Heliyon 9 (2023) e15483

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Evaluation of oral and dermal health risk exposures of contaminants in groundwater resources for nine age groups in two densely populated districts, Nigeria

Daniel A. Ayejoto [a], Johnson C. Agbasi [b], Johnbosco C. Egbueri [b,*], S.I. Abba [c]

[a] Department of Environmental and Sustainability Sciences, Texas Christian University, Fort Worth, TX, USA
[b] Department of Geology, Chukwuemeka Odumegwu Ojukwu University, Uli, Anambra State, Nigeria
[c] Interdisciplinary Research Center for Membranes and Water Security, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Keywords:
Carcinogenic risk
Groundwater quality assessment
HERisk code
Hierarchical dendrogram
Non-carcinogenic risk
Potentially harmful elements

ABSTRACT

Human health and the sustainability of the socioeconomic system are directly related to water quality. As anthropogenic activity becomes more intense, pollutants, particularly potentially harmful elements (PHEs), penetrate water systems and degrade water quality. The purpose of this study was to evaluate the safety of using groundwater for domestic and drinking purposes through oral and dermal exposure routes, as well as the potential health risks posed to humans in the Nnewi and Awka regions of Nigeria. The research involved the application of a combination of the National Sanitation Foundation Water Quality Index (NSFWQI), HERisk code, and hierarchical dendrograms. Additionally, we utilized the regulatory guidelines established by the World Health Organization and the Standard Organization of Nigeria to compare the elemental compositions of the samples. The physicochemical parameters and NSFWQI evaluation revealed that the majority of the samples were PHE-polluted. Based on the HERisk code, it was discovered that in both the Nnewi and Awka regions, risk levels are higher for people aged 1 to <11 and >65 than for people aged 16 to <65. Overall, it was shown that all age categories appeared to be more vulnerable to risks due to the consumption than absorption of PHEs, with Cd > Pb > Cu > Fe for Nnewi and Pb > Cd > Cu > Fe for water samples from Awka. Summarily, groups of middle age are less susceptible to possible health issues than children and elderly individuals. Hierarchical dendrograms and correlation analysis showed the spatio-temporal implications of the drinking groundwater quality and human health risks in the area. This research could help local government agencies make informed decisions on how to effectively safeguard the groundwater environment while also utilizing the groundwater resources sustainably.

1. Introduction

Access to groundwater is crucial for human consumption, agriculture, and commercial purposes, especially in developing countries. Nevertheless, the sustainability of this resource is under constant threat from environmental factors and human activities [1–3]. Nearly one-third of the global population relies on freshwater as their primary source of drinking water [4]. In certain arid and

---

* Corresponding author.
E-mail addresses: johnboscoegbueri@gmail.com, jc.egbueri@coou.edu.ng (J.C. Egbueri).

https://doi.org/10.1016/j.heliyon.2023.e15483
Received 15 December 2022; Received in revised form 10 April 2023; Accepted 11 April 2023

semi-arid regions, groundwater is the sole source of drinking water for communities. Water supply has faced more challenges in recent decades, particularly in terms of management and the depletion of freshwater supplies [5–7]. Overexploitation, geomorphic, hydrological, mineralization, water-rock interactions, including ion exchange, redox reactions, and human impacts are all elements that affect groundwater quality [8–10]. Water quality is equally crucial to supporting fundamental human needs as water availability is, as a lack of both can result in several public health issues [11].

The accessibility of clean drinking water, which is a fundamental human right and a key factor for development, has a significant impact on water quality. Unfortunately, the quality and quantity of groundwater in water resources are gradually declining due to the excessive discharge of potentially harmful elements (PHEs) into water resources in many nations [12,13]. Most of the potentially hazardous elements (PHEs) include arsenic (As), zinc (Zn), lead (Pb), manganese (Mn), iron (Fe), copper (Cu), and nickel (Ni), all of which are released into groundwater due to natural and human activities. Dermal absorption and ingestion are the most basic human exposure routes to PHEs in both industrial and residential regions. If their permissible levels are exceeded, these PHEs can be hazardous [14]. Because HMs are non-biodegradable, they can build up in the environment to dangerous levels for human health [15,16]. Decreasing or rising pH of water are two significant physicochemical processes or setups that lead to PHEs movement into groundwater [17]. In addition to natural and human activities, PHE concentrations in groundwater can also increase due to low hydrological slope leading to reduced water infiltration, or an arid climate leading to evaporative buildup [18]. Furthermore, mining activities, industrial effluent recharge, and agricultural runoff may all contribute to PHE migration into groundwater sources [19,20].

Due to technological and financial constraints in most developing countries, groundwaters are rarely subjected to sophisticated treatment, increasing the health risk associated with PHEs [21]. Furthermore, some of these contaminants are found in higher amounts in groundwater than in surface waters [22]. Exposure to toxic elements can lead to various health outcomes, ranging from acute to chronic implications. These include tumors, skin rashes, melanosis, peripheral arterial disorders, respiratory illnesses, and high blood pressure, among others [23,24]. If current trends persist, the lack of clean water and proper sanitation, as well as other risks linked to poverty and inadequate development, are predicted to have a significant impact on exacerbating health disparities in Sub-Saharan Africa by 2040 [25]. Nigeria has been one of the major contributors to global diarrheal morbidity and mortality. In Nigeria, it is estimated that there are around 151,700 child deaths each year attributed to diarrhea, with peak incidence ranging from 10% to 18.8% [26], and 80,968 deaths caused by unsafe water, sanitation, and hygiene [27].

Water quality and health risks assessment models are two useful tools for preventing and mitigating environmental pollution and human health issues. While numerical models like the IWQI, HMTL, OIP, and SPI aid in analyzing drinking water quality [28–30], health risk assessment models aid in evaluating the deterministic health risks related with PHEs [31,32]. Some researchers have recently begun to combine multiple models to provide a better and more trustworthy study interpretation while limiting the bias associated with single model approach [30]. Thus, the result is obtained from an incremental effect owing to PHEs exposure, resulting in a more accurate assessment. The integrated approach's uniqueness is based on its capacity to deliver meaningful, reliable information throughout the key period of exposure. These findings are critical for environmental monitoring because they allow for quick mitigation of pollution problems in regions and times when exposure levels are not yet critical.

In Nigeria, numerous studies have been conducted across the country to evaluate PHEs in water quality and their potential impact on human health. Researchers in Nigeria have assessed water quality, identified sources, and conducted health risk assessments of PHEs in water resources in densely populated areas [33,34], sing the conventional health risk assessment models proposed by the US-EPA [35]. While this methodology has proven to be useful to some extent, one of its major drawbacks is its inability to analyze PHEs risk at varying levels and times [24,36]. As a result, the HHRISK code (developed by Neris et al. [36]) needed to be expanded and improved. Neris et al. [36] proposed a new HERisk code with expanded scope and functionality to address the limitations of the HHRISK code. The HERisk code evaluates and assesses nine age categories, resulting in a more comprehensive, robust, and accurate assessment.

HERisk is a one-of-a-kind method that uses a systematic tool for evaluating risk in connection to all downstream operations, based on US-EPA-approved toxicological guidelines [37]. The expanded scope and functionality of the HERisk code allows for greater versatility and simplicity in risk assessments, enabling them to be tailored to the changing exposure regime in each location while also accounting for the general impact of aging on the vulnerable population. The HERisk code has been utilized in several studies [24,37–39] to assess the human health risks associated with PHEs in water resources. In a recent study, HERisk was used to evaluate the levels of PTEs in samples of roof-harvested rainwater from wells and storage tanks in Ekpoma, Edo State, Nigeria [38]. In this region of the world, there has not been a comparison assessment of the exposure to water resource health risks using the novel HERisk in two or more densely populated cities. This study would therefore be the first to use the cutting-edge HERisk code to examine health risk exposure related to water resources in two heavily populated Nigerian cities (Awka and Nnewi).

Conducting health risk assessments of PHEs in different age groups provides more comprehensive and reliable information that is crucial for sustainable water resource management [40–43]. Previous research has shown that different age groups are vulnerable to varying levels of PHE risk [44–47]. Additionally, the number of age groups considered in each assessment can affect the amount of information available to policymakers for developing effective water resource management policies [48–51]. Most studies consider only two populations (adults and children), especially for ingestion pathway [42,52–56]. Examining the potential health risks of PHEs for nine distinct age groups can provide a more comprehensive and detailed understanding necessary for effective water resource management. Currently, there are no known studies investigating the potential health risks of PHEs in water sources for different age groups in the Awka and Nnewi regions. Therefore, this study assessed the carcinogenic and non-carcinogenic health risks associated with PHEs in groundwater resources in these areas, specifically considering nine age categories due to potential exposure through ingestion and dermal contact.

The current study used the HERisk code, the NSFWQI, and hierarchical dendrograms in assessing the groundwater quality of the

Awka and Nnewi regions. The samples that were gathered were evaluated to determine their physicochemical characteristics. In this study, the chemical composition of groundwater resources was compared to established regulatory norms, such as those set forth by the World Health Organization (WHO) and the Standard Organization of Nigeria (SON). The resulting estimations were then used to evaluate the health risks associated with oral and dermal consumption of water for nine different age groups. Specifically, the study aimed to (1) assess the elemental composition of groundwater resources and the potential impacts of the PHEs identified; (2) evaluate the suitability of groundwater for drinking using the NSFWQI model; (3) analyze the human health risks associated with PHEs in groundwater resources using the HERisk code; and (4) utilize hierarchical dendrograms to compare and evaluate the spatial-temporal variation in water quality in both the Nnewi and Awka regions. It should be noted that no previous studies have investigated the health risks of PHEs in water supplies for different age groups in these areas. In summary, the objective of our study is to provide detailed and specific information about the quality of groundwater in the disadvantaged areas of Awka and Nnewi urban metropolises in Southeast Nigeria. We aim to identify the major sources of contamination that contribute to the high levels of potentially harmful elements in the groundwater and to calculate relevant indices of interest. By doing so, we aim to provide valuable information for policymakers and stakeholders to implement appropriate remediation strategies and ensure the safety of groundwater for domestic and drinking purposes in these disadvantaged areas. To achieve this objective, we have conducted diversified analyses on the groundwater samples collected from the study area. This research is significant because it determined the level of pollution and its impacts in these areas, especially on the younger ages. It is believed that this paper is comprehensive and novel, as it addresses the urgent need for safe drinking water using a comprehensive health risk evaluation technique.

2. Materials and methods

2.1. Study area description

2.1.1. Location, topography, and climate

The research areas include the Nnewi and Awka districts, both in Anambra State in southeast Nigeria. The study sites are between 5°58′N and 6°12′N in latitude, and 6°53′E and 7°07′E in longitude (Fig. 1), with a maximum altitude of 60–70 m above sea level. The two cities listed above are many kilometres apart and are one of the most industrialized in Anambra State. Both cities are well-known in the Igbo nation due to the industrial activities that occur there. Awka is known for its metal smiting industry [57]. It is home to numerous of leisure, industrial, and governmental institutions, with a populace of about 300,000 people [58]. Nnewi, on the other hand, is a metropolis known for its growing industrialisation and economic activity. Nigeria's first vehicle manufacturing factory is in this city. One of Nigeria's biggest automotive markets is in Nnewi [59]. Owing to the sensitivity of the development in the region, the city is reaching a high population density of over 350,000 persons. In addition, agriculture is the principal source of revenue for many individuals in the study region. In actuality, the research area's residential, economic, industrial, and agricultural activities contribute

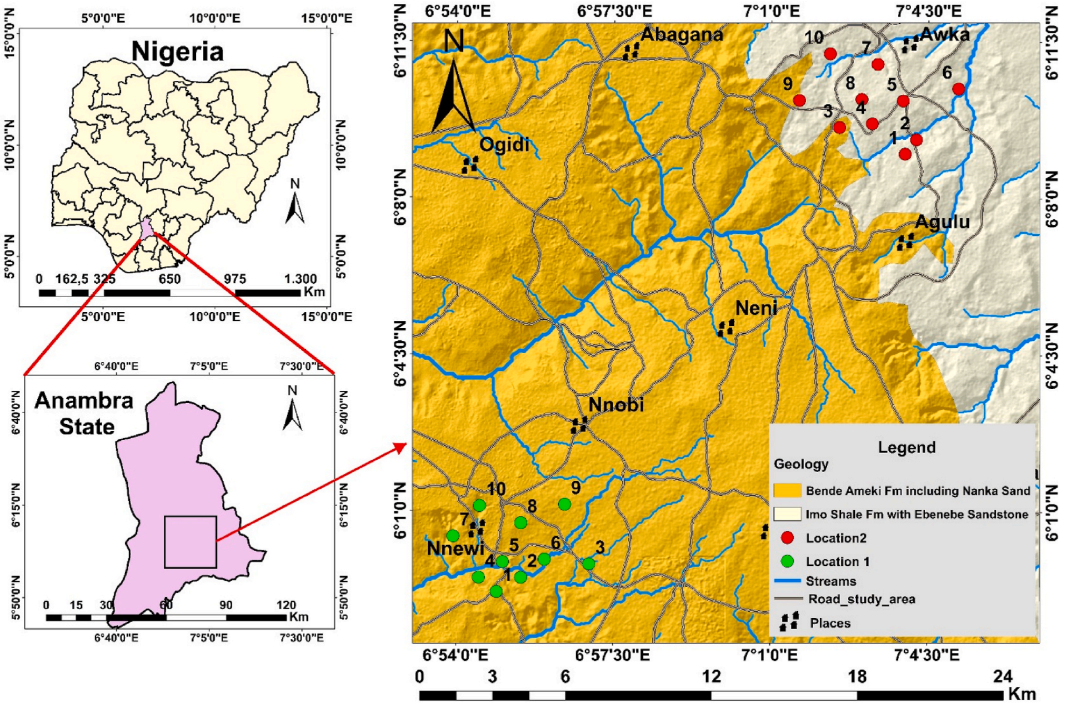

Fig. 1. Location and geologic maps of the study regions with the sample points/numbers represented by Arabic numerals.

significantly to trash production and accumulation. The geography in the research region is uneven, that has an influence on the sewage system via small waterways. The research location, situated in the tropical rainforest region, experiences two distinct seasons: rainy and dry. The rainy season, which lasts from April to October, sees an average annual rainfall of 2000 to 3000 mm. In contrast, the dry season runs from November to March, with an average temperature range of 22 to 33 °C [38,60].

2.1.2. Geology and hydrogeology

Imo and Nanka strata, both of which are in the Niger Delta Basin, are found beneath the research area (Fig. 1). The Imo Formation, which is mostly mudrocks and dates to the Palaeocene era with a few highly compacted sandy parts, is where the majority of Awka City is situated. The Eocene-aged Nanka Formation, on the other hand, underlies the Nnewi region. Light grey mudrocks and ironstones are interbedded with brittle, flaser-bedded fine sand layers [61–63]. The Nnewi metropolis' water table can be as deep as 110 m, with a continuous water volume of 120 m, compared to the Awka district's depth range to the groundwater level of roughly 16 to 35 m and 40 m [60,64].

2.2. Sampling and physicochemical analysis of water resources

Twenty boreholes were collected and analyzed from different places across the study area to check their suitability for human consumption and the associated health risks. Ten groundwater samples were gathered from each district. Previous studies conducted in the same geographical region have shown that heavy metal contamination is likely to be localized and highly variable, depending on factors such as soil composition, land use, and proximity to pollution sources [65,66]. To ensure an accurate assessment of heavy metal contamination, it is crucial to have a sufficient number of sampling points to capture the variability in the area. A review of the literature reveals that previous studies in similar regions have typically used between 10 and 30 sampling points to adequately capture the spatial variability of heavy metals [65–67]. Based on this information, we have selected 20 boreholes for our study, which we believe is a reasonable compromise between ensuring adequate spatial coverage and minimizing the cost and logistical constraints associated with additional sampling points. Groundwater samples were taken in sterile 1-litre plastic containers, marked arbitrarily depending on their sites, and kept in refrigeration condition prior to laboratory investigation. The groundwater samples were tested for various parameters including pH, temperature, electrical conductivity, total dissolved solids, nitrate, chloride, iron, copper, lead, and cadmium. These parameters include physical parameters such as temperature, pH, electrical conductivity, and total dissolved solids, chemical ions such as nitrate and chloride, and heavy metals including iron, copper, lead, and cadmium. The laboratory followed the guidelines set forth by the American Public Health Association (APHA) for sample testing and analysis [68–70]. Using a Testr-2 meter, the pH of the water was assessed in this study. Using a compact, mobile temperature-conductivity-TDS meter, T, EC, and TDS were also recorded on-site (HM Digital COM-100). However, an atomic absorption spectrophotometer (AAS) was used to determine Fe, Cu, Pb, and Cd presence. The detection limit was 0.001 mg/L.

To ensure the accuracy and reliability of our data, we followed a series of quality assurance and quality control (QA/QC) procedures. The APHA-recommended method was employed when doing water sample and preservation [68,69]. Prior to collecting the sample, the groundwater was stirred up many times with the plastic sampler. Before being analyzed, samples were kept at 4 °C in the refrigerator for no more than seven days after being stored in an ice chest and transported to the lab. Portable meters were used to do in-situ measurements on parameters like temperature, pH, conductivity, and total dissolved solids (TDS) [71]. Each sampling day, the meters were calibrated using the appropriate guidelines. Within 6 h after their collection, T, pH, EC, and TDS were all examined in the lab. To prevent any kind of misunderstanding or error, each water sample was accurately labeled [72]. Calibration standards and blanks were included in each batch of samples analyzed to monitor instrument performance and detect potential contamination. All data were recorded and stored in a secure and organized manner, with appropriate metadata included to allow for traceability and reproducibility. Data were reviewed for accuracy and completeness before analysis, and any errors were investigated and addressed [73]. Finally, our results reported in appropriate units were compared with allowable limits according to the guidelines of SON and WHO [74,75].

Table 1
Weighting factor for the NSFWQI evaluation of groundwater quality.

Parameter	Weighting factor
Temperature (°C)	0.10
pH	0.11
EC (μS/cm)	0.18
TDS (mg/L)	0.16
NO_3 (mg/L)	0.10
Cl (mg/L)	0.07
Fe (mg/L)	0.08
Cu (mg/L)	0.02
Pb (mg/L)	0.10
Cd (mg/L)	0.08

2.3. Water pollution evaluation and health risk assessment

2.3.1. Modeling of groundwater quality using the NSFWQI

The National Sanitation Foundation Water Quality Index (NSFWQI) is a widely used index for assessing water quality, developed bys Brown et al. [76] and sponsored by the National Sanitation Foundation of the United States. It is commonly referred to as Brown's index or NSFWQI. The index ranges from 0 to 100, with lower values indicating higher levels of water pollution. The index is scaled downwards as higher pollution levels are associated with lower NSFWQI values.

Many studies have employed NSFWQI in the assessment of water quality [77,78]. Recent research on the NSFWQI water quality index has focused on several key areas, including its application in different settings, its effectiveness at identifying sources of pollution, and its potential for use in predicting future water quality trends. According to a recent study conducted by Tampo et al. [79], NSFWQI was used to assess the water suitability for irrigation and domestic purposes. The study found that the index was able to accurately identify sources of pollution and was effective in predicting future water quality trends based on current data. Another study by Parween et al. [80] evaluated the use of the NSFWQI in assessing the safety of the subtropical urban river in India. The researchers found that the index was able to accurately identify sources of contamination, and that it was effective in guiding public health interventions to improve water quality. The NSFWQI has been extensively used and verified as a means of assessing water quality, which makes it a trustworthy and standardized technique for evaluating the safety of water sources [81].

In this study, we employed water quality parameters, each with a distinct weighting factor to determine the value of this index in both Awka and Nnewi study areas as shown in Equation (1).

The computation of NSFWQI was done in two steps:

$$\sum_{i=1}^{n} wiqi \tag{1}$$

The HERisk code takes into account the weight factor, wi, which assigns a value between 0 and 1 for the importance of the ith water quality parameter, as shown in Equation (2). Table 1 displays the weight factors assigned to the parameters analyzed in this study. The allocation of the weight factors was based on the significance of each water quality parameter and relevant water quality guidelines, as reported in previous studies [24,76,78,81]. The parameter weighting approach is a useful tool to evaluate the water quality index and compare the water quality status of different sources [80,82–84]. In the current study, ten parameters were taken into account when calculating the NSFWQI in the two locations.

$$\sum_{i=1}^{n} w_i = 1 \tag{2}$$

The status of the water quality, based on the NSFWQI, ranges from highly unsuitable (an index value between 0 and 25), unsuitable (an index value between 25 and 50), medium (an index value between 50 and 75), good (an index value between 75 and 90), and excellent (an index value between 90 and 100) [78,82,84] (Table 2).

2.3.2. Modeling the health risk of groundwater using the HERisk code

An important method used in the management of polluted areas is the human health risk assessment, which helps with risk management and hazardous area remediation by identifying risks related to exposure to chemical pollutants [43,85–87]. The present study employed the HERisk code, which was developed by Neris et al. [37] as a novel and innovative approach for assessing health risks. The HERisk code is known for its ability to provide quick and accurate risk analysis. The main innovation of this approach is that it enables risk estimates to be customized toward the varied exposure routes in a region while considering the total aging effect of the affected group, offering HERisk additional flexibility and ease [37,38]. Also, the HERisk code allows for conducting concurrent risk assessments without any restrictions on the number of chemical species, locations, or times.

The first step in the HERisk assessment is to calculate the daily intake dosage (for oral route) and the daily absorbed dosage (for dermal route) in order to represent the actual amount of PHEs that enter human body systems. The daily dose of water consumed orally can be calculated using Equation (3), while the daily dose of water consumed through the skin can be calculated using Equation (4).

$$D^{IA}_{ing\_w}(t) = \sum_{t=\Delta t}^{ED} \frac{C_w(t) \bullet IR_w(i) \bullet FI_w \bullet EF(i) \bullet \Delta t}{BW(i) \bullet AT} \tag{3}$$

Table 2
Water quality classification based on NSFWQI.

Water quality description	Index value range
Excellent	90–100
Good	75–90
Medium	50–75
Unsuitable	25–50
Very unsuitable	0–25

$$D_{der\_w}^{IA}(t) = \sum_{t=\Delta t}^{ED} \frac{C_w(t) \bullet CF_3 \bullet SA_w(i) \bullet PC \bullet ET_w \bullet EV_w(i) \bullet EF(i) \bullet \Delta t}{BW(i) \bullet AT} \tag{4}$$

The initial age is denoted as IA, and $C_w(t)$ represents the concentration of PHEs in water at time t (mg L^{-1}). ED represents the duration of exposure in years, FI_w is the fraction of water consumed, $IR_w(i)$ is the intake rate of water for age category i (L d^{-1}), EF(i) is the exposure frequency for age category i (d y^{-1}), Δt is the time variation in years, AT is the average time in days, BW(i) is the body weight for age category i (kg), CF_3 is the volumetric conversion factor (L cm^{-3}), $SA_w(i)$ is the skin surface area for age category i that is accessible for water contact (cm^2), and PC is the dermal permeability of PHEs (cm h^{-1}). Additionally, ET_w represents the amount of time spent in the water when swimming or taking a bath for age category i (h $event^{-1}$), and $EV_w(i)$ is the number of times spent swimming or taking a bath for age group i (events d^{-1}) [24,37].

The age at which inhabitants are first exposed to PHEs is crucial information since age-dependent characteristics change over time and vary based on the individual's age group. It is significant to note that there are nine age groups covered by the IA. Neris et al. [37] posited that the HERisk code does individual health risk assessments for each beginning age (IA = 1, 2, 3, 6, 11, 16, 18, 21 and 65 years). The age groupings *i* used in this model are as follows: >65 years ($i = 9$), 21 to < 65 years ($i = 8$), 18 to < 21 years ($i = 7$), 16 to < 18 years ($i = 6$), 11 to < 16 years ($i = 5$), 6 to < 11 years ($i = 4$), 3 to < 6 years ($i = 3$), 2 to < 3years ($i = 2$), and 1 to < 2 years ($i = 1$).

After determining the dosages for each exposure pathway and chemical species, it is possible to estimate the non-carcinogenic hazard quotient (HQ) and probable carcinogenic risk (CR) for early ages IA. The non-cancer risk (HQ) at time t for initial age IA was calculated using Eq. (5), while the cancer risk at time t for initial age IA was calculated using Eq. (6). The aggregated non-cancer risk at time t for initial age IA was calculated using Eq. (7), and the total or cumulative non-cancer risk at time t for initial age IA was calculated using Eq. (8). Finally, the total or cumulative cancer risk at time t for initial age IA was calculated using Eq. (10).

$$HQ_w^{IA}(t) = \frac{D(t) \bullet BAF}{RfD} \tag{5}$$

$$CR_w^{IA}(t) = D(t) \bullet SF \bullet BAF \bullet ADAF \tag{6}$$

$$HI_{agg}^{IA}(t) = \sum_{w=1}^{z} HQ_w(t) \tag{7}$$

$$HI_{tot}^{IA}(t) = \sum_{j=1}^{n} HI_{agg.j}(t) \tag{8}$$

$$CR_{agg}^{IA}(t) = \sum\nolimits_{w=1}^{z} CR_w(t) \tag{9}$$

$$CR_{cum}^{IA}(t) = \sum\nolimits_{j=1}^{n} CR_{agg.j}(t) \tag{10}$$

The definitions of the terms used in Eqs. (5)–(10) are as follows: $D^{IA}(t)$ = dose at time *t* for initial age *IA* (mg kg^{-1} d^{-1}); *SF* = slope factor of PHEs (mg kg^{-1} $d^{-1})^{-1}$; *BAF* = PHEs dose fraction or simply the bioavailability factor; *RfD* = reference dose of the PHEs (mg kg^{-1} d^{-1}); *ADAF* = age dependent adjustments factors; and *n* = number of the PHEs [24,37,38].

2.4. Data processing using statistical techniques

Large datasets can be streamlined and organized using statistical analysis to produce actionable information [88]. The water quality dataset was analyzed using various statistical techniques, such as boxplots, correlation analysis, and hierarchical cluster

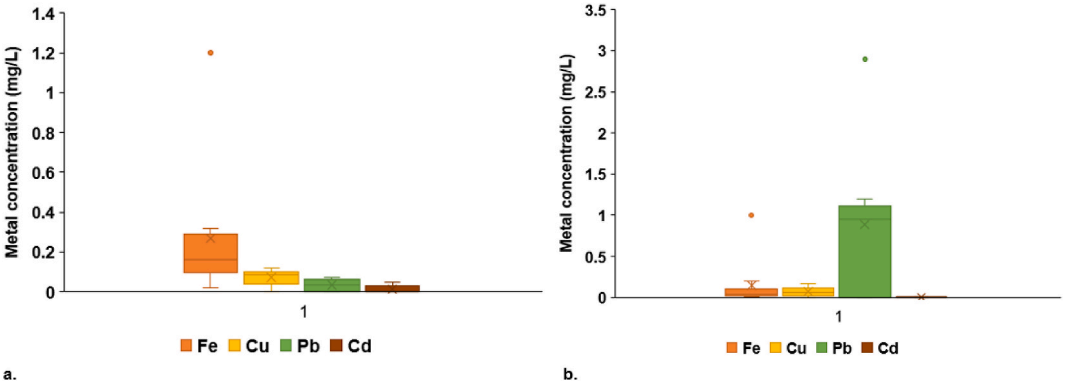

Fig. 2. Statistical distribution and variation of the heavy metals shown using box and whisker plots (**a**) Nnewi, (**b**) Awka.

analysis [89–91]. Boxplots are a highly helpful and practical technique for summarizing a dataset and are frequently used in exploratory data analysis [92]. Additionally, it displays the extent of imbalance, the amount of distribution, and any odd numerical values. Boxplots were used in this study to depict the statistical distribution of the PHE concentrations in the study areas of Nnewi (Fig. 2a) and Awka (Fig. 2b). The concentrations of heavy metals in each region were then presented using box and whisker plots. The utilization of boxplots in this study was highly informative as they offered valuable insights into the distribution of heavy metals in the water samples. This approach facilitated the identification of potential sources of pollution, as illustrated in Fig. 2a and b. In addition, hierarchical cluster analysis (HCA) was conducted to analyze and establish relationships between various water quality and health risk indicators (see Figs. 3–5). HCA was also used to cluster the samples based on their peculiar characteristics. To create spatiotemporal networks among samples, the HCA grouped spatial-temporal variability by commonalities in the groundwater quality datasets. Dendrograms provided visual representations of the clustering process by depicting each group and those nearby while drastically shrinking the size of the initial data (Figs. 3–5). Using Pearson's correlation analysis, it was possible to gauge the level of consistency between the health risk and water quality indices. This analysis also showed the trends in the water quality and health risk indexical models.

3. Results and discussion

3.1. General water quality description

Table 3 presents the groundwater quality data for Nnewi and Awka, including physicochemical analyses and descriptive statistical results (Tables 3a and b). In addition, Table 3(c) provides recommended levels for each parameter according to the Standard Organization of Nigeria [74] and the World Health Organization [75]. Boxplots were used to depict the statistical distribution of heavy metal concentrations in the study areas (Fig. 2a and b). The boxplots reveal that the concentrations of all heavy metals investigated exhibit wide variation, with Fe > Cu > Pb > Cd in Nnewi (Fig. 2a) and Pb > Fe > Cu > Cd in Awka (Fig. 2b) showing the highest amounts. These boxplots provide valuable information about heavy metal distribution and potential pollution sources in the water samples. Hierarchical cluster analysis was also performed to identify the relationships between the water quality parameters and health risk indicators (Figs. 3–5).

3.1.1. pH

pH is a critical factor that influences water quality. The pH scale is used to determine the acidity or alkalinity of water [93]. The pH range for drinking water is typically between 6.50 and 8.50 [75]. Water with a pH of 6 to 8.5 is considered to be safe and beneficial [94], while water with a pH of 6 or lower is corrosive and can cause harm to the skin and eyes [95]. Acidic water can also corrode metal pipes and plumbing. Conversely, alkaline water helps to disinfect water. The water samples from the research locations in Nnewi and Awka have pH values ranging from 4.2 to 7.5 and 4.8 to 6.1, respectively (Table 3). The results indicate that 60% of the water samples from the Nnewi area (N-WS2, N-WS3, N-WS4, N-WS6, N-WS7, and N-WS8) had a slightly higher acidity level than the permissible limit for safe drinking water. However, the pH of the remaining water samples in the region (N-WS1, N-WS5, N-WS9, and N-WS10) fell within the recommended range.

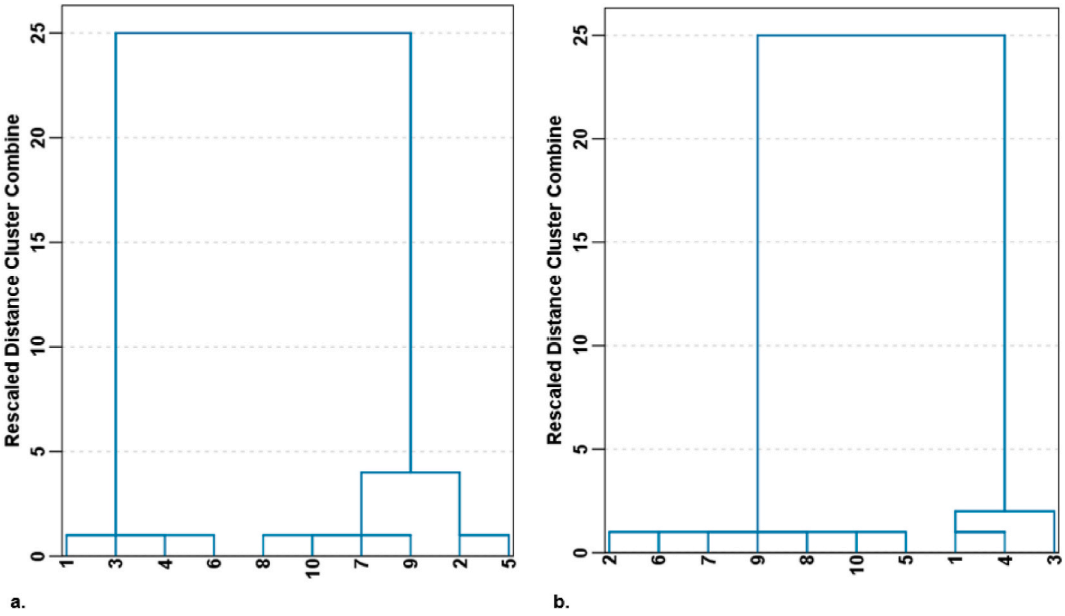

Fig. 3. Hierarchical dendrograms for classifying the water quality based on NSFWQI for (**a**) Nnewi and (**b**) Awka.

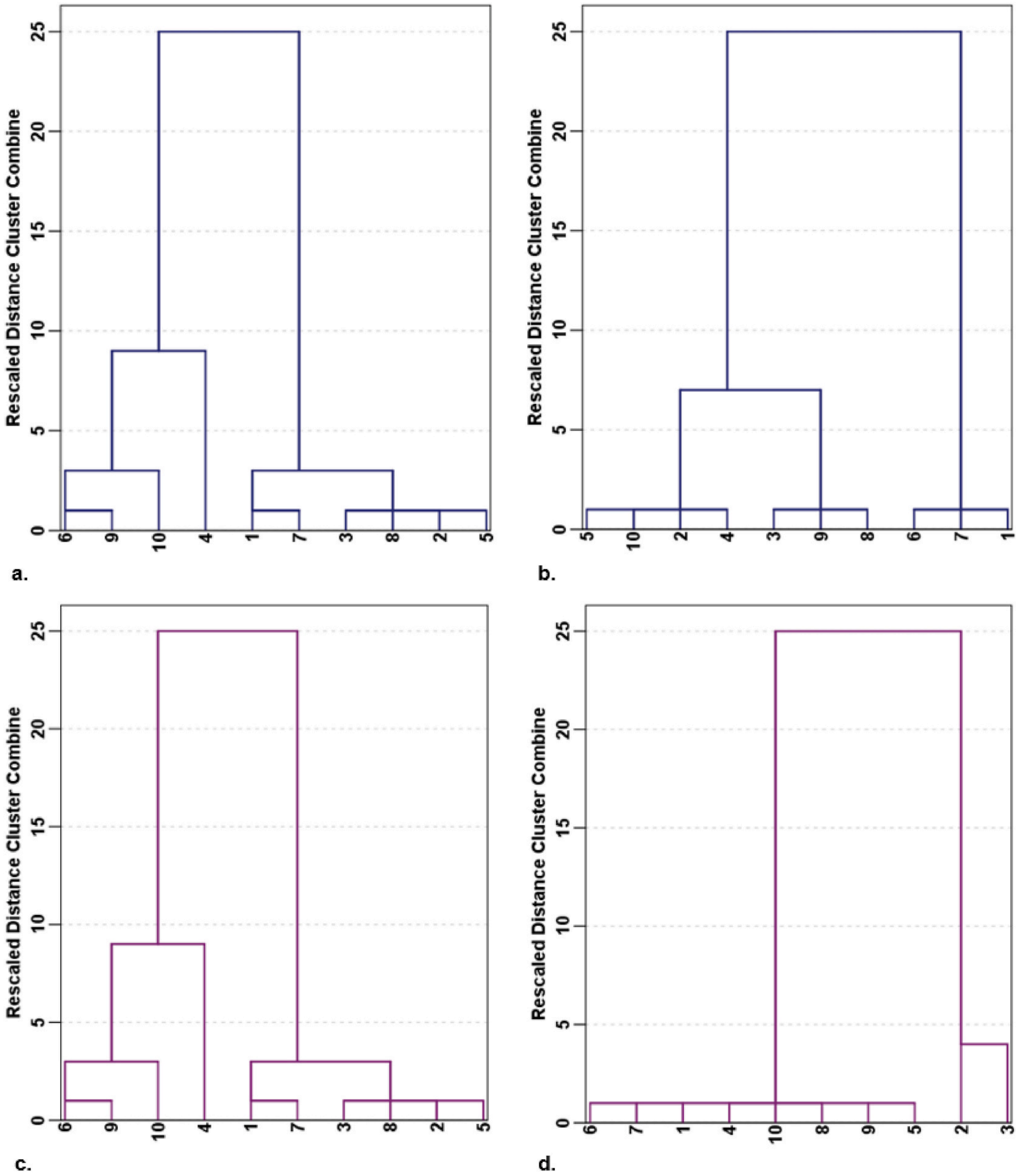

Fig. 4. Hierarchical dendrograms for classifying the health risks in Nnewi (**a**) $HI_{total\text{-}oral}$ (**b**) $CR_{total\text{-}oral}$, (**c**) $HI_{total\text{-}dermal}$, and (**d**) $CR_{total\text{-}dermal}$.

3.1.2. Electrical conductivity (EC)

Water that contains dissolved ions, such as salts, has electrical conductivity, which is the ability to conduct an electric current. When dissolved minerals are present, the water acts as a conductor for electric current [96]. According to Refs. [74,75] recommendations, the allowable limit of EC for drinking purposes is 1000 μS/cm. It was discovered that the two research areas, Nnewi and Awka, had a range of EC values that were within the normal limit (Table 3). Direct effects of conductivity on human health are not present. Due to the water's dissolved minerals, high conductivity can reduce its aesthetic appeal. Conductivity of water must be carefully observed for industrial and agricultural operations. The metal surfaces of equipment like boilers may corrode when exposed to highly conductive water. The water heater system and faucets are two examples of residential appliances to which it also applies. As a result of high conductivity, plant species that provide food and create habitat could also be intensely affected [97].

3.1.3. Total dissolved solids (TDS)

The total dissolved solids (TDS) refer to the combination of inorganic and organic substances present in water in a dissolved state [98]. TDS levels in groundwater samples from the study regions of Nnewi and Awka range from 10.2 to 82.3 mg/L and 12 to 110 mg/L,

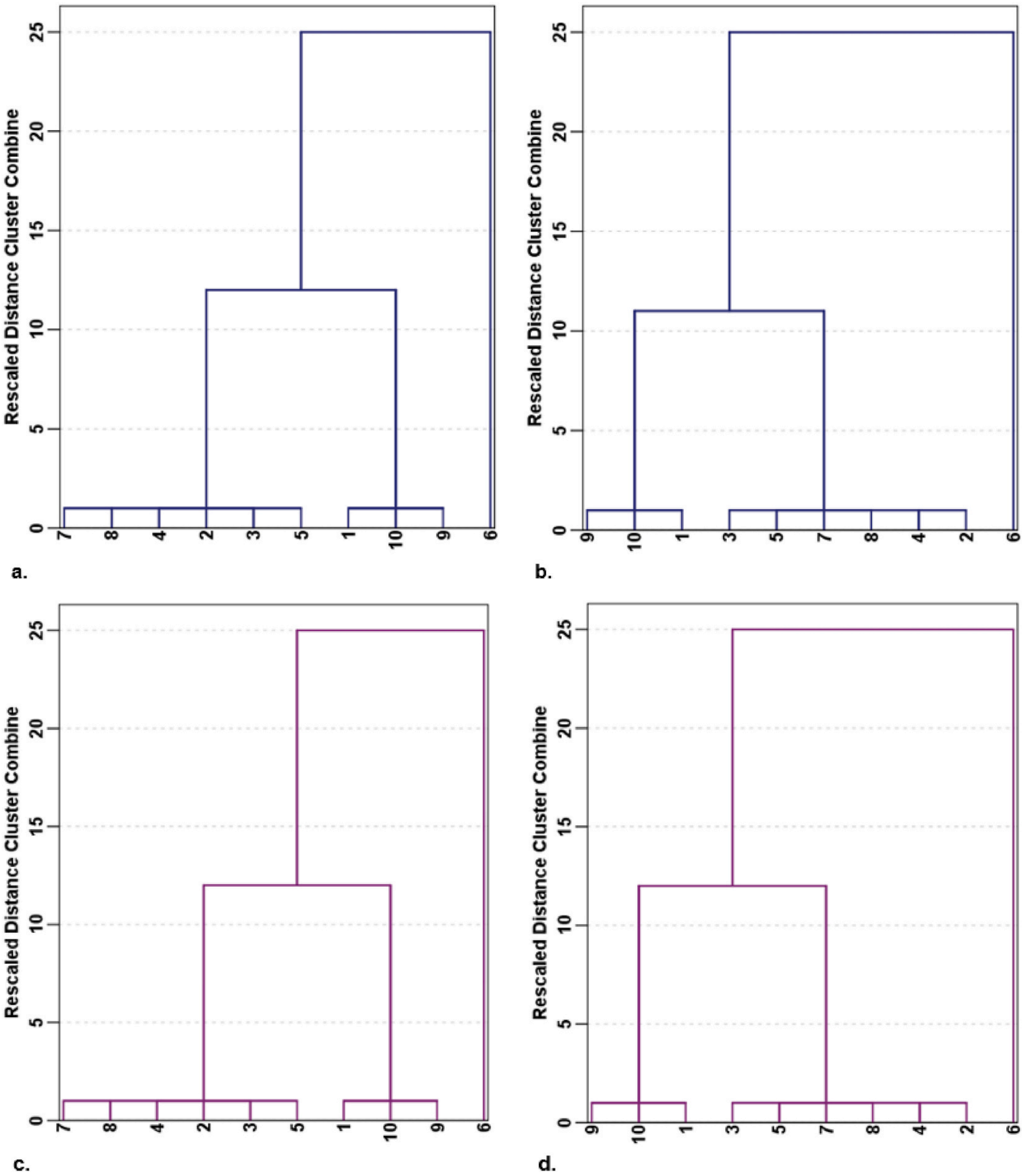

Fig. 5. Hierarchical dendrograms for classifying the health risks in Awka (**a**) $HI_{total\text{-}oral}$ (**b**) $CR_{total\text{-}oral}$, (**c**) $HI_{total\text{-}dermal}$, and (**d**) $CR_{total\text{-}dermal}$.

respectively (Table 3). According to WHO [75], the EC allowable limit for groundwater samples is 1000 mg/L, and all the samples were found to be below this threshold, making them all suitable to drink. The relationship between EC and TDS may be due to calcite and dolomite minerals weathering. The rocks that make up the research area's subsurface geology may be a primary source for these minerals. Additionally, lowering the pH will hasten the breakdown of these minerals, raising the TDS. It can be seen from Table 3 that water samples from the Awka area had higher TDS readings than those in the Nnewi area when the pH of the water was low. These mineral ions may have disintegrated in the water due to the water's low pH, which is known to facilitate chemical weathering.

3.1.4. Nitrate (NO_3)

The data collected revealed a range of nitrate concentrations in the groundwater samples. In the Nnewi study area, nitrate concentrations ranged from 0.03 to 2.10 mg/L, while in the Awka study area, they ranged from 0.4 to 4.2 mg/L (Table 3). None of the water samples exceeded the World Health Organization's (WHO) permissible level of 50 mg/L for nitrate, indicating that the water in these study areas is safe for consumption [75]. Infants with immature digestive systems are particularly susceptible to the adverse effects of high levels of nitrate in drinking water, which can cause methemoglobinemia [32]. Nitrate concentrations between 100 and 200 mg/L begin to harm the general public's health, while the impact on any one person will vary depending on several factors.

Table 3
Analytical physicochemical register of groundwater quality for the current study.

Sample code	T (°C)	pH	EC (µS/cm)	TDS (mg/L)	NO$_3$ (mg/L)	Cl (mg/L)	Fe (mg/L)	Cu (mg/L)	Pb (mg/L)	Cd (mg/L)
(a) Nnewi water quality data										
N-WS1	26	7.5	108.4	82.3	0.18	70.5	0.08	0	0	0
N-WS2	27	4.5	92.5	17.9	0.17	68.2	1.2	0.1	0.06	0
N-WS3	25	6.2	35.2	15.6	1.20	39	0.28	0.09	0.03	0
N-WS4	26	5.1	87.5	11.75	2.10	38	0.12	0.12	0.07	0.05
N-WS5	28	7.3	30.5	62.8	1.00	42	0.13	0.08	0.06	0
N-WS6	28	6.3	89.3	65	0.15	48	0.02	0.04	0	0.03
N-WS7	25	4.7	64.1	21.78	0.04	18.3	0.24	0.09	0	0
N-WS8	28	4.2	50	10.5	0.08	28	0.19	0.03	0.04	0
N-WS9	27	7.3	66	10.2	0.03	20.15	0.32	0.06	0.03	0.02
N-WS10	26	6.9	38	28.8	0.04	25.73	0.1	0.1	0.06	0.03
(b) Awka water quality data										
A-WS1	26	4.8	412	110	1.1	63	0.07	0.02	0	0.007
A-WS2	27	5.5	120	54	0.8	34	0.2	0.09	1.2	0.009
A-WS3	24	5.6	240	87	2.3	55	0.02	0.03	0.8	0.007
A-WS4	26	6	180	92	4.2	76	0.01	0.15	1.09	0.002
A-WS5	24	5.9	17	24	0.8	80	1.00	0.17	0.9	0.001
A-WS6	25	5.8	12	36	0.9	94	0.07	0	2.9	0
A-WS7	23	6.1	41.5	40	0.5	149	0.02	0.08	1	0.003
A-WS8	27	6	43	20	1.2	67	0.01	0.05	1	0.004
A-WS9	27	5.8	60	12	0.6	82	0.05	0.1	0	0
A-WS10	26	5.5	33	25	0.4	60	0.03	0	0	0.006
(c) Water quality standards										
SON (2015)	Ambient	6.5–8.5	1000	1000	50	250	0.3	0.1	0.01	0.003
WHO (2017)	Ambient	6.5–8.5	1000	1000	50	250	0.3	0.05	0.01	0.003

However, they are not thought to be a sign of the presence of more dangerous agricultural or domestic pollutants like pathogens or pesticides [99]. The release of nitrogen-containing pollutants into the environment may result in the conversion of these pollutants to nitrate, which can then percolate into the groundwater at high concentrations. Studies have shown that elevated levels of nitrate in drinking water can have significant health effects, particularly for vulnerable populations such as neonates. Exposure to high nitrate levels in drinking water has been linked to conditions such as hypertension in adults and methemoglobinemia in infants [99].

3.1.5. Chloride (Cl)

The concentration of chloride in water is variable and dependent on the type of water. It is typically present in water as sodium and potassium salts and occurs naturally. Chloride is considered to be a stable component of water, and its concentration is not affected by either biochemical or physicochemical processes [100]. Although the chloride concentrations were found to be within the permissible limit of 250 mg/L in both Nnewi and Awka regions, the water samples from Awka showed higher concentrations than those from Nnewi. The high levels in Awka could be attributed to the discharge of chloride-rich sewage and municipal runoff by the local population, which eventually seeped into groundwater sources. Chloride salts, used as essential components in the manufacture of confectioneries, may also have been discharged as pollutants in both Nnewi and Awka areas under investigation.

3.1.6. Iron (Fe)

In the Nnewi area, the concentration of Fe ranged from 0.02 mg/L to 0.38 mg/L with an average of 0.268 mg/L, while in Awka, the concentration ranged from 0.01 mg/L to 0.07 mg/L with an average of 0.148 mg/L (Table 3). The results indicated that only 20% of water samples from the Nnewi area (N-WS2 and N-WS9) exceeded the permissible limit (0.3 mg/L) set by the Standard Organization of Nigeria (SON) [73] nd the World Health Organization (WHO) [75], whereas only 10% of water samples from the Awka area exceeded the limit. The greater iron content in the study locations may come from natural sources. This can be the result of soil characteristics, iron-rich deposits, and mineral degradation [101]. Even though iron may not be harmful to the human body, it can make water taste sour when it's available in significant quantities. Iron-rich water supplies cause flavor and coloring problems, drainage system deterioration, and liver ailments in those who consumed them. The risk of anemia would be significantly higher for those exposed to low concentrations [3].

3.1.7. Copper (Cu)

Despite being a necessary component of the human diet, copper levels exceeding 1 mg/L can give water an unpleasant flavor. Mineral dissolution, industrial discharges, and pesticide use are all ways that copper enters the water system [102]. The mean Cu concentrations in water samples from Nnewi exceeded the WHO [75] allowable limit (0.05 mg/L), with a mean of 0.071 mg/L. The WHO [75] guidelines indicate that heavy toxic waste from items like coatings, batteries, and freezers caused 70% of the samples (N-WS2, N-WS3, N-WS4, N-WS5, N-WS7, and N-WS9) to exceed the permitted amount. The distribution pattern remained unchanged for groundwater samples taken in the Awka region. A Groundwater samples A-WS2, A-WS4, A-WS5, A-WS7, and A-WS9 also exceeded the WHO [75] guidelines for drinking water (Table 3). A little quantity of Cu is, nevertheless, necessary for metabolism and the production of numerous enzymes, cytochromes, and hemoglobin. On the other hand, excessive copper intake can cause neurological issues, hypertension, liver issues, and renal issues [103].

3.1.8. Lead (Pb)

Lead is known to cause a range of biological, metabolic, and behavioral abnormalities in both humans and animals, which impairs the kidney, liver, central and peripheral neurological systems, as well as the cardiovascular system [104]. Pipes and solder are two things that are virtually always made of Pb. In older plumbing and transport channels, Pb-pipes may be used. It is important to evaluate lead concentrations in water at the tap rather than at the source, as high levels of lead in drinking water can result from the corrosion of pipelines. In the Nnewi area, some groundwater samples had lead concentrations above the allowable limits set by the SON and WHO, with 70% of water samples exceeding these limits (N-WS2, N-WS3, N-WS24, N-WS5, N-WS8, N-WS9, and N-WS10) (Table 3(a, c)). Meanwhile, in Awka, the average lead concentration in groundwater samples was 0.889 mg/L, and 70% of all water samples (A-WS2, A-WS3, A-WS4, A-WS5, A-WS6, A-WS7, and A-WS8) exceeded the WHO and SON drinking water limits of 0.01 mg/L. Higher levels of lead were detected in A-WS2, A-WS4, and A-WS6 (Table 3 (b, c)). The release of Pb-containing home wastewater, car exhaust, industrial discharges, smoke, and photochemical smog from gas and oil fueled plants may be to blame for the elevated Pb levels reported in the water in these areas. Lead contamination in drinking water can lead to anemia, headaches, brain damage, and nervous system disorders in both people and animals.

3.1.9. Cadmium (Cd)

Cadmium is present in nature and can also be released into the environment through natural means or human activities such as the combustion of fossil fuels or waste, as well as the use of fertilizer and application of wastewater sludge on soil [100]. Smoking is a substantial additional cause of cadmium exposure in humans, according to WHO (2008). In this study, the mean concentration of Cd in groundwater samples was compared to the allowable limit of 0.003 mg/L. The results showed that 10% of the water samples from the N-WS4 area exceeded the permissible limit set by the SON (2015) and WHO (2017) guidelines. Additionally, 50% of all water samples exceeded the threshold of 0.003 mg/L established by the drinking water guidelines of SON [74] and WHO [75]. The high levels of Cd may be attributed to the corrosion and eventual breakdown of nearby chalcopyrite and pyrite ores. Overconsumption of cadmium can lead to gastrointestinal problems, while short-term inhalation exposure can cause severe respiratory inflammation and lung problems [100].

3.2. NSFWQI modeling of groundwater quality

It has been possible to swiftly obtain information about freshwater quality and monitor water quality by developing and using indexical and numerical models [77]. Indexical models have shown to be a realistic approach that considers the essential environmental and hydrogeochemical factors that reveal pollution problems in a water body. Groundwater can be used to provide potable water for drinking, and it may not be potentially dangerous to the health of adults or children when public health hazards are taken into account [105]. Furthermore, the use of indexical approaches aids in clearly illustrating the status of groundwater quality during a

Table 4
NSFWQI results and classification of the groundwater samples in Nnewi and Awka districts.

Sample	NSFWQI	Water quality status
(a) Nnewi NSFWQI result		
N-WS1	29.49	Unsuitable
N-WS2	23.27	Very unsuitable
N-WS3	29.42	Unsuitable
N-WS4	34.15	Unsuitable
N-WS5	17.18	Very unsuitable
N-WS6	35.52	Unsuitable
N-WS7	10.74	Very unsuitable
N-WS8	9.68	Very unsuitable
N-WS9	13.10	Very unsuitable
N-WS10	10.05	Very unsuitable
(b) Awka NSFWQI result		
A-WS1	61.69	Medium
A-WS2	26.70	Unsuitable
A-WS3	99.54	Excellent
A-WS4	77.09	Good
A-WS5	15.37	Very unsuitable
A-WS6	26.50	Unsuitable
A-WS7	20.89	Very unsuitable
A-WS8	13.22	Very unsuitable
A-WS9	18.75	Very unsuitable
A-WS10	11.99	Very unsuitable

study period. NSFWQI model was used in this study to estimate the groundwater supplies' appropriateness for drinking. Table 4 exhibits all the NSFWQI scores from the Nnewi and Awka study regions. The NSFWQI for the Nnewi region ranged between the unsuitable quality and very unsuitable quality categories (Table 4a). The findings indicate that in the Nnewi region, 60% of groundwater samples had poor water quality, while 40% of samples had inadequate water quality, as shown in Table 4a.

In the Awka region, the percentages were 50% very unsuitable, 20% unsuitable, 10% medium, 10% good, and 10% excellent (Table 4b). Based on the NSFWQI scores listed in Table 4, it can be inferred that the groundwater quality in both Nnewi and Awka regions is not suitable for drinking purposes. The NSFWQI scores for Nnewi groundwater samples ranged from 9.68 to 35.52, with 40% of samples being deemed unsuitable, while for Awka, the scores ranged from 11.99 to 99.54, with an average NSFWQI of 31.17. Thus, it can be concluded that the groundwater quality in both regions is generally unsuitable for human consumption. These findings suggest that the water quality in the area is directly influenced by the amount of rainfall that occurs there. Runoff from agriculture and urban activities cause significant amounts of these contaminants to enter the groundwater systems. Because wastewater treatment facilities lack separate pipes for wastewater and rainfall water, excess wastewater is further discharged in this area into the groundwater without being treated.

3.3. HERisk modeling of human health risk for nine age groups

3.3.1. Elemental daily dosage consumption, hazard index, and risk of cancer

Based on the results presented in Table 5, the non-carcinogenic risk and carcinogenic risk of PHEs were evaluated using the CRcum, HIagg, and HItot indices. Elemental daily dosage consumption, hazard quotients, and cancer risks were considered to determine the contribution of each PHE. For detailed information on daily dosage intake, hazard quotient, and cancer risk values, please refer to Tables S1–S27 in the Supplementary Material.

The findings of this study show that all age groups consuming contaminated groundwater in the Nnewi and Awka areas are highly vulnerable to ingesting or absorbing Fe, Cu, Pb, and Cd, as shown in Table 5 and S1–S27. The hazard quotient values were calculated using the US-EPA recommended method for human health risk assessment, which involved summing up the ingestion and absorption hazard quotients for the PHEs analyzed in this study. The HQ results revealed that for both adults and children, Cd had the highest average value among the PHEs in Nnewi water samples, followed by Pb, Cu, and Fe, while in Awka water samples, the order was Pb, Cd, Cu, and Fe (Table 5 and S1–S27). Moreover, Tables S1–S27 indicated that the hazard quotients of PHEs demonstrated the same pattern across all age groups.

According to Table 5, it was observed that the effects of the two carcinogens (Pb and Cd) varied among age groups for both oral and dermal exposure. In both the Nnewi and Awka regions, Cd and Pb contributed more to the risk compared to Cu and Fe. Overall, the PHEs posed a greater risk when ingested orally for all the age groups considered in this study. However, dermal absorption was associated with lower hazards in terms of daily dose intake, hazard quotients, and cancer risks for all age groups. Based on these findings, it can be concluded that the residents in these regions are at a higher risk of exposure through drinking contaminated water rather than taking showers in it. Moreover, the younger age groups are expected to be at a higher risk than the adult age groups.

3.3.2. Non-carcinogenic and carcinogenic health risks due to ingestion

The HERisk analysis results for non-carcinogenic health risk (HI_{agg} and HI_{tot}) associated with the consumption of contaminated groundwater resources for the nine age groups in the Nnewi and Awka regions are displayed in Tables 6a and 6b, respectively. In this study, the hazard index (HI) was utilized to assess the likelihood of PHEs causing a non-carcinogenic health risk. An HI value greater than 1 indicates a non-carcinogenic health risk above the acceptable benchmark, while an HI value less than 1 indicates the presence of PHEs within the permissible guideline [24]. HI values less than 0.1 imply no risks, values between 0.1 and 1 imply minimal risks, values between 1 and 4 imply moderate risks, and HI values greater than or equal to 4 suggest chronic risks to human health [106].

According to the observed HI_{agg} values for the different age groups, it was discovered that every age group is exposed to a high chronic risk in the study regions (Nnewi and Awka) because of ingesting contaminated water resources. However, it was found that age groups 1 to <11 and >65 are higher at risk than age groups 16 to <65 in both Nnewi and Awka regions (Table 6a, b). Children between the ages of 1 and 2 are anticipated to be at a higher risk, which may be related to their lower ingestion rates and smaller body weights [37,38]. Furthermore, ageing, which typically causes immune systems to deteriorate, may be the cause of the greater risk shown in people aged 1 to 11 and over 65 compared to those in the age ranges of 16 and over 65. Due to the severe total non-carcinogenic risk

Table 5

Results of the daily dose intake, hazard quotients and carcinogenic risks of the PHEs for the nine age groups.

Initial age (age group range)	Daily dose intake	Hazard quotient	Cancer risk
1 (1 to < 2 years)	Table S1	Table S2	Table S3
2 (2 to < 3years)	Table S4	Table S5	Table S6
3 (3 to < 6 years)	Table S7	Table S8	Table S9
6 (6 to < 11 years)	Table S10	Table S11	Table S12
11 (11 to < 16 years)	Table S13	Table S14	Table S15
16 (16 to < 18 years)	Table S16	Table S17	Table S18
18 (18 to < 21 years)	Table S19	Table S20	Table S21
21 (21 to < 65 years)	Table S22	Table S23	Table S24
65 (> 65 years)	Table S25	Table S26	Table S27

Table 6
Aggregated and cumulative/total non-carcinogenic risk due to water ingestion for the nine age groups in Nnewi and Awka regions.

Sample	HI_{agg}-1	HI_{agg}-2	HI_{agg}-3	HI_{agg}-6	HI_{agg}-11	HI_{agg}-16	HI_{agg}-18	HI_{agg}-21	HI_{agg}-65	HItot
(a) Nnewi aggregated and total oral non-carcinogenic risks										
N-WS1	2.008	2.008	3.008	6.008	11.008	16.008	18.008	21.008	65.008	142.069
N-WS2	2.424	3.424	4.424	7.424	12.424	17.424	19.424	22.424	66.424	154.814
N-WS3	3.748	2.748	3.748	6.748	11.748	16.748	18.748	21.748	65.748	148.733
N-WS4	4.878	6.878	7.878	10.878	15.878	20.878	22.878	25.878	69.878	185.903
N-WS5	1.289	3.289	4.289	7.289	12.289	17.289	19.289	22.289	66.289	153.597
N-WS6	2.069	4.069	5.069	8.069	13.069	18.069	20.069	23.069	67.069	161.617
N-WS7	0.173	2.173	3.173	6.173	11.173	16.173	18.173	21.173	65.173	143.556
N-WS8	2.834	2.830	3.800	6.831	11.830	16.830	18.830	21.830	65.830	149.470
N-WS9	2.035	4.035	5.035	8.035	13.035	18.035	20.035	23.035	67.035	160.317
N-WS10	3.319	5.319	6.319	9.319	14.319	19.319	21.319	24.319	68.319	171.871
(b) Awka aggregated and total oral non-carcinogenic risks										
A-WS1	0.507	2.507	3.507	6.507	11.507	16.507	18.507	21.507	65.507	146.560
A-WS2	23.626	25.626	26.626	29.626	34.626	39.626	41.626	44.626	88.626	354.636
A-WS3	15.757	17.757	18.757	21.757	26.757	31.757	33.757	36.757	80.757	283.810
A-WS4	21.146	23.146	24.146	27.146	32.146	37.146	39.146	42.146	86.146	332.316
A-WS5	17.588	19.588	20.588	23.588	28.588	33.588	35.588	38.588	82.588	300.293
A-WS6	55.245	57.245	58.245	61.245	66.245	71.245	73.245	76.245	120.245	639.203
A-WS7	19.383	21.383	22.383	25.383	30.383	35.383	37.383	40.383	84.383	316.446
A-WS8	19.399	21.399	22.399	25.399	30.399	35.399	37.399	40.399	84.399	317.587
A-WS9	0.171	2.171	3.171	6.171	11.171	16.171	18.171	21.171	65.171	143.543
A-WS10	0.403	2.403	3.403	6.403	11.403	16.403	18.403	21.403	65.403	145.626

that was discovered in every groundwater sample in the study regions, the HI_{tot} result is comparable to the results of the HI_{agg} (Table 6a, b). The results show that all groundwater samples in the Nnewi and Awka regions have a very high non-carcinogenic risk. The samples from NSW-4 in the Nnewi area (185.903) and AWS-6 in the Awka region (639.203) were found to have the highest risk compared to the other samples in their respective regions. The findings from HI_{tot} and HI_{agg} in Tables 6a and 6b are consistent with the high total non-carcinogenic risk observed in all groundwater areas.

Tables 7a and 7b presents the results of the HERisk coding for carcinogenic health risk (CR_{agg} and CR_{tot}) associated with the consumption of contaminated groundwater resources by the nine age groups in the Nnewi and Awka regions, respectively. According to the PHE categorization, a cancer risk rating of less than 1×10^{-6} or between 1×10^{-6} and 1×10^{-4} is permissible [24]. The analysis revealed that ingestion of polluted water in the Nnewi and Awka regions poses a cancer risk to all age groups, as indicated by the CR_{agg} and CR_{tot} results presented in Table 7a and b. Furthermore, it was observed that most age categories in these regions face a high risk of cancer (see Table 7a and b).

Table 7
Aggregated and cumulative/total carcinogenic risk due to water ingestion for the nine age groups in Nnewi and Awka regions.

Sample	CR_{agg}-1	CR_{agg}-2	CR_{agg}-3	CR_{agg}-6	CR_{agg}-11	CR_{agg}-16	CR_{agg}-18	CR_{agg}-21	CR_{agg}-65	CR_{total}
(a) Nnewi aggregated and total oral carcinogenic risks										
N-WS1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
N-WS2	3.40E-05	1.05E-04	1.06E-04	6.13E-04	6.13E-04	3.55E-04	3.55E-06	3.83E-03	1.18E-05	8.56E-03
N-WS3	1.70E-05	5.28E-05	5.28E-03	3.06E-04	3.06E-04	1.77E-04	1.77E-05	1.91E-03	5.92E-06	4.28E-03
N-WS4	3.96E-05	1.23E-04	1.23E-04	7.15E-04	7.15E-04	4.14E-04	4.14E-04	4.46E-04	1.38E-05	9.98E-03
N-WS5	3.40E-05	1.05E-04	1.06E-04	6.13E-04	6.13E-04	3.55E-05	3.55E-04	3.83E-03	1.18E-05	8.56E-03
N-WS6	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
N-WS7	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
N-WS8	2.26E-05	7.04E-04	7.04E-05	4.08E-04	4.08E-04	2.36E-05	2.36E-05	2.55E-04	7.89E-06	5.70E-03
N-WS9	1.7E-05	5.28E-05	5.28E-05	3.06E-04	3.06E-04	1.77E-04	1.77E-04	1.91E-03	5.92E-06	4.28E-03
N-WS10	3.4E-05	1.05E-04	1.06E-04	6.13E-04	6.13E-04	3.55E-04	3.55E-04	3.83E-03	1.18E-05	8.56E-03
(b) Awka aggregated and total oral carcinogenic risks										
A-WS1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
A-WS2	6.8E-04	1.36E-04	2.04E-04	4.08E-04	7.48E-03	1.08E-04	1.22E-04	1.42E-04	4.42E-04	1.63E-03
A-WS3	4.53E-04	9.06E-05	1.36E-04	2.72E-04	4.98667E-05	7.25E-04	8.16E-05	9.52E-05	2.94E-03	1.09E-03
A-WS4	6.17E-04	1.23E-04	1.85E-04	3.70E-04	6.79433E-05	9.88E-05	1.11E-04	1.29E-04	4.01E-03	1.48E-03
A-WS5	5.1E-04	1.02E-04	1.53E-04	3.06E-04	5.61E-05	8.16E-03	9.18E-05	1.07E-04	3.31E-03	1.22E-03
A-WS6	1.64E-03	3.28E-04	4.93E-04	9.86E-04	1.80E-04	2.62E-04	2.95E-04	3.45E-04	1.06E-03	3.96E-03
A-WS7	5.67E-04	1.13E-04	1.7E-04	3.4E-04	6.23333E-05	9.06E-03	1.02E-04	1.19E-04	3.68E-04	1.36E-03
A-WS8	5.67E-04	1.13E-04	1.7E-04	3.4E-04	6.23E-05	9.06E-03	1.02E-04	1.19E-04	3.68E-04	1.36E-03
A-WS9	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
A-WS10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

3.3.3. Non-carcinogenic and carcinogenic risks due to dermal contact

The health risks to humans from dermal absorption—both cancerous and non-cancerous—were assessed in this study. Table 8 a and b provide the HI_{agg} and HI_{tot} used for the assessment of the absorption route for the nine age groups in Nnewi and Awka regions respectively. The aggregated hazard index (HI_{agg}) for all age categories was found to be less than 1 in all sample locations in Nnewi (Table 8a). In contrast to Awka region, a significant of number of samples were found to be higher than 1 (Table 8b). This suggests that these conditions often present greater chronic risk to people living in Awka compared to the Nnewi area. This could be because of improper wastewater discharge by the industries in this region that tends to find its way to some of the major swimming pools in recreation centers close to the source point. Age groups 1 to 11 and >65 are subjected to a greater long-term risk than age groups 16 to 65, which is comparable to the finding obtained in the HI_{agg} for oral consumption. The HI_{tot} scores revealed a higher level of total chronic risk posed to the residents of the Nnewi and Awka area, even though the HI_{agg} values suggested minimal chronic risk to all age categories (Table 8a, b).

Table 9a and b presents the outcomes of CR_{agg} and CR_{tot} used to evaluate the carcinogenic risk for each of the nine age groups due to the dermal absorption of PHEs in the groundwater resources of Nnewi and Awka regions respectively. Given that most age groups' scores were found to be beyond the permitted range of 1×10^{-6} to 1×10^{-4}, it is anticipated that the dermal absorption of PHEs from the waters increases the risk of cancer (Table 9a, b) [106,107]. It is sufficient to mention that when compared to the danger of oral intake, the recurring and cancer risks linked to dermal absorption of contaminated groundwater are substantial and, as a result, have a comparably grave hazard. Residents who drink unclean, contaminated water are therefore more exposed to the adverse effects of heavy metal poisoning. Industrial emissions, urban developments, agriculture, groundwater extraction, and sewage disposal all have an impact on the quality of the groundwater in the Nnewi and Awka study regions.

Numerous studies have evaluated the quality of water in comparable regions by implementing human health risk models and the water quality index. Our results are in agreement with these studies. For instance, Aralu et al. [65] discovered that the dumpsite area was the most polluted among the water samples obtained from the Nnewi region [65]. Similarly, Onyemesili et al. [108] determined that all water samples in the Nnewi region presented minimal cancer risk through dermal contact, but children faced a greater potential for chronic risk through ingestion compared to adults. According to the water quality index, the majority (75%) of the samples tested were classified as poor quality water, indicating that it is not recommended for drinking purposes [108]. Additionally, Omeka and Egbueri [67] concluded that the groundwater in both the Nnewi and Awka areas poses a high risk of chronic and carcinogenic effects through ingestion, especially for children who are more vulnerable [67]. In a recent study conducted by Eboagu and Ajiwe [109], the pollution index values of some heavy metals monitored revealed that borehole water in the Nnewi region is significantly affected by industrial discharges and flooding. Consequently, it was concluded that the borehole water in the area is unsuitable for drinking and should only be used for other domestic purposes. Similarly, Ifeanyichukwu and Okolo [110] found in their recent study that groundwater in the Nnewi region is contaminated, primarily due to anthropogenic sources such as industrial waste.

In a study by Igwe and Omeka [111], indexical and chemometric methods were utilized to evaluate the quality and suitability of water resources for domestic and drinking purposes in mine sites in southeast Nigeria. The study revealed that 69.23% of waters in the east-central and southeastern region were unsuitable for these purposes. Furthermore, another study by Egbueri et al. [66] assessed the quality of groundwater in Awka and Nnewi urban metropolises in Southeast Nigeria, indicating that the groundwater is highly corrosive and has a high encrustation potential. The study also found high levels of potentially harmful elements (PHEs), which are likely

Table 8
Aggregated and cumulative/total non-carcinogenic risk due to water dermal absorption for the nine age groups in Nnewi and Awka regions.

Sample	HI_{agg}-1	HI_{agg}-2	HI_{agg}-3	HI_{agg}-6	HI_{agg}-11	HI_{agg}-16	HI_{agg}-18	HI_{agg}-21	HI_{agg}-65	HItot
(a) Nnewi aggregated and total dermal non-carcinogenic risks										
N-WS1	4.08E-03	4.08E-03	1.22E-03	3.67E-04	1.10E-04	3.31E-05	9.92E-06	2.98E-06	8.93E-07	2.68E-07
N-WS2	7.60E-01	7.62E-01	2.29E-01	6.86E-02	2.06E-02	6.18E-03	1.85E-03	5.56E-04	1.67E-04	5.00E-05
N-WS3	4.07E-02	4.07E-02	1.20E-01	3.61E-02	1.08E-02	3.25E-03	9.74E-04	2.92E-04	8.76E-05	2.63E-05
N-WS4	2.61E+00	2.61E+00	7.84E-01	2.35E-01	7.06E-02	2.12E-02	6.35E-03	1.91E-03	5.72E-04	1.71E-04
N-WS5	6.90E-01	6.90E-01	2.07E-01	6.21E-02	1.86E-02	5.59E-03	1.68E-03	5.03E-04	1.51E-04	4.53E-05
N-WS6	1.11E+00	1.11E+00	3.32E-01	9.97E-02	2.99E-02	8.98E-03	2.69E-03	8.08E-04	2.42E-04	7.27E-03
N-WS7	9.26E-02	9.26E-02	2.78E-02	8.33E-03	2.50E-03	7.50E-04	2.25E-04	6.75E-05	2.03E-05	6.08E-06
N-WS8	4.44E-01	4.45E-01	1.33E-01	4.00E-02	1.20E-02	3.60E-03	1.08E-03	3.24E-04	9.72E-05	2.92E-05
N-WS9	1.09E+00	1.09E+00	3.27E-01	9.81E-02	2.94E-02	8.83E-03	2.65E-03	7.95E-04	2.38E-04	7.15E-03
N-WS10	1.78E+00	1.78E+00	5.33E-01	1.60E-01	4.80E-02	1.44E-02	4.32E-03	1.30E-03	3.89E-04	1.17E-04
(b) Awka aggregated and total dermal non-carcinogenic risks										
A-WS1	2.71E-01	2.71E-01	8.14E-02	2.44E-02	7.33E-03	2.20E-03	6.60E-04	1.98E-04	5.94E-05	1.78E-05
A-WS2	1.27E+01	1.27E+01	3.80E+00	1.14E+00	3.42E-01	1.03E-01	3.08E-02	9.23E-03	2.77E-03	8.30E-04
A-WS3	8.44E+00	8.44E+00	2.53E+00	7.60E-01	2.28E-01	6.84E-02	2.05E-02	6.15E-03	1.85E-03	5.54E-04
A-WS4	1.13E+01	1.13E+01	3.40E+00	1.02E+00	3.06E-01	9.18E-02	2.75E-02	8.26E-03	2.48E-03	7.43E-04
A-WS5	9.42E+00	9.42E+00	2.83E+00	8.48E-01	2.54E-01	7.63E-02	2.29E-02	6.87E-03	2.06E-03	6.18E-04
A-WS6	2.96E+01	2.96E+01	8.88E+00	2.66E+00	7.99E-01	2.40E-01	7.19E-02	2.16E-02	6.47E-03	1.94E-03
A-WS7	1.04E+01	1.04E+01	3.12E+00	9.35E-01	2.80E-01	8.41E-02	2.52E-02	7.57E-03	2.27E-03	6.81E-04
A-WS8	1.04E+01	1.04E+01	3.12E+00	9.35E-01	2.81E-01	8.42E-02	2.53E-02	7.58E-03	2.27E-03	6.82E-04
A-WS9	9.18E-02	9.18E-02	2.76E-02	8.27E-03	2.48E-03	7.44E-04	2.23E-04	6.69E-05	2.01E-05	6.03E-06
A-WS10	2.16E-01	2.16E-01	6.47E-02	1.94E-02	5.83E-03	1.75E-03	5.24E-04	1.57E-04	4.72E-05	1.42E-05

Table 9
Aggregated and cumulative/total carcinogenic risk due to water dermal absorption for the nine age groups in Nnewi and Awka regions.

Sample	CR_{agg}-1	CR_{agg}-2	CR_{agg}-3	CR_{agg}-6	CR_{agg}-11	CR_{agg}-16	CR_{agg}-18	CR_{agg}-21	CR_{agg}-65	CR_{total}
(a) Nnewi aggregated and total dermal carcinogenic risks										
N-WS1	0	0	0	0	0	0	0	0	0	0
N-WS2	1.82E-05	3.64E-06	5.46E-04	1.09E-05	2E-04	2.91E-06	3.28E-06	3.83E-06	1.18E-03	4.39E-03
N-WS3	9.11E-06	1.82E-04	2.73E-04	5.46E-04	1E-04	1.46E-06	1.64E-06	1.91E-06	5.92E-03	2.19E-03
N-WS4	2.13E-05	4.25E-06	6.38E-06	1.28E-04	2.34E-04	3.4E-06	3.83E-06	4.46E-06	1.38E-04	5.12E-04
N-WS5	1.82E-05	3.64E-06	5.46E-06	1.09E-05	2E-04	2.91E-06	3.28E-06	3.83E-06	1.18E-05	4.39E-04
N-WS6	0	0	0	0	0	0	0	0	0	0
N-WS7	0	0	0	0	0	0	0	0	0	0
N-WS8	1.21E-05	2.43E-03	3.64E-04	7.29E-06	1.34E-04	1.94E-06	2.19E-06	2.55E-06	7.89E-03	2.93E-04
N-WS9	9.11E-06	1.82E-03	2.73E-04	5.46E-06	1E-04	1.46E-06	1.64E-06	1.91E-04	5.92E-03	2.19E-04
N-WS10	1.82E-05	3.64E-04	5.46E-04	1.09E-05	2E-06	2.91E-06	3.28E-06	3.83E-04	1.18E-05	4.39E-04
(b) Awka aggregated and total dermal carcinogenic risks										
A-WS1	0	0	0	0	0	0	0	0	0	0
A-WS2	3.64E-04	7.29E-05	1.09 E−04	2.19E-04	4.01E-05	5.83E-05	6.56E-05	7.65E-03	2.37E-04	8.78E-04
A-WS3	2.43E-04	4.86E-05	7.29E-05	1.46E-04	2.67E-05	3.89E-04	4.37E-05	5.1E-03	1.58E-04	5.85E-04
A-WS4	3.31E-04	6.62E-05	9.93E-05	1.99E-04	3.64E-05	5.29E-05	5.96E-05	6.95E-04	2.15E-04	7.97E-04
A-WS5	2.73E-04	5.46E-05	8.2E-05	1.64E-04	3.01E-05	4.37E-04	4.92E-05	5.74E-04	1.78E-04	6.58E-04
A-WS6	8.8E-04	1.76E-04	0.000264	5.28E-04	9.68E-05	1.41E-03	1.58E-04	1.85E-04	5.72E-04	2.12E-03
A-WS7	3.04E-04	6.07E-05	9.11E-05	1.82E-04	3.34E-05	4.86E-05	5.46E-05	6.38E-05	1.97E-04	7.32E-04
A-WS8	3.04E-04	6.07E-05	9.11E-05	1.82E-04	3.34E-05	4.86E-05	5.46E-05	6.38E-05	1.97E-04	7.32E-04
A-WS9	0	0	0	0	0	0	0	0	0	0
A-WS10	0	0	0	0	0	0	0	0	0	0

from natural sources, industrial and agricultural activities, and inadequate wastewater treatment systems. The study concludes that the groundwater in these regions is not suitable for drinking or industrial purposes. In their study, Ibe et al. [112] recommended appropriate treatment for groundwater samples before consumption to prevent potential health risks from the bioaccumulation of metallic contaminants over time. Isiku et al. [113] also conducted a study that found water bodies in Southeastern Nigeria to have very high non-carcinogenic health risks to users through the oral pathway, attributed to high nitrate and phosphate concentrations. In summary, the literature review emphasizes the significance of evaluating and monitoring the quality of water sources for industrial and domestic purposes in Southeast Nigeria. The studies discussed indicate that the groundwater in the region is highly susceptible to contamination from both natural and anthropogenic sources, which may have detrimental effects on public health.

Our study contributes to the existing literature by providing more comprehensive and specific information about the groundwater quality in the Awka and Nnewi urban metropolises of Southeast Nigeria. In addition to confirming previous studies' conclusions on the presence of potentially harmful elements, our research identified the specific sources of contamination that contribute to the high levels of contaminants in the groundwater. Through this, we intend to offer valuable information to policymakers and stakeholders to implement appropriate remediation strategies, ensuring the safety of groundwater for domestic and drinking purposes.

3.4. *Hierarchical cluster modeling of water quality and health risk*

The utilization of a hierarchical dendrogram provides a clear depiction of the mean similarities among different classification factors, given that factor interactions are minimal enough to establish the overall strength of a single factor. In our study, we employed the Ward linkage approach to conduct hierarchical cluster analysis (HCA) to group groundwater in the research areas that exhibit similar chemical characteristics. This analysis was carried out to facilitate the identification of distinct patterns in the data and provide insights into the underlying relationships among the variables. In both the Nnewi and Awka research locations, various hierarchical dendrograms were produced based on the NSFWQI, HI_{tot} (oral), CR_{tot} (oral), HI_{tot} (dermal), and CR_{tot} (dermal). The groundwater sites are categorized by this assessment based on data on health risks and PHE contamination levels.

To evaluate the drinking water quality in the Nnewi and Awka regions, Fig. 3 displays dendrograms regarding the NSFWQI results. In Nnewi region, two cluster groups were found as shown in Fig. 3a. There are two sub-clusters in Cluster 1 (Fig. 3a). According to the NSFWQI, samples 2 and 5 are in the first sub-cluster with NSFWQI values of 23.27 and 17.18 which are very unsuitable for water quality. Four water samples are present in the second sub-cluster with their respective NSWQIs, suggesting the extreme unsuitability of these locations (Fig. 3a; Table 4). In cluster 2, four water locations make up Nnewi's region, which is also thought to be unsuitable (Fig. 3a; Table 4). It is not advised to drink the water in any of the clusters in the Nnewi region at this time due to the typically very low water quality that can be observed in their NSFWQI levels (Table 4). Therefore, when designing and implementing any pollution mitigation strategy, these stations should be given more priority. Cluster 1 in the Awka research region is mainly made up of water samples with NSFWQI ratings of moderate, good, and outstanding water quality (Fig. 3b; Table 4). The cluster with the lowest water quality, cluster 2, is made up of seven water sites (Fig. 3b; Table 4). Therefore, while developing and carrying out any pollution remedial actions, more consideration should be given to these seven stations that formed cluster 2 in the Awka region.

The HCs for the HI_{tot} (oral) in the Nnewi region are shown in Fig. 4a. There were found to be two primary clusters, each with two smaller clusters. Even though all the HI_{tot} (oral) values indicated substantial chronic hazards, the HCs helped to sufficiently divide the groundwaters into groups. Cluster 2 consists of groundwater samples that exhibit very high risk, whereas Cluster 1 includes groundwater areas that pose exceptionally high non-carcinogenic risk to the residents, as depicted in Fig. 4a. The pattern of decreasing chronic risks faced by groundwater resources in the different sites is as follows: Sub-cluster 2 (Cluster 1, HI_{tot} range = 142–143) < Sub-cluster 1 (Cluster 1, HI_{tot} range = 148–154) < Sub-cluster 1 (Cluster 2, HI_{tot} range = 160–161) < Sub-cluster 2 (Cluster 2, HI_{tot} range = 171–185). This pattern indicates that the risk of chronic health effects associated with groundwater consumption is highest in Sub-cluster 2 of Cluster 2, followed by Sub-cluster 1 of Cluster 2, Sub-cluster 1 of Cluster 1, and Sub-cluster 2 of Cluster 1, respectively. In the Nnewi region, two major clusters for the carcinogenic risk (CR_{tot} oral) were found (Fig. 4b). The water samples with the greatest cancer risk between 0.00E+00 and 0.00E+00 are grouped together in the first cluster, which does not include any sub-cluster groups. The samples with a lower probability of developing cancer, on the other hand, make up the second cluster. It is worthy to note that there are two sub-clusters within the second cluster. The cancer risk for the first sub-member cluster ranges from 4.28E-03 to 5.70E-03, whereas the risk for the second sub-member clusters ranges from 8.56E-03 to 9.98E-03 (Fig. 4b; Table 7).

The water resources' HCs in relation to HI_{tot} (dermal) are displayed in Fig. 4c. Additionally, two clusters for the HI_{tot} (dermal) were generated. The first cluster had the least chronic risk from intake, with the risk ranges for its first and second sub-clusters being 2.62E-05 to 5.00E-05 and 6.07E-06 to 2.67E-04, respectively (Fig. 4c; Table 8). The second cluster, on the other hand, had the highest chronic risk from absorption, with its first sub-risk cluster's range being 1.16E-04 to 1.71E-04 and its second sub-risk cluster's range being 7.15E-03 to 7.27E-03 (Fig. 4c; Table 8). In Fig. 4d, the HCs and the cancer risk attributable to dermal absorption (CR_{tot}) are categorized. Although samples from both clusters exhibit significant levels of cancer risk as a result of absorbing PHEs, members of Cluster 2 appear to have a higher cancer risk as a result of absorbing PHEs than members of Cluster 1. (Fig. 4d; Table 9). One sub-cluster of Cluster 1 has risk levels between 2.19E-03 and 4.39E-03 (Fig. 4d; Table 9). On the other hand, Cluster 2 is devoid of sub-clusters and has a risk range of 0.00E+00 to 5.12E-04 (Fig. 4d; Table 9).

Fig. 5a displays the hierarchical clusters (HCs) for the HItot (oral) in the Awka region. Two main clusters were identified, with cluster 1 having no sub-clusters, and cluster 2 having two sub-clusters. Although all HI_{tot} (oral) scores indicated high chronic hazards, the HCs facilitated the proper classification of the groundwater samples. Furthermore, cluster 1 consists of groundwater sites with extremely high non-carcinogenic risks to inhabitants, while cluster 2 contains samples with very high risk (Fig. 5a). The decreasing order trend of the chronic risks presented by groundwater resources is as follows: Sub-cluster 2 (Cluster 2, HI_{tot} range = 283–354) < Sub-cluster 1 (Cluster 2, HI_{tot} range = 145–146) < Cluster 1 (HI_{tot} range = 143–639).

For the carcinogenic risk (CR_{tot} (oral)) in the Awka region, two primary clusters were identified (Fig. 5b). The first cluster had no sub-clusters, while the second cluster had two sub-clusters. Notably, both clusters contained water samples with very high cancer risks. The cancer risks in cluster 1 range from 1.09E-03 to 3.96E-03. In contrast, the first sub-cluster members of Cluster 2 have a cancer risk range of 1.22E-03 to 1.63E-03, whereas the second sub-cluster members have a cancer risk range of 0.00E+00 to 0.00E+00 (Fig. 5b; Table 7).

The dendrograms for the classification of HI_{tot} (dermal) and CR_{tot} (dermal) for the Awka region are shown in Fig. 5c and d. The HCs of the water resources in relation to HI_{tot} are displayed in Fig. 5c (dermal). For the HI_{tot}, two clusters were also realized. Although the samples in the two clusters appear to have very high non-carcinogenic risk, the risk associated with absorption is higher in the second cluster. The risk range for the first cluster is 6.02E-06 to 1.94E-03. The second cluster, however, contains two additional clusters. The risk range for the first sub-cluster is 1.41E-05 to 1.78E-05, while for the second sub-cluster it is 5.53E-04 to 8.30E-04 (Fig. 5c; Table 8). In Fig. 5d, the HCs are used to categorize the cancer risk attributable to dermal absorption (CR_{tot}) in the Awka region. Unlike the first cluster, which has none, the second cluster contains two sub-clusters. Notably, these two Clusters comprised water samples with an extremely high cancer risk. Cluster 1 has a 5.85E-04 to 2.13E-03 cancer risk range. However, while the second sub-cluster members of Cluster 2 have a cancer risk range of 6.85E-04 to 8.78E-04, the first sub-cluster members have a cancer risk range of 0.00E+00 (Fig. 5d; Table 9).

3.5. *Correlation analysis of the water quality and health risk indicators*

The study utilized hierarchical clustering to distinguish between water quality and health risks, and Pearson's correlation analysis was also conducted to examine the relationship between the indices used for spatiotemporal study of drinking water quality and human health hazards. Table 10 a and b present the correlation matrices for the water quality assessment in the Nnewi and Awka regions respectively. The study findings suggest the following presumptions to be accurate for the current study region.

1) The NSFWQI for both Nnewi and Awka regions considerably trended in a manner analogous to the HI_{tot} (oral) and HI_{tot} (dermal).
2) There is a good correlation between the HI_{tot} (oral) and HI_{tot} (dermal) in both study regions, showing great similarities in pattern.
3) The analysis found a strong correlation between CRtot (oral) and CRtot (dermal), indicating a significant relationship between the cancer risk through oral and dermal exposure in both Nnewi and Awka regions.
4) CR_{tot} (oral and dermal) did not exhibit any important connection with NSFWQI and HI_{tot} (oral and dermal), perhaps because they did not take into account the same number of variables in their assessments.

4. Limitations of study, recommendations, and perspectives for future research

This research study revealed that there was an unpalatable impact on the physicochemical characteristics of groundwater in the Nnewi and Awka regions, which can be traced back to the operations of major industries that disperse their waste indiscriminately into the environment and water systems and use of pesticides and fertilizers for agriculture that produce high levels of pollutants.

Table 10
Correlation matrices of the key indices for the water quality assessment (**a**) Nnewi, and (**b**) Awka.

Parameter	NSFWQI	HI_{tot} (oral)	CR_{total} (oral)	HI_{tot} (dermal)	CR_{total} (dermal)
(a) Nnewi district					
NSFWQI	1.000				
HI_{tot} (oral)	0.222	1.000			
CR_{total} (oral)	−0.139	0.628	1.000		
HI_{tot} (dermal)	0.222	1.000[a]	0.628	1.000	
CR_{total} (dermal)	0.181	−0.158	0.312	−0.158	1.000
(b) Awka district					
NSFWQI	1.000				
HI_{tot} (oral)	−0.039	1.000			
CR_{total} (oral)	−0.042	1.000[a]	1.000		
HI_{tot} (dermal)	−0.039	1.000[a]	1.000[a]	1.000	
CR_{total} (dermal)	−0.042	1.000[a]	1.000[a]	1.000[a]	1.000

[a] Correlation is significant at the 0.01 level (2-tailed).

According to the present research, consuming groundwater for home, recreational, and agricultural purposes without first treating it could have a severe impact on the health of people. Therefore, it is crucial to assess the health risks associated with drinking groundwater in the Nnewi and Awka region to mitigate the potential hazards posed by consuming contaminated water.

One of the study's drawbacks is that not many stations were analyzed in each of the study regions due to lack of sufficient funding. The presence of heavy metals in the water samples was assessed using the AAS method. If more advanced equipment like ICP-OES was employed, greater accuracy and sensitivity may be obtained. The following recommendations have been put up to improve the water quality and stop further deterioration based on the current contamination condition of the groundwater in the Nnewi and Awka districts.

- Future studies should also pay attention to the impact of seasonal changes on the concentration of PHEs in groundwater resources found in parts of Nnewi and Awka to estimate the degree of environmental and ecological degradation.
- To prevent further degradation of groundwater quality, it is crucial to establish wastewater treatment plants that can effectively eliminate potentially harmful elements (PHEs). These facilities must comply with the standards set by the Standard Organization of Nigeria (SON) and the World Health Organization (WHO).
- PHEs should be controlled in industrial effluents by the implementation of strict rules. The tax credit or other appropriate financial benefits, such as the provision of necessary technologies at a reduced cost, should be made available to industrial units that offer to establish treatment plants at their sites.
- The public should be made aware of the contaminated groundwater in the Nnewi and Awka region and how it affects human health risks through awareness campaigns.
- Advanced soft computing methods like artificial intelligence algorithms can be integrated for prediction of PHEs in the study region, especially for similar cases of scarce datasets. This would enhance effective monitoring and assessment of groundwater resources, which in turn would raise the management and chances of availability of potable groundwater for future generations.

5. Conclusions

This study utilized the NSFWQI, HERisk code, and multivariate statistical techniques to evaluate the quality of groundwater in the study areas for both drinking and domestic purposes through oral and dermal exposure pathways, as well as the associated health risks to humans. Analysis of the groundwater's elemental composition revealed that PHEs are prevalent in the examined water sources. NSFWQI was used to evaluate the appropriateness of the groundwater in the Nnewi and Awka regions. According to the NSFWQI result, for the Nnewi region, 40% of the groundwater samples under analysis had unsuitable water quality, and 60% had highly unsuitable water quality. In the Awka region, 60% ranked as unsuitable while 40% ranged from medium to excellent. According to the results of the HERisk code, all age groups were found to be significantly exposed to PHEs through oral and dermal pathways, with Cd > Pb > Cu > Fe for Nnewi and Pb > Cd > Cu > Fe for Awka. The hierarchical dendrograms proved effective in categorizing the quality of drinking groundwater and the associated health risks. This study highlights the need for continued monitoring of water quality and underscores the importance of properly treating contaminated water before consumption. It also emphasizes the importance of effective management of groundwater resources to safeguard the health and well-being of the population, particularly vulnerable groups such as children.

The occurrence of PHEs in groundwater can be linked to several sources, such as natural processes, industrial and agricultural practices, and insufficient wastewater treatment systems. In the study areas, the rapid expansion of cities, population increase, and inadequate infrastructure have led to heightened contamination of water sources, particularly groundwater. The outcomes of this investigation highlight the pressing need for better monitoring of groundwater quality and the deployment of appropriate remediation approaches to guarantee the safety of groundwater for domestic and drinking purposes.

It is crucial to acknowledge that the origins of PHEs in the groundwater of the research regions are intricate and diverse. Heavy metals can be released into the environment through natural sources like geological formations and weathering processes. Furthermore, human activities, such as industrial and agricultural practices, can significantly contribute to the pollution of water sources, especially in regions where regulatory measures are insufficient or non-existent. Additionally, substandard wastewater treatment systems and inadequate sanitation facilities can exacerbate the problem, leading to the contamination of groundwater resources.

The findings of this study underscore the need for improved monitoring of groundwater quality in the study regions. The identification of potential sources of pollution and pollutants, including PHEs, is critical in developing appropriate remediation strategies. Regular monitoring can help to identify changes in groundwater quality over time, enabling prompt action to be taken to prevent contamination or mitigate the risk of exposure to hazardous substances.

In summary, this research contributes to the current knowledge on water quality in the study regions and offers crucial information on the specific water quality in the area. Comparing these findings with previous studies can improve our understanding of the sources and consequences of water pollutants, leading to more effective measures for ensuring water quality. The study emphasizes the importance of continuous monitoring and management of water quality to safeguard public health and preserve the environment.

Author contribution statement

Conceptualization: J. C. Egbueri and D. A. Ayejoto; Methodology, experimentation and software: D. A. Ayejoto, J. C. Agbasi, J. C. Egbueri and S. I. Abba; Data analysis and interpretation: D. A. Ayejoto, J. C. Agbasi, J. C. Egbueri and S. I. Abba; Writing - original draft: D. A. Ayejoto; Visualization: J. C. Egbueri and J. C. Agbasi; Writing - review, editing and revision: D. A. Ayejoto, J. C. Agbasi, J. C. Egbueri and S. I. Abba. All authors read and approved the final version.

Data availability statement

No data was used for the research described in the article.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e15483.

References

[1] O.M. Roșca, T. Dippong, M. Marian, C. Mihali, L. Mihalescu, M.-A. Hoaghia, M. Jelea, Impact of anthropogenic activities on water quality parameters of glacial lakes from Rodnei mountains, Romania, Environ. Res. 182 (2020), 109136.
[2] T. Dippong, C. Mihali, D. Nasui, Z. Berinde, C. Butean, Assessment of water physicochemical parameters in the strimtori-firiza reservoir in northwest Romania, Water Environ. Res. 90 (3) (2018) 220–233.
[3] Y. Zhu, B. He, Y. Xiao, Y. Chen, Iron metabolism and its association with dyslipidemia risk in children and adolescents: a cross-sectional study, Lipids Health Dis. 18 (1) (2019) 1–8.
[4] B. Du, G. Fan, W. Yu, S. Yang, J. Zhou, J. Luo, Occurrence and risk assessment of steroid estrogens in environmental water samples: a five-year worldwide perspective, Environ. Poll. 267 (2020), 115405.
[5] V.K. Garg, A. Tanta, A. Lal Srivastav, M. Tiwari, A. Sharma, V.S. Kanwar, Water quality assessment using synchrotron-based TXRF, Water Environ. Res. 94 (7) (2022), e10759.
[6] A.K. Hussien, I.M. Rashwan, M. Elshemy, Surface water quality management for drinking use in El-Beheira Governorate, Egypt, Water Environ. Res. 93 (8) (2021) 1428–1444.
[7] S. Varol, Ş. Şener, E. Şener, Assessment of groundwater quality and human health risk related to arsenic using index methods and GIS: a case of Şuhut Plain (Afyonkarahisar/Turkey), Environ. Res. 202 (2021), 111623.
[8] Y. Wang, P. Li, Appraisal of shallow groundwater quality with human health risk assessment in different seasons in rural areas of the Guanzhong Plain (China), Environ. Res. 207 (2022), 112210.
[9] J.C. Egbueri, Heavy metals pollution source identification and probabilistic health risk assessment of shallow groundwater in onitsha, Nigeria, Anal. Lett. 53 (10) (2020) 1620–1638.
[10] O. Dhaoui, I.M.H.R. Antunes, B. Agoubi, A. Kharroubi, Integration of water contamination indicators and vulnerability indices on groundwater management in Menzel Habib area, south-eastern Tunisia, Environ. Res. 205 (2022), 112491.
[11] P. Li, J. Wu, Drinking water quality and public health, Exp. Heal. 11 (2) (2019) 73–79.
[12] H.R. Ghaffari, Z. Kamari, V. Ranaei, Z. Pilevar, M. Akbari, M. Moridi, K.M. Khedher, Y. Fakhri, A.M. Khaneghah, The concentration of potentially hazardous elements (PHEs) in drinking water and non-carcinogenic risk assessment: a case study in Bandar Abbas, Iran, Environ. Res. 201 (2021), 111567.
[13] A.A. Neshat, H. Tavakoli Ghouchani, A. Gholizadeh, H. Tayebi, M. Rahmatinia, A. Atamaleki, H.R. Mohaddes Hakkak, M. Langari, Concentration, spatial distribution, and health risk assessment of fluoride in rural drinking water resources, North Khorasan Province, Iran, Int. J. Environ. Anal. Chem. (2021) 1–16.
[14] X. Chen, X.-C. Zeng, Y.K. Kawa, W. Wu, X. Zhu, Z. Ullah, Y. Wang, Microbial reactions and environmental factors affecting the dissolution and release of arsenic in the severely contaminated soils under anaerobic or aerobic conditions, Ecotoxicol. Environ. Saf. 189 (2020), 109946.
[15] S. Khalid, M. Shahid, A.H. Shah, F. Saeed, M. Ali, S.A. Qaisrani, C. Dumat, Heavy metal contamination and exposure risk assessment via drinking groundwater in Vehari, Pakistan, Environ. Sci. Pollut. Control Ser. 27 (2020) 39852–39864.
[16] L. Ricolfi, M. Barbieri, P.V. Muteto, A. Nigro, G. Sappa, S. Vitale, Potential toxic elements in groundwater and their health risk assessment in drinking water of Limpopo National Park, Gaza Province, Southern Mozambique, Environ. Geochem. Health 42 (2020) 2733–2745.

[17] M. Alsubih, R. El Morabet, R.A. Khan, N.A. Khan, M. ul Haq Khan, S. Ahmed, A. Qadir, F. Changani, Occurrence and health risk assessment of arsenic and heavy metals in groundwater of three industrial areas in Delhi, India, Environ. Sci. Pollut. Control Ser. 28 (2021) 63017–63031.

[18] M. Kaur, A. Kumar, R. Mehra, I. Kaur, Quantitative assessment of exposure of heavy metals in groundwater and soil on human health in Reasi district, Jammu and Kashmir, Environ. Geochem. Health 42 (2020) 77–94.

[19] N. Masood, A. Farooqi, M.I. Zafar, Health risk assessment of arsenic and other potentially toxic elements in drinking water from an industrial zone of Gujrat, Pakistan: a case study, Environ. Monit. Assess. 191 (2019) 1–15.

[20] Z. Ullah, A. Rashid, J. Ghani, M.A. Talib, A. Shahab, L. Lun, Arsenic Contamination, Water Toxicity, Source Apportionment, and Potential Health Risk in Groundwater of Jhelum Basin, Punjab, Pakistan, Biological Trace Element Research, 2022, pp. 1–11.

[21] P. Amoatey, A. Izady, A. Al-Maktoumi, M. Chen, I. Al-Harthy, K. Al-Jabri, T.A. Msagati, T.T. Nkambule, M.S. Baawain, A critical review of environmental and public health impacts from the activities of evaporation ponds, Sci. Total Environ. 796 (2021), 149065.

[22] F. Abdalla, R. El Attar, M. Shamrukh, Contamination Sources along the Nile Valley, Egypt and its Impact on Groundwater, Sustainability of Groundwater in the Nile Valley, Egypt, Springer, 2022, pp. 73–90.

[23] S.G. Gilbert, Metal Toxicology, Information Resources in Toxicology, Elsevier, 2020, pp. 201–202.

[24] J.C. Egbueri, M.T. Enyigwe, D.A. Ayejoto, Modeling the impact of potentially harmful elements on the groundwater quality of a mining area (Nigeria) by integrating NSFWQI, HERisk code, and HCs, Environ. Monit. Assess. 194 (3) (2022) 150.

[25] S. Dos Santos, E. Adams, G. Neville, Y. Wada, A. De Sherbinin, E.M. Bernhardt, S. Adamo, Urban growth and water access in sub-Saharan Africa: progress, challenges, and emerging research directions, Sci. Total Environ. 607 (2017) 497–508.

[26] C. Odo, C. Onalu, U. Nwatu, N. Nwafor, S. Ebimgbo, Factors Associated with the Prevalence of Diarrhoea Among Children in Rural Areas of Enugu State, Nigeria: Practice Considerations for Social Workers, International Social Work, 2021, 00208728211034229.

[27] U.U. Nwokoro, O. Ugwa, C.D. Onwuliri, I.F. Obi, M.-O. Ngozi, C. Agunwa, Water, sanitation and hygiene risk factors associated with diarrhoea morbidity in a rural community of Enugu, South East Nigeria, Pan Afr. Med. J. 37 (2020).

[28] D.A. Ayejoto, J.C. Egbueri, M.T. Enyigwe, O.I. Chiaghanam, P.D. Ameh, Application of HMTL and novel IWQI models in rural groundwater quality assessment: a case study in Nigeria, Toxin Rev. 41 (3) (2022) 918–932.

[29] J.C. Egbueri, D.A. Ayejoto, J.C. Agbasi, Pollution assessment and estimation of the percentages of toxic elements to be removed to make polluted drinking water safe: a case from Nigeria, Toxin Rev. (2022) 1–15.

[30] J.C. Agbasi, J.C. Egbueri, Assessment of PTEs in water resources by integrating HHRISK code, water quality indices, multivariate statistics, and ANNs, Geocarto Int. (2022) 1–27.

[31] Q. Zhai, H. Rahardjo, A. Satyanaga, Y. Zhu, G. Dai, X. Zhao, Estimation of wetting hydraulic conductivity function for unsaturated sandy soil, Eng. Geol. 285 (2021), 106034.

[32] D.A. Ayejoto, J.C. Agbasi, J.C. Egbueri, K.I. Echefu, Assessment of oral and dermal health risk exposures associated with contaminated water resources: an update in Ojoto area, southeast Nigeria, Int. J. Environ. Anal. Chem. (2022) 1–21.

[33] J.C. Egbueri, C.N. Mgbenu, Chemometric analysis for pollution source identification and human health risk assessment of water resources in Ojoto Province, southeast Nigeria, Appl. Water Sci. 10 (4) (2020) 1–18.

[34] T. Kormoker, A.M. Idris, M.M. Khan, T.R. Tusher, R. Proshad, M.S. Islam, S. Khadka, S. Rahman, M.H. Kabir, S. Kundu, Spatial distribution, multivariate statistical analysis, and health risk assessment of some parameters controlling drinking water quality at selected primary schools located in the southwestern coastal region of Bangladesh, Toxin Rev. 41 (1) (2022) 247–260.

[35] R.J. Kavlock, G.P. Daston, C. DeRosa, P. Fenner-Crisp, L.E. Gray, S. Kaattari, G. Lucier, M. Luster, M.J. Mac, C. Maczka, Research needs for the risk assessment of health and environmental effects of endocrine disruptors: a report of the US EPA-sponsored workshop, Environ. Health Perspect. 104 (suppl 4) (1996) 715–740.

[36] J. Neris, D.M. Olivares, F. Velasco, F. Luzardo, L. Correia, L. González, HHRISK: a code for assessment of human health risk due to environmental chemical pollution, Ecotoxicol. Environ. Saf. 170 (2019) 538–547.

[37] J.B. Neris, D.M.M. Olivares, C.S. Santana, P.C. Emenike, F.G. Velasco, S.F.R. Andrade, C.M. Paranhos, HERisk: an improved spatio-temporal human health risks assessment software, Sci. Total Environ. 772 (2021), 145044.

[38] I.T. Tenebe, P.C. Emenike, E.O. Babatunde, J.B. Neris, O.H. Fred-Ahmadu, N. Dede-Bamfo, E.-E. Etu, N.M. Ogarekpe, J. Emakhu, N.U. Benson, Assessing the state of rainwater for consumption in a community in dire need of clean water: human and health risk using HERisk, Water Pract. Technol. 17 (10) (2022) 2005–2022.

[39] D.M. Montalván Olivares, C. Santana, J. Neris, F.H. Martinez Luzardo, A.W. Mol, F. Garcia Velasco, Assessment of Potential Human Health, Radiological and Ecological Risks Around Mining Areas in Northeastern Brazil, Radiological and Ecological Risks Around Mining Areas in Northeastern Brazil.

[40] Z. Wang, J. Li, X. Mu, L. Zhao, C. Gu, H. Gao, J. Ma, X. Mao, T. Huang, A WRF-CMAQ modeling of atmospheric PAH cycling and health risks in the heavy petrochemical industrialized Lanzhou valley, Northwest China, J. Clean. Prod. 291 (2021), 125989.

[41] M. Mokarram, A. Saber, V. Sheykhi, Effects of heavy metal contamination on river water quality due to release of industrial effluents, J. Clean. Prod. 277 (2020), 123380.

[42] J.N. Jabbo, N.M. Isa, A.Z. Aris, M.F. Ramli, M.B. Abubakar, Geochemometric approach to groundwater quality and health risk assessment of heavy metals of Yankari Game Reserve and its environs, Northeast Nigeria, J. Clean. Prod. 330 (2022), 129916.

[43] T. Dippong, M.-A. Hoaghia, C. Mihali, E. Cical, M. Calugaru, Human health risk assessment of some bottled waters from Romania, Environ. Poll. 267 (2020), 115409.

[44] M. Sarkar, S.C. Pal, Human health hazard assessment for high groundwater arsenic and fluoride intact in Malda district, Eastern India, Groundwat. Sustain. Develop. 13 (2021), 100565.

[45] Z. Wang, P. Luo, X. Zha, C. Xu, S. Kang, M. Zhou, D. Nover, Y. Wang, Overview assessment of risk evaluation and treatment technologies for heavy metal pollution of water and soil, J. Clean. Prod. (2022), 134043.

[46] H.T. Pona, D. Xiaoli, O.O. Ayantobo, N.D. Tetteh, Environmental health situation in Nigeria: current status and future needs, Heliyon 7 (3) (2021), e06330.

[47] R. Ullah, S. Muhammad, I.A. Jadoon, Potentially harmful elements contamination in water and sediment: evaluation for risk assessment and provenance in the northern Sulaiman fold belt, Baluchistan, Pakistan, Microchem. J. 147 (2019) 1155–1162.

[48] S. Apostolaki, P. Koundouri, N. Pittis, Using a systemic approach to address the requirement for integrated water resource management within the water framework directive, Sci. Total Environ. 679 (2019) 70–79.

[49] B.U. Ngene, C.O. Nwafor, G.O. Bamigboye, A.S. Ogbiye, J.O. Ogundare, V.E. Akpan, Assessment of water resources development and exploitation in Nigeria: a review of integrated water resources management approach, Heliyon 7 (1) (2021), e05955.

[50] I. Radelyuk, K. Tussupova, J.J. Klemeš, K.M. Persson, Oil refinery and water pollution in the context of sustainable development: developing and developed countries, J. Clean. Prod. 302 (2021), 126987.

[51] H. Abu-Bakar, L. Williams, S.H. Hallett, A review of household water demand management and consumption measurement, J. Clean. Prod. 292 (2021), 125872.

[52] J. Liu, Y. Peng, C. Li, Z. Gao, S. Chen, An investigation into the hydrochemistry, quality and risk to human health of groundwater in the central region of Shandong Province, North China, J. Clean. Prod. 282 (2021), 125416.

[53] M.F. Hasan, M. Nur-E-Alam, M.A. Salam, H. Rahman, S.C. Paul, A.E. Rak, B. Ambade, A.R.M. Towfiqul Islam, Health risk and water quality assessment of surface water in an urban river of Bangladesh, Sustainability 13 (12) (2021) 6832.

[54] M. da Silva Ferreira, M.P.F. Fontes, A.A. Pacheco, H.N. Lima, J.Z.L. Santos, Risk assessment of trace elements pollution of Manaus urban rivers, Sci. Total Environ. 709 (2020), 134471.

[55] N. Adimalla, H. Qian, P. Li, Entropy water quality index and probabilistic health risk assessment from geochemistry of groundwaters in hard rock terrain of Nanganur County, South India, Geochemistry 80 (4) (2020), 125544.

[56] H. Eslami, A. Esmaeili, M. Razaeian, M. Salari, A.N. Hosseini, M. Mobini, A. Barani, Potentially toxic metal concentration, spatial distribution, and health risk assessment in drinking groundwater resources of southeast Iran, Geosci. Front. 13 (1) (2022), 101276.
[57] Q. Wang, P. Craddock, J. Hudson, A metallographic study of objects and fragments from the site of Igbo Isaiah, Igbo-Ukwu, Nigeria, Afr. Archaeol. Rev. (2022) 1–17.
[58] C.N. Nnamele, C.A. Egwuonwu, Modification of conventional casting techniques: the adaptation of „Lost-clay" technique for casting metal sculpture, Awka J. Fine Appl. Arts 7 (1) (2021).
[59] N. Chinye-Ikejiunor, G.O. Iloegbunam, A. Chukwuka, O. Ogbeide, Groundwater contamination and health risk assessment across an urban gradient: case study of Onitcha metropolis, south-eastern Nigeria, Groundwat. Sustain. Develop. 14 (2021), 100642.
[60] J.C. Egbueri, C.O. Unigwe, M.E. Omeka, D.A. Ayejoto, Urban groundwater quality assessment using pollution indicators and multivariate statistical tools: a case study in southeast Nigeria, Int. J. Environ. Anal. Chem. (2021) 1–27.
[61] C. Nwajide, Outcrop analogies as a learning facility for subsurface practitioners: the value of geology field trips, Petr. Train. J. 3 (2006) 58–68.
[62] C. Nwajide, Geology of Nigeria's Sedimentary Basins, CSS Bookshop Limited, 2013.
[63] V. Oguadinma, A. Okoro, B. Odoh, Lithofacies and textural attributes of the Nanka Sandstone (Eocene): proxies for evaluating the depositional environment and reservoir quality, J. Earth Sci. Geotech. Eng. 4 (4) (2014) 1–16.
[64] B. Nfor, S. Olobaniyi, J. Ogala, Extent and distribution of groundwater resources in parts of Anambra State, Southeastern, Nigeria, J. Appl. Sci. Environ. Manag. 11 (2) (2007).
[65] C.C. Aralu, P.A. Okoye, H.O. Abugu, V.C. Eze, Pollution and water quality index of boreholes within unlined waste dumpsite in Nnewi, Nigeria, Discover Water 2 (1) (2022) 14.
[66] J.C. Egbueri, C.O. Unigwe, J.C. Agbasi, V.E. Nwazelibe, Indexical and artificial neural network modeling of the quality, corrosiveness, and encrustation potential of groundwater in industrialized metropolises, Southeast Nigeria, Environ. Develop. Sustain. (2022) 1–31.
[67] M.E. Omeka, J.C. Egbueri, Hydrogeochemical Assessment and Health-Related Risks Due to Toxic Element Ingestion and Dermal Contact within the Nnewi-Awka Urban Areas, Nigeria, Environmental Geochemistry and Health, 2022, pp. 1–29.
[68] E.W. Rice, L. Bridgewater, A.P.H. Association, Standard Methods for the Examination of Water and Wastewater, American public health association Washington, DC, 2012.
[69] A.P.H. Association, Standard Methods for the Examination of Water and Wastewater, American Public Health Association, 1926.
[70] R.T. Madilonga, J.N. Edokpayi, E.T. Volenzo, O.S. Durowoju, J.O. Odiyo, Water quality assessment and evaluation of human health risk in Mutangwi River, Limpopo Province, South Africa, Int. J. Environ. Res. Publ. Health 18 (13) (2021) 6765.
[71] J. Agbasi, C. Chukwu, N. Nweke, H. Uwajingba, M. Khan, J. Egbueri, Water Pollution Indexing and Health Risk Assessment Due to PTE Ingestion and Dermal Absorption for Nine Human Populations in Southeast Nigeria, Groundwater for Sustainable Development 21 (2023), 100921.
[72] A.S.I.M. Jamal, Y.A. Tarek, M.A.B. Siddique, M.A.A. Shaikh, S.C. Debnath, M.R. Uddin, S. Ahmed, M.A. Akbor, M.A. Al-Mansur, A.R.M.T. Islam, Development of a Fabricated First-Flush Rainwater Harvested Technology to Meet up the Freshwater Scarcity in a South Asian Megacity, Heliyon, dhaka, Bangladesh, 2023, e13027.
[73] E.D. Lange, Manual for Simple Water Quality Analysis, IWT Foundation, Amsterdam (Netherlands), 1994, 1994.
[74] Standard organization of Nigeria (SON), Nigerian Standard for Drinking Water Quality, Nigerian industrial standard, Lagos, 2007.
[75] W.H. Organization, WHO., Guidelines for Drinking-Water Quality, World Health Organization, 2017.
[76] R.M. Brown, N.I. McClelland, R.A. Deininger, R.G. Tozer, A water quality index-do we dare, Water Sewage Works 117 (10) (1970).
[77] G. Matta, A. Nayak, A. Kumar, P. Kumar, Water quality assessment using NSFWQI, OIP and multivariate techniques of Ganga River system, Uttarakhand, India, Appl. Water Sci. 10 (2020) 1–12.
[78] M. Marselina, F. Wibowo, A. Mushfiroh, Water quality index assessment methods for surface water: a case study of the Citarum River in Indonesia, Heliyon 8 (7) (2022), e09848.
[79] L. Tampo, S.-L.A.-S. Mande, A.O. Adekanmbi, G. Boguido, K.V. Akpataku, M. Ayah, I. Tchakala, M.D. Gnazou, L.M. Bawa, G. Djaneye-Boundjou, Treated wastewater suitability for reuse in comparison to groundwater and surface water in a peri-urban area: implications for water quality management, Sci. Total Environ. 815 (2022), 152780.
[80] S. Parween, N.A. Siddique, M.T.M. Diganta, A.I. Olbert, M.G. Uddin, Assessment of urban river water quality using modified NSF water quality index model at Siliguri city, West Bengal, India, Environ. Sustain. Ind. 16 (2022), 100202.
[81] S. Gupta, S.K. Gupta, A critical review on water quality index tool: genesis, evolution and future directions, Ecol. Inf. 63 (2021), 101299.
[82] R. Noori, R. Berndtsson, M. Hosseinzadeh, J.F. Adamowski, M.R. Abyaneh, A critical review on the application of the national sanitation foundation water quality index, Environ. Poll. 244 (2019) 575–587.
[83] M.S. Gradilla-Hernández, J. de Anda, A. Garcia-Gonzalez, C.Y. Montes, H. Barrios-Piña, P. Ruiz-Palomino, D. Díaz-Vázquez, Assessment of the water quality of a subtropical lake using the NSF-WQI and a newly proposed ecosystem specific water quality index, Environ. Monit. Assess. 192 (5) (2020) 296.
[84] J.G. Nayak, L. Patil, V.K. Patki, Development of water quality index for Godavari River (India) based on fuzzy inference system, Groundwater Sustain. Develop. 10 (2020), 100350.
[85] M.M. Cabral-Pinto, M. Inácio, O. Neves, A.A. Almeida, E. Pinto, B. Oliveiros, E.A. Ferreira da Silva, Human health risk assessment due to agricultural activities and crop consumption in the surroundings of an industrial area, Exp. Heal. 12 (2020) 629–640.
[86] K. Ravindra, S. Mor, Distribution and health risk assessment of arsenic and selected heavy metals in Groundwater of Chandigarh, India, Environ. Pollut. 250 (2019) 820–830.
[87] P.C. Emenike, I.T. Tenebe, J.B. Neris, D.O. Omole, O. Afolayan, C.U. Okeke, I.K. Emenike, An integrated assessment of land-use change impact, seasonal variation of pollution indices and human health risk of selected toxic elements in sediments of River Atuwara, Nigeria, Environ. Poll. 265 (2020), 114795.
[88] M. Bresciani, C. Giardino, D. Stroppiana, M.A. Dessena, P. Buscarinu, L. Cabras, K. Schenk, T. Heege, H. Bernet, G. Bazdanis, Monitoring water quality in two dammed reservoirs from multispectral satellite data, Eur. J. Rem. Sens. 52 (sup4) (2019) 113–122.
[89] H.Z. Panseriya, H.B. Gosai, D.J. Gavali, B.P. Dave, Assessment of surface water quality during different tides and an anthropogenic impact on coastal water at Gulf of Kachchh, West Coast of India, Environ. Sci. Pollut. Control Ser. (2022) 1–13.
[90] A. Gorgoglione, J. Gregorio, A. Rios, J. Alonso, C. Chreties, M. Fossati, Influence of land use/land cover on surface-water quality of Santa Lucìa river, Uruguay, Sustainability 12 (11) (2020) 4692.
[91] M.S. Gradilla-Hernández, J. de Anda, A. Garcia-Gonzalez, D. Meza-Rodríguez, C. Yebra Montes, Y. Perfecto-Avalos, Multivariate water quality analysis of Lake Cajititlán, Mexico, Environ. Monit. Assess. 192 (1) (2020) 5.
[92] H. Aydin, F. Ustaoğlu, Y. Tepe, E.N. Soylu, Assessment of water quality of streams in northeast Turkey by water quality index and multiple statistical methods, Environ. Forensics 22 (1–2) (2021) 270–287.
[93] V. Kothari, S. Vij, S. Sharma, N. Gupta, Correlation of various water quality parameters and water quality index of districts of Uttarakhand, Environ. Sustain. Ind. 9 (2021), 100093.
[94] K. O'Dowd, S.C. Pillai, Photo-Fenton disinfection at near neutral pH: process, parameter optimization and recent advances, J. Environ. Chem. Eng. 8 (5) (2020), 104063.
[95] M. Ahmadi, S.H. Seyedin, Investigation of NaOH properties, production and sale mark in the world, J. Multidis. Eng. Sci. Techn. 6 (10) (2019) 10809–10813.
[96] J. Alao, T. Danjuma, M. Nur, Electrical conductivity for selection of viable land for agricultural activities and a suitable sites for borehole, Asi. J. Geolog. Res. 5 (1) (2022) 37–50.
[97] A. Kuriqi, A.N. Pinheiro, A. Sordo-Ward, M.D. Bejarano, L. Garrote, Ecological impacts of run-of-river hydropower plants—current status and future prospects on the brink of energy transition, Renew. Sustain. Energy Rev. 142 (2021), 110833.
[98] L. Bai, Y. Bai, Y. Hou, S. Zhang, S. Wang, A. Ding, Ecological water replenishment to the Yongding River, China: effects of different water sources on inorganic ions and organic matter characteristics, Environ. Sci. Pollut. Control Ser. (2023) 1–14.

[99] B. Panneerselvam, K. Muniraj, C. Pande, N. Ravichandran, M. Thomas, S. Karuppannan, Geochemical evaluation and human health risk assessment of nitrate-contaminated groundwater in an industrial area of South India, Environ. Sci. Pollut. Control Ser. (2021) 1–18.

[100] L.T. Popoola, A.S. Yusuff, T.A. Aderibigbe, Assessment of natural groundwater physico-chemical properties in major industrial and residential locations of Lagos metropolis, Appl. Water Sci. 9 (8) (2019) 191.

[101] C.R. Walton, D. Zak, J. Audet, R.J. Petersen, J. Lange, C. Oehmke, W. Wichtmann, J. Kreyling, M. Grygoruk, E. Jabłońska, Wetland buffer zones for nitrogen and phosphorus retention: impacts of soil type, hydrology and vegetation, Sci. Total Environ. 727 (2020), 138709.

[102] J.M.A. Jose, P.S. Shinu, E.E. Gladis, D. Arthi, J. Joseph, Preliminary assessment for physicochemical quality parameters of groundwater in tirunelveli district, Mater. Today: Proc. 45 (2021) 1843–1848.

[103] S. Mirlohi, Characterization of metallic off-flavors in drinking water: health, consumption, and sensory perception, Int. J. Environ. Res. Publ. Health 19 (24) (2022), 16829.

[104] Z. Fu, S. Xi, The effects of heavy metals on human metabolism, Toxicol. Mech. Methods 30 (3) (2020) 167–176.

[105] J. Ijumulana, F. Ligate, P. Bhattacharya, F. Mtalo, C. Zhang, Spatial analysis and GIS mapping of regional hotspots and potential health risk of fluoride concentrations in groundwater of northern Tanzania, Sci. Total Environ. 735 (2020), 139584.

[106] G.W. Suter, Ecological risk assessment in the United States Environmental Protection Agency: a historical overview, Integrated Environ. Assess. Manag. 4 (3) (2008) 285–289.

[107] Y. Ji, J. Wu, Y. Wang, V. Elumalai, T. Subramani, Seasonal variation of drinking water quality and human health risk assessment in Hancheng City of Guanzhong Plain, China, Exp. Health 12 (2020) 469–485.

[108] O.O. Onyemesili, J.C. Egbueri, C.K. Ezugwu, Assessing the pollution status, ecological and health risks of surface waters in Nnewi urban, Nigeria: implications of poor waste disposal, Environ. Forensics 23 (3–4) (2022) 346–360.

[109] N. Eboagu, V. Ajiwe, Health Risk Assessment of Heavy Metal Contamination of Groundwater Around Nnewi Industrial Area, Anambra State, Nigeria, 2022, https://doi.org/10.21203/rs.3.rs-2269680/v1.

[110] K. Ifeanyichukwu, C. Okolo, A. Odoh, Evaluation of toxic elements in groundwater in the industries area of Nnewi north south-eastern Nigeria, Environ. Cont. Rev.(ECR) 5 (1) (2022) 31–34.

[111] O. Igwe, M. Omeka, Hydrogeochemical and pollution assessment of water resources within a mining area, SE Nigeria, using an integrated approach, Int. J. Ener. Water Res. 6 (2) (2022) 161–182.

[112] F. Ibe, C. Enyoh, A. Opara, B. Ibe, Evaluation of pollution status of groundwater resources of parts of Owerri metropolis and environs, Southeastern Nigeria, using health risk and contamination models, Int. J. Ener. Water Res. 4 (2020) 357–374.

[113] B.O. Isiuku, C.E. Enyoh, Pollution and health risks assessment of nitrate and phosphate concentrations in water bodies in South Eastern, Nigeria, Environ. Adv. 2 (2020), 100018.