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COMPARATIVE ASSESSMENT OF BOREHOLE AND HAND-DUG WELL WATER QUALITY IN ITORI, SOUTHWESTERN NIGERIA USING WATER QUALITY AND HEAVY METAL POLLUTION INDICES.

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Abstract

Groundwater is a major domestic water source in many Nigerian communities, but its quality may vary with source type, aquifer condition, sanitary protection and surrounding land-use activities. This study assessed and compared borehole and hand-dug well water quality in Itori, Ewekoro Local Government Area, Ogun State, Nigeria. Twenty groundwater samples, comprising ten borehole samples and ten hand-dug well samples, were analysed for pH, electrical conductivity, total dissolved solids, turbidity, total hardness, nitrate, iron, manganese and cadmium. Measured values were compared with drinking-water guideline limits and interpreted using a physicochemical Water Quality Index (WQI) and a Heavy Metal Pollution Index (HPI) for selected metals. Borehole water generally showed near-neutral pH, lower dissolved ionic content, lower turbidity, lower hardness, lower nitrate and lower selected metal concentrations. In contrast, hand-dug wells showed greater deterioration, including acidic conditions, elevated total dissolved solids, increased turbidity, higher hardness and higher nitrate concentrations. Iron

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exceeded the adopted screening value in all hand-dug wells and in four boreholes, while cadmium exceeded the adopted screening value in all hand-dug wells. WQI values ranged from 9.85 to 35.53 in boreholes and from 56.21 to 108.90 in hand-dug wells, classifying borehole samples as excellent to good and well samples as poor, very poor or unsuitable. HPI values ranged from 1.06 to 99.58 in boreholes and from 325.42 to 648.59 in hand-dug wells, indicating substantially greater selected-metal pollution in hand-dug wells. The findings indicate that hand-dug wells in the sampled locations are more vulnerable to contamination than boreholes and should not be consumed without treatment, routine monitoring and confirmatory cadmium analysis.

Introduction

Access to safe drinking water remains a major environmental-health concern in many low- and middle-income settings, particularly in communities where public pipe-borne water supply is inadequate, intermittent or absent. In such areas, groundwater obtained from boreholes and hand-dug wells often serves as the principal source of water for drinking, cooking and other domestic uses. Although groundwater is often perceived as safer than surface water because of natural filtration through soil and geological materials, its quality can be altered by aquifer geology, residence time, rock–water interaction, redox conditions, well depth, construction quality, sanitation infrastructure, waste-disposal practices and surrounding land use. Drinking-water safety therefore requires both water-quality monitoring and risk-based management from source to consumer (World Health Organization, 2022).

In Nigeria, dependence on groundwater has increased because many urban, peri-urban and rural communities lack consistent access to treated municipal water. Boreholes and hand-dug wells are widely used, but their vulnerability to contamination differs substantially. Boreholes typically draw water from deeper aquifer zones and may be less exposed to immediate surface contamination when properly constructed and sealed. Hand-dug wells, by contrast, are commonly shallow, poorly protected and located within residential environments where they may receive surface runoff, leachate, septic seepage, domestic wastewater and other near-surface contaminants. These differences make source-specific groundwater assessment important, particularly in communities where untreated groundwater is consumed directly.

Groundwater quality in Nigeria is controlled by both natural and anthropogenic processes. Ighalo et al. (2021) reported that groundwater pollution in Nigeria is strongly influenced by regional hydrogeology, waste-disposal practices and human activities.

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Recent studies from Southwestern Nigeria also show that groundwater chemistry varies spatially and is affected by urbanisation, geology, waste inputs and well characteristics (Ezechinyere & Stanislaus, 2023; Jolaosho et al., 2024; Kayode et al., 2024). These studies demonstrate the value of combining parameter-specific analysis with integrated water-quality indices and statistical interpretation in order to provide clearer evidence for public-health and water-management decisions.

Within Ogun State, groundwater-quality assessment is particularly important because many communities depend heavily on private boreholes and hand-dug wells. Industrial activities, settlement expansion, sanitation practices and local geology may influence groundwater chemistry. David et al. (2024) assessed groundwater around a cement-factory environment in Ewekoro and reported variations in physicochemical parameters and metal ions in boreholes and hand-dug wells. Similarly, Ishola (2024) assessed groundwater quality in Itori District and reported that some parameters, particularly iron, exceeded permissible standards in parts of the groundwater system. Recent water-quality studies in Southwestern Nigeria have also shown the usefulness of combining physicochemical assessment, compliance analysis, hydrochemical interpretation and statistical modelling to understand spatial and seasonal variation in aquatic systems (Laniyan et al., 2025). These findings suggest that groundwater in the area may be affected by both natural mineralisation and local human activities.

Physicochemical parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, hardness and nitrate are commonly used to evaluate the suitability and acceptability of drinking water. pH influences corrosion potential and metal mobility, EC and TDS indicate dissolved ionic content, turbidity reflects suspended particles or poor sanitary protection, hardness affects domestic usability, and nitrate may indicate inputs from sanitation systems, fertilisers or organic waste (Chukwuneke et al., 2026; Edegbai et al., 2026; Igboama et al., 2025). In addition, selected metals such as iron, manganese and cadmium require attention because they may affect water acceptability, aesthetics and long-term safety. Iron and manganese may occur naturally through mineral weathering and reducing groundwater conditions, whereas cadmium is of greater toxicological concern because drinking-water guideline values are very low.

Although previous studies have contributed to understanding groundwater quality in Southwestern Nigeria and parts of Ogun State, there is still limited source-comparative evidence on the relative quality of boreholes and hand-dug wells in Itori using both general water-quality and metal-pollution indices. This study therefore assessed selected physicochemical parameters and metals in groundwater from boreholes and hand-dug wells in Itori, Ogun State. The measured values were compared with relevant drinking-water guideline limits, while the Water Quality Index (WQI) and Heavy Metal Pollution

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Index (HPI) were applied to support interpretation of overall physicochemical quality and selected metal pollution. The study provides local evidence for groundwater monitoring, household water-safety decisions and public-health management in groundwater-dependent communities.

Problem Statement

Despite the widespread domestic use of boreholes and hand-dug wells in Itori, evidence remains limited on how groundwater quality differs between these source types when assessed using both physicochemical indicators and selected-metal pollution indices. This information gap constrains source-specific water-safety decisions, treatment priorities and groundwater-management interventions, particularly because shallow hand-dug wells may be more exposed to surface runoff, sanitation-related seepage and other near-surface contamination pathways.

Objectives of the Study

The main objective of the study was to comparatively assess the quality of borehole and hand-dug well water in Itori, Southwestern Nigeria. Specifically, the study aimed to: (i) determine selected physicochemical and metal concentrations in both groundwater-source types; (ii) compare measured values with adopted drinking-water guideline limits; (iii) evaluate overall physicochemical quality using the Water Quality Index; (iv) assess selected-metal pollution using the Heavy Metal Pollution Index; and (v) determine whether statistically significant differences exist between borehole and hand-dug well water quality.

Research Questions

The study addressed the following questions: What are the physicochemical and selected-metal characteristics of borehole and hand-dug well water in Itori? To what extent do the samples comply with adopted drinking-water guideline limits? How do the Water Quality Index and Heavy Metal Pollution Index classifications differ between boreholes and hand-dug wells? Are the observed differences between the two groundwater-source types statistically significant?

Research Hypotheses

H01: There is no statistically significant difference in the physicochemical quality of borehole and hand-dug well water in Itori. H02: There is no statistically significant difference in selected-metal concentrations between borehole and hand-dug well water in Itori.

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Study area

The study was conducted in Itori town, Ewekoro Local Government Area of Ogun State, Southwestern Nigeria. Itori lies within a groundwater-dependent setting where boreholes and hand-dug wells are widely used for domestic water supply. The area includes residential, commercial, institutional, agricultural and mixed land-use settings. These land-use activities, together with local geology and sanitation practices, may influence groundwater quality. The sampling locations and coordinates are presented in Table 1, while the spatial distribution of sampling points is shown in Figure 1.

Table 1. Sampling locations, coordinates and dominant land use

S/N	Sample ID	Water Source	Sampling Location	Latitude (°N)	Longitude (°E)	Dominant Land Use
1	BH1	Borehole	Itori Town Centre	7.0152	3.2754	Commercial/Residential
2	BH2	Borehole	Wasimi	7.0058	3.2663	Residential
3	BH3	Borehole	Papalanto Road Junction	7.0221	3.2865	Commercial
4	BH4	Borehole	Arigbajo Road	7.0117	3.2589	Residential
5	BH5	Borehole	Onihale Community	7.0345	3.2914	Residential
6	BH6	Borehole	Alaguntan	7.0468	3.3012	Agricultural
7	BH7	Borehole	Olowo Market Area	7.0096	3.2728	Commercial
8	BH8	Borehole	Itori Grammar School Area	7.0189	3.2815	Institutional
9	BH9	Borehole	Iyana Itori	7.0263	3.2698	Transport/Commercial
10	BH10	Borehole	Ewekoro–Itori Road	7.0392	3.3145	Mixed Residential
11	W1	Hand-dug well	Itori Town Centre	7.0143	3.2741	Residential
12	W2	Hand-dug well	Wasimi Community	7.0064	3.2672	Residential
13	W3	Hand-dug well	Onihale	7.0338	3.2901	Residential
14	W4	Hand-dug well	Alaguntan	7.0473	3.3004	Agricultural
15	W5	Hand-dug well	Arigbajo Road	7.0126	3.2598	Residential

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S/N	Sample ID	Water Source	Sampling Location	Latitude (°N)	Longitude (°E)	Dominant Land Use
16	W6	Hand-dug well	Olowo Market	7.0104	3.2736	Commercial
17	W7	Hand-dug well	Itori Primary Health Centre	7.0176	3.2792	Institutional
18	W8	Hand-dug well	Papalanto Road	7.0214	3.2856	Commercial
19	W9	Hand-dug well	Iyana Itori	7.0254	3.2707	Mixed Residential
20	W10	Hand-dug well	Alagbole Area	7.0415	3.3187	Residential

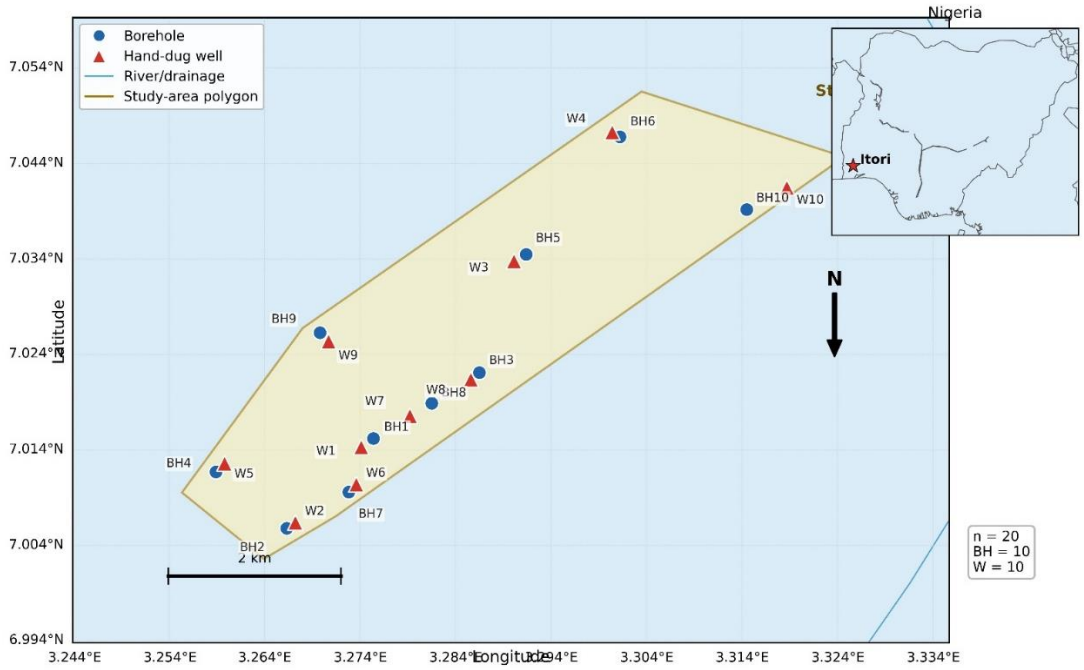


Figure 1. Location map of groundwater sampling points in Itori, Ewekoro Local Government Area, Ogun State, Nigeria showing the distribution of borehole samples (BH1–BH10) and hand-dug well samples (W1–W10).

Research design and sample collection

The study adopted a comparative water-quality assessment design. Two groundwater-source categories were examined: boreholes and hand-dug wells. A total of twenty groundwater samples were analysed, comprising ten borehole samples (BH1–BH10) and ten hand-dug well samples (W1–W10). The comparative design was used to determine whether water quality differed between the two groundwater-source types.

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Water samples were collected in clean sampling bottles following standard water-sampling procedures. Samples for physicochemical analysis were collected in clean plastic bottles. Samples intended for metal analysis were preserved with nitric acid prior to laboratory analysis to minimise adsorption and precipitation of metals. All samples were transported to the laboratory under appropriate conditions and analysed using standard water-quality analytical procedures. The dataset represents a single field-sampling campaign; therefore, seasonal variation was not assessed.

Analytical procedures

The pH of each water sample was determined using a calibrated pH meter. Electrical conductivity was measured using a conductivity meter and reported in microsiemens per centimetre. Total dissolved solids were determined using standard procedures and reported in milligrams per litre. Turbidity was measured and reported in nephelometric turbidity units. Total hardness and nitrate were determined using standard water-analysis procedures and reported in milligrams per litre. Iron, manganese and cadmium concentrations were determined using atomic absorption spectrophotometry (AAS), following standard procedures for trace-metal analysis in water samples.

Quality assurance and quality control

Quality assurance and quality control procedures were implemented to support the reliability, accuracy and reproducibility of the analytical results. Instruments were calibrated before analysis using appropriate standard solutions. Reagent blanks were analysed to check for possible contamination, while duplicate samples were used to assess analytical precision. Analytical-grade reagents were used throughout the laboratory procedures, and samples for metal analysis were preserved before analysis. Where concentrations were reported as 0.000 mg/L in the laboratory dataset, they were interpreted as below detection level and treated as zero for descriptive and index calculations. Because cadmium exceeded the guideline value in all hand-dug well samples, repeat or confirmatory cadmium analysis with explicit reporting of method detection limits is recommended.

Data analysis and guideline comparison

The analytical results were entered into a spreadsheet and grouped by water-source type. Descriptive statistics, including minimum, maximum, mean, standard deviation and coefficient of variation, were calculated separately for borehole and hand-dug well samples. The results were compared with drinking-water guideline values from the World Health Organization and the Nigerian Standard for Drinking Water Quality (World Health

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Organization, 2022; Standards Organisation of Nigeria, 2015) for pH, EC, TDS, turbidity, hardness, nitrate, iron, manganese and cadmium. For pH, values below 6.5 or above 8.5 were treated as outside the acceptable range. For other parameters, values above the adopted screening limits were treated as exceedances.

Table 2. Parameters, adopted screening values and index use

Parameter	Adopted screening value	Use in analysis	Interpretive note
pH	6.5–8.5	WQI; compliance	Ideal value = 7.0 for WQI
EC	1000 µS/cm	WQI; compliance	Conductivity indicator
TDS	500 mg/L	WQI; compliance	Dissolved-solids indicator
Turbidity	5 NTU	WQI; compliance	Particulate/suspended matter
Total hardness	150 mg/L	WQI; compliance	Domestic-use acceptability
Nitrate	50 mg/L	WQI; compliance	Anthropogenic contamination indicator
Iron	0.3 mg/L	HPI; compliance	Selected metal
Manganese	0.1 mg/L	HPI; compliance	Selected metal
Cadmium	0.003 mg/L	HPI; compliance	Selected metal; toxicological concern

Water Quality Index and Heavy Metal Pollution Index

To make the WQI reproducible, only the physicochemical variables pH, EC, TDS, turbidity, total hardness and nitrate were included in the WQI calculation. Selected metals were excluded from the WQI and assessed separately using HPI. The weighted arithmetic WQI was calculated as $WQI = \Sigma(Qi \times Wi)/\Sigma Wi$, where Qi is the quality rating for each parameter and Wi is the unit weight. For EC, TDS, turbidity, hardness and nitrate, $Qi = (Ci/Si) \times 100$, where Ci is the measured value and Si is the adopted screening value. For pH, $Qi = |pH - 7.0|/(8.5 - 7.0) \times 100$. Unit weights were calculated as $Wi = 1/Si$. WQI values were classified as excellent (0–25), good (26–50), poor (51–75), very poor (76–100) and unsuitable (>100). The HPI was calculated using iron, manganese and cadmium to evaluate selected metal pollution. The HPI formula was $HPI = \Sigma(Qi \times Wi)/\Sigma Wi$, where $Qi = (Mi/Si) \times 100$, Mi is the measured metal concentration, Si is the adopted guideline value and $Wi = 1/Si$. An HPI value greater than 100 was interpreted as high selected metal pollution, whereas values below or equal to 100 were interpreted as low or acceptable selected metal pollution under the classification adopted in this study.

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Statistical analysis

Welch's t-test was used to compare mean parameter values between borehole and hand-dug well samples because it does not assume equal variance between groups. The Mann–Whitney U test was also applied as a non-parametric comparison because of the small sample size. Statistical significance was interpreted at $p < 0.05$. Pearson correlation analysis was used to explore relationships among the analysed parameters. Correlation results were interpreted cautiously because the dataset was limited to twenty samples and does not establish causation.

General water-quality characteristics

The raw borehole and hand-dug well water-quality results are presented in Tables 3 and 4, respectively. The dataset indicates clear source-related differences in groundwater quality. Borehole samples generally showed near-neutral pH and lower electrical conductivity (EC), total dissolved solids (TDS), turbidity, hardness, nitrate and selected metal concentrations than the hand-dug well samples. Borehole pH ranged from 6.71 to 7.12, whereas hand-dug well pH ranged from 5.40 to 6.58, indicating slightly acidic conditions in several well samples. Similar source-related variation in groundwater chemistry has been reported in Southwestern Nigeria and other Nigerian groundwater-dependent settings, where shallow wells are often more vulnerable to near-surface contamination than deeper boreholes (Ighalo et al., 2021; David et al., 2024; Ishola, 2024; Jolaosho et al., 2024).

The mean EC and TDS values were lower in boreholes than in hand-dug wells. Borehole EC ranged from 304.34 to 415.71 µS/cm, with a mean of 360.47 µS/cm, while hand-dug well EC ranged from 538.21 to 812.32 µS/cm, with a mean of 656.53 µS/cm. Similarly, borehole TDS ranged from 243.01 to 358.63 mg/L, with a mean of 291.13 mg/L, whereas hand-dug well TDS ranged from 481.01 to 596.04 mg/L, with a mean of 541.11 mg/L. Higher EC and TDS values in hand-dug wells suggest greater dissolved ionic content, which may be associated with shallow groundwater interaction with near-surface materials, domestic wastewater inputs, runoff and local sanitation conditions. Previous groundwater studies have similarly linked elevated EC and TDS to mineral dissolution, waste inputs, hydrogeochemical processes and anthropogenic influence (Ezechinyere & Stanislaus, 2023; Jolaosho et al., 2024; Kayode et al., 2024; Akinwunmi et al., 2026).

Turbidity was also higher in hand-dug wells than in boreholes. Borehole turbidity ranged from 0.52 to 2.43 NTU, while hand-dug well turbidity ranged from 3.62 to 5.91 NTU. The relatively high turbidity values in the wells may indicate poorer sanitary protection, entry of suspended particles, surface runoff or inadequate well covering. This agrees with the general observation that shallow groundwater sources are more susceptible to

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contamination where wellhead protection is poor or where water sources are close to domestic and waste-disposal activities (Ighalo et al., 2021; Ale et al., 2026; Asemota et al., 2026).

Total hardness followed a similar pattern, with borehole values ranging from 67.11 to 151.71 mg/L and hand-dug well values ranging from 131.09 to 248.26 mg/L. Although hardness is not usually a direct health concern, higher hardness may affect water acceptability, soap consumption, scaling and domestic use. Hardness in groundwater is commonly linked to dissolution of calcium- and magnesium-bearing minerals, as well as local hydrogeochemical conditions (World Health Organization, 2022; Kayode et al., 2024; Ganiyu et al., 2026).

Nitrate concentrations were substantially higher in hand-dug wells than in boreholes. Borehole nitrate ranged from 2.16 to 4.03 mg/L, while hand-dug well nitrate ranged from 7.23 to 14.08 mg/L. Although the nitrate values were below the WHO guideline value of 50 mg/L as nitrate, the higher concentrations in wells suggest greater influence from anthropogenic inputs such as septic seepage, domestic wastewater, animal waste, fertiliser application or surface runoff. Nitrate enrichment in shallow groundwater has been widely associated with sanitation systems, agricultural inputs and poor waste management, particularly in communities with limited centralised wastewater infrastructure (World Health Organization, 2022; Ighalo et al., 2021; Chinedu et al., 2025; Musa et al., 2026).

Selected metal concentrations also showed higher values in hand-dug wells. Borehole iron ranged from 0.18 to 0.44 mg/L, while hand-dug well iron ranged from 0.51 to 1.06 mg/L. Manganese ranged from 0.01 to 0.08 mg/L in boreholes and from 0.09 to 0.22 mg/L in hand-dug wells. Iron and manganese in groundwater may originate from natural mineral weathering, reducing aquifer conditions and rock–water interaction, although anthropogenic inputs may also contribute in affected environments (Jolaosho et al., 2024; Akinwunmi et al., 2026; Ganiyu et al., 2026). Cadmium was low in most boreholes with values ranged from 0.001 to 0.003 mg/L. In contrast, cadmium was detected in all hand-dug well samples, ranging from 0.010 to 0.020 mg/L. Because cadmium has a low drinking-water guideline value and greater toxicological significance, its occurrence in all hand-dug wells requires careful interpretation alongside analytical quality-control results, detection limits and confirmatory analysis (World Health Organization, 2022; Asemota et al., 2026; Ozoemenam et al., 2026).

The results generally show that hand-dug wells were more chemically deteriorated than boreholes across most measured parameters. This pattern is consistent with the greater vulnerability of shallow hand-dug wells to surface and near-surface contamination pathways, especially where wells are poorly protected or located close to sanitation

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systems, runoff channels, refuse-disposal points or domestic activity areas. Comparable Nigerian studies have reported that groundwater quality deterioration is often controlled by a combination of hydrogeology, source protection, waste-disposal practices, urbanization and local land-use activities (Ighalo et al., 2021; David et al., 2024; Ishola, 2024; Jimoh et al., 2026).

Table 3. Borehole water-quality results

Sample	pH	EC (µS/cm)	TDS (mg/L)	Turbidity (NTU)	Hardness (mg/L)	Nitrate (mg/L)	Fe (mg/L)	Mn (mg/L)	Cd (mg/L)
BH1	6.90	376.83	358.63	1.20	142.15	3.32	0.25	0.06	0.001
BH2	6.77	376.71	290.97	2.43	125.14	2.61	0.28	0.08	0.001
BH3	6.93	412.10	302.70	1.49	116.53	2.32	0.19	0.05	0.001
BH4	7.10	304.34	243.01	0.97	110.97	3.61	0.18	0.08	0.002
BH5	6.75	313.75	278.22	1.91	75.64	4.03	0.38	0.02	0.001
BH6	6.75	371.89	304.44	0.89	98.40	3.93	0.44	0.07	0.003
BH7	7.12	349.36	253.96	1.60	106.18	2.16	0.29	0.05	0.001
BH8	6.95	415.71	315.03	0.52	151.71	2.69	0.40	0.04	0.001
BH9	6.71	354.60	275.97	0.84	130.31	3.33	0.34	0.05	0.001
BH10	6.91	329.38	288.33	1.60	67.11	3.98	0.24	0.01	0.001

C = electrical conductivity; TDS = total dissolved solids; Fe = iron; Mn = manganese; Cd = cadmium;. pH is unitless.

Table 4. Hand-dug well water-quality results

Sample	pH	EC (µS/cm)	TDS (mg/L)	Turbidity (NTU)	Hardness (mg/L)	Nitrate (mg/L)	Fe (mg/L)	Mn (mg/L)	Cd (mg/L)
W1	6.12	717.20	510.45	3.72	248.26	8.22	0.51	0.20	0.010
W2	6.09	538.21	550.24	5.27	214.94	7.23	1.04	0.22	0.010
W3	6.58	624.56	578.67	3.70	180.37	8.29	1.06	0.19	0.010
W4	6.11	812.32	534.46	5.88	165.38	10.11	0.63	0.10	0.010
W5	5.40	698.52	515.52	5.91	205.96	11.09	0.92	0.11	0.010
W6	6.30	566.12	524.71	5.89	131.09	10.05	1.04	0.09	0.010
W7	6.08	614.20	570.39	3.62	201.45	11.73	0.85	0.19	0.010
W8	6.11	620.59	549.56	4.58	143.41	14.08	0.97	0.21	0.010
W9	6.34	708.19	596.04	4.01	204.82	8.35	0.83	0.17	0.020
W10	6.15	665.39	481.01	5.42	173.56	8.59	0.56	0.20	0.010

EC = electrical conductivity; TDS = total dissolved solids; Fe = iron; Mn = manganese; Cd = cadmium; <LOD = below the laboratory reporting/detection limit. pH is unitless.

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Descriptive statistics

Descriptive statistics for borehole and hand-dug well samples are presented in Tables 5 and 6. Borehole water had pH values ranging from 6.71 to 7.12, with a mean of 6.889 ± 0.145, indicating near-neutral conditions. In contrast, hand-dug well pH ranged from 5.40 to 6.58, with a mean of 6.128 ± 0.301, indicating slightly acidic conditions in most well samples relative to the adopted drinking-water pH range. The pH variation shown in Figure 2 further confirms that borehole samples were generally within the guideline range, whereas several hand-dug well samples fell below the lower acceptable limit. Similar acidic to slightly acidic groundwater conditions have been reported in parts of Southwestern Nigeria and have been linked to local hydrogeochemical conditions, shallow aquifer interaction and anthropogenic influences (Ezechinyere & Stanislaus, 2023; Jolaosho et al., 2024; Ishola, 2024; Laniyan et al., 2025).

Mean EC and TDS values were substantially higher in hand-dug wells than in boreholes, indicating greater dissolved ionic content in the wells. Borehole EC and TDS had mean values of 360.467 ± 37.766 µS/cm and 291.126 ± 32.558 mg/L, respectively, while hand-dug wells had corresponding mean values of 656.530 ± 80.788 µS/cm and 541.105 ± 34.897 mg/L. The relationship between EC and TDS shown in Figure 3 supports the expected association between dissolved ionic load and conductivity. Across the combined dataset, EC and TDS showed a strong positive relationship, indicating that increasing dissolved solids contributed substantially to conductivity. Elevated EC and TDS in shallow groundwater are commonly associated with mineral dissolution, domestic wastewater inputs, runoff, leachate migration and other anthropogenic activities (Ighalo et al., 2021; David et al., 2024; Kayode et al., 2024; Akinwunmi et al., 2026).

Turbidity also differed markedly between the two source types. Borehole turbidity ranged from 0.520 to 2.430 NTU, with a mean of 1.345 ± 0.573 NTU, whereas hand-dug well turbidity ranged from 3.620 to 5.910 NTU, with a mean of 4.800 ± 0.979 NTU. The higher turbidity values in hand-dug wells may reflect poor wellhead protection, surface runoff, entry of suspended particles or inadequate sanitary sealing. This pattern is consistent with reports that shallow wells are more vulnerable to contamination where they are poorly protected or located close to domestic waste, runoff channels or sanitation facilities (Ighalo et al., 2021; Ale et al., 2026; Asemota et al., 2026).

Hardness values were also higher in hand-dug wells than in boreholes. Borehole hardness ranged from 67.110 to 151.710 mg/L, with a mean of 112.414 ± 27.018 mg/L, while hand-dug well hardness ranged from 131.090 to 248.260 mg/L, with a mean of 186.924 ± 35.178 mg/L. Although hardness is mainly an acceptability and domestic-use concern rather than a direct health risk, elevated hardness may affect taste, soap consumption and scaling. Groundwater hardness is usually controlled by dissolution of calcium- and magnesium-

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bearing minerals and by local aquifer chemistry (World Health Organization, 2022; Kayode et al., 2024; Ganiyu et al., 2026).

Nitrate concentrations were consistently higher in hand-dug wells. Borehole nitrate ranged from 2.160 to 4.030 mg/L, with a mean of 3.198 ± 0.707 mg/L, whereas hand-dug well nitrate ranged from 7.230 to 14.080 mg/L, with a mean of 9.774 ± 2.077 mg/L. Although all nitrate values were below the WHO guideline value for drinking water, the higher levels in hand-dug wells may indicate greater influence from septic seepage, domestic wastewater, animal waste, fertiliser application or surface runoff. Nitrate enrichment is commonly used as an indicator of anthropogenic influence in shallow groundwater systems (World Health Organization, 2022; Ighalo et al., 2021; Chinedu et al., 2025; Musa et al., 2026).

Selected metal concentrations followed the same general pattern. Mean iron concentration was 0.299 ± 0.089 mg/L in boreholes and 0.841 ± 0.206 mg/L in hand-dug wells. Mean manganese concentration was 0.051 ± 0.023 mg/L in boreholes and 0.168 ± 0.049 mg/L in hand-dug wells. These results suggest greater metal enrichment in hand-dug wells, which may be linked to shallow aquifer conditions, redox processes, mineral weathering and possible anthropogenic inputs. Iron and manganese enrichment in groundwater has been reported in several Nigerian studies and is often associated with rock–water interaction and reducing groundwater conditions (Jolaosho et al., 2024; Akinwunmi et al., 2026; Ganiyu et al., 2026).

In the borehole dataset, cadmium concentrations were detected in all samples and ranged from 0.001 to 0.003 mg/L. These values were low and did not exceed the adopted drinking-water screening value of 0.003 mg/L. However, the presence of cadmium in all borehole samples still requires attention because cadmium has a very low guideline limit and is toxicologically important even at trace concentrations. The results therefore suggest that borehole water was within the acceptable cadmium limit at the time of sampling, but periodic monitoring is necessary to detect any future increase in concentration. In contrast, cadmium was detected in all hand-dug well samples, ranging from 0.010 to 0.020 mg/L, with a mean of 0.011 ± 0.003 mg/L. Since cadmium has a very low drinking-water guideline value and greater toxicological significance than most aesthetic parameters, the elevated values in hand-dug wells require confirmation using method detection limits, blanks, calibration checks and repeat analysis (World Health Organization, 2022; Asemota et al., 2026; Ozoemenam et al., 2026).

The coefficient of variation (CV) indicates that borehole pH was the most stable parameter, while turbidity, manganese and cadmium showed greater relative variability. However, the very high CV for borehole cadmium should not be overemphasised because most values were below the reporting limit. In the hand-dug wells, CV values were

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generally moderate, with the highest variability observed for manganese, cadmium, iron and nitrate. Overall, the descriptive statistics confirm that hand-dug wells were more chemically variable and more degraded than boreholes, supporting the interpretation that shallow wells in the study area are more vulnerable to near-surface contamination pathways.

Table 5. Descriptive statistics of borehole water-quality parameters

Parameter	Minimum	Maximum	Mean	SD	CV (%)
pH	6.710	7.120	6.889	0.145	2.102
EC	304.340	415.710	360.467	37.766	10.477
TDS	243.010	358.630	291.126	32.558	11.183
Turbidity	0.520	2.430	1.345	0.573	42.580
Hardness	67.110	151.710	112.414	27.018	24.034
Nitrate	2.160	4.030	3.198	0.707	22.096
Iron	0.180	0.440	0.299	0.089	29.641
Mn	0.010	0.080	0.051	0.023	45.705
Cd	0.000	0.003	0.001	0.001	194.365

Table 6. Descriptive statistics of hand-dug well water-quality parameters

Parameter	Minimum	Maximum	Mean	SD	CV (%)
pH	5.400	6.580	6.128	0.301	4.907
EC	538.210	812.320	656.530	80.788	12.305
TDS	481.010	596.040	541.105	34.897	6.449
Turbidity	3.620	5.910	4.800	0.979	20.404
Hardness	131.090	248.260	186.924	35.178	18.819
Nitrate	7.230	14.080	9.774	2.077	21.245
Iron	0.510	1.060	0.841	0.206	24.538
Mn	0.090	0.220	0.168	0.049	29.134
Cd	0.010	0.020	0.011	0.003	28.748

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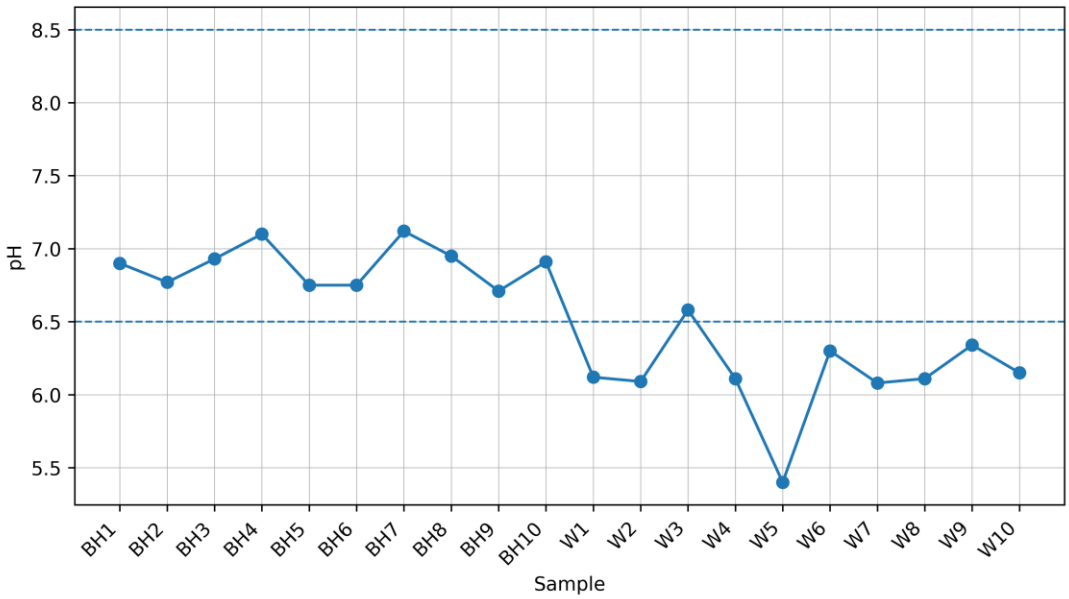


Figure 2. Variation in pH values of borehole and hand-dug well water samples in Itori, Ogun State. Dashed reference lines indicate the adopted lower and upper drinking-water pH guideline range.

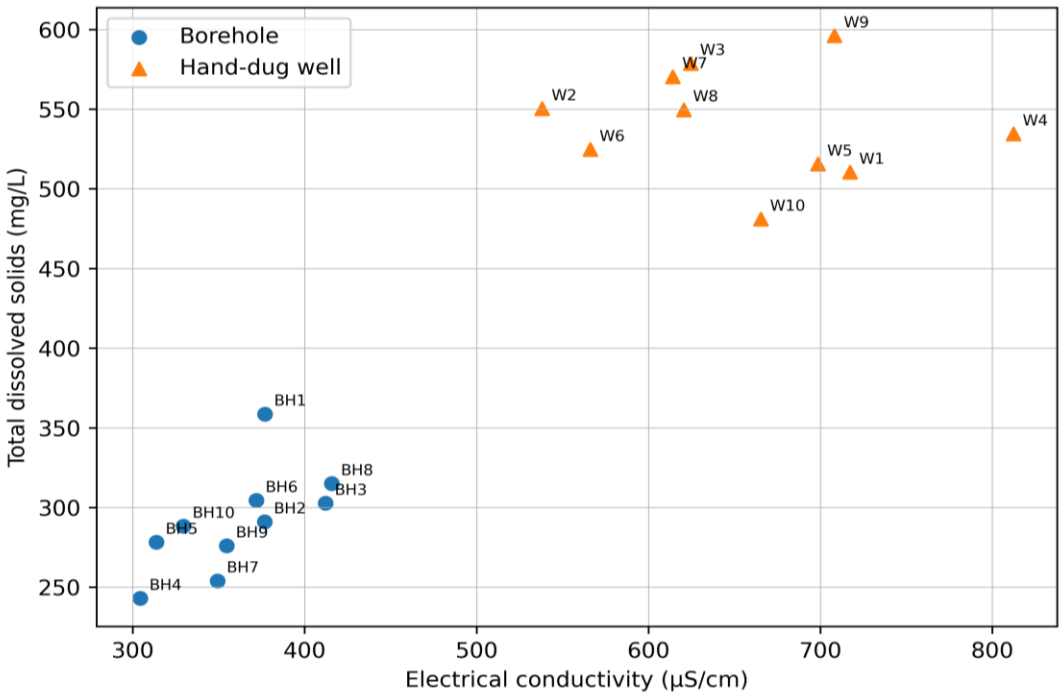


Figure 3. Relationship between electrical conductivity and total dissolved solids in borehole and hand-dug well water samples. The positive association indicates the contribution of dissolved ionic constituents to groundwater conductivity.

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Comparison between boreholes and hand-dug wells

The comparison of mean values confirms that hand-dug wells were more chemically degraded than boreholes across most measured parameters (Table 7). Mean pH decreased from 6.889 in boreholes to 6.128 in hand-dug wells, indicating that the well samples were generally more acidic. This difference may reflect the greater influence of shallow subsurface processes, organic matter decomposition, runoff and local anthropogenic inputs in hand-dug wells. Similar source-related variation in groundwater quality has been reported in Nigerian groundwater studies, where shallow wells are often more vulnerable to near-surface contamination than deeper boreholes (Ighalo et al., 2021; David et al., 2024; Ishola, 2024; Musa et al., 2026).

Mean EC increased from 360.467 µS/cm in boreholes to 656.530 µS/cm in hand-dug wells, while mean TDS increased from 291.126 mg/L to 541.105 mg/L. These increases indicate higher dissolved ionic content in the wells. The higher EC and TDS values may be associated with mineral dissolution, wastewater seepage, surface runoff, leachate influence and other shallow contamination pathways. Previous studies have similarly linked elevated EC and TDS in groundwater to hydrogeochemical processes, urbanisation, waste-disposal practices and local land-use activities (Ezechinyere & Stanislaus, 2023; Jolaosho et al., 2024; Kayode et al., 2024; Akinwunmi et al., 2026).

Mean turbidity increased from 1.345 NTU in boreholes to 4.800 NTU in hand-dug wells, suggesting poorer physical quality in the wells. Elevated turbidity in hand-dug wells may indicate the entry of suspended particles, runoff, inadequate well covering or poor sanitary protection. Although turbidity is not always directly toxic, high turbidity can reduce water acceptability and may indicate vulnerability to microbial or particulate contamination. This agrees with reports that poorly protected shallow groundwater sources are more susceptible to contamination from domestic activities, runoff and waste-disposal environments (Ighalo et al., 2021; Ale et al., 2026; Asemota et al., 2026).

Mean hardness increased from 112.414 mg/L in boreholes to 186.924 mg/L in hand-dug wells. This suggests greater mineral enrichment in the wells, possibly due to longer contact with weathered near-surface materials or local hydrogeochemical conditions. Although hardness is mainly an acceptability and domestic-use concern, elevated levels may affect taste, soap consumption and scaling (World Health Organization, 2022; Kayode et al., 2024; Ganiyu et al., 2026).

Nitrate concentrations remained below the adopted drinking-water screening value in both source types; however, the higher mean nitrate concentration in wells, 9.774 mg/L, compared with 3.198 mg/L in boreholes, suggests greater exposure of wells to shallow anthropogenic inputs. Such inputs may include septic seepage, domestic wastewater, animal waste, fertiliser residues and surface runoff. Nitrate enrichment is widely used as

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an indicator of anthropogenic influence in shallow groundwater systems, especially where sanitation infrastructure is limited or poorly managed (World Health Organization, 2022; Ighalo et al., 2021; Chinedu et al., 2025; Musa et al., 2026).

Selected metal concentrations were also higher in hand-dug wells. Mean iron increased from 0.299 mg/L in boreholes to 0.841 mg/L in wells, while mean manganese increased from 0.051 mg/L to 0.168 mg/L. These results indicate greater selected metal burden in the shallow groundwater sources. Iron and manganese enrichment may result from mineral weathering, reducing aquifer conditions and rock–water interaction, but anthropogenic inputs may also contribute in affected environments (Jolaosho et al., 2024; Akinwunmi et al., 2026; Ganiyu et al., 2026). Cadmium was also higher in wells, with a mean value of 0.011 mg/L compared with an indicative borehole mean of 0.001 mg/L. Because most borehole cadmium values were below the laboratory reporting limit, the borehole cadmium mean should be interpreted cautiously. The consistent detection of cadmium in hand-dug wells is more important and requires confirmatory analysis, detection-limit reporting and quality-control verification because cadmium has a low drinking-water guideline value and greater toxicological relevance (World Health Organization, 2022; Asemota et al., 2026; Ozoemenam et al., 2026).

Figure 4 provides a guideline-normalised comparison of mean parameter values between boreholes and hand-dug wells. Values above the 100% reference line indicate exceedance of the adopted screening or guideline value. The figure shows that hand-dug wells were closer to or above guideline-normalised thresholds for several parameters, particularly turbidity, iron and cadmium. This supports the interpretation that hand-dug wells in the sampled locations were more vulnerable to contamination and less suitable for direct consumption without treatment than boreholes.

Table 7. Mean comparison between borehole and hand-dug well samples

Parameter	Borehole mean	Well mean	Difference (well–borehole)
pH	6.889	6.128	-0.761
EC	360.467	656.530	296.063
TDS	291.126	541.105	249.979
Turbidity	1.345	4.800	3.455
Hardness	112.414	186.924	74.510
Nitrate	3.198	9.774	6.576
Iron	0.299	0.841	0.542
Mn	0.051	0.168	0.117
Cd	0.001	0.011	0.010

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EC is reported in µS/cm; turbidity is reported in NTU; TDS, hardness, nitrate, iron, manganese and cadmium are reported in mg/L, pH is unitless

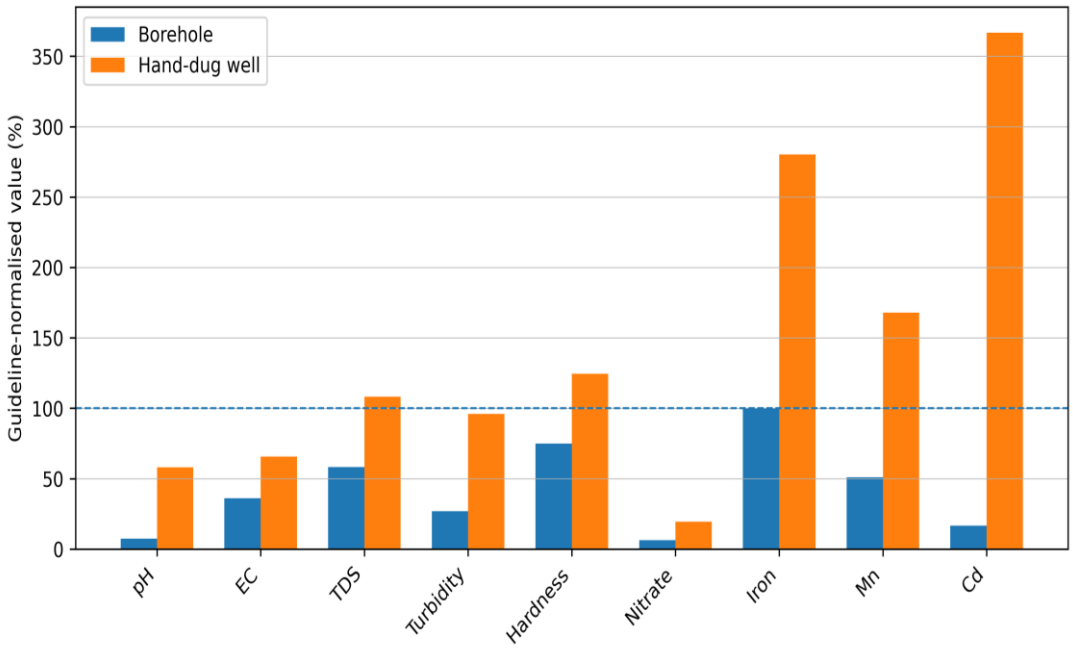


Figure 4. Mean guideline-normalised values of borehole and hand-dug well water-quality parameters. The dashed line represents 100% of the adopted screening or guideline value; values above this line indicate exceedance of the adopted reference limit.

Drinking-water guideline compliance

The drinking-water guideline compliance assessment is presented in Table 8 and Figure 5. Borehole samples generally showed better compliance with the adopted screening limits than hand-dug wells. All borehole samples complied with the adopted limits for pH, EC, TDS, turbidity, nitrate, manganese and cadmium. However, one borehole sample exceeded the adopted hardness screening value, while four borehole samples exceeded the iron limit of 0.3 mg/L. This indicates that borehole water was generally of better quality, although iron enrichment may affect water acceptability, taste, colour and staining in some locations.

In contrast, hand-dug wells showed high levels of non-compliance for several parameters. Nine out of ten hand-dug wells were outside the adopted pH range, indicating slightly acidic conditions. Nine wells exceeded the TDS screening value, five exceeded the turbidity limit, eight exceeded the hardness screening value, all ten exceeded the iron limit, eight exceeded the manganese limit and all ten exceeded the cadmium guideline value. EC and nitrate complied with the adopted limits in all hand-dug well samples,

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indicating that nitrate pollution was not severe based on the adopted drinking-water screening value. However, the higher nitrate levels in wells still suggest greater vulnerability to shallow anthropogenic inputs compared with boreholes.

The non-compliance pattern shows that hand-dug wells were less suitable for direct drinking than boreholes in the sampled locations. However, the significance of each exceedance differs by parameter. TDS, hardness, iron and manganese mainly affect water acceptability, domestic use, taste, staining and scaling, while turbidity may indicate poor sanitary protection and possible particulate or microbial vulnerability. Cadmium exceedance is more serious because cadmium has a low drinking-water guideline value and is of toxicological concern. Therefore, the consistent exceedance of cadmium in all hand-dug well samples requires confirmatory analysis, reporting of method detection limits and additional quality-control verification before final public-health conclusions are made.

The compliance assessment generally supports the conclusion that hand-dug wells in the sampled locations are more vulnerable to contamination than boreholes. The results also indicate that untreated hand-dug well water should not be used directly for drinking without appropriate treatment and routine monitoring, particularly for cadmium, iron, manganese, turbidity and acidity. Similar studies have emphasised the importance of routine groundwater monitoring and source protection in communities that depend on private boreholes and shallow wells for domestic water supply (World Health Organization, 2022; Ighalo et al., 2021; David et al., 2024; Ishola, 2024).

Table 8. Drinking-water guideline compliance assessment

Parameter	Guideline limit	BH within	BH outside	BH non-compliance (%)	W within	W outside	W non-compliance (%)
pH	6.5–8.5	10	0	0.0	1	9	90.0
EC	≤1000	10	0	0.0	10	0	0.0
TDS	≤500	10	0	0.0	1	9	90.0
Turbidity	≤5	10	0	0.0	5	5	50.0
Hardness	≤150	9	1	10.0	2	8	80.0
Nitrate	≤50	10	0	0.0	10	0	0.0
Iron	≤0.3	6	4	40.0	0	10	100.0
Mn	≤0.1	10	0	0.0	2	8	80.0
Cd	≤0.003	10	0	0.0	0	10	100.0

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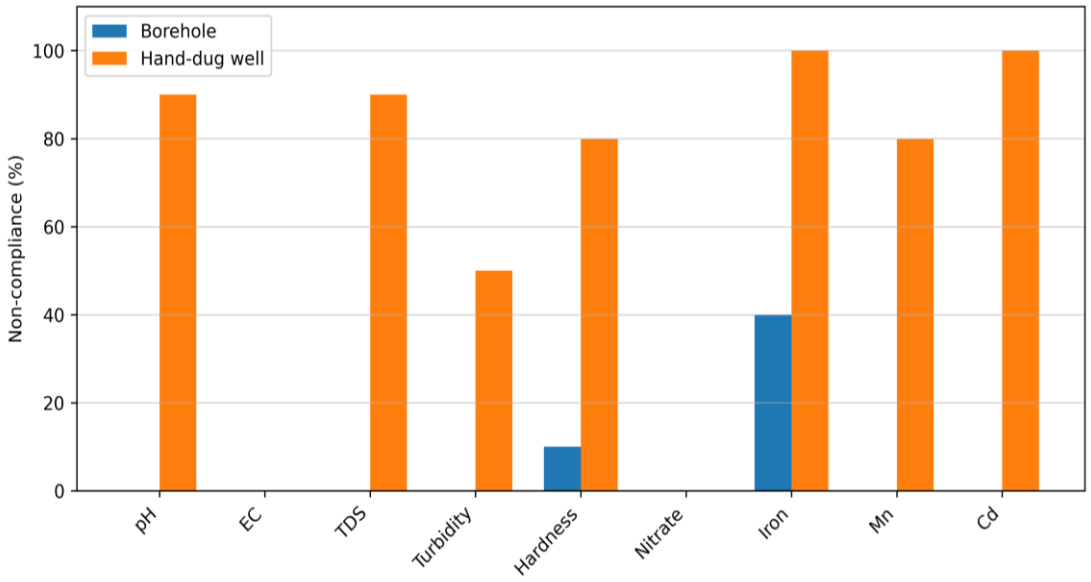


Figure 5. Percentage non-compliance of borehole and hand-dug well samples with adopted drinking-water screening limits. Higher percentages indicate a greater proportion of samples exceeding or falling outside the adopted reference values.

Statistical comparison

The statistical comparison between borehole and hand-dug well samples is presented in Table 9. Welch's t-test showed statistically significant differences between the two water-source types for all analysed parameters ($p < 0.001$). The Mann–Whitney U test also confirmed significant differences for all parameters ($p < 0.001$), supporting the robustness of the comparison despite the small sample size.

The results indicate that hand-dug wells had significantly lower pH and significantly higher EC, TDS, turbidity, hardness, nitrate, iron, manganese and cadmium concentrations than boreholes. This confirms the descriptive pattern observed in the preceding sections and shows that water-source type was an important determinant of groundwater quality in the sampled locations. The largest mean differences were observed for EC, TDS, hardness, nitrate and selected metals, indicating greater dissolved ionic content, mineralisation and contaminant burden in hand-dug wells.

Since the sample size was limited to ten samples per source type, and the dataset represents a single sampling campaign; therefore, seasonal variations in groundwater quality may not be fully captured. In addition, although cadmium was detected in all borehole samples at low concentrations ranging from 0.001 to 0.003 mg/L, confirmatory metal analysis and detailed quality-control reporting would strengthen confidence in the results. Therefore, while the statistical analysis supports clear source-related differences

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in groundwater quality, repeated seasonal sampling and confirmatory laboratory analysis are recommended to improve the reliability of the findings.

Table 9. Statistical comparison between borehole and hand-dug well water quality

Parameter	Borehole mean	Well mean	Mean difference (well – borehole)	Welch t	p-value	Mann–Whitney U	MW p-value	95% CI lower	95% CI upper
pH	6.889	6.128	-0.761	-7.211	<0.001	100.000	<0.001	-0.989	-0.533
EC	360.467	656.530	296.063	10.498	<0.001	0.000	<0.001	235.018	357.108
TDS	291.126	541.105	249.979	16.563	<0.001	0.000	<0.001	218.260	281.698
Turbidity	1.345	4.800	3.455	9.630	<0.001	0.000	<0.001	2.688	4.222
Hardness	112.414	186.924	74.510	5.312	<0.001	3.000	<0.001	44.900	104.120
Nitrate	3.198	9.774	6.576	9.481	<0.001	0.000	<0.001	5.050	8.102
Iron	0.299	0.841	0.542	7.631	<0.001	0.000	<0.001	0.388	0.696
Mn	0.051	0.168	0.117	6.825	<0.001	0.000	<0.001	0.080	0.154
Cd	0.001	0.011	0.010	10.037	<0.001	0.000	<0.001	0.008	0.013

Water Quality Index

The Water Quality Index (WQI) results are presented in Table 10 and Figure 6. In this study, the WQI was calculated using physicochemical parameters only; therefore, it represents the overall physicochemical quality of the groundwater samples and not the total metal-pollution status. The use of WQI is useful because it converts multiple water-quality variables into a single interpretive value, thereby making water-quality classification easier for comparison and decision-making (Horton, 1965; Brown et al., 1970; Tyagi et al., 2013).

Borehole WQI values ranged from 9.85 to 35.53, with a mean value of 21.24. Based on the adopted WQI classification, eight borehole samples were classified as excellent and two as good. This indicates that the borehole samples generally had acceptable physicochemical quality. The low WQI values recorded in boreholes reflect their near-neutral pH, low turbidity, moderate dissolved-solids content and generally lower nitrate concentrations. Similar studies have reported that deeper and properly constructed boreholes often show better physicochemical quality than shallow wells because they are less directly exposed to surface runoff, domestic wastewater and near-surface contamination pathways (Ighalo et al., 2021; David et al., 2024; Ishola, 2024).

In contrast, hand-dug well WQI values ranged from 56.21 to 108.90, with a mean value of 79.30. Four hand-dug wells were classified as poor, five as very poor and one as unsuitable. The poorer WQI classification of the wells was mainly influenced by lower pH, higher TDS, higher turbidity and greater hardness. These parameters contributed to the deterioration of the overall physicochemical quality of the well water. The results agree with previous groundwater studies showing that shallow hand-dug wells are more

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vulnerable to physicochemical deterioration where well protection is poor or where wells are located close to sanitation systems, runoff channels, waste-disposal points or domestic activity areas (World Health Organization, 2022; Jolaosho et al., 2024; Kayode et al., 2024).

The WQI results therefore confirm that borehole water had better overall physicochemical quality than hand-dug well water in the sampled locations. However, because metals were assessed separately using the Heavy Metal Pollution Index, the WQI results should not be interpreted alone. A sample may have acceptable physicochemical WQI but still require attention if metal concentrations exceed drinking-water guideline values. Therefore, the WQI classification should be interpreted together with the HPI results and the parameter-specific compliance assessment.

Table 10. Water Quality Index and Heavy Metal Pollution Index classification of borehole and hand-dug well samples

Sample	Source	WQI	WQI class	HPI	HPI class
BH1	Borehole	18.80	Excellent	2.53	Low/acceptable
BH2	Borehole	35.53	Good	3.21	Low/acceptable
BH3	Borehole	20.97	Excellent	34.10	Low/acceptable
BH4	Borehole	15.63	Excellent	2.88	Low/acceptable
BH5	Borehole	29.49	Good	1.79	Low/acceptable
BH6	Borehole	18.07	Excellent	99.58	Low/acceptable
BH7	Borehole	23.14	Excellent	2.37	Low/acceptable
BH8	Borehole	9.85	Excellent	2.44	Low/acceptable
BH9	Borehole	18.69	Excellent	34.58	Low/acceptable
BH10	Borehole	22.20	Excellent	1.06	Low/acceptable
W1	Hand-dug well	67.63	Poor	327.92	High
W2	Hand-dug well	85.62	Very poor	330.19	High
W3	Hand-dug well	56.21	Poor	329.39	High
W4	Hand-dug well	91.95	Very poor	325.42	High
W5	Hand-dug well	108.90	Unsuitable	326.63	High
W6	Hand-dug well	87.24	Very poor	326.44	High
W7	Hand-dug well	67.23	Poor	328.72	High

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Sample	Source	WQI	WQI class	HPI	HPI class
W8	Hand-dug well	77.11	Very poor	329.68	High
W9	Hand-dug well	65.56	Poor	648.59	High
W10	Hand-dug well	85.57	Very poor	328.08	High

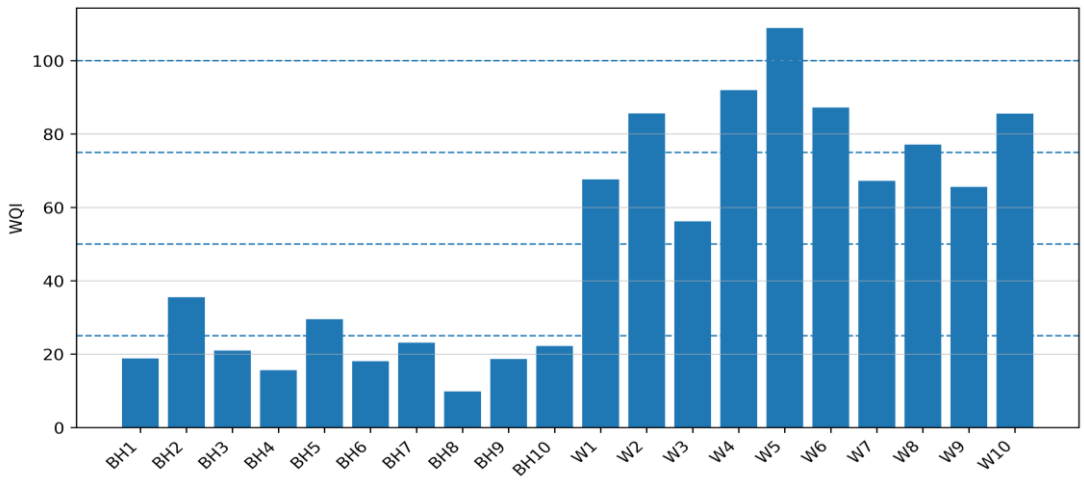


Figure 6. Water Quality Index classification of borehole and hand-dug well samples. Borehole samples were classified as excellent to good, whereas hand-dug well samples were classified as poor, very poor or unsuitable based on the adopted WQI classification scheme.

Heavy Metal Pollution Index

The Heavy Metal Pollution Index (HPI) results are presented in Table 10 and Figure 7. The HPI was calculated using the selected metals analysed in this study, namely iron, manganese and cadmium. Unlike the WQI, which summarises general physicochemical quality, the HPI provides a specific assessment of metal-related pollution. This is important because metals may have different environmental and health implications, and some metals, such as cadmium, have very low drinking-water guideline values (Mohan et al., 1996; Prasad & Bose, 2001; World Health Organization, 2022).

Borehole HPI values ranged from 1.06 to 99.58, with a mean value of 18.45. Based on the adopted HPI classification, all borehole samples were classified as low or acceptable with respect to selected-metal pollution. As shown in Figure 7, most borehole samples were far below the adopted critical HPI value of 100. However, BH6 recorded an HPI value of 99.58, which was close to the critical threshold. This suggests that although borehole samples generally had acceptable selected-metal status, BH6 should be monitored

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because small increases in metal concentration could shift the sample into the high-pollution category.

In contrast, hand-dug well HPI values ranged from 325.42 to 648.59, with a mean value of 360.11. All hand-dug wells exceeded the adopted HPI critical value of 100 and were therefore classified as having high selected-metal pollution, as illustrated in Figure 7. The high HPI values were mainly influenced by cadmium, with additional contributions from iron and manganese. W9 recorded the highest HPI value of 648.59, corresponding to the highest cadmium concentration among the well samples. Since cadmium has a very low drinking-water guideline value, even small increases in concentration can produce a large increase in HPI. Similar studies have shown that HPI is useful for identifying water sources affected by selected-metal pollution and for prioritising groundwater sources requiring monitoring or treatment (Mohan et al., 1996; Prasad & Bose, 2001; Okwesili et al., 2026; Thomas, 2026).

The HPI results show that hand-dug wells had a greater selected-metal burden than boreholes. This pattern may be associated with the shallow nature of wells, poor sanitary protection, interaction with near-surface materials, leachate migration, runoff and possible anthropogenic inputs.

The HPI results strengthen the evidence that untreated hand-dug well water in the sampled locations is less suitable for direct drinking than borehole water. While boreholes were generally within the low or acceptable HPI category, all hand-dug wells exceeded the adopted HPI threshold, indicating the need for treatment, routine metal monitoring and improved sanitary protection of shallow groundwater sources.

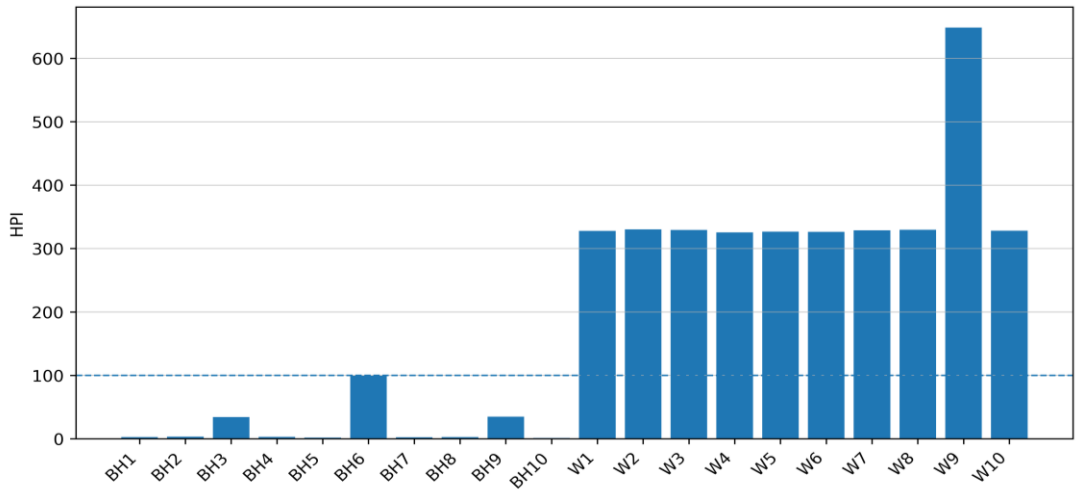


Figure 7. Heavy Metal Pollution Index of borehole and hand-dug well samples. The dashed line represents the adopted critical HPI value of 100; values above this line indicate high selected-metal pollution.

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Correlation analysis

The Pearson correlation matrix is presented in Table 11, while the correlation heatmap is shown in Figure 8. Correlation analysis was used to explore the relationships among the analysed water-quality parameters and to identify patterns of co-variation within the combined groundwater dataset. However, these relationships are exploratory and should not be interpreted as direct evidence of causation.

As shown in Table 11 and Figure 8, EC and TDS were strongly positively correlated (r = 0.91), which is expected because both parameters reflect dissolved ionic constituents in water. Strong positive correlations were also observed between TDS and cadmium (r = 0.93), TDS and nitrate (r = 0.89), and TDS and iron (r = 0.89). These relationships suggest that samples with greater dissolved-solids content also tended to have higher nitrate and selected metal concentrations. Similar associations have been reported in groundwater studies where dissolved ionic load is influenced by mineral dissolution, wastewater inputs, leachate migration and other anthropogenic activities (Jolaosho et al., 2024; Kayode et al., 2024; Akinwunmi et al., 2026).

Turbidity also showed positive correlations with EC (r = 0.85), TDS (r = 0.85), nitrate (r = 0.84) and iron (r = 0.80), indicating that samples with higher suspended matter or poorer physical quality also tended to have higher dissolved constituents and metal concentrations. This pattern may reflect the influence of runoff, poor sanitary protection, shallow contamination pathways or disturbance of particulate matter in hand-dug wells. Comparable groundwater studies have similarly linked elevated turbidity and dissolved constituents to poor source protection and increased vulnerability of shallow wells to contamination (Ighalo et al., 2021; David et al., 2024; Asemota et al., 2026).

Negative correlations were observed between pH and most other parameters, including EC (r = -0.84), TDS (r = -0.81), turbidity (r = -0.87), nitrate (r = -0.86), iron (r = -0.75), manganese (r = -0.67) and cadmium (r = -0.76). These results indicate that lower pH values were generally associated with higher dissolved ionic content and higher selected metal concentrations. This pattern is consistent with the interpretation that acidic conditions may enhance the solubility and mobility of some dissolved constituents and metals in groundwater systems (World Health Organization, 2022; Gad et al., 2024; Jolaosho et al., 2024; Ganiyu et al., 2026).

Hardness showed moderate to strong positive correlations with EC (r = 0.80), TDS (r = 0.79), manganese (r = 0.80) and cadmium (r = 0.75), suggesting that mineral enrichment and dissolved-solids accumulation may partly occur together in the groundwater system. Likewise, nitrate showed positive correlations with iron (r = 0.84), manganese (r = 0.74) and cadmium (r = 0.81), which may indicate that the samples more influenced by shallow anthropogenic inputs also tended to show higher selected metal concentrations.

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The correlation analysis supports the broader interpretation that groundwater quality in the study area is influenced by a combination of physicochemical enrichment and selected-metal loading, with hand-dug wells generally occupying the more degraded end of the dataset. Nevertheless, the observed correlations should be interpreted cautiously. Because the analysis was conducted on the pooled borehole and hand-dug well dataset, some relationships may partly reflect the separation between the two source types rather than a single geochemical process. In addition, correlation does not establish causality, and more detailed hydrogeochemical and seasonal investigations would be needed to confirm the controlling mechanisms.

Table 11. Pearson correlation matrix of analysed groundwater-quality parameters

Parameter	pH	EC	TDS	Turbidity	Hardness	Nitrate	Iron	Mn	Cd
pH	1.0	-0.84	-0.81	-0.87	-0.72	-0.86	-0.75	-0.67	-0.76
EC	-0.84	1.0	0.91	0.85	0.8	0.83	0.71	0.73	0.89
TDS	-0.81	0.91	1.0	0.85	0.79	0.89	0.89	0.84	0.93
Turbidity	-0.87	0.85	0.85	1.0	0.61	0.84	0.8	0.67	0.8
Hardness	-0.72	0.8	0.79	0.61	1.0	0.59	0.61	0.8	0.75
Nitrate	-0.86	0.83	0.89	0.84	0.59	1.0	0.84	0.74	0.81
Iron	-0.75	0.71	0.89	0.8	0.61	0.84	1.0	0.72	0.81
Mn	-0.67	0.73	0.84	0.67	0.8	0.74	0.72	1.0	0.79
Cd	-0.76	0.89	0.93	0.8	0.75	0.81	0.81	0.79	1.0

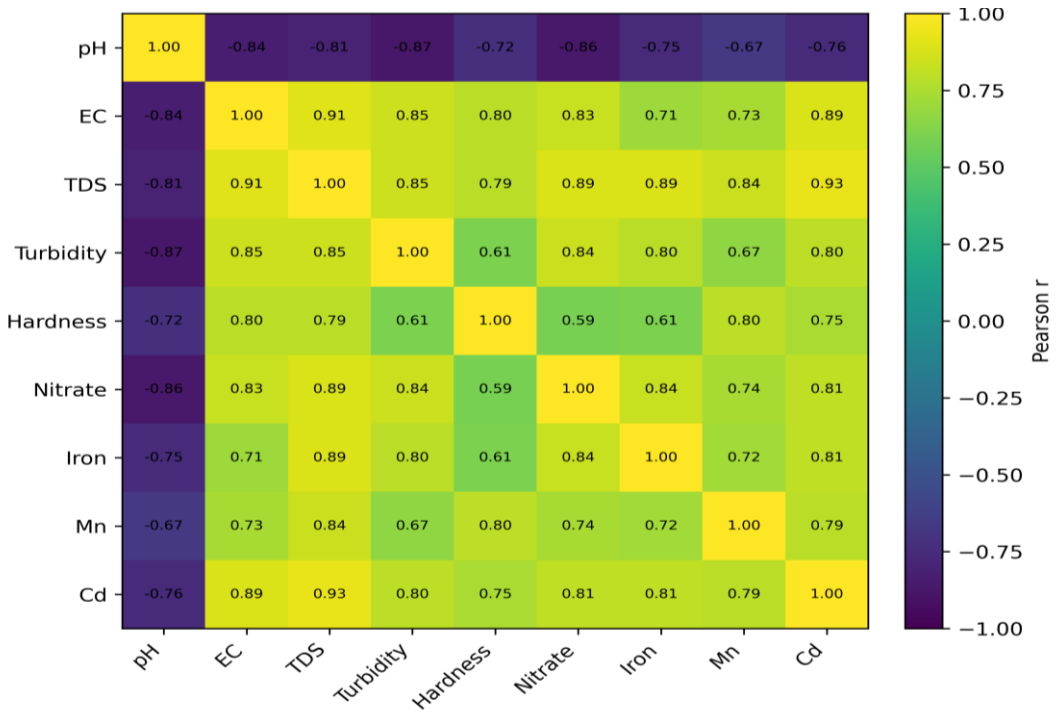


Figure 8. Pearson correlation heatmap of analysed groundwater-quality parameters. Positive correlations indicate that parameters tend to increase together, whereas

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negative correlations indicate that one parameter tends to decrease as the other increases.

Public-health and environmental implications

The findings have important implications for domestic water use and groundwater management in the sampled locations. Although most borehole samples showed better overall quality than hand-dug wells, the results indicate that groundwater safety should not be assumed solely on the basis of source type. Boreholes were generally less contaminated, but iron exceedance in some borehole samples shows that periodic monitoring remains necessary. In contrast, hand-dug wells showed higher levels of physicochemical deterioration and selected-metal contamination, indicating greater vulnerability to shallow contamination pathways.

Elevated TDS, turbidity, hardness, iron and manganese may affect water acceptability, taste, colour, staining, scaling and household use. While these parameters are not always associated with immediate toxic effects at the concentrations observed, they can reduce consumer acceptability and may encourage households to seek alternative water sources of uncertain quality. High turbidity may also indicate poor sanitary protection and possible entry of suspended particles or runoff, although microbial contamination was not assessed in this study. Therefore, the turbidity results should be interpreted as an indication of vulnerability rather than direct microbiological risk evidence.

Cadmium exceedance in all hand-dug well samples represents the most important public-health concern in this study. Unlike hardness, TDS, iron and manganese, cadmium has greater toxicological significance and a very low drinking-water guideline value. Its consistent detection above the adopted guideline limit suggests that untreated hand-dug well water may not be suitable for direct drinking without further verification and treatment. However, because cadmium occurs at trace levels, the interpretation should be supported by confirmatory analysis, method detection limits, reagent blanks, calibration checks and recovery data before final public-health decisions are made.

From an environmental-management perspective, the poorer quality of hand-dug wells suggests the need for improved wellhead protection, proper covering, sanitary lining, drainage control around wells and adequate setback distances from septic tanks, pit latrines, refuse dumps, animal pens and runoff channels. Routine monitoring should prioritise pH, turbidity, TDS, nitrate, iron, manganese and cadmium, while microbial testing should be included in future assessments because shallow wells are particularly vulnerable to faecal contamination.

The results indicate that hand-dug wells in the sampled locations require treatment and routine monitoring before use for drinking. Boreholes appear to be a safer groundwater

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source relative to hand-dug wells, but they should also be monitored periodically, especially for iron and other metals. These findings agree with previous studies that emphasised the influence of poor source protection, sanitation conditions, local geology and anthropogenic activities on groundwater quality in Nigeria and other groundwater-dependent settings (Ighalo et al., 2021; World Health Organization, 2022; David et al., 2024; Ishola, 2024; Jolaosho et al., 2024; Kayode et al., 2024).

Recommendations

Based on the findings, routine monitoring of groundwater sources in Itori is recommended, with priority given to hand-dug wells. Monitoring should include pH, EC, TDS, turbidity, hardness, nitrate, iron, manganese, cadmium and microbial indicators. Hand-dug wells should be properly covered, lined and protected from surface runoff, refuse-disposal points, septic tanks, pit latrines and domestic wastewater channels. Water from hand-dug wells should be treated before drinking, particularly where turbidity, iron, manganese or cadmium exceed guideline values. Boreholes should also be monitored periodically because some borehole samples exceeded the iron screening value.

Future studies should include wet- and dry-season sampling, microbial analysis, additional trace metals, hydrogeochemical characterisation and human-health risk assessment. Confirmatory cadmium analysis using strong quality-control procedures is especially recommended because cadmium exceeded the adopted guideline value in all hand-dug well samples.

Conclusion

This study compared the quality of borehole and hand-dug well water in Itori, Ewekoro Local Government Area, Ogun State, Nigeria, using physicochemical parameters, selected metal concentrations, the Water Quality Index (WQI) and the Heavy Metal Pollution Index (HPI). The results revealed a clear difference between the two groundwater-source types. Borehole water generally showed better quality, with near-neutral pH and lower levels of dissolved solids, turbidity, hardness, nitrate and selected metals. In contrast, hand-dug wells showed greater deterioration, characterised by more acidic conditions, higher dissolved ionic content, increased turbidity, greater hardness, higher nitrate levels and elevated metal concentrations.

The physicochemical WQI classified borehole samples as excellent to good, whereas hand-dug well samples were classified as poor, very poor or unsuitable. The HPI results further showed that selected-metal pollution was substantially higher in hand-dug wells than in boreholes, mainly due to cadmium and iron exceedances. Although boreholes

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appeared relatively safer, iron exceedance in some borehole samples indicates that borehole water should not be assumed to be risk-free without periodic monitoring.

The untreated hand-dug well water in the sampled locations is not recommended for direct drinking without appropriate treatment and routine monitoring. Improved well construction, proper lining and covering, sanitary setback from septic tanks, pit latrines, refuse dumps and drainage channels, and regular water-quality surveillance are recommended. Confirmatory cadmium analysis should be prioritised because cadmium exceeded the adopted guideline value in all hand-dug well samples.

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