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Research article

Contamination of groundwater by petroleum hydrocarbons: Impact of fuel stations in residential areas

Bernard Fei-Baffoe, Esther Badu, Kwodwo Miezah, Lyndon Nii Adjiri Sackey, Alhassan Sulemana, Ebenezer Ebo Yahans Amuah *

Department of Environmental Science, Faculty of Biosciences, Kwame Nkrumah University of Science and Technology, PMB, Kumasi, Ghana

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ABSTRACT

Anthropogenic factors such as leakages from fuel storage facilities contribute to the release of petroleum hydrocarbons into groundwater. Following the proliferation of fuel stations in residential areas, this research assessed physicochemical parameters, salinity, and levels of total petroleum hydrocarbons (TPH) in groundwater sources within selected residential areas. From the study, mean values of temperature (30.5 °C), pH (5.8), EC (181.5 μs/cm), TDS (90.7 mg/L), and salinity (0.1 ppm) were recorded. The highest mean concentration of TPH (9.5 mg/L) was recorded at location A, while three sampling points (J, L, and M) exhibited 0.0 mg/L. Notably, TPH concentrations exceeding permissible limits were observed at three sampling points (A, B, and R). Strong positive correlations were observed between EC and TDS ($r = 0.9$), as well as salinity and EC ($r = 0.9$) and TDS ($r = 0.9$). Matrix plots demonstrated non-linear relationships, except for TDS and EC, although TPH and temperature exhibited a slightly linear pattern. The distance from USTs to the groundwater sources varied in the area. At location H, this distance (25 m) was measured as the shortest, where the mean TPH concentration was 3.71 mg/L. However, site Q exhibited the longest distance of 535 m, accompanied by a mean TPH concentration of 1.1 mg/L. Though the proximity of USTs to groundwater sources exerted some level of influence on the groundwater system, multiple linear regression, ANOVA, and cluster analysis showed that this did not pose direct and major impacts on the concentrations of TPH. However, approaches are needed to remediate the affected groundwater sources.

1. Introduction

Water stands an indispensable resource for the sustenance of life on Earth, serving as a vital resource for both flora and fauna. Its availability and quality have always played a crucial role in the well-being and development of humanity. A country's water resources represent one of its most valuable economic assets [1]. However, human activities pose significant threats to the environment, leading to degradation, destruction, and the depletion of ecological infrastructure [2,3]. Of particular concern is the pervasive and often irreversible pollution of groundwater, as its replenishment rate is considerably slower than that of surface water [4].

Groundwater contamination arises from various sources that are extensive in scope. These sources include unintentional spills, saltwater intrusion, the improper management of landfills, injection wells, surface waste ponds, underground storage tanks, the application of waste and pesticides on land, pipelines, septic tanks, the disposal of radioactive waste, and the release of acidic drainage

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* Corresponding author.
E-mail address: amuahyahans@gmail.com (E.E. Yahans Amuah).

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from mines [1,5,6]. In recent years, the proliferation of numerous fuel stations has increased the potential for leakages from underground fuel storage tanks, resulting in significant adverse environmental impacts worldwide. Gasoline, diesel fuel, waste oil, and other toxic materials found in petroleum products that seep from leaking underground storage tanks (LUSTs) into environmental media can disrupt children's development and cause injury to the neurological and reproductive systems of adults when consumed. They also contain hazardous compounds and recognized carcinogens. Proximity to a leaking UST or consumption of water from a well contaminated by petroleum products can pose serious health threats to vulnerable individuals, particularly children [7,8]. Petroleum products consist of various potentially toxic compounds, including solvents like alkanes, cycloalkanes, alkenes, benzene, aromatics, toluene, xylene, and additives like ethylene dibromide (EDB) and organic lead compounds. EDB for instance is a known carcinogen while benzene is considered a human carcinogen [9,10]. Methyl tertiary-butyl ether (MTBE), used as a fuel oxygenate to reduce air pollution and increase octane ratings, is frequently detected in shallow groundwater samples from urban areas across the United States [11].

Underground fuel tanks represent a significant source of groundwater contamination due to their lifespan of 15–25 years, with an increased likelihood of leakage as they age [12,13]. When there are leaks, fuel permeates the soil and ultimately makes its way into the groundwater. Even a small leakage rate of two drops per second can render nearly half a billion gallons of water unfit for drinking due to odour and taste issues [9]. The time required for leaked fuel to reach the groundwater is influenced by factors such as soil composition, geology, hydrology, and the distance between the fuel source and the underlying aquifer. Once fuel infiltrates the groundwater, it tends to accumulate due to its limited ability to evaporate compared to surface environments. Furthermore, fuel is not easily biodegradable by microorganisms, and groundwater movement is slow, resulting in the persistence and buildup of contaminants in the water [14]. Remediation techniques following such contamination are often complex and expensive. Therefore, considering the vulnerability of groundwater to pollution and its crucial role in direct and indirect human consumption, it is imperative to establish a robust and consistent policy framework to address water pollution [15,16].

The Kumasi area is characterized by an entanglement of challenges since Darko et al. [17], Joy Online [18] and Boateng et al. [19] respectively reported that it is the second largest and most populated city in Ghana, given the alarming proliferation of unauthorized fuel stations and the significant reliance of a considerable population on groundwater sources, it becomes imperative to identify and assess the sources of groundwater contamination, as well as determine their impacts on groundwater quality. This study aims to comprehensively evaluate the concentrations of hydrocarbons in groundwater by delineating the fuel stations and their storage facilities, examining the proximity of groundwater sources to fuel storage facilities near fuel stations, quantifying the distances between underground fuel storage tanks and the collected groundwater, and establishing relationships between these factors and the concentrations of TPH in the studied groundwater samples. Additionally, the study aims to investigate the physicochemical parameters of samples from groundwater sources near fuel storage facilities around fuel stations.

2. Materials and methods

2.1. Study area description

The study was conducted in the Kumasi Metropolitan Area (KMA) (Fig. 1), which serves as the capital of the Ashanti region in Ghana. Kumasi, located in the southern part of the country, is a rapidly developing city characterized by a high population growth rate and an increasing concentration of automobiles to facilitate smooth urban mobility [20,21]. The city has witnessed a surge in the establishment of numerous fuel stations across its expanse in recent years [22]. Geographically, the Kumasi metropolis is situated

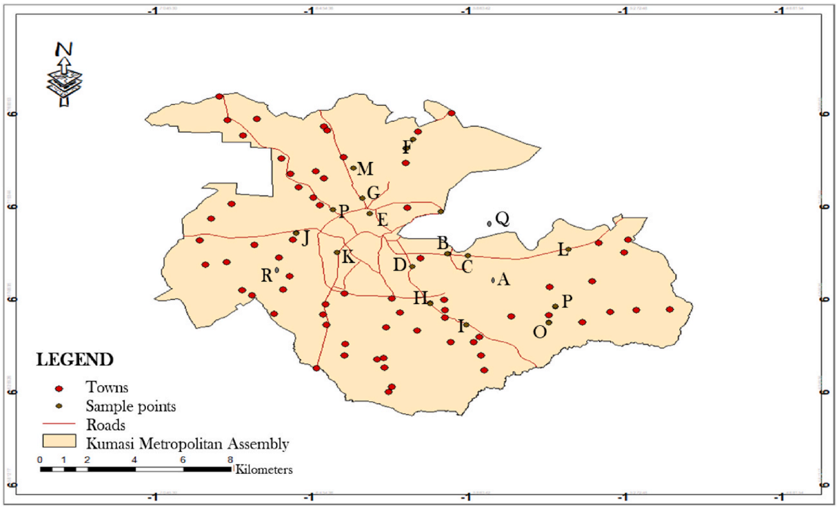


Fig. 1. Point locations within the study area.

centrally within the Ashanti region, approximately 300 km northwest of Accra. It is located between latitude 6.38° N and 6.45° N, and longitude 1.41° W and 1.32° W and has an elevation of 250 m–300 m above sea level [21]. The northern border of Kumasi adjoins the Kwabre district, while the southern border is shared with the Bosomtwe-Kwanwoma district. To the west lies the Ejisu Municipality, and to the east, the Atwima district acts as its boundary [23,24]. Encompassing an area of 214.3 km^2, the Kumasi metropolitan area serves as a vital link between the northern and southern regions of Ghana.

2.2. Geological, topographical, and geo-hydrological properties of the area

The Kumasi metropolitan area's main topography is made up of undulating land with modest slopes ranging from 5° to 15°. At a height of around 282 m on a local watershed, Kumasi is elevated above the surrounding peri-urban area, which ranges in elevation from 250 to 300 m. Within the city, the terrain has a few ridges and a few fairly mountainous sections. It is an advanced dissection of surfaces with tertiary erosion [25,26]. Geologically, the region falls under the Forest Ochrosol great group. It belongs to the South-West physical region plateau, positioned at an elevation of 250–300 m above sea level. The topography exhibits undulating characteristics. The area predominantly consists of strongly foliated and jointed Birimian rocks, which, when exposed or located near the surface, the joints, cracks, and other apertures permit large water percolation [27]. This shows that secondary permeability rather than intrinsic permeability exists in the granitic rocks associated with the Birimian rocks (Fig. 2). Therefore, the increase in porosity through jointing, fracturing, and weathering helps to explain why wells within the Kumasi granitic rocks have considerably greater mean groundwater yields [27]. The city is drained by a complex network of streams and is located within the Pra basin. These dendritic-patterned streams, which include the Daban, Subin, Aboabo, Wiwi, and Santang streams, often run from north to south. According to Dickson et al. [28], they originate from the Sisa, Oda, Sokoban, and Owabi rivers, and their valleys have flat bottoms. To the south of Kumasi, about 9 km, these streams merge to form the Sisa River, which eventually merges with the Oda River. In a small portion of the northwestern area of the city, there is a mass of repair facilities for vehicles, water drains northwestward into the Owabi dam's catchment, which then empties into the Offin River [29].

2.3. Research design

The cluster sampling and purposive sampling methods were used. The metropolis was zoned into ten clusters. A purposive sampling was used to collect 72 groundwater sources in the transitional period between the wet and dry seasons. This translates as eighteen (18) composite groundwater samples for the survey (4 closest groundwater systems from each fuel station). Fig. 3 shows the map of Kumasi city with fuel stations around which groundwater sources were taken for this study. This map indicates the locations of some of the fuel stations found in the metropolis. The fuel stations included Unity Oil, Shell, Pacific Oil, Sky Oil, Modex Oil, Engen Oil, Total, and Top Oil. However, the specific names of the fuel stations were coded to ensure anonymity.

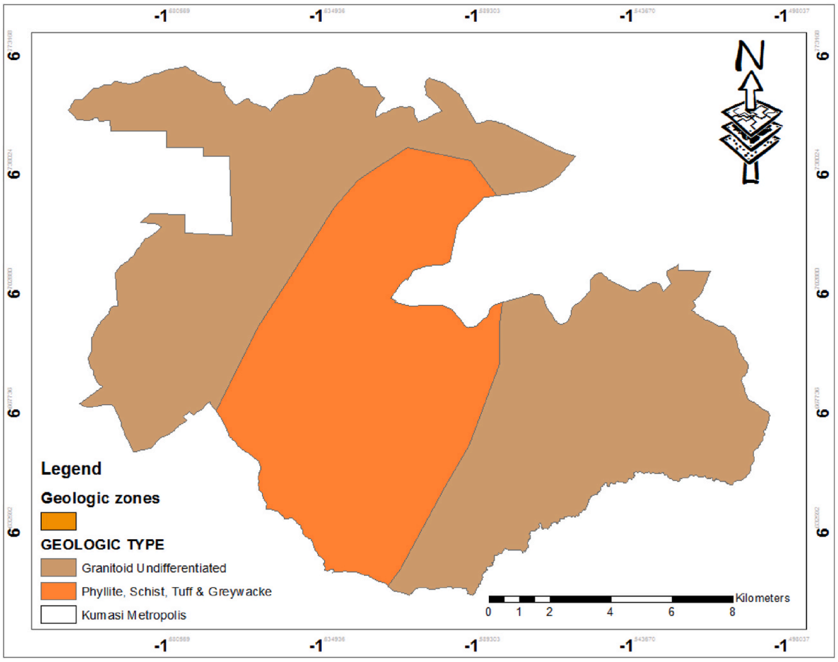
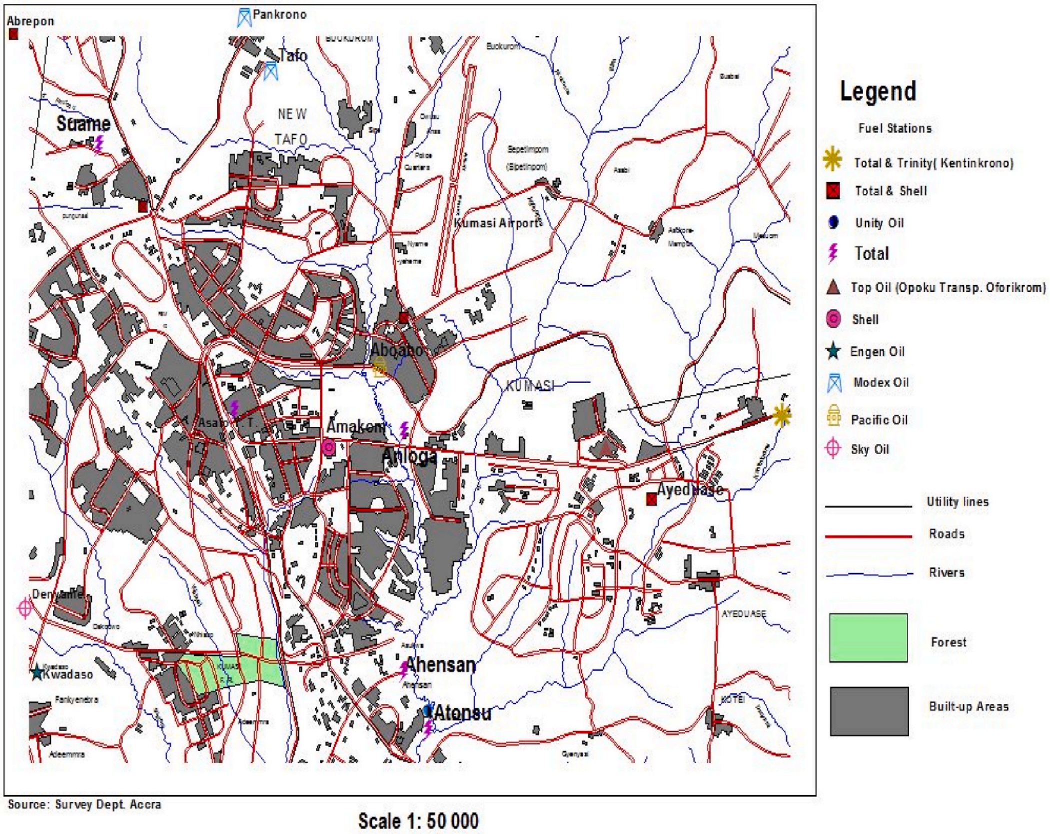


Fig. 2. Geological characteristics of the Kumasi Metro.



Source: Survey Dept. Accra

Fig. 3. Locations of selected fuel stations in the Kumasi Metropolis.

2.3.1. *Distance from groundwater sources to fuel storage tanks*

The spatial data required to determine the distances between fuel storage facilities and the chosen groundwater sources were acquired utilizing ArcGIS 10.3. The geographical coordinates and spatial attributes of the fuel storage facilities and groundwater sources were integrated into the GIS platform. The data were georeferenced and processed to create accurate spatial locations of the facilities and groundwater sources. Subsequently, the GIS functionalities were employed to calculate the distances between these two sets of geographical points, ensuring precision and reliability in determining the spatial relationship between the fuel storage facilities and the identified groundwater sources.

2.3.2. *Collection of groundwater samples*

A total of 72 groundwater sources located in the vicinity of eighteen (18) fuel stations within the study area were selected for water sample collection. At best, the siting was done by considering the water sources at the four cardinal points of each station. The water samples were specifically obtained from pre-existing private boreholes and wells. To facilitate the collection process, 1.5-litre plastic bottles were utilized as the designated containers. At each collection point, the samples were carefully labelled and promptly stored in an ice chest to maintain their integrity until transportation to the laboratory. To ensure accuracy, duplicate samples were also taken. Before sampling, the bottles were properly prepared by rinsing them with distilled water followed by the water to be sampled. Adequate headspace was provided within the bottles to allow for any expansion of the water.

2.3.3. *Measuring physicochemical parameters and TPH of groundwater*

Physicochemical parameters: pH, salinity, temperature, total dissolved solids (TDS), and electrical conductivity (EC) were measured on-site following the guidelines outlined by the American Public Health Association [30] Bekoe et al. [5] and Kpiebaya et al. [31]. pH measurement was done with a calibrated Hanna 3910 pH meter, temperature with a digital thermometer (Checktemp®CL), EC with Hanna 2210 EC m and TDS with Hanna 103 TDS meter. Following de Azevedo et al. [32], **s**alinity was measured with a refractometer (Atago S/Mill-E, Atago Co. Ltd., TokyoTokyo, Japan). While various analytical methods, including gravimetric, immunoassay, and gas chromatography (GC), can be employed to quantify TPH in water, this study utilized GC analysis in conjunction with a Flame Ionization Detector (FID) to analyze TPH in the extracted oil samples [33]. This specific GC method enabled the measurement of hydrocarbons within the C9 to C36 range. To convert the total peak area of a chromatograph into a TPH concentration, the mean response factor of alkanes was applied. It is important to note that in this method, the calculated TPH includes the organic compounds present in the extracted organic phase and those detected by the FID within the chromatographic column. The conditions employed for GC analysis are detailed in Table 1. The analysis procedure began with a solvent blank, followed by calibration verification using a standard mixture of n-alkanes covering the C9 to C36 range of hydrocarbons. Working concentrations of 500 mg/L were prepared for both the calibration verification standard and the oil extracts, following the protocols established by the Environmental Research Institute [34]. The procedure showed a recovery rate ranging between 64.8% and 81.4%.

2.4. *Quality assurance and control*

Quality control and assurance were meticulously implemented throughout the sampling and analytical procedures. The sampling apparatus underwent a rigorous cleaning process, starting with laboratory-grade detergent and distilled water followed by triple rinsing with Milli-Q water. Subsequently, thorough rinsing with methanol, Capillary GC pesticide residue grade methylene chloride, and air-drying were carried out before their application. All in-situ equipment utilized in the study underwent precise calibration to ensure accuracy and reliability in measurements. System calibration verification included a comprehensive assessment with a minimum of three linear concentration points within the calibration range. Zero analyte samples, known as blanks, were consistently run alongside duplicate samples to assess any potential bias. Hydrocarbon analyses via GC had detection limits set at 0.00001 ppm, by established protocols [35].

2.5. *Statistical analysis*

To examine the association between the distance separating fuel storage tanks and groundwater sources, as well as the corresponding TPH concentrations in the groundwater, a Spearman's correlation analysis was performed. This particular correlation analysis was chosen due to the non-normal distribution of the data, rendering it inappropriate to employ traditional parametric correlation methods. Descriptive statistics, factor and covariance-variance analyses, matrix and contour plots, multiple linear regression, cluster analysis, and ANOVA were done using Minitab (21.1.0), SPSS (v 27) and Microsoft Excel (2019).

3. Results and discussion

3.1. *Effects of temperature and pH on groundwater contamination by hydrocarbons*

The recorded temperature values ranged from 28.7 °C at location A to a maximum of 31.9 °C at point L. The permissible limit for temperature in drinking water, as established by WHO/UNICEF [36], is 29.0 °C. Only samples collected from site A fell within this acceptable range, while the remaining seventeen (17) sampling points exceeded the limit (Table 2). Temperature is a critical factor affecting aquatic ecosystems, as it influences the physical and chemical properties of water, as well as the organisms inhabiting it. Groundwater temperature typically aligns closely with the mean air temperature above the land surface and remains relatively stable throughout the year. This observation is consistent with previous findings by Norris and Spieker [37]. The obtained mean temperature values corresponded to the ambient temperature of the KMA at the time of sampling, which is influenced by solar radiation and other environmental factors [38].

In terms of pH, the lowest recorded value was 4.8 at site K, while the highest value of 7.0 at location H (Table 2). The permissible range for pH in drinking water, according to USEPA [39], is 6.5–8.5. However, 89% of the sampled sites exhibited very low pH values, some as low as 4.8, indicating excessive acidity which make them unsuitable for human consumption. Low pH values can produce a metallic taste frequently associated with some groundwater sources, while high pH levels may cause the water to taste bitter. Ayotamuno and Kogbara [40] also reported similar findings regarding the pH levels of groundwater and their impact on taste. Meanwhile, a majority of the population in these areas rely on groundwater for drinking and domestic purposes.

The presence of dissolved acidic salts in the groundwater samples suggests a potential association with the characteristics of the groundwater at the sixteen sampled locations. Movement of such salts from the soil surface to groundwater may occur through seepage, as groundwater pollution can transpire via pollutant seepage and migration from the soil surface. The high infiltration and permeability of sandy loam soils in the area facilitate the leaching or rapid movement of contaminants from the surface into the subsurface, thereby contributing to groundwater contamination. Ayotamuno and Kogbara [40] provide evidence supporting the idea that contaminants present on the soil surface have the potential to percolate through the subsurface and contaminate groundwater sources.

Table 1
Conditions for GC analysis.

Parameter	Condition
Initial temperature	50 °C (hold for 0.2 min)
Final temperature	270 °C (hold for 20 min)
Injector temperature	270 °C
Detector temperature	300 °C
Carrier gas flow rate	1.0 ml/min
Program	50 °C–300 °C at 5 °C/min
Make-up gas	28 ml/min

Table 2
Results of physicochemical parameters.

Location	Temperature (^{o}C)	pH	EC (μs/cm)	TDS (mg/L)	Salinity (ppm)	TPH (mg/L)	Distance (m)
A	28.7 ± 63	6.5 ± 26	519.5 ± 43	260.2 ± 16	0.3 ± 13	9.5 ± 18	185.4 ± 50
B	29.8 ± 15	5.4 ± 31	370.3 ± 06	185.7 ± 72	0.2 ± 45	6.1 ± 34	205.0 ± 14
C	30.0 ± 87	6.5 ± 14	123.0 ± 09	61.5 ± 34	0.1 ± 16	3.8 ± 23	85.4 ± 28
D	31.5 ± 63	6.7 ± 32	427.3 ± 35	213.8 ± 12	0.2 ± 30	2.1 ± 27	112.0 ± 31
E	30.3 ± 19	5.0 ± 18	94.3 ± 16	47.5 ± 18	0.1 ± 24	1.4 ± 12	100.1 ± 14
F	30.8 ± 07	5.5 ± 20	102.5 ± 12	51.6 ± 67	0.2 ± 38	1.6 ± 16	235.3 ± 18
G	31.1 ± 81	5.2 ± 12	237.8 ± 25	118.8 ± 19	0.1 ± 26	2.4 ± 21	358.5 ± 22
H	30.5 ± 73	7.0 ± 08	142.0 ± 38	71.0 ± 13	0.1 ± 03	3.7 ± 32	25.0 ± 25
I	31.2 ± 42	5.5 ± 17	91.3 ± 27	46.2 ± 64	0.1 ± 11	1.5 ± 27	56.2 ± 34
J	31.6 ± 67	5.5 ± 28	224.0 ± 41	112.2 ± 81	0.1 ± 18	0.0 ± 00	486.1 ± 15
K	31.2 ± 09	4.8 ± 26	198.3 ± 17	99.3 ± 03	0.1 ± 07	2.2 ± 17	403.1 ± 27
L	31.9 ± 01	5.2 ± 28	122.1 ± 14	61.5 ± 51	0.2 ± 18	0.0 ± 0.00	200.1 ± 35
M	30.8 ± 10	5.1 ± 13	128.3 ± 18	64.3 ± 23	0.1 ± 04	0.0 ± 0.00	350.4 ± 18
N	31.2 ± 14	5.4 ± 19	169.6 ± 23	85.0 ± 36	0.2 ± 10	0.4 ± 11	105.2 ± 26
O	29.2 ± 19	5.7 ± 07	78.5 ± 03	39.3 ± 28	0.1 ± 18	0.0 ± 20	218.1 ± 14
P	30.0 ± 35	6.1 ± 15	24.5 ± 32	10.0 ± 22	0.1 ± 08	0.9 ± 15	45.5 ± 12
Q	30.0 ± 23	6.2 ± 03	36.5 ± 19	18.5 ± 12	0.1 ± 12	1.1 ± 10	535.1 ± 09
R	29.5 ± 27	6.2 ± 31	176.5 ± 28	88.3 ± 05	0.1 ± 27	9.3 ± 41	110.1 ± 19
Permissible limits	**29.0**	**6.5–8.5**	**1500**	**1000**	**200**	**5.0**	**30.80**

Although the pH of drinking water is not typically a health concern, acidic water (low pH) can facilitate the leaching of metals from underground storage tanks, leading to potential health issues. The observed low pH of the water samples could potentially be attributed to the presence of TPHs and other contaminants. When hydrocarbons are immiscible in water, the pH of the original water may remain unaffected. However, as Ayotamuno and Kogbara [40] suggested, certain types of hydrocarbons can introduce hydrogen ions when mixed with water, potentially increasing the pH of the water. The pH of the water depends on the availability of hydrogen ions within the hydrocarbon-water mixture. The analysis demonstrated a direct relationship (correlation coefficient of 0.4) between the pH of the water samples and TPH concentrations. This suggests that as TPH concentrations in the water samples increased, there was a concurrent rise in the pH of the groundwater.

The findings of this study carry important implications for water quality, public health, and the environment in the studied areas. Excessive temperatures beyond recommended limits indicate potential concerns about water safety and quality, particularly for a population relying on groundwater for domestic use. The prevalence of low pH values raises issues related to water taste and the risk of leaching metals from underground storage tanks, potentially leading to groundwater pollution. These challenges necessitate immediate attention and interventions to ensure the provision of clean, safe, and palatable drinking water. Moreover, the correlations observed between temperature, pH, and hydrocarbon contamination emphasize the need for continuous water quality monitoring and public health protection measures. Future research should focus on comprehensive, long-term studies to better understand and mitigate these issues.

3.2. *Influence of EC and TDS on groundwater contamination by hydrocarbons*

The acceptable limit for EC in drinking water, according to WHO/UNICEF [36], is 1000 μs/cm. However, the mean EC values varied between 24.5 μs/cm at location P and 519.5 μs/cm at point A (Table 2). TDS levels varied across the study sites, with the highest recorded at site A (260.2 mg/L) and the lowest at location P (10.0 mg/L). However, all measured TDS values remained below the permissible limit of 1000 mg/L. Salinity levels, which determine water quality for drinking purposes, were also within acceptable limits, with the highest mean salinity value recorded at 0.3 ppm (location A) and the lowest at 0.01 ppm (point P), well below the threshold of 200 parts per million [36].

The origin of TDS in drinking water can be attributed to various sources, including natural sources, domestic wastewater, municipal runoff, and industrial wastewater. Studies by Hem [41] and Douti et al. [42] have reported a correlation between groundwater EC and TDS levels. Groundwater EC is directly influenced by the TDS content, assuming that the TDS primarily consists of ionic constituents that contribute to EC. While TDS does not provide direct evidence of biodegradation, it serves as a geochemical parameter that closely links groundwater electrical properties to hydrocarbon degradation [41]. The analysis revealed a positive correlation coefficient of 0.6 between TDS and EC.

The elevated salinity and EC measurements observed in the water samples could be attributed to hydrocarbon contamination, as it has the potential to increase the ionic content of groundwater. EC and salinity are closely associated, as indicated by Hayashi [43]. Higher TDS levels indicate the presence of cations and anions in groundwater, leading to increased salinity and EC. Point A exhibited the highest EC and TDS values, while site P had the lowest EC and TDS values. The areas A and P demonstrated the highest and lowest mean salinity values, respectively, with recorded values of 0.3 ppm and 0.1 ppm. The correlation analysis between TDS and EC revealed a strong positive correlation of $r = 0.9$, indicating a significant relationship between these two parameters. Similarly, salinity and EC displayed a strong positive correlation of $r = 0.9$, suggesting that salinity levels directly impact the EC of groundwater.

The findings of this study are highly relevant on multiple fronts. They raise significant concerns about public health as the contamination of groundwater by petroleum hydrocarbons poses potential risks to the communities relying on these water sources.

Also, the environmental impact is underscored, highlighting the need for immediate attention to safeguard aquatic ecosystems and various species. Moreover, these findings provide essential data for regulatory compliance assessment, aiding authorities like the Environmental Protection Agency (EPA) in enforcing water quality standards and implementing preventive measures. The complex interplay of various water quality parameters observed in this study is crucial for long-term planning and sustainable water resource management in the affected areas. Additionally, the inverse relationship between the proximity of fuel storage tanks to groundwater sources and hydrocarbon contamination emphasizes the importance of proper tank siting and maintenance, informing mitigation strategies and regulatory actions. Furthermore, these findings pinpoint areas for further research, particularly concerning the long-term effects of hydrocarbon exposure and health risks for specific vulnerable populations, such as pregnant women and infants. In sum, these findings provide valuable insights for addressing current water quality issues and shaping future policies, research initiatives, and mitigation efforts to protect public health and the environment in the studied regions.

3.3. *Effects of TPHs on groundwater contamination*

The presence of TPH in groundwater samples serves as an indicator of petroleum contamination[44,45]. Though the acceptable limit for TPH concentration in drinking water stands at 5.0 mg/L according to USEPA [44] and WHO/UNICEF [36], location A recorded the highest mean TPH concentration of 9.5 mg/L, while three sampling points (J, L, and M) showed no TPH contamination. In total, three areas (A, B, and R) exhibited TPH concentrations above the permissible limit (Fig. 4).

These areas, namely sites A, B, and R, recorded TPH concentrations of 9.5 mg/L, 9.3 mg/L, and 6.2 mg/L, respectively (Table 2). The presence of waste dumps, garage spills, and LUSTs may contribute to these elevated TPH concentrations. It is well-established that underground storage tanks (USTs) used for storing petroleum products can often leak their contents into the surrounding environment. Giese et al. [46] support this notion, reporting instances of UST leakages. Similarly, Valentinetti [47] posits that UST leakage is a major contributor to groundwater contamination, aligning with the findings of this study.

According to Valentinetti [47], TPH can enter groundwater through various sources, including UST leaks. This observation is consistent with the presence of mechanic shops and fuel storage tanks in proximity to most groundwater sampling points. Mechanic shops are known to release petroleum products into the environment, which can eventually reach the groundwater and increase TPH concentrations, as reported by Sun [48]. Likewise, numerous fuel stations may have leakages in their USTs, resulting in the release of petroleum products into the environment and potential contamination of nearby groundwater due to soil characteristics and groundwater flow. Sun [48] indicated that when gasoline is released into the subsurface, its organic components can be transported through bulk movement, leading to contamination of groundwater, soil, and vapour. Some constituents found in gasoline can undergo biotic or abiotic degradation or transformation, leading to the spatial and temporal distribution of contaminants within the subsurface environment.

Additionally, within the sampling period, it was observed that several vehicle washing bays were situated near certain groundwater sources. These activities have the potential to release hydrocarbons from leaking engine tanks, ultimately making their way into the groundwater sources. The recorded concentrations of TPH could also be influenced by the proximity of the groundwater sources to fuel storage facilities in the study area. For instance, the TPH concentration of 9.3 mg/L at site R could be attributed to the location of the sampled groundwater source downstream from an uphill fuel storage tank, which increases the likelihood of hydrocarbon leakage into the groundwater.

According to ASTDR [45], the presence and concentration of TPH in a sample can serve as a broad indicator of petroleum contamination at a particular site. Even low concentrations of TPH in groundwater, which may not be detectable by smell or taste, can still pose a risk to human health [49]. Although 83.0% of the sampled groundwater sources did not exceed the permissible limit for

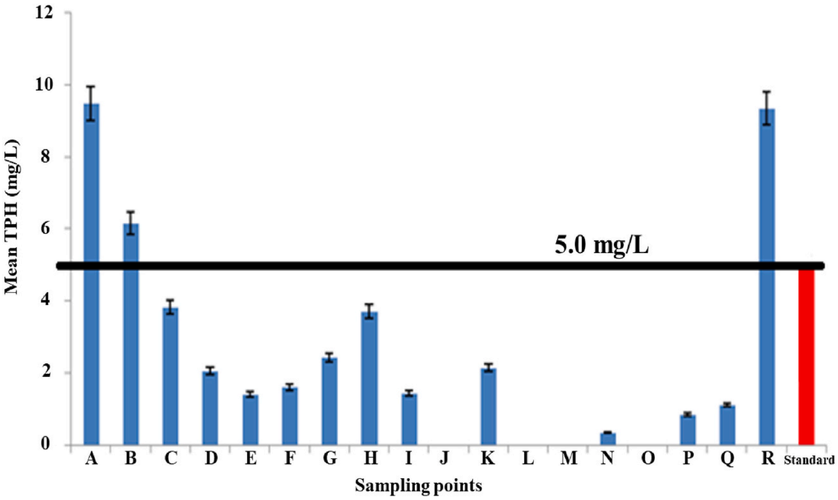


Fig. 4. TPH concentrations in groundwater.

TPH, it remains an area of concern. Once hydrocarbons reach groundwater, their slow evaporation and limited biodegradation in comparison to surface water contribute to their accumulation and persistence in the groundwater, as reported by Kuppusamy et al. [10, 50].

Sampat [51] and Whetzel [12] have indicated that the contamination of groundwater with hydrocarbons can be attributed to the increase in automobile sales and the construction of numerous gasoline stations, often equipped with bare steel tanks for underground storage of gasoline. This pattern is evident in the Kumasi metropolis, as observed in the results. The contamination of groundwater associated with underground fuel tanks can be linked to factors such as corrosion of steel tanks, faulty installation and operation, leaking storage tanks, and spills, as stated by Whetzel [12]. Whetzel [12] further noted that underground storage tanks have a lifespan of 15–25 years, and the probability of leaks increases with age. Even a small leak rate, such as two drops per second, can result in the loss of significant fuel volume and the contamination of a substantial amount of groundwater, rendering it unacceptable for drinking in terms of odour and taste, as suggested by Harris et al. [9].

These findings emphasize the need for comprehensive monitoring and regulatory measures to control and mitigate hydrocarbon contamination. Moreover, the persistence of hydrocarbons in groundwater, as highlighted by their slow evaporation and limited biodegradation, indicates a long-term threat to water resources and necessitates ongoing remediation efforts. The implications extend to public health, as even low concentrations of TPH in groundwater can pose risks to human health. This reinforces the importance of ensuring access to safe and clean drinking water for the affected communities and further research into potential health effects resulting from TPH exposure. These call for immediate environmental and public health actions, including remediation, regulatory enforcement, and long-term planning for sustainable water resource management.

3.4. Effects of the distances between fuel storage tanks and TPH concentrations

At location H, the shortest distance between the fuel storage tank and the groundwater sources was 25 m, while at site Q, the highest distance recorded was 535.0 m. The mean TPH concentrations in samples collected from these two locations were 3.7 mg/L and 1.1 mg/L, respectively. At point H, the groundwater was situated at a depth greater than the permissible limit of 100 feet (30.5 m) from fuel storage facilities [9]. However, the majority of other locations (94.0%) were found to be within the acceptable range of distance between fuel storage tanks and groundwater sources (Table 3).

The spatial distribution between USTs and groundwater sources significantly influences the TPH concentrations in groundwater systems [52]. According to Harris et al. [9], it is recommended to maintain a minimum distance of 100 m between underground storage tanks (USTs) and groundwater sources. The proximity of USTs to groundwater sources directly impacts the TPH concentration in the sampled groundwater. At location H, the USTs were located at the closest distance of 25 m to the groundwater sampling point, resulting in a higher TPH concentration of 3.7 mg/L. Conversely, at site Q, the USTs were situated at a greater distance of 535 m from the groundwater sampling point, leading to a lower TPH concentration of 1.1 mg/L. Though significant concentrations of TPH were present in groundwater sources, an inverse relationship ($r = -0.3$) was established between distance from UST and groundwater sources, and the TPH concentrations (Fig. 5). This could be due to factors such as flow rate, pore space and directionality of pores, permeability, amount of petroleum seeping, and absorption rate by the local soils.

In practical terms, these findings have implications for regulatory agencies and policymakers. They highlight the importance of enforcing safety regulations and guidelines related to the location of USTs, especially in densely populated or environmentally sensitive areas. Additionally, these findings contribute to the body of knowledge about the factors influencing hydrocarbon contamination in groundwater, which is valuable for groundwater resource management and protection. The implications of these findings underscore the significance of maintaining safe distances between USTs and groundwater sources to prevent TPH contamination. They also call attention to the complex interplay of hydrogeological factors in determining TPH concentrations in groundwater, which has

Table 3
Proximities from fuel stations and groundwater sources.

Sample location	Distance (m)	Mean TPH (mg/L)
A	185.4 ± 50	9.5 ± 18
B	205.0 ± 14	6.1 ± 34
C	85.4 ± 28	3.8 ± 23
D	112.0 ± 31	2.1 ± 27
E	100.1 ± 14	1.4 ± 12
F	235.3 ± 18	1.6 ± 16
G	358.5 ± 22	2.4 ± 21
H	25.0 ± 25	3.7 ± 32
I	56.2 ± 34	1.5 ± 27
J	486.1 ± 15	0.0 ± 00
K	403.1 ± 27	2.2 ± 17
L	200.1 ± 35	0.0 ± 0.00
M	350.4 ± 18	0.0 ± 0.00
N	105.2 ± 26	0.4 ± 11
O	218.0 ± 14	0.0 ± 20
P	45.5 ± 12	0.9 ± 15
Q	535.1 ± 09	1.1 ± 10
R	110.1 ± 19	9.3 ± 41

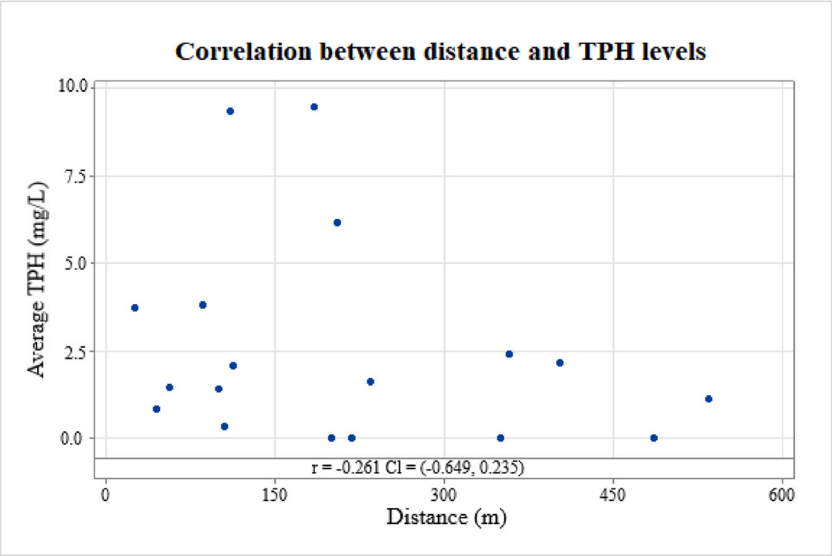


Fig. 5. Scatter plot of TPH concentrations, and distances between fuel stations and groundwater sources.

implications for both urban planning and environmental protection efforts.

3.5. Elemental relationships

Factor analysis (FA) serves as a valuable statistical tool for uncovering underlying relationships among numerous observed variables by identifying latent, unobservable factors that contribute to their covariation [53]. In this study, the application of FA aimed to discern patterns and associations among various environmental parameters. The findings of the FA revealed three distinct factors (F1, F2, and F3) that accounted for the underlying relationships among the measured variables. F1, characterized by high factor loadings of EC (0.9), TDS (0.9), and salinity (0.9), suggested a strong dominance of these variables. This factor was interpreted as being primarily influenced by natural conditions. These parameters are commonly linked to naturally occurring variations in water quality, indicating their origin from geological or environmental factors. Contrastingly, F2 was primarily governed by TPH, signifying an association with anthropogenic influences. The high factor loading of TPH on F2 suggests that this factor is predominantly influenced by human activities, specifically those related to petroleum sources. This relates to the findings of Teng et al. [54] and Huang et al. [55] who described leakage from underground petroleum tanks or other human-related activities associated with petroleum as major sources of TPH in groundwater systems. However, as shown in Table 4, F3 displayed a dominant association solely with pH (0.9). This factor's composition, driven almost entirely by pH, implies that this particular aspect of the environment might result from a combination of both geological and anthropogenic factors. Changes in pH can stem from a variety of influences, including both natural variations in the geology and hydrology of the area and human-induced alterations due to factors like agricultural practices, industrial activities, or land use changes.

The covariance-variance relationships are recorded in Table 5. This was to evaluate the strength and direction of the relationship between assessed variables [5,53]. Strong positive correlations were evident among the values of EC and TDS ($r = 0.9$) and between salinity and EC ($r = 0.9$) as well as between salinity and TDS ($r = 0.9$). These parameters were also found to have associations with the concentrations of TPH (EC: $r = 0.6$, TDS: $r = 0.6$ and salinity: $r = 0.6$) in the water samples. The interrelationship among EC, TDS, and salinity suggests a cohesive influence on the overall dissolved solids and ion concentrations present in the groundwater. Moreover, the associations with TPH concentrations indicate a potential contamination source or influence on the groundwater quality, highlighting the need for further investigation and monitoring to assess the extent and impact of petroleum-related pollutants in the groundwater system. However, the relationships established stand as weak correlations. Conversely, a negative correlation ($r = -0.3$) was observed

Table 4
Factor analysis of groundwater parameters.

Variable	Factor 1	Factor 2	Factor 3
Temperature (^{o}C)	0.01	−0.9	0.2
pH	0.1	0.2	**0.9**
EC (μs/cm)	**0.9**	0.1	−0.1
TDS (mg/L)	**0.9**	0.1	−0.1
Salinity (ppm)	**0.9**	0.1	−0.1
TPH (mg/L)	0.1	**0.9**	−0.2

Table 5
Covariance-variance assessment.

	Temp (°C)	pH	EC (µs/cm)	TDS (mg/L)	Salinity (ppm)
pH	−0.4				
EC (µs/cm)	−0.1	0.2			
TDS (mg/L)	−0.1	0.2	**0.9**		
Salinity (ppm)	−0.2	0.3	**0.9**	**0.9**	
TPH (mg/L)	−0.6	0.4	**0.6**	**0.6**	**0.6**

between the distance of groundwater sources from the fuel storage tanks. The correlation analysis revealed an inverse relationship ($r = -0.3$) between the TPH concentrations in water samples and the locations of USTs, indicating that the proximity of USTs significantly influenced the contamination of groundwater systems near fuel stations in the Kumasi metropolis. However, the relatively weaker correlation value suggests that other factors, such as soil type, rock type, porosity, permeability, and other geological properties of the subsurface materials, as well as the characteristics of the petroleum hydrocarbons present in the groundwater, may also contribute to the recorded TPH concentrations.

To better understand the possible impacts of the distances of the USTs on the groundwater sources, a multiple linear regression was done (Table 6). The results demonstrate non-significant relationships between these parameters and the distance of the groundwater sources. The coefficients showed the direction and strength of the relationships between the groundwater quality parameters and the distance between the USTs. None of the coefficients were statistically significant as indicated by their associated p-values, which are all above conventional significance concentrations (typically 0.05 or lower). This implies that, based on this model, there is no statistically significant linear relationship or influence between the measured groundwater quality parameters and the distance of the groundwater sources. It suggests that these parameters might not be good predictors or explanatory factors for determining the distance between the sources of groundwater. Other variables or unmeasured factors might have a more substantial influence on the spatial distribution of distances among the groundwater sources. Further investigation including additional variables or a different model may be necessary to explore factors affecting the distances between these sources more comprehensively. Coupled with the correlation analysis, these findings are supported by a study conducted by Parcher [56], which emphasized the role of factors like capillary pressure, wettability, saturation, viscosity, and geological properties in determining hydrocarbon distribution and behaviour in groundwater systems.

The matrix plot presented non-linear relationships except for TDS and EC (Fig. 6). TPH and temperature showed a slightly inverse-linear pattern. Also, some significant linearities were observed between TPH and pH, EC, and TDS. The slight linearities shown suggest that there were no constant responses between a majority of the variables. This suggests that the factors influencing these parameters could be from varying sources factors such as soil and rock types, porosity and permeability. Since pH is a factor that influences chemical processes and interactions in soils and water as indicated by Khatri and Tyagi [57] and Akram et al. [58], contours were created to understand how TPH and pH related to the other variables (EC, temperature, TDS and salinity). The study showed that apart from temperature, similar patterns were established between TPH and pH, and EC, TDS and salinity. This affirms the factor loading and correlations presented in Tables 4 and 5 where temperature did not show any significant load or relate significantly with any other variable respectively. It also relates to the inverse association between TPH and temperature as presented in Fig. 6. Also, the presence of multiple concentric shapes between TPH and pH against temperature depicts multi-modal distributions (Fig. 7a). The patterns created for all the variables were generally wide, indicating that the interactions between TPH and EC, TDS and salinity occurred slowly (Fig. 7b–d). This further suggests that the presence of TPH in the groundwater system occurred over a long period which could be a result of factors such as the nature of the underlined rock and soil types.

The aforementioned findings hold significant relevance in the context of groundwater quality assessment and environmental management. By distinguishing between natural and anthropogenic factors influencing groundwater quality, the research aids in the identification and comprehension of different sources of contamination, offering crucial insights for assessing the suitability of groundwater for various uses, including drinking water. Moreover, the study underscores the importance of environmental protection by shedding light on the potential risks associated with anthropogenic sources like petroleum storage tanks, emphasizing the need for preventive measures and ongoing monitoring to mitigate contamination. The examination of correlations between groundwater parameters such as EC, TDS, salinity, and TPH provides a deeper understanding of their complex interactions, enabling the assessment of groundwater system dynamics and the consequences of parameter changes. The study's insights into non-linear relationships and multi-modal distributions highlight the temporal aspects of groundwater contamination, underscoring the necessity for long-term

Table 6
Relationship between distances of USTs and water quality parameters.

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1316.8	2137.3		.7	.6
	Temperature (°C)	−20.9	69.5	−.1	−.3	.8
	pH	−82.6	82.7	−.3	−.1	.3
	TDS (mg/L)	−.7	15.9	−.3	−.0	.1
	Salinity (ppm)	1363.5	16812.0	.6	.1	.1
	TPH (mg/L)	−17.9	24.8	−.3	−.7	.5

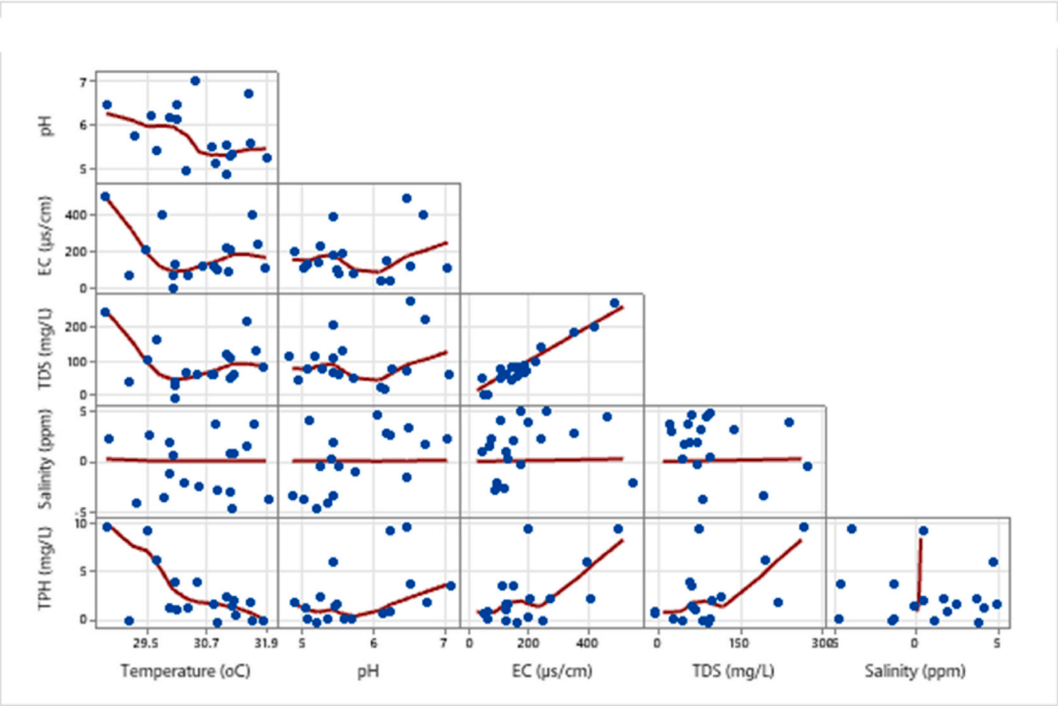


Fig. 6. Matrix plot of groundwater parameters.

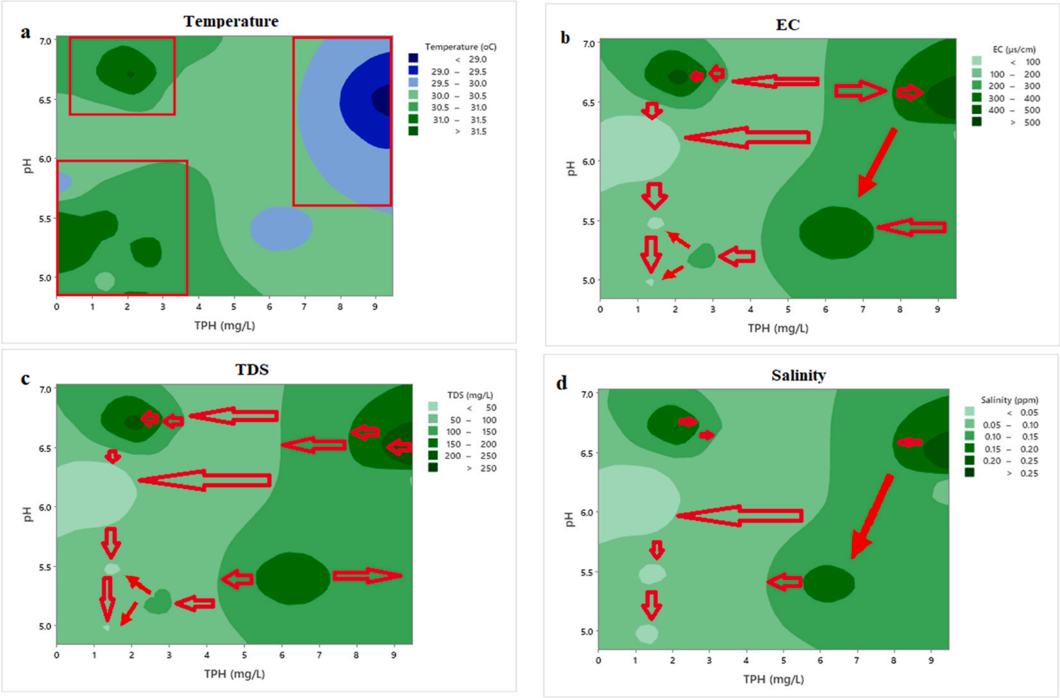


Fig. 7. Contours of TPH and pH against (a) temperature (b) EC (c) TDS and (d) salinity.

environmental management strategies. These findings are directly relevant to groundwater management practices, and environmental policy, and contribute to the scientific understanding of groundwater dynamics and contamination. Overall, they play a crucial role in safeguarding groundwater resources for diverse uses and ensuring environmental sustainability.

The cluster analysis delineates groundwater quality into three discernible groups, each displaying distinctive characteristics (Table 7). The analysis reveals distinct variations in multiple parameters across the identified clusters, indicating diverse characteristics of the sampled groundwater sources. Cluster 1 stands out with elevated values in several aspects. It exhibits higher temperatures (29.99 °C), along with relatively high pH (6.2), EC at 439.0 μs/cm, TDS of 219.6 mg/L, salinity levels at 0.2 ppm, and TPH concentrations of 5.9 mg/L. These metrics suggest a potentially higher mineral load, salinity, and petroleum contamination in Cluster 1 compared to the other clusters. On the contrary, Clusters 2 and 3 demonstrate lower values in these parameters, implying better water quality and lower contamination concentrations. Cluster 2 records the highest mean temperature (30.9 °C) and slightly lower but still significant values in pH (5.7), EC (169.1 μs/cm), TDS (84.6 mg/L), salinity (0.1 ppm), and TPH (2.4 mg/L). Cluster 3 follows with temperature at 30.3 °C, pH of 5.7, EC at 71.3 μs/cm, TDS measuring 35.5 mg/L, salinity of 0.03 ppm, and TPH concentrations at 1.1 mg/L. Cluster 1's distinctiveness, with higher pH, EC, TDS, salinity, and TPH concentrations, suggests a potential scenario of compromised water quality. These elevated metrics could signify increased mineral content, salinity, and contamination, possibly due to anthropogenic activities or natural geological factors. Consequently, it necessitates urgent attention and targeted remediation measures to mitigate the pollution sources affecting this cluster.

Shown in Table 8, the ANOVA results depict comparisons of various groundwater quality parameters concerning their association with TPH concentrations. However, the findings suggest that there is no statistically significant relationship between the physicochemical parameters and TPH concentrations in the groundwater. The lack of statistical significance ($p > 0.05$) in most cases, indicated by the F values and associated p-values, suggests that these parameters may not be influential predictors of TPH concentrations in the groundwater samples analyzed in this study. The non-significant findings from the ANOVA analysis imply that there might not be a direct linear relationship or influence between the measured physicochemical parameters and TPH concentrations in the examined samples. This suggests that other unmeasured factors such as soil characteristics, specific hydrogeological properties or other chemical compositions might have a more significant impact on TPH concentrations in the groundwater. Therefore, further investigation or exploration of additional factors may be necessary to better understand and identify the determinants affecting TPH concentrations in the groundwater.

3.6. Possible public health implications

Groundwater contamination around fuel stations in residential areas presents significant health risks to the local population [59]. Exposure to TPH in groundwater can give rise to a range of health implications, and these implications can vary based on the specific hydrocarbons present, their concentrations, and the duration of exposure. Some of the potential health effects of TPH exposure in groundwater include.

- ➢ Gastrointestinal distress: TPH-contaminated water may contain volatile organic compounds, which can lead to gastrointestinal problems like stomach aches, cramps, nausea, diarrhoea, and vomiting [60]. Prolonged exposure can result in chronic digestive issues.
- ➢ Exposure to TPHs can lead to a spectrum of health disorders, encompassing skin and eye irritation, respiratory issues, neurological problems, and heightened stress levels. TPHs exert a profound influence on mental health, triggering both physical and physiological effects, and they possess the potential to induce toxicity in genetic, immune, and endocrine systems [10].
- ➢ Long-term health risks: Certain TPH components, like benzene, toluene, and xylene (BTX) are classified as potential carcinogens [61]. Chronic exposure to these compounds through contaminated drinking water may elevate the risk of developing cancer over time, particularly if TPH concentrations are high. Based on this, the USEPA has established a standard 0 ppb for benzene in potable and fresh water since it has the propensity to cause leukaemia [62].
- ➢ Haematological effects: Exposure to individual constituents and mixtures rich in BTX can lead to haematological effects [63,64]. Nevertheless, the specific haematological impacts of prolonged exposure to BTX remain uncertain, and it is imperative to establish reference levels based on empirical evidence [65]. In this case, direct exposure to water should be investigated.
- ➢ Secondary effects: Long-term exposure to TPH-contaminated groundwater can lead to more severe health issues, such as damage to the liver, kidneys, and the central nervous system [66,67]. These health effects may not be immediately apparent but can manifest over time.

Health implications can also be influenced by the duration and intensity of TPH exposure, making it essential to promptly address groundwater contamination issues. Monitoring and comprehensive water quality assessments are crucial to understanding the potential risks and mitigating the adverse health effects associated with TPH exposure in groundwater. The areas of major concern are locations A, B and R with potential concern in C, D, G, H and K.

3.7. Proposed plan to manage and mitigate the impacts of TPH driven by fuel stations

Objective: The primary objective of this proposal is to develop a comprehensive plan for managing and mitigating petroleum-hydrocarbon contamination of groundwater systems around fuel stations in residential areas, with a focus on protecting public health and the environment.

Table 7
Cluster analysis of groundwater.

	Cluster		
	1	2	3
Temperature (°C)	30.0	30.9	30.3
pH	6.2	5.7	5.7
EC (μs/cm)	439.0	169.1	71.3
TDS (mg/L)	219.6	84.6	35.5
Salinity (ppm)	.2	.1	.0
TPH (mg/L)	5.9	2.4	1.1

Table 8
ANOVA of physicochemical parameters against TPH concentrations.

		Sum of Squares	df	Mean Square	F	Sig.
Temperature (°C)	Between Groups	12.8	15	.9	2.7	.3
	Within Groups	.6	2	.3		
	Total	13.4	17			
pH	Between Groups	7.0	15	.5	9.0	.1
	Within Groups	.1	2	.1		
	Total	7.0	17			
EC (μs/cm)	Between Groups	298745.6	15	19916.4	6.1	.2
	Within Groups	6483.3	2	3241.7		
	Total	305228.8	17			
TDS (mg/L)	Between Groups	75002.1	15	5000.1	6.2	.2
	Within Groups	1612.6	2	806.3		
	Total	76614.7	17			
Salinity (ppm)	Between Groups	.1	15	.004	8.4	.1
	Within Groups	.001	2	.001		
	Total	.1	17			

- ➢ Conduct a thorough assessment of the affected areas, identifying all fuel stations and their proximity to residential zones. Utilize advanced hydrogeological and geochemical analyses to quantify the extent and severity of TPH contamination in groundwater sources. Categorize the risks to public health and the environment based on the contamination concentrations.
- ➢ Implement immediate containment measures, such as constructing impermeable barriers to prevent further contamination spread. Develop a groundwater extraction system to intercept and treat contaminated groundwater before it reaches residential areas. Implement appropriate remediation techniques, such as in-situ chemical oxidation, enhanced natural attenuation, or soil vapour extraction, based on contamination severity.
- ➢ Establish a continuous groundwater monitoring program to track contamination concentrations, ensuring that early warning signs are identified. Develop a reporting mechanism to inform residents, regulatory authorities, and the public about groundwater quality in real-time real-time.
- ➢ Stakeholders such as the National Petroleum Authority and the Environmental Protection Agency should ensure that all fuel stations comply with regulations related to underground storage tanks, leak detection, and spill prevention. Collaborate with regulatory agencies to enforce penalties for non-compliance and improve inspection and compliance monitoring.
- ➢ Launch public awareness campaigns to educate residents on the risks of groundwater contamination of TPH.
- ➢ Invest in ongoing research to identify emerging contaminants and innovative remediation technologies. Collaborate with academic institutions and research organizations to enhance understanding of groundwater systems and contamination mechanisms.
- ➢ Advocate for stronger policies and legislation to address groundwater contamination, promote sustainable practices in the petroleum industry, and safeguard public health and the environment. Collaborate with lawmakers to draft and enact regulations tailored to the specific needs of the affected residential areas.
- ➢ Develop an emergency response plan that outlines the steps to be taken in the event of sudden contamination events or spikes in groundwater pollution. Conduct regular training and drills for first responders and stakeholders involved in emergency responses.
- ➢ Establish a fund for the long-term sustainability of groundwater management and remediation efforts. Engage local communities in decision-making processes and ensure their voices are heard in the long-term planning and execution of solutions.

This comprehensive proposal plan aims to address the critical issue of petroleum-hydrocarbon contamination of groundwater systems around fuel stations in residential areas. By taking these strategic steps, we can protect public health, preserve the environment, and work toward a sustainable and healthy future for affected communities.

4. Conclusions

The concentration of TPH in groundwater has significant implications for various aspects of water quality. The study findings indicate that TPH was detected in 83.0% of the sampled groundwater sources. Location A exhibited the highest recorded TPH concentration of 9.5 mg/L, while points L, M, and J showed no detectable TPH concentration (0.0 mg/L). The presence of hydrocarbon contaminants in groundwater had noticeable effects on the pH, EC, TDS, temperature, and salinity of the analyzed groundwater samples. Additionally, the proximity of USTs to groundwater sources, such as wells and boreholes, within the KMA, exerted some level of influence on water quality. However, generally, the distances between the USTs did not pose any direct impact on the concentrations of TPH in the groundwater system. This study however highlights the need for monitoring and managing hydrocarbon contamination. The observed variations in TPH concentrations among different locations emphasize the significance of assessing site-specific factors, including the proximity of USTs, to understand and address potential sources of groundwater contamination effectively. These findings contribute to the broader understanding of water quality management and provide insights for targeted remediation efforts in contaminated areas. It is recommended that.

- Further studies should be done to understand the influence of other factors such as soil characteristics, precipitation patterns, water table depth and specific hydrogeological conditions on the groundwater quality of the area.
- Spatial separation between wells/boreholes and USTs influenced TPH concentration in groundwater, highlighting the need to establish wells at safe distances from USTs to prevent TPH contamination.
- Considering the significant impact of UST age on leakage occurrences, it is advisable to enforce regulations mandating the replacement of older storage tanks (exceeding ten years) to minimize the likelihood of leaks.
- Before installing USTs, it is advisable to conduct comprehensive geological surveys of the area to accurately assess the potential consequences of potential leaks on groundwater sources.

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CRediT authorship contribution statement

Bernard Fei-Baffoe: Writing – original draft, Supervision, Resources, Data curation, Conceptualization. **Esther Badu:** Writing – original draft, Visualization, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Kwodwo Miezah:** Validation, Supervision, Software, Formal analysis, Conceptualization. **Lyndon Nii Adjiri Sackey:** Visualization, Supervision, Software, Investigation, Data curation, Conceptualization. **Alhassan Sulemana:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Ebenezer Ebo Yahans Amuah:** Writing – original draft, Supervision, Resources, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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