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Full Length Research

Health risk assessment of borehole water quality in Okpoma, Yala LGA, Cross River State, Nigeria using spectrophotometric techniques

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ABSTRACT: A saltwater lake is found in Okpoma, located in Yala Local Government Area (LGA) in Cross River State, Nigeria. Natural and anthropogenic sources of contaminants may have seeped into the near – surface groundwater with a likelihood of contamination of borehole water in the study locations, resulting in possible exposure of consumers to health risk of acute and chronic toxicity. The populace drinks water from borehole faucets from groundwater. Borehole water was randomly selected for investigation from four (4) different locations within the saltwater lake. The experimental group labelled BWA, BWB, and BWC were in the range of 1.5 km, while BWD, used as a control, was at 3.0 km farther from the salt water lake. Using standard analytical procedures (APHA) and measuring instruments, physical, chemical and heavy metal analyses were carried out to measure and evaluate if borehole water samples are fresh and safe as drinkable water. For the experimental group, twenty per cent (20%) of the parameters comprising lead $(19.98 \pm 1.40\ \mu g\ L^{-1})$, copper $(1{,}500 \pm 131.40\ \mu g\ L^{-1})$ and arsenic $(13.49 \pm 0.61\ \mu g\ L^{-1})$ concentrations exceeded the World Health Organisation (WHO) permissible limit for lead $(10\ \mu g\ L^{-1})$, copper $(1{,}000\ \mu g\ L^{-1})$, arsenic $(10\ \mu g\ L^{-1})$, while other physical and chemical parameters (80%) were within the permissible limit, similar to the control. Borehole water samples from Borehole B (BWB) recorded the highest mean concentrations for lead, copper and arsenic, while the lowest mean concentrations were found in Borehole A (BWA). Potential non – cancer (CDI, HQ, HI) and cancer $(ILCR$, and $TCR)$ human health risk parameter/effects were also determined and reported. CDI, HQ, HI, $ILCR$, and TCR of the experimental group exceeded those of the control. Health risk due to heavy metal toxicity is expected over a long period. Further investigation, including the nearby stream and river, is suggested. Continuous monitoring, physical and chemical remediation, among other proper treatment techniques, are necessary before consumption of borehole water investigated in the study area.

Keywords: Anthropogenic sources, borehole water, contaminants, lithology, remediation, statistics, water quality parameters, World Health Organisation.

INTRODUCTION

Okpoma in Yala Local Government Area (LGA) in Cross River State, South-South (Niger Delta) Nigeria, is one of the towns known for saltwater lake, which is very important to the inhabitants. Depending on the specific location, the distance between Yala LGA in Cross River State, Nigeria and Cameroon, a neighbouring country to the east, is approximately 100 to 150 Km (62 to 93 miles). Crossing of the border is relatively common with trade and culture tiles between the people of Cross River State and Cameroon. Some of the communities in Okpoma are Abachor, Adeni, Iboko, Idiku, Ijama, Itega Okpudu, Okpudun, Oba, Olachor, and Ikega Okpame. The people of Yala settled within the salt lake water because of the high salt content in the underground water, which has encouraged local salt production and farming in the study area, just like the Okposi and Uburu salt water lakes in Ohaozara LGA, Ebonyi State, South-eastern Nigeria (Agu *et al.,* 2025; Nwaka *et al.,* 2022; Avwiri *et al.,* 2017; Ononugbo and Nwaka, 2017). There is a unique chemical composition of groundwater in Okpoma, Cross River State, Nigeria, due to the presence of brine (sodium chloride) that contains high concentrations of sodium chloride followed by calcium, magnesium and potassium ions, suggesting the brines originated from marine rather than continental (Ushie *et al.,* 2014).

Generally groundwater quality is affected by mixing process as composition of groundwater is influenced by various factors, principally by the mineral composition of the aquifer which determines the degree and nature of water – rock interaction process, human and anthropogenic activities, the process of mixing of different water bodies and the exchange with surface water, which may have considerably water impact depending on specific hydrogeological background (Etaghene *et al.,* 2026; John *et al.,* 2025a; Nwaka *et al.,* 2025b; Nwaka *et al.,* 2026b; Etuk *et al.,* 2025; Eyankware *et al*., 2023; Zakir *et al.,* 2020). The populace experiences scarcity of water due to low permeability rock, decrease in surface water, low rainfall and salt water intrusion (Edet and Okereke, 2022; Ushie *et al.,* 2014), so in dry season, the inhabitant walk for some distance in search of safe borehole water or resort to surface water (stream and river water) consumed as drinking water and for other purposes.

A number of possible water contamination in the study area include the use of fertilizers and pesticides for cultivation of crops and plants, indiscriminate discharge of waste into the environment and water bodies, salt water intrusion, growing industrial activities, discharging sewage and untreated water into surface water, runoff water from agricultural farm lands, the use of toxic chemicals from medicine, oil spillage and mining activities. As contaminants are introduced into the groundwater system, borehole water quality may be significantly compromised and adversely affected, which could be dangerous to public health and the environment.

Motion of chemical constituents of water depends on geochemical processes which are influenced by climatic conditions, hydrogeochemical conditions, rock and soil properties (John *et al.,* 2025b; Agaku *et al.,* 2025; Unande *et al.,* 2025; Nwaka *et al.,* 2025a; Egbueri *et al.,* 2025; Nwaka *et al.,* 2025b). Though a number of cations, anions and heavy metals are essential for human nutrition for healthy living, excess intake of heavy metals among other toxic elements may create adverse human health risks such as cancer and non – cancer risks, neurological damage and renal failure with children being most vulnerable due to lower body mass (15 – 30kg) relative to adult (70 – 80 kg).

Geological, geophysical, and hydrogeological studies of the fractured shale aquifer in Yala LGA have revealed the presence of saline groundwater (Edet and Okereke, 2022). Reports highlight that several boreholes drilled in Okpoma, Yala LGA, intended as sources of drinking water, produce water with a salty taste. This raises concerns about its safety for human consumption, given both its physical characteristics and chemical composition. Consequently, further investigation is necessary, as contamination of groundwater by heavy metals such as lead, arsenic, chromium, copper cyanide, and nickel—alongside other toxic substances—poses significant risks. Such pollutants can trigger acute and chronic health problems, while also threatening environmental integrity and public health.

Some environmental monitoring assessment have been carried out in different locations of the world and physical, chemical, heavy metals and radionuclide quality of water were reported in different regions to ascertain the suitability of the water sources for drinking and other purposes (Ggbadebo *et al.,* 2026; Echeweozo *et al.,* 2025; Azeez *et al.,* 2025; Shaibu *et al.,* 2025; Nwaka *et al.,* 2025b; Hossain *et al.,* 2025; Chen *et al.,* 2024; Igelle *et al.,* 2024; Pannerselvam *et al.,* 2023; Joseph *et al.,* 2022; Jacob *et al.,* 2022; Ushie *et al.,* 2015; Zakir *et al.,* 2020). High concentrations of nickel (Ni) and chromium (Cr) in borehole water from some locations in Asaba, South-South Nigeria, were reported (Etaghene *et al.,* 2026). In Edo State and Cross River State, South-South Nigeria (Niger Delta Region), Dimowo *et al.* (2025) established elevated concentrations of Cd, Pb and Fe heavy metals, exceeding regulatory thresholds WHO, SON, USEPA and NESREA, with total mean cancer risk (TCR) exceeding USEPA regulatory threshold of 1.0×10^{-4} in all the water samples.

Turbidity and TDS concentration for both borehole and well water exceeded the Nigerian Standard for Drinking Water Quality (NSDWQ) as well as the World Health Organisation (WHO) guidelines for drinking water quality in Tafawa Balewa, Bauchi State, Northern Nigeria (John *et al.,* 2025a). Data from solid waste around Port Harcourt, Rivers State, South-South Nigeria revealed that pH, TDS and electrical conductivity exceeded the WHO standard (Nwugha *et al.,* 2025), while the calculated hazard index ($HI > 1$) value was obtained for heavy metals (Pb, Ni, Cr, Cd) in offal and muscle tissues of goats, cows and rams slaughtered at the main abattoir in Lokoja, Nigeria

(Emurotu *et al.,* 2024). Cumulative assessment of human health risks of heavy metal contamination in copper and steel factory effluents in Nnewi, Anambra State, Nigeria showed higher carcinogenic risk due to Pb and Cd (Ugwu *et al.,* 2024). Physicochemical analyses report in salty water environments in Ebonyi State, Southeastern Nigeria, revealed that some borehole water samples were not safe for drinking (Nwaka and Avwiri 2021). Titilawo *et al.* (2020) used standard procedures to measure physicochemical and bacteriological quality of surface water and groundwater consumed in Ikwo, in Ebonyi State, Southeastern Nigeria, and established that groundwater was within the WHO guidelines for drinking water quality, whereas bacteriological water quality exceeded the WHO guidelines as there were bacteriological loads.

In other countries of the world, carcinogenic and non-carcinogenic risks assessment of heavy metals in groundwater in Mansa District, Punjab, in India revealed concentrations of heavy metals that highly influenced the non-carcinogenic risk to the people living in the study district, while cancer risk was attributed to cadmium and chromium concentrations in the groundwater (Guron *et al.,* 2025). Mohammadi *et al.* (2024) established carcinogenic and non-carcinogenic risks assessment of heavy metals (Pb, Cd, Zn and Ni) in rice consumed in Iran. They reported that long-term consumption of contaminated rice might endanger the health of the people living in the area. Zakir *et al.* (2020) established that surface water holds more potential non-carcinogenic harmful health risk than groundwater in the study area of Jamalpur Sadar Area in Bangladesh. Investigation on physicochemical water quality of drinking water and human health in a salt range in Pakistan showed a good number of sulphate, iron, chloride, and heavy metal of chromium exceeded the WHO guidelines for drinking water quality (Batool *et al.,* 2018). Furthermore, relatively higher values of some parameters compared with the WHO reference limit suggested saltwater intrusion and contamination of the drinking water (Batool *et al.,* 2018). Physicochemical and microbiological evaluation of organic pollutants in plain salty lakes from protected regions has been reported (Lazar *et al.,* 2017).

Though environmental studies have been carried out in Nigeria and other countries, as recorded in literatures, available studies revealed that physical, chemical and heavy metal risk assessment in the present study locations in Nigeria have not been sufficiently studied, reported and documented as reference materials. There is a need to investigate and monitor borehole water for groundwater quality before consumption. The need for data and useful information has motivated this study. The purpose of the study is to assess the risk level of borehole water quality in Okpoma, Yala LGA, Cross River State, Nigeria. The specific objectives of the study, in line with the purpose, are: (i) to determine and evaluate some physical qualities/ parameters of borehole water in the study area which include: temperature, pH, total dissolved solid (TDS), conductivity and turbidity of water samples, (ii) to measure and evaluate some chemical qualities/ parameters of borehole water in the study area which include the nitrate, sulphate, phosphate, sodium and chloride concentrations, (iii) to determine and evaluate some heavy metals concentration borehole water in the study area including lead, nickel, cyanide, cadmium, copper, arsenic, chromium, and (iv) to evaluate human health risks (non-carcinogenic and carcinogenic risks) of contamination of heavy metals in the borehole water.

MATERIALS AND METHODS

Several materials such as plastic containers for collecting water samples, beakers, funnels, concentrated trioxonitrate (V) acid (HNO_3), sterilised water, thermometer, spectrophotometer, and Flame Atomic Absorption Spectrophotometry (AAS) were used. Standard procedures, such as those outlined by the American Public Health Association (APHA), were adopted in preparing the water samples prior to physicochemical analysis.

The description of the study area

Yala LGA is one of the 18 LGAs in Cross River State, South–southern (Niger Delta Area) Nigeria, where Okpoma town is located, which is notable among other tourist attractions in Cross River State because of the salt lake water in Okpoma. The LGA, found in the Northern Senatorial District of Cross River State, Nigeria, with an area of approximately 1, 740 km^2, was created in 27th of August, 1999, with ten (10) Council Wards in the LGA. It is bordered by Benue State to the North, Ikom (to the Southeast), Obubra LGA to the South, Ogoja LGA to the East and Ebonyi State to the West. It is geographically located at a latitude of 6°32'35"N to 6°40'35"N of the equator and a longitude of 8°36'01"E to 8°41'02"E of the meridian. Okpoma, salt water lake area, is of historical importance to the Yala populace, as the underground salt holds enough salt content to support small scale salt industry. The location was selected for the study based on the major economic activities in the study area, which include trading, fishing, farming, mining, and small-scale production of salt for sale to the surrounding and beyond. During these activities, there is a possibility that the populace consumes water from the salt lake in the LGA. Apart from cooking salt, which is locally produced in the community, rice is produced in commercial quantities in the area from Adeni and Ijama, bordering Ishiaya in Ogoja Local Government Area (LGA). The inhabitants within and surrounding get water for drinking from the borehole, stream and river.

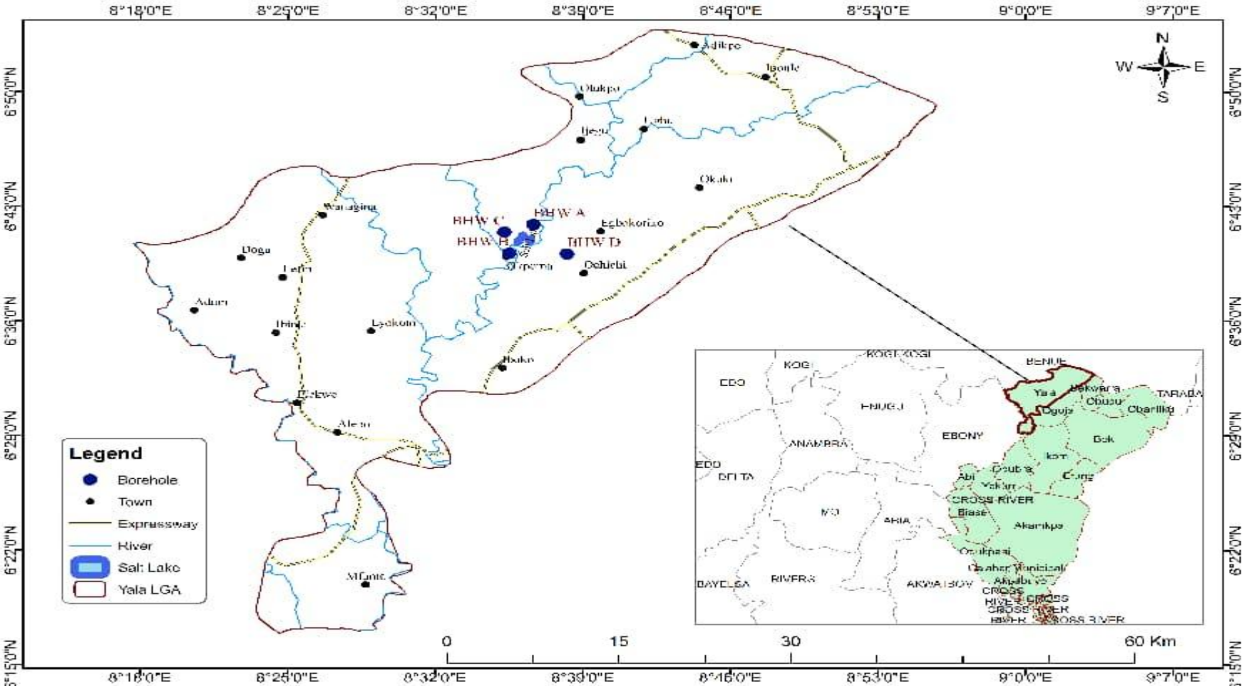


Figure 1. Location map of the study area and borehole water sites.

Unlike Umuahia and Uzuakoli environs in Southeastern Nigeria, where the lithology constitute of sand, clay and shale aquifer units occurring at shallow depths in some locations ranging from 9 to 30 metres (m), with some other locations having deep aquifer units of depth ranging from 40 to 115 metres (Nwugha *et al.,* 2024), the lithology of the Yala area is shale, shelly limestone, shelly grey, fractured shale and sandstone with average depth of the water table in the locality approximately 4.2 metres below the surface (Edet and Okereke, 2022; Ushie *et al.,* 2014; Ushie *et al.,.* 2015). Formations in the study area have been reported, and groundwater in the study area occurs in the Awe Formation (Asu River Group) in association with the brines (Edet and Okereke, 2022; Ushie *et al.,* 2014). The Location map of the study area is shown in Figure 1.

Collection of borehole water samples from the study locations

The study area was stratified into three (3) divisions based on proximity and road networks in the towns as well as closeness to the saltwater lake. Random sampling technique was used to select/sample one borehole each from the three stratified zones for the investigations. Three (3) different sampling sites for borehole water were outlined for investigation as experimental group; comprised of Borehole A (BWA), Borehole B (BWB) and Borehole C (BWC) in the range of 1 to 1.5 km distance away from salty water lake, while Borehole D (BWD) was also sampled as control approximately 3.0 Km distance from the salt lake water.

Similar 0.75 litre (75 centilitre) sterilised containers of the same dimension were used to collect fifteen (15) filtered water samples, using a sieve and a funnel, from each of the three randomly selected borehole water sources, as well as fifteen (15) borehole water samples for the control site. Water samples were directly collected from water faucets/taps after allowing the taps to run for four (4) minutes with each container and cover (lid) rinsed thoroughly with the water sample, thereafter, labelled for easy identification, and acidified with 2.0 ml concentrated trioxonitrate (V) acid (HNO_3) in order to avoid adsorption of heavy metals on the walls of the containers. Borehole water samples for the study were transported to a laboratory for further preparation prior to physical, chemical and heavy metal water analyses.

Preparation of borehole water samples for analyses

The samples were stored in a refrigerator, using beakers, for a short time at five degrees Celsius (5°C) in the laboratory prior to further water analyses to avoid modification in physicochemical qualities, as external factors such as high temperature can alter or modify some of the water parameters. 2.0 ml of concentrated trioxonitrate (V) acid (HNO_3) was used as pretreatment (acid digestion) of samples for the determination of heavy metals and metalloids (As). Concentrated trioxonitrate (V) acid (HNO_3) was used in order to remove organic impurities from the samples and also to prevent interference in the analysis of heavy metals (Ugwu *et al.,* 2022; Nwaka and Avwiri, 2021).

A total of sixty (60) water samples, comprising 15 borehole water samples from each sampled borehole (BWA, BWB, BWC and BWD) was collected and prepared for analyses using standard analytical procedures (APHA, 2012; APHA, 2005; APHA, 2000) and measuring instruments. The average, standard deviation and coefficient of dispersion (CD) in percentage for the three borehole water samples were recorded.

Analyses of physical, chemical and heavy metal concentrations in borehole water

Fifteen (15) water parameters were considered for investigation, grouped into physical, chemical and heavy metals (arsenic as metalloids). While some of the parameters were measured at the point of collection (*in situ*), others were carried out in laboratories. The procedure used was standard methods for the examination of water and wastewater jointly published by the American Public Health Association (APHA), in collaboration with American Water Works Association (AWWA) and Water Environment Federation (WEF), which are cited as APHA (2012), APHA (2005) and APHA (2000). This technique serves as a comprehensive guide for analysing water and wastewater. The procedure was used for analysing the physical, chemical and heavy metals (arsenic as metalloid) characteristics of borehole water in the study area.

Physical tests were carried out to understand or reveal the physical appearance of the borehole water samples, while chemical tests were carried out to ascertain the amounts of minerals that affect the quality of water, the presence of soluble salts and heavy metals in water for different purposes. Presence of bacteria, characteristic of faecal pollution, volatile organic compounds, and radionuclide concentrations were not considered for investigation in the study. The pH concentration was determined at the site of collection of water samples (*in situ*) using a handheld electrical pH meter after standardisation with a buffer solution of pH ranging from 4.0 to 9.0. Similarly, temperature was measured *in situ* using a mercury-in-glass thermometer in degrees Celsius (°C), while turbidity was determined using a HACH spectrophotometer (DR/2000) in Nephelometric Turbidity Unit (NTU). Temperature (in the laboratory), pH concentration (in the laboratory), Total dissolved solids (TDS), and electrical conductivity (EC) were determined using a HANNA meter (H I9828) calibrated with a standard buffer solution of pH ranging from 4.0 to 9.0. The HANNA meter is a four-in-one meter which could measure temperature, pH, TDS and EC. Phosphate, nitrate, and sulfate were read in a JENWAY UV/Visible spectrophotometer (6506). Heavy metals of lead, arsenic (metalloid), nickel, chromium, cyanide, copper, and cadmium concentrations were measured using Flame Atomic Absorption Spectrophotometry (FAAS).

Atomic Absorption Spectrophotometry (AAS) is a commonly used instrument/technique for detecting and quantifying metals and metalloids in various samples. The operation of AAS is based on the principle that a free metallic atom in a gaseous state absorbs light at a characteristic wavelength, allowing for precise analyses of elements. As the sample is atomised, the free atoms can absorb light at specific wavelengths corresponding to an electronic transition between energy levels. The amount of light absorbed is directly proportional to the concentration of elements in the sample.

One liter (L) of water is equivalent to one kilogram of water (kg) at temperature $4℃$ (when density of water is approximately $1\ g\ cm^{-3}$). Furthermore, It has also been established that $1\ cm^3 = 1mL$, and $1\ g\ cm^{-3} = 10^6\ mg\ L^{-1}$. To convert from part per million ($1\ ppm$) to milligram per litre ($1\ mg\ L^{-1}$) as a representation of substance in a solution, the knowledge of the density of the solution or water in $g\ cm^{-3}$ is important. The density of seawater due to dissolved salt is approximately $1.025\ g\ cm^{-3}$, while that of freshwater is $1g\ cm^{-3}$. For a dilute aqueous solution such as most freshwater samples (density approximately $1\ g\ cm^{-3}$), one part per million ($1\ ppm$) is approximate/equivalent to one milligram per litre ($1\ mg\ L^{-1}$), represented in the equation 1:

$$1\ mg\ L^{-1} \approx 1\ ppm \tag{1}$$

$$1\ mg\ L^{-1} = \left[\frac{1}{\text{Density of the substance in } g\ cm^{-3}}\right] ppm \tag{2}$$

As the density of freshwater is approximately $1g\ cm^{-3}$ at standard temperature and pressure (STP: $21℃$ and 1 atmosphere), the conversion is straightforward for a concentration of $1\ ppm$ of substance in the water sample as $1\ ppm = 1\ mg\ L^{-1}$ in equation 1. However, for other conditions or substances with different densities (for example 0.8 or 1.2 $g\ cm^{-3}$), densities matter; so, conversion to ppm might differ as represented in equation 2. Milligram per litre ($mg\ L^{-1}$) was converted to microgram per litre ($\mu g\ L^{-1}$) using the appropriate conversion factor in equation 3.

$$1\ \ mg\ L^{-1} = 10^3\ \mu g\ L^{-1} \tag{3}$$

Quality control and analysis of the data set for the distributions

Three (3) measurements/observations were taken and recorded, averaged as a mean value for each sampling site, so as to minimise systematic sources of error. Quality control was essential to ensure the accuracy, validity and reliability of measured parameters, as observation of each water sample was repeated to make certain the validity of the data. Quality control samples were also determined. Statistical analyses of borehole water samples were carried out using Microsoft Excel as well as Statistical Package for Social Sciences (SPSS), Version 21.0. Descriptive and inferential statistics were employed as statistical tools in the data analyses, including a measure of average or location of the central value (mean) and a measure of variability or dispersion (range, standard deviation, and coefficient of dispersion).

However, determining the spread of the data sets or distributions from the standard deviation may be misleading since its magnitude or size depends on the scale used in the measurement. In this study, a more reliable measure of spread or variation, which is not dependent on scale or unit, was used as the relative dispersion, called the coefficient of dispersion (CD) or coefficient of variation (CV), expressed in percentage (%), which is also useful in comparing distributions where units are different. Data sets with relatively higher percentage (%) concentrations reveal greater relative dispersion/ variation or coefficient of dispersion (CD). Furthermore, information given in statistical graphs (multiple bar charts) was interpreted, and inferences drawn from the information were reported.

Health risk assessment of borehole water (non-carcinogenic and carcinogenic risks)

Non-carcinogenic and carcinogenic human health risk assessment are very important concepts in water quality analyses used by regulatory authorities such as the US Environmental Protection Agency (USEPA) and the World Health Organisation (WHO) to describe the risk category of water and other chemical substances. Based on USEPA guidelines, the non-carcinogenic health risk was determined using equation 4 for the adult population for average daily intake (ADI) or chronic daily intake (CDI) of heavy metals in borehole/tap water via ingestion, measured in $mg\ kg^{-1}\ day^{-1}$, and equation 5 for hazard quotient (HQ) for the adult population. While chronic daily intake (CDI) represents the lifetime average daily dose ($LADD$) of exposure to possible contaminated water (heavy metals and metalloids).

$$CDI\ (mg\ kg^{-1}\ day^{-1}) = \frac{C \times I_R \times E_F \times E_D}{B_W \times AT} \quad (4)$$

Where: C is the concentration of each heavy metal in drinking water measured in mgL^{-1}, I_R is the ingestion rate of drinking water per unit time in litres per day (0.78 $L\ day^{-1}$ for children and 2.50 $L\ day^{-1}$ for an adult), E_F is the frequency of exposure in days/year (365 days/year), E_D is the duration of exposure in $years$ (6 and 30 $years$ respectively for children and adults for the assessment of non-carcinogenic human health risk, B_W is the average body weight in kg (15 kg for children and 70 kg for an adult), AT is the average exposure time ($E_F \times E_D$) for ingestion of borehole water, $AT = 365\ days \times 30\ years = 1,095\ days$ (for non-carcinogens), while $AT = 365\ days \times 70\ years = 25,550\ days$ (for carcinogens).

Hazard quotient (HQ) is a ratio of potential exposure to a substance and the level at which no adverse effects are expected, used primarily to evaluate the health risk of water and toxic air. It is also the ratio of calculated chronic daily intake (CDI) of heavy metal in water to the oral reference dose (R_fD) for the same heavy metal represented in equation 5.

$$HQ = \frac{CDI}{R_fD} \quad (5)$$

A hazard quotient (HQ) less than or equal to one (1) indicates adverse effects are not likely to occur, and thus can be considered as a negligible hazard, while hazard quotients (HQs) greater than unity (1) are not statistically probabilities that harm will occur, rather, it is an indication or simple statement of whether and how much or to what extent an exposure concentration exceeds the reference concentration (RC) or the chronic oral reference dose (R_fD).

Another very important assessment of human health risk due to consumption of water is the hazard index (HI). Hazard index (HI) is the sum of all hazard quotients (HQs) calculated for each heavy metal (substance) that affects the same target organ or organ system. It is also the potential risk posed to human health by exposure to multiple heavy metals, as represented in equation 5

$$HI = \sum_{i=1}^{n} HQ = HQ_{Pb} + HQ_{As} + HQ_{Ni} + HQ_{Cr} + HQ_{Cn} + HQ_{Cu} + HQ_{Cd} \quad (6)$$

Where, HQ_{Pb}, HQ_{As}, HQ_{Ni}, HQ_{Cr}, HQ_{Cn}, HQ_{Cu} and HQ_{Cd} are values of HQ for respective heavy metals (as arsenic is a metalloid). A value of Hazard index (HI) less than or equal to one (1.0), as a threshold value, implies no significant non – cancer risk. In other words, the exposed individual or the populace is unlikely to experience a hazardous health risk. While a value greater than one (1.0) indicates significant non-cancer risks, meaning that there are possibilities of occurrence of non-carcinogenic health risks to the people exposed to the drinking water in the study area. Significant non – cancer risks increase with the increase of hazard quotients (HQ) or hazard index. (HI).

Carcinogenic health risks or cancer health risk are

Table 1. Comparison of the physical borehole water quality in Yala LGA, Cross River State, Nigeria with control group and WHO guidelines for drinking water quality.

Physicochemical parameters	**Borehole A (BWA)**	**Borehole B (BWB)**	**Borehole C (BWC)**	**Mean±SD**	**CD (%)**	**Borehole D (Control) (BWD)**	**WHO Water Guidelines**
pH	8.10	8.30	8.20	8.20±0.08	0.97	7.80	6.5 – 8.5
Temperature	29.12	28.94	27.67	28.58±0.65	2.30	27.20	Ambient (30.0)
Turbidity (NTU)	3.14	3.75	3.30	3.40±0.26	7.64	2.40	5.0
TDS ($mg\ L^{-1}$)	354.62	331.0	376.58	354.07±18.61	5.26	225.64	500
EC (µS/cm)	702.45	659.12	751.68	704.42±37.81	5.37	436.78	1000

Micro Siemens per centimeter (µS/cm); Neophlometric Turbidity Unit (NTU); World Health Organization (WHO, 2022; 2017); CD: coefficient of dispersion (in %).

Table 2. Comparison of the chemical borehole water quality in Yala LGA, Cross River State, Nigeria with control group and WHO guidelines for drinking water quality.

Physicochemical parameters	**Borehole A (BWA)**	**Borehole B (BWB)**	**Borehole C (BWC)**	**Mean±SD**	**CD (%)**	**Borehole D (Control) (BWD)**	**WHO Water Guidelines**
Nitrate ($mg\ L^{-1}$)	33.74	41.31	37.86	37.64±3.09	**8.22**	18.67	50.0
Phosphate ($mg\ L^{-1}$)	2.76	2.41	2.37	2.51±0.18	**6.97**	1.35	5.0
Sulphate ($mg\ L^{-1}$)	75.26	77.12	82.89	78.42±3.25	**4.14**	37.62	100 – 250

Milligram per liter ($mg\ L^{-1}$); World Health Organization (WHO, 2022; 2017); CD: coefficient of dispersion (in %).

derived from the lifetime average dose exposure (70 years) to 1 $mg\ kg^{-1}\ day^{-1}$ of contaminant. It is commonly expressed in terms of incremental lifetime cancer risk ($ILCR$), which was calculated due to potential carcinogens (Pb, As, Ni, Cd, Cr). Potential carcinogenic risk chances (probabilities) that an individual may develop cancer over an average lifetime of 70 years of exposure were calculated using equation 7

$$ILCR = CDI \times CSF \quad (7)$$

Where CDI is the chronic daily intake of heavy metals in water, CSF is the cancer slope factor. Based on the available toxicology data for the slope factor (SF), the values of CSF for Pb, As, Cr, Ni, and Cd, are 0.0085 $mg\ kg^{-1}\ day^{-1}$, (1.5 – 1.7 $mg\ kg^{-1}\ day^{-1}$), 0.5 $mg\ kg^{-1}\ day^{-1}$, 1.7 $mg\ kg^{-1}\ day^{-1}$ and 0.38 $mg\ kg^{-1}\ day^{-1}$ respectively, while Cu and CN are not classified as human carcinogenic. According to USEPA, A carcinogenic risk (CR) below 1.0×10^{-6} can be considered inconsequential, whereas a carcinogenic risk (CR) exceeding 1.0×10^{-4} is likely to be hazardous to human health. Total carcinogenic risk (TCR) is represented as the summation $ILCR$ ($\sum ILCR$) for all the carcinogenic metals and metalloids investigated.

The accepted range for $\sum ILCR$ according to USEPA is 1.0×10^{-6} (lower limit) to 1.0×10^{-4} (higher limit) for a single carcinogenic element and also for multiple carcinogen elements (USEPA, 2010). For social stability and human health, a CSF between 1.0×10^{-4} to 1.0×10^{-6} is considered acceptable or bearable.

RESULTS

Tables 1, 2 and 3 showed the range, mean, standard deviation and coefficient of dispersion for the physical, chemical and heavy concentrations of the investigated borehole water within the salt water lake in Yala LGA, Cross River State, Nigeria, respectively, compared with the control group and World Health Organisation (WHO) guidelines for drinking water quality. Data for chronic daily intake ($CDIs$), hazard quotients (HQs) and hazard indices (HIs) were presented in Table 4, while data for incremental lifetime cancer risk ($ILCR$) or cancer risk (CR) and total cancer risks (TCR) for the studied borehole water samples are presented in Table 5. Bar charts in Figure 2, Figure 3 and Figure 4, respectively, compared lead, arsenic and copper concentrations in borehole water samples with the WHO permissible limit and NSDWQ.

As observed from Table 1**,** pH and turbidity concentrations in the study locations were found in the order of BWB > BWC > BWA > BWD respectively. Results of calculated mean concentrations, experimental

Table 3. Comparison of the heavy metals borehole water quality in Yala LGA, Cross River State, Nigeria with control group and WHO guidelines for drinking water quality.

Heavy metals	Borehole A (BWA)	Borehole B (BWB)	Borehole C (BWC)	Mean±SD	CD (%)	Borehole D (Control) (BWD)	WHO Water Guidelines
Lead ($\mu g\ L^{-1}$)	18.54	21.68	18.92	19.71±1.40	**7.10**	13.37	10.0
Arsenic ($\mu g\ L^{-1}$)	12.73	14.21	13.54	13.49±0.61	**4.50**	11.53	10.0
Nickel ($\mu g\ L^{-1}$)	13.11	15.35	12.74	13.73±1.15	**8.38**	10.38	20.0
Chromium ($\mu g\ L^{-1}$)	31.71	38.67	34.52	34.97±2.86	**8.18**	29.56	50
Cyanide ($\mu g\ L^{-1}$)	1.14	1.76	1.36	1.42±0.44	**30.99**	1.13	3.0
Copper ($\mu g\ L^{-1}$)	1,370	1,680	1,450	1,500±131.40	**8.76**	1,130	1,000
Cadmium ($\mu g\ L^{-1}$)	2.23	2.74	1.48	2.15±0.52	**24.19**	1.12	3.0

World Health Organization (WHO, 2022; 2017), $\mu g\ L^{-1}$: micro gram per liter; CD: coefficient of dispersion (in %).

Table 4. Chronic daily intake (CDI) dose, hazard quotients (HQs) and hazard indices (HIs) due to heavy metals in borehole water quality in Yala LGA, Cross River State, Nigeria

Heavy metals *(μgL^{-}1)*	BWA *(CDI) x 10^{-5}*	BWA *HQ*	BWB *(CDI) x 10^{-5}*	BWB *HQ*	BWC *(CDI) x 10^{-5}*	BWC *HQ*	BWD *(CDI) x 10^{-5}*	BWD *HQ*
Lead (Pb)	66.0	2.200	77.0	2.570	68.0	2.270	48.0	1.600
Arsenic (As)	45.0	1.500	51.0	1.700	48.0	1.600	41.0	1.300
Nickel (Ni)	47.0	0.024	55.0	0.028	45.0	0.023	37.0	0.019
Chromium (Cr)	113.0	3.770	138.0	4.600	123.0	4.100	106.0	3.533
Cyanide (CN)	4.0	0.067	6.0	0.100	5.0	0.083	4.0	0.067
Copper (Cu)	4,893	1.220	6,000	1.500	5,179	1.295	4, 036	1.009
Cadmium (Cd)	8.0	0.160	9.0	0.180	5.0	1.100	4.0	0.080
HI		**8.94**		**10.68**		**9.47**		**7.61**

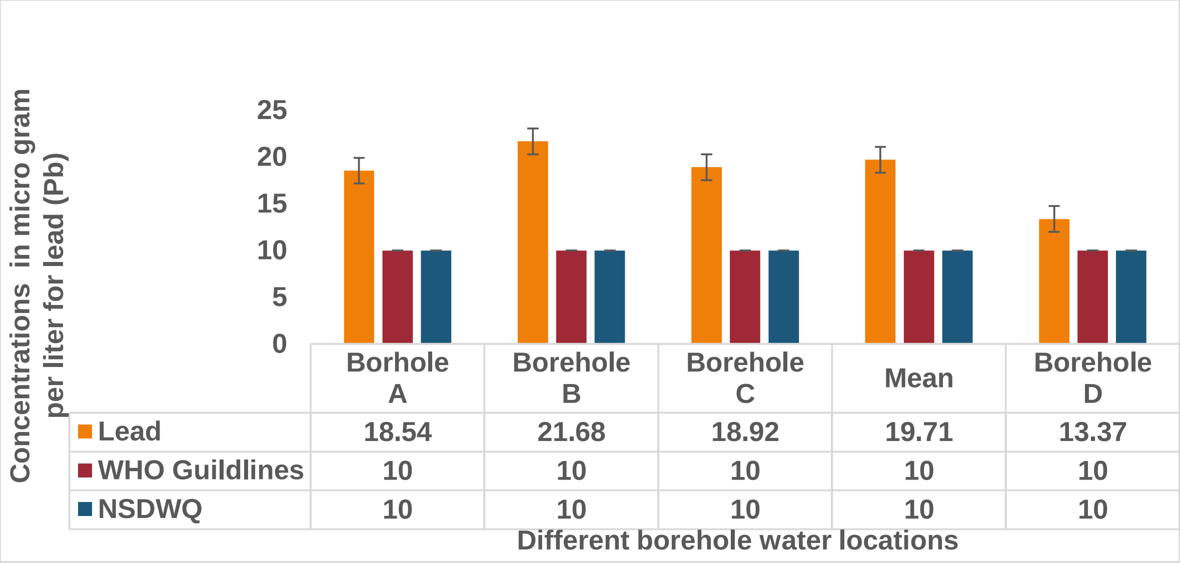
BWA: Borehole water A, BWB: Borehole water B, BWC: (Borehole water C, BWD: Borehole water D (Control).

Table 5. Incremental lifetime cancer risk ($ILCR$) and total cancer risk (TCR) of heavy metals and metalloids in borehole water from Okpoma, Yala LGA, Cross River State, Nigeria.

Heavy metals (μg L^{-1})	CSF (mgkg^{-1}day-^{1})	BWA *ILCR*	BWB *ILCR*	BWC *ILCR*	BWD *ILCR*
Lead (Pb)	0.0085	5.61×10-6	6.55×10-6	5.78×10-6	4.08×10-6
Arsenic (As)	1.500	6.75×10-4	7.65×10-4	7.20×10-4	6.15×10-4
Nickel (Ni)	1.700	7.99×10-4	9.35×10-4	7.60×10-4	6.29×10-4
Chromium (Cr)	0.500	5.65×10-4	6.90×10-4	6.15×10-4	5.30×10-4
Cadmium (Cd)	0.380	3.04×10-5	3.42×10-5	1.90×10-5	1.52×10-5
TCR= ∑(ILCR)		2.08×10-3	2.43×10-3	2.12×10-3	1.79×10-3

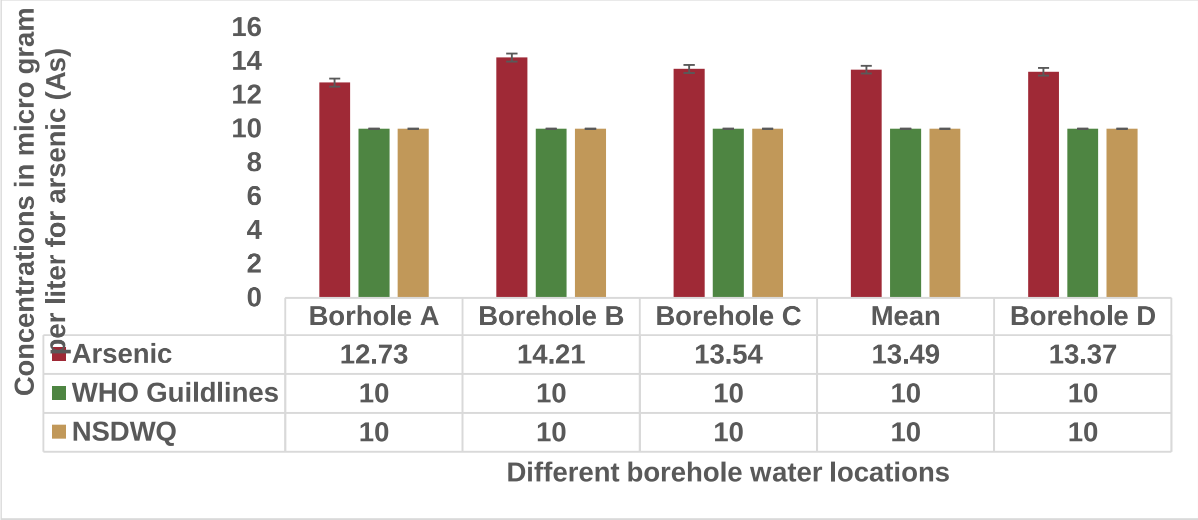
BWA: Borehole water A, BWB: Borehole water B, BWC: (Borehole water C, BWD: Borehole water D (Control)

and control group for both pH and turbidity were within WHO guidelines 6.5 – 8.5 and 5.0 NTU, respectively. In addition, observed TDS and EC concentrations from Table 1, each followed the order of BWC $>$ BWA $>$ BWB $>$ BWD respectively. Experimental group, control group and calculated mean concentrations for TDS and EC were within the WHO guidelines of 500 $mg\ L^{-1}$ and 1000 μS/cm, respectively. Data sets for turbidity, TDS, and EC showed there was no indication of possible microbial contamination as the regulatory limits were not exceeded. Furthermore, observation from Table 2 showed mean concentrations for chemical parameters of the borehole water samples in the study locations/area, which includes nitrate (37.64±3.09 $mg\ L^{-1}$), phosphate (2.51±0.18 $mg\ L^{-1}$) and sulphate (78.42±3.25 $mg\ L^{-1}$) concentrations were within the WHO and NSDWQ guidelines for drinking water



	Borhole A	Borehole B	Borehole C	Mean	Borehole D
🟧 Lead	18.54	21.68	18.92	19.71	13.37
🟥 WHO Guildlines	10	10	10	10	10
🟦 NSDWQ	10	10	10	10	10

Figure 2. Comparison of lead (Pb) concentration of borehole water samples from Yala LGA, Cross River State, Nigeria with the World Health Organization (WHO) permissible limit.

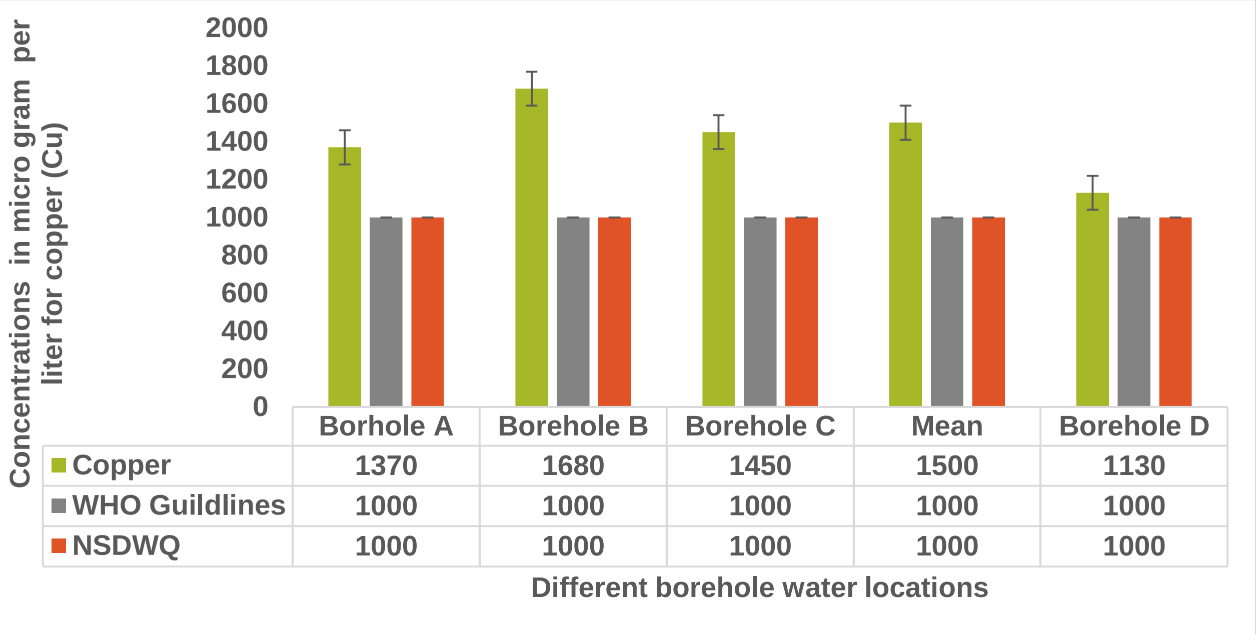


	Borhole A	Borehole B	Borehole C	Mean	Borehole D
🟥 Arsenic	12.73	14.21	13.54	13.49	13.37
🟩 WHO Guildlines	10	10	10	10	10
🟫 NSDWQ	10	10	10	10	10

Figure 3. Comparison of arsenic (As) concentration of borehole water samples from Yala LGA, Cross River State, Nigeria with the World Health Organization (WHO) permissible limit.

quality. There were variations in the order of nitrate concentrations (BWB > BWC > BWA > BWD) when compared with phosphate (BWA > BWB > BWC > BWD) and sulphate (BWC > BWB > BWA > BWD) in $mg\ L^{-1}$. All the observations, including the experimental and control group were below WHO and NSDWQ guidelines for drinking water quality. Data sets observed in this study for chemical parameters agreed with a number of related studies cited in the literature, however, differed from some other related studies.

As observed from Table 3, mean concentrations for some heavy metals (Pb, Ni, Cr, CN, Cu, Cd) and metalloid (As), observed in borehole water samples of the study area, were within the WHO permissible/safe limit recommendation, except for lead (19.71±1.40 $\mu g\ L^{-1}$), arsenic (13.49 ± 0.61 $\mu g\ L^{-1}$) and copper (1,500 ± 131.40 $\mu g\ L^{-1}$) concentration, which exceeded WHO and NSDWQ (10 $\mu g\ L^{-1}$, 10 $\mu g\ L^{-1}$ 1000 $\mu g\ L^{-1}$ respectively) guidelines for drinking water quality as observed from Figures 2, 3 and 4, which should be given attention.



	Borhole A	Borehole B	Borehole C	Mean	Borehole D
🟩 Copper	1370	1680	1450	1500	1130
■ WHO Guildlines	1000	1000	1000	1000	1000
🟥 NSDWQ	1000	1000	1000	1000	1000

Figure 4. Comparison of copper (Cu) concentration of borehole water samples from Yala LGA, Cross River State, Nigeria with the World Health Organization (WHO) permissible limit.

Notably, 80% of the water parameters investigated were below the permissible limits, while 20% (lead, arsenic and copper) exceeded the WHO and NSDWQ permissible limits.

DISCUSSION

Data sets obtained for physical parameters agreed with some related studies cited in the literature; however, differed from some other related studies. Unlike acidic pH concentration observed in mining communities in Ghana (Owusu *et al.,* 2024), the pH concentration of the borehole water samples in the study area is alkaline. The range of values of turbidity results for the present study differ with Owusu *et al.* (2024), where some water samples had maximum turbidity values (86.4 NTU); far exceeding the WHO 5 NTU guidelines for drinking water quality, unlike the present study, where all samples investigated were below the WHO and NSDWQ guidelines.

Observations obtained for heavy metals concentrations agreed with some related studies cited in the literature Echeweozo *et al.* (2025) where Pb > As in addition to Cu > Ni > Cd found in solid waste dumpsite in Ebonyi State, Nigeria, however, differed with the study carried out by Rahman *et al.* (2021) in Southwestern Coastal area of Bangladesh where Pb and As were below the WHO guidelines (2022; 2017). The present study average results for Pb ($19.98\,\mu g\,L^{-1}$) and As ($13.49\,\mu g\,L^{-1}$) concentrations agreed with higher results obtained in Chittagong industrial area of Bangladesh (Hossain *et al.,* 2025), results from village rainwater runoff around antimony mining area in China (Chen *et al.*, 2024), some mining locations in Amansie West District, Ghana, (Owusu *et al.,* 2024), and borehole water from Charanchi LGA, Katsina State, Northern Nigeria (Samaila *et al.,* 2025). Average Pb ($19.98\,\mu g\,L^{-1}$) and As ($13.49\,\mu g\,L^{-1}$) concentrations for the present study were found higher than the results obtained in drinking water samples sourced from two mining sites in Ghana (Ewool *et al.,* 2024); where arsenic (As) concentration were below the WHO standard, as well as borehole water samples from Ifite in Awka, Anamabra State, Nigeria, where lead (Pb) and chromium (Cr) concentrations were within WHO guidelines (Okorie *et al.,* 2024). Moreover, Cu concentrations found in experimental group of the present study was higher than that of Asaba Metropolis (South southern Nigeria). Cadmium concentration for present study was lower than relatively high concentration for borehole water in industrial area of Gboko in Benue State, Nigeria (Agaku *et al.,* 2025), and also in Charanchi LGA, Katsina State, Northern Nigeria (Samaila *et al.,* 2025). Also, Cu, As, and Cr concentrations exceeded borehole water from Niger Delta Area in Port Harcourt Rivers State, Nigeria (Osisanya *et al.,* 2024). Furthermore, mean nickel concentration for the study ($13.73\,\mu g\,L^{-1}$) varied with relatively high level of $298\,\mu g\,L^{-1}$ reported in borehole water at Uyo Metropolis, Akwa Ibom State, South southern Nigeria (Shaibu *et al.,* 2025), where heavy metal concentrations (iron and nickel) from a number of borehole water samples exceeded the WHO guideline for drinking water quality.

The study of potential reasons behind higher concentrations of lead, arsenic and copper in the borehole water are still in progress, however, it could be due to the depth of borehole water, mineral compositions in the study area, lithology of the study area, complex interactions between temperature, pH, solubility, speciation and complexes (Nwaka *et al.,* 2026a; Nwaka *et al.,* 2026b), as solubility of lead, arsenic and copper is significantly influenced by pH concentrations. The range and standard deviation (SD) showed variability or dispersion in all the observations of data sets. Entire measurements for mean physical, chemical, heavy metal and metalloid concentrations recorded in this study exceeded the control group, suggesting transport of dissolved substances from bedrock or lithology to the experimental borehole water, among other aforementioned factors. Relatively higher percentages of coefficient of dispersion (CD) for some of the data sets than others revealed that the spread is more than that of those with low percentages of coefficient of dispersion (CD).

Lead exposure during pregnancy and early childhood may have lasting effects on cognitive and behavioural development. It might also cause increase in blood pressure, neurological damage such as cognitive functions, developmental delays and learning disabilities, cardiovascular diseases and stroke. Long term exposure to arsenic in drinking water has been linked to various types of cancer, skin lesions, cardiovascular disease and stroke. While a high level of copper in drinking water can cause liver and kidney damage, a genetic disorder (Wilson's disease), gastrointestinal symptoms, including vomiting, nausea and diarrhoea.

Focusing on seven (7) heavy metals investigated in all the borehole water samples, the values of HQ for Pb, As, Cr, and Cu exceed the threshold level of 1, while Ni, CN and Cd were found to be less than 1 (one). Therefore, adverse effects are likely to occur (due to Pb, As, Cr, Cu concentrations) when consuming the borehole water samples. There may be significant non – cancer risks if borehole water samples are continuously consumed without treatment. Borehole water samples at the sampled locations are likely to have potential non-carcinogenic and carcinogenic human health risks similar to those obtained by Chris-Onoh *et al.* (2026) in groundwater of Nasarawa West Senatorial Zone, Nigeria. Heavy metals Cr and Ni recorded the highest and lowest HQ respectively. Across all the water samples, a possible contamination trend was found in the order of Cr > Pb > As > Cu as their $HQ > 1$. Also, the sum of all the HQ represented as HI was found in the order of BWB (10.68) > BWC (9.47) > BWA (8.94) > BWD (7.61) > 1 (regulatory limit) similar to Emurotu *et al.* (2024) in Lokoja, Nigeria.

Cancer risk ($ILCR$) due to the heavy metals exposure via consumption of borehole water revealed Pb, As, Ni, Cr, and Cd concentrations were in good agreement with the safety/tolerable threshold in the range of 1.0×10^{-6} to 1.0×10^{-4} (USEPA, 2020; USEPA, 2010). Cumulative cancer risks ($TCRs$) for the heavy metals (Pb, Ni, Cr, Cd) and metalloid (As) contained in all borehole water investigated, revealed that human health in the study locations could be at risk, as the range of values obtained 1.79×10^{-3} (BWD) to 2.43×10^{-3} (BWB) exceeded the USEPA regulatory limits of 1.0×10^{-6} to 1.0×10^{-4} (USEPA, 2020; USEPA, 2010). Data recorded for total cancer risks ($TCRs$) in borehole water samples investigated were relatively high (intolerable), showing chances of cumulative cancer risk, as the data obtained exceeded the USEPA $\sum ILCR$ acceptable/tolerable range (1.0×10^{-6} to 1.0×10^{-4}) for a single carcinogenic element or multiple carcinogenic elements (USEPA, 2020; USEPA, 2010). The present study is in good agreement with studies carried out in water at Nasarawa West groundwater in Nigeria (Chris-Onoh *et al.,* 2026), water from selected oil pollution-prone communities in the Niger Delta region (Cross River and Edo States), Nigeria (Dimowo *et al.,* 2025), and water collected from copper and steel factory effluents, Nnewi, Anambra State, Nigeria (Ugwu *et al.,* 2024). Borehole water investigated in the study area revealed fresh water and fair water quality based on TDS and EC concentration (physical and chemical parameters); however, considerably contaminated with heavy metals (Pb, and Cu) and metalloid (As).

Conclusion

The study appraised borehole water quality from selected borehole locations within the salt water lake in Okpoma town in Yala LGA of Cross River State, South-south Nigeria (Niger Delta) to ascertain if the borehole water quality is safe for consumption. Standard APHA analytical techniques and measuring instruments for physicochemical and heavy metal water quality were used for the measurement, including a HANNA meter, spectrophotometer, flame atomic absorption spectrophotometer (FAAS), among other instruments. Findings showed that 20% of the entire parameters investigated exceeded the WHO permissible limit, whereas 80% were found below the WHO permissible limit. Borehole water samples studied contain relatively high concentrations of lead, arsenic and copper, which was suspected to have a link to complex interactions between temperature, pH, solubility, speciation and complexes, lithology of the study area, bed rock contamination, and perhaps saltwater instruction, as consequences, consumers may have the chances of being exposed to risk of acute and chronic toxicity, cancer, anemia, liver, kidney and intestinal damage. Based on carcinogenic and non – carcinogenic health risk assessments of borehole water samples investigated in the study locations, they are not suitable for drinking due to potential contamination by lead, arsenic, copper and chromium concentration in the water samples investigated; hence, it should be consumed with caution. Treatment procedures is necessary.

Recommendations

Implementing effective water treatment processes such as reverse osmosis, filtration, and physical and chemical remediation is recommended, which can reduce the concentrations of lead, arsenic, copper and possibly chromium in the borehole water used as drinkable water in the LGA. Regular monitoring and testing/evaluating of the borehole water can also help identify potential contamination issues and inform mitigation strategies. Deep groundwater depth may decrease the risk of infiltration of contaminants and leachate transport, thereby reducing the exposure of the population to toxic and hazardous chemicals through the consumption of borehole water. Educating the populace by public health personnel is also recommended. Surface water and food crops sold within the LGA should be investigated to decipher if there is toxicity, traceable to the use of borehole water in the locations. Further investigations on groundwater sources in the study locations and beyond is also recommended.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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