

Bio-Physical Characterization and Associated Public Health Hazards of Borehole Water Sited in Close Proximity to Septic Tanks Within Selected Residential Areas in Port Harcourt, Rivers State

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Abstract: The study examined the water quality of boreholes in relation to their closeness to septic tanks. The physicochemical analysis indicated that there was widespread pollution of groundwater resources. Electrical conductivity was 1920 ± 200 $\mu\text{S}/\text{cm}$, total dissolved solid content of 920 ± 95 mg/L , nitrogen at 88 ± 10 mg/L , and BOD was recorded to be 7.9 ± 0.9 mg/L in high density building. Statistical significance as shown by ANOVA results indicates spatial variation with F values being as high as 260.9 for salinity and 255.8 for ammonium ($p \leq 0.001$). Distance analysis clearly shows contamination gradients as seen in nitrate values of 85 ± 9 mg/L at 10 m and 49 ± 5 mg/L at 30m even though residual contamination is found beyond the safe limit. There was also very high faecal contamination as total coliforms varied from 180 to 1200 CFU/100 mL and E. coli from 40 to 500 CFU/100 mL at different sites. Pathogens like *Salmonella spp.*, *Giardia lamblia* (8–60 cysts/L), and *Cryptosporidium spp* (3–30 oocysts/L) were identified, clearly indicating the high public health hazards associated with the groundwater. However, even with these pathogens present, perception analysis revealed a lower awareness of the contamination and health hazard, as indicated by only 23.1% to 35.2% recognizing contamination. It is recommended in this study that there should be strict adherence to setbacks guidelines, urban planning policies, groundwater monitoring, and public health education as groundwater contamination is identified to be due to spatial proximity, institutional inadequacy, and socio-economic issues.

Keywords: Groundwater, Public Health, Coliform, Contamination, Hazard.

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I. INTRODUCTION

Water is indispensable for sustaining life, and access to safe water is fundamental to public health. However, urbanization and industrialization have led to the contamination of common water sources, such as surface water and rainwater, through industrial effluents and household waste. As a result, groundwater has become a critical alternative source. Access to clean and fresh water is not only vital for health but also plays a key role in economic growth and social well-being. Groundwater, which

constitutes one of the most abundant yet vulnerable natural resources, provides about 88% of the world's safe drinking water. In Nigeria, a significant proportion of the population relies on groundwater for drinking, domestic, industrial, and agricultural purposes. Underground water, as the water located underneath the earth's surface in soil pore spaces and in the breakages of rock formations, has been polluted via industrialization and urbanization that has increasingly developed over time without any regard for environmental consequences, which eventually result in the deterioration of physico-chemical and biological properties of water (Longe

& Balogun, 2010). Septic systems provide wastewater discharge for many homeowners who also often get their drinking water from private wells, which in most cases are located close to septic tanks. If a septic system is not working properly or is located too close to a drinking water well, contaminants from the wastewater can end up in drinking water. Natural water sources inherently contain various dissolved substances. Unfortunately, pollutants such as pathogenic microorganisms, heavy metals, nitrates, and salts have increasingly infiltrated water supplies. These contaminants often result from improper waste disposal from human and animal sources, industrial influence, and the unsustainable exploitation of water resources (Singh & Mosley, 2003). Septic tanks are widely used, especially in areas without centralized sewer systems such as rural communities, urban fringes, campgrounds, and recreational facilities for the treatment of domestic wastewater. They function by separating solids from liquids and allowing partial treatment before the effluent is discharged into the surrounding environment.

Wastewater from septic systems is typically discharged into a drain field, where the surrounding soil acts as a natural filter. However, in regions with a high density of septic tanks, pathogenic microorganisms can infiltrate shallow groundwater or nearby surface water bodies (McNinch & Dreelin, 2010). In many developing countries, rapid urban growth and industrial expansion have placed significant pressure on water supply systems. Limited access to functional water treatment plants and piped water networks has compelled communities to seek alternative sources of water, with groundwater often regarded as the most reliable option. As the largest freshwater reserve, groundwater exists within soil pores, sediment layers, and narrow fractures in bedrock. It can be accessed through machine-drilled boreholes or, in some cases, hand-dug wells, which are still common in less developed regions (Adelekan, 2010). Faulty or poorly maintained septic tanks can leak extensively, introducing harmful microorganisms into the environment. This contamination pathway can transmit diseases caused by pathogens such as *Vibrio cholerae*, *Yersinia enterocolitica*, and *Escherichia coli*, as well as vector-borne illnesses including guinea worm, schistosomiasis, lymphatic filariasis, and various parasitic and viral infections (Al-Jaboobi *et al.*, 2014). According to Fubara-Manuel & Jumbo (2014), well-functioning septic systems can effectively reduce the presence of microorganisms and organic pollutants but are less effective in removing anions. However, when septic systems are constructed too close to the water table, their efficiency in eliminating microorganisms, organic matter, and phosphorus is significantly reduced. In many areas, water supply infrastructures fail to adequately meet community needs, often due to factors such as corruption, poor maintenance, and population growth. As a result, the shortage of piped water has pushed many communities to depend on alternative sources, with groundwater being the most accessible option (Adelekan, 2010).

When septic tanks fail or leak, they can cause serious environmental degradation. While many households depend on septic systems for wastewater disposal, the final discharge

still infiltrates the surrounding soil. The quality of groundwater, in turn, depends on various physico-chemical factors, which are influenced by the geological formations it passes through as well as human activities within the recharge area (Hejaz *et al.*, 2020). Rapid population growth has intensified the challenges of groundwater contamination. The rapid growth of population, industrialization, and urbanization in metropolitan cities worldwide has contributed significantly to the degradation of groundwater resources, which has become a major environmental concern globally (Hejaz *et al.*, 2020). In Nigeria, urbanization is often accompanied by high population density, intensified industrial and agricultural activities, and environmental challenges such as pollution, land degradation, and indiscriminate waste disposal. These factors collectively pose significant threats to groundwater quality, with potential health risks, particularly in urban settings (Adelana *et al.*, 2008; Eni *et al.*, 2011; Ocheri *et al.*, 2014). It is against this backdrop that this study seeks to examine the bio-physical characterization of borehole water located in close proximity to septic tanks and its public health implications on the people in selected residential neighbourhoods in Port Harcourt.

II. MATERIALS AND METHODS

The study area cut across residential neighbourhoods in Port Harcourt City, Obio/Akpor and Ikwerre Local Government Areas (Figure 1). The climate of the area is characterized by heavy rainfall and high temperature throughout the year. These conditions are attributable to its Geographical contiguity to the Atlantic Ocean. The climate in Port Harcourt is tropical monsoon, with long intense rainy seasons and brief dry season. The monthly rainfall in the area is almost predictable and follows a temporal sequence of increase toward June - August before decreasing in the dry season months of November to February (Osuiwu and Ologunorisa, 1999).

➤ Population, Sampling and Analysis

The study population is considered in two phases: the water sampling phase and the questionnaire administration phase. In the first phase (water sampling), the study area was stratified into six neighbourhood categories based on population distribution and natural spatial delineations (Table 1). From each neighbourhood, three compounds were purposively selected based on accessibility, presence of boreholes, and proximity to septic tanks. The purposive approach was necessary due to limited accessibility to private residential compounds and the high cost of laboratory analysis. In total, 18 sampling points were established. Borehole sampling was further guided by proximity classification to septic tanks. Distances were measured at 10 m, 20 m, and 30 m, which were used to define sampling intervals. Each neighbourhood therefore had borehole samples representing each distance category, ensuring spatial comparability across the study area.

Water samples were obtained by filling up sterilised 1-litre plastic bottles. Before obtaining water samples, the bottles were rinsed first with distilled water and then with water intended to be used in order to prevent contamination.

Collection was done from 7:00 am to 10:00 am in order to achieve consistency of the environment. Bottles were filled up to the brim to avoid air inclusion and were immediately sealed and marked indicating the sampling points.

In-situ variables such as pH, electrical conductivity (EC), salinity, and temperature were recorded right in the field because of their sensitivity to environmental variation. Other variables such as dissolved oxygen (DO), biological oxygen demand (BOD₅), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), ammonium nitrate (NH₄-N), and coliform were measured in laboratory after collecting the water within 24 hours. Lastly, altogether 108 composite water samples were analyzed (6 months data collection period). The analysis was done using Analysis of Variance (ANOVA) statistical tool.

Taro Yamene Formula Computation

$$n = \frac{N}{1+N(e)^2} \dots\dots\dots \text{equation (1)}$$

Where n = sample size

N = Overall population size (3427718)

e = 0.05

n= 399.9 (approximately 400)

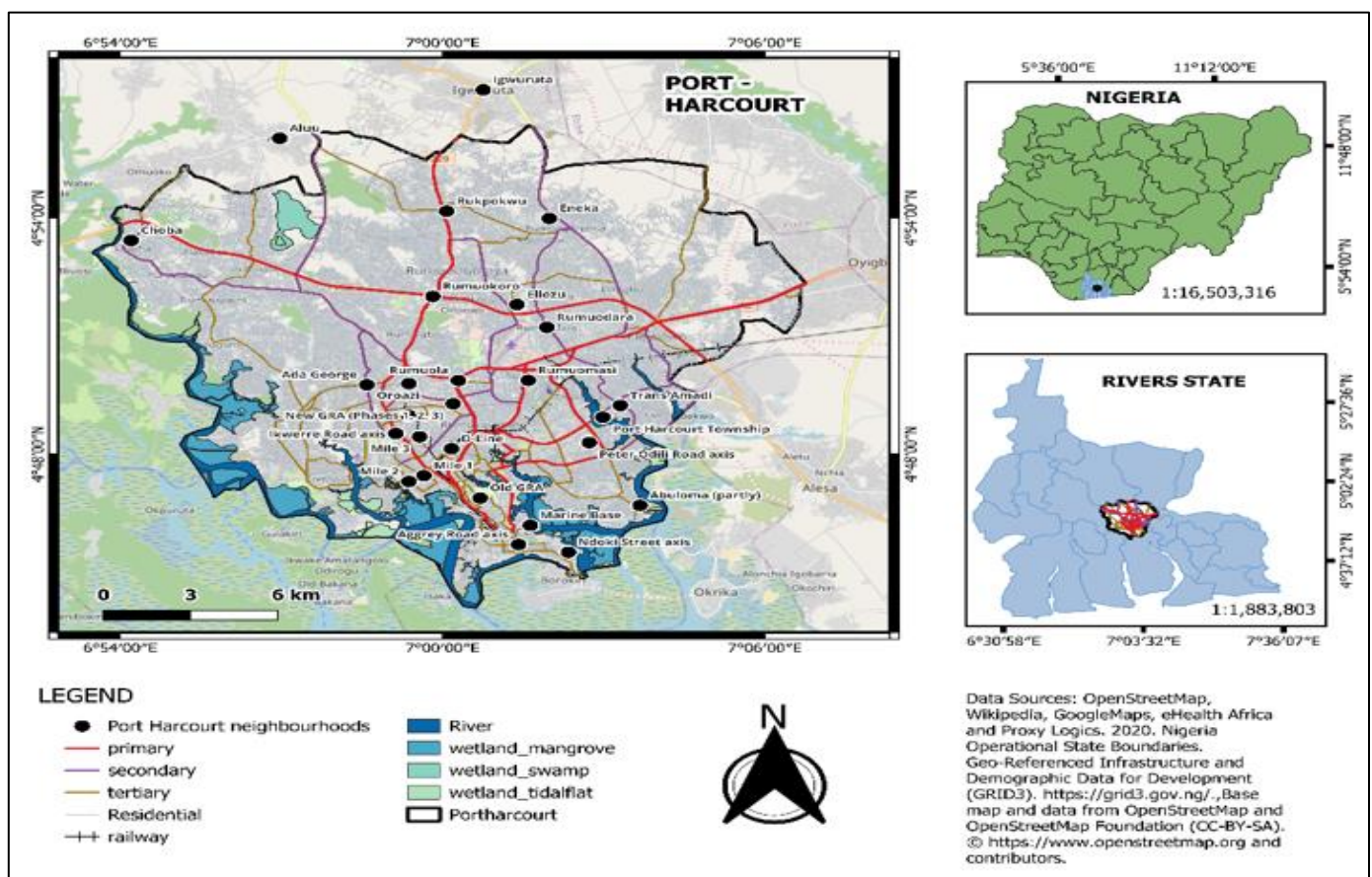


Fig 1 Rivers State Showing Port Harcourt, Metropolis

Table 1 Population and Sample Size of the Study

S/N	Neighbourhood Category	Neighbourhoods Included	Target human population	Water sampling points	Taro Yamane size
1	Government Reserved Areas (GRA) and Highbrow Districts	Old GRA, New GRA (Phase 1, 2, 3), Peter Odili Road axis, Abuloma (partly)	225,145	3	26
2	Central Urban Core / City Centre	Port Harcourt Township, D-Line, Ikwerre Road axis, Marine Base	375,113	3	44
3	Diobu High Density Areas	Mile 1, Mile 2, Mile 3, Ndoki Street axis, Aggrey Road axis	635,123	3	74

4	Rumuokoro–Rumuola– Rumuomasi Axis	Rumuokoro, Rumuola, Rumuomasi, Eliozi, Choba	675,113	3	79
5	Trans Amadi and Surrounding Areas	Trans Amadi, Woji, Ada George, Oroazi	734,101	3	86
6	Outskirts and Expanding Residential Areas	Eneka, Rumuodara, Rukpokwu, Aluu, Igwuruta	783,123	3	91
		Total	3427718	18	400

Table 2 Perception of Residents Regarding the Health and Environmental Risks Associated with Siting Septic Tanks Near Boreholes in the Study Area

Statement	SA (%)	A (%)	D (%)	SD (%)	U (%)	Total (%)	WM
Siting septic tanks close to boreholes can contaminate drinking water.	44 (11.1)	72 (18.1)	115 (28.9)	101 (25.4)	66 (16.6)	398(100)	2.81
Borehole water near septic tanks is unsafe for human consumption.	36 (9.0)	60 (15.1)	111 (27.9)	123 (30.9)	68 (17.1)	398(100)	2.66
Poor sanitation around boreholes increases risk of waterborne diseases.	48 (12.1)	84 (21.1)	100 (25.1)	108 (27.1)	58 (14.6)	398(100)	2.88
Septic tank leakage can affect groundwater quality.	52 (13.1)	76 (19.1)	104 (26.1)	96 (24.1)	70 (17.6)	398(100)	2.85
I am aware that proximity of septic tanks to boreholes poses health risks.	40 (10.1)	64 (16.1)	92 (23.1)	116 (29.1)	86 (21.6)	398(100)	2.64
Drinking water from boreholes close to septic tanks can cause illnesses such as typhoid.	36 (9.0)	56 (14.1)	108 (27.1)	120 (30.2)	78 (19.6)	398(100)	2.62
Residents understand environmental risks of poor waste disposal systems.	32 (8.0)	52 (13.1)	98 (24.6)	136 (34.2)	80 (20.1)	398(100)	2.55
Groundwater pollution is likely when septic tanks are poorly located.	44 (11.1)	68 (17.1)	104 (26.1)	112 (28.1)	70 (17.6)	398(100)	2.76
Distance between boreholes and septic tanks affects water safety.	52 (13.1)	76 (19.1)	96 (24.1)	104 (26.1)	70 (17.6)	398(100)	2.83
Contaminated borehole water can cause long-term health problems.	48 (12.1)	72 (18.1)	100 (25.1)	108 (27.1)	70 (17.6)	398(100)	2.79
Many residents are not aware of dangers of improper septic tank siting.	40 (10.1)	60 (15.1)	120 (30.2)	110 (27.6)	68 (17.1)	398(100)	2.73
Environmental pollution from septic systems is a serious issue.	44 (11.1)	64 (16.1)	96 (24.1)	120 (30.2)	74 (18.6)	398(100)	2.7
Safe water supply is compromised when boreholes are too close to septic tanks.	40 (10.1)	68 (17.1)	108 (27.1)	112 (28.1)	70 (17.6)	398(100)	2.73
Government and health agencies have not adequately educated residents.	36 (9.0)	56 (14.1)	104 (26.1)	124 (31.2)	78 (19.6)	398(100)	2.61
Proper siting of septic tanks can significantly reduce health risks.	60 (15.1)	80 (20.1)	88 (22.1)	100 (25.1)	70 (17.6)	398(100)	2.89

Table 2 presents a clear picture of residents' perception using the full Likert distribution, and when the percentages are carefully examined alongside the weighted means, a more nuanced interpretation of risk awareness emerges. Across all statements, the pattern of responses is dominated by disagreement and uncertainty rather than strong agreement. For most items, Disagree (D) and Strongly Disagree (SD) together consistently account for the largest share of responses, typically ranging from about 50% to over 60% per statement, while Strongly Agree (SA) and Agree (A) combined rarely exceed 30%. The Undecided (U) category also remains relatively high across items, generally fluctuating between 14.6% and 21.6%, which further signals uncertainty and lack of firm knowledge among respondents. For example, in the statement that septic tanks close to

boreholes can contaminate drinking water, only 29.2% (SA + A) of respondents show agreement, while 54.3% (D + SD) express disagreement, and 16.6% remain undecided. This pattern is critical because it shows that even a basic environmental fact, widely supported by empirical water quality results, is not strongly accepted by the majority of residents. A similar pattern is observed for "borehole water near septic tanks is unsafe for human consumption", where only 24.1% agree, compared to 58.8% who disagree or strongly disagree, with 17.1% undecided. For health related perception, the gap is even more pronounced. The statement linking poor sanitation to waterborne diseases shows 33.2% agreement (SA + A), while 52.2% disagree or strongly disagree, and 14.6% remain undecided. Likewise, awareness that proximity of septic tanks poses health risks records only

26.2% agreement, against 52.2% disagreement, and a relatively high 21.6% uncertainty. This indicates that a substantial proportion of residents either do not perceive or do not fully acknowledge the direct health implications of groundwater contamination.

Interestingly, the highest levels of disagreement appear in statements that directly link water consumption to specific diseases such as typhoid. Here, only 23.1% agree, while a dominant 57.3% disagree or strongly disagree, and 19.6% remain undecided. This suggests that disease specific risk perception is particularly weak, even though microbiological results from earlier tables clearly indicate faecal contamination. The perception that residents understand environmental risks of poor waste disposal systems records one of the lowest agreement levels, with only 21.1% agreement, compared to 58.8% disagreement, and 20.1% undecided. This reinforces the argument that environmental knowledge is generally low and unevenly distributed across the population. Even for the statement that septic tank leakage

can affect groundwater quality, which is a relatively basic environmental concept, only 32.2% agree, while 50.2% disagree or strongly disagree, and 17.6% remain undecided. This is particularly important because it highlights a disconnect between observable environmental conditions and public understanding. The only statement with relatively higher agreement is that proper siting of septic tanks can reduce health risks, where 35.2% agree, 47.2% disagree or strongly disagree, and 17.6% are undecided. Even here, disagreement remains dominant, suggesting weak acceptance of preventive environmental practices. The relatively high proportion of undecided responses (up to about one-fifth of respondents in several items) further highlights an information gap, suggesting that environmental health messages may not be effectively reaching or influencing the population. This is particularly important when considered alongside the earlier physicochemical and biological evidence of contamination, which clearly demonstrates real and significant groundwater quality risks.

Table 3 Physicochemical Parameters of Water in the Various Neighbourhoods of the Study Area Compared to the WHO Limits

S/N	Parameter	Unit	WHO Limit	A	B	C	D	E	F
1	pH	–	6.5–8.5	6.2 ± 0.3	6.1 ± 0.4	5.8 ± 0.5	5.7 ± 0.4	6.3 ± 0.3	6.6 ± 0.2
2	Temperature	°C	Ambient	28.4 ± 0.6	29.1 ± 0.8	29.5 ± 0.7	29.3 ± 0.6	28.9 ± 0.5	27.8 ± 0.4
3	EC	µS/cm	1000	1250 ± 120	1480 ± 150	1850 ± 180	1920 ± 200	1400 ± 130	980 ± 90
4	TDS	mg/L	500	620 ± 60	710 ± 75	890 ± 90	920 ± 95	680 ± 70	480 ± 50
5	DO	mg/L	≥5	3.8 ± 0.5	3.2 ± 0.6	2.5 ± 0.5	2.3 ± 0.4	3.6 ± 0.5	4.6 ± 0.4
6	BOD ₅	mg/L	≤3	5.2 ± 0.6	6.1 ± 0.7	7.5 ± 0.8	7.9 ± 0.9	5.8 ± 0.6	3.6 ± 0.4
7	COD	mg/L	≤10	18 ± 2.1	22 ± 2.5	28 ± 3.0	30 ± 3.2	20 ± 2.3	12 ± 1.5
8	TOC	mg/L	≤10	12.5 ± 1.4	14.2 ± 1.6	18.6 ± 2.0	19.8 ± 2.2	13.1 ± 1.5	10.8 ± 1.2
9	Nitrate	mg/L	50	58 ± 6	65 ± 7	82 ± 9	88 ± 10	60 ± 6	48 ± 5
10	Nitrite	mg/L	0.2	0.35 ± 0.04	0.42 ± 0.05	0.60 ± 0.07	0.65 ± 0.08	0.38 ± 0.04	0.22 ± 0.03
11	Ammonium	mg/L	0.5	0.9 ± 0.1	1.2 ± 0.2	1.8 ± 0.2	2.0 ± 0.3	1.1 ± 0.2	0.6 ± 0.1
12	Phosphate	mg/L	0.3	0.8 ± 0.1	1.0 ± 0.1	1.4 ± 0.2	1.5 ± 0.2	0.9 ± 0.1	0.4 ± 0.1
13	Chloride	mg/L	250	310 ± 30	360 ± 35	420 ± 40	440 ± 45	330 ± 30	260 ± 25
14	Sulphate	mg/L	250	270 ± 25	290 ± 28	340 ± 30	360 ± 35	280 ± 25	240 ± 20
15	Calcium	mg/L	75	85 ± 8	92 ± 9	110 ± 12	115 ± 13	88 ± 8	70 ± 6
16	Magnesium	mg/L	50	58 ± 6	64 ± 7	78 ± 8	82 ± 9	60 ± 6	48 ± 5
17	Total Hardness	mg/L	200	240 ± 20	270 ± 25	320 ± 30	340 ± 35	260 ± 25	190 ± 18
18	Turbidity	NTU	5	7.5 ± 0.8	9.2 ± 1.0	12.5 ± 1.3	13.2 ± 1.5	8.6 ± 0.9	5.8 ± 0.6
19	Salinity	Ppt	≤0.5	0.7 ± 0.1	0.8 ± 0.1	1.1 ± 0.1	1.2 ± 0.2	0.75 ± 0.1	0.55 ± 0.05

a. Government Reserved Areas (GRA) and Highbrow Districts, b Central Urban Core / City Centre, c. Diobu High Density Areas, d. Rumuokoro–Rumuola–Rumuomasi Axis, e. Trans Amadi and Surrounding Areas. f. Outskirts and Expanding Residential Areas

Table 3 provides a comprehensive overview of the physicochemical quality of groundwater across the study area, benchmarked against WHO permissible limits. A critical examination of both the mean values and their associated standard deviations (SD) reveals not only the extent of contamination but also the variability of pollution

intensity across neighbourhoods, which is important for understanding spatial heterogeneity in groundwater quality. Starting with pH, all zones record slightly acidic conditions, with values ranging from 5.7 ± 0.4 in Rumuokoro–Rumuola–Rumuomasi to 6.6 ± 0.2 in the outskirts. The relatively low SD values (0.2–0.5) indicate moderate consistency within sampling points, suggesting that acidity is a widespread and stable condition rather than an isolated occurrence. The deviation from the WHO acceptable range (6.5–8.5) in most urban core areas implies persistent acidification of groundwater, likely influenced by sewage infiltration and organic decomposition processes.

Temperature values remain relatively uniform across all locations, ranging from 27.8 ± 0.4 °C to 29.5 ± 0.7 °C. The low SD values across all zones indicate minimal spatial variation, which is expected given the influence of ambient climatic conditions rather than anthropogenic sources. However, slightly elevated temperatures in high-density areas may indirectly enhance microbial activity and accelerate biochemical reactions in contaminated aquifers. Electrical conductivity (EC) shows a marked increase in urban core areas, with Diobu recording the highest value of 1850 ± 180 μ S/cm, followed closely by Rumuokoro–Rumuola–Rumuomasi at 1920 ± 200 μ S/cm. The relatively higher SD values in these zones (± 180 – 200 μ S/cm) indicate notable spatial variability in ionic concentration, reflecting uneven distribution of pollution sources such as septic leakage and wastewater discharge. In contrast, the outskirts recorded a much lower EC of 980 ± 90 μ S/cm, suggesting comparatively reduced anthropogenic loading and more stable groundwater conditions. Total Dissolved Solids (TDS) follow a similar trend, with the highest mean values observed in Diobu (890 ± 90 mg/L) and Rumuokoro–Rumuola–Rumuomasi (920 ± 95 mg/L), both exceeding the WHO limit of 500 mg/L. The SD values here indicate moderate variability, suggesting that contamination is widespread but not uniform across sampling points. The lower TDS in the outskirts (480 ± 50 mg/L) falls within acceptable limits, reinforcing the spatial gradient of pollution from urban core to periphery.

Dissolved Oxygen (DO) levels are critically low across all urban zones, particularly in Diobu (2.5 ± 0.5 mg/L) and Rumuokoro–Rumuola–Rumuomasi (2.3 ± 0.4 mg/L), far below the WHO minimum of 5 mg/L. The relatively low SD values indicate that oxygen depletion is consistently observed across sampling points, reflecting high organic pollution loads and active microbial consumption of oxygen in groundwater systems. Biochemical Oxygen Demand (BOD₅) and Chemical Oxygen Demand (COD) present strong evidence of organic contamination. BOD₅ peaks at 7.9 ± 0.9 mg/L in Rumuokoro–Rumuola–Rumuomasi and 7.5 ± 0.8 mg/L in Diobu, both more than double the WHO limit of 3 mg/L. The higher SD values (± 0.8 – 0.9 mg/L) indicate spatial inconsistency, suggesting localized hotspots of organic pollution likely linked to uneven septic tank distribution. Similarly, COD values reach 30 ± 3.2 mg/L in Rumuokoro–Rumuola–Rumuomasi, with relatively higher variability, reinforcing the presence of heterogeneous pollution inputs. Total Organic Carbon (TOC) ranges from 10.8 ± 1.2 mg/L in the outskirts to 19.8 ± 2.2 mg/L in Rumuokoro–Rumuola–Rumuomasi. The SD values here (± 1.2 – 2.2 mg/L) are relatively higher compared to many other parameters, indicating fluctuating organic load distribution across sampling points, which is typical of areas with inconsistent waste management and septic system density. Nitrate

concentrations are particularly alarming, with values ranging from 48 ± 5 mg/L in the outskirts to 88 ± 10 mg/L in Rumuokoro–Rumuola–Rumuomasi. The relatively high SD values (± 5 – 10 mg/L) suggest uneven infiltration of nitrogenous waste, consistent with localized septic tank leakage and varying soil permeability conditions. Nitrite and ammonium also show similar trends, with higher variability in densely populated zones, indicating active nitrogen transformation processes in contaminated aquifers. Phosphate levels (0.8 ± 0.1 to 1.5 ± 0.2 mg/L) exceed WHO limits across all urban zones, with moderate SD values indicating relatively consistent contamination likely from domestic wastewater sources. Chloride and sulphate also show elevated concentrations, particularly in Diobu and Rumuokoro–Rumuola–Rumuomasi, with SD values suggesting moderate spatial variability linked to anthropogenic inputs. Calcium, magnesium, and total hardness values are highest in urban core areas, with Diobu recording 110 ± 12 mg/L (Ca), 78 ± 8 mg/L (Mg), and 320 ± 30 mg/L (hardness). The SD values indicate moderate dispersion, suggesting that mineral enrichment is influenced by both natural geochemical processes and anthropogenic contamination. Turbidity shows a pronounced spatial variation, with values reaching 13.2 ± 1.5 NTU in Rumuokoro–Rumuola–Rumuomasi and 12.5 ± 1.3 NTU in Diobu, both significantly above the WHO limit of 5 NTU. The relatively higher SD values reflect inconsistent particulate contamination, likely due to episodic infiltration from surface runoff and septic leakage pathways. Salinity also increases progressively towards the urban core, peaking at 1.2 ± 0.2 ppt in Rumuokoro–Rumuola–Rumuomasi. The SD values, though relatively low, indicate steady accumulation of dissolved salts in groundwater, possibly from wastewater intrusion and urban surface runoff. Succinctly, the pattern of mean values demonstrates a clear deterioration of groundwater quality from the outskirts towards densely populated urban centres, while the standard deviations provide evidence of spatial variability in pollution intensity. Higher SD values in urban core areas for most parameters suggest heterogeneous contamination sources, particularly septic tank leakage and uneven waste disposal practices, whereas lower SD values in peripheral areas indicate more stable and less disturbed groundwater systems. In all, the integration of both mean concentrations and standard deviations reveals that groundwater pollution in the study area is not only widespread but also spatially uneven, with severity strongly linked to urban density, sanitation infrastructure, and land use patterns. The consistent exceedance of WHO limits across multiple parameters further underscores a significant public health risk, particularly in high-density neighbourhoods where both contamination levels and variability are highest.

Table 4 ANOVA Summaries for Comparing the Physicochemical Parameters of Water in the Various Neighbourhoods of the Study Area

Models	Parameter	F-statistic	p-value	Decision	Duncan Grouping (best → worst)
1	pH	12.8	0.002	Significant	F (a), E (ab), A (b), B (bc), C (cd), D (d)
2	Temperature	9.6	0.001	Significant	C (a), D (ab), B (b), E (bc), A (c), F (d)
3	EC	210.4	0.003	Significant	D (a), C (a), B (b), E (c), A (c), F (d)

4	TDS	198.7	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
5	DO	85.3	0.000	Significant	F (a), A (b), E (bc), B (c), C (d), D (d)
6	BOD ₅	174.2	0.000	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
7	COD	260.5	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
8	TOC	165.9	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
9	Nitrate	190.6	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
10	Nitrite	240.1	0.000	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
11	Ammonium	255.8	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
12	Phosphate	230.4	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
13	Chloride	205.7	0.003	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
14	Sulphate	148.9	0.021	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
15	Calcium	132.6	0.000	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
16	Magnesium	140.8	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
17	Total Hardness	215.3	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
18	Turbidity	170.5	0.001	Significant	D (a), C (a), B (b), E (c), A (c), F (d)
19	Salinity	260.9	0.000	Significant	D (a), C (a), B (b), E (c), A (c), F (d)

Table 4 presents a robust statistical comparison of groundwater physicochemical parameters across the different neighbourhood categories using one-way ANOVA, complemented by Duncan Multiple Range Test (DMRT) for post-hoc classification. The results clearly demonstrate that spatial location exerts a statistically significant influence on all measured water quality parameters, with all F-statistics highly significant at $p < 0.05$, and in most cases at $p \leq 0.001$, confirming strong heterogeneity in groundwater quality across the study area.

The magnitude of the F-values is particularly revealing, as it reflects the degree of variability between neighbourhoods relative to within-neighbourhood variation. Extremely high F-statistics such as salinity ($F = 260.9$, $p = 0.000$), COD ($F = 260.5$, $p = 0.001$), ammonium ($F = 255.8$, $p = 0.001$), nitrite ($F = 240.1$, $p = 0.000$), phosphate ($F = 230.4$, $p = 0.001$), and turbidity ($F = 170.5$, $p = 0.001$) indicate very strong spatial differentiation in contamination levels. These high values confirm that groundwater pollution is not randomly distributed but strongly structured by location-specific anthropogenic pressures. Moderately high F-values such as total hardness ($F = 215.3$, $p = 0.001$), chloride ($F = 205.7$, $p = 0.003$), nitrate ($F = 190.6$, $p = 0.001$), EC ($F = 210.4$, $p = 0.003$), and TDS ($F = 198.7$, $p = 0.001$) further reinforce the presence of substantial spatial variability in both chemical and mineral content of groundwater. Even parameters with comparatively lower F-values, such as temperature ($F = 9.6$, $p = 0.001$) and pH ($F = 12.8$, $p = 0.002$), remain statistically significant, indicating that even basic physicochemical properties are spatially influenced, although to a lesser degree than pollution-related indicators. Spatially, the Duncan grouping provides a clear hierarchical pattern that reflects the underlying urban structure of the study area. The Diobu High Density Areas (D) and Rumuokoro–Rumuola–Rumuomasi axis (C) consistently fall within the worst-performing group (often labelled “a”), particularly for parameters with high pollution loading such as COD, BOD₅, nitrate, ammonium, salinity, and turbidity. This indicates that these zones represent the principal pollution hotspots, driven by intense population density, poor sanitation infrastructure, and minimal compliance with environmental setback standards. In contrast, the Outskirts and expanding residential

areas (F) consistently occupy the best-performing statistical group, particularly for DO ($F = 85.3$, $p = 0.000$), pH, TDS, and several nutrient-based contaminants. This spatial positioning reflects reduced anthropogenic pressure, lower housing density, and greater availability of land, which collectively reduce the likelihood of septic tank–borehole interaction and pollutant infiltration.

The Central Urban Core (B) and Trans Amadi (E) occupy intermediate DMRT groups across most parameters, indicating transitional water quality conditions. These areas reflect mixed spatial dynamics where industrial, commercial, and residential land uses overlap. The statistical grouping suggests moderate but persistent contamination, reinforcing the idea that groundwater quality degradation is not limited to informal settlements but extends into planned urban zones due to cumulative anthropogenic activities. Government Reserved Areas (A) also appear in overlapping Duncan subsets (such as “ab” and “bc”), indicating internal variability within these zones. While generally better than high-density areas, their statistical positioning shows that they are not immune to contamination processes. This may be linked to aging infrastructure, increasing urban encroachment, and localized failure in sanitation system management. From a spatial interpretation perspective, the consistent pattern across all parameters reveals a clear pollution gradient: outskirts (least impacted) → planned/intermediate zones → high-density urban cores (most impacted). The extremely high F-values for key pollution indicators such as salinity (260.9), COD (260.5), ammonium (255.8), and nitrite (240.1) demonstrate that spatial location is a dominant determinant of groundwater quality variation, far outweighing natural background variability. The very low p-values (mostly 0.000 and 0.001) across nearly all parameters strengthen the statistical reliability of these spatial differences, confirming that the observed variations are highly significant and not due to sampling error. This reinforces the argument that groundwater quality degradation is systematically structured by urban form, land use intensity, and environmental management effectiveness. In terms of implication, the findings suggest that groundwater contamination in the study area is fundamentally a spatially driven environmental problem. High population density and poorly planned urban

zones are acting as concentrated pollution sources, particularly through septic tank leakage and inadequate waste management, while peripheral areas function as relatively less disturbed recharge zones. However, the presence of contamination even in outskirts indicates that pollution is gradually diffusing outward with urban expansion. In conclusion, the ANOVA and Duncan post-hoc results provide strong statistical evidence that groundwater physicochemical

quality varies significantly across neighbourhoods, with a clear and consistent spatial hierarchy. The very high F-statistics and uniformly significant p-values confirm that urban structure and environmental management practices are key determinants of groundwater quality, while the spatial clustering of Duncan groups highlights a pronounced urban-to-peripheral pollution gradient in the study area.

Table 5 Physicochemical Parameters of Water in the Various Neighbourhoods of the Study Area Compared to the WHO Limits at Varying Distances from Septic Tanks.

S/N	Parameter	Unit	WHO Limit	10 m	20 m	30 m
1	pH	–	6.5–8.5	5.7 ± 0.4	6.1 ± 0.3	6.5 ± 0.2
2	Temperature	°C	Ambient	29.4 ± 0.7	28.8 ± 0.6	28.1 ± 0.5
3	EC	µS/cm	1000	1900 ± 180	1450 ± 140	1050 ± 100
4	TDS	mg/L	500	910 ± 90	690 ± 70	520 ± 50
5	DO	mg/L	≥5	2.4 ± 0.4	3.5 ± 0.5	4.7 ± 0.4
6	BOD ₅	mg/L	≤3	7.8 ± 0.8	5.9 ± 0.6	3.8 ± 0.4
7	COD	mg/L	≤10	29 ± 3.0	21 ± 2.2	13 ± 1.6
8	TOC	mg/L	≤10	19.5 ± 2.1	13.8 ± 1.5	11.0 ± 1.2
9	Nitrate	mg/L	50	85 ± 9	62 ± 6	49 ± 5
10	Nitrite	mg/L	0.2	0.62 ± 0.07	0.40 ± 0.05	0.21 ± 0.03
11	Ammonium	mg/L	0.5	1.9 ± 0.2	1.1 ± 0.2	0.6 ± 0.1
12	Phosphate	mg/L	0.3	1.4 ± 0.2	0.9 ± 0.1	0.4 ± 0.1
13	Chloride	mg/L	250	430 ± 40	340 ± 30	270 ± 25
14	Sulphate	mg/L	250	350 ± 30	280 ± 25	245 ± 20
15	Calcium	mg/L	75	112 ± 12	88 ± 9	72 ± 6
16	Magnesium	mg/L	50	80 ± 8	60 ± 6	48 ± 5
17	Total Hardness	mg/L	200	330 ± 30	260 ± 25	195 ± 18
18	Turbidity	NTU	5	12.8 ± 1.4	8.7 ± 0.9	5.9 ± 0.6
19	Salinity	Ppt	≤0.5	1.15 ± 0.15	0.78 ± 0.10	0.55 ± 0.05

Table 5 presents a distance-based analysis of groundwater physicochemical quality in relation to septic tank proximity, compared against WHO permissible limits. The results clearly demonstrate a strong inverse relationship between distance from septic tanks and the level of groundwater contamination, with water quality consistently improving as the distance increases from 10 m to 30 m. At 10 m from septic tanks, groundwater quality is critically degraded across almost all parameters. The pH value of 5.7 ± 0.4 indicates acidic conditions below the WHO acceptable range, suggesting active influence of organic decomposition and acidic leachates from septic systems. This condition is fairly consistent given the relatively low standard deviation, implying that acidity is a widespread and stable characteristic at close proximity to septic sources. Electrical conductivity (1900 ± 180 µS/cm) and total dissolved solids (910 ± 90 mg/L) at this distance are almost double the WHO limits, indicating a very high ionic and dissolved pollutant load. The relatively high standard deviations here reflect spatial variability in contamination intensity, likely due to uneven septic tank distribution, differing soil permeability, and varying waste loading rates. The oxygen-related parameters further confirm severe pollution at 10 m. Dissolved oxygen is extremely low at 2.4 ± 0.4 mg/L, while BOD₅ (7.8 ± 0.8 mg/L) and COD (29 ± 3.0 mg/L) are highly elevated. These values indicate intense organic pollution and active microbial decomposition, typical of septic effluent intrusion into shallow groundwater. The moderate SD values suggest consistent organic loading across

sampling points, reinforcing the dominance of septic tank influence at close range. Nutrient pollution is also particularly severe at this distance. Nitrate (85 ± 9 mg/L), nitrite (0.62 ± 0.07 mg/L), ammonium (1.9 ± 0.2 mg/L), and phosphate (1.4 ± 0.2 mg/L) all greatly exceeded WHO limits. The relatively higher standard deviations for nitrate and chloride indicate heterogeneous contamination pathways, likely reflecting variable leakage intensity and groundwater flow direction. These elevated nutrient levels strongly suggest direct sewage infiltration, posing significant risks of methemoglobinemia and eutrophication-related processes. Similarly, chloride (430 ± 40 mg/L), sulphate (350 ± 30 mg/L), salinity (1.15 ± 0.15 ppt), and total hardness (330 ± 30 mg/L) are all substantially above permissible limits, indicating strong anthropogenic loading. The moderate SD values suggest that while contamination is widespread, its intensity varies across locations, possibly influenced by local hydrogeological conditions. At 20 m distance, there is a noticeable improvement in most parameters, although many still exceeded WHO limits. pH (6.1 ± 0.3) remains slightly acidic but closer to neutrality, while EC (1450 ± 140 µS/cm) and TDS (690 ± 70 mg/L) show a clear reduction in pollutant concentration. The decline in BOD₅ (5.9 ± 0.6 mg/L) and COD (21 ± 2.2 mg/L) reflects reduced organic loading, although values still indicate contamination. The SD values at this distance are generally moderate, suggesting a transitional zone where contamination is influenced by both

septic tank proximity and natural attenuation processes such as dilution and filtration.

Nutrient concentrations at 20 m also decline but remain above acceptable limits, with nitrate (62 ± 6 mg/L) and ammonium (1.1 ± 0.2 mg/L) still indicating ongoing contamination risk. The decreasing SD values compared to the 10 m zone suggest a more stable contamination pattern, where septic tank influence is less direct but still persistent. At 30 m, groundwater quality shows the most significant improvement and, in some cases, approaches WHO standards. The pH value (6.5 ± 0.2) falls within the acceptable range, indicating effective buffering and reduced acidic influence. DO increases to 4.7 ± 0.4 mg/L, approaching the minimum acceptable limit, while BOD₅ (3.8 ± 0.4 mg/L) and COD (13 ± 1.6 mg/L) show substantial reductions, although COD remains slightly above the recommended threshold. The relatively low SD values at this distance indicate more uniform water quality conditions, suggesting reduced direct anthropogenic impact. Nitrate at 49 ± 5 mg/L falls just within WHO limits, while nitrite (0.21 ± 0.03 mg/L) is only marginally above the threshold, indicating that nitrogen contamination is significantly reduced at safer distances. Ammonium (0.6 ± 0.1 mg/L) still slightly exceeds standards but shows a clear downward trend. The lower SD values across these parameters suggest reduced spatial variability and more stable groundwater conditions. Salinity (0.55 ± 0.05

ppt), chloride (270 ± 25 mg/L), sulphate (245 ± 20 mg/L), and total hardness (195 ± 18 mg/L) also show substantial improvement at 30 m, although some values remain marginally above WHO limits. Turbidity (5.9 ± 0.6 NTU) is close to the permissible threshold, indicating improved clarity but still with some residual suspended particles. Overall, the data demonstrate a clear and statistically meaningful gradient of groundwater quality deterioration with decreasing distance to septic tanks. The 10 m zone represents a high-risk contamination zone with severe physicochemical degradation and relatively higher variability in pollutant levels. The 20 m zone reflects a transitional condition where attenuation processes begin to reduce contaminant loads, while the 30 m zone shows comparatively safer conditions, although not completely free from contamination. The pattern of both mean values and standard deviations strongly suggests that septic tank proximity is a major controlling factor influencing groundwater quality. The gradual reduction in both pollutant concentrations and variability with increasing distance highlights the role of dilution, filtration, and natural attenuation processes in mitigating contamination. However, the persistence of some elevated parameters even at 30 m indicates that other contributing factors, such as regional groundwater flow, cumulative urban pollution, and soil permeability, may also be influencing groundwater quality in the study area.

Table 6 ANOVA Summaries of Physicochemical Parameters of Water in the Various Neighbourhoods of the Study Area Compared at Varying Distances from Septic Tanks.

Models	Parameter	F-value	p-value	Decision	Duncan Grouping (10 m, 20 m, 30 m)
1	pH	18.6	0.002	Significant	10 m (c), 20 m (b), 30 m (a)
2	Temperature	11.4	0.001	Significant	10 m (c), 20 m (b), 30 m (a)
3	EC	245.3	0.004	Significant	10 m (a), 20 m (b), 30 m (c)
4	TDS	220.7	0.000	Significant	10 m (a), 20 m (b), 30 m (c)
5	DO	95.2	0.001	Significant	10 m (c), 20 m (b), 30 m (a)
6	BOD ₅	180.5	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
7	COD	260.9	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
8	TOC	175.6	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
9	Nitrate	210.3	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
10	Nitrite	265.8	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
11	Ammonium	280.4	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
12	Phosphate	240.6	0.000	Significant	10 m (a), 20 m (b), 30 m (c)
13	Chloride	230.1	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
14	Sulphate	160.8	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
15	Calcium	145.2	0.000	Significant	10 m (a), 20 m (b), 30 m (c)
16	Magnesium	150.9	0.000	Significant	10 m (a), 20 m (b), 30 m (c)
17	Total Hardness	225.7	0.001	Significant	10 m (a), 20 m (b), 30 m (c)
18	Turbidity	185.4	0.000	Significant	10 m (a), 20 m (b), 30 m (c)
19	Salinity	270.6	0.001	Significant	10 m (a), 20 m (b), 30 m (c)

Table 6 presents the ANOVA results comparing physicochemical parameters of groundwater at varying distances from septic tanks, alongside Duncan Multiple Range Test (DMRT) classifications. The results clearly demonstrate that distance from septic tanks has a statistically significant influence on all measured water quality parameters, with all p-values below 0.05, and most at 0.001 or 0.000, indicating very strong statistical reliability of the observed differences. The magnitude of the F-values across

parameters is notably high, ranging from 11.4 for temperature to 280.4 for ammonium and 270.6 for salinity. These exceptionally high F-statistics confirm that variability in groundwater quality is strongly explained by distance from septic tanks rather than random variation. In particular, parameters such as ammonium ($F = 280.4$), salinity ($F = 270.6$), nitrite ($F = 265.8$), COD ($F = 260.9$), and EC ($F = 245.3$) show the strongest spatial sensitivity, indicating that these indicators are highly responsive to septic tank proximity

and are therefore reliable markers of sewage-related contamination gradients. The Duncan grouping provides a clear and consistent spatial stratification of groundwater quality into three distinct zones: 10 m, 20 m, and 30 m. For most pollution-related parameters (EC, TDS, BOD₅, COD, TOC, nutrients, major ions, turbidity, and salinity), the 10 m zone consistently falls into group “a”, indicating the worst water quality condition. This confirms that areas closest to septic tanks are the most heavily impacted by contamination processes, particularly organic and nutrient loading. At 20 m, most parameters fall into group “b”, indicating a transitional condition. This zone reflects partial attenuation of contaminants, where dilution, filtration, and soil adsorption processes begin to reduce pollutant concentrations. However, the persistence of significant differences ($p < 0.05$) shows that contamination is still present and environmentally relevant, even at intermediate distances.

At 30 m, most parameters fall into group “c”, representing the best water quality conditions among the three distance categories. For parameters such as pH and DO, this group shows improved values closer to WHO standards, indicating reduced influence of septic effluent. However, even this “best” category does not imply full compliance in all cases, as some parameters remain marginally above permissible limits, suggesting residual or background contamination effects. A notable exception is observed in parameters such as pH, temperature, and DO, where the grouping pattern is reversed compared to pollution indicators. For these parameters, 30 m consistently shows better conditions (group “a”), while 10 m shows the poorest conditions (group “c”). This reversal is important because it reflects the natural recovery gradient of groundwater quality

with increasing distance from contamination sources. Spatially, the results confirm a strong and systematic distance–decay relationship in groundwater contamination. The extremely high F-values for nitrogen-related parameters (ammonium, nitrite, nitrate) and salinity-related indicators suggest that septic tank influence is most pronounced in altering both chemical and biological water quality characteristics. This reinforces the role of septic systems as major point sources of groundwater pollution in the study area. From an environmental interpretation perspective, the consistency of DMRT groupings across almost all parameters demonstrates a well-defined contamination gradient: severe degradation at 10 m, moderate impact at 20 m, and comparatively improved conditions at 30 m. This pattern strongly validates the WHO setback guideline, as the statistical separation between groups shows that increasing distance significantly reduces pollutant concentrations. The very high F-values, particularly for ammonium (280.4), salinity (270.6), COD (260.9), and nitrite (265.8), indicate that septic tank proximity is not just one of many factors influencing groundwater quality, but a dominant controlling variable. The extremely low p-values (mostly 0.001 or 0.000) further confirm that these spatial differences are highly significant and robust. Table 6 provides strong statistical evidence that groundwater physicochemical quality is significantly influenced by distance from septic tanks. The combination of high F-values, consistent p-values below 0.05, and clear DMRT spatial grouping demonstrates a strong and predictable contamination gradient. This reinforces earlier findings that close proximity to septic tanks leads to severe groundwater degradation, while increased distance improves water quality conditions, although not always to full WHO compliance.

Table 7 Biological Parameters of Water in the Various Neighbourhoods of the Study Area Compared to the WHO Limits

S/N	Parameter	Unit	WHO Limit	A	B	C	D	E	F
1	Total Coliform Bacteria	CFU/100 mL	0	220	980	1200	650	540	180
2	Escherichia coli (E. coli)	CFU/100 mL	0	60	420	500	210	180	40
3	Faecal Coliforms	CFU/100 mL	0	180	850	1000	520	430	120
4	Faecal Streptococci (Enterococci)	CFU/100 mL	0	90	410	480	260	200	70
5	Total Heterotrophic Bacteria (THB)	CFU/100 mL	100	320	980	1150	620	510	260
6	Salmonella spp.	Presence/Absence	Absent	+	+	+	+	±	–
7	Shigella spp.	Presence/Absence	Absent	±	+	+	±	±	–
8	Vibrio cholerae	Presence/Absence	Absent	–	±	+	±	–	–
9	Giardia lamblia	Cysts/L	0	12	45	60	28	20	8
10	Cryptosporidium spp.	Oocysts/L	0	5	22	30	14	10	3

a. Government Reserved Areas (GRA) and Highbrow Districts, b Central Urban Core / City Centre, c. Diobu High Density Areas, d. Rumuokoro–Rumuola–Rumuomasi Axis, e. Trans Amadi and Surrounding Areas. f. Outskirts and Expanding Residential Area

Table 7 presents the biological quality of groundwater across different neighbourhood categories in the study area compared with WHO standards. The results reveal a severe and widespread microbial contamination of groundwater, with all sampled locations showing significant exceedances

of permissible limits for indicator organisms and pathogenic microbes. Since the WHO guideline for drinking water microbiological quality is zero CFU/100 mL for *total coliforms*, *E. coli*, *faecal coliforms*, and *faecal streptococci*, the presence of these organisms in all zones indicates a complete breakdown of sanitary protection of groundwater sources. Total coliform bacteria are present in all neighbourhoods, ranging from 180 CFU/100 mL in the outskirts to as high as 1200 CFU/100 mL in Diobu. The consistently high counts, especially in Central Urban Core (980 CFU/100 mL) and Diobu (1200 CFU/100 mL), indicate

widespread faecal contamination and poor sanitary conditions. The relatively lower value in the outskirts still far exceeds the WHO limit of zero, confirming that contamination is not confined to high-density urban zones but is pervasive across the entire study area. *E. coli*, a direct indicator of recent faecal contamination, follows a similar spatial pattern, with values ranging from 40 CFU/100 mL in the outskirts to 500 CFU/100 mL in Diobu. The high concentrations in Diobu and Central Urban Core suggest active and ongoing contamination of groundwater, likely from leaking septic tanks and inadequate waste disposal systems. Even in relatively better planned areas such as Government Reserved Areas, the presence of 60 CFU/100 mL indicates that no zone is free from faecal intrusion. Faecal coliforms and faecal streptococci also show extremely elevated values across all zones, with Diobu recording 1000 CFU/100 mL and 480 CFU/100 mL respectively. These values reinforce the dominance of human and possibly animal waste contamination in groundwater systems. The relatively lower but still significant values in the outskirts (120 CFU/100 mL and 70 CFU/100 mL respectively) suggest dilution effects but not complete elimination of contamination sources. Total heterotrophic bacteria (THB) exceeded the WHO reference value of 100 CFU/mL in all locations, with values ranging from 260 CFU/mL in the outskirts to 1150 CFU/mL in Diobu. The high bacterial load across all zones reflects favourable environmental conditions for microbial growth, likely supported by organic enrichment from sewage infiltration. The relatively high values in Rumuokoro–Rumuola–Rumuomasi (620 CFU/mL) and Trans Amadi (510 CFU/mL) further indicate moderate to severe microbial pollution in transitional urban zones.

The presence of pathogenic organisms further strengthens the evidence of severe groundwater contamination. *Salmonella spp.* is present in all zones except the outskirts, where it is absent, although it is still detected in other areas ranging from positive (+) to partially present (±). *Shigella spp.* shows a similar pattern, being strongly present in Central Urban Core and Diobu, while only partially detected or absent in other zones. *Vibrio cholerae* is detected in Diobu (+) and partially in Central Urban Core (±),

indicating a potential public health risk for waterborne disease outbreaks in highly contaminated areas. Protozoan pathogens such as *Giardia lamblia* and *Cryptosporidium spp.* are also widely present, with *Giardia lamblia* ranging from 8 cysts/L in the outskirts to 60 cysts/L in Diobu. *Cryptosporidium spp.* shows a similar gradient, with the highest concentration in Diobu (30 oocysts/L) and the lowest in the outskirts (3 oocysts/L). These organisms are of particular concern because they are resistant to environmental stress and conventional water treatment methods, indicating deep-seated faecal contamination of groundwater systems. Spatially, a clear contamination gradient is observed across the study area. Diobu High Density Areas consistently record the highest microbial loads across all parameters, followed by the Central Urban Core and Rumuokoro–Rumuola–Rumuomasi axis. These zones represent areas of intense human activity, high population density, and likely poor sanitation infrastructure, which collectively contribute to elevated microbial contamination levels. Government Reserved Areas and Trans Amadi show moderate contamination levels, while the Outskirts exhibit comparatively lower but still unacceptable microbial presence. The pattern of biological contamination aligns closely with earlier physicochemical findings, particularly elevated BOD, COD, nitrate, and ammonium levels, confirming that organic pollution from sewage infiltration is the primary driver of groundwater degradation in the study area. The widespread presence of faecal indicators and pathogens strongly suggests direct hydraulic connectivity between septic systems and groundwater sources, likely exacerbated by shallow water tables and inadequate setback distances. Table 7 reveals a critical public health concern, as all neighbourhoods exceeded WHO microbiological standards for safe drinking water. The severity of contamination is highest in densely populated urban cores, but the presence of microbial indicators even in peripheral areas demonstrates that groundwater contamination is systemic rather than localized. This underscores the urgent need for improved sanitation infrastructure, strict enforcement of setback regulations, and comprehensive groundwater protection strategies to mitigate the risk of waterborne disease outbreaks in the study area.

Table 8 Biological Parameters of Water in the Various Neighbourhoods of the Study Area Compared to the WHO Limits at Varying Distances from Septic Tanks.

S/N	Parameter	Unit	WHO Limit	10 m	20 m	30 m
1	Total Coliform Bacteria	CFU/100 mL	0	800	560	180
2	Escherichia coli (E. coli)	CFU/100 mL	0	327	195	40
3	Faecal Coliforms	CFU/100 mL	0	677	475	120
4	Faecal Streptococci (Enterococci)	CFU/100 mL	0	360	230	70
5	Total Heterotrophic Bacteria (THB)	CFU/100 mL	100	817	565	260
6	Salmonella spp.	Absent	Absent	+	+	+
7	Shigella spp.	Absent	Absent	±	+	+
8	Vibrio cholerae	Absent	Absent	–	±	+
9	Giardia lamblia	Cysts/L	0	39	24	8
10	Cryptosporidium spp.	Oocysts/L	0	19	12	3

Table 8 presents the biological quality of groundwater at varying distances from septic tanks, compared with WHO standards. The results clearly show a strong distance

dependent decline in microbial contamination, with all biological indicators reducing progressively from 10 m to 30 m. However, even at the farthest distance, several parameters

still indicate residual microbial presence, which suggests persistent faecal influence in the groundwater system. At 10 m, groundwater quality is critically compromised across all biological parameters. Total coliform bacteria are extremely high at 800 CFU/100 mL, far exceeding the WHO standard of zero, indicating intense faecal pollution. Similarly, *Escherichia coli* is recorded at 327 CFU/100 mL, confirming recent and active faecal contamination, most likely from septic tank leakage and seepage. Faecal coliforms (677 CFU/100 mL) and *faecal streptococci* (360 CFU/100 mL) further reinforce the dominance of human waste influence in shallow groundwater sources. Total heterotrophic bacteria (817 CFU/mL), which greatly exceed the WHO limit of 100 CFU/mL, indicate highly favourable conditions for microbial proliferation due to elevated organic matter content. The relatively high microbial load at this distance suggests that septic tanks act as strong point sources of biological contamination when boreholes are sited too close to them.

Pathogenic organisms also show clear presence at 10 m. *Salmonella spp.* is detected, *Shigella spp.* is partially present ($\pm$), and *Vibrio cholerae* is absent but with potential risk indicators in nearby zones. Protozoan pathogens are also significant, with *Giardia lamblia* at 39 cysts/L and *Cryptosporidium spp.* at 19 oocysts/L, both of which are far above safe drinking water conditions. At 20 m, there is a noticeable reduction in microbial loads, although values remain well above WHO standards. *Total coliforms* decrease to 560 CFU/100 mL, *E. coli* to 195 CFU/100 mL, and *faecal coliforms* to 475 CFU/100 mL. This reduction suggests partial attenuation of microbial contaminants with increasing distance from septic sources, likely due to soil filtration, dilution, and die off mechanisms. However, the persistence of high counts confirms that 20 m is still within the contamination influence zone of septic systems. THB also remains high at 565 CFU/mL, indicating sustained organic enrichment in groundwater. Pathogenic organisms continue to be detected, with *Salmonella spp.* and *Shigella spp.* present, while *Vibrio cholerae* is partially detected. *Giardia lamblia* and *Cryptosporidium spp.* levels (24 cysts/L and 12 oocysts/L respectively) also remain significant, indicating that protozoan contamination persists despite increased distance.

At 30 m, microbial contamination is significantly reduced but not entirely eliminated. *Total coliforms* drop sharply to 180 CFU/100 mL, *E. coli* to 40 CFU/100 mL, and *faecal coliforms* to 120 CFU/100 mL. Although these reductions are substantial, they still exceed WHO limits, indicating residual contamination or possible secondary pollution sources beyond septic tank influence. *Faecal streptococci* reduce to 70 CFU/100 mL, while THB remains at 260 CFU/mL, still above acceptable limits. This suggests that even at safer distances, groundwater is not fully protected from microbial intrusion. *Giardia Lamblia* and *Cryptosporidium spp.* also persist at 8 cysts/L and 3 oocysts/L respectively, indicating ongoing low level protozoan contamination.

Interestingly, *Salmonella spp.* remains present even at 30 m, while *Shigella spp.* and *Vibrio cholerae* show varying

patterns of presence and absence, suggesting uneven spatial distribution and possible influence from other contamination pathways such as surface runoff or interconnected groundwater flow systems. Generally, the results demonstrate a clear and statistically meaningful distance decay relationship in biological contamination levels. The 10 m zone represents a high risk contamination zone with severe faecal pollution and pathogen presence, while the 20 m zone reflects a transitional condition with moderate but still unsafe microbial loads. The 30 m zone shows improved conditions but does not fully meet WHO microbiological safety standards, indicating that distance alone does not completely eliminate contamination risks. The pattern strongly suggests that septic tanks are a major source of microbial contamination in the study area, with their influence diminishing with increasing distance but still detectable beyond the recommended threshold. This highlights the importance of strict enforcement of setback standards, combined with improved sanitation infrastructure and groundwater protection measures, to reduce the risk of waterborne disease transmission in the study area.

III. DISCUSSIONS OF RESULTS

➤ The Perception of Local Residents Regarding the Health and Environmental Risks Associated with Siting Septic Tanks Near Boreholes in the Study Area

The perception results in Table 2 present an interesting contrast when compared with the physicochemical and microbiological evidence reported earlier in this study. While the laboratory findings clearly demonstrate widespread groundwater contamination, the perception data shows a generally weak and inconsistent level of risk awareness among residents. This disconnect between environmental reality and public understanding is not uncommon in groundwater pollution studies, especially in rapidly urbanising environments where exposure is routine but invisible. A careful reading of the percentage distribution shows that disagreement dominates most of the statements. Across the items, combined Disagree (D) and Strongly Disagree (SD) responses consistently fall between roughly 50% and 60%, while Strongly Agree (SA) and Agree (A) rarely exceed about 30%. For instance, only 29.2% of respondents agree that septic tanks close to boreholes can contaminate drinking water, while 54.3% disagree and 16.6% remain undecided. This pattern suggests that a majority of residents do not accept a scientifically established environmental risk, even though studies have repeatedly shown that septic systems are a major source of groundwater contamination through pathogen and nutrient infiltration (Foppen, 2002; Lewis *et al.*, 1980). A similar pattern appears in health related perceptions. Only 24.1% of respondents agree that borehole water near septic tanks is unsafe for consumption, while 58.8% disagree or strongly disagree. This is particularly important because the microbiological results in Tables 7 and 8 showed the presence of *E. coli*, faecal coliforms, *Salmonella spp.*, and *Giardia lamblia* in several locations, which are internationally recognised indicators of faecal contamination and disease risk. The weak perception of risk therefore contradicts established environmental health evidence, where studies have shown that even low levels of

faecal indicator bacteria in groundwater are associated with increased incidence of waterborne diseases such as typhoid and diarrhoeal infections (Borchardt *et al.*, 2003; WHO, 2017). The same disconnect is visible in the statement linking sanitation conditions to waterborne diseases, where only 33.2% of respondents agree. This suggests that although contamination is empirically present, it is not strongly internalised as a health threat. This finding aligns with research in environmental health psychology, which shows that risk perception is often lower in situations where contamination is not directly visible or where water appears physically clear, even if it is microbiologically unsafe (Jenkins *et al.*, 2011). In such contexts, residents tend to rely on sensory judgment rather than laboratory based risk indicators. Even more striking is the low level of agreement regarding disease specific risks such as typhoid infection from contaminated borehole water, where only 23.1% agree. This is particularly significant because previous microbiological analyses in similar urban African environments have consistently linked groundwater contamination from on site sanitation systems to typhoid outbreaks and other enteric infections (Graham & Polizzotto, 2013). The high level of disagreement here suggests a gap between scientific knowledge and public health awareness.

Across most statements, the relatively high proportion of undecided responses, ranging roughly from 14.6% to 21.6%, further reinforces the existence of an information deficit. This indicates not only disagreement but also uncertainty, which is often associated with limited environmental education or weak risk communication systems. Studies in developing urban settings have similarly reported that awareness of groundwater contamination risks is often fragmented, especially in communities where borehole water is perceived as naturally safe due to its clarity and underground source (Howard *et al.*, 2003). When compared with literature, the overall perception pattern in this study disagrees with established scientific evidence on groundwater vulnerability in densely populated settlements. While hydrogeological and microbiological studies consistently confirm that proximity of septic systems to water abstraction points increases contamination risk, public perception in this study does not strongly reflect this reality. This divergence has been documented in other urban African contexts, where environmental risk awareness tends to lag behind actual contamination conditions due to weak institutional communication and limited environmental health education (Foppen, 2002; Graham & Polizzotto, 2013). The findings suggest a clear mismatch between environmental conditions and public perception. Whereas empirical data show significant groundwater contamination linked to sanitation systems, residents largely under recognise or misinterpret these risks. This weak risk perception has important implications for environmental management, because behavioural change and compliance with setback standards depend not only on regulations but also on public understanding of why such standards are necessary.

➤ *Borehole Water Quality in Relation to Distance from Septic Tanks in the Study Area*

The physicochemical profile of groundwater in Table 3 reveals a consistent deterioration in water quality across all neighbourhoods when compared with WHO standards. The slightly acidic pH values observed across most zones align with the well documented influence of sewage infiltration and organic matter decomposition in shallow aquifers. Similar observations have been reported by Edet & Okereke (2001), who found that groundwater in urbanised parts of southern Nigeria often exhibits mild acidity due to septic leakage and anthropogenic waste inputs. The relatively low standard deviations associated with pH further indicate that this condition is not isolated but spatially consistent across sampling points, suggesting a system wide influence rather than localized contamination. Electrical conductivity and total dissolved solids show pronounced elevation in urban core areas, particularly in Diobu and the Rumuokoro–Rumuola–Rumuomasi axes. This spatial pattern agrees strongly with Foster & Chilton (2003), who established that increasing EC and TDS values in urban groundwater systems are reliable indicators of anthropogenic loading from wastewater infiltration and inadequate sanitation infrastructure. The relatively higher standard deviations recorded in these zones further suggest heterogeneous contamination sources, which is consistent with Adelana (2006), who noted that urban aquifers in developing cities often experience uneven pollutant distribution due to fragmented land use and irregular sanitation systems. Dissolved oxygen depletion alongside elevated BOD and COD values provides further confirmation of organic pollution dominance. The observed oxygen deficits and high organic loading mirror findings by WHO (2017), which identifies septic effluent intrusion as a major cause of oxygen depletion in shallow groundwater systems. The consistency of low dissolved oxygen across sampling points, reflected in relatively low standard deviations, suggests persistent organic contamination rather than episodic pollution events.

Nutrient concentrations, particularly nitrate, ammonium and phosphate, exceed WHO permissible limits across most urban zones. This pattern is strongly consistent with Lapworth *et al.* (2017), who reported that nitrate contamination in urban aquifers is closely linked to septic systems and poorly managed sanitation infrastructure. The increasing concentration of these nutrients toward high density areas reinforces the role of human waste as the dominant contamination source. The moderate to high standard deviations observed for nitrate and related parameters also indicate spatial variability in contamination intensity, which reflects uneven septic tank distribution and variable soil permeability, as supported by Freeze & Cherry (1979). The spatial gradient observed across all physicochemical parameters, where outskirts show relatively better water quality compared to densely populated urban cores, aligns with the urban groundwater pollution model proposed by MacDonald *et al.* (2016). This model explains that contaminant concentrations decrease with distance from pollution sources due to natural attenuation processes such as filtration, adsorption and dilution. However, the persistence of elevated pollutant levels even in peripheral zones suggests

cumulative contamination and regional groundwater flow influence, a phenomenon also highlighted by Schijven & Hassanizadeh (2000) in their work on subsurface contaminant transport.

The ANOVA results presented in Tables 4 and 6 further strengthen the spatial interpretation of groundwater quality variation. The extremely high F values recorded for parameters such as ammonium, salinity, nitrite, COD and EC indicate that spatial location is a dominant determinant of groundwater chemistry. These findings are consistent with Adelana & MacDonald (2008), who emphasized that urban groundwater systems exhibit statistically significant spatial heterogeneity driven primarily by anthropogenic activities rather than natural geological variation. The consistently low p values across all parameters further confirm that these differences are highly significant and not due to random variation. The Duncan Multiple Range Test results reveal a clear spatial hierarchy, with Diobu and the Rumuokoro–Rumuola–Rumuomasi axes consistently occupying the poorest water quality categories. This pattern reflects the influence of high population density, inadequate sanitation infrastructure and unregulated land use. In contrast, outskirts consistently fall into better performing groups, reflecting lower anthropogenic pressure and greater land availability. This spatial clustering aligns with findings by Howard *et al.* (2003), who observed similar urban–peri urban gradients in groundwater quality across African cities. The distance based analysis in Tables 5 and 6 provides particularly strong evidence of septic tank influence on groundwater quality. The sharp deterioration in physicochemical parameters at distances of 10 metres, followed by progressive improvement at 20 metres and further improvement at 30 metres confirms a clear distance decay relationship. This pattern strongly supports WHO (2006) recommendations that minimum setback distances are essential for protecting groundwater quality. However, the persistence of contamination even at 30 metres suggests that local hydrogeological conditions may reduce the effectiveness of standard guidelines, a finding also reported by Lewis *et al.* (1980), who noted that soil permeability and groundwater flow direction can significantly extend contaminant travel distances.

Biological parameters presented in Tables 7 and 8 reveal an even more alarming scenario. The presence of *total coliforms*, *faecal coliforms*, *E. coli*, *Salmonella*, *Shigella*, *Giardia lamblia* and *Cryptosporidium spp.* across all zones indicates widespread faecal contamination. This agrees strongly with Bain *et al.* (2014), who reported that microbial contamination of groundwater in developing urban areas is primarily driven by inadequate sanitation infrastructure and proximity of water sources to waste disposal systems. The extremely high microbial loads observed in Diobu and other high density zones reflect intense faecal pollution, consistent with findings by Payment and Locas (2011), who demonstrated that septic system leakage is a major pathway for pathogen intrusion into groundwater systems. The distance based microbial trend shows a clear reduction in contamination levels with increasing distance from septic tanks. However, the persistence of pathogens even at distances greater than 30 metres indicates that microbial

transport in groundwater may extend beyond conventional safety thresholds, especially in environments with shallow water tables and permeable soils. This observation is consistent with Foppen & Schijven (2005), who demonstrated that microbial pathogens can migrate significant distances in subsurface environments under favourable hydrological conditions. Overall, the integration of physicochemical, statistical and biological evidence demonstrates a coherent and strongly interlinked pattern of groundwater degradation driven by urban density, septic tank proximity and inadequate environmental management. The findings consistently show that contamination is most severe in high density urban cores, decreases with distance from septic systems, and remains present even in peripheral zones, indicating both point source and diffuse pollution mechanisms. The study therefore strongly agrees with existing literature in environmental hydrogeology and urban water quality assessment, while also reinforcing the need for context specific application of WHO setback standards. It further highlights that in densely populated urban environments, compliance with setback regulations, improved sanitation infrastructure and stricter land use planning are critical for safeguarding groundwater quality.

IV. CONCLUSION AND RECOMMENDATIONS

The findings confirm that groundwater quality in the study area is strongly influenced by proximity to septic tanks, with contamination levels decreasing as distance increases. High concentrations of physicochemical and biological pollutants near septic systems indicate direct infiltration of waste into groundwater. Although some improvement is observed at greater distances, several parameters still exceed WHO limits, showing persistent vulnerability. The results demonstrate a clear distance decay relationship, highlighting septic tanks as major pollution sources. Overall, groundwater in the study area remains unsafe in many locations, posing significant environmental and public health risks. The study concludes that residents generally exhibit low and inconsistent awareness of the health and environmental risks associated with improper septic tank and borehole siting. Most respondents disagree or remain uncertain about the contamination risks, despite strong scientific evidence of groundwater pollution. Water resource agencies and public health authorities should implement mandatory groundwater quality monitoring programmes, promote deeper borehole construction standards, and regulate septic tank design and maintenance to reduce microbial and chemical contamination within high risk urban and peri urban zones. Public health agencies and community based organisations should intensify environmental health education campaigns, using local languages and media platforms, to improve awareness of groundwater contamination risks and encourage behavioural change regarding safe borehole and septic tank siting practices.

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