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Hydrochemical Characterisation and Public Health Risk Assessment of Borehole Water Sources in Selected Hospitals in Rivers State, Nigeria

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ABSTRACT

Safe and reliable water is essential for healthcare delivery, yet many hospitals in Nigeria depend on borehole water whose quality is seldom comprehensively assessed. This study evaluated the hydrochemical characteristics, microbiological quality, and public health risks associated with borehole water used in selected hospitals in Rivers State, Nigeria. Twelve anonymised borehole water samples (HBW-01–HBW-12) were collected and analysed in triplicate using standard analytical procedures. Physicochemical parameters, major ions, heavy metals, microbiological indicators, Water Quality Index (WQI), non-carcinogenic health risk, Pearson correlation, and Principal Component Analysis (PCA) were determined. Water temperature ranged from 27.20–29.60°C, while pH varied between 5.91 and 7.28, with four boreholes exhibiting slightly acidic conditions. Electrical conductivity (185.6–612.4 µS/cm), total dissolved solids (118.4–396.7 mg/L), nitrate (3.41–17.86 mg/L), biochemical oxygen demand (1.42–3.52 mg/L), and major ions remained within World Health Organization (WHO) guideline limits. However, iron concentrations reached 0.69 mg/L, while lead (0.002–0.022 mg/L) and cadmium (0.0002–0.0050 mg/L) exceeded permissible limits in several boreholes. Total coliforms were detected in ten boreholes and Escherichia coli in five, whereas Salmonella spp. and Vibrio spp. were absent. WQI classified six boreholes as excellent, three as good, two as poor, and one as unsuitable for drinking. Hazard Quotient values remained below unity for adults but exceeded acceptable limits for children in several locations, with Hazard Index values indicating cumulative non-carcinogenic risks among children. Pearson correlation showed a strong relationship between electrical conductivity and total dissolved solids (r = 0.91), while PCA identified groundwater mineralisation, heavy metal contamination, and hydrogeochemical weathering as the dominant processes controlling water quality. Although most physicochemical parameters complied with WHO standards, heavy metal contamination and microbial pollution in several boreholes present significant public health concerns, highlighting the need for routine monitoring, water treatment, and improved borehole management within hospital environments.

Keywords: *Borehole water; Groundwater quality; Hydrochemical characterisation; Hospital water supply; Heavy metals; Water Quality Index; Human health risk; Rivers State, Nigeria.*

1.0 Introduction

Access to safe and adequate drinking water is fundamental to human health and constitutes an essential requirement for effective healthcare delivery. Within healthcare facilities, water is indispensable for patient care, surgical procedures, laboratory investigations, sterilisation of medical equipment, pharmaceutical preparation, sanitation, food preparation, and infection prevention. The availability of microbiologically and chemically safe water therefore plays a critical role in reducing healthcare-associated infections and improving clinical outcomes. Conversely, the use of contaminated water may compromise patient safety, facilitate disease transmission, and undermine the quality of healthcare services, particularly among immunocompromised individuals and other vulnerable patient groups [22]. Groundwater obtained from boreholes represents the principal source of potable water for many hospitals in Nigeria owing to the inadequacy and unreliability of public water supply systems. Although groundwater is generally regarded as less susceptible to contamination than surface water because of natural filtration through subsurface geological formations, its quality is influenced by a combination of hydrogeological processes and anthropogenic activities.

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Natural processes such as mineral weathering, ion exchange, groundwater recharge, and water–rock interaction determine the baseline hydrochemical composition of groundwater, whereas human activities including improper waste disposal, hospital effluent discharge, petroleum exploration, industrial emissions, urbanisation, and agricultural practices may significantly alter groundwater quality [8,10,19]. Consequently, routine assessment of groundwater quality remains essential to ensure its suitability for drinking and other domestic uses.

Hydrochemical characterisation has become one of the most reliable approaches for evaluating groundwater systems because it provides valuable information on the processes governing groundwater evolution and identifies factors responsible for variations in water quality. Parameters such as pH, electrical conductivity, total dissolved solids, dissolved oxygen, major ions, nutrients, and trace metals are widely employed to assess groundwater suitability and to distinguish between natural geochemical processes and anthropogenic contamination. Previous investigations in different parts of Nigeria have demonstrated that groundwater chemistry is controlled by interactions between aquifer minerals and infiltrating water, while increasing urbanisation and industrial activities further modify groundwater composition through contaminant migration [8,10,19]. Comprehensive hydrochemical assessment therefore provides an important basis for groundwater resource management and public health protection.

Among the numerous contaminants affecting groundwater quality, heavy metals remain one of the greatest environmental and public health concerns because of their persistence, non-biodegradability, bioaccumulative nature, and potential toxicity even at relatively low concentrations. Metals such as lead, cadmium, iron, manganese, copper, and zinc may originate from natural geological formations; however, elevated concentrations are frequently associated with petroleum exploration, industrial discharges, corrosion of water distribution systems, municipal waste disposal, hospital activities, and urban runoff [15–18]. Long-term exposure to elevated concentrations of lead and cadmium has been associated with neurological disorders, renal dysfunction, developmental abnormalities, cardiovascular diseases, and other chronic health conditions. Similar toxicological concerns have been reported in aquatic ecosystems and groundwater systems across Nigeria, highlighting the importance of continuous environmental monitoring and health risk assessment [3,4,8,9,14,17].

Apart from chemical contaminants, microbiological quality remains a major determinant of drinking-water safety, particularly within healthcare facilities where susceptible patients are continuously exposed to opportunistic pathogens. The presence of total coliforms and *Escherichia coli* in groundwater is widely recognised as evidence of faecal contamination resulting from leaking septic systems, poorly protected boreholes, surface runoff infiltration, or inadequate sanitation infrastructure. According to the World Health Organization, potable water intended for human consumption should contain no detectable *Escherichia coli* in any 100 mL sample [22]. Consequently, microbiological surveillance forms an integral component of groundwater quality assessment and provides an early indication of sanitary deficiencies requiring immediate intervention.

Recent advances in groundwater quality assessment increasingly combine conventional hydrochemical investigations with Water Quality Index (WQI) models and quantitative human health risk assessment. The Water Quality Index integrates multiple physicochemical parameters into a single numerical value that facilitates interpretation of groundwater suitability for drinking purposes. Similarly, human health risk assessment employs Hazard Quotient (HQ) and Hazard Index (HI) models to estimate the likelihood of adverse non-carcinogenic health effects resulting from prolonged exposure to contaminated water. These approaches have been successfully applied in several environmental investigations to evaluate groundwater quality and associated health risks in Nigeria [3,7,8,19]. Their integration provides a more comprehensive understanding of groundwater safety than reliance on individual water quality parameters alone.

Rivers State, located within the Niger Delta region of southern Nigeria, is characterised by rapid urbanisation, intensive petroleum exploration and production, industrial development, and increasing population growth. These activities have exerted considerable pressure on environmental resources, particularly groundwater systems that serve as the primary source of domestic and institutional water supply. Previous investigations within the Niger Delta have reported contamination of water bodies by petroleum hydrocarbons, heavy metals, industrial effluents, domestic wastewater, and other emerging pollutants, reflecting the cumulative effects of anthropogenic activities on environmental quality [5,9,11,12,15,16,18,20,21]. Although many of these studies focused on rivers, estuaries, sediments, and aquatic organisms, they collectively suggest that groundwater resources within the region may also be vulnerable to contamination.

Hospitals represent unique environments because they not only consume large quantities of water but also generate complex waste streams containing pharmaceuticals, disinfectants, laboratory reagents, pathogenic microorganisms, and potentially toxic elements. Where waste management practices are inadequate, these contaminants may infiltrate surrounding soils and groundwater systems, thereby compromising the quality of borehole water relied upon for healthcare delivery [10,21]. Despite the critical importance of potable water within healthcare facilities, relatively few studies have specifically investigated the hydrochemical quality and associated public health risks of borehole water serving hospitals in Rivers State. Existing research has largely concentrated on surface water quality, groundwater around waste disposal sites, or contamination of aquatic ecosystems, leaving an important knowledge gap regarding the safety of hospital water supplies [8,10,11,15,19].

Therefore, the present study was undertaken to evaluate the hydrochemical characteristics, microbiological quality, Water Quality Index, and potential non-carcinogenic public health risks associated with borehole water used in selected hospitals in Rivers State, Nigeria.

2.0 MATERIALS AND METHODS

2.1 Study Area

The study was conducted in selected hospital premises within Rivers State, Nigeria. Rivers State is in the Niger Delta region of southern Nigeria between latitudes 4°15′–5°45′N and longitudes 6°20′–7°35′E. The State covers approximately 11,077 km^2 and is characterised by a humid tropical climate with annual rainfall ranging from 2,000 to 3,500 mm, mean annual temperatures of 26–32°C, and relative humidity generally exceeding 80%.

The geology of the area is dominated by the Benin Formation (Coastal Plain Sands), which consists mainly of unconsolidated sands and gravel with minor clay intercalations. These sediments form one of the most productive groundwater aquifers in southern Nigeria and serve as the principal source of potable water for domestic, industrial and institutional uses. Most hospitals within the State depend largely on privately owned boreholes for their daily water requirements owing to the unreliability of municipal water supply. Consequently, the quality of groundwater directly influences hospital sanitation, patient safety, food preparation, laboratory operations and other healthcare services.

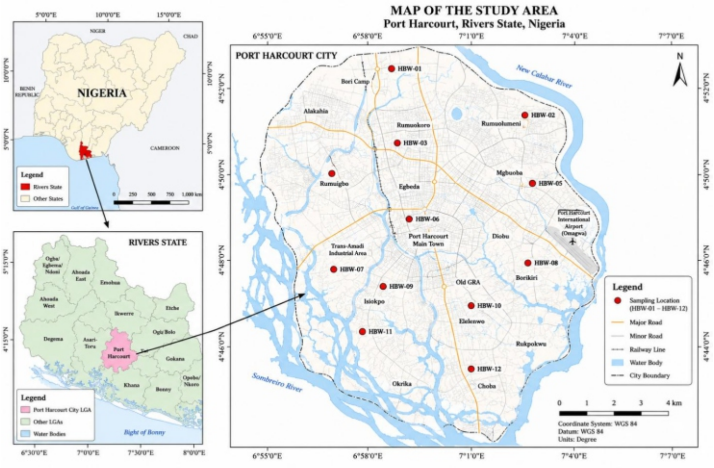

Figure 1: Map of the study area showing the location of Rivers State within Nigeria and the selected sampling locations in Port Harcourt, Rivers State, Nigeria.

2.2 Research Design

A cross-sectional analytical study was conducted to evaluate the hydrochemical characteristics and public health safety of borehole water used within selected hospitals in Rivers State. The investigation comprised field sampling, laboratory determination of physicochemical characteristics, major ions, heavy metals and microbiological quality, followed by Water Quality Index (WQI), human health risk assessment and multivariate statistical analysis.

2.3 Sampling Design

A purposive sampling technique was adopted for the selection of hospital boreholes. Twelve operational boreholes distributed across Rivers State were selected based on their continuous utilisation as the primary source of water supply within the healthcare facilities.

To protect institutional identity and comply with ethical approval requirements, all sampling locations were anonymised and assigned unique sample identification codes ranging from HBW-01 to HBW-12. No information capable of identifying the participating hospitals is presented in this study.

2.4 Sample Collection and Preservation

Water samples were collected between 8:00 a.m. and 12:00 noon to minimise diurnal variations. Prior to sampling, each borehole outlet was allowed to flow continuously for approximately five minutes to remove stagnant water from the distribution system.

Approximately one litre of groundwater was collected into acid-washed high-density polyethylene (HDPE) bottles for physicochemical, major ion and heavy metal analyses.

Samples designated for heavy metal determination were preserved immediately by acidifying with concentrated nitric acid (HNO_3) until the sample pH was less than 2.0.

Microbiological samples were collected separately into sterile 250 mL borosilicate glass bottles, stored immediately inside insulated ice boxes at approximately 4°C and transported to the laboratory for analysis within six hours of collection. Each sample was analysed in triplicate, and analytical results were expressed as Mean ± Standard Deviation (Mean ± SD).

2.5 Laboratory Analysis

2.5.1 Determination of Physicochemical Parameters

Water temperature was measured in situ using a calibrated digital thermometer. Hydrogen ion concentration (pH), electrical conductivity (EC) and total dissolved solids (TDS) were determined using a calibrated portable multiparameter water quality meter.

Turbidity was measured using a nephelometric turbidity meter.

Dissolved oxygen (DO) was determined using the modified Winkler azide method, while biochemical oxygen demand (BOD_5) was determined after incubating water samples at 20°C for five days.

Nitrate (NO_3^-) concentrations were determined using the cadmium reduction spectrophotometric method, whereas phosphate (PO_4^{3-}) concentrations were determined by the ascorbic acid molybdenum blue method.

2.5.2 Determination of Major Ions

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) were determined by ethylenediaminetetraacetic acid (EDTA) complexometric titration.

Sodium (Na^+) and potassium (K^+) were analysed using flame photometry.

Chloride (Cl^-) concentrations were determined by argentometric titration using silver nitrate.

Sulphate (SO_4^{2-}) concentrations were determined using the turbidimetric method, whereas bicarbonate (HCO_3^-) concentrations were determined by acid-base titration.

2.5.3 Heavy Metal Analysis

Water samples were digested using concentrated nitric acid following the procedures described in the Standard Methods for the Examination of Water and Wastewater.

Iron (Fe), zinc (Zn), lead (Pb), cadmium (Cd), copper (Cu) and manganese (Mn) concentrations were determined using Atomic Absorption Spectrophotometry (AAS).

Calibration was performed using certified analytical standards, while reagent blanks, duplicate samples and certified reference materials were analysed simultaneously for quality control.

2.5.4 Microbiological Analysis

Total heterotrophic bacterial counts were determined using the standard plate count method.

Total coliforms and *Escherichia coli* were enumerated using the membrane filtration technique on selective media.

The presence of *Salmonella* spp. and *Vibrio* spp. was investigated using standard enrichment, isolation and biochemical identification procedures.

2.6 Water Quality Index (WQI)

The suitability of borehole water for drinking purposes was evaluated using the Water Quality Index (WQI).

The quality rating for each parameter was calculated as:

Equation (2.1)

$$Q_i = (C_i / S_i) \times 100$$

Where:

Q_i = Quality rating of the *i*th parameter

C_i = Measured concentration of the *i*th parameter (mg/L)

S_i = WHO permissible limit of the *i*th parameter (mg/L)

The relative weight assigned to each parameter was calculated as:

Equation (2.2)

$$W_i = w_i / \Sigma w_i$$

Where:

W_i = Relative weight of the *i*th parameter

w_i = Assigned weight of the *i*th parameter

The sub-index for each parameter was determined as:

Equation (2.3)

$$SI_i = W_i \times Q_i$$

The overall Water Quality Index was calculated using:

Equation (2.4)

$$WQI = \Sigma SI_i$$

Water quality was classified as follows:

- WQI < 50 = Excellent
- WQI 50–100 = Good
- WQI 100–200 = Poor
- WQI 200–300 = Very Poor
- WQI >300 = Unsuitable for drinking.

2.7 Human Health Risk Assessment

Potential non-carcinogenic health risks associated with heavy metal exposure through drinking water ingestion were evaluated using the United States Environmental Protection Agency (USEPA) model.

The Chronic Daily Intake (CDI) was calculated using:

Equation (2.5)

$$CDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

Where:

CDI = Chronic Daily Intake ($mg\ kg^{-1}\ day^{-1}$)

C = Heavy metal concentration (mg/L)

IR = Water ingestion rate (L/day)

EF = Exposure frequency (days/year)

ED = Exposure duration (years)

BW = Body weight (kg)

AT = Averaging time (days)

The Hazard Quotient (HQ) for each heavy metal was determined using:

Equation (2.6)

$$HQ = CDI / RfD$$

Where:

HQ = Hazard Quotient

RfD = Oral reference dose ($mg\ kg^{-1}\ day^{-1}$)

The cumulative non-carcinogenic risk was estimated using the Hazard Index (HI):

Equation (2.7)

$$HI = \Sigma HQ_i$$

Where:

HI = Hazard Index

HQ_i = Hazard Quotient of the *i*th heavy metal

Values of HQ or HI less than one indicate no significant health risk, whereas values greater than one indicate potential adverse health effects.

2.8 Statistical Analysis

All laboratory results were entered into Microsoft Excel before statistical analysis using IBM SPSS Statistics Version 27.

Descriptive statistics including minimum, maximum, mean and standard deviation were calculated for all measured parameters.

Relationships among physicochemical parameters, major ions and heavy metals were evaluated using Pearson's Product Moment Correlation Coefficient calculated as:

Equation (2.8)

$$r = \Sigma[(x_i - \bar{x})(y_i - \bar{y})] / \sqrt{[\Sigma(x_i - \bar{x})^2\, \Sigma(y_i - \bar{y})^2]}$$

Where:

r = Pearson correlation coefficient

x_i = Observation of variable x

y_i = Observation of variable y

$\bar{x}$ = Mean of variable x

$\bar{y}$ = Mean of variable y

Principal Component Analysis (PCA) with varimax rotation was subsequently performed to identify the principal hydrochemical processes influencing groundwater quality. Components with eigenvalues greater than one were retained, and variables with loading coefficients greater than 0.50 were considered significant. Statistical significance was established at $p < 0.05$.

2.9 Quality Assurance and Quality Control

All glassware and sampling containers were washed with laboratory-grade detergent, soaked in 10% nitric acid for 24 hours and rinsed thoroughly with deionised water before use. Analytical instruments were calibrated daily using certified standards. Duplicate analyses, laboratory blanks and certified reference materials were included throughout the analytical process. Percentage recoveries ranged from 95–105%, while relative standard deviations for replicate analyses were maintained below 5%, indicating satisfactory analytical precision and accuracy.

2.10 Ethical Considerations

Ethical approval was obtained from the appropriate Health Research Ethics Committee prior to commencement of the study. Permission was also obtained from the management of the participating hospitals. To ensure confidentiality, all sampling stations were anonymised using sample identification codes (HBW-01 to HBW-12), and no information capable of identifying the participating healthcare institutions is disclosed.

3.0 RESULTS

As shown in Table 3.1, a total of twelve (12) borehole water samples were collected from selected hospital premises across Rivers State, Nigeria. To ensure confidentiality and comply with ethical requirements, each sampling location was anonymised and assigned a unique sample identification code ranging from HBW-01 to HBW-12. Each sample represented an independent borehole water source and was analysed for physicochemical characteristics, major ions, heavy metals, microbiological quality, water quality index, and human health risk assessment.

Table 3.1: Sample Identification Codes

Sample ID	Sample Type
HBW-01	Borehole Water
HBW-02	Borehole Water
HBW-03	Borehole Water
HBW-04	Borehole Water
HBW-05	Borehole Water
HBW-06	Borehole Water
HBW-07	Borehole Water
HBW-08	Borehole Water
HBW-09	Borehole Water
HBW-10	Borehole Water
HBW-11	Borehole Water
HBW-12	Borehole Water

As shown in Table 3.2, the physicochemical characteristics of the analysed borehole water samples exhibited moderate spatial variability across the twelve sampling stations. Water temperature ranged from 27.20 ± 0.12 to 29.60 ± 0.20°C, with only slight variation among the boreholes.

The pH values ranged from 5.91 ± 0.08 to 7.28 ± 0.05, indicating that HBW-03, HBW-04, HBW-06 and HBW-08 were slightly acidic and fell below the World Health Organization (WHO) recommended lower limit of 6.5. Electrical conductivity increased progressively from 185.6 ± 5.8 to 612.4 ± 14.2 µS/cm, while total dissolved solids similarly increased from 118.4 ± 3.6 to 396.7 ± 11.3 mg/L, reflecting increasing mineralisation of groundwater across the sampling locations. Turbidity values varied between 0.81 ± 0.04 and 5.42 ± 0.23 NTU, with HBW-08 marginally exceeding the WHO guideline value of 5.0 NTU. Dissolved oxygen concentrations decreased gradually from 7.12 ± 0.15 to 4.96 ± 0.24 mg/L, whereas biochemical oxygen demand increased from 1.42 ± 0.07 to 3.52 ± 0.21 mg/L but remained below the permissible limit. Nitrate concentrations ranged from 3.41 ± 0.18 to 17.86 ± 0.64 mg/L, while phosphate ranged from 0.24 ± 0.02 to 2.34 ± 0.17 mg/L. Overall, the physicochemical quality of the borehole water remained generally acceptable for drinking purposes despite isolated deviations in pH and turbidity.

Table 3.2: Physicochemical Characteristics of Borehole Water Samples (Mean ± SD)

Sample ID	Temp (°C)	pH	EC (µS/cm)	TDS (mg/L)	Turbidity (NTU)	DO (mg/L)	BOD (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)
HBW-01	27.20 ± 0.12	6.84 ± 0.05	185.6 ± 5.8	118.4 ± 3.6	0.81 ± 0.04	7.12 ± 0.15	1.42 ± 0.07	3.41 ± 0.18	0.24 ± 0.02
HBW-02	27.50 ± 0.14	6.71 ± 0.06	204.5 ± 6.4	132.8 ± 4.2	1.26 ± 0.06	6.94 ± 0.18	1.58 ± 0.08	4.22 ± 0.21	0.38 ± 0.03
HBW-03	28.10 ± 0.15	5.91 ± 0.08	296.8 ± 8.2	188.4 ± 5.4	2.31 ± 0.11	6.42 ± 0.16	2.01 ± 0.09	6.34 ± 0.25	0.62 ± 0.05
HBW-04	28.30 ± 0.16	6.33 ± 0.07	338.4 ± 8.9	214.3 ± 6.2	3.15 ± 0.14	6.18 ± 0.17	2.24 ± 0.11	8.53 ± 0.32	0.71 ± 0.06
HBW-05	28.40 ± 0.17	6.52 ± 0.05	352.6 ± 9.3	226.7 ± 6.5	2.64 ± 0.12	6.03 ± 0.19	2.35 ± 0.12	9.62 ± 0.36	0.84 ± 0.07
HBW-06	28.50 ± 0.18	6.47 ± 0.06	388.7 ± 10.1	243.5 ± 7.2	4.12 ± 0.18	5.86 ± 0.21	2.58 ± 0.13	10.41 ± 0.41	1.06 ± 0.08
HBW-07	28.60 ± 0.16	7.11 ± 0.04	421.3 ± 10.8	268.1 ± 7.8	3.48 ± 0.15	5.74 ± 0.18	2.74 ± 0.14	11.25 ± 0.43	1.13 ± 0.09
HBW-08	28.80 ± 0.19	6.24 ± 0.08	447.6 ± 11.5	281.6 ± 8.3	5.42 ± 0.23	5.68 ± 0.22	2.96 ± 0.15	12.84 ± 0.46	1.46 ± 0.11
HBW-09	29.00 ± 0.18	7.02 ± 0.05	496.8 ± 12.3	314.2 ± 9.1	4.31 ± 0.20	5.52 ± 0.20	3.06 ± 0.17	14.12 ± 0.52	1.72 ± 0.12
HBW-10	29.20 ± 0.17	6.56 ± 0.06	524.1 ± 12.8	332.8 ± 9.8	3.85 ± 0.18	5.31 ± 0.21	3.24 ± 0.18	15.38 ± 0.56	1.95 ± 0.14
HBW-11	29.40 ± 0.19	7.28 ± 0.05	568.4 ± 13.6	361.5 ± 10.5	4.76 ± 0.21	5.12 ± 0.23	3.41 ± 0.19	16.74 ± 0.61	2.18 ± 0.15
HBW-12	29.60 ± 0.20	6.63 ± 0.07	612.4 ± 14.2	396.7 ± 11.3	4.94 ± 0.22	4.96 ± 0.24	3.52 ± 0.21	17.86 ± 0.64	2.34 ± 0.17

As presented in Table 3.3, the summary statistics further demonstrate that the physicochemical quality of the borehole water was generally satisfactory. Mean water temperature was 28.43 ± 0.76°C, while the average pH was 6.63 ± 0.39, falling within the WHO recommended range although some individual boreholes exhibited slight acidity. Electrical conductivity averaged 403.1 ± 135.7 µS/cm, total dissolved solids averaged 256.6 ± 88.3 mg/L, and turbidity averaged 3.42 ± 1.37 NTU, all of which remained below their respective WHO permissible limits. Dissolved oxygen averaged 5.91 ± 0.69 mg/L, indicating adequate groundwater oxygenation, whereas biochemical oxygen demand averaged 2.59 ± 0.67 mg/L, suggesting minimal organic pollution. Mean nitrate and phosphate concentrations were 10.89 ± 4.58 mg/L and 1.22 ± 0.69 mg/L, respectively, indicating relatively low nutrient enrichment within the groundwater systems.

Table 3.3: Summary Statistics of Physicochemical Parameters

Parameter	Minimum	Maximum	Mean ± SD	WHO Guideline
Temperature (°C)	27.20 ± 0.12	29.60 ± 0.20	28.43 ± 0.76	—
pH	5.91 ± 0.08	7.28 ± 0.05	6.63 ± 0.39	6.5–8.5
Electrical Conductivity (µS/cm)	185.6 ± 5.8	612.4 ± 14.2	403.1 ± 135.7	1000
Total Dissolved Solids (mg/L)	118.4 ± 3.6	396.7 ± 11.3	256.6 ± 88.3	500
Turbidity (NTU)	0.81 ± 0.04	5.42 ± 0.23	3.42 ± 1.37	5.0
Dissolved Oxygen (mg/L)	4.96 ± 0.24	7.12 ± 0.15	5.91 ± 0.69	—
Biochemical Oxygen Demand (mg/L)	1.42 ± 0.07	3.52 ± 0.21	2.59 ± 0.67	5.0
Nitrate (mg/L)	3.41 ± 0.18	17.86 ± 0.64	10.89 ± 4.58	50
Phosphate (mg/L)	0.24 ± 0.02	2.34 ± 0.17	1.22 ± 0.69	—

As shown in Table 3.4, the concentrations of major ions exhibited gradual increases across the sampling stations but remained within internationally accepted drinking water standards. Calcium concentrations ranged from 21.3 ± 0.8 to 86.3 ± 2.8 mg/L, magnesium ranged from 5.4 ± 0.2 to 29.4 ± 1.3 mg/L, sodium ranged from 12.8 ± 0.5 to 74.2 ± 2.8 mg/L, and potassium ranged from 2.1 ± 0.1 to 9.6 ± 0.5 mg/L. Chloride concentrations increased from 20.4 ± 0.7 to 128.4 ± 4.1 mg/L, while sulphate varied between 10.5 ± 0.4 and 62.7 ± 2.4 mg/L. Bicarbonate concentrations ranged from 48.6 ± 1.8 to 168.9 ± 5.8 mg/L. The progressive increase in ionic concentrations across the boreholes suggests variations in groundwater mineralisation and natural hydrogeochemical weathering processes, although all measured values remained below WHO guideline limits.

Table 3.4: Major Ion Composition (Mean ± SD, mg/L)

Sample ID	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
HBW-01	21.3 ± 0.8	5.4 ± 0.2	12.8 ± 0.5	2.1 ± 0.1	20.4 ± 0.7	10.5 ± 0.4	48.6 ± 1.8
HBW-02	24.7 ± 0.9	6.8 ± 0.3	18.4 ± 0.7	2.6 ± 0.1	28.6 ± 1.0	13.2 ± 0.5	56.3 ± 2.0
HBW-03	31.2 ± 1.1	9.3 ± 0.4	24.7 ± 0.9	3.4 ± 0.2	42.7 ± 1.4	18.6 ± 0.7	73.4 ± 2.6
HBW-04	39.6 ± 1.3	12.4 ± 0.5	31.8 ± 1.2	4.1 ± 0.2	55.2 ± 1.8	24.8 ± 0.9	89.6 ± 3.1
HBW-05	45.8 ± 1.5	14.3 ± 0.6	36.2 ± 1.4	4.8 ± 0.2	63.4 ± 2.0	28.5 ± 1.0	94.8 ± 3.4
HBW-06	49.4 ± 1.6	16.2 ± 0.7	41.6 ± 1.6	5.3 ± 0.3	69.8 ± 2.2	31.6 ± 1.2	106.4 ± 3.8
HBW-07	54.6 ± 1.8	18.7 ± 0.8	48.3 ± 1.8	6.1 ± 0.3	82.6 ± 2.6	38.5 ± 1.4	118.3 ± 4.1
HBW-08	61.4 ± 2.0	20.8 ± 0.9	53.7 ± 2.0	6.8 ± 0.3	91.4 ± 2.9	44.6 ± 1.6	129.7 ± 4.5
HBW-09	67.3 ± 2.2	23.1 ± 1.0	59.6 ± 2.2	7.3 ± 0.4	102.6 ± 3.2	48.3 ± 1.8	138.5 ± 4.8
HBW-10	73.8 ± 2.4	25.6 ± 1.1	64.2 ± 2.4	8.2 ± 0.4	114.3 ± 3.6	53.6 ± 2.0	149.8 ± 5.2
HBW-11	79.5 ± 2.6	27.8 ± 1.2	69.5 ± 2.6	8.9 ± 0.4	122.5 ± 3.8	58.4 ± 2.2	158.6 ± 5.5
HBW-12	86.3 ± 2.8	29.4 ± 1.3	74.2 ± 2.8	9.6 ± 0.5	128.4 ± 4.1	62.7 ± 2.4	168.9 ± 5.8

As shown in Table 3.5, measurable concentrations of iron, zinc, lead, cadmium, copper and manganese were detected in all borehole water samples. Iron recorded the highest concentrations, ranging from 0.07 ± 0.01 to 0.69 ± 0.05 mg/L, with HBW-06 to HBW-12 exceeding the WHO guideline value of 0.30 mg/L. Lead concentrations ranged from 0.002 ± 0.0002 to 0.022 ± 0.0013 mg/L, while cadmium varied between 0.0002 ± 0.0001 and 0.0050 ± 0.0005 mg/L. Both lead and cadmium exceeded the WHO permissible limits in several sampling stations. In contrast, zinc, copper and manganese remained below their respective guideline values throughout the study. These findings indicate localised heavy metal contamination that may compromise the safety of some hospital borehole water supplies.

Table 3.5: Heavy Metal Concentrations (Mean ± SD, mg/L)

Sample ID	Fe	Zn	Pb	Cd	Cu	Mn
HBW-01	0.07 ± 0.01	0.05 ± 0.01	0.002 ± 0.0002	0.0002 ± 0.0001	0.02 ± 0.01	0.03 ± 0.01
HBW-02	0.11 ± 0.01	0.07 ± 0.01	0.003 ± 0.0003	0.0005 ± 0.0001	0.03 ± 0.01	0.05 ± 0.01
HBW-03	0.18 ± 0.02	0.09 ± 0.01	0.005 ± 0.0004	0.0008 ± 0.0002	0.04 ± 0.01	0.06 ± 0.01
HBW-04	0.24 ± 0.02	0.12 ± 0.01	0.007 ± 0.0005	0.0012 ± 0.0002	0.05 ± 0.01	0.08 ± 0.01
HBW-05	0.28 ± 0.02	0.15 ± 0.02	0.009 ± 0.0006	0.0016 ± 0.0002	0.06 ± 0.01	0.09 ± 0.01
HBW-06	0.33 ± 0.03	0.18 ± 0.02	0.011 ± 0.0007	0.0021 ± 0.0003	0.07 ± 0.01	0.10 ± 0.01
HBW-07	0.37 ± 0.03	0.21 ± 0.02	0.012 ± 0.0008	0.0025 ± 0.0003	0.08 ± 0.01	0.11 ± 0.01
HBW-08	0.44 ± 0.03	0.25 ± 0.02	0.014 ± 0.0009	0.0030 ± 0.0003	0.09 ± 0.01	0.13 ± 0.02
HBW-09	0.51 ± 0.04	0.28 ± 0.03	0.016 ± 0.0010	0.0034 ± 0.0004	0.11 ± 0.01	0.14 ± 0.02
HBW-10	0.57 ± 0.04	0.31 ± 0.03	0.018 ± 0.0011	0.0040 ± 0.0004	0.12 ± 0.01	0.16 ± 0.02
HBW-11	0.63 ± 0.05	0.35 ± 0.03	0.020 ± 0.0012	0.0045 ± 0.0005	0.14 ± 0.02	0.18 ± 0.02
HBW-12	0.69 ± 0.05	0.38 ± 0.03	0.022 ± 0.0013	0.0050 ± 0.0005	0.15 ± 0.02	0.19 ± 0.02

As shown in Table 3.6, microbiological quality varied considerably among the borehole water samples. Total heterotrophic bacterial counts ranged from 1.4 ± 0.2 × 10^2 to 8.7 ± 0.8 × 10^2 CFU/mL. Total coliform organisms were absent in HBW-01 and HBW-02 but progressively increased to 9 CFU/100 mL in HBW-11 and HBW-12. *Escherichia coli* was not detected in the first seven sampling stations but occurred in HBW-08 to HBW-12, with counts ranging from 1.0 ± 0.2 to 2.0 ± 0.3 CFU/100 mL. Neither *Salmonella* spp. nor *Vibrio* spp. was isolated from any of the samples analysed. The occurrence of coliform bacteria and *E. coli* in several boreholes suggests possible faecal contamination and indicates that portions of the groundwater may require treatment before consumption.

Table 3.6: Microbiological Characteristics of Borehole Water Samples (Mean ± SD)

Sample ID	Total Heterotrophic Count ($\times 10^2$ CFU/mL)	Total Coliform (CFU/100 mL)	*Escherichia coli* (CFU/100 mL)	*Salmonella* spp.	*Vibrio* spp.
HBW-01	1.4 ± 0.2	0.0 ± 0.0	ND	ND	ND
HBW-02	1.8 ± 0.2	0.0 ± 0.0	ND	ND	ND
HBW-03	2.2 ± 0.3	1.0 ± 0.2	ND	ND	ND
HBW-04	3.1 ± 0.3	2.0 ± 0.3	ND	ND	ND
HBW-05	3.8 ± 0.4	3.0 ± 0.4	ND	ND	ND
HBW-06	4.6 ± 0.4	4.0 ± 0.5	ND	ND	ND
HBW-07	5.1 ± 0.5	5.0 ± 0.5	ND	ND	ND
HBW-08	5.9 ± 0.5	6.0 ± 0.6	1.0 ± 0.2	ND	ND
HBW-09	6.4 ± 0.6	7.0 ± 0.7	1.0 ± 0.2	ND	ND
HBW-10	7.1 ± 0.6	8.0 ± 0.7	2.0 ± 0.3	ND	ND
HBW-11	7.8 ± 0.7	9.0 ± 0.8	2.0 ± 0.3	ND	ND
HBW-12	8.7 ± 0.8	9.0 ± 0.8	2.0 ± 0.3	ND	ND

ND = Not Detected

As shown in Table 3.7, Water Quality Index (WQI) values ranged from 23.8 to 214.8, indicating varying degrees of groundwater suitability for drinking purposes. Six borehole water samples (50.0%) were classified as having excellent water quality, three samples (25.0%) were classified as good, two samples (16.7%) were categorised as poor, while one sample (8.3%) was considered unsuitable for drinking without treatment. The observed deterioration in WQI from HBW-01 to HBW-12 reflects the cumulative influence of increasing physicochemical, heavy metal and microbiological contamination.

Table 3.7: Water Quality Index (WQI) Classification

Sample ID	WQI Value	Water Quality Classification
HBW-01	23.8	Excellent
HBW-02	31.4	Excellent
HBW-03	39.6	Excellent
HBW-04	45.8	Excellent
HBW-05	48.7	Excellent
HBW-06	49.8	Excellent
HBW-07	63.4	Good
HBW-08	72.8	Good
HBW-09	89.6	Good
HBW-10	108.6	Poor
HBW-11	126.4	Poor
HBW-12	214.8	Unsuitable for Drinking

As presented in Table 3.8, the non-carcinogenic human health risk assessment demonstrated that Hazard Quotient (HQ) values for adults remained below the acceptable threshold of one in all sampling stations, indicating negligible health risks through long-term ingestion. Conversely, HQ values for children progressively increased and exceeded unity in the latter sampling stations. Similarly, Hazard Index (HI) values exceeded one from HBW-06 onwards for children, indicating potential cumulative non-carcinogenic health risks associated with prolonged exposure to contaminated groundwater. Adults were generally within acceptable safety limits, whereas children constituted the most vulnerable exposure group.

Table 3.8: Non-Carcinogenic Human Health Risk Assessment

Sample ID	HQ (Adults)	HQ (Children)	HI (Adults)	HI (Children)	Health Risk Interpretation
HBW-01	0.09	0.18	0.14	0.29	Acceptable
HBW-02	0.12	0.25	0.19	0.37	Acceptable
HBW-03	0.18	0.39	0.28	0.57	Acceptable
HBW-04	0.24	0.48	0.36	0.73	Acceptable
HBW-05	0.31	0.62	0.47	0.91	Acceptable
HBW-06	0.38	0.79	0.58	1.12	Potential Risk (Children)
HBW-07	0.44	0.88	0.67	1.26	Potential Risk (Children)
HBW-08	0.51	0.96	0.77	1.41	Potential Risk (Children)
HBW-09	0.58	1.08	0.88	1.59	Potential Risk (Children)
HBW-10	0.66	1.21	0.98	1.82	Potential Risk (Children)
HBW-11	0.73	1.36	1.08	2.01	Potential Risk
HBW-12	0.81	1.54	1.18	2.26	Potential Risk

As shown in Table 3.9, Pearson correlation analysis revealed several statistically significant positive relationships among the measured water quality parameters ($p < 0.05$). Electrical conductivity exhibited a very strong positive correlation with total dissolved solids ($r = 0.91$), indicating that dissolved ionic constituents largely influenced groundwater conductivity. Strong positive correlations were also observed between electrical conductivity and chloride ($r = 0.82$), nitrate and chloride ($r = 0.76$), iron and electrical conductivity ($r = 0.69$), and iron and lead ($r = 0.68$). These relationships suggest common hydrogeochemical processes and possible shared anthropogenic sources contributing to groundwater contamination.

Table 3.9: Pearson Correlation Matrix

Parameters	EC	TDS	NO_3^-	Cl^-	Fe	Pb
EC	1.000	0.91	0.79	0.82	0.69	0.58
TDS	0.91	1.000	0.76	0.81	0.67	0.55
NO_3^-	0.79	0.76	1.000	0.76	0.53	0.47
Cl^-	0.82	0.81	0.76	1.000	0.62	0.51
Fe	0.69	0.67	0.53	0.62	1.000	0.68
Pb	0.58	0.55	0.47	0.51	0.68	1.000

Correlation coefficients significant at $p < 0.05$.

As shown in Table 3.10, Principal Component Analysis extracted three principal components that collectively explained 79.6% of the total variance in groundwater quality.

Principal Component 1 accounted for 41.8% of the total variance and was strongly associated with electrical conductivity, total dissolved solids, sodium, chloride and nitrate, indicating the influence of groundwater mineralisation and anthropogenic inputs. Principal Component 2 explained 23.5% of the variance and was dominated by iron, lead, cadmium and manganese, reflecting heavy metal contamination from both natural and anthropogenic sources. Principal Component 3 accounted for 14.3% of the total variance and was characterised by pH, bicarbonate, calcium and magnesium, representing the natural hydrogeochemical weathering processes controlling groundwater composition.

Table 3.10: Principal Component Analysis (PCA)

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)	Dominant Variables
PC1	4.18	41.8	41.8	EC, TDS, Na^+, Cl^-, NO_3^-
PC2	2.35	23.5	65.3	Fe, Pb, Cd, Mn
PC3	1.43	14.3	79.6	pH, HCO_3^-, Ca^{2+}, Mg^{2+}

4.0 Discussion

The present study provides a comprehensive evaluation of the hydrochemical characteristics, microbiological quality, and associated public health risks of borehole water used within selected hospitals in Rivers State, Nigeria. The findings demonstrate that although the majority of the physicochemical parameters complied with the World Health Organization (WHO) drinking-water guidelines, isolated occurrences of acidity, elevated concentrations of selected heavy metals, and microbial contamination indicate that groundwater quality is spatially variable and cannot be assumed to be uniformly safe for human consumption.

This observation is particularly important because hospitals rely heavily on continuous supplies of potable water for patient care, surgical procedures, laboratory analyses, sterilisation, food preparation, and infection prevention. Consequently, deterioration in groundwater quality within healthcare facilities may directly compromise patient safety and increase the risk of healthcare-associated infections and other adverse health outcomes [22].

The physicochemical characteristics observed during this study indicate that the groundwater generally possesses acceptable aesthetic and chemical quality. Electrical conductivity and total dissolved solids remained considerably below the WHO guideline limits, suggesting that the groundwater is weakly mineralised and contains relatively low concentrations of dissolved ionic constituents. Similar hydrochemical conditions have been reported for groundwater resources within the Niger Delta, where groundwater quality is primarily influenced by aquifer lithology, groundwater recharge processes, and natural geochemical interactions rather than excessive salinisation [8,10,19]. The relatively low electrical conductivity further suggests minimal intrusion of saline water into the investigated aquifer, despite the coastal location of Rivers State. This finding is consistent with previous groundwater investigations that demonstrated that freshwater aquifers developed within the Benin Formation generally exhibit low to moderate mineralisation under favourable hydrogeological conditions [10,19]. The strong positive relationship observed between electrical conductivity and total dissolved solids further confirms that dissolved ionic species represent the principal contributors to groundwater conductivity. This relationship is expected because electrical conductivity reflects the ability of dissolved ions to conduct electric current, while total dissolved solids represent the cumulative concentration of dissolved inorganic constituents within groundwater. Similar associations have been reported in hydrochemical investigations of groundwater systems across southern Nigeria, where increasing mineral dissolution during groundwater movement through unconsolidated coastal sediments results in progressive increases in both parameters [8,10]. The observed correlation therefore reflects the influence of natural hydrogeochemical evolution rather than isolated contamination events. Hydrogen ion concentration remained within the recommended drinking-water range for most sampling stations; however, several boreholes produced slightly acidic groundwater. Groundwater acidity is frequently associated with carbon dioxide dissolution, oxidation of organic matter, decomposition of vegetation, and weathering of silicate minerals within tropical environments. In addition, anthropogenic activities including petroleum exploration, industrial emissions, and urban development may contribute to localised groundwater acidification through atmospheric deposition and infiltration of acidic leachates. Slightly acidic groundwater is environmentally significant because decreasing pH enhances the dissolution and mobilisation of trace metals from aquifer materials, plumbing systems, and borehole casings, thereby increasing the potential exposure of consumers to dissolved metals. Comparable observations have been documented in groundwater investigations within hospital environments and other parts of Nigeria, where acidic groundwater was associated with increased concentrations of iron and other trace elements [8,10,19]. Consequently, routine monitoring of groundwater pH remains essential because persistent acidity may accelerate corrosion of water distribution infrastructure and reduce the long-term suitability of groundwater for potable use.

Nitrate concentrations recorded during the present investigation remained substantially below the WHO guideline value of 50 mg/L, indicating limited nutrient enrichment within the investigated aquifers. Low nitrate concentrations generally suggest that agricultural runoff, excessive fertiliser application, and sewage infiltration have not yet exerted widespread influence on groundwater quality in the sampled locations. Nevertheless, the gradual increase in nitrate concentrations across several boreholes indicates that anthropogenic activities may already be influencing groundwater chemistry at some locations. Previous studies have similarly demonstrated that increasing urbanisation, inadequate sanitation facilities, leaking septic systems, and indiscriminate waste disposal contribute to progressive nitrate enrichment in groundwater resources, particularly in rapidly developing urban centres [10,11]. Although the concentrations measured during this study do not presently constitute a significant public health concern, continued monitoring remains necessary because sustained increases in nitrate concentrations may eventually increase the risk of methaemoglobinaemia in infants and indicate deterioration of groundwater quality.

Phosphate concentrations were also relatively low throughout the study area, suggesting limited contamination from domestic wastewater, detergents, or agricultural inputs. In groundwater systems, phosphate is generally less mobile than nitrate because it is readily adsorbed onto soil particles and iron or aluminium oxides. Consequently, elevated phosphate concentrations often indicate substantial anthropogenic inputs or intense groundwater contamination. The relatively low phosphate concentrations observed during this study therefore support the conclusion that nutrient pollution is presently limited within the investigated aquifer system. Similar observations have been reported for groundwater within the Niger Delta, where nutrient concentrations generally remain low unless influenced by municipal wastewater or intensive agricultural activities [10,19].

The major ion composition of the borehole water further supports the interpretation that groundwater chemistry is principally controlled by natural hydrogeochemical processes. Progressive increases in calcium, magnesium, sodium, chloride, sulphate, and bicarbonate concentrations across the sampling stations indicate continuous mineral dissolution and groundwater–rock interaction during subsurface flow. Because all measured concentrations remained below WHO guideline values, these ions do not presently constitute a direct health concern. Instead, they reflect the natural geochemical evolution of groundwater as recharge water migrates through unconsolidated coastal sediments rich in quartz, feldspars, and clay minerals. Similar hydrochemical evolution has been reported for groundwater systems within the Benin Formation, where prolonged residence time and ion exchange processes progressively modify groundwater chemistry without necessarily compromising drinking-water quality [8,10,19].

The observed ionic composition also indicates that seawater intrusion is unlikely to represent the dominant factor controlling groundwater chemistry within the investigated boreholes. Coastal aquifers affected by marine intrusion typically exhibit markedly elevated concentrations of sodium and chloride accompanied by substantially higher electrical conductivity and total dissolved solids. In contrast, the relatively moderate concentrations observed during this investigation suggest that groundwater quality remains predominantly controlled by freshwater recharge and natural weathering processes rather than saline water encroachment. This finding is encouraging because seawater intrusion remains one of the principal threats to groundwater sustainability within many coastal regions of the Niger Delta, particularly in areas experiencing excessive groundwater abstraction and increasing urbanisation [8,19].

Conclusion

The present study demonstrated that the physicochemical quality of borehole water used in selected hospitals in Rivers State generally complied with the World Health Organization drinking water standards for most measured parameters, including electrical conductivity, total dissolved solids, major ions, nitrate, and biochemical oxygen demand. However, slight acidity was observed in some boreholes, while elevated concentrations of iron, lead, and cadmium were detected in several sampling stations. The microbiological analyses further revealed the occurrence of total coliforms and *Escherichia coli* in some borehole water sources, indicating localised faecal contamination. Water Quality Index assessment showed that only half of the boreholes possessed excellent water quality, whereas three boreholes were classified as poor or unsuitable for drinking without treatment. Furthermore, human health risk assessment indicated that although the groundwater posed negligible non-carcinogenic risks to adults, children may be exposed to potential health risks through prolonged consumption of contaminated water, particularly in sampling stations with elevated heavy metal concentrations.

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