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Comparative assessment of groundwater quality and stability around active and closed dumpsites in Ibadan, Nigeria

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The research intended to appraise the worth, corrosion, and scale formation of well water samples collected near active and shut dumpsites. Groundwater samples were analyzed for physicochemical parameters using standard analytical procedures. All samples near the active dumpsite (DS) were potable, meeting the World Health Organization standards for drinking water. In contrast, samples near the abandoned DS did not meet the acceptable limits. The water quality index values classified 90% of water samples near the active DS as "Excellent to good quality". Near the closed DS, 90% of water samples were deemed "poor to unsuitable" for drinking, with only 10% meeting good quality standards. Most irrigation parameters indices (IPI) indicated that aquifer units near the abandoned DS were suitable for irrigation, while only a few IPIs suggested suitability for GW near the active DS. Stability tests revealed corrosive tendencies in groundwater near the active DS, while scale-forming tendencies were observed near the abandoned DS. The study recommends regular assessment of groundwater quality and water treatment for shallow dug wells near the studied residential areas, with the use of corrosion inhibitors. Similar evaluations should be conducted in other locations near operational and closed waste disposal sites under different geological formations to ensure sustainable management of groundwater resources.

Keywords Corrosion and scaling potentials, Hydro-geochemistry, Groundwater, Active and Abandoned DS, Physicochemical properties, Water Quality

Groundwater is extracted from the underlying aquifer unit and accounts for approximately 97% of the available freshwater resources worldwide[1,2]. It is considered the most practical source of freshwater that greatly assists in meeting the demand for water supply by the population in most provinces of the continent[3,4]. Groundwater is vital to the populace for several uses such as drinking, irrigation, and industrial purposes[5,6]. According to[7], a total of 68% of the global's water withdrawal goes to agricultural uses, 23% for consumption needs, whereas manufacturing use accounts for the remaining 9%. Groundwater is not available in adequate quantity everywhere; therefore, there must be management and monitoring processes to preserve the quality of available sources. A considerable threat to aquifer resources is worsening fitness due to pollutants derived from anthropogenic inputs[8,9]. Human-caused activities contribute significantly to groundwater pollution in many developing countries, including Nigeria. Pollutants alter the inherent status of water extracted from a shallow dug well/tube well, thereby resulting in deterioration of its quality as well as limiting its fitness for various daily purposes[10].

The determinants of the quality status of shallow aquifer within a specific region include geographical position, underlying rock types, dominant rock-water interaction processes, and prevailing human-induced activities[6,11]. Notably, the upsurge in the quantity of metropolitan solid waste created per head on a daily basis, as well as indiscriminate disposal of such waste near groundwater sources, has contributed immensely to the decline in suitable groundwater for drinking, industrial, and agricultural purposes[11,12]. Community hand-dug wells near the solid waste landfill site are explicitly prone to contamination by landfill leachate. Leachate flows unhindered via the permeable subsoil horizons, faults, fractures and voids, infiltrating nearby shallow groundwater sources

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and reduces their suitability status[11]. Hence, it is essential to continuously checking the aquifer origins located in the neighborhood of garbage disposal site, so as to safeguard potable water for the local populace and maintain the sustenance of the fragile ecosystem[11,13–15].

Detailed information about the geochemical reactions prevalent between the source rock and aquifer units offers insight into the levels of water quality indicators. Furthermore, probable origins of dissolved constituents ions as well as extent of impact of potential pollutants (leachate in this case) on nearby water sources can be inferred from hydrogeochemical characterization[9,16,17].

Corrosion problems in water distribution facilities cause worsening of water potability and its effectiveness, degradation of the life span of water distribution networks, formation of cavities leading to appreciable water loss, and leaching of some potentially toxic elements into drinking water[17,18]. On the contrary, scale formation inside the water distribution pipe results in the formation of sediment deposition in both the water heating system and distribution pipes[10]. The extent and rate of water corrosion effect are influenced by levels of water's physico-chemical indicators like water pH value, total dissolved salts, electrical conductivity, oxygen saturation, temperature, alkalinity, complete hardness, as well as the type of water distribution pipe influence the extent and rate of corrosion and scale deposition[3,11]. The determination of stability prospective of aquifer system is extremely multifarious and collaborative reaction[13,19]. Consequently, several indices were characteristically employed to assess corrosive tendency for industrial uses. Frequently utilized indices comprise the larson-skold index, aggressiveness index, Langelier saturation index, ryznar stability index, puckorius Index, and chloride-to-sulphate-mass ratio[3,18–20]. The majority of published research works on groundwater quality within the vicinity of active anthropogenic sources, such as dumpsite, focused on assessing the concentrations of quality-induced physicochemical variables vis-á –viz fitness for domestic and agricultural purposes[21–24]. Several published studies detailing the suitability or otherwise of freshwater for industrial functions are also available[4,25,26]. However, there is a dearth of literature on the suitability of groundwater sources near municipal solid waste disposal sites for industrial purposes. Furthermore, regarding the operational and closed prominence of municipal garbage dumping place, available published works seem to focus more on comparing the levels of quality induced parameters (physico-chemical and/or microbial variables) in groundwater extracted from shallow wells nearby active and abandoned dumpsites with regards to its suitability for domestic consumption[27–29].

There is, however, scarcity of literature on the comprehensive study regarding the hydrogeochemical categorization and quality of groundwater sources near active and closed dumpsites within Southwest part of Nigeria. Additionally, considering the fact that the two selected sampling areas are located within a peri- urban setting where water sources can be used for different needs such as consumption, agricultural and industrialized purposes, there is a need to appraise the quality status of available groundwater sources near the active and closed dumpsites. Therefore, this present study is aimed at ascertaining and characterizing the geochemical reactions influencing the groundwater chemistry in the two study areas as well as assessing their suitability for domestic, irrigation and industrial uses through indexical approach.

This research work sought to evaluate the quality of groundwater near functional and closed garbage lots by calculating water quality index (WQI), irrigation parameter indices (IPI), and stability index for drinking, agricultural, and industrial uses, respectively. This present study endeavors to accomplish these specific goals : (i) to determine and compare the concentrations of physico-chemical parameters in nearby groundwater sources, (ii) to evaluate groundwater suitability for various uses using indexical approaches, (iii) to evaluate the effects of activity and abandonment on physico-chemical characteristics and stability of nearby groundwater systems, (iv) to pinpoint geochemical reactions influencing the overall aquifer quality, and (v) examining the interrelationships among corrosion indices based on the dumpsite's activity and abandonment status. The merit of the study can be attributed to the fact that it employs different indexical approaches to evaluate the ecological consequences of abandonment and the activity of the dumpsite on shallow aquifer units. The indices used in this study not only quantify the suitability or otherwise of nearby groundwater sources for a specific task, but also provide standardized frameworks for comparing the degree of impact across different dumpsite types and thus provide a more complete perspective.

Materials and methods

Study locations

The active and abandoned dumpsites are situated within the Ibadan metropolis in southwest Nigeria. There are residential households adjacent to both active (Aba Eku) and abandoned dumpsites. A shopping mall has been built on part of the abandoned dumpsite. The investigation develops on earlier works by[30] and[31]. The study involves the collection of water samples extracted from dug wells at the same sample locations comparable to[30] and[31] in May and June (rainy season) 2020. The reports provided detailed descriptions of the study sites, climatic conditions, drainage patterns, and geological settings of the research sites. 10 samples were collected from ten dug wells (less than 30 m depth) located within a radius of less than 500 m from each dumpsite (Table 1). Water samples were collected after obtaining informed consent from the well owners. Figure 1 shows the maps of the study areas with the groundwater sampling points marked, while Table 1 lists the geographical coordinates of the sampling points and their distances from the dumpsites. The major lithology in the two investigated locations is Quartzite/quartz schist (Fig. 1).

Groundwater samples collection and physico-chemical laboratory procedures

Ten samples collected near the active dumpsite were branded S1 – S10, whereas the second set of ten water samples near the abandoned dumpsite were labeled GW1—GW10. All the groundwater samples were placed in 1L polyethylene bottles. At every water sampling location, the groundwater to be investigated was initially used to clean the sampling plastic container three times prior to the collection of the actual sample[32]. Samples in airtight polythene bottles were later stored in ice chests and quickly taken to the Chemistry Laboratory at

Sample Code	Latitude	Longitude	Elevation	Approximate distance to the dumpsite
S1	7°19′21.79″N	3°59′09.59″E	194	110
S2	7°19′20.0″N	3°59′14.22″E	187	30
S3	7°19′22.06″N	3°59′18.37″E	176	50
S4	7°19′22.72″N	3°59′19.03″E	177	52
S5	7°19′21.49″N	3°59′14.94″E	188	20
S6	7°19′31.81″N	3°59′03.00″E	207	350
S7	7°19′32.60″N	3°59′01.86″E	198	360
S8	7°19′33.15″N	3°59′02.10″E	179	362
S9	7°19′17.21″N	3°59′09.45″E	181	170
S10	7°19′17.74″N	3°59′08.36″E	194	200
GW1	7°21.439N	3°52.103E	218	33
GW2	7°21.525N	3°51.481E	195	15
GW3	7°21.520N	3°51.492E	206	05
GW4	7°21.556N	3°51.448E	184	25
GW5	7°21.586N	3°51.433E	256	28
GW6	7°21.585N	3°51.455E	199	26
GW7	7°21.591N	3°51.480E	196	30
GW8	7°21.571N	3°51.415E	212	24
GW9	7°21.578N	3°52.468E	206	25
GW10	7°21.580N	3°51.458″E	186	23

Table 1. Geographic details of water sampling points near active and abandoned dumpsites. (S1—S10 represent groundwater samples near active dumpsite while GW1- GW10 represent the groundwater samples near closed MSWD.).

Federal University of Agriculture, Abeokuta, Ogun State (FUNAAB), Nigeria, for required sample preservation. Collected specimens were reposited below 4 °C in the fridge prior to the initiation of the examination[15]. The parameters considered in this work include pH, TDS, EC, main cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}), anions (Cl^{-}, SO_4^{2-},NO_3^-,HCO_3^- and CO_3^-), and total hardness. Parameters like pH, TDS, and EC were measured in the field using a multipurpose conductivity meter (Extech EC 600). HCO_3^- and CO_3^- were determined by titrimetric analysis with hydrochloric acid, while Cl^{-} was analyzed using the standard silver nitrate titration. The levels of sulphate and nitrate ions in water samples were determined using turbidimetric and UV spectrophotometry, respectively[11,30]. Total hardness in the water sample was analyzed by titration with ethylenediaminetetraacetic acid employing Eriochrome black-T as indicator[11]. Tested cation content was measured utilizing the flame photometry technique. The consistency of the measured parameters' readings was established by computing the ionic charge balance errors, where the error values obtained were typically below 10%[33,34]. Quality assurance include replica readings of the analyzed quality induced variable, standardization of systematic instruments and chemical agents, conducting a blank sample analysis after completion of each set of five analyses, and performing a reference investigation.

Statistical data treatment

Basic descriptive statistics and cluster analysis were performed on the physicochemical and corrosion indices data. Cluster analysis was performed in accordance with agglomerative program where a blend of ward's linkage as well as squared euclidean distances were used to quantity the connection or dissimilarity in properties of analyzed quality-induced parameters and stability indices. Furthermore, basic statistics and Kendall's correlation analysis were conducted on the corrosion indices data for all water samples collected around the two dumpsites. Bar graphs showing the trend of variation of each of the corrosion indices in water samples from the two study locations were also obtained. Statistical data treatment in this study was done using SPSS 20.

Groundwater quality index

This is a ranking measure that expresses reliable facts on the overall fitness in simplest format. The GWQI is regarded as a simple, compliant, and numerically simple grading means to observe water quality status of a particular groundwater system[4,35]. Several environmental scientists have employed GWQI to categorize groundwater into different quality statuses solely for drinking purposes[32,36]. The calculation of GWQI in this study considered 10 analyzed quality induced variables: SO_4^{2-}, Cl^-, NO_3^- pH, TDS, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and Cl^{-}. A weight (w_j) is allocated to every selected variable according to its comparative worth in contribution to water quality for drinking[37,38]. Subsequently, the comparative weight (W) was calculated by the relation:

$$W = \frac{w_j}{\sum_{i=1}^{n} w_j} \tag{1}$$

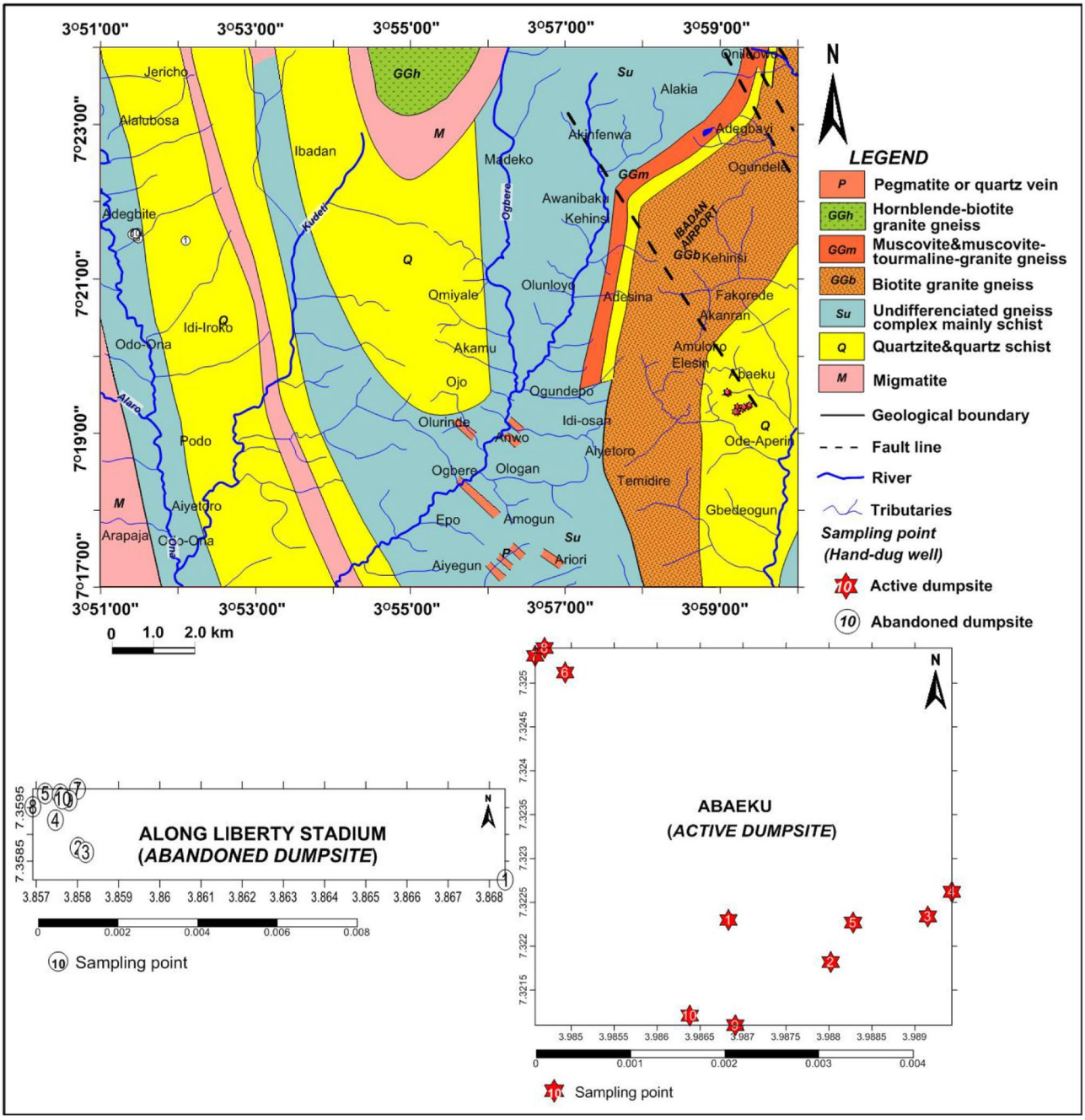

Fig. 1. Geological map showing the rock types that underlie the two study areas and water sampling points.

Here w_j stands for the allotted weight of each considered factor, whereas n denotes the size of measured variables employed in the calculation of GWQI[9,11].

The quality rating (q_j) of each variable was calculated by Eq. 2:

$$q_j = \left(\frac{C_j - C_o}{S_j}\right) \times {}^{100}/_{1.00} \tag{2}$$

Here, C_j signifies the measured level of the jth parameter, S_j is the WHO acceptable value for jth variable, and $C_o = 0$ for most physicochemical variables except DO and pH[15]. However, the quality rating of pH is calculated using Eq. 3 as:

$$q_{pH} = \left(\frac{C_j - 7.00}{1.50}\right) \times \frac{100}{1} \tag{3}$$

where C_j in Eq. 3 denotes the level of water pH per sample[37,38].

Finally, the overall GWQI of every tested water sample was calculated using the equation:

$$GWQI = \sum W_i q_i \tag{4}$$

The suitability of analyzed samples for domestic consumption based on GWQI value is classified into five different clusters[37–39]. The five groups are—exceptional (0–25); decent (26–50); pitiable (51–75), shoddy (76–100), while GWQI values greater than 100 signify unsuitable for domestic consumption.

The allocated weight (w_j), comparative weight (W_j), and global guideline thresholds of analyzed physico-chemical variables are shown in Table 2.

Identification of hydrochemical facies and geochemical processes

Calculating ionic ratios provides a way to acquire a comprehensive grasp of the associations among the electrolytes in groundwater and to fully comprehend the precise geochemical reactions that influence their levels in water samples[8,9,40]. Ionic ratios can also offer insights and supportive evidence for potential man-made inputs and/or influencing geogenic processes[6,41].

The present study employs the ionic ratios: $\frac{Cl^-}{SO_4^{2-}}$, $\frac{Na^+}{Cl^-}$, $\frac{Na^+}{Na^+ + Cl^-}$, $\frac{Ca^{2+}+Mg^{2+}}{HCO_3^-}$ and $\frac{Ca^{2+}}{Ca^{2+}+SO_4^{2-}}$.

were considered. The kind of ionic hydrogeochemical reactions influencing the water quality can also be successfully comprehended via the Chloro-alkaline indices (CAI)[2,11,42]. For the computation of chloro-alkaline indices 1 and 2, the causative dissolved ions employed in the calculation of CAI must be in mg/L[8,9].

Chloro-alkaline index 1 and chloro-alkaline index 2 are calculated using the relations[2,8,15,43,44,44,45,45–48].

$$CAI\,1 = \frac{Cl^- - (Na^+ + K^+)}{Cl^-} \tag{5}$$

$$CAI\,2 = \frac{Cl^- - (Na^+ + K^+)}{SO_4^{2-} + CO_3^{2-} + HCO_3^-} \tag{6}$$

Suitability of samples for agricultural Use

The suitability of groundwater samples near active and abandoned DSs for irrigation purposes was evaluated based on the concentrations of assessed physico-chemical parameters and irrigation parameter indices (IPI). The considered IPI in this study include sodium adsorption ratio (SAR), Total hardness (TH), soluble sodium percentage (SSP), permeability index (PI), potential salinity (PS), Kelly ratio (KR), Residual sodium carbonate (RSC), and comprehensive hazard coefficient (k). The IPI was computed utilizing the established relations (7) to (15):-

$$TH = 2.497\,Ca^{2+} + 4.11\,Mg^{2+} \tag{7}$$

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{8}$$

$$\%\ \mathrm{Na} = \frac{Na^+ + K^+}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \mathrm{x} \frac{100}{1} \tag{9}$$

$$RSC = (HCO_3^- + CO_3^-) - (Ca^{2+} + Mg^{2+}) \tag{10}$$

Parameters	WHO standard (2017, 2022)	Weight (w_i)	Relative weight (W_i)
pH	6.5–8.5	2	0.067
TDS	500	5	0.167
Ca^{2+}	75	2	0.067
Mg^{2+}	20	2	0.067
Na^{2+}	200	2	0.067
K^+	10	2	0.067
SO_4^{2-}	250	5	0.167
Cl^-	250	3	0.096
NO_3^-	50	5	0.167
HCO_3^-	125	3	0.096
		$\sum w_i = 31$	$\sum W_i = 1.028$

Table 2. The assigned weight, relative weight and WHO quality guidelines used in the GWQI calculation.

$$PS = Cl^- + \frac{SO_4^{2-}}{2} \tag{11}$$

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \tag{12}$$

$$PI = \frac{(Na^+ + \sqrt{HCO_3^-}) \times 100}{(Ca^{2+} + Mg^{2+} + Na^+)} \tag{13}$$

$$MR = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100 \tag{14}$$

However, **k** is computed using the equation:

$$\mathbf{k} = 12.4\ \mathrm{M}\ +\ \mathrm{SAR} \tag{15}$$

Where M is the total dissolved salts in g/L, while SAR retains the same meaning[2,48].

Determination of corrosivity indices

Corrosion and scale formation tendencies in collected groundwaters near the active and abandoned DSs were evaluated through the computation of corrosion and scaling indices. Six (6) main corrosivity indices utilized in this study include Ryznar Stability Index (RSI), Langelier Saturation Index (LSI), Puckorius Scaling Index (PSI), Larson–Skold Index (LS), Aggressive Index (AI), and Chloride – Sulfate – Mass Ratio (CSMR).

Langelier saturation index (LSI)

This index expresses the extent of saturation of water with respect to the calcite[26,49,50]. The LSI is computed by:

$$\mathrm{LSI}\ =\ \mathrm{pH}\ -\ \mathrm{pHs} \tag{16}$$

In Eq. 16, pH refers to the definite pH of the sample, whereas pHs refers to the calculated pH value at the saturation state of $CaCO_3$:

$$pHs = A + B - \log(Ca^{2+}) - \log(HCO_3^- + CO_3^-) \tag{17}$$

where $A = 2.2496 - 0.0178T + 0.0008347T^2 - 0.00000041T^3$.

$$\mathrm{B}\ =\ 9.70\ +\ \frac{2.5(\mu)^{1/2}}{1.0 + 5.3(\mu)^{1/2} + 5.5\mu}$$

Where $\mu = 0.000025$ TDS, Ca^{2+} is the calcium hardness (mg/L of $CaCO_3$), T stands for temperature in °C, and TDS equals the total dissolved solids in mg/L[50–52]. A negative value of LSI denotes that the water is undersaturated and tends to dissolve $CaCO_3$. A positive value of LSI denotes that the water is supersaturated with $CaCO_3$ and scale formation is advocated[49,50]. According to[19], a range of ($-4 < \mathrm{LSI} < -2$) indicates slight corrosion; range of ($-1 < \mathrm{LSI} < 0$) indicates little corrosion; LSI equals to zero indicates water that does not tend to dissolve or precipitate $CaCO_3$) and range of ($0 < \mathrm{LSI} < 2$) indicates little to modest scale formation.

Aggressive index (AI)

This index is considered a simplistic form of the LSI. It is expressed mathematically as:

$$AI = pH + \log[(HCO_3^- + CO_3^{2-}) \times Ca^{2+}] \tag{18}$$

where CO_3^{2-}, HCO_3^- and Ca^{2+} are in meq/L[50,51]. AI value < 10.0 signpost water is extremely aggressive, AI (10.0–11.9) indicates moderately aggressive water, while AI ≥ 12.0 indicates non-aggressive water[50,51,53].

Larson – skold index (LS)

This index describes the quotient of the levels of strong anions (chloride sulfate) to the levels of weak anions (bicarbonate + carbonate) in water[17,18]. The formula calculates the LS as:

$$LS = \frac{Cl^- + SO_4^{2-}}{HCO_3^- + CO_3^{2-}} \tag{19}$$

where the concentration of Cl^-, SO_4^{2-}, HCO_3^- and CO_3^{2-} are expressed in meq/L[6,52]. An LS value < 0.80 indicates water tends to scale formation; $0.80 \le \mathrm{LS} \le 1.20$ indicates a greater corrosion rate can be observed in the water, while LS value greater than 1.20 suggests a great rate of confined corrosion can be anticipated in the studied groundwater[5,54].

Puckorius scaling index (PSI)

This index specifies the softening ability and precipitation features of water to attain equilibrium[17,18,55]. The expression to determine PSI is:

$$PSI = 2.00[pH_{eqs}] - pH_s \tag{20}$$

where pH_s denotes the hydrogen ion concentration at wetness, while pH_{eqs} is potential of hydrogen at balance, and is given by Eq. 21:

$$pH_{eqs} = 1.47 \times \log_{10}[(HCO_3^- + CO_3^-) \times Ca^{2+}] \tag{21}$$

PSI value < 6 indicates water has scale formation propensity; 6 ≤ PSI ≤ 7 indicates water has little scaling and corrosive tendencies, while PSI > 7 suggests water has noteworthy corrosive inclination[54].

Ryznar stability index (RSI)

This is a kind of index used to predict the extent of scaling deposition in subsurface water[17,55]. RSI is expressed through the relation:

$$RSI = 2pHs - pH \tag{22}$$

where pH and pHs retain their usual meanings.

According to[17,18], RSI ≤ 5.50 signposts water has a severe scale formation, 5.50 < RSI < 6.20 suggests the aquifer has comparatively scale formation and corrosion tendency, 6.20 ≤ RSI ≤ 6.80 indicates stable water, while PSI > 6.80 indicates corrosive water.

Chloride – sulfate – mass ratio (CSMR)

This index, as proposed by[56], is used to evaluate the likelihood of leaching of Pb from galvanized distribution pipes[51,53]. It is computed by using the ratio of chloride to sulphate concentration as:

$$CSMR = \frac{Cl^-}{SO_4^{2-}} \tag{23}$$

As stated by[51,57], CSMR values < 0.50 imply water is not prone to pitting corrosion, while CSMR > 0.50 indicates water is vulnerable to bimetallic corrosion.

Results and discussions

Physico-chemical characteristics of groundwater near active and abandoned dumpsites

The concentrations of analyzed physico-chemical parameters in groundwater within the vicinity of active and abandoned dumpsites are summarized in Table S1. The descriptive statistics of physico-chemical parameters in groundwater samples around active and closed DSs are listed in Tables 3 and 4. The pH in water samples around active and abandoned DSs ranged from 6.67 to 7.59 (average = 7.03) and 7.91 to 8.92 (average = 8.51), respectively. All groundwater samples near active dumpsites had pH that conforms to the allowable threshold (6.5–8.5) recommended for drinking[58,59]. However, only 60% of water samples near abandoned DS had pH values that lie within the allowable pH range for drinking water (Table S1). The mean alkaline nature of GW samples near abandoned DS observed in this study concurs with the findings of[60] on the same study site. The

Groundwater near active DS					
Parameter	Size	Minimum	Maximum	Mean	Std. Deviation
Temp	10	25.51	25.56	25.5440	.01578
pH	10	6.7	7.6	7.030	.2869
EC	10	148	784	290.20	184.110
TDS	10	74	392	144.80	92.112
chloride	10	17	106	35.60	28.698
HCO3	10	122.0	366.0	200.080	66.8716
CO3	10	60	181	98.50	33.164
TH	10	8	288	92.20	76.049
SO4	10	13.39	144.03	33.1500	39.99713
NO3	10	1.36	4.81	2.4290	1.17065
Na	10	8	40	18.00	9.684
K	10	1	5	1.50	1.269
Mg	10	.4	14.8	6.840	4.3925
Ca	10	.12	5.87	2.3150	1.87397

Table 3. Descriptive statistics of physico-chemical parameters.

Parameter	Size	Minimum	Maximum	Mean	Std. Deviation
Temp	10	26.41	26.52	26.4700	.03590
pH	10	7.9	8.9	8.530	.3057
EC	10	78	836	432.10	282.918
TDS	10	40	419	216.00	141.247
Chloride	10	9	28	19.00	5.907
HCO3	10	72	488	258.90	130.497
CO3	10	36	240	127.20	64.050
TH	10	58	320	189.40	93.865
SO4	10	6	159	53.70	45.243
NO3	10	43	46	44.70	.949
Na	10	12	60	25.20	17.931
K	10	3	21	9.00	5.395
Mg	10	24	122	79.80	32.802
Ca	10	20	218	109.00	70.700

Table 4. Descriptive statistics of physico-chemical parameters Groundwater near Abandoned DS.

ranges of pH values in GWs around active and closed dumpsites for this study were comparatively higher than the ranges 5.3–6.6 and 4.1–4.4 in groundwater near active and closed dumpsites, respectively as reported by[29]. However, the ranges of pH in GW near the active and closed dumpsites for this study are comparable to the reported pH ranges of 6.8–7.3 and 7.9 to 8.1 in groundwater within the vicinity of active and closed dumpsites, respectively, in Lagos, Southwest Nigeria, by[27].

All the GW sampling sites near both active and closed dumpsites conformed to the acceptable standard (1000 µs/cm) for EC in groundwater for domestic purposes[58,61]. The total dissolved solids (TDS) concentrations in groundwater near active and abandoned DSs varied from 74 to 392 mg/l (average = 144.8 mg/L) and 40 to 419 mg/L (average = 243.4 mg/L), respectively. It was observed that the average EC of groundwater samples near the abandoned dumpsite (414.7 µs/cm) was higher than its corresponding value in GW samples near active dumpsite (290.2 µs/cm), indicating that the aged leachate from the abandoned DS still release dissolved salts[62]. Generally, the average concentrations of EC and TDS in groundwater samples near the closed dumpsite were relatively higher than those near the active dumpsite. This is in contrast to the reported higher values of TDS and EC in groundwater near active DS relative to those of the closed dumpsite in Selangor, Malaysia, as reported by[28]. Furthermore, higher mean values of EC and pH in groundwater samples within the vicinity of closed dumpsite relative to those nearer to active dumpsite for this study is in contrast to findings by[62] that reported significant reduction in concentrations of EC and pH amongst other dissolved ions in groundwater after landfill closure. The disparity might be due to differences in waste composition, dumpsite/landfill design, site-specific factors and underlying lithology.

The concentrations of EC and TDS in 100% of groundwater samples near both dumpsites lie within the acceptable standards of 1000 and 600 mg/L, respectively, for drinking water[58,61]. This aligns with similar results for aforementioned parameters in groundwater near the active and closed dumpsites by[29]. The total hardness (TH) levels in water samples near active and closed dumpsites ranged from 08—288 mg/L (average = 92.2 mg/L) and 58–320 mg/l (average = 189.4 mg/l), respectively. A total of 90% of collected water samples near the active dumpsite had TH levels that lie within the WHO guideline limit (200 mg/L) for drinking water[61]. Only sample S5, collected from well located at approximately 20 m from the fence of the active dumpsite, had a TH value (288 mg/L). The higher mean TH value for GW systems near the abandoned dumpsite for this study is in contrast with the earlier higher average TH value in GW near the Solouos 3 (active) dumpsite in Lagos, Nigeria by[27]. However, higher mean TH value in groundwater systems around closed dumpsite concurs with similar finding by[29].

The mean values of Ca^{2+} and Mg^{2+} in samples near active DS were 2.32 and 6.84 mg/L, respectively. The Ca^{2+} and Mg^{2+} values in GW samples near active DS conform with the acceptable standards of 75 and 50 mg/L, respectively, for drinking[59]. However, average concentrations of Ca^{2+} and Mg^{2+} in GW near the closed dumpsite were 109 and 79.8 mg/l, respectively. Only 30% and 20% of samples near abandoned DS had Ca^{2+} and Mg^{2+} levels, respectively, within the acceptable limits for drinking water. The concentrations of Na^{+} and K^{+} for all the groundwater lie below the guideline thresholds of 200 and 30 mg/L, correspondingly, for drinking purposes[61,63]. The relatively higher ($Na^{+} + K^{+}$) values in GW samples near closed DS compared to those near active DS recorded for this work are consistent with previous comparable outcomes by[27]. The concentration of sulphate in samples around active and abandoned dumpsites ranged from 13.39 to 144.03 mg/l (mean = 33.2 mg/l) and 6 −159 mg/l (mean = 53.7 mg/l), correspondingly, and fell within the acceptable standard (250 mg/L) for consumption purpose[5962]. however reported decrease in sulphate concentration in groundwater system after landfill closure. It must be stated here that there are uneven effects of site-specific factors and waste composition on the groundwater chemistry of a particular region. The average nitrate value in water samples near active DS (2.43 mg/L) was significantly lower than that near abandoned DS (44.70 m). Higher mean nitrate value in groundwater systems around abandoned dumpsite relative to its corresponding value in aquifer units within the

vicinity of active dumpsite was also reported by[29,62]. obtained similar significant elevated nitrate concentration in GW around closed landfill.

The chloride ion concentration in GW samples around active and closed dumpsites ranged from 17 to 106 mg/L (mean = 35.6 mg/L) and 9 to 28 mg/L (mean = 19.1 mg/L), respectively. All the GW samples from the two study areas had Cl^- concentration within the guideline standard (250 mg/L) for domestic use[58]. Similar decrease in chloride content in GW samples around closed landfill was also reported by[62]. In closed dumpsite, there is less leachate production, resulting in reduced leaching potential of salts from the waste body[62]. The levels of bicarbonate in 100% samples lie within the tolerable edge of 500 mg/l for consumption[58]. The average bicarbonate value in GW samples around abandoned DS (258.7 mg/L) was higher than at active DS (200.8 mg/L). The relatively higher mean bicarbonate concentration in GW near abandoned DS suggests depletion of leachable salts from the old waste body in abandoned DS[62]. Additionally, microbial degradation of organic matter and dissolution of mineral salts in a closed dumpsite could contribute to the relatively high mean value of bicarbonate in GW near abandoned DS[62,64].

Generally, sample S5 around the active dumpsite had higher levels of the majority of tested physico-chemical variables, possibly as a result of its proximity to the dumpsite. Similarly, GW4 collected from well which is at a distance of 25 m downgradient from the abandoned DS exhibited higher concentrations of most of tested quality parameters. Similar enrichment of dissolved ions in GW situated downgradient of landfill were also described by[65,66]. Overall, the average concentrations of all inorganic parameters excluding Cl^- in GW samples near abandoned DS were higher than those around active DS. This observation concurs with the findings of[29] that GW near non-active DS contains more inorganic contaminants than the active DS groundwater. Specifically, the mean values of Ca^{2+} and Mg^{2+} in GW near abandoned DS surpassed the global and Nigerian potable water references for consumption. In addition, the greater mean values of most of the analyzed parameters in groundwater near abandoned DS compared to those near active DS concur with the earlier assertion by[67]that water, soil, and sediment around abandoned DS showed higher levels of contamination due to complete disintegration and biochemical processes of municipal solid garbage in the closed DS. However[27], reported higher mean values of dissolved solids, Cl^-, and hardness in GW near active DS relative to those near closed DS. Furthermore[28], reported higher mean values of electrical conductivity (EC), TDS, and nitrate in GW near functional DS compared to closed DS groundwater in Selangor, Malaysia. The disparity in mean values of some assessed parameters in GWs near both active and closed dumpsite for this present study with related works could be due to metropolitan refuse composition, age of the DS, lithological setting, and climatic conditions of the sampling period[62].

Hydrogeochemical composition of groundwater near active and abandoned dumpsites

Table S2 presents the outcomes of hydrochemical indices utilized to deduce the hydrogeochemical properties of the aquifer nearby active and closed dumpsites. From Table S2, the $\frac{Na^+}{Cl^-}$ ratio in GW samples around active and closed DSs ranged from 0.582 to 1.156 and 1.055 to 4.023, respectively. Further scrutiny of this ratio in GW around active DS showed that 60% of water sampling points had $\frac{Na^+}{Cl^-} < 1.00$, indicating reverse ion exchange process, while the remaining 40% with the ratio > 1.00 suggest direct deionization. Furthermore, the range of $\frac{Na^+}{Cl^-}$ ratio for GW around active Aba Eku dumpsite implied that silicate weathering is not majorly responsible for Na^+ in GW samples around the dumpsite. However, all the GW samples around the abandoned DS had $\frac{Na^+}{Cl^-}$ ratio > 1.00, suggesting that silicate weathering is responsible for the leaching of Na^+ in groundwater samples around the closed DS[42]. In addition, $\frac{Na^+}{Cl^-}$ ratio greater than unity in samples around closed DS suggests halite dissolution, cation exchange reaction, and weathering of sodium-rich feldspar[34,68]. The values of the ratio > 1 in the GW samples around abandoned dumpsite also indicate that aquifer units at the research location are also prone to pollution by the nearby dumpsite[69,70]. The ion exchange reaction can be described by values of chloro-alkaline indices (CAI-1 and CAI–II). Table 4 shows that 60% of GW samples near active DS have affirmative values of chloro-alkaline indices, while the remaining 40% had negative values of CAIs. This affirms the prevalence of base ion exchange processes and non-silicates influencing groundwater chemistry at the location[8,9]. However, values of chloro-alkaline indices in 100% of groundwater samples around abandoned DS were all negative, suggesting dominance of the direct ion exchange process and silicate dissolution in the groundwater chemistry of the area[71–73]. This is a further confirmation that the weathering or dissolution of host aquifer material is the key origin of dissolved ions in the GW samples around abandoned DS where the direct ion exchange is responsible for the elevated Na^+ in the abandoned DS groundwater samples[66,74,75]. Furthermore, negative values of CAIs for GW samples around abandoned DS also indicate that the water could be termed as softened water, with an average concentration of bicarbonate ions greater than that of ($Ca^{2+} + Mg^{2+}$) ions[76,77]. $\frac{Ca^{2+}}{Ca^{2+}+SO_4^{2-}}$ ratios in GW samples around active and closed dumpsites ranged from 0.02 to 0.27 (mean = 0.16) and 0.71 to 0.94 (mean = 0.83), respectively. 100% of GW samples around active DS had $\frac{Ca^{2+}}{Ca^{2+}+SO_4^{2-}}$ ratio < 0.5, indicating calcium removal-ion exchange, or calcite precipitation[42]. However, the values of $\frac{Ca^{2+}}{Ca^{2+}+SO_4^{2-}}$ the ratio were > 0.5 in all samples within the vicinity of abandoned DS, suggesting that dolomite dissolution, deionization process, and carbonate dissolution may have contributed to the levels of Ca^{2+} and Mg^{2+} in GW samples around closed DS[42,78]. Ratio $\frac{Cl^-}{SO_4^{2-}}$ has values greater than unity in 60% of GW samples collected around active DS, indicating

the absence of groundwater acidification in those sampling sites (Table 4). The remaining 40% of the sample locations within the vicinity of the active dumpsite had the ratio > 1.0, suggesting possible corrosion tendency. However, 80% of sampling points around the abandoned DS had $\frac{Cl^-}{SO_4^{2-}} < 1.0$, suggesting corrosion tendency of most samples near the abandoned DS, with only 20% (GW1 and GW10) indicating no corrosive tendency[51]. The ratio $\frac{Na^+}{Na^+ + Cl^-}$ was slightly greater than 0.5 in 40% of GW samples near active DS, while the remaining 60% had the ratio < 0.5 (Table S2). This is an indication that the sodium source is other than halite dissolution in 40% of active groundwater samples, thus corroborating that cation exchange process partly responsible for Na^+ in those samples. However, values of $\frac{Na^+}{Na^+ + Cl^-}$ ratio were > 0.5 in all samples around the abandoned DS, suggesting that sodium source in those water samples is other than halite dissolution.

The ratios of $\frac{Ca^{2+} + Mg^{2+}}{HCO_3^-}$ in GW samples within the vicinity of active and closed dumpsites ranged from 0.016 to 0.339 (average = 0.178) and 1.299 to 5.312 (average = 3.091), respectively. The average value of $\frac{Ca^{2+} + Mg^{2+}}{HCO_3^-}$ ratio in GW samples around active DS was < 3.00 and lower compared to that of samples around closed DS. This is an indication of prevalence of carbonation as donor to Ca^{2+}, Mg^{2+} and HCO_3^- ions in GW samples within the vicinity of the active DS. However, the average value of $\frac{Ca^{2+} + Mg^{2+}}{HCO_3^-}$ in water samples near abandoned DS was greater than 3.00, indicating that silicate weathering is the governing geochemical reaction influencing the groundwater quality in the research location[11,79]. This assertion is supported by mean $\frac{Na^+}{Cl^-} > 1.0$ for GW near abandoned DS.

Groundwater quality index

The calculated GWQI values for samples collected around active and abandoned dumpsites are listed in Table S3. From Table S3, the results of GWQI for all water samples near active and closed dumpsites ranged from 20.92% to 77.59% (mean = 31.74%) and 48.95% to 162.07% (mean = 99.08%), respectively. Table S3 further presented that 60% of total groundwater samples near active DS were in the "Good" class, 10% and 30% belong to "very poor" and "excellent", correspondingly. It was observed that sample S5, very close to the fence of the active DS (approximately 20 m), has the highest GWQI value (77.59%) and falls within the "very poor" category. However, 50% of GW samples around closed DS belong to the "Unsuitable for drinking" class with GWQI > 100%, 20% belong to the "very poor" class, 20% belong to the "poor" class, and the remaining 10% (GW5) belongs to the "Good" class with a GWQI value of 48.95% (Table S3). Sample GW4 around the closed DS has the highest GWQI value (162.07%) and might be due to the fact that it is located down gradient of the abandoned DS[31]. It should be noted that the status of GW samples near abandoned DS in terms of GWQI is in contrast to the reported "Excellent to Good water quality" status of GW near abandoned landfills in Port-Harcourt, Niger Delta part of Nigeria by[80]. Generally, the mean GWQI values of GW samples near active and abandoned dumpsites obtained in this study depict "Good" and "very poor" classes, respectively.

Appropriateness for irrigation purpose

Table S4 lists the IPI values of samples near active and abandoned dumpsites. The range of pH in all water samples bordering the active DS falls within the normal pH range for irrigation water (6.5—8.4)[81,82]. However, only 30% of water samples around abandoned DS had pH values within the prescribed limit for irrigation use (Table S4). Values of EC in irrigating water provide levels of salinity threats presented by irrigating water to produce[2]. Surplus salt content affects plant development by affecting soil porosity and oxygenation[2]. According to EC values, groundwater is categorized as "Excellent" (EC < 250 µs/cm), "Good and Suitable" (EC = 250–750 µs/cm), "Eligible and should be used with caution" (EC = 750–2250 µs/cm), and "Not recommended" (EC > 2250 µs/cm) for irrigation[2,81–83]. In this study, 70% of groundwater samples near active DS were classified as "Excellent," 20% as "Good and Suitable," and 10% as "Unsuitable for irrigation" based on EC values (Table S4). Sample S5, located very close to the active DS fence, was found unsuitable for irrigation based on EC values. For groundwater samples around abandoned DS, 30% were classified as "Excellent," 50% as "Good and Suitable," and 20% as "Eligible and should be used with caution" due to their EC values falling within the range of 750–2250 µs/cm[84].

All groundwater samples near active and abandoned DSs had total dissolved solids (TDS) values below the stipulated reference (0—2000 mg/l) for irrigating water by FAO[85]. Specifically, TDS values in all samples were < 450 mg/L, indicating suitability for irrigation purposes[86,87]. Nitrate levels in groundwater near active and abandoned DSs ranged between 1.36 and 4.81 mg/l and 43.00 and 46.03 mg/L, respectively. In accordance with FAO[86] guidelines, nitrate content in irrigation water should be within 0 –10 mg/L. This means that 100% of water samples around active DS were suitable for irrigation, while none near abandoned DS met the criteria[81,82]. For potassium (K^+), 90% of samples around active DS had K^+ content within the 0—2 mg/L range recommended for irrigation water. However, only 10% of samples (S5) around active DS had $K^+ > 2$ mg/L, making it unsuitable for irrigation. All groundwater samples around abandoned DS had $K^+ > 2$ mg/L, indicating their unsuitability for irrigation use. Sodium adsorption ratio (SAR) values in groundwater near active and abandoned DSs ranged from 0.668 to 4.055 (average = 1.660 meq/L) and 0.200 to 1.101 (average = 0.460 meq/L), respectively. By virtue of SAR values, irrigating water could be categorized into 4 groups: SAR less than 10 = excellent, SAR of 10–18 denotes Good, SAR of 18–26 signifies Uncertain, and SAR > 26 as unfitting for agriculture[82,87]. All groundwater samples were in the "Excellent" category, indicating suitability for irrigation. Permeability index (PI) varied

between 0.712 and 4.489 (average = 1.349) for GW near active DS and 0.570 to 2.445 (average = 1.095) for water samples near abandoned DS. Based on the classification by[88], 90% of samples near active DS were in the "Excellent to Good" category, while 100% near abandoned DS were in the same category, indicating suitability for irrigation.

According to[89,90], a high RSC value in irrigation water signifies an intensification in the absorption of Na^+ by the soil[91] categorized irrigating water according to RSC as follows: RSC less than 1.25 denotes suitability for irrigation; RSC = 1.25—2.50 is marginally suitable, and RSC > 2.50 indicates unsuitability. From Table S4, RSC values in GW samples around active and abandoned DSs varied from 3.608 to 10.487 (average = 5.880) and −10.579 to 3.213 (average = −3.522). On average, GW around active DS was not suitable for irrigation purposes based on RSC values. However, 20% of GW samples near abandoned DS were "unsuitable" for irrigation according to RSC values, while the remaining 80% were in the "suitable" class with RSC < 1.25 (Table S4). The extent of sodicity of irrigation water to soil is also quantified by the Kelly ratio (KR)[92]. Water with a Kelly ratio below 1.0 is considered suitable for watering, whereas a Kelly ratio > 1.0 denotes unsuitability for watering purposes[21,90]. From Table S4, 60% of GW samples near active DS had KR < 1.0, thus fit for irrigation, while the remaining 40% (S2, S5, S6, and S7) had KR > 1.0, thus unsuitable for irrigation use[90,93]. This unsuitability indicates that 40% of the GW samples around active DS have high sodium content relative to calcium and magnesium. Such an imbalance in ion concentrations can lead to alkali hazards that adversely affect soil permeability, causing it to become compacted and reducing its ability to absorb and retain soil moisture[94,95]. However, all the GW samples near abandoned DS have KR < 1.0 and were fit for sprinkling needs.

The existence of an immoderate amount of Mg in the earthen matrix can bring about alkalization and degradation of soil structure, hence a decrease in crop yield[96]. When using the magnesium ratio (MR) to determine suitability for irrigation purposes[91], classified waters with MR > 50 as "unsuitable" for irrigation use, as such water favors poor crop yield; MR < 50 signifies water appropriate for spraying needs. Therefore, Table S4 exposed that all GW samples near active DS had MR > 50, suggesting their unsuitability for irrigation. However, 70% and 30% of GW samples near abandoned DS showed "unsuitability" and "suitable for irrigation," respectively. This mixed result suggests that there is noteworthy variance in magnesium levels among the GW samples near closed DS. While less than half of the samples are fit for spraying, the higher magnesium concentrations in the remaining samples may present challenges for long-term irrigation. If these waters are used for irrigation over extended periods, they could contribute to soil degradation, water infiltration problems, stunted plant growth culminating in reduced crop yield, especially if magnesium levels are not properly managed[95,97].

High values of % Na in water intended for irrigation promote the depletion of soil permeability and soil aeration[1,83,93]. From Table S4, the values of % Na in samples around active and abandoned dumpsites varied from 29.52 to 89.77 (average = 54.62) and 3.40 to 18.61 (average 8.92), respectively. 100% of GW samples near active DS had % Na > 20 and belong to the "doubtful to unsuitable" class for irrigation use[43,90]. However, Table S4 showed that all the GW samples near abandoned DS had % Na < 20, indicating their "excellent" class for irrigation use. According to[88,98] categorization based on the permeability index (PI), PI values between 25 and 75 indicate " moderate suitability for irrigation," while PI < 25 suggests "safe" class. Therefore, all the GW samples around active and abandoned DS had PI < 25 and thus belong to the "safe" group for irrigation use. This is an indication that all the groundwater samples will not pose long –term significant hazard to soil permeability[98].

The comprehensive hazard coefficient (**κ**) values of irrigation water can be utilized to reflect the degree of salt as well as alkali hazard prompted by irrigating water to the crops[2]. Water with κ values < 25 denotes "excellent," 25 < κ < 36 signifies "good," 36 < κ < 44 denotes a "moderately unsuitable" class, while κ > 44 represents an "unsuitable" class for irrigation use[2,99]. From Table S4, all samples around active and abandoned DSs had κ values < 25, indicating that groundwater samples in the two study sites belong to an "excellent" class for irrigation use[2]. In terms of TH in ppm, all the GW samples except S5 around active DS were soft as their TH concentration was < 75 ppm. However, GW samples around abandoned DS showed a "very hard" nature (TH > 180 mg/L) and thus portray a hazardous condition[87]. The SSP (meq/L) values as listed in Table S4 showed that none of the GW samples around active DS has SSP < 20, which denotes an "excellent" class, 10% is good for irrigation with SSP = 20–40 while 80% had SSP in the range 40–80, thus "fair" for irrigation purpose[84]. However, all the GW samples near closed DS had SSP values < 20 meq/L and thus belong to an "excellent" class for agricultural uses.

Corrosion and scale formation status of samples

The corrosion status of water samples around the active and abandoned dumpsites, based on the indices adopted in this research, is enumerated in Table S5. The descriptive statistics of values of diverse corrosion indices employed in this research are listed in Tables 5 and 6 for GW samples near active and closed DSs, while Figs. 2,3,4,5,6 and 7 show the graphs of corrosion indices against water samples around active and closed

Corrosion Index	Sample Size	Minimum	Maximum	Mean	S.D	Inference based on average of indices
LSI	10	−1.80	−12.56	−2.23	0.559	Water is under saturated and has corrosion tendency
RSI	10	10.09	12.63	11.50	1.113	Water has rigorous corrosion tendency
PSI	10	5.49	8.63	7.01	0.915	Water has significant corrosion tendency
AI	10	9.08	10.65	9.67	0.569	Water is severely corrosive
LS	10	0.10	0.46	0.26	0.109	Water has sealing tendency
CSMR	10	0.61	4.35	1.50	1.111	Water is susceptible to galvanic corrosion

Table 5. Descriptive statistics of computed corrosive Indices groundwater near active DS.

Corrosion index	Sample Size	Minimum	Maximum	Mean	S.D	Inference based on average of indices
LSI	10	−0.19	2.14	1.12	0.682	Water is supersaturated and displays scaling tendency
RSI	10	4.62	8.28	6.30	1.171	Water is balanced and has no corrosive or scaling tendencies
PSI	10	6.73	10.58	9.08	1.174	Water has significant aggressive tendency
AI	10	11.66	14.06	13.00	0.703	Water has scaling tendency with no corrosive tendency
LS	10	0.06	0.37	0.21	0.177	Water has scaling tendency
CSMR	10	0.18	3.00	0.69	0.844	Water shows galvanic corrosion tendency

Table 6. Descriptive statistics of computed corrosive Indices groundwater near Abandoned Dumpsite.

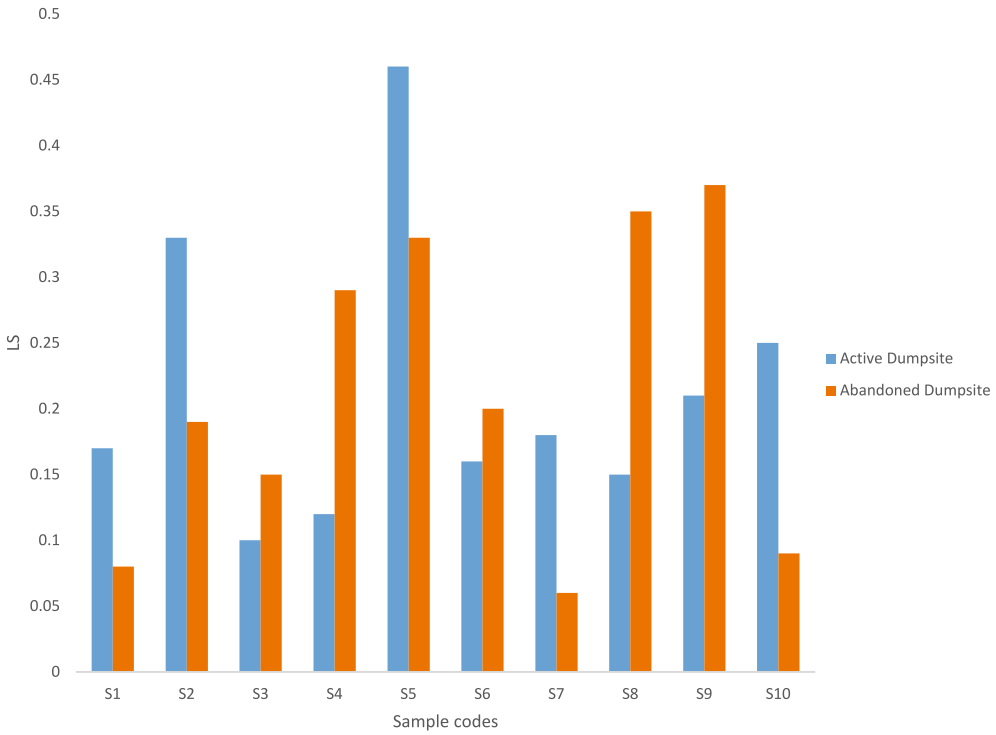

Fig. 2. Values of LS for GW samples near active and abandoned dumpsites.

dumpsites. From Table S5, the Langelier Saturation Index (LSI) values of GW bordering active DS ranged from −1.80 to −2.56 with a mean value of −2.23 (i.e., LSI < 0), indicating that corrosion is possible[50,51]. For GW near abandoned DS, the LSI values varied between −0.19 and 2.14 with a mean of 1.12, suggesting water with a scaling tendency[10]. Specifically, sample GW1 has LSI < 0, indicating its corrosive tendency, while the remaining 90% of GW samples around closed DS revealed a tendency to form scale deposition[5,13,54]. The Ryznar Stability Index (RSI) values of GW samples near active DS ranged between 10.09 and 12.63 with an average of 10.49. This signifies that the mean RSI falls in the class RSI > 8.5, indicating that the GW in the area is very aggressive[10,100]. However, the RSI values of GW near abandoned DS varied from 4.62 to 8.28 with a mean of 6.30, indicating water with no difficulties and no scaling or corrosive tendency (i.e., 6.2 ≤ RSI ≤ 6.8).

The PSI values in the GW samples around active DS ranged between 5.49 and 8.63 with a mean value of 7.01, suggesting that the mean PSI reveals water that has corrosive tendency. Specifically, Samples S2 and S6 had PSI in the range 6 ≤ PSI ≤ 7, indicating that these two samples had little scaling and corrosive tendencies[5,20]. However, samples S7 and S10 had PSI ˂ 6, indicating waters that show scaling tendency[13]. Groundwater samples around closed DS had PSI values that ranged from 6.73 to 10.58 (average = 9.08), indicating water that has significant corrosion tendency on average[10,51]. Specifically, GW5 has PSI = 6.73, suggesting little scaling and corrosive tendencies[51].

The aggressive index (AI) values in GW near active DS ranged from 9.08 to 10.65 with a mean of 9.67, suggesting that the water near the active dumpsite was highly corrosive[5]. Specifically, 40% of GW samples near actives DS have AI in the range AI = 10–12, suggesting moderately corrosive tendency while the remaining 60% lie in the "highly corrosive state "since their AI values were ˂ 10[10,13]. In case of samples around abandoned DS, their AI values ranged between 11.66 and 14.06 with a mean value of 13.00, suggesting water that tend to form scale deposition[20]. According to Larson – Skold (LS) values, all the GW samples near active DS had LS ˂ 0.8, an evidence of non-corrosive water[54]. Similarly, the values of LS for all groundwater samples near abandoned

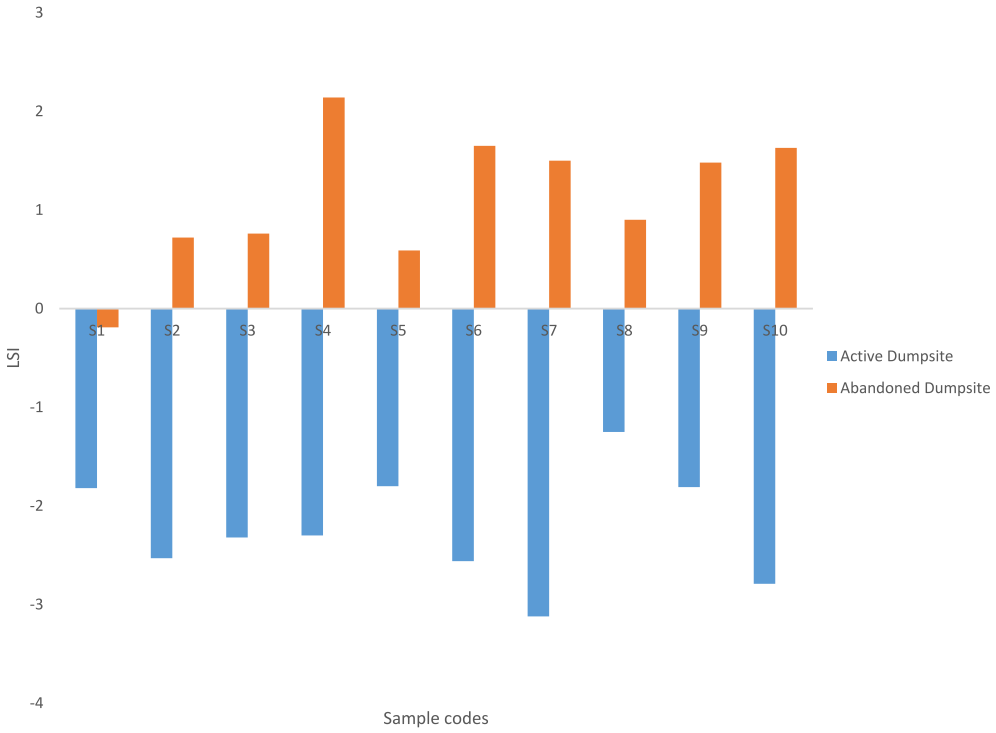

Fig. 3. Values of LSI for GW samples near active and abandoned dumpsites.

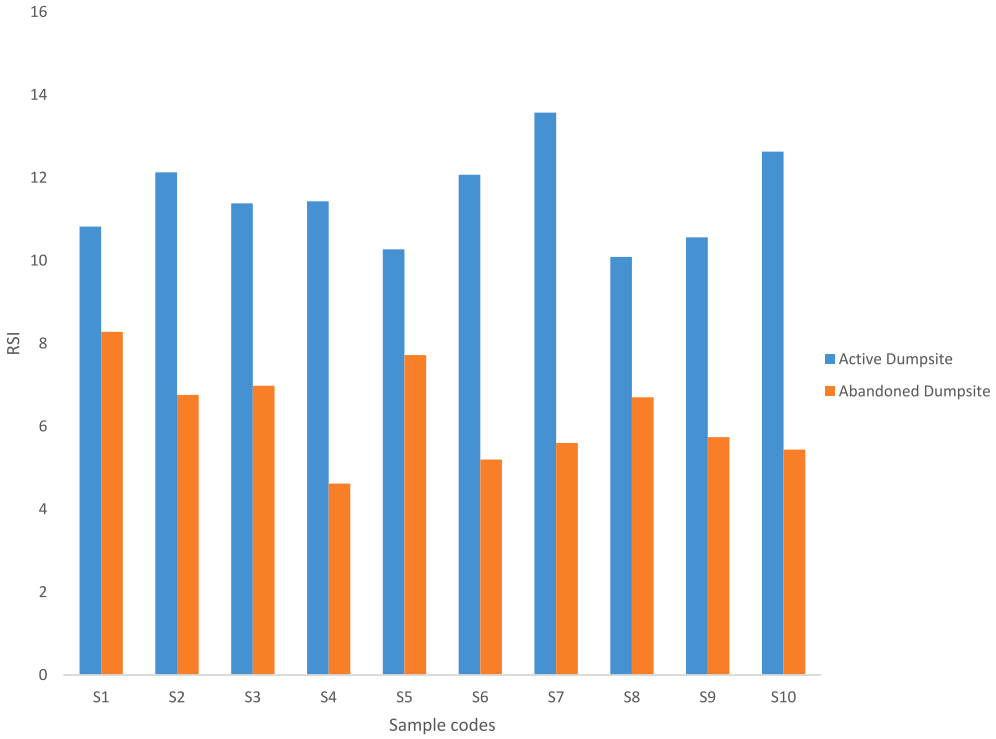

Fig. 4. Values of RSI for GW samples near active and abandoned dumpsites.

DS varied between 0.06 and 0.37 with a mean of 0.21, inferring water that has a scale forming tendency. As regards to CSMR, all the GW samples near active DS had CSMR > 0.50, suggesting water vulnerable to galvanic corrosion (Table S5). The CSMR values of GW samples near abandoned DS ranged from 0.176 to 3.000 with an average of 0.698, indicating that the groundwater systems showed galvanic corrosion potential on average. It was

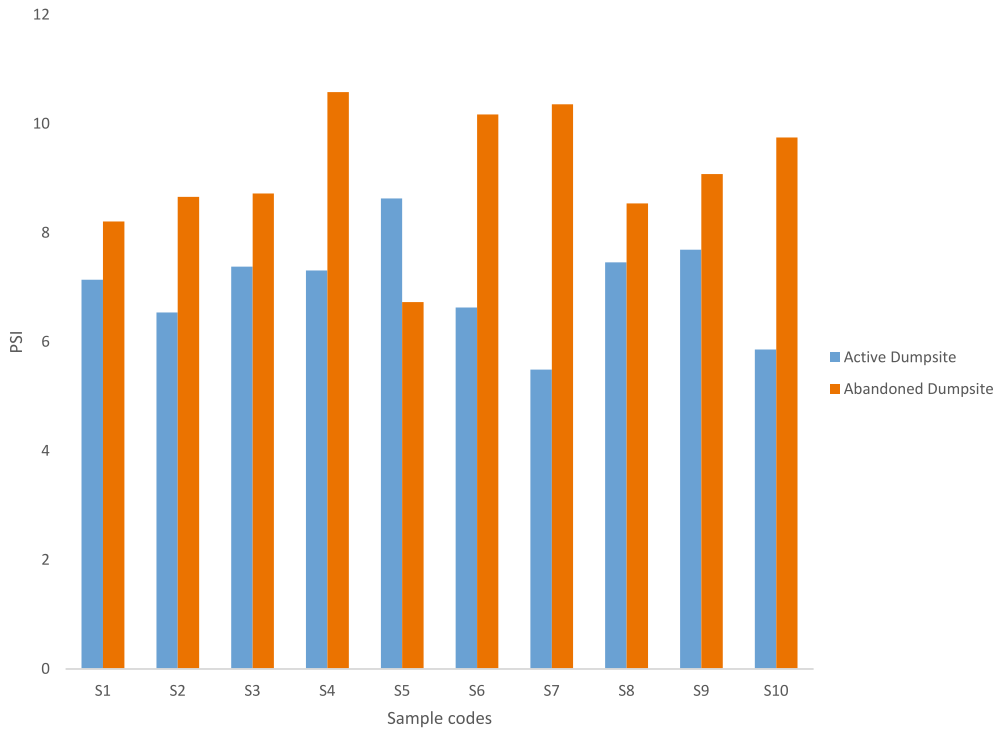

Fig. 5. Values of PSI for GW samples near active and abandoned dumpsites.

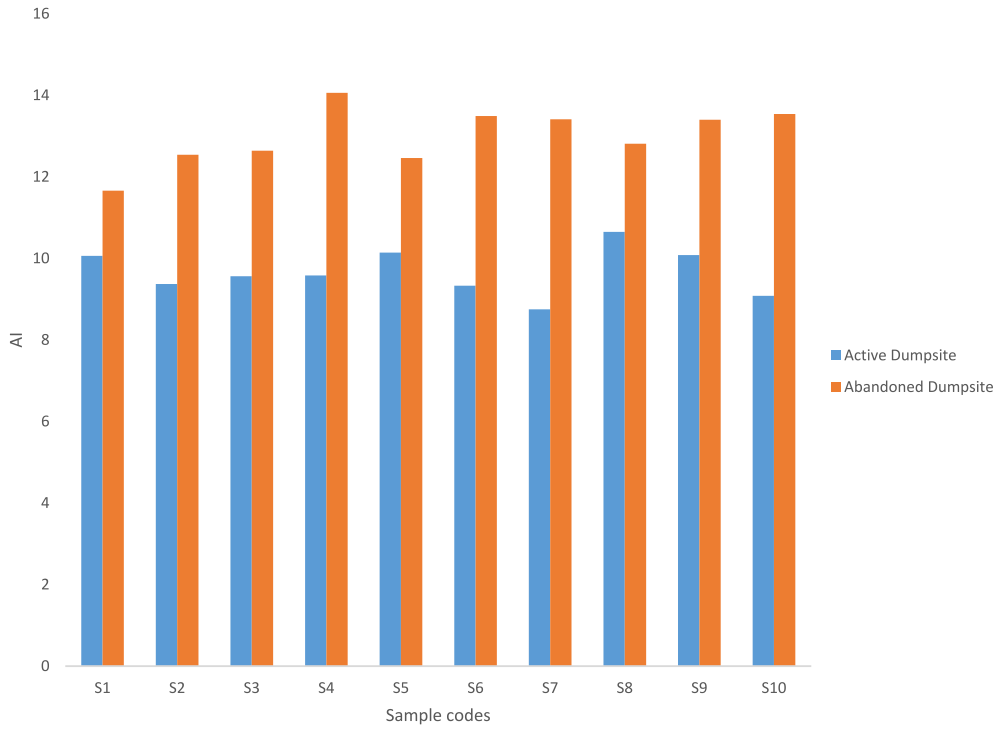

Fig. 6. Values of AI for GW samples near active and abandoned dumpsites.

observed that GW samples around the two dumpsites showed possibility of galvanic corrosion tendency. This is an indication that the underlying geological settings of the two study sites have no impact on galvanic corrosion tendency. This is in agreement with similar observation by[52] who reported that the geology of the study site has insignificant impact on possibility to encourage galvanic corrosion. Specifically, 60% of samples near abandoned DS had CSMR < 0.50, suggesting that these water samples cannot form lead deposition in galvanic

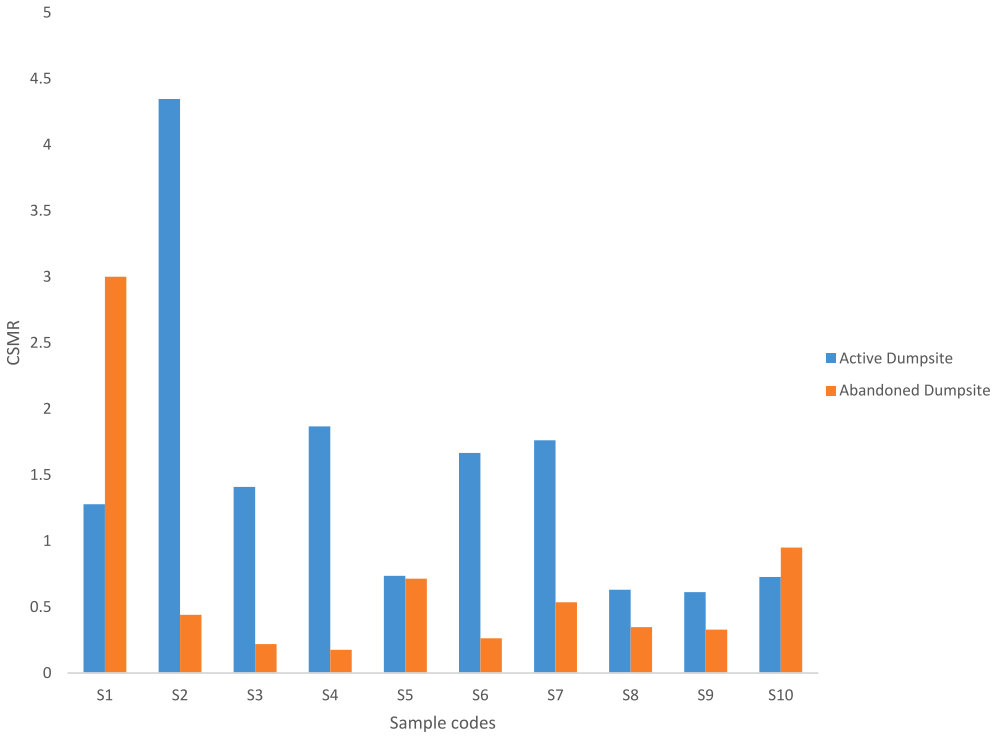

Fig. 7. Values of CSMR for GW samples near active and abandoned dumpsites.

connections[17,18,55]. The remaining 40% (GW1, GW5, GW7 and GW10) had CSMR > 0.5, a clear indication of GW systems that show galvanic corrosion potential[54]. The Revelle index ($\frac{Cl^-}{HCO_3^-}$) values of samples near active DS were < 0.50, indicating that the corrosion and scale formation inclinations are not influenced by salination[101]. The Revelle index values < 0.5 also indicate that the source of chloride ion in water around the active DS is ascribed to halite dissolution[101]. The same holds for $\frac{Cl^-}{HCO_3^-}$ values of GW samples near abandoned DS.

According to the mean values of corrosion indices used in this study, all calculated indices except that of Larson –Skold revealed GW samples near active DS to be corrosive in nature. However, the computed corrosion indices revealed that water samples near abandoned DS had scaling and corrosion potentials.

Results of cluster analysis

Dendrograms based on analyzed physicochemical parameters and corrosion indices in groundwater samples around active and abandoned dumpsites identified 3 and 5 clusters, respectively (Figs. 8 and 9).

From Fig. 8, Cluster 1 contains only EC, Cluster 2 contains bicarbonate, carbonate, TH and TDS while Cluster 3 contains the remaining physico-chemical properties and corrosion indices. Cluster 1 containing EC only indicates that EC is controlled by natural factors such as mixing of ions during rock-groundwater interaction[102]. Cluster 2 denotes rock-groundwater interaction and mineral dissolution. Cluster 2 further suggests weathering of silicate minerals could be the primary source of the weak anions in the groundwater system around active dumpsite[103]. Additionally, TDS, bicarbonate and carbonate ions as member of cluster 2 indicate influence of soil carbon dioxide on TDS concentration[72]. Cluster 3 contains physicochemical parameters that influence the rate and/or extent of corrosion potential and scale formation[104,105]. The corrosive tendency and scaling susceptibility are often influenced by the alterations in the concentrations of physical–chemical properties embedded in Cluster 3.

From Fig. 9, Cluster 1 contains only EC, Cluster 2 contains bicarbonate only, Cluster 3 contains TDS while Cluster 4 contains TH, carbonate and Ca^{2+} ions. Cluster 5 comprises remaining physico-chemical properties and corrosion indices. Cluster 4 can be regarded as carbonate weathering and mineral dissolution group[9]. Furthermore, Cluster 4 suggests larger precipitation of $CaCO_3$ in GW around closed DS[105].

Correlation matrix analysis of corrosion and stability indices

Tables 7 and 8 present the correlation matrices of corrosion and stability indices used in assessing the stability of groundwater samples around active and abandoned dumpsites. For sample locations around active DS, the LSI is strongly and inversely correlated with the RSI ($r = -0.911$) but positively correlated with the PSI (0.733) at a importance level of 1% ($p < 0.001$). There is a very strong direct association between LSI and the Aggressiveness Index (AI) ($r = 1.000$) at a significance level of 0.01. This strong direct relationship between LSI and AI may be attributed to the fact that AI is basically an abridged type of the LSI[50,106]. The inverse correlation between RSI and

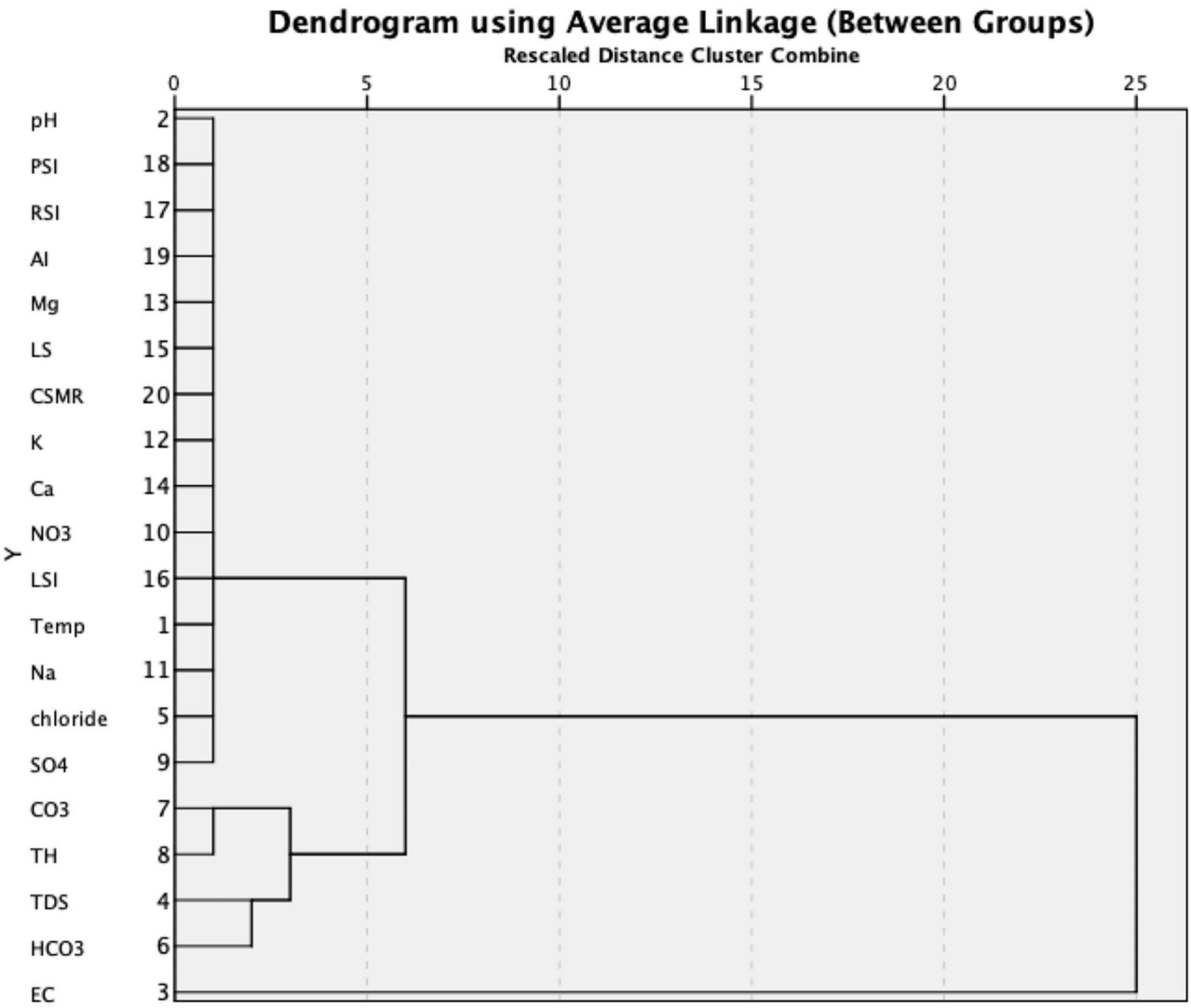

Fig. 8. Dendrogram of physicochemical parameters and corrosion indices in groundwater samples around active DS.

LSI observed for this study concurs with similar observations by[106]. However, the direct relationship that occurred between RSI versus PSI observed in this study at both locations contrasts with the high inverse association between LSI and PSI (r = −0.757) reported by[106]. RSI exhibits a strong negative correlation with PSI (r = −0.822) and with AI (r = −0.911) in the study location where the active DS is situated. This differs from the robust direct relationship between RSI and PSI stated by[13,106]. Nevertheless, an inverse correlation observed between RSI and AI (r = −0.911) at a significance level of 0.01 was also reported by[106]. Table 7 further demonstrates a strong direct correlation between AI and PSI (r = 0.733), while the CSMR shows a moderate direct relationship only with RSI (r = 0.511) and weak negative or weak positive correlations with the other corrosion indices.

Table 8 shows that for GW near abandoned DS, LSI is also strongly and inversely correlated with RSI (r = −0.956) but has a strong direct relationship with PSI (r = 0.778) at a consequence level of 0.01. Analogous to the location of active DS, RSI is negatively correlated with PSI (r = −0.733). A strong inverse relationship also occurs between RSI and AI (r = −0.911) as observed in the study location of active DS. A similar direct relationship between PSI and AI (r = 0.733) is also evident in the location of closed DS. However, CSMR shows weak negative or weak positive correlation with each of the other corrosion indices.

Limitations of the study

It should be noted that the research being carried out was only within Ibadan metropolis of basement complex geological formation. Future research should incorporate added metropolis (densely populated areas) of different geological settings in Southwest part of Nigeria to fully comprehend the impacts of underlying lithologies on quality of nearby groundwater sources to both active and closed anthropogenic sources. This will enhance the understanding of the geological/regional variations in water quality-induced parameters and stability

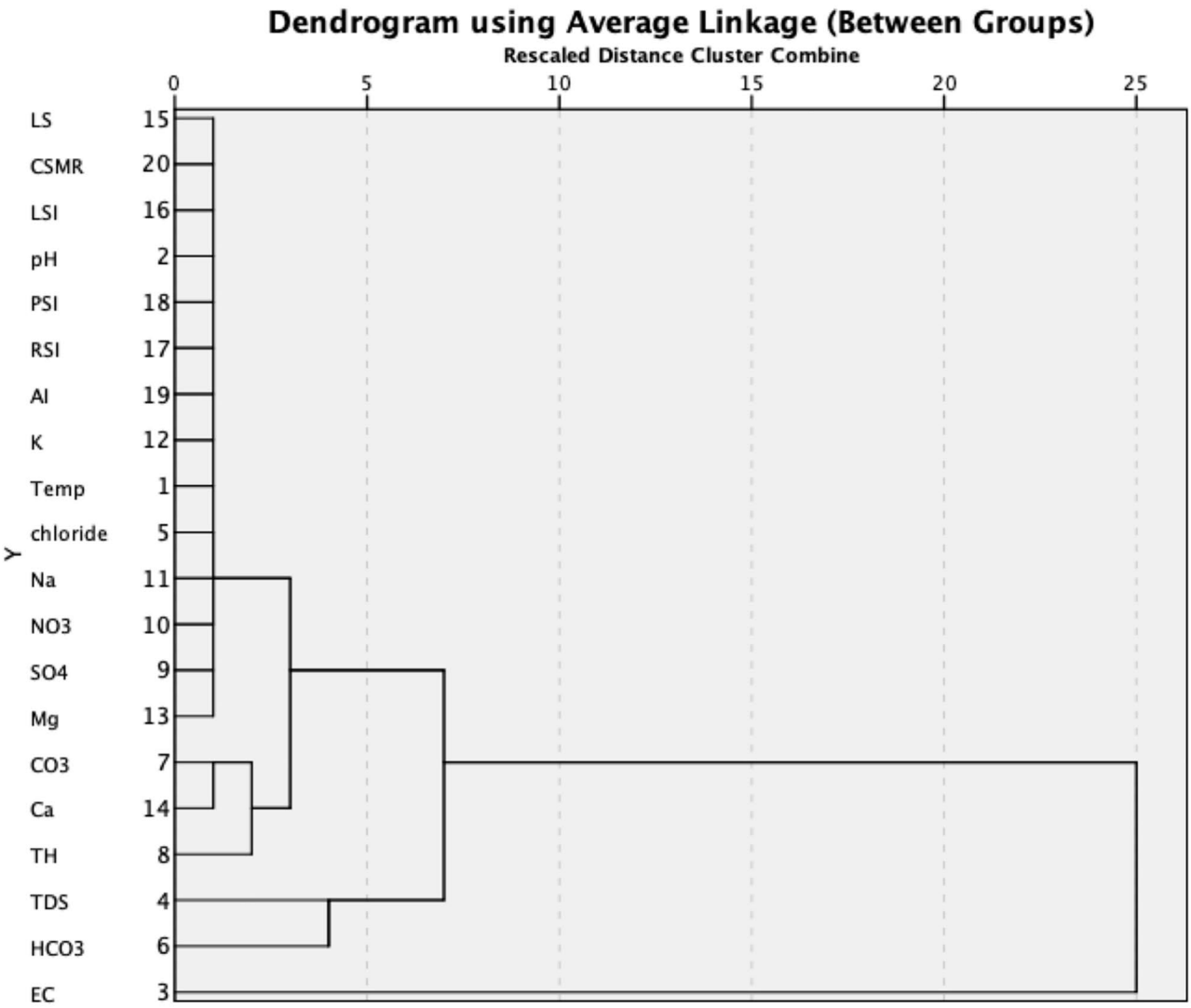

Fig. 9. Dendrogram of physicochemical parameters and corrosion indices in groundwater samples around abandoned DS.

		LS	LSI	RSI	PSI	AI	CSMR
Kendall's tau_b	LS	1.000					
	LSI	.022	1.000				
	RSI	.067	-.911**	1.000			
	PSI	-.067	.733**	-.822**	1.000		
	AI	.022	1.000**	-.911**	.733**	1.000	
	CSMR	-.067	-.422	.511*	-.422	-.422	1.000

Table 7. Correlation coefficient of corrosion indices for water samples around active DS.

indices. Regular monitoring of groundwater from shallow dug wells near active and closed DSs allows one to track alterations in the water chemistry status during a specific period and assists in sustainable groundwater management.

Conclusions

The study evaluated the groundwater quality near active and closed dumpsites using an integrated approach of hydrochemical analysis, GWQI, IPI, and stability indices. The outcomes of the hydrochemical investigation reveal that the collected water samples near the active dumpsite meet the WHO permissible limits for drinking

		LS	LSI	RSI	PSI	AI	CSMR
Kendall's tau_b	LS	1.000					
	LSI	.111	1.000				
	RSI	-.156	-.956**	1.000			
	PSI	-.111	.778**	-.733**	1.000		
	AI	.067	.956**	-.911**	.733**	1.000	
	CSMR	-.333	-.422	.378	-.378	-.378	1.000

Table 8. Correlation coefficient of corrosion indices for water samples around abandoned DS.

water in terms of physicochemical properties. Some parameters in samples near the abandoned dumpsite also meet acceptable thresholds for potable use. However, more than 50% of groundwater samples near the closed dumpsite had concentrations of Mg^{2+} (24.0 to 122.0 mg/L) and Ca^{2+} (20.0 to 218.0 mg/L) above the WHO and NIS guideline limits for drinking water. The mean values of dissolved ions, except chloride, in groundwater near the closed dumpsite were higher than those around the active dumpsite. The average values of Ca^{2+} (109 mg/l) and Mg^{2+} (80 mg/l) in water samples near the abandoned dumpsite surpassed the global and Nigerian regulatory acceptable references for drinking. Ionic ratios and chloro-alkaline indices suggest carbonate weathering and reverse deionization reactions as controlling factors influencing groundwater quality near the active dumpsite, while silicate weathering and direct ion exchange reactions were major geochemical processes near the abandoned dumpsite. Based on the GWQI rating, most samples near active dumpsites were classified as "Good to Excellent water," while 90% of groundwater samples near closed dumpsites were rated as "poor to unsuitable" for drinking purposes. Only a few irrigation parameters (SAR, PS, PI, nitrate, and **k**) indicate that groundwater near the active dumpsite is suitable for irrigation, while most indices propose that groundwater near the abandoned dumpsite is suitable for sprinkling. Corrosion and stability indices indicate that groundwater near the active dumpsite tends to be corrosive, except for LS. Conversely, average values of LSI, AI, and LS near the abandoned dumpsite suggest a tendency for scale formation but corrosive behavior according to PSI and CSMR. Regular monitoring of water quality and treatment of shallow hand-dug wells near the dumpsites is highly recommended.

Data availability

The data that support the findings of this study are available from [Saheed Adekunle Ganiyu]. Still, restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. However, data are available from the authors upon reasonable request and with permission of [Saheed Adekunle Ganiyu].

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Saheed Adekunle Ganiyu, John Oluwadamilola Olutoki,: Conceptualisation, Methodology, Investigation, Formal analysis, Visualisation, – original draft. Saheed Adekunle Ganiyu, John Oluwadamilola Olutoki,Meshel Q. Alkahtani, Nadeem A Khan: Writing – review &; editing, Methodology, Supervision. Saheed Adekunle Ganiyu, John Oluwadamilola Olutoki,: Software, Supervision, Data curation, Validation, Writing – review &; editing. Saheed Adekunle Ganiyu, John Oluwadamilola Olutoki,: Software, Formal analysis. Saheed Adekunle Ganiyu, John Oluwadamilola Olutoki,: Supervision, Methodology. Owais Ahmad Bhat: Visualisation, Investigation. Saheed Adekunle Ganiyu, John Oluwadamilola Olutoki,: Resources, Data curation. Saheed Adekunle Ganiyu, John Oluwadamilola Olutoki,: Supervision, Project administration.

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Declarations

Competing interests
The authors declare no competing interests.

Ethics approval
The author declares that the manuscript has not been submitted to other journals.

Consent to publish
All the authors agree to publish.

Concent for Sampling
The author (Saheed Adekunle Ganiyu) have no relevant financial or non-financial interests to disclose and took proper permission for sample collection before and after.Reconnaissance survey/inspection was firstly made to the two locations, locating shallow hand dug wells nearer to the two dumpsites. Thereafter, we met with the owners of those houses with dug wells, informing them about the motive of the research work. They obliged us (by willingly allow us to collect the samples whenever we are ready) and also provide us with necessary information about the well (year and depth). The owners asked us to let them know about the outcomes of the study.

Additional information

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