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Evaluation of Heavy Metal Levels and Contamination Indices of Groundwater Sources in Kaduna South Local Government Area, Kaduna State, Northern Nigeria

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ABSTRACT: Global concern over heavy metal pollution in groundwater resources has recently increased because of its potential impact on public health. Evidence shows that unsafe water is responsible for approximately 1.2 million deaths yearly, prompting a surge in research on groundwater quality worldwide, particularly in developing nations. Thus, this paper aims to evaluate the heavy metal levels and contamination indices of groundwater sources in the Kaduna South Local Government Area, Kaduna State, Northern Nigeria, using appropriate standard methods. Findings indicate that a significant majority (67%) of the pollution metrics demonstrated high levels of heavy metal contamination, exceeding the established threshold values, suggesting its unsuitability for consumption. Also, correlation analysis revealed a statistically significant positive association ($p < .05$) between the pollution indices, particularly with Pb, suggesting its role as a prevalent contaminant affecting the groundwater quality. Our findings demonstrate the varying extent of groundwater contamination and emphasise the importance of a multi-index approach in presenting a holistic overview of the status of groundwater pollution, with significant implications for improving water quality in the study area and for strategic planning and intervention in water quality monitoring and surveillance.

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The challenge of accessing safe drinking water remains a critical concern worldwide, with developing nations particularly affected by the alarming rise in water pollution. Evidence indicates that groundwater contamination is one of the most significant environmental concerns in the present era (WHO, 2011; Nwankwo, 2013), and heavy metals (HM) are a crucial concern considering their potential health risks (Abata *et al.*, 2019; Noh *et al.*, 2020), even at low concentrations (Marcovecchio *et al.*, 2007). Consequently, evaluating HM pollution in groundwater has emerged as a significant concern, particularly in areas of extensive industrial and artisanal mining operations, such as Northern Nigeria. Studies linking artisanal mining to HM contamination of groundwater sources have been well documented (Vivan *et al.*, 2020; Zou *et al.*, 2021; Wang *et al.*, 2022). As evidenced, lead poisoning due to artisanal mining resulted in the tragic deaths of 163 people in Zamfara State in 2010 (Centre for Disease Control, 2016), highlighting the pressing need to mitigate the continuous pollution of groundwater sources to safeguard public health. Several factors affect the quality of the groundwater. However, HM

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contamination remains a significant hindrance to safe water availability, making it unsuitable even at low levels. Thus, there has been a recent increase in studies examining HM pollution in the global context of water pollution, with a particular focus on developing countries.

However, despite previous investigations on HM contamination of groundwater sources in northern Nigeria, it is evident from the literature that there is a significant shortage of methods for understanding the HM pollution status of groundwater sources. Several recent studies have employed various indices to assess water quality (Simonyan *et al*., 2018; Wang *et al*., 2019; Onyemesili *et al*., 2020). Among these, the indexical method stands out for its distinct approach of incorporating multiple indicators to evaluate contamination levels holistically (Egbueri *et al*., 2020). Despite their potential benefits, indexical methods for evaluating HM contamination remain largely unexplored in the study area. Most studies have focused on the comparative assessment of HM concentration levels (Akinola *et al*., 2015; Okegye and Gajere, 2015; Oyatayo *et al*., 2015) or have used a single indexical approach to evaluate HM contamination levels (Ekwule *et al*., 2019; Vivan *et al*., 2020; Badamasi *et al*., 2021). Thus, there is a deficiency in the comprehensive insights necessary to understand pollution's extent and level thoroughly. Inadequate understanding of HM contamination through indexical methods may lead to underestimating pollution levels, misidentifying sources, and disregarding potential remediation approaches.

Therefore, the present study addresses this gap by exploring the HM contamination status of groundwater sources in the KSLGA through an integrated indexical approach, the probable association among these indices, and their implications for groundwater quality, thus providing a holistic understanding of the pollution levels and their suitability for various household purposes.

MATERIALS AND METHODS

Study Location: The present study was conducted in the KSLGA, located in the north-central part of Kaduna State (Figure 1). The area spans 59 km^2, with geographic coordinates of approximately 10°27'43″N and 7°25'38"E. According to the 2006 census, the population of the KSLGA was 402,731 (National Bureau of Statistics, 2007). However, this figure is estimated at approximately 595,000, indicating an annual population growth rate of 2.5% (City Population, 2023). Kaduna South is known for its large agricultural and mining activities. It is home to many industries, ranging from carpets to textiles, among others.

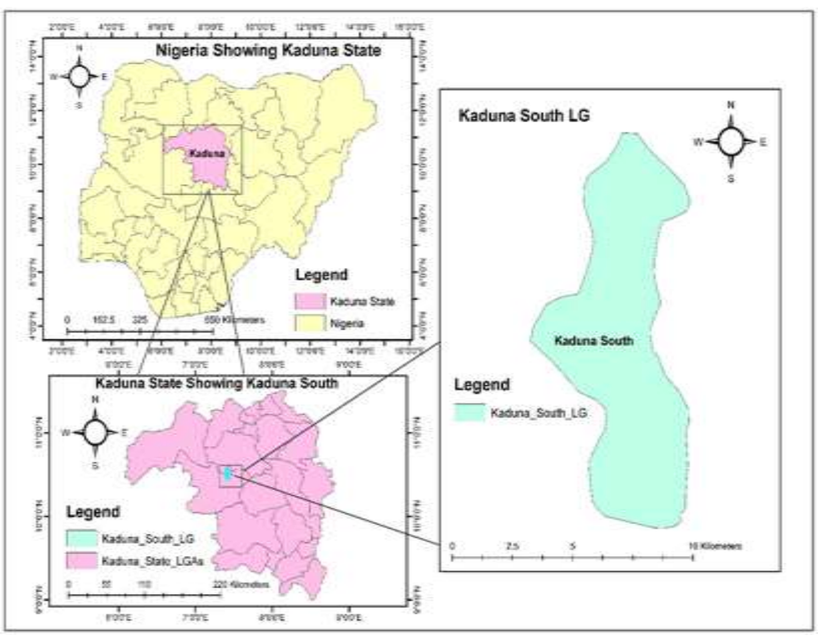

Fig. 1: Study area map of KSLGA

Sample Collection and Preparation: To analyse the concentration of HMs in the groundwater within the designated study region, we, through purposive sampling, selected four hand-dug wells, emphasising the accessibility and representation of water sources to the local population. We carefully cleaned the laboratory glassware and sampling bottles (1000 ml PVC bottles) to prepare for sample collection. This involves washing, rinsing with 10% nitric acid, double distillation, deionisation, and a final rinse with on-site sample water. After collecting, the samples were acidified by adding concentrated nitric acid (HNO3) to obtain a pH below 2.0. Subsequently, a Metrohm E-744 model pH meter was used to measure the samples. This measure helped to prevent metal precipitation and preserve samples until they were ready for analysis. We accurately labelled the samples to avoid mix-up, stored them in sampling kits at a temperature of 4°C, and transported them to the laboratory for analysis.

Sample Analysis: An acidic digestion method was employed to prepare the HMs in the water samples based on the technique outlined in previous studies (Ogbonna, 2022). The samples were prepared by adding 2 ml of concentrated HNO_3 and 1 ml of concentrated HCL to each 100 ml sample. The mixture was then heated until the volume was reduced to approximately 20 ml, as indicated by the characteristic colour, signifying complete digestion (Nyambura *et al*., 2020). To enhance the sensitivity of metal detection using atomic absorption spectrophotometry (AAS), the samples were treated with concentrated nitric acid to remove organic impurities and prevent interference in the analysis. The mixture was then digested on a heated plate, cooled, and filtered using a 0.45-mm Whatman pore membrane (Alidadi *et al*., 2019). Following digestion, the samples were placed in plastic bottles and maintained at 4 °C. Subsequently, an AAS analysis was performed. The presence of cadmium (Cd), copper (Cu), chromium (Cr), zinc (Zn), manganese (Mn), and lead (Pb) in the acidified water samples was determined using AAS (Varian AA-932). As described in a study by Emmanuel *et al*. (2022), the AAS technique uses an air-acetylene flame. The acidified samples were subjected to duplicate analyses to determine the average metal concentrations extrapolated from the calibration curve. This value was then compared to the minimum allowable limits specified in the Nigerian Drinking Water Standard (NIS) (2007) and the international standards by the WHO (2017) and subsequently used for the estimation of the pollution indices, as illustrated in the following section.

Pollution Evaluation Indices: The HM pollution index is the most reliable technique for evaluating the pollution levels of water sources caused by HMs. Thus, to provide a holistic understanding of the pollution level of groundwater sources, we performed an integrated analysis of the pollution indices, including the Dc, HPI, mHPI HEI, PLI, and WQI, providing insight into the overall quality of groundwater in the study area and its suitability for various usages. The evaluation indices employed in this study were determined using Cd, Cr, Cu, Mn, Pb, and Zn, while additional standard parameters were obtained from the NIS (2007) and WHO (2017) (see Table 1).

Table 1: Standards adopted for indices computation (mg/L)

Parameters	Range	Si	Ii	MAC	Wi	Rw
Cd	.00 - .001	.003	.003	.003	333.5	.73
Cr	.010 - .17	.05	.05	.05	20.00	.04
Cu	.190 - 1.36	1.00	2.00	2.00	.50	.001
Mn	2.50 - 3.31	.20	.40	.40	2.50	.005
Pb	.200 - .76	.01	.01	.01	100.00	.22
Zn	6.12 - 99.14	3.00	5.00	5.00	.20	.0004
					∑456.5	**∑ 1.00**

Si: Standard value (NIS, 2007); Ii: Guided/Ideal value (WHO, 2017); MAC: Maximum admissible concentration/Upper permissible (WHO, 2017); Wi: weightage (1/MAC); Rw: Relative weight

Degree of Contamination: As a pollution metric, Dc reflects the cumulative impact of various quality parameters considered harmful to domestic water. To establish this, the water quality assessment involved the separate computation of the Dc for each analysed water sample and summing the contamination factors of individual components that exceeded the upper permissible value using the function described in Eq. 1 (Edet and Offiong, 2002; Onyemesili *et al*., 2020).

$$Cd \sum_{i=1}^{n} Cfi \qquad (1)$$

C_{fi} represents the contaminant factor for the ith parameter and is calculated from Eq. 2 (Edet and Offiong, 2002; Onyemesili *et al*., 2020).

$$C_{fi} = \frac{CAi}{CNi} - 1 \qquad (2)$$

Where CAi is the analytical value, CNi is the upper permissible concentration of the ith component (N denotes the normative value), and CNi is the maximum admissible concentration (MAC) (see Table 1). Notably, the resultant Dc value plays a significant role in identifying zones with diverse contamination levels, which are classified as low (Dc < 1), medium (Dc = 1–3), or high (Dc > 3) (Edet and Offiong, 2002).

Heavy Metal Pollution Index: To assess the suitability of using groundwater for household consumption, we estimated the HPI, which reveals the collective impact of individual HMs on groundwater quality (Sirajudeen *et al*., 2014). The HPI estimation entails assigning a rating or weightage (Wi) to each selected parameter. The rating is a numerical value ranging from zero to one, signifying the relative significance of specific quality considerations. This is inversely proportional to the recommended standard for each HM (Mishra *et al*., 2017). However, the concentration limits for each parameter in this study were derived from the NIS (2007) and WHO (2017) standards, specifically the standard permissible value (Si) and the highest desirable value (Ii) (see Table 1). In estimating the HPI for the present study, the weightage (Wi) was taken as the inverse of the MAC (Edet and Offiong, 2002; Rezaei *et al*., 2019), Si is the NIS standard for drinking water, and Ii is the guide value for the selected parameter (WHO, 2017). HPI was estimated using the following expression (Rezaei *et al*., 2019; Kumar *et a*l., 2020):

$$HPI = \frac{\sum_{i=1}^{n} WiQi}{\sum_{i=1}^{n} Wi} \qquad (3)$$

Where Qi is the sub-index of the ith parameter, Wi is the unit weightage of the ith parameter, and n is the number of parameters considered. The sub-index (Qi) of the parameter was computed using Eq. 4 (Prasanna *et al*., 2012):

$$Q = \sum_{i=1}^{n} \frac{(Mi(-)Ii)}{(Si-Ii)} \times 100 \qquad (4)$$

Where Mi is the monitored value of HM for the ith parameter, Ii is the ideal value of the ith parameter, and Si is the standard value of the ith parameter. The sign (−) indicates the numerical difference between two values, ignoring the algebraic sign. The critical pollution index of the HPI value for drinking water is given as >100 (high), 50–100 (medium), and < 50 (low) (Rizwan *et al*., 2011; Chung *et al*., 2019; Egbueri and Mgbenu, 2020).

Modified Heavy Metal Pollution Index: The mHPI, a recently implemented indexical approach based on Egbueri *et al*. (2020), was employed to assess the influence of HMs on groundwater quality. However, in their study, Egbueri *et al*. (2020) used a weighting system on a scale of 1 to 5 to assess the significance of HMs in water quality analysis and their potential effect on human health. This method introduces the potential for outcomes to be influenced by over- or under-emphasising specific parameters. To avoid this, we assigned the unit weight (Wi) for different water quality parameters based on an inverse relationship with the maximum admissible concentration (MAC) for each parameter (Rezaei *et al*., 2019). This method ensures a more objective estimate of the weightage of the parameters and, thus, a reliable outcome. Hence, the functions in Eq. 5 (Egbueri *et al*., 2020) were applied to obtain the relative weights (Rw) of the HMs (see Table 1), and the final mHPI values for each sample were then estimated using Eq. 6 (Egbueri *et al*., 2020):

$$Rw = \frac{wi}{\sum_{i=1}^{n} wi} \qquad (5)$$

$$\text{MHPI} = \sum_{i=1}^{n} Rw \times \frac{Mi}{Si} \qquad (6)$$

Where R_w is the relative weight, w_i is the weight derived from (1/MAC), M_i is the metal concentration in the sample, n is the total number of parameters, and S_i is the NIS (2007) standard limit for each HM. According to Egbueri *et al*. (2020), the estimated values of the mHPI are classified as excellent (< 50), good (50 – 100), poor (100 – 200), very poor (200 – 300), and unsuitable for drinking (> 300).

Heavy Metal Evaluation Index: The HEI provides an overall water quality regarding heavy metals (Edet and Offiong, 2002), which, compared to the HPI, provides a better picture of HM pollution status (Kwaya *et al*., 2019). The computation used the function in Eq. (7) (Edet and Offiong 2002):

$$\sum_{i=1}^{n} Hc/Hmac \qquad (7)$$

Where H_c and H_{mac} represent the monitored value and the maximum admissible concentration (MAC) of the ith parameter, respectively. The computed values, according to Edet *et al*. (2002) and Maskooni *et al*. (2020), were categorised as low (HEI < 10), medium (HEI = 10–20), and high (HEI > 20).

Pollution Load Index: To further understand the effects of the examined HMs on the quality of groundwater in the study area, we evaluated the PLI, which considers the extent to which HM concentrations in groundwater deviate from the background concentration (Egbueri *et al*., 2020), thereby providing a holistic measure of the overall level of HM pollution. Equations 8 and 9 (Egbueri *et al*., 2020) were used to calculate the PLI of the groundwater samples.

$$PLI = \sum_{k=1}^{n} (PI \times PI \times \ldots PI)^{1/n} \qquad (8)$$

Where,

$$\text{PI} = \frac{Cs}{Cb} \qquad (9)$$

Where PI is the pollution index, n is the number of HMs, C_s is the HM concentration in the sample, and C_b is the corresponding NIS (2007) standard value. The pollution index classification varies from unpolluted (< 1), unpolluted to moderately polluted (1–2), moderately polluted (2–3), moderately polluted to highly polluted (3–4), highly polluted (4–5), and very highly polluted (>5) (Bhutiani *et al*., 2017; Adimalla *et al*., 2019).

Water Quality Index: Additionally, the WQI was used to summarise the quality of groundwater samples for domestic use (Mgbenu and Egbueri 2019). The WQI for this study was calculated using the method described by Egbueri *et al*. (2020), as shown below.

The initial estimation of the relative weights, as shown in Table 1, was determined using Eq. 5 (Egbueri *et al*., 2020). Subsequently, Eq. 10 (Egbueri *et al*., 2020) was used to determine the rating scale for quality for each sample component:

$$qi = \frac{Ci}{Si} \times 100 \qquad (10)$$

Where Ci is the sample concentration, and Si is the parameter's NIS (2007) standard value.
Next, the parameter (SI) was calculated using Eq. 11 (Egbueri *et al*., 2020):

$$SI = \mathrm{wi} \times qi \qquad (11)$$

Finally, the WQI value for each sample was derived using Eq. 12 (Egbueri *et al*., 2020):

$$WQI = \sum_{i=1}^{n} (\mathrm{SI}) \qquad (12)$$

The WQI values were compared with the index classifications provided by Mgbenu and Egbueri (2019) and Egbueri *et al*. (2020) to interpret the water quality of the analysed HMs as 50–100 (good), 100–200 (poor), 200–300 (very poor), and >300 (unsuitable for drinking).

Statistical Analysis: A statistical evaluation of the data obtained from the analysis was performed using SPSS software (version 23.0). Descriptive statistics, such as mean, standard deviation, minimum, and maximum, were calculated. A Pearson's correlation matrix was used to determine the association between different variables, and the results were interpreted using a standard correlation spectrum. A strong correlation analysis with a correlation coefficient (r) close to +1 or -1 indicates a positive or negative correlation between the two variables. Conversely, a correlation coefficient close to zero suggests no significant relationship, with a p-value of < .05. Thus, a correlation coefficient (r) greater than 0.7 is considered a strong correlation, while a correlation coefficient between 0.5 and 0.7 indicates a moderate correlation (Chung *et al*., 2019; Mgbenu and Egbueri, 2019).

RESULTS AND DISCUSSION

Pollution Evaluation Indices: The current study employs a multi-indexical approach to investigate heavy metal (HM) contamination in groundwater in northern Nigeria. Findings indicate varying degrees of groundwater pollution levels. To understand the cumulative impacts of HMs in groundwater samples, we calculated the degree of contamination (Dc) for each sample using the function in Eq. 1. The findings, as presented in Table 2, demonstrated that every groundwater source analysed (100%) surpassed the previously stated critical value of 1, indicating a significant degree of pollution across the investigated sites and posing potential health risks. For instance, a recent study on the human health risk of groundwater sources in KSLGA found both non-carcinogenic and carcinogenic risks for adult and child populations (Opasola and Otto, 2023). As a result, urgent actions to find alternate water sources are needed to ensure that residents have access to safe drinking water. The findings are consistent with previous studies demonstrating high Dc levels in groundwater sources (Prasanna *et al*., 2012; Chung *et al*., 2019; Kumar *et al*., 2022).

However, the HPI results showed contrasting findings; all groundwater samples (100%), as shown in Table 2, had HPI values below 50, signifying low pollution levels and acceptable for domestic use. Regardless of the low level of HPI, it is crucial to note that even low concentrations of certain HMs might have adverse health effects over time, especially with chronic exposure. Therefore, proactive steps to mitigate groundwater pollution are required to ensure the community's access to a sustainable and safe water supply. Similar investigations have shown low levels of HPI in groundwater sources (Prasanna *et al*., 2012; Tiwari *et al*., 2016; Chung *et al*., 2019; Rezaei *et al*., 2019), supporting the current findings. In contrast, our findings are inconsistent with those reported in a study investigating the influence of coal mining on water quality in Nigeria (Ekwule *et al*., 2019). This disparity may be due to coal mining's direct impact on sampling sites, emphasising the importance of tackling artisanal mining to safeguard groundwater sources while decreasing the health risks associated with HM pollution.

Table 2: Pollution evaluation indices of the groundwater samples

Stations	Dc	HPI	mHPI	HEI	PLI	WQI
Sample 1	24.86	6.50	4.7	31.10	1.85	474.43
Sample 2	43.10	10.15	44.3	49.10	2.04	475.91
Sample 3	82.98	6.81	16.8	88.0	2.50	1768.10
Sample 4	26.70	5.90	5.04	32.71	1.90	508.40
Mean	44.39	7.34	7.85	50.23	2.07	806.71
Minimum	24.86	6.50	4.73	31.10	1.85	474.43
Maximum	82.89	10.15	16.84	88.00	2.50	1768.10

The mHPI was also carried out to further understand the groundwater's HPI status. The findings demonstrated that all studied groundwater sources (100%) had mHPI values below 50 (Table 2). Results indicate excellent water quality, confirming the suitability of these sources for drinking and agreeing with previously reported HPI findings. This finding is consistent with an earlier study by Egbueri *et al*. (2020), who observed excellent groundwater quality in the Ikem community of Nigeria. The HEI findings reflected a more concerning picture, as seen in Table 2. Despite the apparent excellence indicated by the mHPI, the HEI values revealed uniformly high pollution levels across all groundwater samples, exceeding the stated threshold of 20. This disparity suggests that, while the mHPI may provide a simplified view of pollution, the HEI offers a broader understanding of the toxicological impact of specific HMs. The result is comparable to the findings reported by Chung *et al*. (2019). However, in contrast, a study of HEI in Riruwai, northern Nigeria, found significant levels of HEI (Badamasi *et al*., 2021), which were linked to mining operations in the Riruwai community, emphasising the importance of addressing artisanal mining and the associated pollution risk to groundwater quality.

Additionally, evaluating the PLI offered additional insights into the pollution status of the analysed HMs on groundwater quality. The findings in Table 2 revealed varied contamination levels among samples. At the same time, some samples indicated moderate pollution levels, particularly samples 2 and 3, and others (samples 1 and 4) varied from unpolluted to moderately polluted. This variability emphasises the heterogeneity of groundwater pollution and the significance of site-specific assessments. Overall, the groundwater samples showed low to moderate pollution levels, indicating that they should be used cautiously. Similar results were reported by Egbueri *et al*. (2020), who found varying levels of PLI in groundwater sources in the Nigerian community of Ikem.

Furthermore, we used the WQI to assess overall water quality and suitability for household use. Regrettably, the WQI assessment found similarly poor quality across all samples, with all samples (100%) exceeding the threshold value of 300 (Table 2), indicating unsuitability for household use. Compared to previous indications of the suitability for drinking, this finding emphasises the multidimensional nature of water quality and the significance of considering multiple factors and intended uses when determining suitability. The findings are consistent with those Vivan et al. (2020) reported, who discovered low groundwater quality because of artisanal mining in Jema'a Local Government Area, Kaduna State, Nigeria. However, our findings contradict those published by Egbueri *et al*. (2020). This inconsistency may be attributed to subjective weightage allocation, which may have influenced the results due to over- or underestimating specific parameters.

Overall, the evaluation indices in the current study suggest that less than half of the groundwater samples in the study area are safe to use, with two (HPI and mHPI) of the six indices indicating low pollution and suitability for consumption by locals. Conversely, more than half (67%) of the index (Dc, HEI, WQI, and PLI) exceeded the critical values, suggesting that the groundwater sources are unsuitable for diverse purposes due to differing levels of pollution and further highlighting the potential risk to health following continuous use by the locals, and the urgent need to address the groundwater conditions, to safeguard public health. Of note, these divergent findings highlight the complexities of assessing HM pollution in groundwater and the importance of considering multiple indices for a thorough understanding. Hence, our findings emphasise the relevance of using integrated approaches to water quality evaluation to support successful water management plans and protect public health.

HMs Correlation: Additionally, we performed a Pearson's correlation analysis, as shown in Table 3, to understand the relationship between the various parameters and the assessment indices and the implications for groundwater contamination sources. The test analysis demonstrated a few significant associations ($p < .05$) between the HMs studied, except for Pb and Cd, which is consistent with the previous result by Onyemesili *et al*. (2020). However, a bidirectional link was identified with a weak to strong association between the HMs. Notably, Pb revealed a positive and moderate connection with Cu (r(2) =.68, p >.05), implying the possibility of shared contamination or comparable geochemical behaviour that could affect their subsurface presence. Similarly, Zn showed a strong and positive relationship with Mn (r(2) =.94, p >.05), indicating a possible link between these metals, presumably caused by similar pollution sources or environmental conditions. Similarly, Cr showed a non-significant positive and moderate association with Cu (r(2) =.51, p >.05) (see Table 3). This implies a single contamination pathway contributing to groundwater samples' Cr and Cu levels. Conversely, a statistically significant negative and strong correlation was identified between Pb and Cd (r(2) = -1.00, p <.05), indicating potentially specific contamination sources or environmental behaviour influencing their presence in the groundwater. This outcome aligns with the findings of Xie et al. [43]. Furthermore, Cr had non-significant negative correlations with Zn (r(2) = -.70, p >.05, and Mn (r(2) = -.67, p >.05), demonstrating differences in pollution sources affecting these metals. Thus, this highlights the diverse nature of HM pollution in groundwater, with individual metals impacted by various environmental conditions or anthropogenic activities.

Table 3: Correlation matrix of the analysed HM parameters

Parameters	Pb	Cr	Cd	Zn	Cu	Mn
Pb	1.00					
Cr	.22	1.00				
Cd	-1.00*	-.21	1.00			
Zn	-.35	-.70	.34	1.00		
Cu	.68	.51	-.67	-.03	1.00	
Mn	.00	-.67	-.01	.94	.22	1.00

**Correlation is significant at the 0.05 level (2-tailed)*

Notably, the lack of statistically significant relationships among the analysed HMs shows that their presence in groundwater samples may not be directly related to or influenced by shared causes. Also, the observed bidirectional correlations of diverse strengths suggest underlying interactions that require further investigation. Overall, our findings highlight the complexities of HM pollution in groundwater, with some metals showing co-occurrence patterns while others have opposing relationships, indicating various pollution sources. However, given the country's increasing prevalence of illegal mining, it seems likely that this is associated with artisanal mining. Studies have linked high levels of HMs in groundwater to artisanal mining (Orosun *et al*., 2016; Vivan *et al*., 2020). These findings are critical for identifying and addressing the underlying sources of contamination and informing targeted remediation efforts to protect groundwater quality.

Correlation of Evaluation Indices: Furthermore, closely observing the relationship between the pollution indices highlights some trends, as shown in Table 4. Findings demonstrated statistically significant relationships between many contamination indices, offering insight into probable common contamination mechanisms influencing groundwater quality. Notably, Dc was found to have a statistically significant positive and strong association with both the PLI (r(2) = 1.00, p <.05) and the HEI (r(2) = 1.00, p <.05), indicating a strong correlation between the degree of contamination and the pollution burden in groundwater sources (refer to Figure 2), implying that regions with higher contamination degrees have higher levels of pollution across numerous HM metrics, indicating possible sources of concern for groundwater quality management. Further observation reveals a statistically significant positive association between the Dc and both the WQI (r(2) =.95, p =.05) and mHPI (r(2) =.95, p =.05), respectively (see Figure 2), corroborating the idea of a shared contamination component influencing groundwater quality. These findings highlight Dc's usefulness as a reliable indication of contamination severity, with implications for broader water quality assessments and management techniques in the study area.

Similarly, the PLI shows a significant positive and strong association with both the HEI (r(2) = 1.00, p <.05) and WQI (r(2) =.96, p <.05, and the mHPI (r(2) =.96, p <.05), respectively (see Figure 3), further supporting the concept of shared contamination factors affecting the groundwater quality of the study area. These findings emphasise the need to consider several contamination indices when assessing overall groundwater quality and identifying potential sources of pollution.

Furthermore, the mHPI showed a non-statistically significant positive link with the HEI (r(2) =.95, p >.05) but a significant positive relationship with the WQI (r(2) = 1.00, p <.05) (Table 5). These findings point to a possible relationship between the mHPI and groundwater quality, although with varied degrees of association with other pollution indices.

Table 4: Correlation matrix of HM with evaluation indices

	Pb	Cr	Cd	Zn	Cu	Mn	Dc	mHPI	HPI	WQI	PLI	HEI
Dc	.95*	.04	-.95*	-.04	.75	.31	1.00					
mHPI	1.00*	.23	-1.00*	-.35	.68	-.01	.95	1.00				
HPI	-.19	-.71	.18	.99*	.07	.98*	.12	-.20	1.00			
WQI	1.00*	.23	-1.00*	-.35	.68	.00	.95	1.00*	-.20	1.00		
PLI	.96*	.10	-.96*	-.09	.77	.26	1.00*	.96*	.07	.96*	1.00	
HEI	.95	.04	-.95*	-.04	.74	.31	1.00*	.95	.12	.95	1.00*	1.00

**. Correlation is significant at the 0.05 level (2-tailed).*

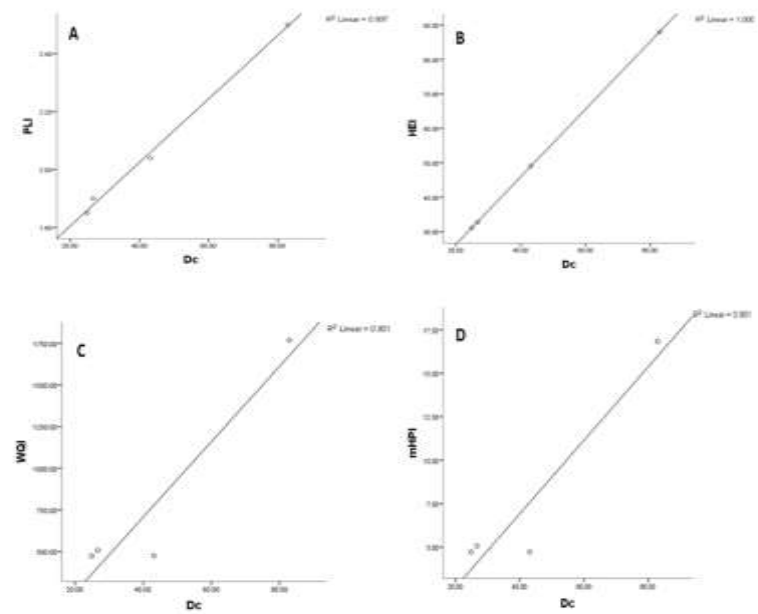

Fig. 2: Scatterplot of Dc relationship with PLI, HEI, WQI, and mHPI

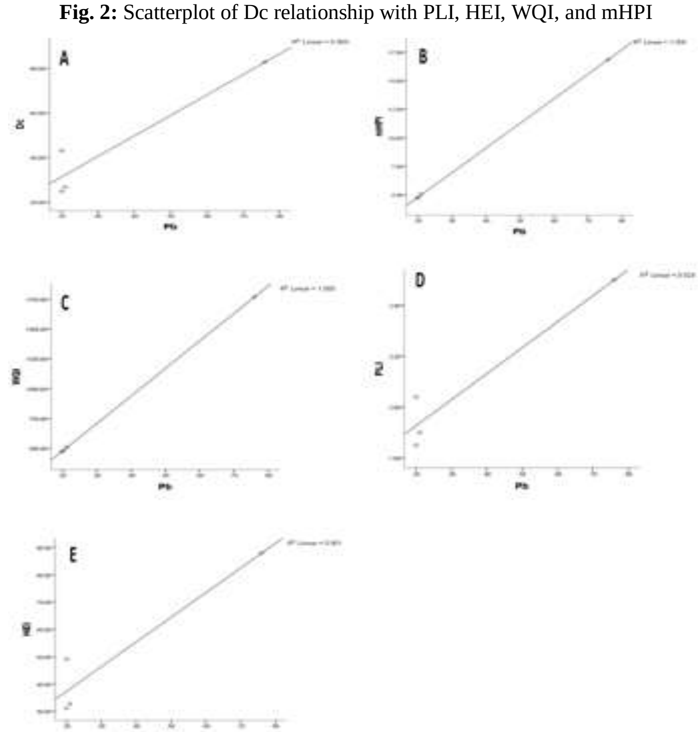

Fig. 3: Scatterplot of PLI relationship with HPI, HEI, and WQI

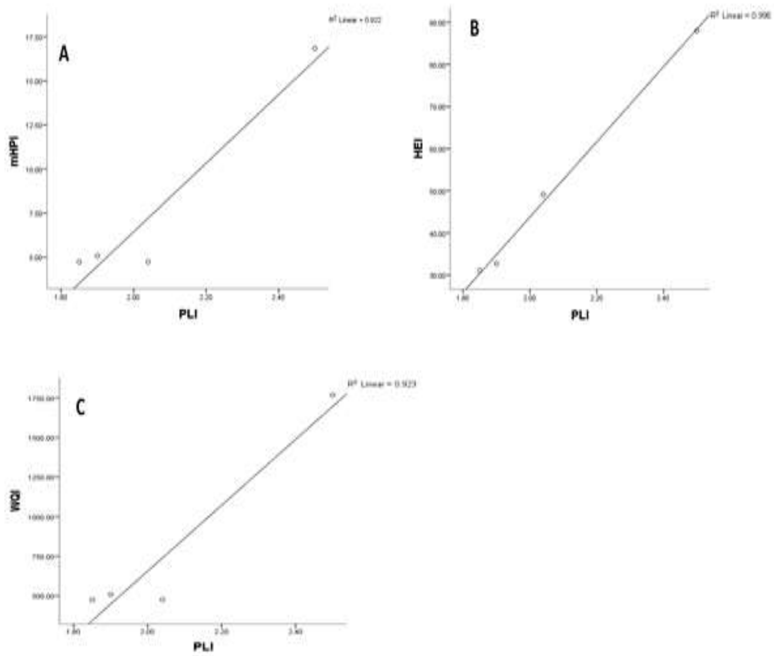

Fig. 4: Scatterplots of association between Pb and pollution indices

The correlation study also revealed a significant positive and strong relationship between Pb and the pollutant indices. A previous Prasanna et al. (2012) study found substantial correlations between Pb and similar indices, supporting its significance as a common pollution factor influencing groundwater quality (see Figure 4). Elevated levels of Pb and other HMs represent significant health risks to consumers, including long-term impacts such as neurological disorders, organ damage, and an increased risk of cancer (Noh *et al*., 2020). Thus, focused mitigation measures to address specific HM contamination and protect groundwater resources are critical for environmental and human health considerations.

Study's Implications and Limitations: Our findings hold significant implications. Firstly, it proves helpful for environmental monitoring efforts by providing practical insights to authorities and stakeholders involved in pollution and water quality monitoring. This more holistic assessment approach allows for more detailed monitoring of pollution levels and promotes timely interventions. In addition, the results of our investigation can assist in informing evidence-based decision-making procedures concerning environmental policy formation, land use planning, and pollution management strategies. This ensures that judgments are supported by empirical data, resulting in environmental management techniques that are more sustainable and effective.

While our study offers valuable insights, it is critical to recognise the limits imposed by the small number of groundwater samples. This limitation restricts our findings' broader applicability. Similarly, while the current study's findings show associations between parameters indicating source commonality, our inability to consider factor analysis on potential sources and underlying factors contributing to HM contamination in the studied groundwater samples is a notable limitation. As such, future studies should consider integrating factor analysis to improve contamination source identification in similar investigations. Notwithstanding, our study makes significant contributions by emphasising the importance of a holistic approach to groundwater quality assessment in northern Nigeria as the first of such investigation. As a result, our findings are helpful for policymakers and water resource managers, directing informed decisions and targeted remediation activities, which is critical in ensuring safe water sources for the nation's groundwater-dependent communities.

Conclusion: The study investigates groundwater pollution levels in KSLGA using multi-indexical approaches. The findings reveal varying pollution levels across groundwater sources, with 67% of the pollution metrics exceeding critical values, thus indicating the water's unsuitability for various domestic uses. Also, the correlation analysis shows varying relationships among parameters, with few significant correlations among the studied HMs, indicating diverse pollution sources. However, most pollution indices show strong positive relationships, particularly with Pb, highlighting its role as a common contamination factor influencing groundwater quality. Our study offers empirical insights into the HM contamination status of groundwater sources in KSLGA. These insights may apply to the country's wider northern region with similar geographical settings, contributing to the national and global drive for safe drinking water sources in sync with Sustainable Development Goal 6.

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