Fountain Journal of Basic Medical and Health Sciences (FUJBMHES), 1(2), 36 – 55.

Health Risk Implications of Heavy Metals Contamination on Drinking Water in Densely Populated Markets of Abeokuta, Nigeria

Dami-Adekunle, A. G.[1*]., Akinyemi, O. D[2]., Awomeso, J.[3]., & Bada, B. S.[4]

[1]Centre of Excellence in Agricultural Development and Sustainable Environment, Federal University of Agriculture, Abeokuta, Nigeria;
[2]Department of Physics, College of Physical Sciences, Federal University of Agriculture, Abeokuta, Nigeria;
[3]Department of Water Resources and Agrometeorology, College of Environmental Resources Management, Federal University of Agriculture, Abeokuta, Nigeria;
[4]Department of Environmental Management and Toxicology, College of Environmental Resources Management, Federal University of Agriculture, Abeokuta, Nigeria.

**Corresponding Author: aanudamiadekunle@gmail.com, +234 806 489 3167*

Abstract

Background: Access to safe drinking water is vital for public health; issues like water quality aberrations and pollution continue to affect urban dwellers, calling for an evaluation of health risks and pollution levels in water resources. **Objectives:** The study aimed at presenting an aggregate assessment of the pollution index and health risk of physical, chemical, and heavy metal constituents in drinking water resources across the markets of Abeokuta metropolis. **Methodology:** Three densely populated markets, including Kuto, Lafenwa, and Osiele, were selected for monitoring over three months during the wet season. Five hand-dug wells were sampled from each market and evaluated for groundwater quality parameters including pH, Temperature, Electrical conductivity (EC), Total Dissolved Solids (TDS), Sodium (Na), Potassium (K), Cadmium (Cd), Lead (Pb), Nickel (Ni), and Zinc (Zn). The data obtained were subjected to descriptive (mean and standard deviation) and inferential statistics (Pearson's Correlation matrix and linear regression). Heavy Metal Pollution Index (HPI) and Health Risk Assessment (HRA) were estimated in the water samples. **Results:** Significantly, high levels of TDS and EC were observed in drinking water from Lafenwa, while high Pb, Ni, and Cd were observed in the water samples from Kuto, Lafenwa, and Osiele. The HPI revealed higher metal contamination at Lafenwa, but the value was generally below the critical index. The HRA showed high Pb, Cd, and Ni hazard quotients in adults, children, and infants, indicating non-carcinogenic adverse health effects. In contrast, cancer risk assessment showed elevated cancer risk. **Conclusion:** The drinking water from hand-dug wells at Kuto, Lafenwa, and Osiele markets of Abeokuta is contaminated and poses significant threats to human health upon consumption. **Recommendations:** The study advises the local health authorities to implement a regular monitoring programme for groundwater quality within the Abeokuta metropolis, especially in densely populated areas, to ensure safety and compliance with health standards. They can also launch educational campaigns to raise residents' awareness of the potential health risks associated with contaminated drinking water. Information on the importance of water quality testing can empower communities to proactively manage their health risks and advocate for improvements in water safety.

Keywords: Public health, Water pollution index, Health quotient, Cancer risk, SDG3.

Introduction

Water contamination is considered a deviation from the expected concentrations of natural elements within its composition, often due to chemicals, hazardous substances, and other foreign particles that may have been added naturally or by human activities (Li et al., 2021). Contaminated groundwater and surface water sources cause the spread of epidemic and chronic diseases in human beings (Ayedun et al., 2012). In areas where population density is high and human use of the land is intensive, water resources become vulnerable. Water contamination can result from natural or anthropogenic sources. Natural elements such as arsenic, boron, and selenium can move in groundwater as particles and pose a health threat when consumed. The everyday activities that lead to contamination in water resources include solid waste landfills, onsite excreta disposal systems, open refuse dumpsites, cemeteries, and animal wastes (Lapworth et al., 2017). Increase in industrial activities, climate change, land-use changes, population growth, urbanisation, and chemical contamination, as well as other activities, have resulted in significant changes and degradation to many aquifers (Mishra et al., 2014; Ouedraogo et al., 2016).

Literature indicates substantial environmental degradation due to improper wastewater disposal, leaching of agricultural residues, inappropriate land use, and poor management procedures associated with hand-dug wells and their operations contribute to significant adverse changes in many water sources (Sharma et al., 2019; Akhtar et al., 2021). Additionally, pollutants can be transported through porous media via advection, diffusion, or biological transformation, resulting in changes in groundwater's physical, chemical, and microbial characteristics. Observational and model-based monitoring practices have helped characterise and monitor water quality. Routine sampling and analysis of physical and chemical parameters can assess basic water conditions, whereas analyses of major cations and anions can determine general recharge and discharge rates; this study of the chemistry of hand-dug wells' water quality has aided the understanding of how these sources of supply may be affected by factors in their vicinity (Egbueri et al., 2020). National and international regulatory bodies such as World Health Organization (WHO) standards, United States Environmental Protection Agency (USEPA), Standards Organization of Nigeria (SON), and Nigerian Standard for Drinking Water Quality (NSDWQ) have set limits for the specified amount of elements or substances that can be permitted in potable water because of their negative impacts on peoples' health status. When changes in chemical properties occur beyond set limits, water is considered to be contaminated. Water with a high concentration of chemical elements should neither be used for drinking nor for domestic uses without treatment.

In developing countries, drinking water is commonly sourced from hand-dug wells; however, poor construction and lack of proper sanitation make them prone to contamination from surrounding sources such as sewage, animal manure, solid waste, and chemical runoff (McArthur et al., 2020). Nigeria's concern for drinking water quality has increased due to an upward surge in urbanisation and industrialisation. Reports suggest that many shallow aquifers contain pollutants in concentrations higher than regulatory standards, especially within densely populated areas (Egbinola & Amanambu, 2014; Izah et al., 2016; Egbueri et al., 2020). Poor waste management practices further exacerbate the situation and unsustainable agricultural practices such as over-fertilization, improper disposal of solid wastes and hazardous materials, and lack of regulatory enforcement (Siddiqua et al., 2022). As a result, groundwater contamination varies from one region to another, with significant levels observed in central coastal areas and lower levels in northern regions (Shahid et al., 2017). To this end, more water quality studies than the present have to focus on areas with high rates of human activities, such as market activities.

The communities within Abeokuta, with their increasing population in the last decade, have relied on shallow and deep wells for potable water (Omole, 2013; Omole & Okunowo, 2016; Shah et al., 2017). Human activities such as indiscriminate waste disposal, poor drainage management, and other unsanitary practices within the market areas continue to increase the contamination potential of drinking water sources. Routine analysis of chemical constituents in drinking water has been commonly reported in Abeokuta communities with little or no emphasis on aggregate pollution indices for human health (Akinyemi et al., 2011; Taiwo, 2012; Adekunle et al., 2013; Aladejana & Talabi, 2013; Ishola et al., 2016; Eseigbe et al., 2018; Taiwo et al., 2022). Hence, this study intends to bridge the identified gap by investigating the pollution index of drinking water in Abeokuta market areas and its implications on human health. Therefore, the study's objectives were to determine chemical contamination in drinking water and evaluate the health risks associated with residents across the market areas. The study aimed to provide a robust reference system for future studies on water contamination in congested areas using pollution indices and a health risk assessment model.

Materials and Methods

Study Area

Three major markets in Abeokuta, Kuto, Lafenwa, and Osiele, were sampled for this study. Kuto is a primary market in the Abeokuta South Local Government Area that attracts about 2,000 people for daily transactions. It is also a five-day market attracting up to 5,000 buyers, which brings the population to about 8,000 people, including residents and buyers (Ayinde, 2005). A significant feature of the market is the public toilet, which was constructed to attend to the needs of the market users. Kuto market mostly suffers from overcrowding, traffic congestion, and poor waste management. The prevalent activities in the market include buying and selling fresh farm produce, clothing items, electronics, and other household goods (Laniyan et al., 2015).

Lafenwa market is also a bustling commercial centre in the Abeokuta North Local Government Area that is popular with locals and visitors. It is a one-stop market that attracts at least 3,000 persons daily and up to 10,000 persons every 4-day market for sales and purchase of various products, ranging from food, meat, clothing, household goods, electronics, and other services (Omotayo et al., 2017). This market is divided by a major road and intersected by an old railway line on the northern side. A public toilet facility sits in the southern part of the market. A lot of rice production happened around this part. There is also an abattoir within the market, where unquantifiable animal waste is generated.

Osiele market is located at the outskirts of the metropolis within Odeda Local Government Area along the central road that connects Abeokuta to Ibadan, Oyo State. The market is close to the Federal College of Education, Osiele, attracting about 1,500 persons for daily transactions. The market day runs on a 4-day cycle with about 6,000 persons from all over Abeokuta coming for business. The prevalent activities in the market include buying and selling fresh farm produce, clothing items, electronics, and other household goods (Olatunde et al., 2021).

For the geology of the study area, Abeokuta metropolis is located in the sub-humid tropical region of Southwestern Nigeria between Latitudes 7° 7′ N to 7° 13′ N and Longitudes 3° 19′ E to 3° 27′ E. It covers approximately 1,256 km^2, including Abeokuta South, Abeokuta North, and part of Obafemi Owode and Odeda Local Government Areas. Abeokuta falls on southwestern Nigeria's Precambrian basement complex rocks, part of the Nigerian basement complex terrain and the Dahomey basin sedimentary rocks. The basement complex of southwestern Nigeria lies east of the West African Craton in the region of late Precambrian to early Palaeozoic Orogeny (Rahman, 1976; Edunjobi et al., 2023). These rocks are of Precambrian age to early Palaeozoic age and extend from the north-eastern part of Ogun State (to which Abeokuta belongs), running south-westward and dipping towards the coast. Various folds, structures of various degrees of complexity, faults, foliation, and many more characteristics characterise the basement complex metamorphic rocks. These structural features have a predominant North-South or North-North-East-South-South-West orientation, particularly strong within the low-grade metamorphic. The common metamorphic rocks present in the metropolis include Gneiss, Schist, and Quartzite. Other rock types include granite, porphyritic granite, granitic gneiss, hornblende-biotite gneiss, porphyroblasts gneiss, and pegmatite (Oloruntola & Adeyemi, 2014; Okeyode et al., 2019). Abeokuta belongs to the stable plate, which was not subjected to intense tectonics in the past. The underground faulting system is believed to be minimal and has contributed to the occurrence of groundwater in this area.

Water Sampling Configuration

The water samples for this study were sourced from the prevalent drinking water sources in the study area, which were hand-dug wells. Five hand-dug wells were selected from each of the three densely populated markets in Abeokuta. In situ measurements were designed to determine chemical parameters, while laboratory measurements were designed to determine the metal contents of the water samples. Fifteen wells were selected, and 135 samples were collected during the three-month sampling period (September to October). The coordinates of each well were recorded using the Garmin-12 Global Positioning System (GPS). After rigorous agitation, the samples were collected in prewashed 1 L plastic containers using a bailer to thoroughly mix the water samples. The location of the sampled wells is presented in Fig. 1.

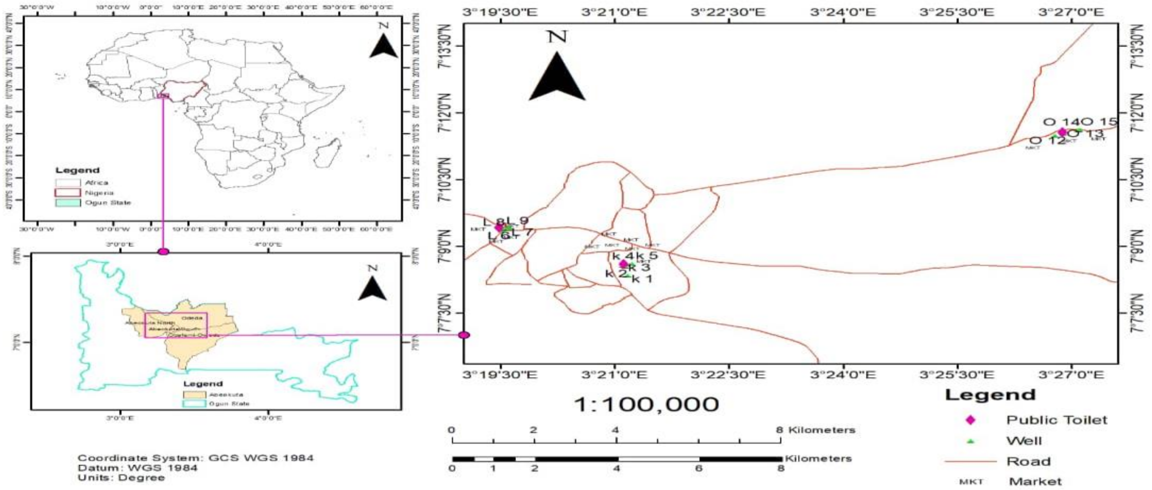

Figure 1: Map of Abeokuta showing the locations and sampled wells

Determination of Physical and Chemical Parameters

The physical and chemical parameters, including Temperature, pH, Electrical Conductivity, and Total Dissolved Solids, of the water samples were analysed in situ using the portable HANNA COMBO pH/TDS/Conductivity meter. The HANNA meter was prepared for use according to the manufacturer's directions. The probe was rinsed with distilled water and inserted into the samples. Readings were taken when the indicator on the screen displayed them.

Determination of Metal Contents

The water samples for metal content were digested to a smaller volume by heating 100 mL with 10 mL of concentrated HNO_3. Digested water samples were analysed using the Atomic Absorption Spectrophotometry (AAS) technique with the S4 Atomic Absorption Thermo Electron Corporation Spectrometer to determine their metal content. The analysis was conducted using standard methods described by APHA/AWWA/WEF (2022). The water samples were evaluated for Zn, Pb, Cd, and Ni. The water samples were also evaluated for concentration of Na and K using a flame photometer adapted from Banerjee & Prasad (2020).

Statistical Analysis

The data obtained from the analysis of the water samples' physical, chemical, and metal contents were subjected to descriptive (mean and standard deviation) and inferential (Pearson's Correlation and Linear Regression) statistics. The Pearson's correlation analysis was conducted to establish the association among the investigated parameters in the study area. The regression analysis was conducted to establish the degree of contribution and impact of the investigated parameters on the quality and contamination levels.

Heavy Metal Pollution Index

The mean value of the heavy metal concentrations of each location during the sampled period was subjected to the Heavy Metal Pollution Index (HPI). HPI is a technique of rating that provides the composite influence of individual heavy metal on the overall quality of water. The rating is a value between zero and one reflecting the relative importance of individual quality considerations and inversely proportional to the recommended value (S_i) for each parameter. The estimation of HPI involves the following steps

The first step is to calculate of weight age of ith parameter, W_i. Secondly, the quality rating for each of the heavy metal, Qi must be calculated.

Thirdly, the summation of these sub-indices in the overall Index (Singh and Kamal, 2017; Lotfi et al., 2020; Matta et al., 2020).

The weightage of ith parameter is calculated as

$$W_i = \frac{k}{Si} \quad \text{……………………………(1)}$$

(Where W_i is the unit weightage and S_i is the recommended value for the ith parameter while k is the constant of proportionality).

Quality rating for each of the heavy metal, Qi is given by the following mathematical expression in the equation below

$$Qi = \frac{100 \times Vi}{Si} \quad \text{..……………………… (2)}$$

Where Q_i is the sub index of ith parameter, V_i is the monitored value of the ith parameter and S_i is the guideline or permissible limit for the ith parameter.

Therefore, the Heavy Metal Pollution Index is then calculated as

$$HPI = \frac{Qi \times Wi}{100} \quad \text{……………………………(3)}$$

Where Q_i is the sub index of ith parameter, W_i is the unit weightage for the ith parameter. The critical pollution index is 100. The World Health Organization guideline for drinking water was used for this model

The HPI for a set of samples is thus calculated as

$$HPI = \frac{\sum_{i=1}^{n} Qi \times Wi}{\sum_{i=1}^{n} Wi}$$

$$\text{……………………………………… (4)}$$

Health Risk Assessment

The human health risk assessment was determined by calculating Estimated Daily Intake (EDI), Hazard Quotient (HQ), Hazard Index (HI), Cancer Risk (CR) using the mathematical models presented in the equations below (Adedokun et al., 2016, Emmanuel et al., 2022, Taiwo et al., 2022 and Ogarekpe et al., 2023).

$$EDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \text{……………………........ (5)}$$

$$HQ = \frac{EDI}{RfD} \text{………………………………… (6)}$$

$$HI = \sum_{i=1}^{n} HQ \text{……………………………(7)}$$

$$CR = EDI \times CSF \text{……….………………….(8)}$$

Where

EDI is the estimated daily intake (mg/kg/day) of Heavy Metals (HMs), C is the amounts of HMs (mg/L) observed in groundwater samples, IR is the ingestion rate of groundwater samples (2, 1, 0.5 L/day for adults, children and infants, respectively, Kaur et al., 2020), ED is the exposure duration (30, 6 and 1 year (s) for adults, children, and infants, respectively Taiwo et al., 2022), EF is the exposure frequency (350 days/year, Taiwo et al., 2022), AT is the averaging time/life expectancy = 54.5, 6 and 1 years for adults, children and infants, respectively (WHO, 2017),

BW is the body weight (60, 15 and 10kg for adults and children, respectively, Adeyemi and Ojekunle, 2021). RfD is the reference dose of metals (mg/kg/day; Chaturvedi et al., 2019), n is the number of elements observed, CR is Cancer Risk, CSF is the cancer slope factor (1/mg/kg/day, Rubenstein and Segal, 2020), HQ > 1 indicates non-carcinogenic adverse health effects, HQ < 1 denotes no adverse effects, CR < 1.0×10^{-4} indicates no cancer risk, while the CR > 1.0×10^{-4} establishes possible development of cancer (Rubenstein & Segal, 2020).

Results

Physical and Chemical Parameters of Water Samples

The results of the evaluation of physical and chemical parameters of groundwater samples from Kuto, Lafenwa and Osiele throughout the sampling periods are presented in Table 1. The mean temperature of the groundwater samples ranged from 28.17 to 29.59 °C, with mean values of 29.20, 29.28, and 28.51°C at Kuto, Lafenwa, and Osiele, respectively. The mean pH of the groundwater samples ranged from 5.74 to 6.73, with a mean value of 6.46, 6.52, and 6.10 at Kuto, Lafenwa, and Osiele, respectively. The mean TDS value in the groundwater samples ranged from 393.67 to 872.47 ppm, with mean values of 425.40, 830.83, and 402.31 ppm at Kuto, Lafenwa, and Osiele, respectively. The mean EC value in the groundwater samples ranged from 1200.67 to 544.33 µScm^{-1}, with mean values of 592.67, 1144.00, and 556.78 µScm-1 at Kuto, Lafenwa, and Osiele, respectively.

Metal Concentrations of Water Samples

Table 2 evaluates the metal concentrations in the groundwater samples from the Kuto, Lafenwa, and Osiele markets. The mean concentration of K in the groundwater samples ranged from 1.82 to 34.03, 13.47 to 40.86, and 2.79 to 41.73 mg/L, with mean values of 10.28, 26.69, and 21.85 mg/L at Kuto, Lafenwa, and Osiele, respectively. The mean concentration of Na in the groundwater samples ranged from 8.16 to 108.39, 21.41 to 90.39, and 15.96 to 65.78 mg/L, with mean values of 49.49, 56.42, and 39.12 mg/L at Kuto, Lafenwa, and Osiele, respectively. The mean concentration of Zn in the groundwater samples from Kuto, Lafenwa, and Osiele ranged from 0.00 to 1.01, 0.01 to 0.06, and 0.01 to 0.11 mg/L, with a mean value of 0.08, 0.03, and 0.03 mg/L at Kuto, Lafenwa, and Osiele, respectively. The mean concentration of Pb in the groundwater samples from the study area ranged from 0.16 to 0.82, 0.19 to 1.03, and 0.17 to 1.22 mg L^{-1}, with mean values of 0.44, 0.52, and 0.57 mg L-1 at Kuto, Lafenwa, and Osiele, respectively. The mean concentration of Ni in the groundwater samples ranged from 0.12 to 5.49, 0.18 to 5.85, and 0.46 to 6.22 mg/L, with mean values of 2.15, 2.05, and 2.42 mg/L at Kuto, Lafenwa, and Osiele, respectively. The mean concentration of Cd in the groundwater samples from the study area ranged from 0.01 to 0.04, 0.01 to 0.06, and 0.02 to 0.04 mg L^{-1}, with mean values of 0.02, 0.03, and 0.03 mg L-1 at Kuto, Lafenwa, and Osiele, respectively.

Heavy Metal Pollution Index

Table 3 presents the results of the Heavy Metal Pollution Index of the sampled markets. Throughout the sampling period, the HPI ranged from 12.21 to 21.80 at the Kuto market, 13.40 to 26.49 at the Lafenwa market, and 15.95 to 26.42 at the Osiele market.

Human Health Risk Assessment

Non-Carcinogenic Risk Assessment

The non-carcinogenic risk was assessed by computing the Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) of heavy metals (Zn, Pb, and Cd), which are presented in Tables 4 and 5. The EDIs of Zn, Pb, and Cd in the groundwater samples consumed by adults at Kuto, Lafenwa, and Osiele ranged from 6.39E-04 to 1.41E-02, 9.59E-04 to 1.66E-02, and 9.59E-04 to 1.82E-02, respectively. The EDIs of Zn, Pb, and Cd in the groundwater samples consumed by children at Kuto, Lafenwa, and Osiele ranged from 5.11E-03 to 1.37E-01, 1.91E-04 to 1.31E-01, and 1.92E-03 to 1.55E-01, respectively. The EDIs of Zn, Pb, and Cd in the groundwater samples consumed by infants at Kuto, Lafenwa, and Osiele ranged from 9.59E-04 to 1.03E-01, 1.44E-03 to 2.50E-02, and 9.59E-04 to 1.16E-01, respectively. The HQs of Zn, Pb, and Cd in the groundwater samples consumed by adults at Kuto, Lafenwa, and Osiele ranged from 8.52E-03 to 3.91E+00, 3.20E-03 to 4.62E+00, and 3.20E-03 to 5.06E+00, respectively. The HQs of Zn, Pb, and Cd in the groundwater samples consumed by children at Kuto, Lafenwa, and Osiele ranged from 1.70E-02 to 7.81E+00, 6.39E-03 to 9.23E+00, and 6.39E-03 to 2.56E+00, respectively. The HQs of Zn, Pb, and Cd in the groundwater samples consumed by infants at Kuto, Lafenwa, and Osiele ranged from 1.27E-03 to 5.88E+00, 4.80E-03 to 6.93E+00, and 4.80E-03 to 7.59E+00, respectively. The heavy metals' Hazard Index (HI) was estimated as the summation of the HQs. The HIs of Zn, Pb, and Cd in the groundwater samples consumed by adults at Kuto, Lafenwa, and Osiele were estimated as 5.54, 6.87, and 6.73, respectively. The HIs of Zn, Pb, and Cd in the groundwater samples consumed by children at Kuto, Lafenwa, and Osiele were estimated as 11.07, 13.73, and 13.46, respectively. The HIs of Zn, Pb, and Cd in the groundwater samples consumed by infants at Kuto, Lafenwa, and Osiele were estimated as 8.31, 10.30, and 10.09, respectively.

Table 1: Results of physicochemical parameters across the sampled wells from Abeokuta markets.

Parameters	Market	September	October	November	WHO(2017)
Temp (°C)	Kuto(n)	28.93 ± 0.17^{a}	28.53 ± 0.52^{a}	29.58 ± 0.63^{a}	**Ambient**
	Lafenwa(n)	29.59 ± 1.08^{a}	28.66 ± 0.64^{a}	29.58 ± 1.02^{a}	
	Osiele(n)	29.07 ± 1.15^{a}	28.17 ± 0.55^{a}	28.29 ± 0.68^{a}	

pH	Kuto(n)	6.27 ± 0.26^{a}	6.43 ± 0.20^{a}	6.66 ± 0.16^{a}	**6.5-8.5**
	Lafenwa(n)	6.27 ± 0.25^{a}	6.55 ± 0.26^{a}	6.73 ± 0.18^{a}	
	Osiele(n)	5.74 ± 0. 22^{a}	6.17 ± 0.29^{a}	6.38 ± 0.28^{a}	
TDS (ppm)	Kuto(n)	472.40 ± 183.88^{b}	377.67 ± 138.10^{b}	426.13 ± 144.85^{b}	**600**
	Lafenwa(n)	843.60 ± 102.09a	872.47 ± 177.44^{a}	775.00 ± 103.51^{a}	
	Osiele(n)	393.67 ± 177.09^{c}	405.20 ± 183.53^{b}	408.07 ± 215.39^{b}	
EC (μS cm^{-1})	Kuto(n)	668.00 ± 232.94^{b}	523.33 ± 195.00^{b}	586.67 ± 200.91^{b}	**1000**
	Lafenwa(n)	1162.00 ± 138.83^{a}	1200.67± 236.14^{a}	1069.33 ± 141.24^{a}	
	Osiele(n)	544.33 ± 256.94^{c}	561.33 ± 256.65^{b}	564.67 ± 301.80^{b}	

n= 45 Temp = Temperature, TDS = Total Dissolved Solids, EC = Electrical Conductivity

Table 2: Mean of metal concentrations across the sampled wells from Abeokuta markets.

Parameters (mg L^{-1})	Market	September	October	November
K	Kuto(n)	4.06 ± 2.63^{c}	15.01 ± 10.68^{b}	11.77 ± 8.80^{c}
	Lafenwa(n)	15.32 ± 1.59^{a}	31.05 ± 12.80^{a}	33.70 ± 5.88^{a}
	Osiele(n)	11.28 ± 6.94^{b}	29.23 ± 12.43^{a}	25.03 ± 16.05^{b}
Na	Kuto(n)	23.68 ± 11.05^{a}	54.04 ± 16.51^{b}	70.77 ± 36.80^{b}
	Lafenwa(n)	25.77 ± 3.08^{a}	62.88 ± 14.82^{a}	80.61± 10.95^{a}
	Osiele(n)	16.93 ± 2.24^{b}	53.62 ± 12.99^{b}	46.81 ± 16.13^{c}
Zn	Kuto(n)	0.01 ± 0.00^{c}	0.22 ± 0.77^{a}	0.02 ± 0.02^{b}
	Lafenwa(n)	0.02 ± 0.01^{b}	0.02 ± 0.02^{c}	0.03 ± 0.02^{a}
	Osiele(n)	0.03 ± 0.04^{a}	0.04 ± 0.04^{b}	0.02 ± 0.01^{b}
Pb	Kuto(n)	0.32 ± 0.11^{b}	0.65 ± 0.19^{b}	0.37 ± 0.25^{b}
	Lafenwa(n)	0.37 ± 0.06^{a}	0.86 ± 0.23^{a}	0.32 ± 0.16^{c}
	Osiele(n)	0.37 ± 0.05^{a}	0.85 ± 0.39^{a}	0.48 ± 0.20^{a}
Ni	Kuto(n)	0.23 ± 0.13^{c}	5.10 ± 0.51^{a}	1.12 ± 0.54^{b}
	Lafenwa(n)	0.41 ± 0.09^{b}	5.12 ± 0.68^{a}	0.62 ± 0.16^{c}
	Osiele(n)	0.55 ± 0.10^{a}	5.45 ± 0.54^{a}	1.27 ± 1.12^{a}
Cd	Kuto(n)	0.02 ± 0.01^{b}	0.02 ± 0.01^{a}	0.02 ± 0.01^{c}
	Lafenwa(n)	0.02 ± 0.01^{b}	0.02 ± 0.01^{a}	0.05 ± 0.02^{a}

Osiele(n)	0.03 ± 0.00^{a}	0.02 ± 0.01^{a}	0.03 ± 0.01^{b}

K= Potassium, Na = Sodium, Zn = Zinc, Pb = Lead, Ni= Nickel, Cd = Cadmium

Table 3: Results of heavy metal pollution indices (HPI).

Location	$\text{HPI}_{\text{September}}$	$\text{HPI}_{\text{October}}$	$\text{HPI}_{\text{November}}$
Kuto	12.21	21.80	13.73
Lafenwa	13.40	26.49	20.05
Osiele	15.95	26.42	18.74

Table 4: Estimated Daily Intake (EDI)

Metals	Location	$\text{EDI}_{\text{Adults}}$	$\text{EDI}_{\text{Children}}$	$\text{EDI}_{\text{Infants}}$
Zn	Kuto	2.56E-03	5.11E-03	3.83E-03
	Lafenwa	9.59E-04	1.92E-03	1.44E-03
	Osiele	9.59E-04	1.92E-03	1.44E-03
Pb	Kuto	1.41E-02	2.81E-02	2.11E-02
	Lafenwa	1.66E-02	3.32E-02	2.50E-02
	Osiele	1.82E-02	3.64E-02	2.73E-02
Ni	Kuto	6.87E-02	1.37E-01	1.03E-01
	Lafenwa	6.55E-02	1.31E-01	9.83E-02
	Osiele	7.74E-02	1.55E-01	1.16E-01
Cd	Kuto	6.39E-04	1.28E-03	9.59E-04
	Lafenwa	9.59E-04	1.9E-04	1.44E-03
	Osiele	6.39E-04	1.28E-03	9.59E-04

Zn = Zinc, Pb = Lead, Ni= Nickel, Cd = Cadmium

Table 5: Hazard Quotient (HQ) and Hazard Index (HI)

	Location	Adults	Children	Infants
HQ (Zn)	Kuto	8.52E-03	1.70E-02	1.27E-02
	Lafenwa	3.20E-03	6.39E-03	4.80E-03
	Osiele	3.20E-03	6.39E-03	4.80E-03
HQ (Pb)	Kuto	3.91E+00	7.81E+00	5.88E+00
	Lafenwa	4.62E+00	9.23E+00	6.93E+00
	Osiele	5.06E+00	1.01E+01	7.59E+00
HQ (Ni)	Kuto	3.44E-01	6.87E-01	0.52E+00
	Lafenwa	3.23E-01	0.66E+00	4.91E+00
	Osiele	3.87E-01	7.74E-01	5.80E-01
HQ (Cd)	Kuto	1.28E+00	2.56E+00	1.92E+00
	Lafenwa	1.29E+00	3.84E+00	2.88E+00
	Osiele	1.28E+00	2.56E+00	1.92E+00
HI	Kuto	5.54	11.07	8.31

Lafenwa	6.87	13.73	10.30
Osiele	6.73	13.46	10.09

Zn = Zinc, Pb = Lead, Ni= Nickel, Cd = Cadmium

Cancer Risk Assessment

Table 6 presents the cancer risk (CR) of heavy metals in groundwater samples consumed by adults at Kuto, Lafenwa, and Osiele. The CRs of Pb, Ni, and Cd of groundwater samples consumed by adults at Kuto, Lafenwa, and Osiele ranged from 1.20E-04 to 1.55E-04, 5.96E-02 to 7.04E-02, and 3.90E-03 to 5.85E-03, respectively. The CRs of Pb, Ni, and Cd of groundwater samples consumed by children at Kuto, Lafenwa, and Osiele ranged from 2.39E-04 to 3.90E-04, 1.25E-01 to 1.19E-01, and 1.16E-03 to 7.81E-03, respectively. The CRs of Pb, Ni, and Cd of groundwater samples consumed by infants at Kuto, Lafenwa, and Osiele ranged from 1.79E-04 to 2.82E-04, 1.06E-01 to 9.37E-02, and 5.85E-03 to 8.78E-03, respectively.

Correlation of Water Quality Parameters

The correlation of water quality parameters in the study area is presented in Tables 7, 8, and 9**.** Positive and significant correlations were found for the September sampling between Temperature and K, TDS and EC, TDS and K, TDS and Na, EC and K, EC and Na, K and Zn, Ni and Cd (r = 0.608). A negative and significant correlation was obtained between pH and Cd (r = - 0.709). During the October sampling, positive and significant correlations were found between TDS and EC, TDS and K, EC and K, and K and Pb. A negative and significant correlation was obtained between pH and Cd. During the November sampling, Positive and significant correlations were found between pH and TDS, pH and EC, TDS and EC, TDS and K, TDS and Na, EC and K, and EC and Na. Negative and significant correlation was obtained between pH and Cd, EC and Ni, and K and Ni.

Regression of Water Quality Parameters

The results of the linear regression model applied to the groundwater parameters in the study across the sampled period are presented in Tables 10, 11, and 12. The physical, chemical parameters, and metal concentrations were plotted as the independent variable against Electrical Conductivity as the dependent variable. The regression analysis confirmed the correlation results that TDS is the most significant contributor to the high EC concentrations in the study area. The relationship between all these parameters and EC is deduced as

$$EC = -388 + 9.843\ \text{Temp.} \ldots (9)$$

$$EC = -388 + 1.360\text{TDS} \quad \ldots (10)$$

$$EC = -388 + 29.403\text{pH} \ \ldots (11)$$

$$EC = -388 + 421.366\ \text{Zn} \ldots.. (12)$$

$$EC = -388 - 182.661\ \text{Pb} \quad \ldots (13)$$

Table 6: Cancer Risk Assessment

Metals	CSF	Sample Location	Adults	Children	Infants
Pb	0.70085	Kuto	1.20E-04	2.39E-04	1.79E-04
		Lafenwa	1.41E-04	2.82E-04	2.13E-04
		Osiele	1.55E-04	3.09E-04	2.32E-04
Ni	0.91	Kuto	6.25E-02	1.25E-01	9.37E-02
		Lafenwa	5.96E-02	1.19E-01	8.95E-02
		Osiele	7.04E-02	1.41E-01	1.06E-01
Cd	6.10	Kuto	3.90E-03	7.81E-03	1.06E-01
		Lafenwa	5.85E-03	1.16E-03	8.78E-03
		Osiele	3.90E-03	7.81E-03	5.85E-03

Pb = Lead, Ni= Nickel, Cd = Cadmium

Table 7: Correlations of water quality parameters in September Sampling

	TEMP	pH	TDS	EC	K	Na	Zn	Pb	Ni	Cd
TEMP	1	-0.269	0.351	0.358	.552*	0.022	-0.064	0.142	0.095	0.117
pH		1	0.375	0.383	-0.177	0.425	-0.183	0.090	-0.383	-.709**
TDS			1	.999**	.677**	.673**	0.232	0.283	-0.086	-0.335
EC				1	.679**	.661**	0.234	0.249	-0.114	-0.339
K					1	0.081	.575*	0.266	0.336	0.285
Na						1	-0.116	0.265	-0.234	-0.442
Zn							1	0.292	0.398	0.469
Pb								1	.592*	0.110
Ni									1	.608*
Cd										1

Table 8: Correlations of water quality parameters in October Sampling

	TEMP	pH	TDS	EC	K	Na	Zn	Pb	Ni	Cd
TEMP	1	-0.126	0.269	0.272	-0.027	-0.082	-0.026	0.086	0.010	-0.172
pH		1	0.403	0.410	0.123	0.433	-0.021	0.164	-0.235	-0.556*
TDS			1	1.000**	.630*	0.378	-0.104	0.362	-0.087	-0.145
EC				1	.629*	0.380	-0.102	0.368	-0.091	-0.142
K					1	0.246	0.199	.589*	0.201	-0.001
Na						1	-0.348	0.196	-0.017	0.182
Zn							1	0.040	-0.083	-0.057
Pb								1	-0.046	-0.206
Ni									1	0.408
Cd										1

*- Correlation is significant at the 0.05 level

Table 9: Correlations of water quality parameters in November Sampling

	TEMP	pH	TDS	EC	K	Na	Zn	Pb	Ni	Cd
TEMP	1	0.117	0.156	0.155	0.035	0.434	0.371	-0.124	-0.228	0.011
pH		1	.533*	.530*	0.089	0.334	-0.123	-0.045	-0.356	-0.574*
TDS			1	1.000**	.703**	.624*	0.067	-0.311	-.710**	0.495
EC				1	.706**	.623*	0.068	-0.309	-.714**	0.494
K					1	0.381	0.160	0.075	-.594*	0.455
Na						1	.566*	-0.393	-0.380	0.291
Zn							1	-0.248	-0.109	0.386
Pb								1	0.224	-0.360
Ni									1	-0.449
Cd										1

*- Correlation is significant at the 0.05 level

Table 10: Linear regression of the water quality parameters and EC in September

Parameters	Coefficients	Standard Error	P-value
Temp	0.027	2.391	0.01
pH	0.03	6.79	0.01
TDS	1.00	0.02	0.00
K	-0.01	0.76	0.51
Na	-0.01	0.43	0.28
Zn	0.02	128.63	0.02

Pb	-0.03	37.04	0.00
Ni	-0.02	17.06	0.06
Cd	0.02	635.08	0.12

P-value is considered significant at $p \leq 0.05$, Dependent Variable: EC

Table 11: Linear regression of the water quality parameters and EC in October

Parameters	Coefficients	Standard Error	P-value
Temp	0.01	4.09	0.39
pH	0.01	9.38	0.28
TDS	0.99	0.01	0.00
K	-0.00	0.30	0.88
Na	-0.00	0.22	0.86
Zn	0.00	9.63	0.79
Pb	0.01	9.89	0.27
Ni	-0.00	4.99	0.51
Cd	0.01	312.58	0.27

P-value is considered significant at $p \leq 0.05$, Dependent Variable: EC

Table 12: Linear regression of the water quality parameters and EC in November

Parameters	Coefficients	Standard Error	P-Value
Temp	-0.01	0.75	0.09
pH	-0.01	4.54	0.06
TDS	1.00	0.01	0.00
K	-0.00	0.10	0.82
Na	-0.00	0.05	0.67
Zn	0.01	70.57	0.15
Pb	0.00	5.02	0.44
Ni	-0.01	1.67	0.02
Cd	0.01	63.79	0.03

P-value is considered significant at $p \leq 0.05$. Dependent Variable: EC.

The results in October which was a good fit model with an R^2 of 1.00. The results in October showed that the Total Dissolved Solids contributed significantly to the concentration of Electrical Conductivity. The relationship between EC and TDS from the results is presented as

$$\mathrm{EC} = -167 + 1.363\,\mathrm{TDS} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

The results in November were a good fit model with an R^2 of 1.00. The results in November showed that the Total Dissolved Solids contributed significantly to the concentration of Electrical Conductivity. The relationship between EC and TDS from this result is presented as

$$\mathrm{EC} = -120 + 1.391\,\mathrm{TDS} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(15)$$

Discussion

The mean value of the physical and chemical parameters in groundwater samples from Kuto, Lafenwa, and Osiele across the sampled period was compared with the WHO recommended limits. The mean pH value of groundwater samples from the Kuto, Lafenwa, and Osiele areas was slightly acidic across the sampled period. All the pH values were greater than 5 but less than 7. Water with acidic pH is susceptible to containing microbial contaminants that can adversely impact human gastrointestinal tracts when ingested, resulting in diarrhea (Elemile et al., 2019). Meanwhile, the pH value in groundwater samples from Abeokuta has also been reported to vary according to season. At Kuto, slightly alkaline pH values were reported by Taiwo et al. (2022) during the wet and dry seasons. The study of Falola et al. (2021) also reported high and alkaline pH values in wells sampled at Lafenwa during the dry season. However, the findings of Olatunde et al. (2021) reported slightly acidic to alkaline pH values at Osiele during the dry season.

The TDS in groundwater is often associated with natural sources, sewage, urban runoff, and industrial wastewater (Ekeleme et al., 2014). The TDS value in the groundwater samples at the Kuto, Lafenwa, and Osiele ranged from 130.70 to 667.67, 601.70 to 1191.00, and 125.70 to 676.30 ppm, with mean values of 425.40, 830.36, and 402.31 ppm, respectively, across the sampled period. TDS consists of inorganic salts which are mainly calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulphates and little amounts of organic matter that are dissolved in water The study found that only 60% of the sampled wells at Kuto had mean TDS value that were higher than the WHO limits for palatable consumption in September and 20% of the sampled wells in November. The study of groundwater sources at Kuto by Taiwo et al. (2022) reported TDS values within the WHO palatable limits in wet and dry seasons. The high TDS value reported in this study could thus be attributed to the proximity of the sampled wells to sewage waste. At Lafenwa, the TDS value for 100% of the sampled wells (601.70 to 1191.00 ppm) was higher than the WHO limit throughout the sampled period. High TDS value in the dry season, as well, can be inferred from the study of Falola et al. (2021) at Lafenwa. This lack of significant variation in TDS values at Lafenwa across both seasons can be attributed to the heavy presence of abattoir operations, among other market activities. At Osiele, High TDS values were also recorded at 40% of sampled wells in October and November. Only 20% of the sampled wells at Osiele consistently had TDS values above the WHO palatable limits throughout the sampled period. Lower TDS values were reported from wells at Osiele during the dry season by Olatunde et al. (2021). Furthermore, Akinyemi et al. (2011) have reported low TDS values from other areas in Abeokuta.

The EC indicates the presence of dissolved solids and contaminants, especially electrolytes, but does not give information about specific chemicals. It represents the total number of ions dissolved in water (Behailu et al., 2018). EC of the water samples at Kuto, Lafenwa, and Osiele ranged from 173.37 to 926.67, 833.30 to 1296.67, and 166.67 to 940.00 $\mu\mathrm{Scm}^{-1}$, with mean values of 592.67, 1144.00, and 556.78 µScm-1, respectively. All the sampled wells have EC values above 200 µScm-1, but the mean concentration of 80% of the sampled wells at Lafenwa exceeded the maximum permissible limits for the entire sampled period. High EC value at Lafenwa has been reported during the dry season by Falola et al. (2021). The EC value of wells at Kuto and Osiele was below the WHO maximum permissible limit. Low EC values have also been reported from wells at Kuto and Osiele during the dry season by Taiwo et al. (2022) and Olatunde et al. (2021), respectively.

The mean concentration of K, Na, and Zn was within the WHO permissible limits for drinking water. The K is released into groundwater from rocks, sewage, and leaching weathering. Na occurs naturally in groundwater. It is tasteless and odourless but can be tasted at a concentration greater than 200 mg L^{-1}. Sodium could get into groundwater through sewage infiltration or leachate from landfills in industrial areas (Affum et al., 2015). The Na value from all the sampled wells at Kuto, Lafenwa, and Osiele was below the WHO recommended limits. The Zn is a significant metal that catalyses enzymatic activity in the human body. It is usually found in minute quantities in drinking water (Behailu et al., 2018). Similarly, Zn value within recommended limits in groundwater has been reported from other areas in Abeokuta by Adekunle et al. (2013).

However, the Pb, Ni, and Cd concentrations exceeded the WHO recommended limits in all the Kuto, Lafenwa, and Osiele sampled wells. Pb is considered poisonous for humans when ingested in large quantities, especially for pregnant women and their fetuses. Children below the age of 6 are most vulnerable to its adverse impacts, which can be devastating to the body's central nervous system. Excess lead in drinking water is often attributed to corrosion of plumbing systems (Behailu et al., 2018). Lead may also result in autoimmunity, making the human immune system attack its cells; this often results in joint ailments and diseases affecting the kidney and circulatory system (Orosun et al., 2016). Laniyan et al. (2015) also reported high levels of Pb in groundwater at Kuto. High levels of Pb were also reported during the wet and dry seasons at Kuto, Lafenwa, and Osiele by Taiwo et al. (2022). The Pb levels can be attributed to the leaching of waste such as batteries, jewellery, and synthetic rubber from activities in the market area, finding its way into the groundwater resources in the study area. The levels of Ni reported in this study could be attributed to the proximity of refuse points to the groundwater sources. Nickel enters water from power plants, waste sites, and industrial wastes. Nickel is also found in sludge and fly ash from waste incinerators. High concentrations of nickel can cause teratogenic and carcinogenic diseases in humans (Tadiboyina & Rao, 2016).

Cd is primarily transported in groundwater through natural sources such as rock minerals, sediment flow, and man-induced sources such as fertilizer overuse, sewage, and industrial application (Tadiboyina & Rao, 2016). Cd is easily found in groundwater and bio-accumulates in various organs of humans, which can lead to gastrointestinal diseases and cancer (Kubeir et al., 2019). Cd is thus regarded as hazardous when found in concentrations above recommended limits in groundwater sources. High Cd concentration can be due to a variety of sources in the environment or industrial wastes. However, high levels of Cd had been reported from wells at Kuto by Laniyan et al. (2015). The results of this study, when compared with the findings of Ishola et al. (2016), found metal concentration above recommended limits in groundwater sources in Lafenwa and other areas in Abeokuta during the wet season. The metal concentration reported by Ishola et al. (2016) was lower in the dry season than the wet season, though it exceeded the WHO recommended limits.

Heavy Metal Pollution Index (HPI) is a suitable tool for assessing water bodies' ultimate contamination by the presence of metals (Majhi & Biswal, 2016). The highest HPI value was recorded at Lafenwa across the sampled period. The HPI value of this study indicated a low degree of metal contamination in the groundwater resources of the study area. Water with an HPI value less than 100 is regarded as low heavy metal pollution, HPI at the threshold of 100 signifies heavy metal pollution, and Water with a critical pollution index greater than 100 (HPI > 100) is regarded as highly polluted by heavy metals (Sobhanardakani et al., 2016). The level of contamination by HPI evaluation in this study decreased in the order of Lafenwa > Osiele > Kuto. The HPI results of this study thus indicate that the level of heavy metal pollution in the study area is low and is not yet at levels that can cause immediate damage to the health of its consumers. However, the HPI in October doubled; the value in September at all locations indicates higher metal dissolution and leaching into groundwater due to higher precipitation levels in October. The potential of metal toxicity, as revealed by the HPI evaluation, could be due to the proximity of the wells to the open refuse dumpsites within the market.

The estimated daily intake (EDI) of the metals was less than the daily acceptable intake of 0.9 and 3.6 mg/kg/day for adults and children, respectively (WHO, 2017). The HQs for Zn with value of 3.20 to 8.52×10^{-4}, 6.39×10^{-4} to 1.7×10^{-2}, 4.8×10^{-3} to 1.72×10^{-2} in adults, children and infants respectively, were lower than acceptable limit of 1.0 indicating no non-carcinogen adverse health effects through oral exposure to this metal in drinking the sampled water. However, the HQs of Pb with values of 3.91, 4.62, and 5.06 exceeded the permissible limit of 1.0 for adults at Kuto, Lafenwa, and Osiele. The HQs of Pb with values of 7.81, 9.23, and 10.1 exceeded the permissible limit of 1.0 for children at Kuto, Lafenwa, and Osiele. The HQs of Pb with values of 5.88, 6.93, and 7.59 exceeded the permissible limit of 1.0 for infants at Kuto, Lafenwa, and Osiele. It was also observed that the value of HQs for Pb in children was double that of HQs for Pb in adults; this implies an increased risk of adverse effects due to Pb on children's health. Young children are essentially susceptible to the toxic effects of Pb, which can result in permanent adverse impacts on the brain and nervous system. Pb can also cause long-term harm in adults, such as increased risk of high blood pressure and kidney damage. Exposure of pregnant women to high levels of Pb can cause miscarriage, stillbirth, premature birth, and low birth weight (WHO, 2023).

Furthermore, the HQs of Cd with values of 1.28, 1.92, and 1.28 exceeded the permissible limit of 1.0 for adults at Kuto, Lafenwa, and Osiele. Similarly, the HQs of Cd with values of 2.56, 3.84, and 2.56 exceeded the permissible limit of 1.0 for children at Kuto, Lafenwa, and Osiele. The HQs of Cd with values of 1.92, 2.88, and 1.92 also exceeded the permissible limit of 1.0 for infants at Kuto, Lafenwa, and Osiele. These high HQs implied possible non-carcinogenic deleterious health effects from consuming the groundwater in the area. Children had also been found to suffer from kidney stones resulting from excess exposure to Cd. Infants that are exposed to high amounts of Cd are at risk of neurological problems such as cognitive deficits and attention deficit hyperactivity disorder (ADHD) (Sanders et al., 2015). The HQs of Ni for infants only exceeded the limit of 1.0 at Lafenwa, with the value of 4.91. The HI values of metals estimated for adults, children, and infants were greater than 1.0, thus further establishing the cumulative effects of the metals in groundwater from sampled wells in the study area. Pb was the largest contributor to the HI (70.55%), while Cd was the second contributing metal (23.09%). Taiwo et al. (2022) also recognised Pb as a significant contributor to HI, studying groundwater in Abeokuta.

The cancer risk assessment showed that Pb, Ni and Cd had CR value ranging from 1.2×10^{-4} to 1.06×10^{-2} which were greater than the permissible threshold of 1.0×10^{-4} (USEPA, 2016) in the groundwater samples at Kuto, Lafenwa and Osiele, indicating probable development of cancer. This is possibly due to the contributions of the solid waste disposal activities from the market areas around the sampled wells. Studies had reported that children living in areas contaminated with Cd even at low levels were associated with enhanced oxidative stress with DNA damage and protein modification in early life and associated with the higher risk of developing cardiovascular disease, osteoporosis and some types of cancer (Thevenod & Lee, 2013; Baek & Chung, 2017). In adults, Cd could result in the development of serious diseases such as toxic effects on kidneys, bone, stomach, lung, and prostate cancer (Neslund-Dudas et al., 2018; Noor et al., 2018). It has also been established by the Agency for Toxic Substances and Disease Registry (ATSDR, 2015) that Ni can lead to cancer of the lungs and nasal sinus, primarily through inhalation. The adverse effects of Ni in children are similar to those experienced in adults as well. The correlation matrix revealed a significant association between the physical and chemical parameters, indicating that the pollution at Kuto, Lafenwa, and Osiele market areas comes from similar sources. There was a negative correlation between pH and Cd concentrations, which implies that a reduction in the pH value of the groundwater samples in the study area will increase Cd concentrations in the study area. The linear regression results have confirmed the correlation results that TDS is the most significant contributor to the high EC concentration in the study area; this shows that the hand-dug wells were equally affected by a similar factor, possibly due to waste disposal in the market area.

Conclusion

The evaluation of physical and chemical parameters at Kuto, Lafenwa, and Osiele showed that the pH value during the wet season was slightly acidic. Low pH values support microbial growth, resulting in groundwater contamination. There was high TDS with the value of 830.36 ppm, above the WHO maximum permissible limits in the sampled wells at Lafenwa. High TDS in healthy water affects the taste and palatability of the water for drinking purposes. EC of sampled water at Lafenwa, with the value of 1144.00 µS cm-1, was above the WHO recommended limit for drinking. The evaluation of metal concentration showed Cd, Ni, and Pb levels above the WHO maximum permissible limits in all the sampled wells at Kuto, Lafenwa, and Osiele. The drinking water was significantly polluted with high concentrations of Pb with values of 0.44, 0.52, and 0.57 mg L-1, Cd with values of 2.15, 2.05, and 2.42 mg L-1, and Ni with values of 0.02, 0.03, and 0.02 mg L-1 at Kuto, Lafenwa, and Osiele, respectively. This is attributed to contamination from waste products such as plastics, batteries, jewelry, and synthetic rubber resulting from the market activities at the locations. The HPI only showed a low degree of heavy metal contamination with a value below 100. However, the highest HPI value of 26.49 was found at Lafenwa. Therefore, the potential for metal toxicity was higher at Lafenwa than at Kuto and Osiele markets.

The health risk assessment established the possibility of adverse effects on the health of groundwater consumers at Kuto, Lafenwa, and Osiele market areas due to high hazard quotients and indices of Pb, Ni, and Cd in the water resources. Non-carcinogenic adverse health risk due to Cd with values of 1.92, 1.28, 1.28, 3.84, 2.56, and 2.56, 2.88, 1.92 for adults, children, and infants, respectively, was highest at Lafenwa market. There was a significant cancer risk from Pb, Ni, and Cd, with values ranging from 1.2 × 10-4 to 1.06 × 10-1 at Kuto, Lafenwa, and Osiele markets. Therefore, the residents of Kuto, Lafenwa, and Osiele are at risk of cancerous diseases from prolonged exposure and ingestion of the Pb, Ni, and Cd-contaminated water resources. This study's findings have established that the TDS and EC values of drinking water at Lafenwa are responsible for the unpalatable taste experienced while drinking. Water from hand-dug wells was significantly contaminated with high Pb, Cd, and Ni concentrations at Kuto, Lafenwa, and Osiele markets due to indiscriminate market activities such as unsanitary refuse points. Continuous groundwater consumption at Kuto, Lafenwa, and Osiele will result in carcinogenic, neurological, and gastrointestinal diseases in residents and consumers.

Recommendations

- The study advises the local health authorities to implement a regular monitoring programme for groundwater quality within the Abeokuta metropolis, especially in densely populated areas, to ensure safety and compliance with health standards.
- They can also launch educational campaigns to raise residents' awareness of the potential health risks associated with contaminated drinking water.
- Information on the importance of water quality testing can empower communities to proactively manage their health risks and advocate for improvements in water safety.
- The government should set up water treatment systems such as mobile water purifiers in market

areas to help remove heavy metals from the water used by residents and other market users.

- Residents and market users should be educated on cancer risk and associated health risks resulting from exposure and ingestion of metals-polluted groundwater.

Professional Implications of the Study

- This paper highlights environmental and groundwater quality impacts of improper waste disposal and market activities.
- The findings of this study enable policymakers to establish better water quality regulations and enhance monitoring of groundwater sources, especially where populations remain dense.
- The paper establishes a research plan that other studies can use to study groundwater pollution risks and human health impacts across different geographic areas.
- Civil and environmental engineers retrieve the data to build better water foundation infrastructure with standards that stop well contamination.

Limitations of the Study

- Though the study covered the majorly patronized markets in Abeokuta, it couldn't cover more markets due to socio-environmental factors such as access denial and hostility.
- The study could only examine some of the toxic heavy metals. Others were not evaluated due to a lack of technical and financial resources at the time of the study.

Funding

The World Bank's Africa Centre for Excellence in Agricultural and Sustainable Environment, Federal University of Agriculture, Abeokuta, financially supported this work, with reference number PG 17/0662.

Acknowledgements

The authors acknowledge the contributions of the academic and laboratory staff of the Africa Centre for Excellence in Agricultural and Sustainable Environment, Federal University of Agriculture, Abeokuta.

Conflict of Interests

The authors declare no conflict of interest.

References

Adedokun, A.H., Njoku, K.L., Akinola, M.O., Adesuyi, A.A., & Jolaoso, A.O. (2016). Potential human health risk assessment of heavy metals intake via consumption of leafy vegetables obtained from four markets in Lagos metropolis. *Nigeria. Journal of Applied Sciences and Environmental Management,* 20(3), 530-539.

Adekunle, A.A., Badejo, A.O., and Oyerinde, A.O. (2013). Pollution studies on groundwater contamination: water quality of Abeokuta, Ogun State, South West Nigeria. *Journal of Environmental and Earth Sciences,* 3(5), 161-166.

Akhtar, N., Syakir Ishak, M. I., Bhawani, S. A., and Umar, K. (2021). Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water* 13(19): 26 - 60.

Akinyemi, O.D., Bello, R., Ayodeji, A.A., Akanbi, D.E., Ibine, M.M., and Popoola, J.A. (2011). Evaluation of Water Quality in Abeokuta, Southwest Nigeria. *International Journal of Water Resources and Environmental Engineering* 3(13), 341-369.

Aladejana, J.A., and Talabi, A.O. (2013). Assessment of Groundwater Quality in Abeokuta, SouthWest Nigeria. *International Journal of Engineering and science* 2(6), 21-31

APHA, AWWA, WEF (2022). *Standard Methods for the Examination of Water and Wastewater. American Public Health Association, American Water Works Association, and Water Environment Federation. 24th Edition*: Washington, DC.

ATSDR, (2015). *United States Agency for Toxic Substances. Toxicological Profile for Nickel:* U.S. Department of Health and Human Services 351.

Ayedun, H., Oyede, R.T., Osinfade, B.G., Umar, B.F., and Abiaziem, C.V. (2012). Groundwater Quality around New Cement Factory, Ibese, Ogun State, South West Nigeria. *African Journal of Pure and Applied Chemistry* 6(13), 219-223.

Banerjee, P., & Prasad, B. (2020). Determination of concentration of total sodium and potassium in surface and ground water using a flame photometer. *Applied Water Science*, *10*(5), 1-7.

Behailu T. W., Badessa T. S. and Tewodros B. A. (2018). Analysis of Physical and Chemical Parameters in Ground Water consumed within Konso area, Southwestern Ethiopia. *African Journal of Environmental Science and Technology* 12(3), 106-114.

Edunjobi, H.O., Layade, O.G., Makinde, V., Bada, B.S., Ogunbayo, A.F. and Atunrase, K.A. (2023). Qualitative Interpretation of High Resolution Aeromagnetic Data of Abeokuta Metropolis for Geological Characterisation. *Results in Geophysical Sciences* 15, 1-11.

Egbinola, C.N. and Amanambu, A.C. (2014). Groundwater Contamination in Ibadan, South-west Nigeria. *SpringerPlus* 3(1), 1-6.

Egbueri, J. C., Ezugwu, C. K., Ameh, P. D., Unigwe, C. O., and Ayejoto, D. A. (2020). Appraising Drinking Water Quality in Ikem Rural Area (Nigeria) based on Chemometrics and Multiple Indexical Methods. *Environmental monitoring and assessment* 192(5), 308-312.

Elemile O O, Raphael O D, Omole D O, Oluwatuyi O E, Ajayi E O, Umukoro O and Elemile M G. (2019). Assessment of the Impact of Abattoir Activities on the Physicochemical Properties of Soils within a Residential Area of Omu-Aran, *Nigeria IOP Conference Series: Materials Science and Engineering* 640 (1), 125-135.

Emmanuel, U.C., Chukwudi, M.I., Monday, S.S. and Anthony, A.I. (2022). Human Health Risk Assessment of Heavy Metals in Drinking Water Sources in Three Senatorial Districts of Anambra State, Nigeria. *Toxicology Reports* 9, 869-875.

Eseigbe, A.P., Ibhadode, O., Ayoola, A.R., and Sosanolu, O.M. (2018). Experimental Determination of Drinking Water Quality in Abeokuta Metropolis, South-Western Nigeria. *International Journal of Advances in Scientific Research and Engineering* 4(12), 241-256.

Ishola, S.A., Makinde, V., Okeyode, I.C., Akinboro, F.G., Ayedun, H., and Alatise, O.O. (2016) Assessment of Pollution Hazards of Groundwater Resource in Abeokuta North Local Government Area, Ogun state, Southwestern Nigeria. *Journal of Natural Science, Engineering and Technology* 15(1), 42-56.

Izah, S. C., Chakrabarty, N., and Srivastav, A. L. (2016). A Review on Heavy Metal Concentration in Potable Water Sources in Nigeria: Human Health Effects and Mitigating Measures. *Exposure and health* 8, 285-304

Laniyan, T.A., Ajibade, O.M., Bayewu, O.O, and Oshomoji, A.O. (2015). Impact of Urban Activities on Groundwater Qualities in Abeokuta, Southwestern, Nigeria. *Ife Journal of Science* 17(2), 239-246.

Lapworth, D.J., Nkhuwa, D.C.W., Okotto-Okotto, J., Pedley, S., Stuart, M.E., Tijani, M.N. and Wright, J.J. (2017). Urban Groundwater Quality in Sub-Saharan Africa: Current Status and Implications for Water Security and Public Health. *Hydrogeology Journal* 25(4): 1-12.

Li, P., Karunanidhi, D., Subramani, T. and Srinivasamoorthy, K. (2021). Sources and Consequences of Groundwater

Contamination. *Archives of Environmental Contamination and Toxicology* 80, 1-10.

Lotfi, S., Chakit, M. and Belghyti, D. (2020). Groundwater Quality and Pollution Index for Heavy Metals in Saïs Plain, Morocco. *Journal of Health and Pollution* 10 (26), 1-13

Majhi, A., and Biswal, S.K. (2016). Application of HPI (Heavy Metal Pollution Index) and Correlation Coefficient for the Assessment of Ground Water Quality near Ash Ponds of Thermal Power Plants. *International Journal of Science Engineering and Advance Technology* 4(8), 395-405.

Matta, G., Nayak, A., Kumar, A., Kumar, P., Kumar, A., Tiwari, A.K. and Naik, P.K. (2020). Evaluation of Heavy Metals Contamination with Calculating the Pollution Index for Ganga River System. *Taiwan Water Conservancy* 68(3), 10-37.

McArthur, F., Lauermann, K., and Rice, R. (2020). Groundwater Quality from Hand-dug Wells in Developing Countries: A Review. *International Journal of Environmental Research and Public Health*, 17(10), 36-50.

Mishra, N., Khare, D., Gupta, K. K., and Shukla, R. (2014). Impact of Land Use Change on Groundwater—A Review. *Advances in Water Resource and Protection* 2(28), 28-41.

Ogarekpe, N.M., Nnaji, C.C., Oyebode, O.J., Ekpenyong, M.G., Ofem, O.I., Tenebe, I.T. and Asitok, A.D. (2023). Groundwater Quality Index and Potential Human Health Risk Assessment of Heavy Metals in Water: A Case Study of Calabar metropolis, *Nigeria. Environmental Nanotechnology, Monitoring & Management* 19, 1-10

Okeyode, I. C., Oladotun, I. C., Alatise, O. O., Bada, B. S., Makinde, V., Akinboro, F. G., and Al-Azmi, D. (2019). Indoor Gamma Dose Rates in the High Background Radiation Area of Abeokuta, South Western Nigeria. *Journal of Radiation Research and Applied Sciences* 12(1), 72-77.

Olatunde, K.A., Sanni, M., Omodayo, A., Odedeyi, D., Eze, J., Ojo, A., Aje, D., and Oyewole, O. (2021). Assessment of Groundwater Quality and Hydrogeological Profiles within Odeda Local Government, Abeokuta, Southwest Nigeria. Journal of Applied Sciences and Environmental Management 25(5), 723-726.

Oloruntola, M. and Adeyemi, G. (2014). Geophysical and Hydrochemical Evaluation of Groundwater Potential and Character of Abeokuta Area, Southwestern Nigeria. *Journal of Geography and Geology* 6(3), 162-177.

Omole, D.O. (2013). Sustainable Groundwater Exploitation in Nigeria. *Journal of Water Resources and Ocean Science* 2(2), 9-14.

Omole, D.O., and Okunowo, O.S. (2016). People Perception of Domestic Water Supply Situation in Ogun State, Nigeria. *Research Journal of Applied Sciences, Engineering and Technology* 12(1), 94-99.

Orosun, M. M., P. Tchokossa, L. I. Nwankwo, T. O. Lawal, S. A. Bello, and S. O. Ige. (2016). "Assessment of heavy metal pollution in drinking water due to mining and smelting activities in Ajaokuta, Nigeria." *Nigerian Journal of Technological Development* 13(1), 31-39.

Ouedraogo, I., Defourny, P., and Vanclooster, M. (2016). Mapping the Groundwater Vulnerability for Pollution at the Pan African Scale. *Science of the Total Environment* 544, 939-953.

Rahaman, M.A. (1976). *Review of Basement Geology of SouthWestern Nigeria In:* Geology of Nigeria, Kogbe,C.A (ed). Elizabethan Publishing, Lagos, Nigeria.

Shah, T., J. Burke and K. Villholth. (2017). Groundwater: A Global Assessment of Scale and Significance. Retrieved from: http://www.iwmi.

cgiar.org/assessment/Water%20.pdf.

Shahid, S., Alamgir, M., Wang, X. J., and Eslamian, S. (2017). *Climate Change Impacts on and Adaptation to Groundwater*. In Handbook of Drought and Water Scarcity: CRC Press.

Sharma, B., Vaish, B., Monika, Singh, U. K., Singh, P., and Singh, R. P. (2019). Recycling of Organic Wastes in Agriculture: An Environmental Perspective. *International Journal of Environmental Research* 13, 409 - 429.

Siddiqua, A., Hahladakis, J. N., And Al-Attiya, W. A. K. (2022). An Overview of the Environmental Pollutiona and Health Effects associated with Waste Landfilling and Open Dumping. *Environmental Science and Pollution Research* 29 (39), 58514 - 58536.

Sobhanardakani, S., Yari A., Taghavi, L., Tayebi L. (2016). Application of Water Quality Pollution Indices to assess the Heavy Metal Contamination, Case study: Groundwater Resources of Asadabad Plain in 2012. *Archive of Hygiene Sciences* 5(4), 221-228.

Tadiboyina, R., and Ptsrkb, P. (2016). Trace Analysis of Heavy Metals in Ground Waters of Vijayawada Industrial Area. *International Journal of Environmental and Science Education* 11(10), 3215-3229.

Taiwo, A. M. (2012). Source identification and Apportionment of Pollution Sources to Groundwater Quality in Major Cities in South western Nigeria. *GEOFIZIKA* 29(2), 157-74

Taiwo, A. M., Somade, O. C., Ojekunle, O. Z., Atayese, A. O., Obuotor, T. M., and Taiwo, O. T. (2022). Effects of Waste Sanitation Facilities on Water Quality Index and Human Health Risk Assessment of Groundwater Resources in Abeokuta Markets, Southwestern Nigeria. *Research Square* 1, 1-18.

Thévenod, F. and Lee, W. K. 2013. Toxicology of Cadmium and Its Damage to Mammalian Organs. *Journal of Elementology* 13(2), 415 - 490.

USEPA (2016) (US Environmental Protection Agency). "National summary of impaired waters and TMDL information". United States Environmental Protection Agency: Washington DC.

WHO (2011) *Guidelines for Drinking Water Quality.* 4th Edition, World Health Organisation Press: Geneva, Switzerland 223-230.

WHO. (2017). *Guidelines for Drinking Water Quality*, 4th Edition: First Addendum to the Fourth Edition. World Health Organisation Press: Geneva, Switzerland, 5(2), 537–544.

WHO. (2023). Lead Poisoning (Online). World Health Organisation. Available at https://www.who.int/news-room/fact-sheets/detail/lead-poisoning-and-health (3 Mar, 2023).

Citation:
Dami-Adekunle, A. G., Akinyemi, O. D., Awomeso, J., & Bada, B. S. (2025). Health Risk Implications of Heavy Metals Contamination on Drinking Water in Densely Populated Markets of Abeokuta, Nigeria. *Fountain Journal of Basic Medical and Health Sciences (FUJBMHES), 1(2),* 36-55.