Assessment of heavy metals contamination and associated risks in shallow groundwater sources from three different residential areas within Ibadan metropolis, southwest Nigeria

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Abstract
This study has been conducted to appraise the concentrations of selected heavy metals and total dissolved solids (TDSs) in the drinking water from shallow wells in parts of Ibadan metropolis, southwest Nigeria. Fifteen (15) water samples were collected from three representative residential locations [traditional core area (TCA), peri-urban area (PUA), and urban area (UA)] for geochemical analysis. Heavy metals and TDS were analyzed with the aid of atomic absorption spectrophotometer and calibrated meter, respectively. The mean concentration (mg/L) of Zn, Pb Mn, Fe, and Cd has been 3.930, 0.658, 0.0304, 1.698, and 0.501, respectively, and as a consequence, the order of abundance of studied metals was Zn > Fe > Pb > Cd > Mn. Concentrations of Zn, Fe, Pb, and Cd were higher than recommended standards in 60%, 86.7%, 100%, and 100% of groundwater samples, respectively. However, at all points tested, the mean concentrations of Mn and TDS in water samples lie within the safe limits set by World Health Organization. The evaluation of geoaccumulation index ($I_{geo}$), enrichment factor (EF), and contamination factor suggests that representative water samples were low-to-moderate contamination. The potential ecological risk index advocates low-to-moderate ecological risk in TCA and PUA, while it demonstrated exclusive “moderate” risk in UA. Further, the range of pollution load index (PLI) (0.55–1.32) in both TCA and PUA shows nil-to-moderate pollution status, while PLI values > 1 in UA indicate moderate contaminated state. The degree of contamination in groundwater showed the following trends: UA > TCA > PUA in the study area. Moreover, the results of EF and quantification of contamination of analyzed metals in water samples indicate geogenic and anthropogenic inputs. The contribution of studied metals to the incidence of non-cancer risk via oral intake within the residential sites follows the order: cadmium > lead > zinc > iron > manganese. The hazard index as a result of ingested heavy metals for the three population classes surpasses the acceptable range in the order of infant < child < adult. Cadmium and lead made considerable impact to the estimation of cancer risk in the study area for the three human population categories. Factor analysis extracted only one component that explained 94.64% of the entire variance, while cluster analysis identified three distinct groups based on similar water quality characteristics. Based on the findings of the study, awareness programs toward protecting the shallow groundwater sources should be launched, encouraged, and sustained. Moreover, the study suggests better hygienic practices and pre-treatment of contaminated water before consumption.

Keywords Heavy metals · Groundwater · Ibadan metropolis · Health and ecological risks · Residential areas

Introduction

Water is an indispensable natural resource used on a daily basis for various purposes. Humans use water from various sources for a variety of daily activities, including household, agricultural, and manufacturing uses. However, each of the aforesaid uses has its own unique water quality categorization that determines its fittingness. Groundwater serves as a major source of water resources and readily available in many countries (Prasad and Kumar 2008; Amadi et al. 2013;
Selvakumar et al. 2017). Subsurface water is the main supply of drinking water in most third world countries (Lutterodt et al. 2018). According to Kim and Park (2016), groundwater is used for drinking purpose by more than 20% of the world population. The alternative to groundwater, i.e., surface water, that can supplement insufficient quantity of water from hand-dug wells and boreholes, is not voluntarily present everywhere and, more importantly, is more easily contaminated than groundwater sources (Sorensen et al. 2015; Mbaka et al. 2017; Mazhar et al. 2019). However, unhygienic practices such as washing of clothes, dumping of animal wastes, and open defecation around groundwater sources also pose as threats to groundwater sources and contribute significantly to the decline in potable water (Mbaka et al. 2017). The need to guard diligently the available groundwater resources is therefore of utmost priority to environmental scientists and policy makers as quality of water is as important as its available quantity (Singh and Singh 2018). Contaminants in various forms can come in contact with the water body through natural and various anthropogenic sources, reduce the amount of potable water to the populace, and likely rise in health risks linked with the use of polluted water.

Metals are an inextricable part of the earth’s crust, but their levels in water and porous media such as soil and sediment are a major source of worry for conservationists due to their dangerous, non-biodegradable, and long-lasting properties (Chen et al. 2017; Giri and Singh 2019; Shah et al. 2019; Kumar et al. 2020a). Heavy metals (HMs) are group of metals and metalloids characterized by specific gravities greater than 5 and atomic densities larger than 4 g/cm³ (Barzegar et al. 2015; Ganiyu et al. 2017; Enuneku et al. 2018; Kumar et al. 2020c). HMs can be found in water from geological or manmade activities (Nawab et al. 2017; Paul et al. 2019).

Toxicity of HMs can be introduced into the body through inhalation, dermal contact, and ingestion (Olujimi et al. 2014; Ayedun et al. 2015; Ogundele et al. 2019; Kumar et al. 2020b). It should be noted that only a small number of HMs (in very small quantities) are considered important for different biochemical reactions in the human body (Singh et al. 2011; Selvam et al. 2017; Shankar 2019; Kumar et al. 2020a, b, c). Because of their long biological half lives, the majority of heavy metals such as Cd, As, Pb, Mn, Fe, Cr, and Hg pose a significant threat to the normal performance of human body tissues, resulting in various diseases (Suvarapu and Baek 2017; Barzegar et al. 2019; Kumar et al. 2020a,b,c). For instance, lead (Pb) is reported to be the second most toxic metal after arsenic (As) and comprises 0.002% of earth’s crust (Arias et al. 2010; Kumar et al. 2020a). The contamination of groundwater with arsenic in certain geographical locations can occur either through geogenic or through anthropogenic inputs (Pal et al. 2020; Kumar et al. 2021). Large number of peoples residing in different countries is reported to be exposed to increased intake of arsenic-rich groundwater (Ravindra and Mor 2019; Kumar et al. 2021). The existence of dissolved metals beyond permissible values in drinking water may lead to damaging risks to residents where enormous farming and metal-induced human activities are taken place (Wu et al. 2019; Kumar et al. 2021). It has been reported that persons respond comparatively fast to air and water contamination; therefore, it is necessity to evaluate concentrations and probable origin of trace metals in the existing groundwater resources (Mirzabeygi et al. 2017; Shankar 2019; Ukah et al. 2019).

The use of several metal and environmental risk indices will offer comprehensive health risks coupled with HM ingestion via drinking water by the populace, allowing for a better understanding of the effects of HMs in water resources. Children, for instance, was reported to be the most responsive age group as a result of their physiological and behavioral patterns (Cao et al. 2015; Tripti et al. 2019). As a result, evaluating and considering the similarities/contrast in the health risks of different age groups are critical duties in monitoring the health condition of residents in a given specific area. Researchers have studied at the physicochemical and HMs content of shallow groundwater sources (Ganiyu et al. 2017; Ling and Zhang 2017; Akoto et al. 2019; Przydatek and Kanownik 2019) and the levels of dissolved HMs in surface/groundwater bodies (Ganiyu et al. 2017; Akoto et al. 2019; Gaokar and Matta 2019; Egberu 2020). Exposure of human beings to metal sources in the surroundings and the health risks associated with it is also adequately reported (Bhutiani et al. 2017; Gu and Gao 2018; Ogundele et al. 2019; Kumar et al. 2020a, b).

Hand-dug wells in comparison with deep boreholes are relatively cheap to construct, require fewer numbers of workforces, make use of low-scale technology, and can be sited in most geological and urban settings (Ebgoka et al. 1988; Ayantobo et al. 2013; Mbaka et al. 2017). Hand-dug well is a circular hole with diameter approximately (1–1.8 m) large enough to allow for easy drawing out of water with the aid of drawer and rope, in few cases with manually operated mechanical pulley form (Orebiyi et al. 2010; Ebgoka et al. 1988; Mbaka et al. 2017). Kim and Park (2016) classified well with depth < 30 m as shallow well; 30 m < depth < 80 m as intermediate well and deep well with depth of more than 80 m. Shallow hand-dug wells are the most common source of water in most urban, suburban, and peri-urban areas in Nigeria (Orebiyi et al. 2010; Amadi et al. 2013).

Ibadan, the capital city of Oyo state, southwest Nigeria has history of prevalent scarcity of pipe-borne water. It is continually growing both in human population and level of urbanization, which result in the sprawling of buildings in the outskirts. Ibadan is a major city in southwest part of Nigeria that was for a long time allowed to grow without a
master plan (Areola and Ikporukpo 2018). The present study was carried out within Ibadan, which has a combinatorial setting of traditional core (urban slum), suburban, and peri-urban components (Adeluye and Olayiwola 2016). Built-up areas (traditional core areas) in Ibadan are characterized by overcrowded urban slums, derelict houses, and low-quality houses with little or no compliance to urban development and planning regulations. On the other hand, urban areas are characterized with well-defined/better planned residential buildings than in the traditional core areas (Adelekan 2016). Peri-urban areas (PUA) are settlements found on the border of cities and towns and are on switch to be included into urban areas (Orebiyi et al. 2010; Adelekan et al. 2014). The PUAs of Ibadan metropolis are relatively low-density areas with better arranged houses, mainly single apartments and flats. For this study, shallow hand-dug wells with depths < 30 m in selected built-up area (BUA/TCA), i.e., high-density residential area, urban area (UA), i.e., medium-density area and PUA (low-density area) were investigated for levels of metallic elements in groundwater. The aim of this study was to evaluate the quality of water by assessing selected trace metals in groundwater from three different residential areas within Ibadan using an urban pattern classification system. The study’s goals are: assessment of water quality through the concentration and extent of metals contamination in shallow groundwater sources based on Ibadan’s urban planning, determination of suitability for drinking, identification of potential contaminants, assessment of health and environmental risks associated with drinking of heavy metal-polluted water, and investigation of the interrelationship between studied water parameters in different residential areas within Ibadan metropolis.

Materials and methods

Site description

Ibadan lies within latitudes 7°20′–7°40′ and longitudes 3°35′–4°10′. It represents the high point of pre-colonial urban development in southwest Nigeria and was once described as the largest city in Africa (Lloyd and Mabogunje 1968). Ibadan still remains as the largest indigenous urban city in sub-Saharan Africa (Adelekan et al. 2014). It is the second most populated city after Lagos in Nigeria with an estimated population of 2,550,993 according to the national population commission (NPC) of 2006 (NPC 2010; Adelekan 2016). Ibadan city covers a total land area of 3123 km² out of which about 15% (468.45 km²) is classified as peri-urban (Adelekan et al. 2014; Wahab and Popoola 2018). Urban growth in Ibadan has been linked with a process of peri-urbanization, which then resulted in areas earlier characterized as rural areas being integrated into peri-urban and locations (Ayantobo et al. 2013; Adelekan et al. 2014). With a mean annual rainfall of about 1230 mm and a mean maximum temperature of 32 °C, Ibadan has a humid and sub-humid typical climate of southwest Nigeria.

Geological setting

The study area falls within the basement complex formation and consists mainly of Precambrian metamorphic rocks with little intrusions of Jurassic granites and porphyries (Okunlola et al. 2009; Bolarinwa 2017). The meta-sedimentary eries quartzites, banded gneiss, augen gneisses, and migmatites that make up the gneiss–migmatite complex are the most common rock types. Pegmatite, quartz, aplites, amphibolites, and xenoliths are some of the minor rock types (Okunlola et al. 2009). Groundwater presence, movement, and storage are present in usable quantity in the weathered and fractured portions of basement complex formation (Clark 1985; Olorunfemi and Fasuyi 1993; Akanbi 2018). Figure 1 is the geological map showing the rock types that underlie the study areas and water sampling locations.

Description of well type in the study area

Among the noticeable features for majority of sampled hand-dug wells in selected high density area (TCA) are wells not lined with either slotted or non-perforated concrete rings in the sidewalls, use of corroded aluminum/iron roofing sheet and wood materials as well cover and well ages exceeding 100 years. However, in the investigated PUA (low-density residential area), the sampled hand-dug wells were characterized with concrete ring linings, circular painted steel as well cover, well head protected by plastered cement/steel slab, presence of extra concrete ring from the ground surface acting as fence/barrier to surface contaminants and year of construction not exceeding fifteen (15) years. The sampled hand-dug wells in medium density area (urban area (UA)) comprise both lined and unlined ones and had year of construction (well age) within 20–50 years. The selected medium density area is within the vicinity of Ona River. The well data such as depth and water level during the time of collection of samples were noted and recorded while information about year of construction of wells and depth were provided by the well owners (Table 1). The longitude, latitude, and elevation of each sampling point were taken with the aid of handheld etrex 10 Garmin GPS equipment. The location map of water sampling point is shown in Fig. 2.

Water sampling and analyses

Fifteen (15) water samples were collected from 15 shallow groundwater sources (depths < 30 m) within three areas (TCA, UA, and PUA) in Ibadan metropolis. The
concentration of each analyzed quality indicator in each water sample is presented in the study. Water samples from five hand-dug wells with depths ranging from 0.7 to 6.2 m were collected from TCA and labeled S1–S5; S6–S10 were collected from another five wells with depths varying from 16.8 to 25.6 m in PUA, while S11–S15 were collected from five wells in UA with depths varying from 5.8 to 10.0 m.

Water samples were collected in 2-L polyvinyl chloride bottles for heavy metal analyses. After collecting the water samples, each sampling bottle’s cap was tightly screwed on to prevent leakage (Odukoya and Abimbola 2010; Ganiyu et al. 2018). Unwanted minerals were removed from the collected groundwater samples using a 0.45-m membrane filter. Before beginning chemical analysis, the water samples were kept in an ice-crested cooler to prevent any kind of chemical/biological reaction prior to chemical analysis (Ukah et al. 2019). The water chemistry laboratory of the Institute of Agricultural Research and Training (IAR&T), Moor Plantation, Ibadan, Nigeria, conducted the quantitative chemical analysis. Trace metals, viz. Zn, Fe, Pb, Cd, and Mn, were analyzed using atomic absorption spectrophotometer (AAS Buck 200, Germany) (Bhutiani et al. 2017; Popoola et al. 2019; Egbueri et al. 2020). TDS was measured in situ using a portable TDS meter (HM Digital COM-100).

**Heavy metal pollution index**

Several pollution indices can be employed to assess the degree to which trace elements contaminate water resources (Devanesan et al. 2017; Rahman et al. 2020; Kumar et al. 2020b). The integrated index method is used in the present study to evaluate heavy metal contamination in groundwater. The pollution indicators such as contamination factor (CF), pollution load index (PLI), degree of contamination (DoC), quantification of contamination (QoC), modified degree of contamination (mDoC), enrichment factor (EF), and geoaccumulation index \( I_{geo} \) are some of the contamination indicators considered in the study (Table 2).
Potential health risk assessment of metals in groundwater samples

The evaluation of the probable extent of undesirable health effects and their likelihood of happening due to the use of contaminated groundwater over a lifetime is required for the evaluation of health risk via oral intake pathway (Osipova et al. 2015; Ogundele et al. 2019). The most common route for population’s exposure to heavy metals is via ingestion pathway (Paul et al. 2019; Egbueri and Mgbenu 2020).

The chronic daily intake (CDI) of metals in groundwater via oral ingestion route was established by:

\[
\text{CDI} = \frac{C \times \text{WIR} \times \text{EF} \times \text{ED} \times \text{BW} \times \text{AT}}{\text{EF} \times \text{ED} \times \text{BW} \times \text{AT}}
\]  

where \( C \) represents the concentration of metal in water (mg/l), WIR signifies the oral ingestion rate (0.75, 1, and 2 L/day for infant, child, and adult, respectively (Egbueri 2020), EF is the exposure frequency in the water (365 days/year), ED is the exposure duration time (70 years as adult ED, while 10 years = child ED) (Kumar et al. 2020b), BW (in kg) denotes the mean body weight (equivalent to 5 kg, 10 kg, and 60 kg for infant, child, and adult, respectively), and AT (the averaging time in days) (equals 3650 days and 25,550 days for child and adult, respectively). Using \( AT = EF \times ED \), Eq. (1) reduces to

\[
\text{CDI} = \frac{C \times \text{WIR}}{\text{BW}}
\]  

The non-carcinogenic risk calculated as hazardous quotient (HQ) in contaminated groundwater for non-cancer risk is evaluated by adopting the expression:

\[
\text{HQ}_i = \frac{\text{CDI} \times \text{RfD}}{\text{RfD}}
\]

where RfD signifies the oral reference dose of a specific metal (mg/kg/day). The RfD equivalent for Cd, Zn, Fe, Mn and Pb is 0.001, 0.3, 0.7, 0.14, and 0.0036, respectively (Duggal et al. 2017; Enuneku et al. 2018; Mgbenu 2020).

| Well no. | Longitude and latitude | Total depth (m) | Depth to water table (m) | Sample code |
|----------|------------------------|----------------|--------------------------|-------------|
| BUA1     | 7°22′53.6″ 3°53′45.0″  | 5.6            | 4.7                      | S1          |
| BUA2     | 7°22′51.3″ 3°53′47.4″  | 5.2            | 4.4                      | S2          |
| BUA3     | 7°22′50.9″ 3°53′56.7″  | 6.2            | 5.7                      | S3          |
| BUA4     | 7°22′51.5″ 3°53′44.6″  | 5.4            | 5.0                      | S4          |
| BUA5     | 7°23′35″ 3°54′22″        | 0.7            | 0.6                      | S5          |
| PUA1     | 7°28′51.5″ 3°53′47.4″  | 16.8           | 7.3                      | S6          |
| PUA2     | 7°28′10.0″ 3°52′48.7″  | 20.4           | 6.4                      | S7          |
| PUA3     | 7°28′14.4″ 3°52′44.0″  | 18             | 9.2                      | S8          |
| PUA4     | 7°28′09.5″ 3°52′47.3″  | 22.8           | 10.1                     | S9          |
| PUA5     | 7°28′08.2″ 3°52′51.9″  | 25.2           | 2.7                      | S10         |
| UA1      | 7°23′43.2″ 3°53′11.9″  | 6.0            | 2.1                      | S11         |
| UA2      | 7°22′58.2″ 3°51′06.9″  | 6.2            | 5.8                      | S12         |
| UA3      | 7°23′03.2″ 3°50′43.9″  | 6.2            | 5.2                      | S13         |
| UA4      | 7°22′50.2″ 3°51′03.9″  | 10             | 3.7                      | S14         |
| UA5      | 7°22′45.0″ 3°51′03.9″  | 7.0            | 6.6                      | S15         |

Table 1 Well data for BUA, PUA, and UA water samples in Ibadan metropolis
The final value for the non-carcinogenic risk evaluation is the hazard index (HI) (Egbueri and Mgbenu 2020; Kumar et al. 2020b). It assists in determination of the total effects of all dissolved HMs (Egbueri and Mgbenu 2020) in analyzed water. The HI value is the summation of all donating HQs caused by ingested HMs in water:

$$HI = \sum_{i=1}^{n} HQ_i$$  \hspace{1cm} (4)

For non-carcinogenic risk, HI > 1 signifies a high potential health risk; it suggests that the non-carcinogenic risk of ingesting a specific metal surpasses the acceptable safe limit (Ukah et al. 2019). However, HI less than unity means that the non-carcinogenic health risk lies within the acceptance limit (Afrifa et al. 2013; Kladsomboon et al. 2019; Wu et al. 2019; Egbueri and Mgbenu 2020).

**Cancer risk (CR)**

The probability of cancer risk of drinking groundwater was evaluated as the incremental likelihood of human being developing cancer over a life span, resulting from the exposure to a prospective carcinogenic element (Enuneku et al. 2018; Ukah et al. 2019; Egbueri and Mgbenu 2020). The CR is computed using Eq. (5):

$$CR = ADD \times SF_i$$  \hspace{1cm} (5)

where $SF_i$ is the slope factor (mg/kg/day). The tolerable CR value is within the range $1 \times 10^{-6}$ to $1 \times 10^{-4}$ (USEPA 2012; Rahman et al. 2018; Ukah et al. 2019; Egbueri and Mgbenu 2020).

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**Fig. 2** Location map showing the access roads and water sampling points (adapted from Google Earth Imagery 2019)
| Contamination index                | Definition                                                                 | Contamination categories                                                                 | References               |
|-----------------------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------------------------|--------------------------|
| Contamination factor (CF)         | $CF = \frac{C_n}{C_b}$; $C_n$ is the concentration of metal in water; $C_b$ is the background value of the metal | $CF < 1$, low contamination; $1 \leq CF < 3$, moderate contamination; $3 \leq CF < 6$, considerable contamination; and $CF \geq 6$, very high contamination | Hakanson (1980)          |
| Pollution load index (PLI)        | $PLI = \sqrt{CF_1 \times CF_2 \times CF_3 \times \cdots \times CF_n}$; $CF$ is the contamination factor and $n$ is the number of metals | $PLI < 1$, no pollution; $1 < PLI < 2$, moderate pollution; $2 < PLI < 3$, heavy pollution; $3 < PLI$, extremely | Tomlinson et al. (1980)  |
| Degree of contamination (DoC)     | $DoC = \sum_{i=1}^{n} CF_i$                                               | $DoC < 1$, low contamination; $DoC$ values ranging from 1 to 3 indicate mild contamination; $DoC > 3$, high pollution. | Edet and Ofiong (2002)  |
| Modified degree of contamination (mDoC) | $mDoC = \sum_{i=1}^{n} CF_i$                                             | $mDoC < 1.5$, uncontaminated; $1.5 \leq mDoC < 2$, slightly contaminated; $2 \leq mDoC < 4$, mild contaminated; $4 \leq mDoC < 8$, moderately—heavily contaminated; $8 \leq mDoC < 16$, severely contaminated; $16 \leq mDoC < 32$, heavily contaminated; $mDoC \geq 32$, extremely contaminated | Abraham and Parker (2008) |
| Geoaccumulation index ($I_{geo}$) | $I_{geo} = \log_2 \left( \frac{C_n}{B_n} \right) ; \frac{C_n}{B_n}$ is the concentration of metal in sample, $B_n$ is the background concentration of metal, while the factor 1.5 is used due to possible variations of the background value due to lithological variations | $I_{geo} \leq 0$, uncontaminated; $0 < I_{geo} \leq 1$, uncontaminated to moderately contaminated; $1 < I_{geo} \leq 2$, moderately contaminated; $2 < I_{geo} \leq 3$, moderately to heavily contaminated; $3 < I_{geo} \leq 4$, heavily contaminated; $4 < I_{geo} \leq 5$, extremely contaminated | Muller (1969)           |
| Enrichment factor (EF)            | $EF = \left( \frac{C_n}{C_{Fe(s)}} \right)_{sample} / \left( \frac{C_n}{C_{Fe(b)}} \right)_{reference}$ | $EF \leq 1$, background rank; $1 < EF < 2$, minimal enrichment; $2 < EF < 5$, moderate enrichment; $5 < EF < 20$, significant enrichment; $20 < EF < 40$, very high enrichment; $EF > 40$, extremely high enrichment | Deely and Fergusson (1994), Bhutiani et al. (2017) |
| Ecological risk index (ERI)       | $ERI = T_{RI} \times CF_j$                                               | $ER < 5$, low ecological risk; $5 \leq ER < 10$, mild ecological risk; $10 \leq ER < 20$, considerable ecological risk; $20 \leq ER < 40$, high ecological risk; $ER > 40$, very high ecological risk. | Tomlinson et al. (1980)  |
| Quantification of contamination (QoC) | $QoC (%) = \frac{|C_n - B_n|}{C_n} \times 100$ | $+ve$ QoC—Anthropogenic origin $-ve$ QoC—Lithogenic origin | Asaah et al. (2006)      |
Statistical analyses

Data from laboratory analysis of water samples were subjected to descriptive statistics, Pearson’s correlation matrix, and multivariate statistical analysis (MSA). Pearson correlation is a statistical method for determining and measuring the association between two variables. The sign of the correlation coefficient value shows whether the relationship is positive or negative, while the absolute value of correlation coefficient reveals the linear relationship’s strength (Saleem et al. 2017; Paul et al. 2019; Adhikari and Mal 2019). The factor analysis allows the size of the initial data set to be reduced to a lesser number of factors devoid of sacrificing the original data set’s inherent information (Panthi et al. 2017; Amfo-Otu et al. 2014; Selvakumar et al. 2017; Singh and Singh 2019; Adhikari and Mal 2019). Because of the normal distribution of raw data and the various units of measurement of analyzed parameters, the original data have to undergo normalization and standardization for proper factor analysis (Barakat et al. 2016; Barzegar et al. 2019). Factors with eigenvalues greater than one were selected and then varimax-rotated using Kaiser normalization (Kaiser 1960; Usman et al. 2014; Egbueri 2020). The hierarchical cluster analysis (HCA) can be used for grouping data into classes according to characteristics, sources, and features that are similar or dissimilar (Hamid et al. 2016; Hajigholizadeh and Melesse 2017). The HCA can be obtained by employing the most widely used data clustering method and application of Ward’s method of linkage (Bilgin and Konan 2016; Barzegar et al. 2019; Liu et al. 2021). Dendrogram is a pictorial representation of the CA result based on either the analyzed parameters or sampling locations.

Results and discussion

Levels of HMs and TDS in groundwater samples

The mean concentrations of studied HMs and TDS in sampled groundwater are presented in Table 3. The concentrations of Zn (mg/L) ranged between 0.53–5.73, 0.67–3.62 and 2.95–8.26 for TCA, PUA, and UA, respectively. Sixty percentage of water samples were higher than the recommended permissible limit of 3.00 mg/L (NIS 2015; WHO 2015). The concentrations of Fe in the groundwater within TCA, PUA, and UA in mg/L were 0.16–3.28, 0.21–1.24, and 1.21–3.94, respectively (Table 2). 86.7% of the samples from investigated residential locations were above 0.30 mg/L recommended for drinking purpose. The concentrations of Pb in groundwater within TCA, PCA, and UA in mg/L were 0.44–0.76, 0.48–0.68 and 0.67–0.84, respectively. All the groundwater samples in the residential areas were above the acceptable limit of 0.01 mg/L (WHO 2015). The concentration of cadmium in mg/L ranged from 0.33 to 0.58, 0.36 to 0.50, and 0.51 to 0.64 in groundwater within TCA, PUA, and UA, respectively. The levels of Cd were higher than the acceptable limit of 0.003 in all the groundwater samples. The concentration of manganese (mg/L) in groundwater from shallow wells within TCA, PUA, and UA was less than 0.2 mg/L recommended by WHO as permissible limit for consumption purpose. These low values of Mn2+ in S1–S15 may be due to the fact that Mn2+ concentration in groundwater increases with depth of the well (Barzegar et al. 2019). All the wells sampled for this study were shallow wells with depths <30 m. The TDS ranged between 44.37 and 113.46, 53.65–87.38 and 67.35–136.59 in mg/L within TCA, PUA, and UA, respectively. All the groundwater samples in the three residential locations had TDS values lower than 500 mg/L recommended by WHO 2015 guidelines for drinking water. Based on TDS values, all groundwater samples in representative BUA, PUA, and UA can be classified as freshwater since their TDS values lie below 1000 mg/L (Bolarinwa 2017; Ukah et al. 2019). In general, the least value of TDS (44.4 mg/L) was found in S5 (confined spring water) located within TCA in migmatite bedrock setting, while relatively the highest value of TDS (136.6 mg/L) was observed in S13 (water sample from an unlined well in UA) located within the undifferentiated gneiss schist setting. It was observed that lowest and highest values of TDS in S5 and S13 correspond with the minimum and maximum values of Fe2+ in analyzed water samples. The fitnessness of analyzed water samples for ingestion use was evaluated through the comparisons of HM results with the acceptable safe drinking water quality standards (WHO 2015). The concentrations of zinc, iron, lead, and cadmium were above permissible standards in 60%, 86.7%, 100%, and 100% of water samples, respectively. However, values of TDS and Mn were less than WHO 2015 permissible limits for drinking purpose.

Statistical analysis of groundwater data

The details of descriptive statistics of water parameters from the TCA, PUA, and UA settings of Ibadan are presented in Table 4, while Table 5 presents the results of ANOVA to examine significant variations in the observed parameters among the 3 locations. Table 6 presents the observed correlation coefficient results of water quality parameters of studied groundwater samples, while
Table 3 shows the model summary of categorical PCA. Table 8 shows the centroid coordinates and total variance as Table 9 shows the factor loading and eigenvalue of single extracted component. The average concentration value and coefficient of variation for each analyzed parameter as presented in Table 4 revealed that there were statistically no significant differences in all analyzed parameters at 5% level. Table 4 further reveals that the average concentration of each assessed quality parameter at UA is relatively higher than that of PUA and TCA in Ibadan. However, the value of C.V. of each parameter at TCA is relatively higher than that of PUA and UA residential locations. The results of ANOVA (Table 5) show that mean Zn concentration of the collected water samples varied from 2.58 ± 1.37 to 6.18 ± 2.17 with the highest value observed in samples collected from UA, while the least value was observed in samples from PUA. The result further reveals that mean Zn concentration of water samples collected from UA was significantly higher than those of the samples from the other two locations (TCA and PUA). The mean concentration of Pb in collected groundwater samples from the three locations varied from 0.60 ± 0.14 to 0.77 ± 0.06 with the highest concentration recorded in samples from UA, while the least concentration was observed in samples from TCA. Furthermore, the result reveals that mean Pb concentration of water samples collected from UA was significantly higher than those of the other two locations. Cadmium concentration varied from 0.46 ± 0.06 to 0.59 ± 0.05 with the highest concentration observed in water samples from UA, while the least concentration was recorded in groundwater samples from PUA. The result shows further that the mean value of Cd concentration in samples collected from UA was considerably higher than those of samples collected from the other two locations (i.e., TCA and PUA). The mean value of TDS in collected water samples ranged from 76.52 ± 14.93 to 110.18 ± 25.84 with the highest mean value recorded in samples collected from UA, while the least value was recorded in samples from PUA. Moreover, the result reveals that TDS of soil samples collected from UA was significantly higher than those of samples collected from the other two locations (i.e., TCA and PUA). The mean value of TDS in collected water samples ranged from 76.52 ± 14.93 to 110.18 ± 25.84 with the highest mean value recorded in samples collected from UA, while the least value was recorded in samples from PUA. Moreover, the result reveals that TDS of soil samples collected from UA was significantly higher than those of the PUA and TCA locations. From this result, it is observed that concentrations of the observed parameters did not differ significantly between water samples collected from TCA and PUA.

It can be seen from Table 6 that all the observed correlations showed that most of the studied HMs and TDS have significant relations with one another at 1% level. The correlation matrix (Table 5) revealed that every pair of assessed parameter has a significant relationship.
parameters (between two HMs/metal and TDS) correlate positively at 1% level ($p < 0.01$). This is an indication that all the analyzed metals were possibly from the same pollutant sources (Zarei et al. 2014; Vettrimurugan et al. 2017; Kumar et al. 2017; Egbueri 2019). Specifically, very strong direct association at 1% level ($r^2 > 0.9$) in the matrix was noticed for Fe–Zn, Mn–Zn, Mn–Fe, Pb–Zn, Pb–Fe, Zn–Cd and Pb–Cd pairs. Similarly, highest determination coefficient ($r^2 > 0.9$) at 1% level was also found between Cd–Fe, Pb–Mn, and Cd–Mn pairs. Strong positive association between Pb and Cd concurs with similar result reported by Bhutiani et al. (2017), Mgbenu and Egbueri (2019) and Ukah et al. (2019). Very strong positive associations ($r^2 > 0.95$) between Zn–Cd pair and Zn–Pb pair agree with the result of Aigberua et al. (2020). Similar positive association for Fe–Mn pair was also reported by Barzegar et al. (2015), Palmucci et al. (2016), and Kshetrimayum and Hegue (2016). Strong positive relation between Zn–Mn pair concurs with similar association reported by Vettrimurugan et al. (2017). A very strong direct

### Table 4: Descriptive statistics of analyzed parameters in TCA, PUA, and UA of Ibadan metropolis

| Parameters | Locations          | N  | Mean  | Std. deviation | Std. error | 95% confidence interval for mean | Minimum | Maximum | C.V  |
|------------|--------------------|----|-------|----------------|------------|---------------------------------|---------|---------|------|
| Zinc       | Traditional core area | 5  | 3.05  | 2.48           | 1.11       | $-0.03$                        | 6.13    | 5.75    | 81.30|
| Iron       | Traditional core area | 5  | 1.53  | 1.57           | 0.70       | $-0.42$                        | 3.49    | 3.28    | 102.50|
| Manganese  | Traditional core area | 5  | 0.03  | 0.01           | 0.00       | $-0.02$                        | 0.04    | 0.04    | 13.00|
| Lead       | Traditional core area | 5  | 0.60  | 0.14           | 0.06       | $-0.43$                        | 0.78    | 0.76    | 23.10|
| Cadmium    | Traditional core area | 5  | 0.46  | 0.11           | 0.04       | $-0.33$                        | 0.60    | 0.58    | 23.70|
| TDS        | Traditional core area | 5  | 76.95 | 25.45          | 11.39      | $-0.45$                        | 108.56  | 113.46  | 33.10|
| Zinc       | Peri-urban area     | 5  | 2.58  | 1.37           | 0.61       | $-0.08$                        | 4.28    | 3.62    | 53.20|
| Iron       | Peri-urban area      | 5  | 0.78  | 0.48           | 0.22       | $-0.18$                        | 1.38    | 0.21    | 62.10|
| Manganese  | Peri-urban area      | 5  | 0.03  | 0.00           | 0.00       | $-0.02$                        | 0.03    | 0.02    | 13.00|
| Lead       | Peri-urban area      | 5  | 0.61  | 0.09           | 0.04       | $-0.49$                        | 0.72    | 0.48    | 14.90|
| Cadmium    | Peri-urban area      | 5  | 0.46  | 0.06           | 0.03       | $-0.37$                        | 0.53    | 0.36    | 14.00|
| TDS        | Peri-urban area      | 5  | 76.52 | 14.93          | 6.68       | $-0.59$                        | 75.98   | 53.65   | 19.50|
| Zinc       | Urban area           | 5  | 6.18  | 2.17           | 0.97       | $-3.48$                        | 8.88    | 2.92    | 35.20|
| Iron       | Urban area           | 5  | 2.78  | 1.17           | 0.52       | $-1.33$                        | 4.23    | 1.21    | 41.90|
| Manganese  | Urban area           | 5  | 0.04  | 0.00           | 0.00       | $-0.03$                        | 0.04    | 0.03    | 8.20 |
| Lead       | Urban area           | 5  | 0.77  | 0.06           | 0.03       | $-0.69$                        | 0.84    | 0.67    | 8.30 |
| Cadmium    | Urban area           | 5  | 0.46  | 0.11           | 0.04       | $-0.33$                        | 0.60    | 0.33    | 23.70|
| TDS        | Urban area           | 5  | 110.18| 25.85          | 11.56      | $-78.08$                       | 142.27  | 76.35   | 23.50|

Table shows mean ± standard deviation values. Values along the same row with different superscripts are significantly different at 5% ($p < 0.05$) level. Bold depicts the three different residential locations used for this study.

### Table 5: ANOVA result for analyzed parameters based on residential location

| Parameters | Traditional core area | Peri-urban area | Urban area |
|------------|-----------------------|-----------------|------------|
| Zinc       | 3.05 ± 2.48a          | 2.58 ± 1.37a    | 6.18 ± 2.17b|
| Iron       | 1.53 ± 1.57ab         | 0.78 ± 0.48a    | 2.78 ± 1.17b|
| Manganese  | 0.03 ± 0.01a          | 0.03 ± 0.00a    | 0.04 ± 0.00b|
| Lead       | 0.60 ± 0.14a          | 0.61 ± 0.09a    | 0.77 ± 0.06b|
| Cadmium    | 0.46 ± 0.11a          | 0.46 ± 0.06a    | 0.59 ± 0.05b|
| TDS        | 76.95 ± 25.46a        | 76.52 ± 14.93a  | 110.18 ± 25.85b|

Table shows mean ± standard deviation values. Values along the same row with different superscripts are significantly different at 5% ($p < 0.05$) level. Bold depicts the three different residential locations used for this study.

### Table 6: Correlation coefficient matrix of analyzed heavy metals and TDS of groundwater samples

|        | Zinc    | Iron     | Manganese | Lead     | Cadmium | TDS     |
|--------|---------|----------|-----------|----------|---------|---------|
| Zinc   | 1       | .970**   | .969**    | .965**   | .969**  | .950**  |
| Iron   | .970**  | 1        | .931**    | .914**   | .996**  | .890**  |
| Manganese | .969**  | .931**   | 1         | .996**   | .999**  | .915**  |
| Lead   | .965**  | .914**   | .996**    | 1        | .997**  | .910**  |
| Cadmium| .969**  | .927**   | .999**    | .997**   | 1       | .915**  |
| TDS    | .950**  | .890**   | .915**    | .910**   | .915**  | 1       |

**Correlation is significant at the 0.01 level (2-tailed)**
association in the correlation pair Mn–Cd ($r^2 > 0.95$) agrees with the comparable association reported by Popoola et al. (2019) in their assessment of physicochemical properties of groundwater samples in industrial and residential locations in Lagos metropolis.

A strong positive association at 1% level occurs between TDS and each of analyzed metals. This is an indication that the dissolved HMs significantly influence the TDS of the collected water samples. Zhang et al. (2020) also reported positive correlation between TDS and Fe, and TDS and Mn in their assessment of groundwater quality in Shuangliao city, northeast China. Similar strong direct association between TDS and Zn was also obtained by Herngren et al. (2005). Furthermore, significant correlation between TDS and Cd ($r^2 > 0.85$) obtained in this study was also reported by Popoola et al. (2019).

The reliability analysis for PCA shows a good level of internal consistency among the items as the Cronbach’s alpha value for the extracted component $\alpha = 0.989$ (Table 7). Only one (1) component has eigenvalue over Kaiser’s criterion of 1, and this component accounts for 94.637% of the total variance in the data set. Each of the items contributes substantially to the principal component as each item has high mean coordinate value (Table 8). Moreover, the result of the component loadings shows that all the parameters have very high positive loadings on the extracted component (Table 9). Strong positive loadings of extracted factors in only PC imply lithogenic and anthropogenic sources of heavy metals in analyzed groundwater samples (Barzegar et al. 2017; Wagh et al. 2018). Based on the component loadings’ scatter plot (Fig. 3), all the six items cluster together at the upper range of the extracted component. On the other hand, the biplot (Fig. 4) shows a large amount of variation among the cases (blue dots).

According to the dendrogram of assessed water quality parameters (Fig. 5a), only 1 cluster was identified and contains all the analyzed water quality parameters. This cluster is in agreement with elements that have strong positive loadings in only extracted component. The cluster branches of water sampling positions (Fig. 5b) show that three major clusters were created. The first cluster comprises S3–S6, and S9, cluster 2 contains S7, S8, S10 and S14, while cluster 3 contains S1–S2, S11–S12, S13 and S15. Cluster 1 comprises water samples with < 2 mg/L of Zn, < 0.75 mg/L of Fe, < 0.03 mg/L of Mn, < 0.6 mg/L of Pb and < 0.45 mg/L of cadmium. Cluster 2 comprises samples with similar characteristics such as Pb values of ≈ 0.7 mg/L and Cd values of ≈ 0.5 mg/L. Cluster 3 contains samples with > 5 mg/L of Zn, > 2 mg/L of Fe, > 0.035 mg/L of Mn and > 7 mg/L of Pb$^{2+}$ ions.

### Table 7 Model summary of categorical PCA

| Dimension | Cronbach’s alpha | Variance accounted for |
|-----------|------------------|------------------------|
|           |                  | Total (eigenvalue)     | % of variance |
| 1         | 0.99             | 5.68                   | 94.64        |
| Total     | 0.99             | 5.68                   | 94.64        |

### Table 8 Centroid coordinates and total variance

| Centroid coordinates | Total (vector coordinates) |
|----------------------|---------------------------|
| Dimension | Mean | Dimension | Total |
| Zinc | 0.98 | 0.98 | .956 | 0.96 |
| Iron | 0.97 | 0.97 | .903 | 0.90 |
| Manganese | 1.00 | 1.00 | .976 | 0.98 |
| Lead | 0.98 | 0.98 | .969 | 0.97 |
| Cadmium | 1.00 | 1.00 | .972 | 0.97 |
| TDS | 0.93 | 0.93 | .902 | 0.90 |
| Active total | 5.86 | 5.86 | 5.678 | 5.68 |
| % of Variance | 97.66 | 97.66 | 94.637 | 94.64 |

### Table 9 Varimax-rotated component loadings in PCA

| Variables | Factor 1 |
|-----------|----------|
| Zn (mg/L) | 0.98     |
| Mn (mg/L) | 0.99     |
| Cd (mg/L) | 0.99     |
| Pb (mg/L) | 0.98     |
| Fe (mg/L) | 0.95     |
| TDS (mg/L) | 0.95 |
| Eigenvalue | 5.68     |
| Cumulative eigenvalue | 5.68 |
| % total variance | 95.69 |
| Cumulative % | 94.64 |

### Extent of metal pollution

The results of degree of metal pollution based on CF, EF, PLI, and $I_{geo}$ are listed in Table 10. According to Hakanson (1980) classification approach, the CF values for Pb, Cd, and Mn were found to be in the range of CF < 1, an indication of low contamination of these metals in S3–S6, and S9, while the trio metals were in moderate contamination class (1 ≤ CF < 3) in samples S7–S8, S10 and S14, while cluster 3 contains S1–S2, S11–S12, S13 and S15. Cluster 1 comprises water samples with < 2 mg/L of Zn, < 0.75 mg/L of Fe, < 0.03 mg/L of Mn, < 0.6 mg/L of Pb and < 0.45 mg/L of cadmium. Cluster 2 comprises samples with similar characteristics such as Pb values of ≈ 0.7 mg/L and Cd values of ≈ 0.5 mg/L. Cluster 3 contains samples with > 5 mg/L of Zn, > 2 mg/L of Fe, > 0.035 mg/L of Mn and > 7 mg/L of Pb$^{2+}$ ions.
class according to Hakanson (1980) classification. It must also be noted that Fe in S13 and S15 belongs to considerable contamination class. The values of PLI for the studied HMs in groundwater samples as presented in Table 10 varied from 0.55 to 1.47. The highest value of PLI was found in S15 (1.47), while the least value of PLI was found in S5 (0.55). In terms of PLI values, samples S3–S6 as well as S9 are characterized with PLI < 1, indicating nil pollution condition. However, PLI values were greater than unity in S1–S2, S7–S8, and S10–S15, suggesting pollution state of mentioned samples. The enrichment factor (EF) for each HM in the study area is presented in Table 10. There is background enrichment of Cd, Pb, and Mn in S1–S2, S7–S8, and S11–S15 but moderately enriched in S3–S6. However, Zn exhibited background concentration in S1–S2 and S11–S5 and minor enrichment in S3–S10. Anthropogenic sources of Pb in samples S3–S6 as well as S9 were discovered by their EF values greater than 1.5. Lithogenic inputs of Pb in S7–S8, S10–S12 as well as S14 were indicated by their EF values in the range of 0.5–1.5 (Nowrouzi and Pourkhabbaz 2014). The sources of Cd in samples S3–S6 and in S9 were found to be anthropogenic origins, while Cd in S7–S8, S10–S12 as well as S14 had lithogenic source. The Mn dissolution in groundwater samples S7–S8, S10–S12 and S14 was discovered to be due to lithogenic/crustal source, while S7–S8 and S9 had Mn contents to be from anthropogenic activities. Samples S1–S8 and S10–S15 had Zn origin to be from crustal source. However, EF value of Zn in S9 (> 1.5) indicates possible anthropogenic source.

The $I_{geo}$ evaluated for assessed HMs (as listed in Table 10) indicated that $I_{geo}$ for manganese, cadmium, and lead in S1–S15 were found to be in the range of $I_{geo} > 0$, suggesting “practically unpolluted” class. However, the $I_{geo}$ for Fe in samples S1–S2 and S11–S12 were found to be in the range (0 < $I_{geo} ≤ 1$), an indication of slight impact of Fe in the contamination of water. The $I_{geo}$ values of Fe in S13 and S15 lie in the range (1 < $I_{geo} < 2$), which can be categorized in moderately contaminated status. Table 10 further shows that the $I_{geo}$ values of Zn contents in S1–S2, S11–S13 and S15 indicate “slightly polluted” state, while there is unpolluted state of Zn in S3–S10 and S14.

Table 11 lists the results of DoC, mDoC, ERI, and ERIP. The DoC for the sampled groundwater ranged from 2.36 to 10.23 (Table 11). The lowest and highest values of DoC were discovered in S5 and S15, respectively. According to Edet and Offiong (2002) classification of DoC, all the groundwater samples except S5 and S15 fall within high contamination class. However, it was revealed that S3–S10 as well as S14 lie

Fig. 3 Component loading scatter plot

![Component Loadings](image-url)
in low contamination status (DoC < 7), while S1–S2, S11–S13 and S15 reflect significant extent of contamination according to Hakanson (1980) and Odukoya (2015) classification. The mDoC ranged from 0.47 to 2.05 as listed in Table 11. The mDoC results in S3–S10, S9, S12 and S14 were < 1.5, an indication of unpolluted class, while mDoC values in S1–S2, S11, S13 indicate their slightly polluted state (Brady et al. 2015; Gargouri et al. 2018). The mDoC value (2.05) in S15 denotes its moderately polluted state.

**Ecological risk assessment for groundwater samples**

The ecological risk values for Pb in the groundwater samples varied from 3.40 to 6.50, suggesting “mild ecological risk.” In particular, the ERI results for lead in S3–S6 and S9 revealed low risk, while mild ecological risk of Pb exists in S1–S2, S7–S8 and S10–S15. The ERI values for cadmium in all the collected groundwater samples varied from 20.4 to 39.3; this revealed “high ecological risk” of Cd in sampled groundwater. For elements Mn, Fe and Zn, their ERI values indicated that the three metals demonstrated low ecological risk in groundwater samples from the three residential locations. The ERIP values ranged from 25.17 to 52.14 and lie in the range “low-to-moderate potential risk.” For instance, samples S1–S3 in TCA had their ERIP values ranging from 25.17 to 47.67 an indication of being within “low-to-moderate ecological potential risk.” The same goes for samples S6–S10 in PUA that had ERIP values ranging from 25.25 to 38.86. However, water samples in UA (S11–S15) lie within “moderate potential ecological risk” class.

The analysis of QoC values (Table 12) showed that the concentrations of Pb, Cd, and Mn for the samples S1–S2, S7–S8 and S10–S15 were mainly derived from anthropogenic inputs, while the trio metals (Pb, Cd, and Mn) show geogenic sources in samples S3–S6 and S9. The values of Fe also varied between the geogenic and anthropogenic sources. For instance, Fe concentrations in S1–S2, S7–S8 and S11–S15 showed anthropogenic source of contamination but of geogenic origin in S3–S6 and S9–S10. The positive QoC values of Zn exceeded the geogenic sources in the samples S1–S2, S7–S8, S10–S15 and S15. However, the Zn concentrations in S3–S6, S9 and S14 were shown to be associated with geogenic sources. There is disparity in identification of sources of analyzed metals in collected water samples by EF and QoC in this study. This may be due to the difference in the magnitude of input for each metal in the sample and/or the differences in the removal rate of each metal from the water samples (Zarei et al. 2014).

**Health risk assessment for groundwater samples**

Table 13 shows the results of non-carcinogenic health risks and probability of cancer risks for adult, child, and infant as a result of ingesting heavy metals in groundwater samples. The hazardous quotient (HQ) results for heavy metals (Fe, Mn, and Zn) were less than one (HQ < 1) for adult, child, and infant, suggesting that those metals pose no apparent...
health risks. However, the HQ values (Table 13) for Cd and Pb were greater than unity, implying that these two metals pose a significant health risk. The computed HIs for adult, child, and infant were 4.65E+01, 2.33E+01, and 1.75E+01, respectively. The result of HI for adult (4.65E+01) revealed that adults’ population were more susceptible to non-carcinogenic health risk in the three residential sites.
Table 13 lists the contribution of the assessed metals to the computation of HIs for the populace in the investigated residential sites. From Table 13, it was noticed that Cd and Pb have the highest input to HI when compared to other assessed metals. It is worth noting that Cd played a significant role in the study area’s non-carcinogenic risk assessment (see Table 13). The HI contribution of the analyzed HMs reduced in the order: Cd > Pb > Zn > Fe > Mn.

**Carcinogenic health risk assessment**

As presented in Table 13, out of the 5 studied HMs in this present work, only Pb and Cd made considerable input into the evaluation of cancer risk. The probability of CR results for adult, child, and infant as a result of exposure to Cd was 5.00E−01; 2.50E−01, and 1.87E−01, respectively. Table 13 further shows that CR values due to Pb in drinking water for adult, child, and infant were 3.72E−04; 1.86E−04; and 1.40E−04, respectively. This clearly reveals that Cd contamination had more input to the evaluation of CR than Pb for...
the populace in the study area. The analyzed water samples have high Cd and Pb cancer risks for adult, child, and infant in the three residential sites. The CR values obtained for the three residential areas lie above the acceptable range of $10^{-4}$ to $10^{-6}$ (Rahman et al. 2018; USEPA 2011; USEPA 2012).

### Conclusions

This study was conducted in three different residential areas within Ibadan metropolis to evaluate the water quality through the assessment of levels and associated risks of selected heavy metals (HMs) in groundwater samples. The HMs analyzed included Pb, Cd, Zn, Fe, and Mn. The following conclusions can be drawn.

1. The values of Pb, Cd, Fe, and Zn for all the groundwater samples were above the recommended standard in 100%, 100%, 86.7%, and 60% of water samples, respectively. However, the levels of Mn and TDS are within the safe limits set by World Health Organization.
2. The results of CF showed that groundwater samples from all the investigated residential areas could be classified between not contaminated ($< 1$) to moderately contaminated ($1 \leq \text{CF} < 3$). However, samples $S_{13}$ and $S_{15}$ in UA are considerably contaminated.
3. Integrated pollution indices indicated that groundwater within the three residential sites lie in the range of “unpolluted” to “slightly polluted” class. The ERI for cadmium demonstrated high ecological risk in all assessed groundwater samples, while Mn, Fe, and Zn demonstrated little ERI in assessed groundwater within the residential sites. However, the calculated ERIP suggests low-to-moderate ecological risk ($25.17–52.14$) of these metals in residential sites.
4. The results of EF and QoC of analyzed metals in water samples indicate geogenic and anthropogenic sources. The degree of contamination in groundwater showed the following trends: UA > TCA > PUA.
5. Principal component analysis (PCA) extracted only one component that explained 95.68% of the total variance and linked the probable sources of analyzed parameters to both geogenic and anthropogenic inputs.
6. Possibility of sampled groundwater posing non-carcinogenic health risk through the oral intake route was identified in the three residential areas with the order of trace metals impacts as Cd $>$ Pb $>$ Zn $>$ Fe $>$ Mn. The obtained HQ results are $> 1$ for Pb and Cd in adult, child, and infant, representing a possible health risk. The CR values of Cd and Pb contamination were higher than the acceptable range of $\leq 1 \times 10^{-6}$ to $1 \times 10^{-4}$. Cadmium impacted more to the evaluation of CR than lead for the three categories of peoples in the studied residential locations.
7. The study recommends awareness programs toward protecting the shallow wells (especially in UA), improved hygienic practices, and pre-treatment of contaminated water before use.

### Table 12
Quantification of contamination (QoC) values of HMs in the water samples of Ibadan metropolis

| Sample code | Pb   | Cd   | Mn   | Fe   | Zn   |
|-------------|------|------|------|------|------|
| $S_1$       | 15.16| 15.270| 15.63| 65.72| 47.37|
| $S_2$       | 15.16| 15.270| 15.63| 66.35| 47.64|
| $S_3$       | −17.23| −18.02| −18.19| −120.76| −84.06|
| $S_4$       | −17.23| −18.02| −18.19| −116.44| −82.94|
| $S_5$       | −46.54| −47.52| −47.44| −589.89| −466.07|
| $S_6$       | −46.54| −47.52| −47.44| −425.63| −347.79|
| $S_7$       | 2.31 | 2.05 | 2.03 | 8.01 | 15.96|
| $S_8$       | 2.31 | 1.85 | 2.03 | 10.98| 13.54|
| $S_9$       | −19.40| −18.88| −19.13| −234.49| −91.09|
| $S_{10}$    | 2.31 | 2.63 | 2.67 | −21.30| 17.12|
| $S_{11}$    | 16.26| 16.42| 16.57| 57.05| 51.22|
| $S_{12}$    | 15.16| 15.12| 15.15| 51.16| 45.55|
| $S_{13}$    | 19.40| 19.58| 19.72| 71.98| 62.73|
| $S_{14}$    | 3.77 | 4.15 | 4.23 | 8.78 | −2.75|
| $S_{15}$    | 23.24| 23.71| 23.63| 71.91| 63.68|

### Table 13
Calculated chronic daily intake (CDI), hazardous quotient (HQ), hazard index (HI), and cancer risk (CR) for studied heavy metals in water samples

| Parameters | CDI | HQ | CR |
|------------|-----|----|----|
|            | Adult | Child | Infant | Adult | Child | Infant | Adult | Child | Infant |
| Pb         | 4.38E−02 | 2.19E−02 | 1.64E−02 | 1.22E+01 | 6.09E+00 | 4.56E+00 | 3.72E−04 | 1.86E−04 | 1.40E−04 |
| Cd         | 3.33E−02 | 1.67E−02 | 1.25E−02 | 3.33E+01 | 1.67E+01 | 1.25E+01 | 5.00E−01 | 2.50E−01 | 1.87E−01 |
| Mn         | 2.03E−03 | 1.01E−03 | 7.60E−04 | 1.45E−02 | 7.23E−03 | 5.43E−03 | |
| Fe         | 1.13E−01 | 5.66E−02 | 4.25E−02 | 1.62E−01 | 8.09E−02 | 6.06E−02 | |
| Zn         | 2.62E−01 | 1.31E−01 | 9.84E−02 | 8.74E−01 | 4.37E−01 | 3.28E−01 | |
| HI         | |
|            | 4.65E+01 | 2.33E+01 | 1.75E+01 | | | | | |
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Declaration

Conflict of interest The authors declare that they have no conflicts of interest.

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