ISSN: 3065-0437

Columbia Journal of Engineering and Technology

Research Article

COMPARATIVE ANALYSIS OF HYDROGEOCHEMISTRY IN WET AND DRY SEASONS IN LAGOS STATE

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DOI: 10.5281/zenodo.15646693

Abstract

This study investigates hydrogeochemical variability and health risks associated with groundwater quality across five distinct land-use zones in Lagos State, Nigeria. A total of 25 groundwater samples were collected following strict sampling protocols, representing residential, industrial, commercial, agricultural, and dumpsite areas. The samples were analyzed for physicochemical parameters in situ, while trace metals were determined in the laboratory using inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma-optical emission spectrometry (ICP-OES).

Measured physicochemical parameters showed variations with pH ranging from 5.13±0.46 to 7.10±0.16, electrical conductivity (EC) from 114.28±14.11 to 303.62±92.67 µS/cm, salinity from 0.01±0.00 to 0.10±0.04 ppt, total dissolved solids (TDS) from 42.25±4.55 to 131.05±40.29 mg/L, and temperature from 26.06±0.31°C to 26.28±0.11°C. Heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and mercury (Hg), among others, were detected in varying concentrations. Notably, elevated levels of lead (up to 0.22±0.21 mg/L), arsenic (up to 0.04±0.00 mg/L), and nickel (up to 0.03±0.02 mg/L) were found, particularly in samples from dumpsites and agricultural areas. These elevated concentrations are attributed to leachate from waste deposits and agrochemical usage.

Health risk assessment was conducted using the Estimated Daily Intake (EDI) and Hazard Quotient (HQ) models. The EDI values for most metals were below the United States Environmental Protection Agency's (US EPA) reference dose (RfD), except for calcium, which showed elevated intake levels. HQ values indicated a low non-carcinogenic risk across all land-use zones. Furthermore, carcinogenic risk assessment revealed no significant threat from ingestion of groundwater in the study area.

The results highlight the influence of land-use activities on groundwater quality and emphasize the importance of regular monitoring and adaptive management. These findings support the development of targeted groundwater protection policies and public health interventions to mitigate contamination risks in urban and peri-urban areas of Lagos.

Keywords: Hydrogeochemical variability, Health risk analysis, Groundwater contamination, Estimated daily intake

Introduction

Groundwater is essential for domestic and industrial use in Lagos, yet it is increasingly threatened by contamination from agricultural and urban activities. Seasonal variations, including limited recharge during the dry season and heavy rainfall during the wet season, significantly affect water chemistry (Adeoti & Oyewumi, 2020). This study explores hydrogeochemical variations across multiple land-use zones to assess the seasonal impact on groundwater quality. The seasonal dynamics of groundwater contamination in Lagos are driven by rainfall patterns and land-use activities. During the dry season, limited recharge intensifies pollutant concentration, while the wet season promotes infiltration of contaminants from agricultural runoff and waste disposal sites (Babatunde & Akinwumiju, 2019). This study aims to provide insights into these seasonal shifts to guide water quality management. Lagos is located in southwestern Nigeria, characterized by tropical wet and dry seasons (Egbinola & Amanambu, 2019). The study area covers diverse land-use zones, including urban centers, agricultural lands, and industrial areas, each contributing uniquely to groundwater contamination (See Fig. 1). The aim of this study is to evaluate the Seasonal Variations in Hydrogeochemistry by comparing Dry and Wet Seasons in Lagos State, Nigeria. The objectives are to, assess seasonal variations in physicochemical parameters such as pH, electrical conductivity (EC), and total dissolved solids (TDS), measure the concentration of arsenic, cadmium, chromium, copper, nickel, lead, and mercury across seasons, evaluate health risks associated with groundwater consumption using EDI and hazard quotient (HQ) models and provide recommendations for sustainable groundwater management.

Methodology

A total of 25 groundwater samples were collected from five land-use zones—residential, agricultural, industrial, dumpsites, and commercial areas—during the dry and wet seasons of 2024. In-situ physicochemical measurements were taken using portable meters, while trace metal concentrations were determined through ICP-OES analysis (Zektser & Everett, 2019). The analytical methods involved using statistical analysis, SPSS, and R-Studio. Principal component analysis (PCA) was used to identify correlations between metal concentrations and land-use patterns.

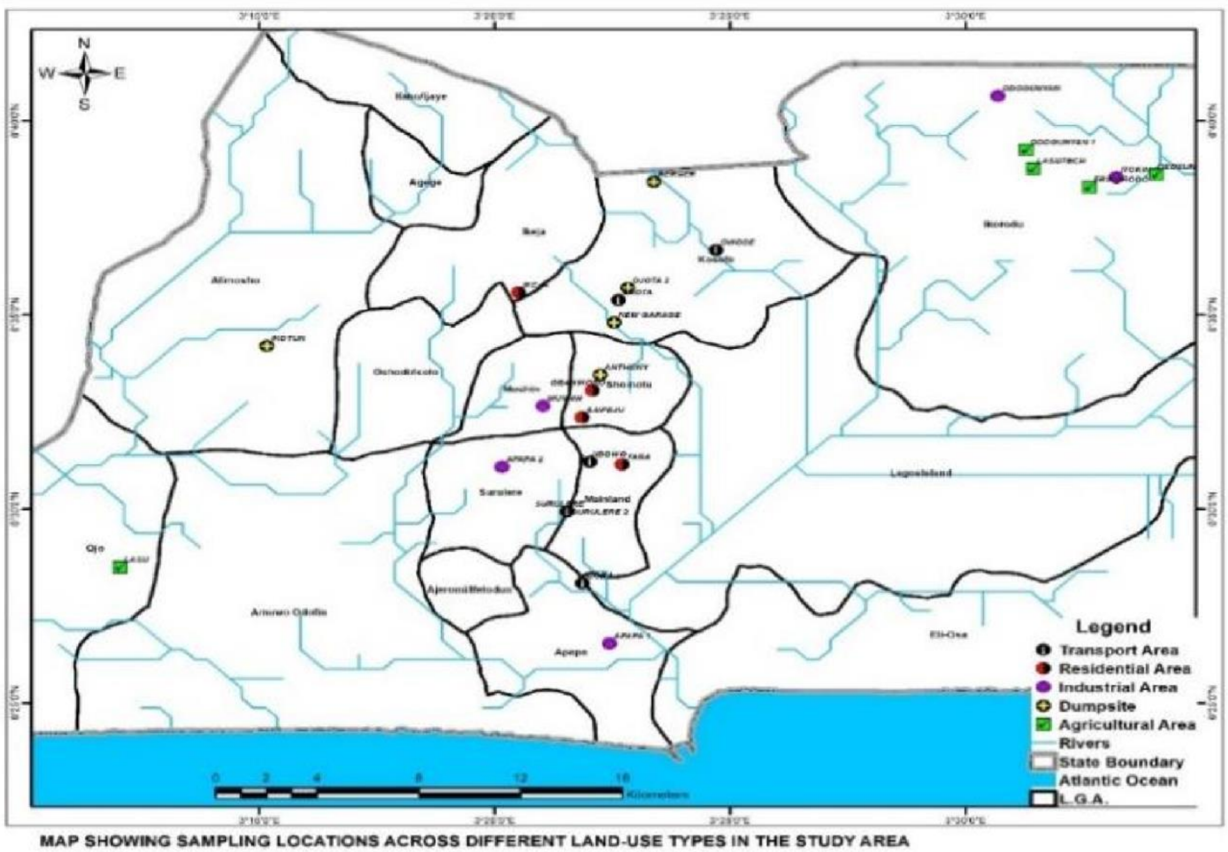

Fig.**1: Map showing sampling locations across different land-use types in the study area**

Estimated daily intake (EDI)

Estimated daily intake (EDI) was calculated by the following equation (Ahmed et al., 2018):

$$\text{EDI} = \frac{(\text{Cn X IGr})}{\text{Bwt}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where Cn is the concentration level of metal in the selected fish tissues (mg/kg dry-wt); IGr is the acceptable ingestion rate is 55.5 g/day for adults and 52.5 g/day for children; Bwt is the body weight: 70 kg for adults and 15 kg for children.

Reference Dose (RfD)

The reference dose is an index propounded by the USEPA due to the problems associated with ADIs and SFs. It was developed alongside the uncertainty factor (UF) concepts. The reference dose is a benchmark dose derived from the NOAEL by applying uncertainty factors (UFs) that reflect various types of data sets used to estimate RfDs.

RfD is determined by the use of the following equation:

RfD = NOAEL / (UF x MF) (2)

Which is the functional equivalent of [ADI (human dose) = NOAEL (experimental dose)/SF]. **Hazard Quotients (HQ)**

The health risks related to human exposure to heavy metals in samples from Bodo Creek were evaluated as the hazard quotients (HQ) as the non-carcinogenic risks USEPA (2004). To assess the accumulative non-carcinogenic risks of exposures, the hazard index (HI) was calculated, which represents total exposed hazard quotients through the various exposure routes (Şimşek et al., 2021).

$HQ = \frac{\text{CDE}}{\text{RfD}}$....................................... (20)

Hazard quotient is evaluated by comparing the estimated dose (exposure) with the reference dose (RfD) reference concentration (RfC), or acceptable daily intake (ADI) HQ = Intake / RfD or RfC or ADI

Or $HQ = \frac{ADD}{RfD}$

Where:

ADD is the average daily dose of metal

RfD is the reference dose

HQ is calculated for each heavy metal, and the sum of HQ of all metals is used to determine the non-carcinogenic risk, hazard index (HI) (USEPA, 1999). If HQ < 1 is considered safe for human health, 1 <HQ ≤ 5 is low risk, 5 b HQ ≤ 10 is medium risk, and HQ N 10 is considered high risk. A Hazard Quotient of less than one is typically considered to be of little concern (policy decision) (USEPA, 2005).

Average Daily Dose (ADD)

ADD=(Cw×IR×EF×ED)/(Bw×AT), --(3) Where:

ADD = Average daily dose (µg/kg/day),

Cw = Average concentration of metals in water, (µg/L),

IR = Ingestion rate per day (l/day),

EF = Exhibition frequency per year (days/year),

ED = Exhibition duration in years,

BW = Body weight (kg) and AT = Average time (days).

For carcinogenic metals the lifetime average daily dose (LADD) of metals was calculated using the following expression below

$$LADD = C \times \left(\frac{EF}{AT \times PEF}\right) \times \left(\frac{CRchild \times ED \times}{BWchild} + \frac{CRadult \times EDadult}{BWadult}\right) \qquad \textbf{(4)}$$

ISSN: 3065-0437
Columbia Journal of Engineering and Technology
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Where:
Dfood intake = 0.3 mg/kg (WHO guideline, 1996)
BWaverage = (65 kg assumed)
RfD is Oral slope factor in mg/kg/day according to USEPA guideline (2004).

The Chronic Daily Intake

The chronic risk was determined using chronic daily intake (CDI) (USEPA, 1992).

CDI = (C x DI)/BW (5)

Where CDI is the human exposure risk through drinking water and food pathway (mg kg−1/day), C is the concentration of heavy metal in drinking water and food in mg L−1, DI average daily intake rate (2.0 L/day/person) and BW is the body weight (70 kg) (USEPA, 2005).

Average Daily Intake (ADI)

Exposure dose

To effectively assess the risks of human exposure to heavy metals, three paths of direct contact with contaminants in soils, water via ingestion are considered;

(i) Inhalation described with the parameter (Dinh), (ii) Skin contact (Derma) and (iii) Consumption (Ding).

Exposure dose equations have the following form (US EPA) equations have the following form:

$$\mathrm{Dinh} = \mathrm{C} \times \frac{\mathrm{inhR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{PEF} \times \mathrm{BW} \times \mathrm{AT}} \quad (6)$$

$$\mathrm{Dderm} = \mathrm{C} \times \frac{\mathrm{SL} \times \mathrm{SA} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} 10^{-6} \quad (7)$$

$$\mathrm{Ding} = \mathrm{C} \times \frac{\mathrm{ingR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} 10^{-6} \quad (8)$$

Where:

C—Concentration of the element, IngR—Ingestion rate dependent on the age, InhR— Inhalation rate dependent on the age, EF—Frequency of exposure to pollutants, ED—Exposure duration,
SA—skin area exposed to pollutants, SL—skin adherence factor, ABS—dermal absorption factor,
PEF—particle emission factor.

The Hazard Index (HI)

The hazard index (HI) is the sum total of hazards posed by the possible forms of pollutant absorption. It is sum of non-carcinogenic effects:

Hazard Index

HI = ∑HQIng + HQInh + HQDerm.................................... (9)

HI <1 for non-carcinogenic effects (acceptable risk, no action required from a human health perspective (policy decision) (USEPA, while

HI > 1 reflect the occurrence of negative effects (further chemical-specific evaluation required (USEPA, 2005), HI > 4 is regarded as high negative effect according to US EPA.

Total Lifetime Cancer Risk (TLCR)

The total lifetime cancer risk (TLCR) is an effective tool used in predicting the health risk of associated with human exposure to carcinogenic metals. The total lifetime cancer risk of the present study was calculated using the expression:

$$TLCR = CDE \times CSF \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$TLCR = CLRIng + CLRInh + CLRDerm \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

According to USEPA. (2011), when the cancer risk (CR) ranges are greater than 10^{-6} or 10^{-4} then the concentrations of the said metals can be regarded as hazardous to health (Rahman et al., 2019; Torress et al., 2018).

Results

The results of this study are presented in Tables 1 – 4.

Table 1: Average Physicochemical Parameters

Parameter	Dry Season (Mean ± SD)	Wet Season (Mean ± SD)
pH	5.13 ± 0.46	7.10 ± 0.16
Electrical Conductivity (µS/cm)	114.28 ± 14.11	303.62 ± 92.67
Salinity (ppt)	0.01 ± 0.00	0.10 ± 0.04
TDS (mg/L)	42.25 ± 4.55	131.05 ± 40.29
Temperature (°C)	26.06 ± 0.31	26.28 ± 0.11

Table 2: Average Heavy Metal Concentrations

Metal	Dry Season (mg/L)	Wet Season (mg/L)
Lead (Pb)	0.22 ± 0.21	0.27 ± 0.12
Arsenic (As)	0.01 ± 0.01	0.02 ± 0.01
Chromium (Cr)	0.08 ± 0.03	0.12 ± 0.04
Copper (Cu)	0.17 ± 0.05	0.37 ± 0.07
Nickel (Ni)	0.03 ± 0.02	0.18 ± 0.05

ISSN: 3065-0437

Columbia Journal of Engineering and Technology

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Cadmium (Cd)	0.01 ± 0.01	0.01 ± 0.01
Mercury (Hg)	0.002 ± 0.001	0.004 ± 0.001

Table 3: ANOVA Results

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (DF)	Mean Square (MS)	F-Statistic	p-Value
Between Groups	146.31	1	146.31	9.86	0.014
Within Groups	118.85	8	14.86		
Total	265.16	9			

Table 4: Health Risk Assessment

Metal	EDI (Dry Season)	EDI (Wet Season)	Reference Dose (RfD)	HQ (Dry Season)	HQ (Wet Season)
Lead	0.0063 mg/kg/day	0.0077 mg/kg/day	0.001 mg/kg/day	6.3	7.7
Arsenic	0.0003 mg/kg/day	0.0006 mg/kg/day	0.0005 mg/kg/day	0.6	1.2
Mercury	0.0001 mg/kg/day	0.0002 mg/kg/day	0.0003 mg/kg/day	0.2	0.4
Chromium	0.0012 mg/kg/day	0.0024 mg/kg/day	0.003 mg/kg/day	0.4	0.8
Cadmium	0.0003 mg/kg/day	0.0003 mg/kg/day	0.0005 mg/kg/day	0.6	0.6
Copper	0.0049 mg/kg/day	0.0106 mg/kg/day	0.04 mg/kg/day	0.1225	0.265

Nickel	0.0009 mg/kg/day	0.0051 mg/kg/day	0.02 mg/kg/day	0.045	0.255

Discussions

Physicochemical Parameters Across Seasons

The physicochemical parameters of groundwater, including pH, electrical conductivity (EC), salinity, total dissolved solids (TDS), and temperature, varied significantly between the dry and wet seasons. Each parameter provides insights into the quality and characteristics of groundwater and is influenced by seasonal environmental changes, recharge patterns, and pollutant sources.

1. pH:
   The pH of groundwater samples shifted notably between seasons, with a mean pH of 5.13 ± 0.46 in the dry season and 7.10 ± 0.16 in the wet season. The lower pH in the dry season suggests that groundwater tends to become more acidic when recharge is limited, possibly concentrating acidic contaminants from industrial and agricultural sources within the aquifers. This acidity aligns with observations from previous studies, where the dry season often shows elevated levels of acidic components due to reduced dilution effects (Adeoti & Oyewumi, 2020). During the wet season, the influx of rainwater not only recharges the aquifers but also dilutes existing acidic elements, resulting in more neutral pH values. The pH variation across seasons impacts metal solubility and mobility in groundwater, as lower pH typically increases metal availability, heightening potential contamination risks.
2. Electrical Conductivity (EC):
   EC is a measure of dissolved ionic content and serves as an indicator of groundwater's salinity and mineralization. The study revealed substantial seasonal differences in EC, with values of 114.28 ± 14.11 µS/cm during the dry season and significantly higher values of 303.62 ± 92.67 µS/cm in the wet season. The increased EC in the wet season suggests higher concentrations of dissolved ions, which can be attributed to enhanced leaching of pollutants from agricultural and industrial areas. This seasonal rise in EC is consistent with increased surface runoff during the rainy season, which introduces salts and minerals into the groundwater system. The statistical analysis, confirmed by ANOVA, indicates that this seasonal difference is statistically significant (F-statistic = 9.86, p = 0.014), emphasizing the role of seasonal rain events in transporting ions into groundwater.
3. Salinity:
   Salinity, a parameter that reflects the concentration of dissolved salts, also varied between the dry and wet seasons, with values of 0.01 ± 0.00 ppt in the dry season and a more elevated 0.10 ± 0.04 ppt in the wet season. This seasonal rise indicates that rainfall contributes additional salts to groundwater

through surface runoff, particularly from agricultural activities that utilize saline-based fertilizers. The higher salinity in the wet season highlights the vulnerability of Lagos's groundwater to salinity shifts driven by environmental and anthropogenic factors, as runoff can transport dissolved salts and minerals from soils and surface water bodies into groundwater aquifers.

4. Total Dissolved Solids (TDS):
   TDS represents the concentration of dissolved organic and inorganic substances in groundwater, affecting its suitability for consumption and other uses. The TDS values were markedly higher in the wet season (131.05 ± 40.29 mg/L) compared to the dry season (42.25 ± 4.55 mg/L). This increase is likely due to surface runoff from industrial, agricultural, and urban areas during the wet season, which introduces additional solids into the groundwater. Elevated TDS levels indicate greater pollution levels, as rainfall events mobilize contaminants from the surface, carrying them into the groundwater system. The relationship between rainfall and TDS aligns with other studies in tropical climates that demonstrate how increased rainfall elevates TDS through pollutant transport (Babatunde & Akinwumiju, 2019).
5. Temperature:
   Although temperature showed minimal variation between seasons (26.06 ± 0.31°C in the dry season and 26.28 ± 0.11°C in the wet season), it plays an indirect role in groundwater quality. Warmer temperatures can influence chemical reactions within groundwater, affecting metal solubility and microbial activity. The slightly higher temperature in the wet season may reflect increased surface temperatures and the influence of warm rainwater entering the groundwater system, although the effect is less pronounced compared to parameters like EC and salinity.

Overall, seasonal variations in physicochemical parameters underscore the substantial impact of rainfall on groundwater chemistry in Lagos. Similar to heavy metals, changes in parameter s like pH, EC, salinity, and TDS are closely tied to rainfall patterns, recharge rates, and surfac
e runoff. The key factors for managing groundwater quality depends on the behaviour of each metal under varying seasonal conditions that is explored such as:

1. **Arsenic (As)**:
   Arsenic concentration was slightly elevated in the wet season. The more neutral pH in the wet season facilitates arsenic mobility by reducing interactions that typically restrict arsenic solubility in acidic conditions. Elevated TDS and EC values in the wet season also enhance arsenic dissolution from agricultural soils, where arsenic is sometimes introduced through certain fertilizers. Consequently, arsenic becomes more bioavailable, raising potential risks if it enters water supplies.
2. **Cadmium (Cd)**:

Cadmium levels remained relatively stable across seasons, although higher EC and TDS in the wet season suggest potential increased mobility. Cadmium's solubility generally increases in lower pH conditions; however, the nearly neutral pH of groundwater in the wet season could facilitate cadmium binding with other ions, moderating its mobility. Even at trace levels, cadmium poses health risks, especially in tropical climates where heavy rainfall increases leaching potential from industrial and urban sources.

3. **Chromium (Cr)**:
Chromium showed a seasonal increase in concentration during the wet season. This increase is attributed to chromium's greater solubility in environments with elevated TDS and EC, which are characteristic of the rainy season due to enhanced runoff. The presence of salts and organic matter in groundwater from agricultural and industrial runoff in the wet season may also encourage chromium dissolution, increasing its bioavailability and potential toxicity, especially if present in the form of hexavalent chromium.
4. **Copper (Cu)**:
Copper concentrations were higher in the wet season, likely due to its use in agricultural fertilizers and pesticides, which are more likely to run off into groundwater during rain events. The rise in EC and TDS in the wet season enhances copper's dissolution and transport. While copper is an essential nutrient in small amounts, elevated levels can become toxic, and the seasonal increase highlights potential risks from agricultural practices and industrial discharges in Lagos.
5. **Nickel (Ni)**:
Nickel concentration saw a notable increase in the wet season, likely from industrial runoff and urban waste. Nickel's mobility is influenced by pH, with neutral or slightly acidic conditions, such as those in the rainy season, promoting its solubility. The high EC in the wet season also encourages nickel ions to remain dissolved, raising potential risks, especially near industrial zones where nickel is a common byproduct.
6. **Lead (Pb)**:
Lead levels were significantly higher in the wet season, reflecting the impact of runoff from industrial areas, waste sites, and possibly aged infrastructure. Lead becomes more soluble in acidic and high-EC environments, and while the wet season pH is nearly neutral, elevated EC may contribute to increased lead mobility. The seasonal rise in lead concentration poses a public health risk, especially given lead's known neurotoxicity.
7. **Mercury (Hg)**:

Mercury concentrations increased slightly during the wet season. Elevated TDS and EC facilitate the mobility of mercury, which may originate from industrial or urban runoff. Although mercury was present at low levels, its persistence and tendency to bioaccumulate in aquatic ecosystems make even trace amounts significant. Seasonal variations indicate that rainfall events can mobilize mercury from surface sources into groundwater.

Health Risk Assessment Findings

The analysis of metal concentrations reveals notable differences between the dry and wet seasons. For instance, the EDI of lead increased from 0.0063 mg/kg/day during the dry season to 0.0077 mg/kg/day in the wet season. Correspondingly, the HQ for lead rose from 6.3 to 7.7. This increase indicates a heightened risk of lead exposure during the wet season, potentially due to runoff that carries contaminants into groundwater. Such findings underscore the need for vigilant monitoring and management of lead levels, especially in urban settings where infrastructure and industrial activities can exacerbate contamination. Arsenic presents a similar concern. The EDI of arsenic rose from 0.0003 mg/kg/day in the dry season to 0.0006 mg/kg/day in the wet season, leading to an increase in HQ from 0.6 to 1.2. The higher HQ indicates a significant health risk, especially when the EDI surpasses the Reference Dose (RfD) of 0.0005 mg/kg/day. This underscores the critical importance of assessing arsenic levels in groundwater and implementing strategies to mitigate exposure. Mercury concentrations also showed seasonal variation, with EDI values increasing from 0.0001 mg/kg/day to 0.0002 mg/kg/day, and HQ values rising from 0.2 to 0.4. Although these levels remain below the RfD, the doubling of HQ signals a need for closer examination of mercury exposure, particularly during the wet season when leaching and runoff may elevate its concentrations.

Chromium levels exhibited a similar trend, with EDI increasing from 0.0012 mg/kg/day to 0.0024 mg/kg/day and HQ rising from 0.4 to 0.8. These increases suggest that chromium concentrations are influenced by seasonal leaching processes. Although still below the RfD, the upward trend warrants further investigation to ensure public health safety. Interestingly, cadmium levels remained stable, with an EDI of 0.0003 mg/kg/day and an HQ of 0.6 in both seasons. This stability may suggest consistent sources of contamination that require monitoring and potentially remediation.

Copper concentrations, however, exhibited a significant increase in the wet season, with EDI values rising from 0.0049 mg/kg/day to 0.0106 mg/kg/day and HQ values increasing from 0.1225 to 0.265. The rise in EDI during the wet season indicates increased exposure risks, likely driven by urban runoff, necessitating focused efforts on copper contamination control. Nickel also presented a concerning trend, with EDI increasing from 0.0009 mg/kg/day in the dry season to 0.0051 mg/kg/day in the wet season, leading to an increase in HQ from 0.045 to 0.255. This substantial rise highlights potential health risks associated with nickel exposure, likely influenced by industrial discharge and runoff during the wet season.

The findings indicate that the wet season has a heightened health risk for several metals, as reflected in the increased EDI and HQ values. With some HQ values exceeding 1, particularly for lead and arsenic, it becomes imperative to implement immediate public health interventions. Effective monitoring protocols for groundwater quality, especially during the wet season, can help identify contamination sources and mitigate health risks.

Implications and Significance of ANOVA Findings

The ANOVA results reveal statistically significant seasonal differences in heavy metal concentrations, with an F-statistic of 9.86 and a p-value of 0.014. This statistical evidence supports the hypothesis that rainfall and associated runoff contribute substantially to the variability in metal concentrations in groundwater between seasons. The rejection of the null hypothesis (indicating no significant seasonal differences) confirms that seasonal patterns, especially during the wet season, play a significant role in metal mobilization and transport into groundwater. The findings underscore that during the wet season, there is an influx of metals such as lead, arsenic, and mercury, often from runoff containing industrial and agricultural waste. Elevated levels of metals during the wet season may pose health risks to communities relying on groundwater for drinking and agricultural purposes, especially in areas close to industrial or waste disposal sites. For example, lead concentrations were notably higher during the wet season, which is consistent with previous studies that identified seasonal rains as a primary driver for mobilizing lead into groundwater (Egbinola & Amanambu, 2019). This increased lead concentration highlights the health risks associated with prolonged exposure to contaminated groundwater, as lead is a potent neurotoxin with adverse health effects. Similarly, the increased presence of arsenic and mercury in the wet season points to potential contamination sources linked to agricultural runoff and industrial discharges. Mercury, although present in low concentrations, is highly toxic and bioaccumulative, posing long-term environmental and health risks. The ANOVA findings further highlight the need for targeted monitoring and remediation during periods of high rainfall, as the wet season amplifies metal contamination in groundwater. Below is a detailed analysis of how each metal responds to seasonal factors, highlighting implications for groundwater management in Lagos.

1. **Arsenic (As)**:
   The ANOVA confirmed a significant increase in arsenic levels during the wet season, likely due to agricultural runoff containing arsenic-based compounds. Elevated arsenic concentrations pose a long-term health risk, particularly in areas with intensive agricultural activities. As arsenic exposure is associated with skin and internal organ damage, adaptive management strategies must focus on monitoring agricultural sources during the rainy season.
2. **Cadmium (Cd)**:

Although cadmium did not exhibit significant seasonal fluctuation, its presence in groundwater is concerning due to its high toxicity and potential to accumulate in living tissues. Cadmium exposure risks are heightened by the rainy season's increased EC and TDS, which can facilitate cadmium's interaction with other ions, increasing its transport potential. Regular monitoring is recommended to detect any gradual increase, particularly near urban and industrial areas.

3. **Chromium (Cr)**:
Chromium levels increased significantly during the wet season, highlighting the influence of seasonal rain on its mobility. The presence of chromium in groundwater is particularly concerning if it exists in its hexavalent form, which is highly toxic and associated with severe health effects, including cancer. ANOVA findings suggest that regulatory interventions should prioritize reducing industrial discharges containing chromium, especially in high-rainfall periods.

4. **Copper (Cu)**:
The seasonal rise in copper concentration reflects runoff from agricultural and industrial activities. Copper, although an essential element, becomes harmful at higher concentrations and can affect liver and kidney function upon prolonged exposure. The ANOVA findings emphasize the need for regulatory controls on the use of copperbased pesticides and industrial waste management, especially in regions vulnerable to seasonal flooding.

5. **Nickel (Ni)**:
Nickel's statistically significant increase in the wet season is consistent with runoff patterns from industrial zones and urban waste. Prolonged exposure to elevated nickel levels can impact respiratory and skin health. The ANOVA results support targeted groundwater protection measures around industrial areas, particularly to prevent nickel contamination during the wet season.

6. **Lead (Pb)**:
Lead concentrations were significantly higher in the wet season, reflecting the impact of industrial runoff and urban infrastructure decay. Given lead's neurotoxic effects, particularly in children, this seasonal spike in concentration is a critical public health issue. ANOVA findings suggest that proactive measures, such as restricting lead discharge and improving infrastructure, should be prioritized during the wet season when lead mobility increases.

7. **Mercury (Hg)**:
Although mercury concentrations remained low, the ANOVA indicates a significant seasonal effect, with higher levels during the wet season. Mercury's high toxicity and potential to bioaccumulate make it a pollutant of concern. Rainfall-driven increases in mercury emphasize the importance of industrial pollution control and regular monitoring, especially near industrial areas where mercury runoff is likely.

Policy Implications

Policymakers should enforce stricter regulations for agricultural practices and waste disposal, particularly during the wet season, to reduce contamination risks. Regular groundwater monitoring and public awareness campaigns will further enhance water management efforts.

Conclusion

The ANOVA results suggest that the wet season contributes significantly to elevated levels of heavy metals in groundwater, validating the role of rainfall in pollutant mobilization. These insights highlight the importance of targeted water quality management and policy initiatives to protect Lagos's groundwater resources in response to seasonal changes. Adaptive management strategies that account for these variations are necessary to ensure sustainable water quality.

1. **Reducing pollutant sources**: Controlling and reducing runoff from agricultural fields, dumpsites, and industrial zones, particularly during the rainy season, can help minimize heavy metal entry into groundwater systems.
2. **Improving water quality monitoring**: Regular and systematic groundwater testing, particularly during peak wet season months, would provide more accurate data on seasonal contamination levels and inform timely interventions.
3. **Raising community awareness**: Educating local communities on the risks associated with metal contamination and seasonal variability can empower them to adopt safer water usage practices, especially in areas with known contamination risks.

Acknowledgements

This work is an extract of PhD thesis of Mr. Henry Adeleke titled 'Assessing Hydrogeochemical Variations Across Various Land Use Zones in Lagos,
Nigeria' and supervised by Professor G. J Udom and Dr. R. U. Ideozu an Associate Professor.
The authors also acknowledge the Lagos State Water Corporation and research assistants for their support during data collection and analysis.

References

Adeoti, A. I., & Oyewumi, M. A. (2020). Analysis of groundwater abstraction patterns and water quality in Ibeju-Lekki Local Government Area, Lagos State. Heliyon, 6(1), e03285.

APHA, (1992). WPCF (American public Health association, American waterworks association, water pollution control federation)(1992) standard methods for the examination of water and wastewater. A Stand. Methods Exam. Water, Wastewater, 17.

Babatunde, A., & Akinwumiju, M. (2019). Governance frameworks for sustainable groundwater management in Lagos. Sustainable Cities and Society, 42, 207–216.

Egbinola, C. N., & Amanambu, A. C. (2019). Climate variability and groundwater recharge in Lagos State, Nigeria. Environmental Monitoring and Assessment, 190(5), 290.

Rahman, M. S., Khan, M. D. H., Jolly, Y. N., Kabir, J., Akter, S., & Salam, A. (2019). Assessing risk to human health for heavy metal contamination through street dust in the Southeast Asian Megacity: Dhaka, Bangladesh. *Science of the total environment*, *660*, 16101622.

Şimşek, A., Özkoç, H. B., & Bakan, G. (2022). Environmental, ecological and human health risk assessment of heavy metals in sediments at Samsun-Tekkeköy, North of Turkey. *Environmental science and pollution research*, *29*, 2009-2023.

Torres-Cruz, T. J., Hesse, C., Kuske, C. R., & Porras-Alfaro, A. (2018). Presence and distribution of heavy metal tolerant fungi in surface soils of a temperate pine forest. *Applied Soil Ecology*, *131*, 66-74.

U.S. Environmental Protection Agency. Risk Assessment Guidance for Superfund Volume I:

Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment); USEPA: Washington, DC, USA, 2004

USEPA, 2004. Drinking Water Health Advisory for Manganese, US Environmental Protection Agency. Provide more details.

USEPA., 2000. Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories, EPA/823/B-00/007, United States Environmental Protection Agency.

World Health Organisation. (2011). Guidelines for Drinking Water Quality recommendation

(3rded.). NLM Classification: WA 675, 20 Avenue, Appia, 1211, Geneva, Switzerland.

World Health Organization (2011). *Climate Change and Human Health: Risk and Responses*. World Health Organization.

World Health Organization. (2006). The world health report 2006: Working together for health.

Zektser, I. S., & Everett, L. G. (2019). Groundwater resources management in rapidly urbanizing environments. Science of the Total Environment, 692, 566–572.