Groundwater Quality Suitability Using Indices for Industrial and Domestic Purposes in Oredo LGA of Benin City, Nigeria

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Abstract

Groundwater is a vital resource for industrial and domestic purposes, particularly in regions where surface water is scarce. Its suitability, however, is often compromised by corrosion and anthropogenic activities, which reduce industrial efficiency and pose risks to infrastructure and public health. Although physicochemical parameters provide valuable insights into groundwater quality, they do not capture all aspects of suitability. To address this limitation, water quality indices were applied to integrate multiple parameters into a single measure of suitability for industrial and domestic purposes. Borehole samples were collected and tested for pH, Temperature, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Dissolved Oxygen (DO), Bicarbonate (HCO_3^-), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), Sodium (Na^+), Chloride (Cl^-), Nitrite (NO_2^-), Nitrate (NO_3^-), Sulfate (SO_4^{2-}), Iron (Fe), Zinc (Zn), Copper (Cu), Manganese (Mn), Ammonium Nitrogen (NH_4N), and Coliforms. The Langelier Saturation Index (LSI) indicated a high tendency toward corrosion due to groundwater acidity, rendering it unsuitable for industrial applications. In contrast, the Water Quality Index (WQI) classified the groundwater as suitable for drinking and other domestic uses, though potential threats from anthropogenic activities were evident. These findings highlight the dual nature of groundwater suitability: acceptable for domestic consumption but problematic for industrial use. Regular monitoring, treatment, and management strategies are recommended to mitigate corrosion risks and safeguard public health.

Keywords: Groundwater, Index, Parameter, Suitability, Industrial, Corrosion, Oredo LGA.

1.0 INTRODUCTION

Groundwater refers to water beneath the earth's surface, filling void spaces in soil and rock formations. It resides in aquifers and can be accessed through wells or natural springs (Hermann and Prunes, 2022). Although hidden underground, groundwater plays a crucial role in maintaining surface water levels and replenishing rivers and streams. Rain and snowmelt seep into the ground, recharging these water-bearing strata (Mukherji, 2006; Rawlings and Ikediashi, 2020). Approximately 22% of Earth's freshwater exists as groundwater, with about 97% suitable for human use (Foster, 1998; Panaskar *et al.,* 2016). It serves essential purposes such as drinking, irrigation, and industrial processes, especially in regions lacking developed tap water infrastructure and experiencing surface water scarcity (Agossou and Yang, 2021; Hermann and Prunes, 2022). Benin City, Nigeria, is one such area where groundwater is crucial to meeting these needs.

Groundwater faces significant challenges due to its underground nature, which makes direct monitoring difficult. As a result, supplies can be unknowingly polluted or overexploited without adequate recharge (Peterson and Kennedy, 1997; Hsan *et al.,* 2017; Hermann and Prunes, 2022). Benin City, including Oredo LGA, experiences population growth, urbanization, and industrialization, leading to increased anthropogenic activities (Balogun and Orimoogunje, 2015). These human impacts alter the natural water cycle and groundwater quality (Nicole *et al.,* 2019). Contaminants from sources such as landfills, septic tanks, and fertilizers can pollute groundwater (Panaskar *et al.,* 2016; Hermann and Prunes, 2022), affecting human health and industrial use (WHO, 2017; Adegbite *et al.,* 2018). Given that groundwater is a major source of potable water supply, continuous monitoring in Benin City is crucial (Agatemor and Okolo, 2007).

Several studies have assessed groundwater quality in Nigeria using physicochemical parameters and indices. For example, Agatemor and Okolo (2007) examined groundwater in Benin City and reported contamination risks from anthropogenic activities. Adegbite *et al.,* (2018) assessed groundwater quality in southwestern Nigeria, identifying heavy metal contamination linked to urbanization. Abbasnia *et al.,* (2019) investigated groundwater corrosion and scaling tendencies, showing how industrial use can be compromised by water chemistry. More recently, Rawlings *et al.,* (2024) applied the Langelier Saturation Index (LSI) to evaluate groundwater suitability for industrial purposes in Oredo LGA, highlighting corrosion as a major challenge for local industries. While these studies demonstrate the importance of indices such as the Water Quality Index (WQI) and LSI in providing comprehensive assessments, most previous work in Benin City has focused primarily on either domestic suitability or single-parameter industrial concerns. This gap underscores the need for a dual assessment approach that considers both industrial and domestic suitability simultaneously, especially in rapidly urbanizing areas like Oredo LGA.

In many industrial processes, water usage (commonly seen in industries within Oredo LGA) often leads to either corrosion or scaling. Scaling reduces pipe capacity, affecting process efficiency, while corrosion can cause pipe failure, impacting process reliability (Abbasnia *et al.,* 2019). These issues are inherent to certain groundwater sources and are influenced by the type of rocks or sediments in contact with the water. Corrosion, a physicochemical reaction, alters material properties and gradually dissolves metals in plumbing pipes and fixtures (McFarland *et al.,* 2020). This can introduce toxic heavy metals (such as lead, iron, copper, zinc, arsenic, and cadmium) into water, posing health risks (Abbasnia *et al.,* 2019). Scaling occurs due to reactions between divalent cations and water-soluble substances, forming thin layers in pipes (Abbasnia *et al.,* 2019; UGA Extension, 2020). Elevated scaling levels pose a risk to water distribution networks and equipment. These scaling deposits can impair the efficiency of industrial operations, affecting pipes, machinery, and infrastructure (Mirzabeygi *et al.,* 2016; Mirzabeygi *et al.,* 2017; Mohammadiet *et al.,* 2018).

However, corrosion and scaling are not the only effects of groundwater use in industrial processes. Other challenges include fouling and biofouling, where suspended solids or microbial growth reduce system efficiency; chemical contamination from heavy metals or industrial pollutants; and hardness-related deposits beyond calcium carbonate, such as sulfates and silicates, which can form stubborn scales. Industrial withdrawals may also contribute to resource competition, while wastewater discharge can re-enter aquifers, creating long-term contamination risks (WHO, 2017; Adegbite *et al.,* 2018). These broader impacts highlight the complexity of groundwater suitability assessment.

The Langelier Saturation Index (LSI) is commonly used to predict corrosiveness or scaling, indicating water's saturation with respect to calcium carbonate (Energy Pulse, 2023). Although physicochemical parameters provide valuable insights into groundwater quality, they do not capture all aspects of suitability. To address this limitation, water quality indices such as the LSI and Water Quality Index (WQI) provide integrated measures that synthesize multiple parameters into comprehensive indicators of industrial and domestic suitability. In rapidly urbanizing areas like Oredo LGA, monitoring groundwater quality is crucial to safeguard public health, ensure reliable industrial operations, and secure sustainable water resources. Therefore, this study assesses groundwater suitability for industrial and domestic purposes in Oredo LGA using LSI and WQI, providing valuable data for future monitoring and management efforts.

2.0 MATERIALS AND METHODS

2.1 Study Area

Oredo Local Government Area (Figure 1), situated in Edo State, Nigeria, has its administrative headquarters in Benin City. The Local Government Area covers an area of approximately 319 square kilometres, it lies between latitudes 6°00' and 6°30' North of the equator and longitudes 5°25' and 5°35' East of the Greenwich meridian (Ojiako *et al.,* 2018). Oredo is located within the rainforest zone, experiencing an annual rainfall range of 1500 mm to 2500 mm and monthly temperature varying from 25°C to 28°C (Rawlings and Ikediashi, 2020). The LGA comprises several districts, including Ekehuan, Orogo, Abiala, Gelegele, Ibaro, Igbobi, Ikpako, and Oduna (Manpower, 2023). With an estimated population of 536,827 people (NPC, 2006), Oredo witnesses two distinct seasons: the dry season and the rainy season, with an average humidity level of about 61% (Manpower, 2023). Besides its vibrant trade sector, the LGA hosts various banks, government establishments, hotels, restaurants, relaxation spots, privately owned firms, and primarily food industries, all contributing to its economy.

2.2 Sample Collection and Analysis

In the Oredo Local Government Area, groundwater samples were collected from fifteen different boreholes between May and June 2023. The samples were obtained through taps using a simple random sampling technique. Table 1 presents the GPS coordinates of the boreholes, which were recorded using a handheld GPS device to ensure precise spatial documentation. These coordinates provide the exact locations of the groundwater sources and support the spatial representation shown in Figure 1. For collection, pretreated plastic containers (each with a capacity of 75 liters) were used. These containers were sealed, labeled, and transported to the Martlet Environmental Research Laboratory in Benin City for analysis. The laboratory analyzed the samples for twenty physiochemical parameters, including pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and various ions such as Bicarbonate (HCO_3^-), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), Sodium (Na^+), Chloride (Cl^-), Nitrite (NO_2^-), Nitrate (NO_3^-), Sulfate (SO_4^{2-}), Iron (Fe), Zinc (Zn), Copper (Cu), Manganese (Mn), Ammonium Nitrogen (NH_4N), and a biological parameter (Coliforms-Col.). The methods followed the guidelines set by the American Public Health Association (APHA, 1985 and 2005). Water quality data were statistically analyzed using the Statistical Package for the Social Sciences (SPSS, version 26.0, 2018) and Microsoft Excel (2013 version).

Table 1: GPS Coordinates for Groundwater Samples

Sample ID	Industry	GPS Coordinates	
		Longitude (E)	Latitude (N)
BH1	Food Processing	5°37'20.77"	6°19'35.80"
BH2	Food Processing	5°37'47.91"	6°17'53.20"
BH3	Food Processing	5°37'21.66"	6°18'41.74"
BH4	Laundry	5°36'22.14"	6°17'7.95"
BH5	Food Processing	5°37'3.31"	6°18'23.47"
BH6	Food Processing	5°36'58.69"	6°18'34.00"
BH7	Food Processing	5°37'8.28"	6°18'10.18"
BH8	Food Processing	5°37'42.70"	6°18'52.94"
BH9	Food Processing	5°36'35.07"	6°17'9.33"
BH10	Pure and Bottle Water	5°36'13.66"	6°20'5.94"
BH11	Food Processing	5°36'34.26"	6°18'17.73"
BH12	Pure and Bottle Water	5°37'15.08"	6°16'24.33"
BH13	Laundry	5°36'46.91"	6°19'15.45"
BH14	Pure and Bottle Water	5°36'46.90"	6°19'32.71"
BH15	Laundry	5°36'22.30"	6°15'44.79"

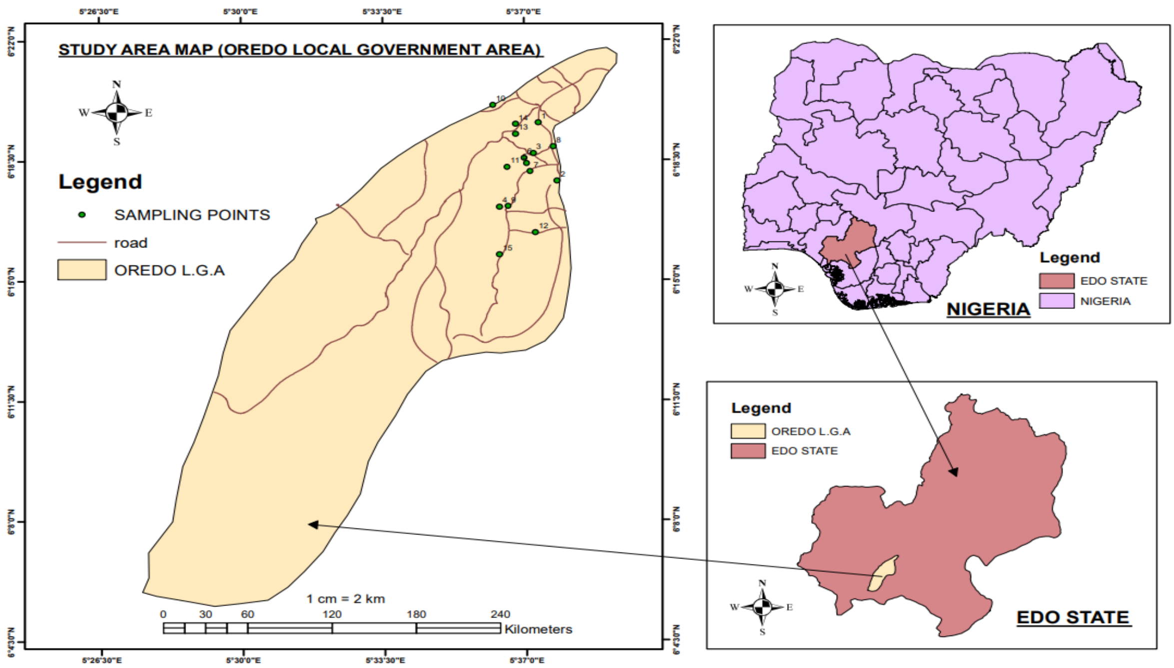

Figure 1: Map of the Study Area with Groundwater Sampling Points

Table 2: Analytical Techniques for the Groundwater Quality

Parameters	Analytical Methods
pH	Flame Photometric Method
Temperature	Thermometer Method
Electrical Conductivity	Flame Photometric Method
Total Dissolved Solids	Flame Photometric Method
Dissolved Oxygen	Titrimetric Method
Bicarbonate	Titrimetric Method
Calcium	Titrimetric Method
Magnesium	Titrimetric Method
Potassium	Flame Photometric Method
Sodium	Flame Photometric Method
Chloride	Titrimetric Method
Nitrite	Spectrophotometry Method (Atomic Absorption Spectrophotometer)
Nitrate	Spectrophotometry Method (Atomic Absorption Spectrophotometer)
Sulfate	Spectrophotometry Method (Atomic Absorption Spectrophotometer)
Iron	Spectrophotometry Method (Atomic Absorption Spectrophotometer)
Zinc	Spectrophotometry Method (Atomic Absorption Spectrophotometer)
Copper	Spectrophotometry Method (Atomic Absorption Spectrophotometer)
Manganese	Spectrophotometry Method (Atomic Absorption Spectrophotometer)
Ammonium Nitrogen	Titrimetric Method
Coliforms	Membrane Filtration Method

2.3 Langelier Saturation Index (LSI)

The Langelier Saturation Index (LSI) is employed to assess the need for controlling calcium carbonate precipitation scale in water sources with a total dissolved solids (TDS) content below 10,000 mg/L (Arthur, 2020). It serves as an indicator of water corrosivity. Scaling within pipes or heat exchanger tubes can lead to heat transfer insulation or metal loss due to water's corrosion tendencies. The LSI, an equilibrium model based on saturation theory, indicates the degree of water saturation with respect to calcium carbonate (Lenntech, 2021). Groundwater is widely used in various industries for cooling, product treatment, cleaning, and boiler makeup (Islam and Mostafa, 2023). Corrosion and pollutants, including rust, are inherent in some groundwater, posing risks to environmental quality, infrastructure durability, and industrial efficiency. LSI provides guidance for mitigating scale formation and internal corrosion, making it crucial for operational management in industry. In this study, the LSI was calculated using the formulas provided by Arthur (2020) and Lenntech (2021).

$$\mathrm{LSI} = \mathrm{pH} - \mathrm{pH_S} \quad \text{………} \quad (1)$$

where:

pH =Measured water pH

pH_s = pH at saturation in calcite or calcium carbonate and is given as:

$$pH = (9.3 + A + B) - (C + D) \quad \text{………} \quad (2)$$

where;

$A = {}^{log_{10}[TDS] - 1}/_{10}$

$B = -13.12 \times log_{10}(°C + 273) + 34.55$

$C = log_{10[Ca^{2+}\ as\ CaCO_3]-0.4}$

$D = \ log_{10[Alkalinity\ as\ CaCO_3]}$

where:

TDS = Total Dissolved Solids

°C = Temperature in degree Celsius

$CaCO_3$ = Calcium Carbonate

Ca^{2+}= Calcium

In this study, bicarbonate alkalinity was employed as a proxy for total alkalinity, since bicarbonate is the dominant contributor to alkalinity in groundwater within the observed pH range (4.5–6.5). The LSI values obtained from the study were interpreted according to Table 3.

Table 3: Interpretation of LSI (Arthur,2020)

LSI	Interpretation
If LSI is negative (LSI< 0)	No potentials to scale, water will dissolve $CaCO_3$
If LSI is positive (LSI > 0)	Scale will be formed and $CaCO_3$ precipitation occurs
If LSI is zero (LSI = 0)	Water is considered as stable water

2.4 Water Quality Index (WQI)

The Water Quality Index (WQI) is a numerical value that represents the overall quality of water at a specific location and time (Adelagun *et al.,* 2021). It takes into account various water quality parameters. The Water Quality Index (WQI) considers the combined impact of various water quality parameters and is calculated to assess the suitability of both surface and groundwater for their intended uses (Adelagun *et al.,* 2021). The Water Quality Index (WQI) condenses extensive water quality data into a single value, making it more understandable and practical (Shweta *et al.,* 2013). It encompasses physical, chemical, and biological factors, resulting in a score ranging from 0 to 100 (Pius *et al.,* 2012). Values of WQI exceeding 100 signal pollution and render the water unfit for human consumption (Mohammad and Amba, 2018). Researchers employ methods like weighted arithmetic indices to assess water quality, considering variables related to purity (Paiu and Breaban, 2010). The weighted arithmetic index was used for the calculation of the WQI of the groundwater (Brown *et al.,* 1972; Tyagi *et al.,* 2013; Egun and Ogiesoba-Eguakun, 2018; Rawlings and Ikediashi,2020). From this method, the quality rating (q_n) was calculated using the following equation:

$$q_n = 100\frac{[V_n - V_i]}{[S_n - V_i]} \qquad (2)$$

where:

q_n= Quality Rating

V_n = Observed Value

V_i=Ideal Value

S_n= Recommended Standard Value for the nth Parameters (NSDWQ 2015)

W_n = Unit Weight for the nth Parameters, which is $\frac{K}{S_n}$

K= Constant for Proportionality = $\frac{1}{\Sigma\left(\frac{1}{S_n}\right)}$

The overall WQI was then calculated using equation 3:

$$WQI = \frac{\sum q_n \times W_n}{\sum W_n} \quad (3)$$

Based on the WQI values obtained from equation 3, the groundwater quality was categorized as shown in Table 4.

Table 4: Water Quality Rating Based on the Weighted Arithmetic Water Quality Index Technique (Tyagi *et al.,* 2013; Egun and Ogiesoba-Eguakun, 2018)

Range	**Rating of Water Quality**
0-25	Excellent
26-50	Good
51-75	Poor
76-100	Very Poor
>100	Unsuitable for Drinking

3.0 RESULTS AND DISCUSSION

The study results are displayed across Tables 5 to 8. Table 5 provides statistical details about the physiochemical parameters in the groundwater samples. Table 6 shows the physiochemical quality of groundwater samples within the study area. Additionally, Table 7 presents the Langlier Saturation Index (LSI) for the groundwater samples, while Table 8 outlines the Water Quality Index (WQI) for the same samples.

Table 5: Statistical Characterization of Physiochemical Parameters in Groundwater Samples and Comparison with Standards

						Standards		
Parameters	**Min.**	**Max.**	**Mean**	**Std. Deviation**	**Variance**	**WHO (GDWQ, 2011 and 2017)**	**NIS (NSDWQ, 2015)**	**FIS (Islam and Mostafa, 2023)**
pH	4.5	6.4	5.313	0.474893	0.226	6.5-8.5	6.5-8.5	6.5-7.5
Temp. (^{o}C)	28.0	28.9	28.513	0.432380	0.186952	Ambient	Ambient	-

EC (µS/cm)	34	659	189.267	151.96544	23093.5	1500	1500	-
TDS (mg/l)	19.0	328.0	95.933	73.808117	5447.64	1000	500	500
DO (mg/l)	2.7	5.1	4.073	0.716606	0.513524	N/A	5	-
HCO_3^- (mg/l)	48.8	152.5	84.213	25.833585	667.374	500	500	200
Ca^{2+} (mg/l)	0.63	1.85	1.527	1.098652	1.207035	200	N/A	20
Mg^{2+} (mg/l)	0.41	3.33	0.961	0.739299	0.546564	50	20	10
K^+ (mg/l)	0.1	0.88	0.477	0.263212	0.069281	N/A	20	-
Na^+ (mg/l)	0.18	1.85	0.653	0.439991	0.193592	200	200	-
Cl^- (mg/l)	35.5	159.5	72.093	31.73719	1007.249	250	250	200
NO_2^- (mg/l)	0.011	0.881	0.0997	0.218172	0.0475	3	0.2	-
NO_3^- (mg/l)	0.14	2.921	0.8048	0.676671	0.457884	50	50	5
SO_4^{2-} (mg/l)	0.014	0.155	0.0531	0.038272	0.00146	N/A	N/A	50
Fe (mg/l)	0.031	1.881	0.271	0.452389	0.204656	0.3	0.3	-
Zn (mg/l)	0.02	1.22	0.1507	0.297159	0.0883	N/A	3	-
Cu (mg/l)	0.005	0.662	0.056	0.167876	0.0281	2	1	-
Mn (mg/l)	0.015	0.877	0.108	0.213713	0.04567	N/A	0.2	-
NH_4N (mg/l)	0.281	0.851	0.437	0.13534	0.018317	0.5	0.5	-
Col. (Pt.Co)	ND	ND	ND	ND	ND	0	0	0

ND=Not Detected; N/A= Not Applicable; WHO=World Health Organization; NIS=Nigerian Industrial Standard; FIS= Food Industry Standard

Table 6: Physiochemical Quality of Groundwater Water Samples from the Study Area

	Sampling Points														
Parameters	**BH1**	**BH2**	**BH3**	**BH4**	**BH5**	**BH6**	**BH7**	**BH8**	**BH9**	**BH10**	**BH11**	**BH12**	**BH13**	**BH14**	**BH15**
pH	5.5	5.3	5.1	5.1	5.1	5.2	4.9	6.1	5.3	6.4	5.8	5.1	5.1	5.2	4.5
Temp. (^oC)	28.0	28.9	28.5	28.9	28.9	28.8	28.9	28.9	28.0	28.9	28.9	28.0	28.1	28.0	28.0
EC (µS/cm)	261	36	34	100	243	239	158	289	64	154	146	160	184	112	659
TDS (mg/l)	130	19	42	50	121	119	79	141	32	77	73	80	92	56	328
DO (mg/l)	3.4	5.0	5.1	4.6	3.6	3.5	4.5	3.3	5.0	4.0	4.2	3.7	3.9	4.6	2.7
HCO_3^- (mg/l)	103.7	61.0	48.8	67.1	97.6	91.5	85.4	110.3	61.0	73.2	67.1	85.4	91.5	67.1	152.5
Ca^{2+} (mg/l)	1.85	0.70	0.63	0.88	1.76	1.63	1.32	2.01	0.74	1.23	1.17	1.44	1.51	0.87	5.17
Mg^{2+} (mg/l)	1.12	0.44	0.41	0.51	1.02	0.99	0.73	1.74	0.48	0.70	0.66	0.85	0.87	0.56	3.33
K (mg/l)	0.77	0.15	0.10	0.22	0.73	0.71	0.43	0.80	0.18	0.41	0.33	0.56	0.61	0.27	0.88
Na (mg/l)	0.89	0.21	0.18	0.31	0.87	0.77	0.54	1.22	0.27	0.51	0.43	0.61	0.73	0.40	1.85
Cl^- (mg/l)	88.6	35.5	35.5	53.2	88.6	88.6	70.9	106.4	53.2	53.2	53.2	70.9	70.9	53.2	159.5
NO_2^- (mg/l)	0.087	0.011	0.011	0.022	0.061	0.055	0.044	0.121	0.018	0.031	0.028	0.048	0.053	0.025	0.881
NO_3^- (mg/l)	1.084	0.177	0.140	0.394	1.041	0.993	0.721	1.084	0.199	0.604	0.465	0.823	0.971	0.455	2.921
SO_4^{2-} (mg/l)	0.084	0.017	0.014	0.024	0.071	0.067	0.037	0.094	0.022	0.033	0.028	0.063	0.063	0.024	0.155
Fe (mg/l)	0.284	0.053	0.031	0.084	0.231	0.230	0.154	0.301	0.084	0.133	0.132	0.155	0.180	0.130	1.881
Zn (mg/l)	0.114	0.040	0.020	0.053	0.105	0.098	0.061	0.124	0.051	0.073	0.071	0.077	0.087	0.066	1.220
Cu (mg/l)	0.028	0.005	0.005	0.007	0.020	0.017	0.009	0.035	0.005	0.008	0.008	0.010	0.011	0.010	0.662
Mn (mg/l)	0.088	0.028	0.015	0.036	0.080	0.073	0.052	0.087	0.033	0.050	0.043	0.056	0.061	0.047	0.877
NH_4N (mg/l)	0.491	0.312	0.281	0.341	0.488	0.472	0.422	0.514	0.320	0.392	0.389	0.451	0.460	0.372	0.851
Col. (Pt. Co)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

The findings from Tables 5 and 6 indicate that most of the examined water quality parameters fall within acceptable limits set by the World Health Organization (WHO) and the Nigerian Industrial Standard (NIS) for drinking water. However, pH and temperature exceeded these limits. Also, all parameters examined were below or within the food industry standard (FIS) except for pH. Specifically, the mean pH value of 5.313, which was below the acceptable 6.5–8.5 limits of WHO (2011 and 2017), NIS (2015), and food industry standards (adapted from Islam and Mostafa, 2023) suggests that the groundwater samples are strongly acidic, which could be attributed to waste generation due to population growth and industrial activities in the study area. These factors may contribute to the uncontrolled disposal of acidic waste materials. These materials, when carried by surface runoff and infiltrating into the aquifer, could lead to the pronounced acidity of groundwater (Egbueri *et al*., 2021). Researchers have consistently observed the acidic nature of groundwater quality in Benin City (Omoigberale *et al.,* 2009; Orjiekwe *et al.,* 2013; Achadu *et al.,* 2018; Ogbeifun *et al.,* 2019). Although pH itself does not directly impact humans (WHO, 2011 and 2017), low pH levels enhance the dissolution of heavy metals and minerals in water (Rawlings and Ikediashi, 2020; Egbueri *et al.,* 2021), leading to drinking water contamination and potential health risks. Additionally, acidic waters with abundant H^+ ions can accelerate corrosion processes (Hem, 1985; Islam and Mostafa, 2023). Subsequently, these may lead to various issues, including the degradation of the water distribution network and water-using equipment (Mirzabeygi *et al.,* 2016; Mirzabeygi *et al.,* 2017; Abbasnia *et al.,* 2019; Mohammadi *et al.,* 2018). The recorded temperature of borehole water samples was notably high, with a mean value of 28.513 °C-well above the recommended limits set by the World Health Organization (WHO) in 2011 and 2017, as well as the National Industrial Standard (NIS) in 2015 for drinking water quality. This elevated temperature suggests warm groundwater. The cause may be geochemical processes (rock-water interactions) occurring in the aquifer basement, particularly in areas underlain by sedimentary rock (Ikhile, 2016). Consequently, the groundwater flow path likely involves a deep aquifer system with geothermal heating (Betageri and Patil, 2020). Such high water temperatures can promote microorganism growth and exacerbate taste, odour, colour, and corrosion issues (WHO, 2011 and 2017).

From Table 5, the borehole water samples recorded comparatively higher mean values for EC (189.267 µS/cm), TDS (95.933 mg/l), DO (4.073 mg/l), HCO_3^- (84.213 mg/l), and Cl^- (72.093 mg/l) relative to other measured parameters. Nevertheless, all values remained within the acceptable limits set by the World Health Organization (WHO), Nigerian Industrial Standard (NIS), and Food Industry Standards (FIS). While pH is generally recognized in the literature as a factor influencing mineral solubility in groundwater (WHO, 2017), this relationship was not directly established in our dataset. Additionally, the increased DO levels could result from the indiscriminate disposal of organic waste (such as food waste) in the study area, infiltrating the aquifer through surface runoff. The comparatively higher levels of these parameters (EC, TDS, DO, HCO_3^-, and Cl^-) have a significant impact on corrosion rates (Hamzah *et al.,* 2008; Kumar *et al.,* 2015; Omeka *et al.,* 2022; Islam and Mostafa, 2023). Moreover, these increased concentrations in water not only reduce its taste but may also lead to gastrointestinal discomfort, laxative effects, and high blood pressure in humans (WHO, 2017; Srigirisetty *et al.,* 2017; Lewin, 2023).

As shown in Table 7, the LSI values of the borehole water samples ranged from –5.29 to –3.38, with a mean of –4.4. According to the classification presented in Table 3, LSI values less than zero indicate that water is undersaturated with respect to calcium carbonate and therefore not prone to scaling. Instead, such negative values suggest dissolution of $CaCO_3$, which increases the potential for corrosion. Thus, the deduction of higher corrosion tendency is derived directly from the established metric in Table 3, confirming that the groundwater has a greater likelihood of corrosion rather than scale formation. This underscores the need for treatment before industrial application, as corrosive water can damage equipment, infrastructure, and pose risks to public health (Rawlings and Ikediashi, 2020; Islam and Mostafa, 2023). Recommended treatments include pH adjustment (using lime or soda ash), application of corrosion inhibitors, and partial softening or blending to stabilize water chemistry, thereby reducing corrosivity and enhancing suitability for industrial use.

Table 7: LSI of Groundwater Water Samples

Borehole Water Samples	LSI
BH1	-4.05
BH2	-4.8
BH3	-5.29
BH4	-4.91
BH5	-4.47
BH6	-4.46
BH7	-4.85
BH8	-3.38
BH9	-4.82
BH10	-3.45
BH11	-4.1
BH12	-4.63
BH13	-4.59
BH14	-4.83
BH15	-4.49
Mean	-4.4

According to Table 8, the Water Quality Index (WQI) falls within the range of 15.994–417.177. Based on Table 4, most of the borehole samples had excellent to good water quality, while a few had poor water quality, and only one of them was unsuitable for drinking. BH2 (19.353), BH3 (15.994), BH4 (25.136), and BH9 (23.409) had excellent water quality; BH6 (48.725), BH7 (37.579), BH10 (32.590), BH11 (31.195), BH12 (39.564), BH13 (42.937), and BH14 (31.016) had good water quality; BH1 (59.776), BH5 (51.183), and BH8 (66.225) had poor water quality; BH15 (417.477) had water quality unsuitable for drinking. The excellent to good water quality recorded in most of the borehole samples (BH2, BH3, BH4, BH9, BH6, BH7, BH10, BH11, BH12, BH13, and BH14) suggests that the water is suitable for drinking and other domestic purposes. In contrast, the poor and unsuitable samples (BH1, BH5, BH8, and BH15) highlight the impact of intense anthropogenic activities on groundwater quality in the area. Periodical assessment and monitoring are therefore essential to safeguard and improve water quality. Moreover, although the WQI confirms suitability for drinking, the high corrosion tendency revealed by the negative LSI values necessitates treatment before domestic use. Recommended measures include pH adjustment with lime or soda ash, application of corrosion inhibitors to protect household plumbing, and standard filtration and disinfection to ensure potable safety. These interventions collectively enhance the reliability and sustainability of groundwater for domestic consumption.

Table 8: WQI of Groundwater Samples

Sampling Points	WQI	Rating of Water Quality
BH1	59.776	Poor
BH2	19.353	Excellent
BH3	15.994	Excellent
BH4	25.136	Excellent
BH5	51.183	Poor
BH6	48.725	Good
BH7	37.579	Good
BH8	66.225	Poor
BH9	23.409	Excellent
BH10	32.590	Good
BH11	31.195	Good
BH12	39.564	Good
BH13	42.937	Good
BH14	31.016	Good
BH15	417.477	Unsuitable for drinking

4.0 CONCLUSION

An assessment of groundwater suitability for industrial and domestic purposes was conducted in Oredo LGA, Benin City, Nigeria. The physiochemical analysis indicated that most parameters were within acceptable limits established by the World Health Organization (WHO) and the Nigerian Industrial Standards (NIS) for drinking water quality. However, both pH and temperature levels exceeded these limits. The groundwater was found to be acidic, with elevated levels of electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), bicarbonate (HCO_3^-), and chloride (Cl^-), all of which remained within permissible ranges. The Langelier Saturation Index (LSI) suggested a high corrosion potential due to the acidity of the groundwater, rendering it unsuitable for industrial use. While the Water Quality Index (WQI) indicated adequate water quality for drinking and other domestic purposes, it also highlighted that the groundwater is threatened by the intense anthropogenic activities in the area. Precautions are necessary to prevent corrosion in industrial equipment and safeguard public health. Regular monitoring and treatment are recommended to improve groundwater quality. In addition, regulatory agencies should implement policies and enforce standards aimed at reducing groundwater acidity and corrosion, including stricter control of waste disposal, regulation of industrial effluents, and promotion of environmentally sustainable practices. Such efforts will help mitigate anthropogenic impacts and ensure the long-term safety and sustainability of groundwater resources in the study area.

AUTHORS' CONTRIBUTIONS STATEMENT

AR: Conceptualization, Investigation, Methodology, Formal analysis, Research supervision, Writing original draft.

JAO: Data collection, Investigation, Formal analysis.

SS: Methodology, Review & editing of initial write-up. All authors read and approved the final manuscript.

DATA AVAILABILITY

Datasets generated or analysed during the current study will be made available on request.

STATEMENTS AND DECLARATIONS

ETHICAL

Ethical approval was not required for this study.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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