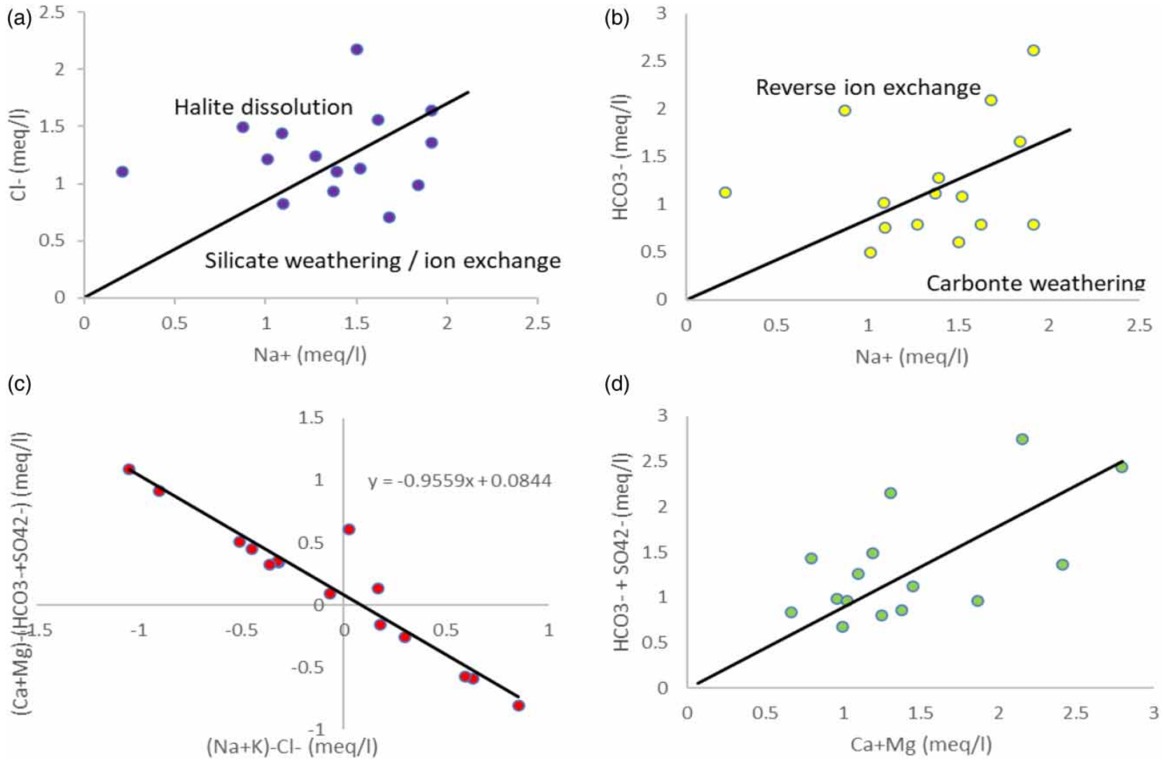


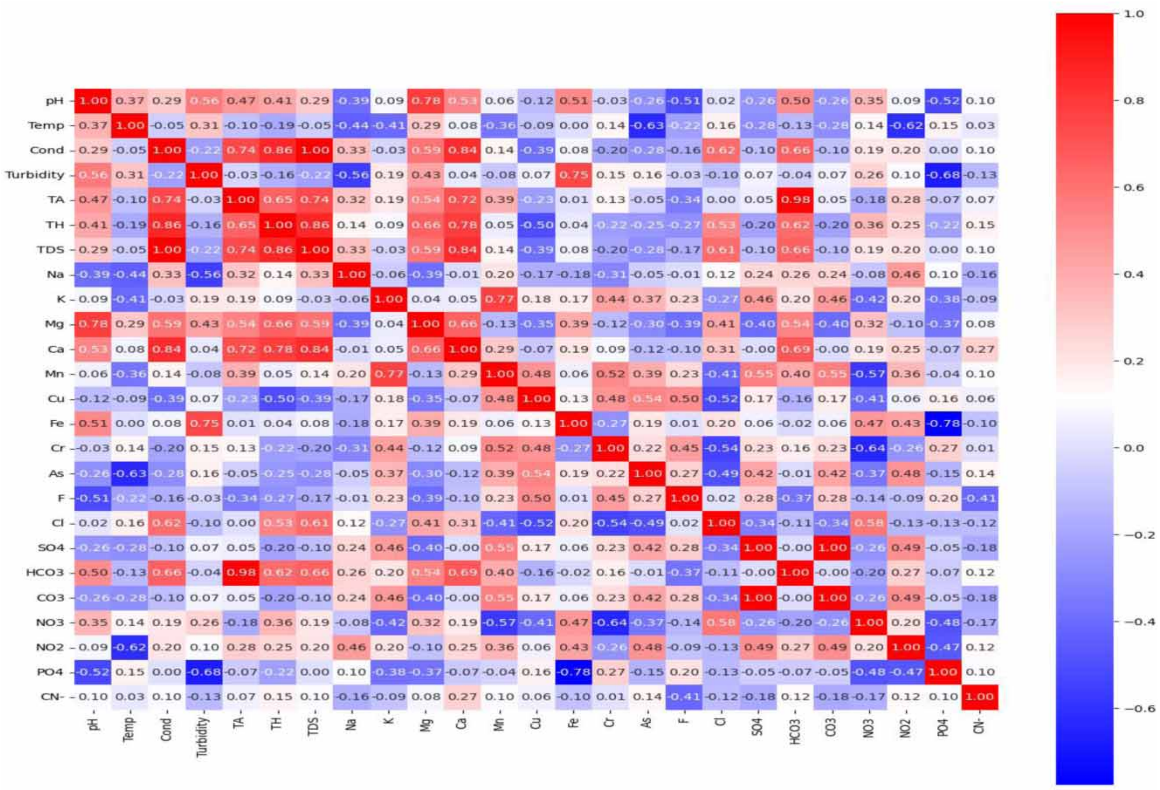
Figure 3 | Scatter plots showing the relationship between major ions.

Bivariate plots between major ions are often used by hydrogeochemists to explain groundwater geochemical processes. According to Loh *et al.* (2020), a bivariate plot between sodium and chloride ions concentration in water reveals the possible geochemical process taking place in water. Plots above the equiline suggest the possibility of halite dissolution (Loh *et al.* 2020). However, those plotted below the line could suggest either silicate weathering or the ion exchange process (Loh *et al.* 2020). As illustrated in Figure 3(a), the samples are plotted above and below the equiline. This suggests that a combination of these processes could be the mechanisms influencing groundwater chemistry in the groundwater.

To further understand the geochemical processes, a plot of sodium versus bicarbonates (Figure 3(b)) and carbonates plus sulfate versus calcium plus magnesium has been employed (Figure 3(d)). El-Rawy *et al.* (2023) reported that these plots can assist in identifying the sources of the ions. According to the report, ions plotting above the equilines of these two plots reveal reverse ion exchange between calcium, magnesium, and sodium ions (El-Rawy *et al.* 2023). However, ions plotting below the equiline of these plots could suggest ion exchange, silicate weathering, and carbonate weathering as sources of these ions. As shown in Figure 3(b) and 3(d), 53 and 47% of the samples are plotted above and below the equilines. This further confirms the observation made in Figure 3(a).

To confirm the effect of ion exchange in the Tongo town groundwater geochemical process, a bivariate plot of calcium plus magnesium minus carbonates plus sulfate versus sodium plus potassium minus chloride has been employed. According to Madhav *et al.* (2020), the sodium plus potassium minus chloride represents the amount the sodium plus potassium achieves or vanished relative to that supplied by the dissolution of chloride minerals in the water. Also, the calcium plus magnesium minus carbonates plus sulfate represents the amount of calcium or magnesium achieved or vanished relative to that supplied by calcite, gypsum, and dolomite rock minerals dissolution processes (Madhav *et al.* 2020). According to Madhav *et al.* (2020), all data would be plotted at the origin, if there is no ion exchange process occurring in the groundwater. However, a linear relationship between these ions in the bivariate plot with a slope of −1 suggests the possibility of the ion exchange process influencing groundwater chemistry (Madhav *et al.* 2020). From Figure 3(c), a clear linear relationship can be observed with the slope approximately being −1. This confirms the fact that ion exchange plays a role in controlling Tongo town groundwater chemistry.

The use of a correlation matrix to examine factors influencing the major ions' hydrochemistry of groundwater has been adopted by many researchers. Talib *et al.* (2019) reported that a good, positive correlation between magnesium and calcium with bicarbonates suggests carbonate dissolution as sources of these ions in the water. As illustrated in Figure 4, magnesium and calcium both demonstrated a good, positive correlation with bicarbonates. This suggests the dissolution of carbonates like calcite and dolomites as contributing sources of these ions in the groundwater. Furthermore, the strong, positive correlation of magnesium with calcium suggests they could be coming from the same sources. Talib *et al.* (2019) further explained that the strong positive correlation of sodium with chloride could suggest silicate weathering as the major source of these ions. Figure 4 shows that there is a weak, positive correlation between sodium and chloride, suggesting silicate dissolution as minor sources of these ions. Ion exchange could, however, be a significant source of sodium ions in the groundwater. Also, a strong, positive relationship between magnesium and calcium with sulfate suggests gypsum dissolution as sources of these ions (Talib *et al.*, 2019). As shown in Figure 4, there is a strong inverse relationship between magnesium and sulfate, while calcium shows a weak inverse relationship with sulfate. This could suggest that gypsum dissolution does not contribute these ions to the groundwater. In a report by Madhav *et al.* (2021), anthropogenic activities were highlighted as contributing sources of major ions, showing a positive, strong correlation with TDS. Figure 4 shows a good, positive correlation of TDS with magnesium, calcium, bicarbonates, and chloride. This could indicate that anthropogenic factors are contributing sources of these ions. However, sodium shows a weak, positive correlation with TDS. This suggests that anthropogenic activities could be minor sources of sodium ions in the groundwater. These observations further confirm that the major ions' hydrochemistry of groundwater in the area is controlled by combined mechanisms.



	pH	Temp	Cond	Turbidity	TA	TH	TDS	Na	K	Mg	Ca	Mn	Cu	Fe	Cr	As	F	Cl	SO4	HCO3	CO3	NO3	NO2	PO4	CN-
pH	1.00	0.37	0.29	0.56	0.47	0.41	0.29	-0.39	0.09	0.78	0.53	0.06	-0.12	0.51	-0.03	-0.26	-0.51	0.02	-0.26	0.50	-0.26	0.35	0.09	-0.52	0.10
Temp	0.37	1.00	-0.05	0.31	-0.10	-0.19	-0.05	-0.44	-0.41	0.29	0.08	-0.36	-0.09	0.00	0.14	-0.63	-0.22	0.16	-0.28	-0.13	-0.28	0.14	-0.62	0.15	0.03
Cond	0.29	-0.05	1.00	-0.22	0.74	0.86	1.00	0.33	-0.03	0.59	0.84	0.14	-0.39	0.08	-0.20	-0.28	-0.16	0.62	-0.10	0.66	-0.10	0.19	0.20	0.00	0.10
Turbidity	0.56	0.31	-0.22	1.00	-0.03	-0.16	-0.22	-0.56	0.19	0.43	0.04	-0.08	0.07	0.75	0.15	0.16	-0.03	-0.10	0.07	-0.04	0.07	0.26	0.10	-0.68	-0.13
TA	0.47	-0.10	0.74	-0.03	1.00	0.65	0.74	0.32	0.19	0.54	0.72	0.39	-0.23	0.01	0.13	-0.05	-0.34	0.00	0.05	0.98	0.05	-0.18	0.28	-0.07	0.07
TH	0.41	-0.19	0.86	-0.16	0.65	1.00	0.86	0.14	0.09	0.66	0.78	0.05	-0.50	0.04	-0.22	-0.25	-0.27	0.53	-0.20	0.62	-0.20	0.36	0.25	-0.22	0.15
TDS	0.29	-0.05	1.00	-0.22	0.74	0.86	1.00	0.33	-0.03	0.59	0.84	0.14	-0.39	0.08	-0.20	-0.28	-0.17	0.61	-0.10	0.66	-0.10	0.19	0.20	0.00	0.10
Na	-0.39	-0.44	0.33	-0.56	0.32	0.14	0.33	1.00	-0.06	-0.39	-0.01	0.20	-0.17	-0.18	-0.31	-0.05	-0.01	0.12	0.24	0.26	0.24	-0.08	0.46	0.10	-0.16
K	0.09	-0.41	-0.03	0.19	0.19	0.09	-0.03	-0.06	1.00	0.04	0.05	0.77	0.18	0.17	0.44	0.37	0.23	-0.27	0.46	0.20	0.46	-0.42	0.20	-0.38	-0.09
Mg	0.78	0.29	0.59	0.43	0.54	0.66	0.59	-0.39	0.04	1.00	0.66	-0.13	-0.35	0.39	-0.12	-0.30	-0.39	0.41	-0.40	0.54	-0.40	0.32	-0.10	-0.37	0.08
Ca	0.53	0.08	0.84	0.04	0.72	0.78	0.84	-0.01	0.05	0.66	1.00	0.29	-0.07	0.19	0.09	-0.12	-0.10	0.31	-0.00	0.69	-0.00	0.19	0.25	-0.07	0.27
Mn	0.06	-0.36	0.14	-0.08	0.39	0.05	0.14	0.20	0.77	-0.13	0.29	1.00	0.48	0.06	0.52	0.39	0.23	-0.41	0.55	0.40	0.55	-0.57	0.36	-0.04	0.10
Cu	-0.12	-0.09	-0.39	0.07	-0.23	-0.50	-0.39	-0.17	0.18	-0.35	-0.07	0.48	1.00	0.13	0.48	0.54	0.50	-0.52	0.17	-0.16	0.17	-0.41	0.06	0.16	0.06
Fe	0.51	0.00	0.08	0.75	0.01	0.04	0.08	-0.18	0.17	0.39	0.19	0.06	0.13	1.00	-0.27	0.19	0.01	0.20	0.06	-0.02	0.06	0.47	0.43	-0.78	-0.10
Cr	-0.03	0.14	-0.20	0.15	0.13	-0.22	-0.20	-0.31	0.44	-0.12	0.09	0.52	0.48	-0.27	1.00	0.22	0.45	-0.54	0.23	0.16	0.23	-0.64	-0.26	0.27	0.01
As	-0.26	-0.63	-0.28	0.16	-0.05	-0.25	-0.28	-0.05	0.37	-0.30	-0.12	0.39	0.54	0.19	0.22	1.00	0.27	-0.49	0.42	-0.01	0.42	-0.37	0.48	-0.15	0.14
F	-0.51	-0.22	-0.16	-0.03	-0.34	-0.27	-0.17	-0.01	0.23	-0.39	-0.10	0.23	0.50	0.01	0.45	0.27	1.00	0.02	0.28	-0.37	0.28	-0.14	-0.09	0.20	-0.41
Cl	0.02	0.16	0.62	-0.10	0.00	0.53	0.61	0.12	-0.27	0.41	0.31	-0.41	-0.52	0.20	-0.54	-0.49	0.02	1.00	-0.34	-0.11	-0.34	0.58	-0.13	-0.13	-0.12
SO4	-0.26	-0.28	-0.10	0.07	0.05	-0.20	-0.10	0.24	0.46	-0.40	-0.00	0.55	0.17	0.06	0.23	0.42	0.28	-0.34	1.00	-0.00	1.00	-0.26	0.49	-0.05	-0.18
HCO3	0.50	-0.13	0.66	-0.04	0.98	0.62	0.66	0.26	0.20	0.54	0.69	0.40	-0.16	-0.02	0.16	-0.01	-0.37	-0.11	-0.00	1.00	-0.00	-0.20	0.27	-0.07	0.12
CO3	-0.26	-0.28	-0.10	0.07	0.05	-0.20	-0.10	0.24	0.46	-0.40	-0.00	0.55	0.17	0.06	0.23	0.42	0.28	-0.34	1.00	-0.00	1.00	-0.26	0.49	-0.05	-0.18
NO3	0.35	0.14	0.19	0.26	-0.18	0.36	0.19	-0.08	-0.42	0.32	0.19	-0.57	-0.41	0.47	-0.64	-0.37	-0.14	0.58	-0.26	-0.20	-0.26	1.00	0.20	-0.48	-0.17
NO2	0.09	-0.62	0.20	0.10	0.28	0.25	0.20	0.46	0.20	-0.10	0.25	0.36	0.06	0.43	-0.26	0.48	-0.09	-0.13	0.49	0.27	0.49	0.20	1.00	-0.47	0.12
PO4	-0.52	0.15	0.00	-0.68	-0.07	-0.22	0.00	0.10	-0.38	-0.37	-0.07	-0.04	0.16	-0.78	0.27	-0.15	0.20	-0.13	-0.05	-0.07	-0.05	-0.48	-0.47	1.00	0.10
CN-	0.10	0.03	0.10	-0.13	0.07	0.15	0.10	-0.16	-0.09	0.08	0.27	0.10	0.06	-0.10	0.01	0.14	-0.41	-0.12	-0.18	0.12	-0.18	-0.17	0.12	0.10	1.00

Figure 4 | Correlation matrix with heatmap showing the relationship between parameters.

3.3. Hydrochemical facies

Groundwater is categorized into facies based on the prevalent ions they contain. One diagram used for this classification is the Piper diagram. The trilinear plot shown in Figure 5 represents the groundwater samples from the study area on the Piper diagram. The hydrochemical facies identified consist of $Na-Ca-HCO_3^-$, $Na-Ca-Cl-HCO_3^-$, $Na-Ca-Mg-HCO_3^-$, $Mg-Ca-HCO_3^-$, and $Na-Ca-HCO_3^-$ water facies. Figure 5 illustrates the dispersion of cation (Ca^{2+}, Mg^{2+}, and $K^+ + Na^+$) and anion (HCO_3^-, Cl^-, and $NO_3^- + SO_4^{2-}$) content in the groundwater samples from the study area. This suggests that these variables could be linked to either variations in lithology or human activities.

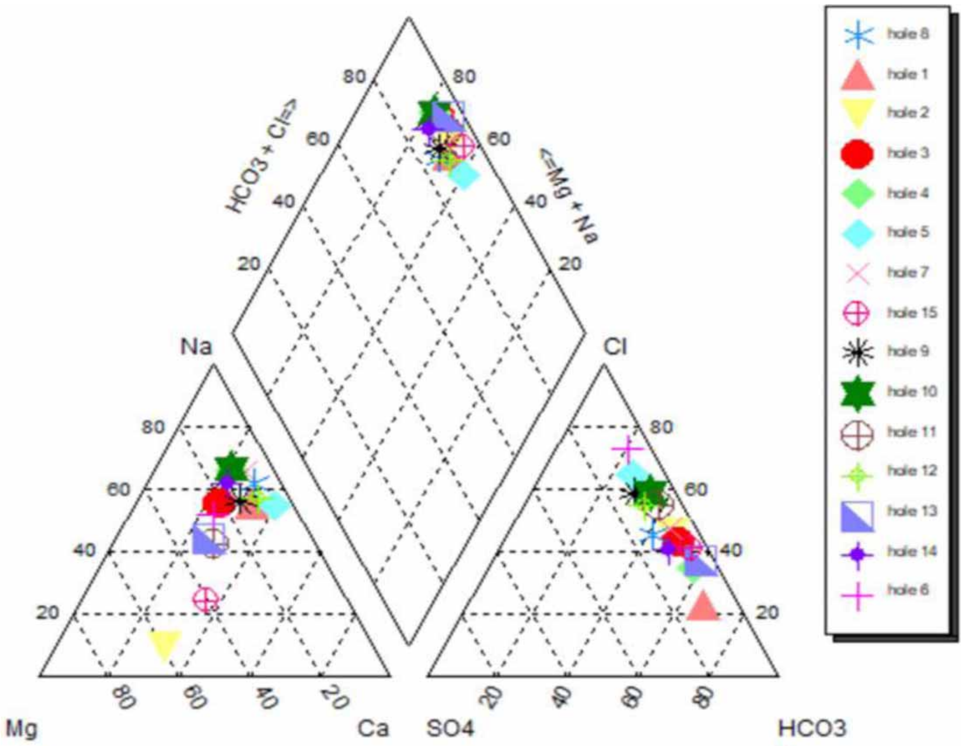


Figure 5 | Piper trilinear plot showing the distribution of major ions and various water types.

The hydrochemical facies of groundwater within the studied communities exhibit a wide range, including types like $Na-Ca-Cl-HCO_3^-$, $Na-Ca-HCO_3^-$, and $Mg-Ca-HCO_3^-$. The most prevalent type is the $Na-Ca-HCO_3^-$ facies, indicating that groundwater hydrochemistry may be influenced by interactions between water and rocks, soil characteristics, and human-generated pollution. The distribution of cations and anions tends to cluster on the ternary diagram, primarily involving ($Na^+ + K^+$), Ca^{2+}, Mg^{2+}, Cl^-, and HCO_3^-. Generally, higher concentrations of ($Na^+ + K^+$), Ca^{2+}, Mg^{2+}, Cl^-, and HCO_3^- are observed in groundwater samples collected from Korig, Zubeong, and Puhig (Figure 5). This suggests that these areas experience minimal human intervention and that natural processes are the primary sources of ($Na^+ + K^+$), Ca^{2+}, Mg^{2+}, Cl^-, and HCO_3^- in the groundwater.

3.4. Groundwater quality based on trace elements and minor ions

Table 3 presents the trace elements and minor ions data for representative groundwater samples in Tongo Town.

Table 4A presents the range, mean, and standard deviation values of some inorganic constituents in the groundwaters of Tongo Town and the WHO (2011) drinking water quality guideline values.

The lists of substances in drinking water, although not necessarily harmful to health, but may give rise to complaints from consumers, are presented in Table 4A. Table 4B lists those chemicals of health significance in drinking water according to the WHO (2011) report.

Table 3 | Trace elements and minor ions data for representative groundwater samples in Tongo town

Source	Borehole No	Cr	Fe	Mn	As	Zn	Cu	CN^-	PO_4^{2-}	NH_3	NO_3^-	NO_2^-	F^-	CO_3^{2-}
Seok-1	558	0.02	0.12	0.00	0.01	0.00	0.06	0.018	0.75	0	6.4	0.066	0.91	20.0
Seok-2	453-C15	0.02	0.12	0.00	0.00	0.06	0.02	0.01	0.74	0	9.8	0.066	0.9	24.0
Seok-3	WELL	0.00	0.16	0.00	0.00	0.02	0.05	0.017	0.67	0	10.8	0.067	0.62	20.0
Gbeogo1	1347	0.04	0.10	0.008	0.005	0.00	0.07	0.018	0.82	0	2	0.067	0.97	28.0
Gbeogo2	WELL	0.03	0.19	0.00	0.00	0.05	0.04	0.011	0.54	0	8.5	0.007	0.65	24.0
Gbeogo3	GWSC/CID	0.02	0.03	0.00	0.00	0.08	0.01	0.033	1.00	0	3.5	0.022	0.17	28.0
Korig1			3256	0.00	0.00	0.00	0.02	0.007	0.87	0	7.6	0.005	1.03	40.0
Korig2	1295	0.03	0.03	0.00	0.00	0.02	0.03	0.001	1.09	0	4.8	0.016	1.09	26.0
Korig3	453C-8	0.03	0.05	0.00	0.00	0.08	0.06	0.016	1.20	0	7.5	0.011	1.05	28.0
Puhig1		0.03	0.04	0.00	0.00	0.03	0.05	0.014	0.87	0	5.5	0.002	0.73	24.0
Tongo1	C-7	0.02	0.06	0.00	0.00	0.02	0.01	0.013	0.65	0	10.3	0.037	0.76	20.0
Tongo2	AFD199	0.02	0.08	0.00	0.00	0.04	0.02	0.022	0.87	0	9.2	0.026	0.82	24.0
Zubeong1	10512	0.01	0.13	0.00	0.00	0.03	0.00	0.015	0.66	0	10.6	0.068	0.26	38.0
Zubeong2	453-C24	0.01	0.05	0.00	0.00	0.03	0.02	0.006	0.92	0	7.3	0.027	0.28	24.0
Zubeong3	2225	0.02	0.07	0.00	0.00	0.12	0.04	0.025	1.01	0	8	0.02	0.59	22.0
WHO Guidelines (2011)		0.05	1.0	0.4	0.01	5.0	2.0	0.07	–	1.5	10	1.0	1.5	–

Units are in mg/l unless otherwise stated.

Table 4 | The range, mean, and standard deviation values of some inorganic constituents in the groundwaters of Tongo Town

Parameters	Range	Mean	Standard deviation	WHO (2011)
A				
Ammonia	0–0	0	0	1.5
Chloride	29–77	44.60	13.10	250
Iron	0.03–0.16	0.10	0.05	1
Zinc	0–0.08	0.04	0.03	5
Sodium	4.90–38.60	31.15	10.43	50
Sulfate	8.30–12.50	10.09	2.47	400
B				
Arsenic	0–0.01	0.00	0.00	0.01
Chromium	0–0.04	0.02	0.01	0.05
Copper	0–0.07	0.03	0.02	2
Fluoride	0.17–1.09	0.72	0.30	1.50
Manganese	0–0.01	0.00	0.00	0.40
Nitrate	2–10.80	7.45	2.63	10
Nitrite	0.01–0.07	0.03	0.03	1

Units are in mg/l unless otherwise stated.

3.4.1. Major ions quality of groundwater and their effects on human health

The study examined several major ions including Mg^{2+}, Na^{+}, Ca^{2+}, K^{+}, HCO_3^-, Cl^-, and SO_4^{2-}. As shown in Table 1, the concentrations of these major ions (both cations and anions) in borehole water were consistently at low levels, consistently falling below the consumption limits recommended by WHO, except for HCO_3^- and CO_3^{2-}, for which guidelines were not available. In general, the presence of these ions in drinking water does not typically pose significant harm to human health. However, they might present physiological or esthetic concerns for consumers (WHO 2011). Elevated levels of Na^+ and Cl^- beyond the WHO recommended limits of 200 and 250 mg/l, respectively, could contribute to an enhanced taste in the water (WHO 2011). According to Oyelude *et al.* (2013), excessive SO_4^{2-} levels in drinking water might lead to a bitter taste and even a mild laxative effect on some individuals. Furthermore, as indicated by Clase *et al.* (2020), potassium imbalances are frequently observed in patients with kidney disorders, particularly those with tubular issues and a low glomerular filtration rate.

3.4.2. Minor inorganic ions quality of groundwater and their effects on human health

The minor ions considered in this study are those shown in Table 4A and 4B, namely, fluoride, nitrate, nitrite, and iron. Fluoride ions within groundwater primarily originate from natural origins and, occasionally, they can stem from human activities (WHO 2011). Phosphate fertilizers having hexafluorosilicic acid (HFSA) can be a significant source of fluoride in groundwater. In this study, the fluoride ion concentration ranged from 0.17 to 1.09 mg/l with a mean of 0.72 mg/l. According to Oyelude *et al.* (2013), fluoride in drinking water is beneficial to human health as it reduces tooth decay. However, high concentrations may lead to dental and skeletal fluorosis (Oyelude *et al.* 2013). Li *et al.* (2021) also confirmed that fluoride is crucial in trace concentrations for promoting dental health but could be harmful when present in water at high concentrations. The maximum allowable fluoride concentration is 1.5 mg/l (WHO 2011). As shown in Table 4A, fluoride concentrations in boreholes and wells in Tongo Town are generally low and mostly below the range beneficial for human health (0.3–1.5 mg/l). That said the fluoride needs of the people of Tongo Town should be met with other sources such as toothpaste to prevent dental fluorosis from occurring. On the contrary, problems related to high fluoride concentrations due to drinking from groundwater sources are unlikely to occur in the town. Nitrate-N and nitrite levels recorded in groundwater in Tongo Town ranged from 2.00 to 10.80 and 0.01 to 0.01 mg/l, respectively, with a mean of 7.45 and 0.03 mg/l, respectively. High nitrate levels in drinking water can lead to methemoglobinemia (blue baby syndrome) in newborns under the age of four and in adults with particular enzyme deficiencies (Bani 2015). Also, Karwowska & Kononiuk (2020) reported that an increase in the amount of reactive nitrogen species could cause nitrosative stress. A nitrosative stress is a deleterious mechanism that can be a significant mediator of damage to cell structures, as well as lipids, membranes, DNA, and proteins (Karwowska & Kononiuk 2020). The nitrate concentration in the groundwater of Tongo Town is found to consistently fall below the maximum allowable limit except in few places like Seok well, Zubeong borehole number one, and Tongo borehole number one which were above the maximum permissible limit. That is, the threat to health from methemoglobinemia and nitrosative stress could be very low except for groundwaters from Seok well, Zubeong borehole number one, and Tongo borehole number one. Treatment through membrane filtration or ion exchange and other processes may rehabilitate these boreholes and well. Also, prevention, such as reduced dependence on nitrogen-rich fertilizers, putting a stop to open defecation, and burying dead bodies away from boreholes locations or wells can lower the influx of nitrates to groundwaters in the Tongo Town.

Piskin *et al.* (2022) reported that iron is an essential element to the human body owing to its participation in several functions like oxygen transport, cell division and differentiation, immunity, and energy metabolism. The soluble ferrous ion (Fe^{2+}) is the most common form of iron in the pH range of urban groundwater. When Fe^{2+} is exposed to air, it oxidizes to Fe^{3+}. It hydrolyzes and precipitates as iron hydroxide in this state, causing a brown discoloration of the water as well as the characteristic brown stains in sinks and washed fabrics. Furthermore, Fe^{3+} imparts a metallic flavor to the water. According to WHO (2011), the maximum allowable concentration of 0.30 mg/l in drinking water is primarily for taste and to avoid stains on sinks and washed textiles. However, an upper limit of 1.00 mg/l should be sufficient for most purposes (WHO 2011). Because iron concentrations in Tongo Town groundwater are well below the WHO recommended limit, the town may not face any iron-related problems.

3.4.3. Trace elements quality of groundwater and their effects on human health

Contrary to what one might expect from a mining area, the trace metal contamination of Tongo Town's groundwater is relatively low. High Mn concentrations in groundwater can cause problems with taste and discoloration, as well as scale buildup in pumps and pipes. Mn can cause headaches, apathy, irritability, insomnia, and leg weakness in high doses. Long-term heavy exposure can cause nervous system disorders. The oxide hydrate forms black stains in sinks and also stains washed textiles. As reported by the Minnesota Department of Health (2016), manganese also supports the growth of iron bacteria as well as impart taste, odor, and turbidity problems in water. The manganese concentration ranged from 0.0 to 0.01 mg/l with a mean of 0.00. In general, the Tongo Town groundwater recorded a low Mn concentration. Therefore, groundwaters in Tongo Town are free from problems related to Mn in drinking water.

The International Agency for Research on Cancer, the WHO, and the US-EPA categorized arsenic (As) as a known carcinogen and toxin (WHO 2011). Kuivenhoven & Mason (2023) cited that chronic arsenic poisoning is a world concern affecting people everywhere through exposure to contaminated drinking water. The report also highlights that classic acute toxicity of arsenic causes gastroenteritis followed by hypotension, dehydration, and volume loss (Kuivenhoven & Mason 2023). Acute arsenic poisoning may also cause cough, chest pain, proteinuria, hematuria, and renal failure (Kuivenhoven & Mason 2023). The arsenic concentration ranged from 0.0 to 0.01 mg/l with a mean of 0.001 mg/l. Thus, groundwater in Tongo Town is safe for arsenic as its arsenic concentrations are consistently below the WHO recommended limit.

Zinc is a natural mineral found in many drinking waters. According to Sangeetha *et al.* (2022), zinc is an essential micronutrient for human growth and the immune system. Inadequate dietary zinc causes about 116,000 deaths annually worldwide (Sangeetha *et al.* 2022). Sangeetha *et al.* (2022) also reported that the National Institute of Health (NIH) recommended daily intake of zinc to be 8 mg for adult females and 11 mg for adult males. About 3,000 proteins are zinc-dependents, namely transcription factors and signaling enzymes that are present at all stages of signal transduction (Sangeetha *et al.* 2022).

On the other hand, excess concentration of zinc can cause esthetic effects on water and also impart metallic taste. For these reasons, the WHO (2011) recommended a limit value of 5.0 mg/l for drinking water. Zinc concentrations in groundwater in Tongo Town were consistently below the WHO recommended limit. The zinc concentration varied between 0.00 and 0.10 mg/l with a mean value of 0.03 mg/l. That is, zinc does not pose a water quality problem for groundwater supply and development in Tongo Town.

Copper concentration ranged from 0.0 to 0.07 mg/l with a mean of 0.03 mg/l. As such, all groundwater samples are consistently below the permissible WHO recommended limit of 2.0 mg/l for water carrying capacity. Therefore, copper poses neither physiological nor esthetic problems for groundwater quality in Tongo Town.

3.5. Microbial condition of groundwater in the study area

The outcomes regarding the microbial state of the groundwater samples employed in the investigation are showcased and deliberated upon. The findings of the laboratory assessments are displayed in Table 5, while Table 6 presents the computed proportions of the diverse parameters pertaining to microbiological quality identified within the water samples.

Table 5 | Microbiological quality parameters

Source	**Borehole No**	**Total coliform**	**Fecal coliform**	***E. coli***	**Salmonella**
Seok-1	558	0	0	0	0
Seok-2	453-C15	53	0	34	9
Seok-3	WELL	0	0	0	0
Gbeogo1	1347	0	0	0	0
Gbeogo2	WELL	107	44	103	19
Gbeogo3	GWSC/CID	0	0	0	0
Korig1	3256	0	0	0	0
Korig2	1295	0	0	0	0
Korig3	453C-8	0	0	0	0
Puhig1		0	0	0	0
Tongo1	C-7	0	0	0	0
Tongo2	AFD199	69	0	5	1
Zubeong1	10512	50	0	117	0
Zubeong2	453-C24	40	0	0	0
Zubeong3	2225	77	100	44	0
WHO (2011)		0	0	0	0

Units are in cfu/100 mL unless otherwise stated.

Table 6 | Bacteria quality parameters and their percentages

Parameters	**Total percentage**
Total coliform	40
Fecal coliform	13
E. coli	33
Salmonella	20

Coliform bacteria are consistently present in the gastrointestinal tracts of various animals, including humans, and are also found in their waste. These bacteria are also detected in plant matter and soil. Identifying TC in water samples serves as an indicator of potential bacterial contamination or pollution. These pollution indicator bacteria, referred to as TC, were generally below the WHO threshold of 0 cfu/100 mL, except for Seouk well number one, Gbeogo well, Tongo well number two, and Zubeong well numbers one to three. The TC counts for these wells ranged from 0 to 107 cfu/mL, accounting for 40% of the total count. Elevated TC levels in all water samples can be attributed to a variety of human activities, including inadequate sanitation practices in various communities, uncontrolled defecation, establishment of burial sites near wells, and the use of organic fertilizers on farms near well sites. Additionally, improper disposal of household waste, poor borehole development practices leading to water accumulation during rainfall, positioning of septic tanks near boreholes due to space constraints, leakages from poorly constructed septic tanks, and construction on old landfill sites contribute to waste and effluent seepage into boreholes, as well as the introduction of animal waste into water sources.

These elevated levels signify a substantial and escalating risk of transmitting infectious diseases when using the water for domestic purposes. Therefore, water from these wells is considered unsafe for drinking and household use. To ensure safety, water from these wells should be disinfected before consumption, either through boiling or using chemical disinfectants like hypochlorite (commonly known as bleach), as high levels of TC are indicative of fecal contamination. FC bacteria typically constitute 93–99% of the coliform bacteria present in the feces of humans, poultry, cats, dogs, and rodents. FC ranged from 0 to 100 cfu/mL, and *E. coli* counts ranged from 5 to 117 cfu/mL, constituting 13, 33, and 20%, respectively. Most boreholes adhered to WHO recommended limits, with exceptions including Gbogo well number two, Seok well number two, Tongo well number two, and Zubeong well number three. This study attributes the higher prevalence of fecal indicators to human activities, particularly poor sanitation practices across various communities, unregulated defecation, the establishment of burial sites near well locations, and the use of organic fertilizers on farms adjacent to well sites. Water samples from these wells are unsuitable for both drinking and household use. As a precautionary measure, water from these wells should undergo disinfection before being used, either through filtration or the application of chemical disinfectants like hypochlorite (commonly referred to as bleach). Table 6 illustrates the distribution of distinct bacterial quality parameters in the collected groundwater samples from Tongo Town.

4. CONCLUSIONS AND RECOMMENDATIONS

The groundwater in Tongo Town predominantly contains low levels of main ions, making it suitable for drinking water without quality concerns. Overall, minor and trace elements are also present at low concentrations, with no significant potential quality issues. However, in certain wells such as ZB(B1), KW(B3), and TO(B1) with ID numbers 10512, 453C-8, and C-7, elevated nitrate concentrations exceed the WHO recommended limits, posing a physiological risk. This problem seems to arise from human activities and can be mitigated by discontinuing the use of organic fertilizers near the wells, ensuring proper sanitation practices, and refraining from burying bodies in proximity to the wells. Regarding bacterial quality analysis, most wells adhere to WHO guidelines, except for Gbeogo, SB(B2), TO(B2), and ZB(B3) with well IDs 453-C15, C-7, and 2225. These wells display contamination with TC, FC, *E. coli*, and salmonella, indicating that their water is unfit for consumption. Disinfection is necessary through filtration or using chemical agents like hypochlorite. Geochemical assessment indicates that the groundwater is generally fresh, ranging from soft to moderately hard. The hydrochemical facies – $\mathrm{Na - Ca - Cl - HCO_3^-}$, $\mathrm{Na - Ca - HCO_3^-}$, and $\mathrm{Ca - Mg - HCO_3^-}$ underscore the impact of water–rock interaction, soil properties, ion exchange, and anthropogenic activities. Concentrations of ($\mathrm{Na^+ + K^+}$), $\mathrm{Ca^{2+}}$, $\mathrm{Mg^{2+}}$, $\mathrm{Cl^-}$, and $\mathrm{HCO_3^{2-}}$ were notable in Korig, Zubeong, and Puhig wells, with both human interference and natural processes contributing to their presence. Evidence of ion exchange emerges from bivariate plots, scatter plots, and correlation matrix, emphasizing the interplay between various ions like calcium, magnesium, carbonates, sulfates, sodium, and potassium. To gain a comprehensive understanding of contaminant sources, further research is advised on groundwater recharge sources and seasonal patterns. Employing modeling techniques can aid in the effective management of groundwater resources within the region.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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