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GROUNDWATER SAFETY, AESTHETIC QUALITY, AND PUBLIC HEALTH RISKS: AN INTEGRATED PHYSICOCHEMICAL AND MICROBIOLOGICAL ASSESSMENT OF BOREHOLE WATER IN BENIN CITY, EDO STATE, NIGERIA

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Abstract

In Benin City, Edo State, Nigeria groundwater supplies domestic water in many homes but the city's urbanization and inadequate sanitation is a significant challenge to the quality of the groundwater and its public health safety. The study was used to determine the suitability of the groundwater from forty (40) privately owned boreholes for drinking and domestic use based on their physicochemical and microbiological quality parameters. Physicochemical parameters (pH, turbidity, total dissolved solids, electrical conductivity, nitrate, chloride, iron, zinc, copper, lead and cadmium) and microbiological indicators (total coliforms and Escherichia coli) were analyzed by standard APHA methods. Groundwater quality and the hydrogeochemical relationships were evaluated using descriptive statistics, Pearson's correlation analysis and the Weighted Arithmetic Water Quality Index (WQI). Most of the physicochemical parameters were within the World Health Organization (WHO) and Standards Organization of Nigeria (SON) guideline values. Mean values were 7.00 ± 0.28 for pH, 0.48 ± 0.18 NTU for turbidity, 129.2 ± 10.7 mg L^{-1} for total dissolved solids, 258.5 ± 21.3 µS cm^{-1} for electrical conductivity, and 5.77 ± 2.35 mg L^{-1} for nitrate. Lead was present at trace levels, and cadmium was not detected, except in low concentrations, in the trace metals. Total coliforms were detected in some boreholes and Escherichia coli in one sample, indicating localized faecal contamination. Although the groundwater exhibited good physicochemical quality (WQI = 28.93), localized microbial contamination demonstrates that chemical compliance alone does not ensure microbiological safety. Routine microbial surveillance, sanitary protection of boreholes, and integrated groundwater management are therefore essential for safeguarding public health.

Keywords: *Groundwater quality, Borehole water, Physicochemical characteristics, Microbial contamination, Public health, Benin City*

Introduction

Groundwater is considered one of the world's most significant sources of fresh water. It is used for drinking by over 2 billion people, especially in developing countries, where centralized water supply is either inadequate or unreliable (UNESCO, 2021; WHO, 2023; Nandi and Swain, 2024). Population growth, urbanization, and poor maintenance of water infrastructure in municipal systems in Nigeria have significantly elevated the use of privately-owned boreholes for household water supply (Archibong *et al.,* 2025; Irene *et al.,* 2025). Groundwater is less likely to be affected by human activities compared to surface water; however, many cities in Nigeria have a high vulnerability to groundwater, with anthropogenic activities like indiscriminate garbage disposal, improperly managed septic systems, agriculture, and urbanization as the source of contamination (Bassey & Archibong, 2022; Ferreira *et al.,* 2023; La Vigna, 2022). As a result, the protection of groundwater quality is increasingly recognized as a critical element in the SDGs' clean water and sanitation (SDG 6) target (UN-Water, 2023; Nandi and Swain, 2024).

Groundwater quality is the result of both natural hydrogeological processes and anthropogenic activities. The geology, mineral weathering, groundwater recharge and aquifer properties govern the natural chemical makeup of groundwater, while infiltration of wastewater, refuse dumps, industrial processes, agricultural runoff and inadequate sanitation can lead to the introduction of nutrients, heavy metals, and pathogenic microorganisms into aquifers (Lin *et al.,* 2022; Jagaba *et al.,* 2024). Physiochemical parameters like pH, turbidity, electrical conductivity, total dissolved solids, nitrate, chloride and trace metals are essential tools for understanding hydrogeochemical processes and aesthetic water quality while Microbiological parameters, especially total coliforms and Escherichia coli are widely accepted indicators of faecal contamination and possible presence of pathogens (WHO, 2023; Okafor *et al.,* 2023; Odewade *et al.,* 2025). However, recent studies have revealed the deterioration of the groundwater quality in Nigeria due to urbanization, poorly protected borehole, waste dump site, and poor sanitation, which calls for an integrated physicochemical and microbiological assessment (Badmus *et al.,* 2024; Omeka *et al.,* 2024; Akanbi *et al.,* 2025).

The Benin Formation (Coastal Plain Sands) overlies Benin City, and is very permeable, leading to high recharge rates to the groundwater, but also making the groundwater system very susceptible to contamination from surface sources (Ikhile, 2016; Etuk *et al.,* 2022). As a result of the ongoing residential and commercial growth as well as the high reliance on onsite sanitation systems, concerns have been raised about the safety of groundwater in the metropolis (Iduseri *et al.,* 2024; Rawlings and Matthew, 2024). Several studies have investigated some of the physicochemical and microbial indicators of groundwater quality in Benin City, and other parts of southern Nigeria, but most have dealt with either aspect alone, and not combined with Water Quality Index analysis and statistical evaluation (Ogbeifun *et al.,* 2019; Omorogieva *et al.,* 2022; Oria-Usifo *et al.,* 2025). Consequently, this study has integrated a comprehensive physicochemical characterization, microbiological analysis, Pearson's correlation analysis, and Application of Weighted Arithmetic Water Quality Index to assess the groundwater safety, aesthetic quality and public health risks in Benin City, Nigeria

Materials and Methods

Study Area

The study was conducted in Benin City, Edo State, Nigeria, which lies between latitudes 6°10′N and 6°30′N and longitudes 5°30′E and 5°45′E within the humid tropical rainforest region of southern Nigeria. The area experiences a tropical wet-and-dry climate characterized by a rainy season extending from March to October and a dry season from November to February. Annual rainfall exceeds 2,000 mm, resulting in significant groundwater recharge (Aiguobarueghian *et al.,* 2025).

Geologically, the study area is underlain predominantly by the Benin Formation (Coastal Plain Sands), consisting mainly of unconsolidated sands and gravels with high porosity and permeability (Akujieze and Oteze, 2006). These hydrogeological characteristics favour groundwater storage and abstraction but simultaneously increase aquifer vulnerability to contamination from anthropogenic activities. Land use within the study area comprises residential neighbourhoods, commercial centres, institutional facilities, transportation corridors, and peri-urban settlements. Figure 1 illustrates the map of the study area with the sampling coordinates presented in Table 1.

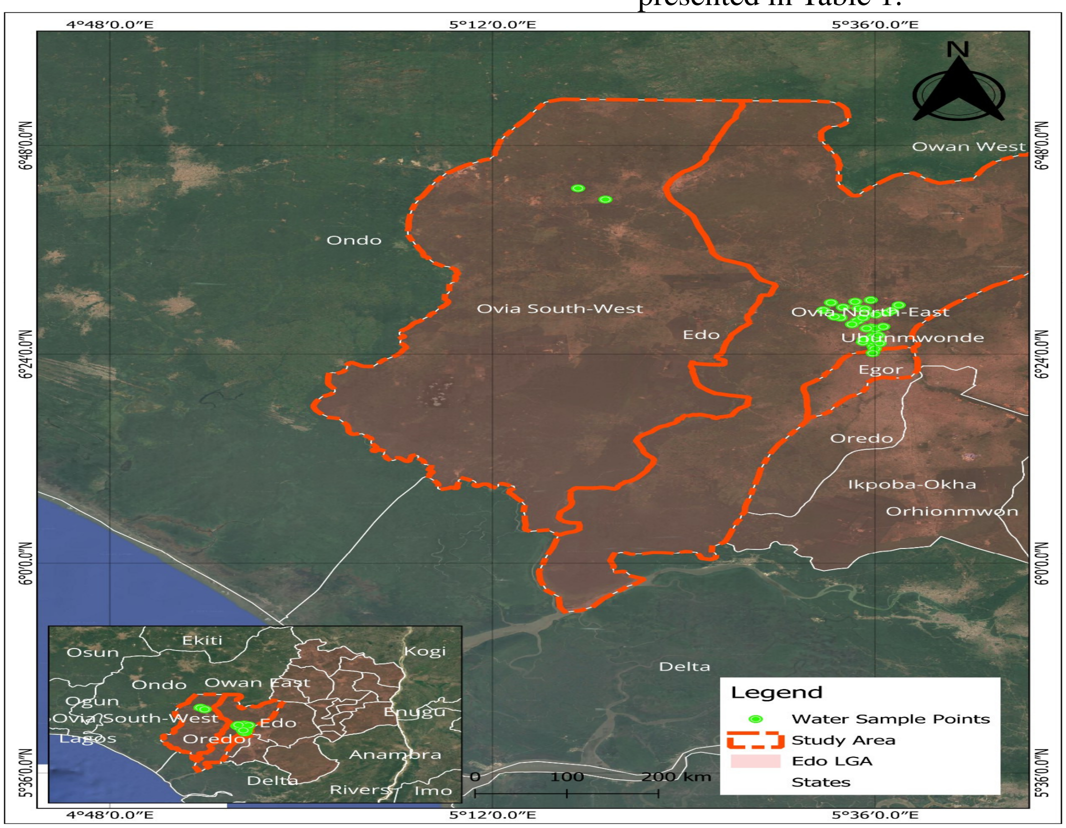

Fig. 1: Map showing Local Government Areas (LGAs) and Sample Points in the Study Area

Table 1: Geographic coordinates and characteristics of groundwater sampling locations in the Study Area

S/N	SAMPLE ID	Latitude (Decimal °)	Longitude (Decimal °)	Elevation (m)
1	Evidence	6.421389	5.604444	130
2	Oluku	6.434167	5.597778	110
3	Okhun	6.431667	5.596944	120
4	Ovbiogie	6.420556	5.601944	120
5	BDPA	6.451111	5.596111	120
6	Nitel	6.415	5.598333	140
7	Aso Rock	6.424167	5.598333	130
8	Iguosa	6.410278	5.599722	120
9	Evbomore	6.434167	5.597778	110
10	Newton	6.401944	5.5975	120
11	Uniben	6.433056	5.598056	140
12	Iyowa	6.401944	5.5975	120
13	Agen	6.420833	5.604722	120
14	Ekosodin	6.433056	5.598056	140
15	Edo Street	6.425833	5.589444	110
16	Ekiadolor	6.469722	5.563889	138
17	25th Street	6.425833	5.589444	110
18	20th Street	6.423333	5.587222	118
19	Isihor	6.448333	5.600278	120
20	Nifor	6.435833	5.603333	130
21	Ogua	6.463333	5.581111	150
22	Iwu	6.469722	5.587222	158
23	Iduwina	6.456944	5.575833	162
24	Iguodia	6.475556	5.600556	140
25	Evboeka	6.449167	5.591111	148
26	Utekon	6.4525	5.608611	135
27	Egbaen	6.479167	5.613056	155
28	Odighi	6.487222	5.582778	170
29	Uhogia	6.500278	5.579167	165
30	Uhiere	6.489444	5.566389	175
31	Iguoshodin	6.486111	5.589167	142
32	Okokhuo	6.503333	5.595556	160
33	Boundary	6.483056	5.6175	138
34	Isiuwa	6.493611	5.624722	146
35	Okada Town	6.718056	5.289444	168
36	Okada Junction	6.696667	5.318056	172
37	Uhogua	6.483889	5.545833	178
38	Osasimiwinoba	6.471667	5.5575	150
39	Ufese	6.498333	5.553889	173
40	19th Street	6.428333	5.588333	118

Sampling Design and Sample Collection

The cross-sectional design was used to gather data from 40 representative boreholes sampled from October 2025 to January 2026, in accordance with the standard protocol of the American Public Health Association (APHA, 2023) and the World Health Organization (WHO, 2023).

Boreholes in selected commercial areas were purposively selected based on accessibility, frequency of use, spatial distribution and proximity to potential source of contamination. Boreholes were purged for 5-10 min before sampling to eliminate stagnant water and to get a representative sample of the groundwater. Physicochemical samples were taken in high density polyethylene bottles pre-cleaned with detergent then washed with distilled water and finally sample water from the site. Samples for heavy metal analyses were acidified in the field to pH < 2.0 with ultrapure nitric acid (HNO_3). Microbiological samples were obtained in individual sterile 250-mL glass bottles and refrigerated at 4°C for transportation and processed no later than within 6 h (Archibong *et al.,* 2025).

Determination of Physicochemical Parameters

In situ measurements of hydrogen ion concentration (pH), electrical conductivity (EC) and total dissolved solids (TDS) were collected using the Hach HQ40d Portable Meter. Standard solutions were used daily for calibration prior to field measurements. The turbidimetric values were measured by the Hach 2100Q Series Turbidimeter and value obtained in nephelometric turbidity unit (NTU). The nitrate concentration was measured by the Cary 60 Agilent ultraviolet-visible spectrophotometry after the standard procedure outlined in APHA (2023). Chloride concentration was measured by argentometric titration with standard solution of silver nitrate. The water samples were subjected to acid digestion and the concentrations of Fe, Zn and Cu were determined by Agilent (*280FS AA*, *AA Duo*) Atomic Absorption Spectrophotometry (AAS). Certified stock solutions were used to prepare the calibration standards, and the instrument was calibrated periodically during the analytical sequence. To guarantee analytical accuracy and precision, quality control procedures were used, such as reagent blanks, duplicate analyses, and recovery studies (Ogbeifun *et al.,* 2019).

Microbiological Analysis

Microbiological quality assessment was directed on the determination of the total coliform bacteria and Escherichia coli. The membrane filtration method was used for the analyses following the standard methods of the APHA (2023). The volume of water was filtered through sterile 0.45 µm membrane filters. The membranes were then placed onto selective culture media and cultured under the proper conditions. The total coliform counts were determined after incubation and reported in colony forming units per 100 mL (CFU/100 mL). Identification of E. coli colonies was done by the standard biochemical identification methods (Archibong *et al.,* 2025).

Quality Assurance and Quality Control

Quality assurance and quality control procedures were applied during sampling, transport and laboratory analyses. To assess possible contamination in the handling of the samples, field blanks and laboratory blanks were performed. All glassware and sample containers were cleaned and sterilized before use. Calibration of analytical equipment was done as per manufacturer's specifications and duplicate analysis was carried out for certain samples for assessing the reproducibility. The analytical limits of 90–110% were considered acceptable for efficiency of recovery obtained for standard reference materials.

Data Analysis

IBM SPSS Statistics Version 26 was used to calculate descriptive statistics (mean, standard deviation, minimum and maximum values). Pearson's correlation analysis was used to assess the relationships between physicochemical variables. The significance of statistical values is determined by $p < 0.05$. Groundwater suitability for domestic use was assessed by comparing the results with the guideline values set by the World Health Organization (WHO, 2023) and the Standard Organization of Nigeria (SON, 2021) criteria for drinking water quality.

Water Quality Index (WQI)

The Weighted Arithmetic Water Quality Index (WQI) method of Raman & Geetha, 2005, as adopted by Shuaibu *et al.* (2024) was used to determine the suitability of groundwater for drinking purposes. Each parameter was subsequently given a quality rating (Q_i) as follows

$$Q_i = \frac{V_i - V_0}{S_i - V_0} \times 100 \qquad (1)$$

Where,

The observed value is written as V_i, and the WHO/SON standard for the same is written as S_i, and V_0 is the ideal value (0 for all parameters except for pH, which is 7.0). The unit weight (W_i) was calculated as:

$$W_i = \frac{1}{S_i} \qquad (2)$$

The overall WQI was calculated as follows:

$$WQI = \frac{\sum(Q_i W_i)}{\sum(W_i)} \qquad (3)$$

The quality of the groundwater was classified as listed in Table 2. The WQI was only based upon the physicochemical parameters and therefore the results were interpreted alongside the microbiological results for a complete assessment of the suitability of the ground water for human consumption.

Table 2: Water Quality Classification

WQI	Quality
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very Poor
>100	Unsuitable

Results and Discussion

Physicochemical Characteristics of Groundwater

The physicochemical and microbiological characteristics of groundwater collected from forty boreholes are presented in this section. The results are discussed in relation to World Health Organisation (WHO, 2023) and the Standards Organisation of Nigeria (SON, 2021) drinking-water standards, hydrogeochemical processes, microbial contamination, and public health implications. This is indicative of the fact that the groundwater system is not overwhelmingly impacted by chemical contaminants despite the rising urbanization and anthropogenic activities in the study area. The descriptive statistics of water quality parameters are presented in Table 3.

Table 3: Descriptive statistics of physicochemical and microbiological parameters of groundwater samples from Benin City, Edo State, Nigeria

S/N	Parameter	Units	Mean ± SD	Range (Min–Max)	WHO/SON Threshold
1	pH		7.00 ± 0.28	6.4 -7.6	6.50 - 8.50
2	Turbidity	NTU	0.48 ± 0.18	0.2 – 1.0	5.0
3	TDS	mg/L	129.2 ± 10.7	110 - 155	500 – 1500
4	EC	µS/cm	258.5 ± 21.3	220 - 310	900 – 1200
5	Nitrate	mg/L	5.77 ± 2.35	2.8 – 12.4	45.00 -50.00
6	Chloride	mg/L	30.8 ± 4.0	24.3 – 42.0	10.00 -50.00
7	Iron (Fe)	mg/L	0.1116 ± 0.053	0.012 – 0.23	0.3 - 3.0
8	Zinc (Zn)	mg/L	0.057 ± 0.027	0.004 – 0.12	100 – 500
9	Copper (Cu)	mg/L	0.056 ± 0.048	0.01 – 0.19	0.00 - 2.00
10	Lead (Pb)	mg/L	-	0.001 - 0.006	0.00 - 0.01
11	Cadmium (Cd)	mg/L	ND	ND	0.00 - 0.003
12	Total Coliform	CFU/100ML	5.7 ± 14.8	0 – 84	0.00
13	*E.* coli	CFU/100mL	0.03 ± 0.16	0 – 10	0.00

* *ND = Not Detected at laboratory detection limit*

Results obtained indicate that the drinking water standards are being met and the Benin Formation aquifer is still an effective natural filter that can attenuate dissolved contaminants prior to ground water extraction. Groundwater recharge has been observed to be very fast, and residence times are relatively short, in some groundwater systems developed in the Coastal Plain Sands in southern Nigeria, which results in a reduced time for mineral dissolution and contaminant buildup (Omeka *et al.,* 2024; Abdu-Raheem *et al.,* 2024). However, even when the physicochemical water quality meets the requirements, microbiological safety has to be assessed as well, which underlines the need for integrated groundwater quality assessment.

pH

The pH of groundwater was found to be from 6.4 to 7.6 with the average of 7.00 ± 0.28, which is generally a neutral pH. of the samples, around 97.5% fell within the recommended range of WHO and SON (6.5–8.5) and one was slightly acidic. The near neutral pH is the result of the buffering capacity of the Benin Formation aquifer, which is held under control by the buffering of carbonate minerals, the weathering of silicate minerals and groundwater-rock interactions (Wambui *et al*., 2025). According to Rika Sensor (2026), the pH stability is beneficial, as it leads to a lower solubility of metals, lower corrosion of water distribution systems, and better acceptability of the drinking water. It is likely that the slightly acidic sample was due to local rainwater infiltration of rainwater with dissolved carbon dioxide or decomposition of organic matter rather than industrial pollution. Groundwater pH decreases have also been observed in isolated areas of rapidly urbanized areas in southern Nigeria where seasonal recharge is known to temporarily change the chemistry of the groundwater (MacDonald *et al.,* 2021; Bjørklund *et al.,* 2024). Aesthetic quality and duration of use of infrastructure may also be impacted by the measured pH values, as the mobility of Fe and other trace metals may increase with prolonged acidification, but from a public health point of view, the acidity is likely to have little effect (Rashid *et al.,* 2023). Therefore, it is recommended that continuous monitoring is carried out, especially where residential development is spreading out.

Turbidity

Turbidity ranged from 0.20 to 1.00 NTU, with an average of 0.48 ± 0.18 NTU which was far less than the guideline value recommended by WHO of 5.00 NTU. These low turbidity levels reflect excellent natural filtration by the highly permeable sandy aquifer, and are indicators of relatively low levels of suspended particulate matter in the groundwater (Castillo-Sánchez *et al.,* 2025). Generally, low turbidity helps to improve the aesthetic qualities of drinking water, such as clarity and consumer rejection. Most importantly, lower particulate levels enhance the efficacy of the disinfection process of chlorination, since fewer particles are available to protect against disinfectants (Chahal *et al.,* 2016). Although these have favourable turbidity values, microbiological contamination in some boreholes was found. This finding reveals that low turbidity is not a good indicator of microbiological safety. A similar situation has been reported from groundwater sources in many parts of sub-Saharan Africa, where clear groundwater has been found to be contaminated with faecal bacteria as a result of bad well design, poor sanitary protection, or seepage from the surrounding septic systems (WHO, 2023; Odewade *et al.,* 2025). Therefore, regular physicochemical monitoring should always be supplemented with microbial analysis.

Total Dissolved Solids (TDS) and Electrical Conductivity (EC)

In general, the values measured for both TDS and EC were found to be approximately equal. The water quality for TDS and EC was low (129.2 ± 10.7 mg L^{-1} and 258.5 ± 21.3 µS cm^{-1} respectively) with good aesthetic water quality. A study by Edegbai *et al.* (2026), revealed that these low values indicate limited interaction between groundwater and soluble minerals in the geologic environment, indicating the highly permeable nature of the Benin Formation where the residence time of groundwater is short, and thus less time available for mineral dissolution. Hence, the groundwater is not saline. The results of the boreholes indicated slightly higher EC readings at 250 µScm-1, but were still significantly below the international drinking-water standards. The localized rise in conductivity could be due to higher concentrations of ions in the domestic wastewater infiltrating into the aquifer, agricultural activities, weathering of aquifer materials, or presence of dissolved organic matter, but it does not necessarily indicate that the aquifer is contaminated on a regional scale (Ruth *et al.,* 2025). The almost perfect positive correlation found between EC and TDS (r = 0.998) validates the fact that groundwater conductivity is mainly attributed to the presence of dissolved ionic constituents. This has been substantiated with groundwater reporting from throughout the world and is indicative of the use of EC as an effective surrogate indicator of dissolved mineral content (Shuaibu *et al.,* 2024). Generally, the low mineralization indicates that the groundwater is generally suitable for various uses, such as potable and non-potable, and is not likely to pose taste, salinity or scaling issues.

Nitrate

The nitrate levels were found to be 2.8 to 12.4 mg L-1, with an average of 5.77 ± 2.35 mg L-1, which significantly low the maximum guideline value of WHO (50 mg L-1). The results indicate low anthropogenic nitrate loadings despite the growth of urban centers within the aquifer (Ward *et al.,* 2018). Abascal *et al.* (2022) found that the relatively low concentrations indicate that natural nitrogen cycling and soil mineralization are the major sources of nitrate, rather than widespread contamination from sewerage or fertilizers. However, the moderate increases seen in some boreholes may be due to local septic tank, pit latrine, domestic wastewater or urban run-off contamination (Ogwo & Ogu, 2014). A moderate positive correlation between nitrate and chloride (r = 0.69) indicates this, as both are typically found in the infiltration of domestic wastewater. While current levels are not harmful to health, population growth, expansion of onsite sanitation systems and additional agricultural activities could potentially lead to a gradual increase in nitrate loading. However, long-term monitoring of groundwater is then important to identify trends in contamination before concentrations reach regulatory levels.

Chloride

The mean concentration of chloride was 30.8 ± 4.0 mg L^{-1} which is significantly lower than the guideline value of 250 mg L^{-1} set by WHO. Hong *et al.* (2023) observed that the low chloride concentrations indicate that there is no major groundwater salinization. Variability of the observed data between sampling locations is probably due to natural mineral weathering and also some local domestic wastewater inputs. The high correlation between chloride and TDS (r = 0.78) also indicates that chloride is a significant component of the aquifer's dissolved ionic content. As a result, elevated chloride concentrations in the vicinity of high-density communities could thus be considered as early warning signs for anthropogenic impacts prior to the onset of more significant contamination (Verma *et al.,* 2025). In general, the chloride concentrations indicate that the aquifer is fairly well protected from broad scale domestic and industrial contamination

Trace Metal Assessment

The concentration of iron, zinc and copper were all significantly lower than the guideline values recommended by WHO, indicating that the heavy-metal contamination is very low. The low concentrations of iron, zinc, and copper observed in this study suggest limited heavy-metal contamination within the study area, contrasting with elevated concentrations reported in groundwater influenced by municipal dumpsites in Benin City (Asemota *et al.,* 2026). This difference underscores the importance of the local impact of land use and disposal practices on groundwater quality. Moderate positive relationships between iron, zinc and copper indicate that these elements are from a geogenic source associated with mineral dissolution and ground water interactions. In the present study, no significant anthropogenic enrichment in the concentrations of the trace metals was found, except for aquifers with long water–rock interaction time and anthropogenic inputs (Fuentes-Rivas *et al.,* 2026). Lack of higher levels of heavy metals greatly diminishes the risk of chronic toxicological effects from long-term groundwater use. The geochemistry of the groundwater may alter as the urbanization progresses over time, however, and should be monitored on a periodic basis.

Microbiological Quality

The microbiological quality varied from physicochemical quality. Localized faecal contamination was seen as the total coliform concentration was as high as 84 CFU 100mL-1 and one borehole was positive for Escherichia coli. This indicates that even though the physicochemical parameters of the water sources are good, chemical quality is not a good indicator of safe drinking water. The presence of total coliforms and *E.* coli in some boreholes indicates point source contamination which may be due to poor sanitary protection, backed up septic tanks or waste disposal. The same has been found by Traoré *et al.* (2023), who considered poor sanitation infrastructure and nearness to contamination sources as significant risk factors for groundwater contamination in Burkina Faso. Inadequate sanitary protection, and setback from septic tanks, can pollute shallow groundwater, as well as infiltration from heavy rainfall, as illustrated here, and from faulty borehole construction. The intermittent contamination indicates that contamination is point source and not pervasive. The same conclusion was reached in many other groundwater surveys carried out in Nigeria where the microbiological standard was not met by a few boreholes, and the chemical standard was acceptable (Jagaba *et al.,* 2024; Odewade *et al.,* 2025). These considerations of public health importance of even sporadic presence of E. coli are important as it can suggest the presence of enteric pathogens which can lead to gastroenteritis and dysentery along with typhoid fever. So, in addition to physicochemical monitoring, routine chlorination, sanitary inspections and better protection of the groundwater should be carried out.

Correlation Analysis

Table 4. Correlation Matrix describing Relationships among Parameters

Parameter	pH	Turbidity	TDS	EC	Nitrate	Chloride	Iron	Zinc	Copper
Ph	1.00								
Turbidity	0.31	1.00							
TDS	0.82	0.71	1.00						
EC	0.99	0.72	0.998	1.00					
Nitrate	0.54	0.42	0.63	0.63	1.00				
Chloride	0.66	0.51	0.78	0.78	0.69	1.00			
Iron	0.39	0.47	0.44	0.44	0.51	0.42	1.00		
Zinc	0.28	0.34	0.36	0.36	0.41	0.38	0.63	1.00	
Copper	0.23	0.29	0.31	0.31	0.47	0.44	0.68	0.72	1.00

Significance level: $p < 0.05$

Groundwater quality parameters were also investigated for the significant correlative relationship using Pearson's correlation analysis (Table 4) which provided information on hydrogeochemical processes controlling groundwater quality. The extremely high positive correlation between EC and TDS also agrees with the results of Raman and Geetha (2005), who found that the correlation analysis is a good method to determine hydrochemical relationships and predict groundwater quality. In a similar way, chloride and TDS are also positively correlated suggesting that chloride is a major significant mineralizer in groundwater (El Mountassir and Bahir, 2023). Nitrate and chloride were moderately correlated suggesting a common anthropogenic source, such as domestic wastewater infiltration from septic systems and pit latrines. The relationships suggest that any groundwater contamination may increase with urban development.

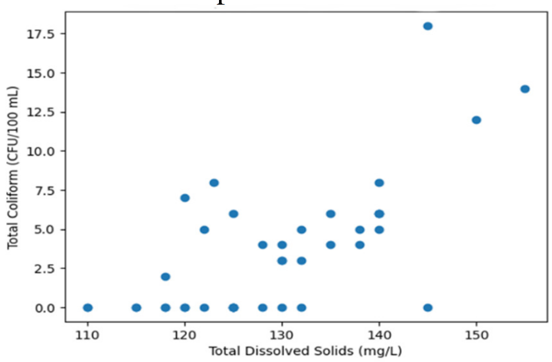

Fig. 2: Relationship between TDS and Total coliform

On the other hand, the lack of strong links between the microbial indicators and the physicochemical variables (Figure 2) confirms that the bacteriological contamination is mainly related to local sanitary conditions and not to the groundwater chemistry (Traoré *et al.*, 2023). Thus, physicochemical monitoring isn't sufficient to ensure microbiological safety.

Water Quality Index (WQI)

A widely-used hydrochemical tool is the Water Quality Index (WQI), which is a combination of several physicochemical parameters. It offers a comprehensive evaluation of the groundwater suitability for drinking water and helps in comparison of different hydrogeological settings (Aladejana *et al.,* 2021, Shuaibu *et al.,* 2024).

Table 5: Weighted Arithmetic Water Quality Index (WQI) Values for Groundwater Samples

Parameter	**Observed Value (V_i)**	**Standard (S_i)**	**Quality Rating (Q_i)**	**Weight (W_i) = $1/S_i$**
pH	7.00	8.5	0.00	0.1176
Turbidity	0.48	5	9.60	0.2000
TDS	129.2	500	25.84	0.0020
EC	258.5	900	28.72	0.0011
Nitrate	5.77	45	12.82	0.0222
Chloride	30.8	250	12.32	0.0040
Iron	0.1116	0.30	37.20	3.3333
Zinc	0.057	3	1.90	0.3333
Copper	0.056	2	2.80	0.5000
WQI	$\frac{\sum(Q_i W_i)}{\sum(W_i)} = \frac{130.56}{4.5135} = \mathbf{28.93}$			

The calculated WQI is 28.93 (Table 5) that indicated the groundwater is good for drinking purpose as shown in Table 2. This shows the value of WQI as a practical tool to support decision making for communicating overall water quality status. While Uddin *et al.* (2021) noted that conventional WQI models are mostly based on physicochemical parameters, they fail to consider the presence of microbes and emerging pollutants. Therefore, WQI should be used in conjunction with microbiological testing and sanitary inspections to give a more holistic picture of the safety of drinking water. Water quality inspection and microbial risk assessment should be performed in future groundwater assessment programmes to create a comprehensive assessment of the safety of drinking-water.

Conclusion

Most borehole water in Benin City is found to be acceptable in terms of physicochemical parameters but occasional presence of total coliforms and sporadic *E.* coli suggests there is a persistent public health issue. These microorganisms are present, indicating the need for sanitary protection and regular treatment; however, chemical parameters are not frequently found above the guidelines. Regular chlorination of boreholes should be carried out and users encouraged to practice safe water handling, to enhance safety. A sanitary inspection of each borehole should also be undertaken, and damaged headworks/casing repaired or upgraded as soon as possible.

Also, a community monitoring initiative should be established to provide for seasonal water quality checks and the early stage of detection of contamination. The risk of recontamination can be reduced through proper latrine positioning, proper disposal, and household water treatment (HWT) in the context of public-health education. Groundwater management in the study area should consider the routine monitoring of chemicals and microbiology for sustainable protection of public health.

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