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Water Quality Index, Hydrogeochemical Facies and Pollution Index of Groundwater in Port Harcourt, Niger Delta, River State, Nigeria.

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ABSTRACT

Groundwater contamination by heavy metals presents a growing environmental and public health concern, particularly in regions like Port Harcourt, Nigeria, where groundwater is a primary source of drinking water. This study assessed heavy metal (HM) pollution in groundwater and its potential health implications by analyzing 18 water samples and corresponding tooth dentine from local residents. Laboratory analyses employed indices such as the Nemerow Pollution Index (NPI), Modified Degree of Contamination (MDc), Pollution Load Index (PLI), and Quantification of Contamination (QoC), alongside multivariate statistical techniques including Principal Component Analysis (PCA) and correlation matrices. Results revealed NPI values that categorized 85.9% of samples as heavily polluted, while mCd values showed that 41.5% had a very low degree of contamination, and 22.2% exhibited moderate contamination. PLI values indicated low pollution levels across all samples, whereas QoC analysis showed 100% negative values, pointing to geogenic sources as the dominant contributors. Multivariate correlation analysis highlighted weak but notable relationships among HMs and physicochemical parameters, suggesting complex geochemical interactions and potential anthropogenic influence. The spatial pattern of pollution, especially the north-to-south gradient observed in NPI values, aligns with localized human activities and natural geological factors. The overall assessment reflects some degree of heavy metal presence in the groundwater while the PLI depocts limited contamination, These findings underscore the urgent need for continuous groundwater monitoring and the deployment of appropriate treatment technologies to safeguard public health and prevent long-term ecological damage.

Keywords. Groundwater, Pollution, Heavy Metals, Geochemical index, Statistical techniques.

1. Introduction

Groundwater remains the primary source of potable water for millions of inhabitants in Nigeria's Niger Delta region, particularly in urban and peri-urban centers such as Port Harcourt. As surface water bodies become increasingly compromised due to oil-related activities, population pressure, and infrastructural decay, reliance on groundwater has intensified (Adewusi et al., 2021). Despite its subterranean origin, groundwater is not immune to contamination. The physicochemical integrity and usability of this resource now demand rigorous assessment due to escalating anthropogenic stressors and geogenic influences (Ehirim & Nwankwo, 2020). Evaluating groundwater quality extends beyond elemental concentration analysis; it necessitates integrative indices that synthesize multiple water quality parameters. The Water Quality Index (WQI) is a composite measure that simplifies complex datasets into a single metric indicating the suitability of water for domestic or other uses (Srinivasamoorthy et al., 2014). The Niger Delta, an area in Nigeria experiencing rapid development, hosts a variety of rural communities that depend significantly on groundwater to meet their domestic and agricultural water requirements. Unlike surface water, groundwater provides a comparatively stable source that is generally resistant to depletion under normal conditions (Eyankware, et al, 2019). Effective agricultural practices and household activities are dependent on groundwater, which plays a crucial role in maintaining sustainable ecosystems and assisting humans in adapting to climate change. The use of groundwater has risen sharply, becoming the primary water source for various activities in both rural and urban areas of Nigeria, especially during dry periods (Eyankware and Ephraim, 2020).

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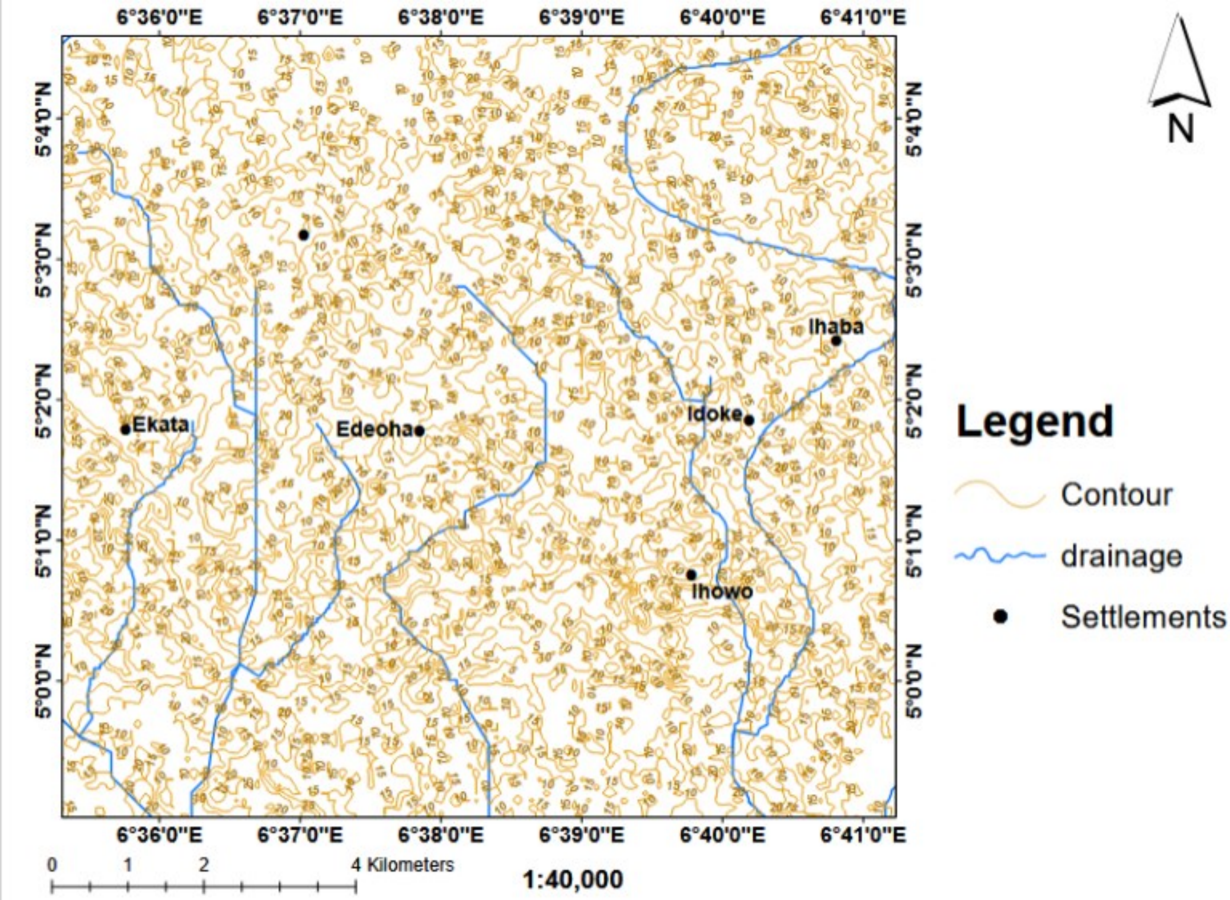

Fig. 1: Topographic Map of the study area.

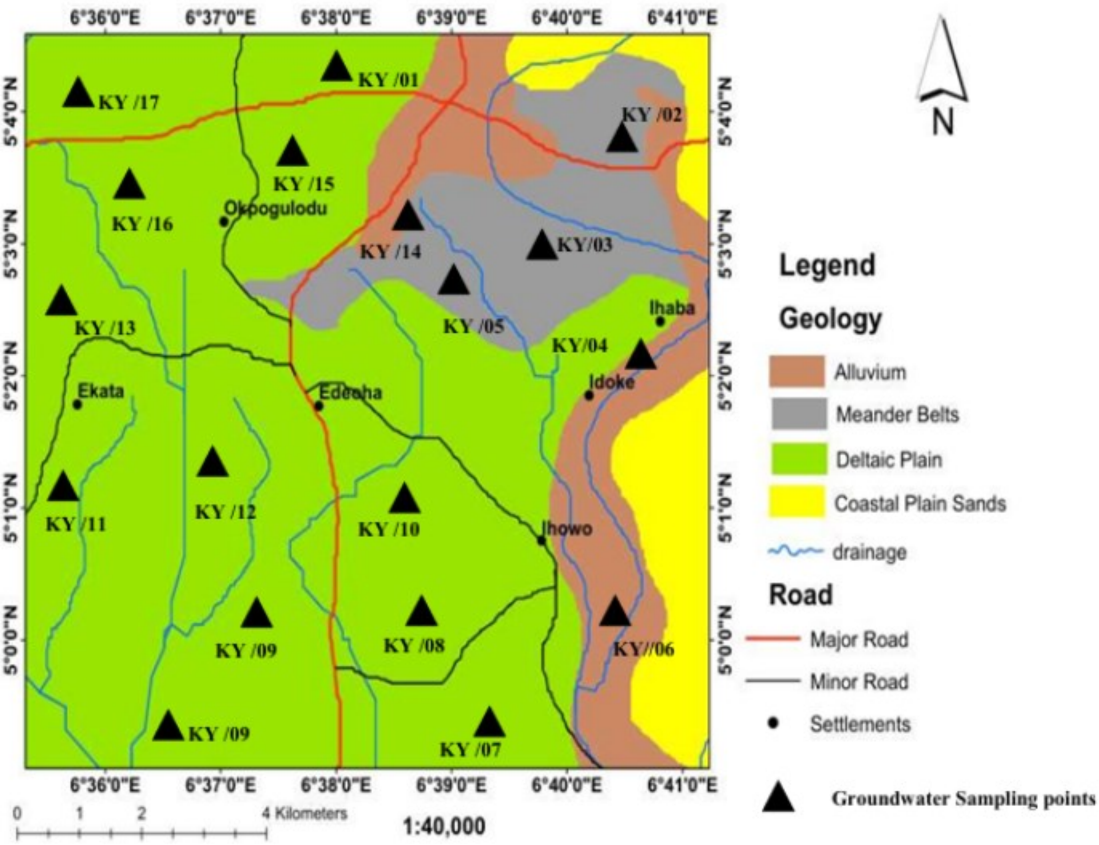

Fig. 2: Geological Map of of Nigeria showing sample locations

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and secondary roads. The geographical characteristics of Port Harcourt are marked by its mostly low-lying and swampy landscape, which is mainly categorized as a lowland swamp forest zone. Situated within the vast Niger Delta, this region is noted for its flat terrain and numerous rivers and creeks. The city was deliberately built on slightly raised ground within the mangrove swamps, facilitating better drainage and accessibility.

2. Geology of the study area

A significant stretch of saline and brackish mangrove swamps acts as a shield between the research area and the ocean, particularly in the coastal zone (Oteri and Atolagbe 2003). This mangrove swamp, along with its sandy islands and barrier ridges, represents the only regions facing challenges associated with salinity in their water resources. In their examination of the Niger Delta Formation, Short and Stauble (1967) identified three unique categories: Akata, Agbada, and Benin (Fig. 1). The Benin Formation within the delta is distinguished by a network of aquifers that mainly consists of large, highly permeable sands and gravels, interspersed with thin layers of shale and clay. A significant number of boreholes have been established in the aquifers associated with the Benin Formation, producing positive outcomes; nonetheless, many of these boreholes have been left unused due to high salinity levels (Oteri and Atolagbe 2003). Weber and Daukoru (1976) indicate that the Benin Formation, which formed during the continental stage of the Niger Delta, has a sedimentary thickness of approximately 2100 meters. Onyeagocha (1980) points out that this formation predominantly consists of sandstone, sand, and gravel, with clay occurring in lens-like deposits. The sand and sandstone grains range from fine to coarse, are partially unconsolidated, and display variations in thickness. Furthermore, Oteri (1990) notes that the primary composition of the Benin Formation consists of robust continental sand and gravel that can retain freshwater, along with alternating strata of clay and shale.

2.1. Hydrogeology of the study area

The Niger Delta Basin features broad, permeable strata of sand and gravel, along with a sophisticated multi-aquifer system. In the unconfined aquifer situated within the coastal beach ridges, there exists a freshwater layer positioned above the underlying seawater. In contrast, many of the confined aquifers in the area have freshwater situated over saltwater. Certain parts of the Niger Delta exhibit saltwater-saturated sand formations resting atop freshwater-saturated layers, leading to instances of saltwater intrusion in particular confined aquifers. Oteri and Atolagbe (2003) note that these sands, heavy with saltwater, are located above the freshwater layers. The area is subjected to saltwater intrusion in both unconfined and confined aquifers. Unconfined aquifers, located in coastal beach ridges or sandy islands amidst the saline mangrove ecosystem, feature freshwater lenses that rest above sand layers infused with saltwater (Oteri 1990). Regarding the saline water sands' depth, the confined aquifers found within the Benin Formation can be divided into two main zones: the first zone includes shallow freshwater sands situated above saline water sands, while the second zone, also at shallow depths, comprises saline water sands that are underpinned by both freshwater and saline water sands beneath them (Oteri and Atolagbe 2003).

3. Methodology

The infiltration of saltwater has an impact on both unconfined and confined aquifers in the Niger Delta region. Within the unconfined aquifers located in coastal beach ridges or sandy islands amidst the saline mangrove belt, freshwater lenses are found floating above sand layers that harbor saltwater (Oteri 1990). In terms of the distribution of saline water sands at varying depths, the confined aquifers linked to the Benin Formation can be categorized into two primary regions: one region contains freshwater sands at shallow depths, supported by underlying saline water sands, while the other region also has saline water sands at shallower depths, which are successively underlain by both freshwater and saline water sands (Oteri and Atolagbe 2003). To mitigate the precipitation of heavy metals (HM), the samples were treated in the field with 1.0 ml of concentrated HNO3. To inhibit absorption, three drops of HNO3 were introduced using new syringes. The samples obtained were later transferred into beakers filled with ice, which were securely sealed and kept at a controlled temperature of 4°C. During the transportation to the analytical laboratory, efforts were made to maintain a stable temperature to avoid any evaporation (Singh et al. 2005; Sehgal et al. 2012). A fast sequential (FS) atomic absorption spectrophotometer (Varian 240 AA) was employed for the chemical analysis of the samples, enabling the quantification of heavy metals such as Fe, Cu, Co, Br, Mn, Zn, Cr, Ni, and Pb (AAS). The temperature of each sample was recorded using a portable thermometer, while pH measurements were taken with a portable pH meter (WGS 84) equipped with temperature electrode accessories.

3.1. Nemerow Pollution Index (NPI)

The NPI evaluates the overall degree of soil contamination by considering the concentrations of all tested heavy metals (Gong et al. 2008; Cheng et al., 2007). This assessment is conducted utilizing the formula outlined below:

$$PI_{nemerow} = \sqrt{\frac{\left(\frac{1}{n}\sum_{i=1}^{n} PI\right)^2 PI_{max}^2}{n}} \quad (1)$$

In this context, PI denotes the computed values of the Single Pollution Index, while PI max indicates the maximum value of the Single Pollution Index across all heavy metals. Additionally, n signifies the total count of heavy metals involved.

3.2. Modified Degree of Contamination (mC_d)

According to Abrahim and Parker (2008), the Hakanson (1980) equation provides a framework for evaluating the overall contamination level at a designated sample or coring site. This equation includes the following elements: (i) the contamination level is determined by summing all contamination factors associated with a defined group of estuarine pollutants and dividing this sum by the number of pollutants analyzed; (ii) the average concentration of a particular pollutant is derived from at least three samples; and (iii) baseline concentrations are calculated using a modified formula based on standard geological materials. Equation 3 represents an updated formulation designed to more accurately assess the degree of contamination through an improved methodology.

$$mC_d = \frac{\sum_{i=1}^{i=n} C_f^i}{n} \quad (2)$$

Within this framework, n denotes the number of elements subjected to analysis, whereas C_f^i indicates the contamination factor. Employing this comprehensive and somewhat ambiguous equation for determining mCd enables the research to encompass an unlimited array of metals, without any upper limit being established.

3.3. Pollution Load Index (PLI)

The calculation of the PLI was performed using the formula proposed by Hakanson in 1980, which was later cited by Eyankware and Akakuru, (2022).

$$PLI = \sqrt[n]{CF1 \times CF2 \times} CF3 \times \ldots \times CFn \quad (3)$$

Within this framework, CF signifies the contamination factor, whereas n indicates the total number of elements.

3.4. Quantification of contamination (QoC)

The method of assessing Quality of Contaminants (QoC) is utilized to ascertain the source of pollutants, distinguishing between those that are geogenic and those that are anthropogenic. This identification was accomplished through the use of Equation 5.

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Table 1: The result of the study area's groundwater.

Sample Code	pH	TDS (mg/L)	EC (µS/cm)	Pb (mg/L)	Cr (mg/L)	Cu (mg/L)	Zn (mg/L)	Co (mg/L)	Fe (mg/L)	Mn (mg/L)	Br (mg/L)	Ni (mg/L)	Cd (mg/L)
KY/01	3.05	16.48	155.54	0.0001	0.002	0.07	0.03	0.01	0.47	0.03	0.95	0.13	0.006
KY /02	3.40	181.23	304.78	BDL	0.001	0.56	0.97	0.01	0.01	0.01	1.43	0.05	0.001
KY /03	5.35	196.92	148.66	BDL	0.001	0.98	0.75	0.02	1.48	0.24	0.58	0.009	0.002
KY /04	6.33	127.43	162.01	BDL	0.003	0.58	0.18	0.001	0.94	0.15	2.59	0.018	0.004
KY /05	5.51	134.46	246.45	BDL	0.001	0.97	0.76	0.10	0.42	BDL	0.39	0.004	0.021
KY /06	6.08	84.3	98.19	BDL	0.004	0.63	0.54	0.08	0.27	0.32	1.43	1.023	0.06
KY /07	5.93	94.73	439.55	0.00001	0.011	0.25	0.49	0.1	0.83	0.48	0.91	1.044	0.051
KY /08	5.45	277.35	689.72	BDL	0.020	0.65	2.06	0.02	0.13	0.36	2.54	0.003	0.001
KY /09	6.77	49.33	236.09	BDL	0.009	0.08	0.03	0.07	0.27	0.42	3.52	0.22	0.002
KY /10	6.87	54.23	212.87	BDL	0.01	0.04	2.86	0.05	0.51	1.37	1.35	0.764	0.310
KY /11	5.07	95.34	398.76	BDL	0.20	0.02	1.65	0.07	0.72	BDL	2.46	0.450	0.041
KY /12	6.96	276.55	701.44	0.0001	0.097	0.25	0.45	0.11	0.59	0.64	3.01	0.093	0.016
KY /13	6.89	164.54	453.35	0.0001	0.27	0.14	0.89	0.12	1.81	0.11	4.16	0.077	0.006
KY /14	6.33	195.97	589.25	BDL	0.07	0.06	0.58	0.03	0.57	0.47	0.85	0.054	0.004
KY /15	4.92	57.54	482.33	BDL	0.110	0.75	1.86	0.15	1.04	0.53	1.03	0.040	0.007
KY /16	4.94	85.9	383.23	0.0001	0.0005	0.64	1.21	0.08	0.16	BDL	1.82	0.064	0.003
KY /17	6.12	133.2	300.34	BDL	0.030	0.06	0.14	0.44	0.37	BDL	0.29	1.05	0.014
KY/18	5.39	94.48	169.32	BDL	0.007	0.13	0.87	0.24	0.64	0.15	1.23	0.006	0.001
Min.	3.05	16.48	98.19	0.00001	0.0005	0.02	0.03	0.001	0.01	0.01	0.29	0.003	0.001
Max.	3.05	16.48	98.19	0.00001	0.0005	0.02	0.03	0.001	0.01	0.01	0.29	0.003	0.001
Ave.	5.37	117.6	318.41	6.143E-05	0.0423	0.345	0.819	0.0851	0.562	0.3312	1.55	0.255	0.027

BDL= Below Detection

Within this framework, QoC denotes the contamination index, while Cn indicates the concentration of metal present in the sample, and Bn corresponds to the concentration of metal found in the background. The analysis of concentration patterns and dispersion trends in the region was carried out using Microsoft Excel. Additionally, Pearson's correlation coefficient was computed with the aid of version 23 of the Statistical Package for Social Science (SPSS).

4. Results and Discussion

Table 1 presents the concentrations of heavy metals (HMs) found in the groundwater samples.

4.1. Heavy metal pollution Assessment

Heavy metal (HM) pollution has emerged as a critical environmental concern. The reason for this is that drinking water tainted with heavy metals poses detrimental effects on health and ecosystems. To facilitate a clear comprehension of the pollution levels and the extent of contamination, the HM evaluation index is employed.

4.2. Nenerow Pollution Index (NPI)

NPI value of ≤ 0.7 indicates that the water is clean, NPI value of 0.7< NPI ≤ 1.0 implies slightly clean, NPI value of 1.0< NPI≤ 2.0 implies slightly polluted, NPI value of 2.0< NPI≤ 3.0 implies moderately polluted, while NPI value of > 3.0 implies heavy pollution (Table 3). The NPI (Nemerow, 1974) serves as a numerical index that synthesizes multiple factors into a single metric. Conversely, the NPI value reflects the overall water quality level as influenced by various pollution parameters. Regarding empirical validity, it is more advantageous to utilize an integrated water quality index for assessing inherent groundwater risks rather than focusing solely on the concentrations of one or two specific pollutants (Kowalska et al. 2018; Kong et al. 2019).The NPI evaluates the relative impact of each parameter on the pollution levels found in a water sample. This methodology facilitates the identification of the parameters that influence the quality status. As indicated in Table 5, 5.6% of the total sample showed a value of less than 1, implying that this segment of the sample is relatively unpolluted. In contrast, another 5.6% of the sample had a value of 3, which points to considerable

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pollution. An in-depth analysis of Fig. 4a shows that the Pollution Index (NPI) in the area under investigation trends from the North to the South, exhibiting variations throughout the region. The heightened pollution levels detected in this analysis can likely be linked to human activities. Importantly, these findings differ from those documented in a study by Egbueri et al. (2020) carried out in Nigeria.

Table 3: NPI Classification

Pollution	Pollution Index	Pollution level
I	P ≤ 0.7	Clean
II	0.7< P ≤ 1.0	Slightly clean
III	1.0< P ≤ 2.0	Slightly polluted
IV	2.0< P 2≤ 3.0	Moderately polluted
V	P >3.0	Heavy Pollution

4.3. Modified degree of contamination (mCd)

Classification and description of the mCd are mCd<1.5 is a very low degree of contamination, 1.5≤ mCd< 2 is a Low degree of contamination, 2≤ mCd< 4 is categorized as a Moderate degree of contamination, 4≤ mCd< 8 is High degree of contamination, 8≤ mCd< 16 is said to have a very high degree of contamination, 16≤ mCd< 32 is said to have an extremely high degree of contamination, mCd> 32 is said to have Ultra-high degree of contamination As a result, the determined Cd reflects the sum of the Cf values obtained from the five pollutant samples, as described by Hakanson (1980). Cd acts as an indicator for evaluating the level of contamination found in the surface layers at a particular sampling location. On the other hand, the classification criteria and calculation techniques suggested by Hakanson are limited to the seven metals and Polychlorinated Biphenyls, (PCB) identified in his study. Additionally, to accurately calculate the Cd for the specified classification categories, it is essential to examine all five species, which complicates the implementation of this index. Given the challenges involved in accurately estimating Cd, a new and generalized formula has been developed to evaluate the overall level of contamination at a specific sampling or cor-ing site: (i) This revised formula calculates the degree of contamination (mCd) by summing all contamination factors pertinent to a particular category of pollutants and then dividing by the number of pollutants under examination. (ii) In order to determine the mean concentration of a pollutant element, it is necessary to gather a minimum of three samples from the impacted soils or water, specifically obtained from the pertinent surface soils. (iii) Baseline concentrations are determined by comparing them with lower core concentrations or uncontaminated soils and water from nearby areas, According to the mCd results in Table. 5, 44.5 % of samples have a very low degree of contamination, 33.3 % have a low degree of contamination, and 22.2 % of the samples have a moderate degree of contamination.

4.4. Pollution Load Index (PLI)

PLI is typically classified as having no pollution (PLI<1), moderate pollution (1<PLI<2), heavy pollution (2<PLI<3), or extremely heavy pollution2 (3>PLI). PLI has proven to be a useful method for evaluating the amount of toxicity in groundwater samples that have been contaminated (Akakuru, et al., 2021b; Agidi et al. 2022; Eyankware and Akakuru 2022). According to the results in (Tables 2), 100% of the groundwater has a concentration value of less than one, indicating that there is no contamination. Human activities play a crucial role in raising the levels of PLI in a particular region. The spatial distribution of PLI within the study area, which shows that PLI emanates from the northern region and extends towards the center. The findings from the PLI indicate that there is no direct correlation between the anthropogenic activities present in this area and the groundwater resources. This analysis is consistent with results from a separate study conducted in Nigeria (Eyankware, et al., 2022), although it contrasts with the research carried out by Yahaya et al. (2021) in Nigeria.

4.5. Quantification of Contamination (QoC)

The recognition of heavy metals as considerable pollutants in the study area required the utilization of the QoC model to investigate the origins of these metals. As a result, this review introduces the QoC model, thereby finalizing the source categorization of the PLI model. Table 3, displays the QoC values obtained for each analyzed heavy metal. In general, positive QoC values indicate a human influence, whereas negative values point to a natural geogenic influence. According to the data presented in Table 5, the elements Cr, Cu, Zn,

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Table 4. Status Modified Degree of Contamination mC_d in water, (Hakanson, 1980).)

S/No	mC_d Class	Modified Degree of Contamination	Percentage sample
1	mC_d <1.5	Nil to very low degree of contamination	
2	$1.5 \leq mC_d$ <2	Low degree of contamination	
3	$2 \leq mC_d$ <4	Moderate degree of contamination	
4	$4 \leq mC_d$ <8	High degree of contamination	
5	$8 \leq mC_d$ <16	Very high degree of contamination	
6	$16 \leq mC_d$ <32	Extremely high degree of contamination	
7	mC_d ≥32	Ultra high degree of contamination	

Co, Fe, Mn, Br, Ni, and Cd across the entire study area demonstrate a complete 100% negative Quality of Concern (QoC), indicating that the groundwater in this region has been adversely affected by geogenic processes. Overall, our understanding of the geogenic mechanisms that affect the movement of these metals in water resources remains significantly limited. The escalating toxicity levels of heavy metals continue to represent a serious environmental challenge. Soil contamination by various heavy metals has occurred through both natural processes, such as the leaching and weathering of geological structures, and human activities, including large -scale metal extraction, smelting, fossil fuel combustion, pesticide use, and the addition of sewage sludge (Eyankware et al. 2023). The incorporation of these metals into the food chain negatively influences the physiological growth of plants, while also posing a continual and extensive health risk to human populations.

4.6. Multivariate statistical analysis for identification of pollution source

Correlation matrix

One prevalent approach to assess the relationship between two variables is the use of Pearson correlation coefficient, which measures the linear association between two variables. This coefficient can take on values from -1 to 1, where -1 indicates a perfect negative linear correlation, 0 signifies no linear correlation, and 1 indicates a perfect positive linear correlation. The correlation matrix is an effective instrument for exploring the relationships and origins of hydrogeochemical parameters when evaluating groundwater quality (Akakuru, et al., 2022). As the value of the correlation coefficient moves away from zero, the intensity of the relationship between the two variables intensifies. Conversely, a value of zero suggests that the data points are uncorrelated (Srivastava et al., 2014). The correlation matrix (Table 6) indicated a positive correlation of 0.475 between pH and manganese (Mn), as well as 0.485 with bromine (Br). When the pH levels are lower, the solubility of metals typically rises, leading to an increase in the toxicity of compounds such as cyanide and sulfide. Moreover, acidic water plays a role in the deterioration of metal piping. As a result, heavy metals found in low pH water demonstrate heightened toxicity due to their increased solubility and bio-availability. There exists a correlation of 0.591 between Total Dissolved Solids (TDS) and electrical conductivity (EC). Since measuring TDS can be quite laborious, it is often estimated using electrical conductivity, based on the premise that the dissolved solids consist mainly of ionic species at low enough concentrations to establish a linear correlation between TDS and EC. Additionally, a thorough examination of both precipitation water and groundwater in the shallow circulation zone has identified precipitation as the main current source of copper and zinc in the area under investigation. Notable correlations were observed for chromium and cobalt (0.427), copper and manganese (-0.413)—where the negative correlation signifies an inverse relationship—manganese and nickel (0.424), as well as nickel and cadmium (0.374). A detailed examination of Table 6, reveals that most of the correlation values are negative. A negative correlation refers to the relationship between two variables in which an increase in one variable corresponds to a decrease in the other. This relationship is quantified by the correlation coefficient, which ranges from +1 to -1. It is crucial to recognize that percolating water can absorb significant amounts of heavy metals, leading to contamination of the groundwater as it enters the aquifer system. Utilizing bore water

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Table 5: Quantification of contamination (QoC) of analyzed HMs in groundwater

Name of Locations	Cr	Cu	Zn	Co	Fe	Mn	Br	Ni	Cd
KY/01	-232.08	-49.76	1087..27	-573.32	-55.56	-5030.03	-170.33	-2511.86	-240.26
KY /02	-897.98	-79.65	-40.86	-1464.53	-2010.35	-1009.30	-141.32	-653.24	-140.23
KY /03	-3432.8	-31.43	-30.65	-454.25	-61.33	-142.43	-260.65	-92.5445	-186.32
KY /04	-109.86	-40.54	-209.65	-1401.49	-1233.35	-94.64	-56.76	-104.45	-223.76
KY /05	-118.87	-117.23	-65.87	-70.23	-301.43	-	-444.64	-69.54	-81.56
KY /06	-385.08	-100.54	-117.58	-109.44	-70.43	-40.54	-125.43	-89.43	-156.43
KY /07	-576.98	-80.23	-16.97	-54.45	-533.34	-138.44	-380.84	-184.44	-91.63
KY /08	-987.97	-100.76	-37.73	-135.54	-300.64	-220.32	-76.33	-124.04	-168.65
KY /09	-309.44	-174.32	-1797.11	-743.94	-220.64	-35.23	-65.23	-74.43	-162.67
KY /10	-518.54	-255.83	-72.57	-700.34	-71.74	-25.33	-134.53	-65.42	-61.35
KY /11	-33.75	-184.13	-49.53	-84.35	-267.36	-	-86.38	-113.44	-90.35
KY /12	-107.14	-126.75	-700.53	-24.64	-110.54	-165.43	-59.39	-109.33	-81.96
KY /13	-37.05	-79.65	-57.24	-57.35	-70.32	-143.54	-40.24	-68.32	-151.66
KY /14	-16.82	-46.71	-270.41	-60.64	-104.54	-246.33	-102.53	-154.34	-70.44
KY /15	-53.23	-107.65	-58.43	-124.53	-70.54	-228.44	-180.33	-68.55	-64.07
KY /16	-311.84	-235.83	-84.28	-88.45	-142.23	-	-142.33	-212.93	-97.07
KY /17	-57.44	-129.64	-84.39	-39.34	-47.33	-31.33	-118.35	-68.32	-178.45
KY/18	-28.65	-204.39	-150.64	-50.34	-53.42	-283.43	-67.85	-81.33	-59.23

Table 6: shows the Pearson's correlation coefficients (r) for several HMs in groundwater samples evaluated in the research area.

	pH	TDS	Ec	Cr	Cu	Zn	Co	Fe	Mn	Br	Ni	Cd
pH	1											
TDS	.109	1										
Ec	.073	.493	1									
Cr	.243	.214	.286	1								
Cu	.096	.206	-.278	-.011	1							
Zn	-.234	.254	.403	-.043	-.253	1						
Co	.149	.213	.255	.495	-.294	.063	1					
Fe	.258	-.203	-.275	.297	-.003	-.225	.226	1				
Mn	.367	-.298	-.223	-.213	-.423	-.143	.013	.198	1			
Br	.413	.197	.237	.299	-.145	-.045	-.017	-.006	.000	1		
Ni	.236	-.018	.027	.269	-.227	.032	.174	.304	.439	.170	1	
Cd	-.172	-.163	.136	.247	-.387	.121	.146	.201	-.051	-.224	.536	1

that is tainted can result in health issues. According to the information presented in Table 8, a weak but positive correlation exists among the various elements. The contamination of groundwater by toxic metals undermines the quality of water and its appropriateness for human consumption. Furthermore, these metals contribute to the generation of reactive oxygen species within aquatic ecosystems, potentially leading to detrimental effects on the physiological processes of fish and other marine organisms.

5. Conclusion

The research conducted utilizing the HM index and statistical analysis has successfully identified the factors that affect the impact of heavy metals on groundwater. Analysis of the water samples demonstrated the presence of heavy metal pollution. The correlation matrix indicated a weak relationship among the assessed parameters. It was determined that the PLI values indicated low levels of pollution, whereas the NPI for the study area suggested significant pollution, and the concentrations of mCd were found to reflect a moderate level of

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pollution. The Environmental Risk Index (ERI) indicated a low potential risk, while the Quality of Contaminants (QoC) highlighted that geogenic activities were the primary contributors to pollution. The results of this research demonstrated that both natural geogenic processes and human-induced activities played significant roles in elevating HM concentrations in groundwater. The ongoing exposure to heavy metals poses significant risks to public health, potentially leading to grave consequences in the future. In the designated study area, effective strategies to mitigate heavy metal toxicity will be established through the monitoring of groundwater quality and the implementation of suitable treatment technologies to ensure the water is safe for consumption.

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