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Integrated Assessment of Groundwater Quality Using Water Quality Index and Physicochemical Characterization: Implications for Human Health and Sustainable Water Treatment in selected Settlements of Ibadan Metropolis, Nigeria.

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ABSTRACT
Groundwater remains a major source of domestic water supply in rapidly urbanizing environments. This study assessed groundwater quality in ten selected settlements within Ibadan metropolis using physicochemical parameters, heavy metal analysis, and Water Quality Index (WQI) evaluation. Ten groundwater samples were analyzed for physical parameters (pH, electrical conductivity, total dissolved solids), chemical parameters (bicarbonate, total hardness, total alkalinity, fluoride, chloride), and heavy metals (Mn, Fe, Zn, Cr, Ni). Results were compared with WHO and SON drinking water standards. pH values ranged from 6.77–7.75 (mean 7.24), within permissible limits. Electrical conductivity and total dissolved solids exceeded limits at Agbowo, Sango, Obaleye, and Basorun. Fluoride was deficient across all samples (0–0.09 mg/L), below the recommended 0.8–1.0 mg/L. Heavy metal analysis revealed that chromium exceeded the 0.05 mg/L limit at eight of ten points (80%, highest 0.776 mg/L), while nickel exceeded the 0.02 mg/L limit at all ten points (100%, range 0.031–0.293 mg/L). Iron exceeded limits at five points (highest 1.85 mg/L). WQI values ranged from 170 (Polytechnic Ibadan) to 1035 (Ojoo-Iwo), classifying groundwater as poor to toxic. Chromium and nickel were identified as the dominant contaminants driving groundwater unsuitability. The study concludes that groundwater in the study area is unsuitable for drinking without treatment and recommends low-cost activated carbon filtration for heavy metal removal.

Keywords: *Groundwater quality; Water Quality Index; Heavy metals; Chromium; Nickel; Ibadan metropolis*

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I. INTRODUCTION

Groundwater constitutes a critical freshwater resource supporting domestic, agricultural, and industrial demands globally. Approximately 2.5 billion people depend exclusively on groundwater for their daily water supply, and in many developing countries, groundwater accounts for over 50% of domestic water use (Gleeson et al., 2012; United Nations World Water Assessment Programme, 2022; World Health Organization [WHO], 2022). The reliability of groundwater, particularly in regions with seasonal rainfall, makes it an essential buffer against climate variability and water scarcity (MacDonald &Calow, 2009).

In developing urban centers, groundwater exploitation has increased significantly due to population growth, inadequate public water supply infrastructure, and the intermittent nature of municipal water services (Foster & Chilton, 2003; Adelana et al., 2008). Nigeria, with an urbanization rate of approximately 4.3% per annum, has seen its urban population more than double in the past two decades (National Population Commission, 2019). This rapid urbanization has placed immense pressure on existing water infrastructure, compelling households to seek alternative sources, with groundwater from boreholes and hand-dug wells being the most common alternative (Olayinka et al., 2017).

Ibadan, the largest city in West Africa by geographical area, has experienced rapid urbanization without commensurate investment in water infrastructure (Olajuyigbe&Adegboyega, 2016). The city, with an estimated population exceeding 3.5 million and an area of approximately 3,080 km², relies on a combination of municipal supply from the Eleyele and Asejire dams and numerous private boreholes and wells (Oyo State Government, 2018). However, municipal supply meets less than 40% of demand, forcing many households to rely on boreholes and hand-dug wells (Akinwumiju&Oloruntade, 2017). Consequently, groundwater quality assessment has become imperative for public health protection and environmental management.

Despite the natural filtration capacity of geological formations, groundwater quality is increasingly threatened by anthropogenic pollution and geogenic contamination (Li & Wu, 2019). In urban areas like Ibadan, sources of contamination include improper waste disposal, industrial effluents, septic tank leakage, automobile workshop discharges, and urban runoff (Adesogan et al., 2018; Oyelude&Yakubu, 2017). The basement complex geology of Ibadan, consisting predominantly of granite, gneiss, and schist, also contributes geogenic contaminants through mineral dissolution (Jones & Hockey, 1964; Oloruntola&Adeyemo, 2020).

Groundwater quality is controlled by hydrogeological conditions and influenced by physical, chemical, and geochemical interactions within the subsurface environment. Parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, hardness, bicarbonate, fluoride, and chloride are commonly used to evaluate groundwater suitability for human consumption (WHO, 2022). Variations in these parameters may indicate mineral dissolution, groundwater recharge characteristics, and contamination pathways. While physicochemical assessment provides insight into groundwater composition, heavy metals remain among the most critical contaminants because of their persistence, toxicity, and ability to accumulate in biological systems.

Heavy metals including iron (Fe), manganese (Mn), zinc (Zn), chromium (Cr), and nickel (Ni) may enter groundwater through natural weathering processes, urban runoff, industrial discharge, vehicle-related activities, and groundwater–rock interactions (Adesogan et al., 2018). Among these contaminants, chromium and nickel present significant public health concerns. Chromium (VI) has been classified as carcinogenic to humans and is associated with respiratory disorders, skin irritation, and organ toxicity (International Agency for Research on Cancer [IARC], 2012). Prolonged exposure to elevated nickel concentrations has also been linked with neurological disorders, reproductive effects, and increased cancer risk (WHO, 2005).

To simplify groundwater quality evaluation and support decision-making, Water Quality Index (WQI) has become a widely adopted assessment tool. WQI integrates multiple water quality parameters into a single numerical value that reflects overall suitability for intended use and allows comparison across locations (Tyagi et al., 2013). The approach has proven effective for identifying contamination hotspots and guiding water resource management interventions.

Despite increasing dependence on groundwater within Ibadan metropolis, integrated studies combining physicochemical assessment, heavy metal evaluation, and Water Quality Index analysis remain limited across multiple settlements. Therefore, this study assesses groundwater quality in selected settlements of Ibadan metropolis using physicochemical characterization, heavy metal analysis, and WQI. The study aims to identify dominant contaminants influencing groundwater quality, evaluate implications for human health, and propose sustainable treatment strategies for improving groundwater safety.

II. MATERIALS AND METHODS

2.1 Study Area and Sampling Points

Ten sampling points (A1–A10) were selected representing University of Ibadan community, Agbowo, The Polytechnic Ibadan community, Akobo, Ashi, Sango, Adogba,Ojoo-Iwo, Obaleye, and Basorun as shown in Figure 1.

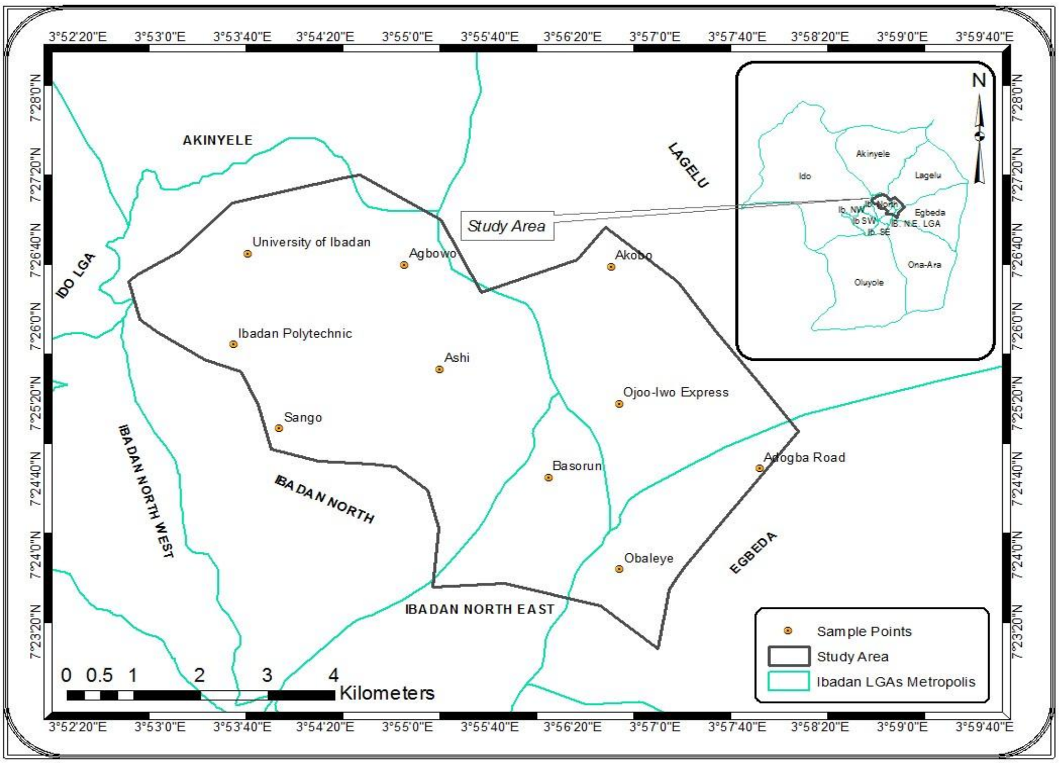

Figure 1: Study Area showing sampling points (Source: Author's production, 2019)

2.2 Sample Collection and Analysis

Groundwater samples were collected from the selected sampling locations during the dry season to minimize seasonal variations and obtain representative groundwater quality conditions. Sample collection, preservation, and laboratory procedures were carried out in accordance with established protocols outlined in the Standard Methods for the Examination of Water and Wastewater developed by the American Public Health Association (APHA, 2017). Prior to collection, sampling containers were properly cleaned and rinsed to prevent cross-contamination as shown in Figure 2. Samples designated for heavy metal analysis were collected in acid-washed polyethylene containers and preserved immediately after collection to maintain sample integrity.

The groundwater samples were analyzed for selected physical, chemical, and heavy metal parameters. Physical and chemical parameters examined included pH, electrical conductivity (EC), total dissolved solids (TDS), bicarbonate (HCO_3^-), total hardness, total alkalinity, fluoride (F^-), and chloride (Cl^-) as shown in Figure 3. Heavy metals analyzed included manganese (Mn), iron (Fe), zinc (Zn), chromium (Cr), and nickel (Ni). Measurements of physical and chemical parameters were conducted using standard laboratory analytical procedures, while heavy metal concentrations were determined using Atomic Absorption Spectrophotometry (AAS) following APHA Standard Method 3111B (APHA, 2017). The analytical results obtained were subsequently evaluated against the permissible limits specified in the World Health Organization Guidelines for Drinking-water Quality(WHO, 2022) and the Nigerian Standard for Drinking Water Quality(SON, 2015*)* to determine groundwater suitability for domestic consumption.

Figure 2: Collected Samples for Examination

Figure 3: AAS Machine Model: 210/211 VGP (Buck Scientific Atomic Absorption Spectrophotometer).

2.3 Water Quality Index Computation

The suitability of groundwater for drinking purposes was evaluated using the Weighted Arithmetic Water Quality Index (WQI) method**,** which integrates multiple water quality parameters into a single numerical value that represents the overall quality status of water for human consumption. The method provides a simplified approach for interpreting complex hydro chemical datasets and has been widely applied in groundwater quality assessment studies (Brown et al., 1970; Tyagi et al., 2013).The Water Quality Index was computed using Equation (1):

$$\mathbf{WQI = \Sigma (Q_i \times W_i) / \Sigma W_i} \quad (1)$$

Where
Q_i = quality rating,
W_i = unit weight.

The calculated WQI values were interpreted using established classification categories adapted from Brown et al. (1970), as presented in Table 1.

Table 1: Water Quality Index Classification

WQI Range	Water Quality Status
< 50	Excellent
50–100	Good
100–200	Poor
200–300	Very Poor
> 300	Unsuitable for Drinking

2.4 Drinking Water Quality Standards

The selected physicochemical and heavy metal parameters were evaluated against permissible drinking water guideline values recommended by the World Health Organization (WHO, 2011) and the Nigerian Standard for Drinking Water Quality issued by the Standards Organization of Nigeria (SON, 2015). These standards served as benchmark values for assessing groundwater suitability and for computing the Water Quality Index as depicted in Table 2.

Table 2: Drinking Water Guideline Values for Selected Parameters Source: Adapted from WHO (2011) and SON (2015).

S/N	Parameter	Unit	Permissible Standard	Reference
1	pH	–	6.5–8.5	WHO/SON
2	Total Dissolved Solids (TDS)	mg/L	500	WHO/SON
3	Electrical Conductivity (EC)	µS/cm	1000	WHO/SON
4	Total Hardness	mg/L	150	WHO/SON
5	Bicarbonate	mg/L	300	WHO
6	Total Alkalinity	mg/L	40	WHO
7	Fluoride	mg/L	1.5	WHO/SON
8	Chloride	mg/L	250	WHO/SON
9	Iron (Fe)	mg/L	0.30	WHO/SON
10	Zinc (Zn)	mg/L	3.00	WHO/SON
11	Nickel (Ni)	mg/L	0.02	WHO/SON
12	Chromium (Cr)	mg/L	0.05	WHO/SON
13	Manganese (Mn)	mg/L	0.40 (WHO); 0.20 (SON)	WHO/SON

III. RESULTS AND DISCUSSION

3.1 Physical Parameters Analysis

In Figure 4, it can be deduced that the pH present in the groundwater within the study area all fall within the recommended value of 6.5 – 8.5 for drinking water standards by WHO, 2011 as well as that of the SON, 2007. The maximum value of 7.75 was observed at sample point A1 while point A5 showed had a minimum value of 6.77. This therefore implies that the groundwater under investigation is almost neutral with an average value of 7.24.

The pH is of great importance in determining the water's corrosive state. Generally, lower pH has an inverse relationship with higher corrosion level. However, pH is just one of a variety of corrosion-related factors. Human health is affected when the pH values are on the extremes of the measurement scale (i.e below 4.5 and above 9.5) which causes. Gastrointestinal irritation and redness of the eye (WHO, 2003).

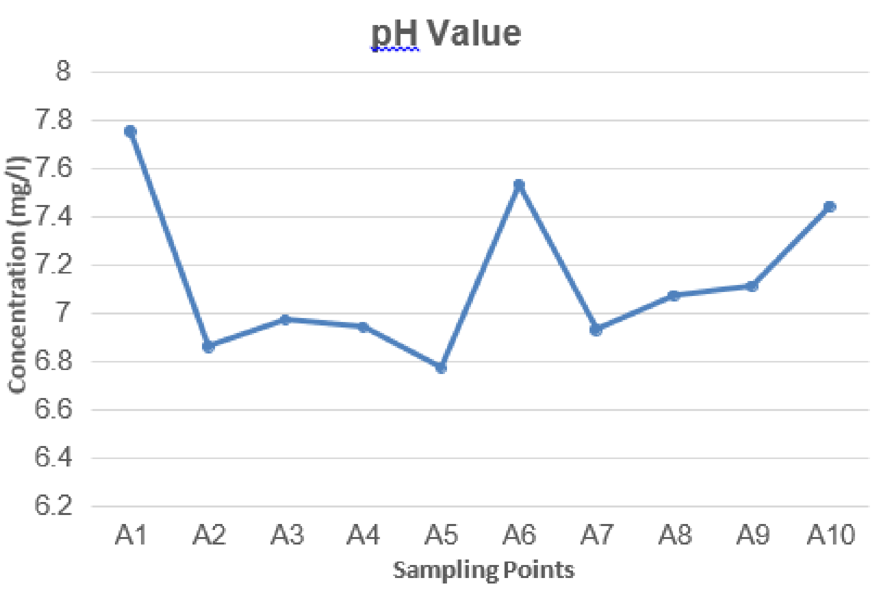

Figure 4: Distribution of Groundwater pH Values across Sampling Locations

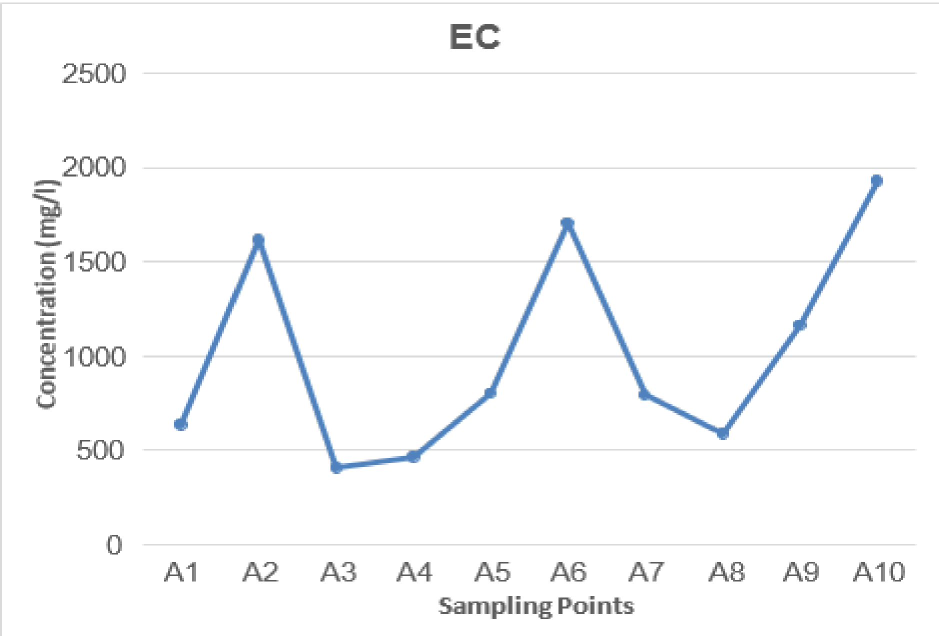

Figure 5: Distribution of Electrical Conductivity (EC) across Sampling Locations

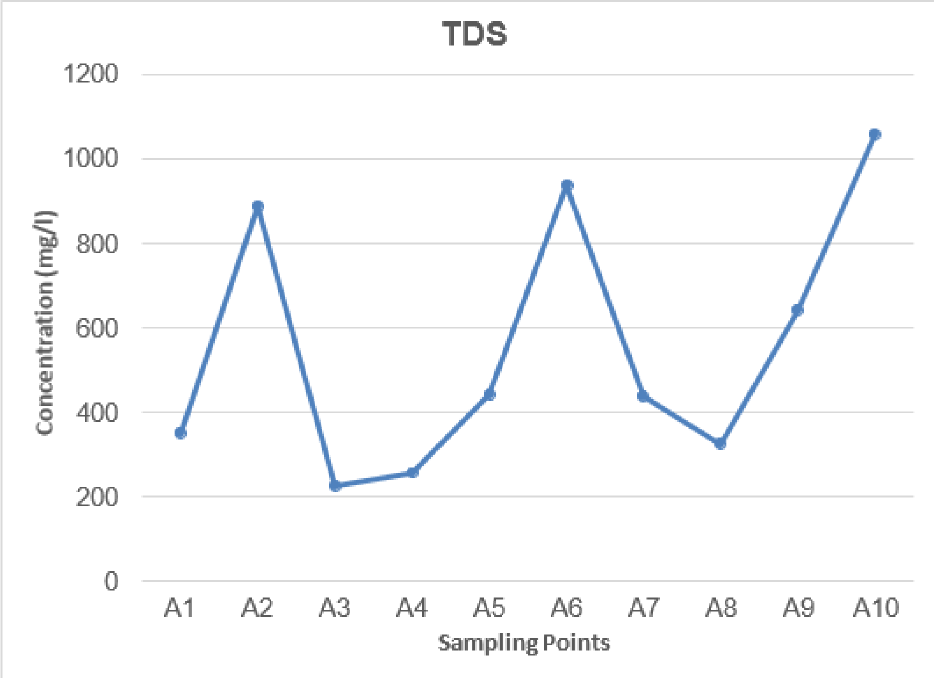

Figure 6: Distribution of Total Dissolved Solids (TDS) across Sampling Locations

Figure 5 shows that sampling point A1, A3, A4, A5, A7 and A8 are all below the maximum permissible limit of 1000 mg/l as recommended by the WHO as well as the SON standard for drinking water while points A2, A6, A9, and A10 are well above the recommended limit having the value 1617 µs/cm, 1706 µs/cm, 1167 µs/cm and 1920 µs/cm respectively.

Its ability depends on dissolved ion concentrations, ionic strength, and temperature of measurements. The dissolved ions concentration is usually measured as TDS which therefore implies that the EC concentration is directly proportional to the concentration of the TDS content in water.

Figure 6 shows that the concentration of TDS in point A2, A6, A9 and A10 lie above the permissible limits for drinking water guidelines of 500 mg/l. TDS concentration identifies the presence of inorganic salts and trace amounts of organic matter in water. This can be as a result of chemical weathering of the soil formation. Water with low TDS is generally considered as “fresh water” which is adequate for drinking as well as for irrigation.

3.2Chemical Parameters Analysis

The bicarbonate concentration presented in Figure 7 indicates that all sampled locations within the study area recorded values below the permissible limit of 300 mg/L. The highest bicarbonate concentration of 268.40 mg/L was measured at sampling point A6, whereas the lowest concentration of 73.20 mg/L was recorded at point A3. Bicarbonate is a naturally occurring constituent in groundwater, primarily derived from the dissolution and weathering of soil and geological formations. It also contributes significantly to the development of carbonate hardness in water systems.

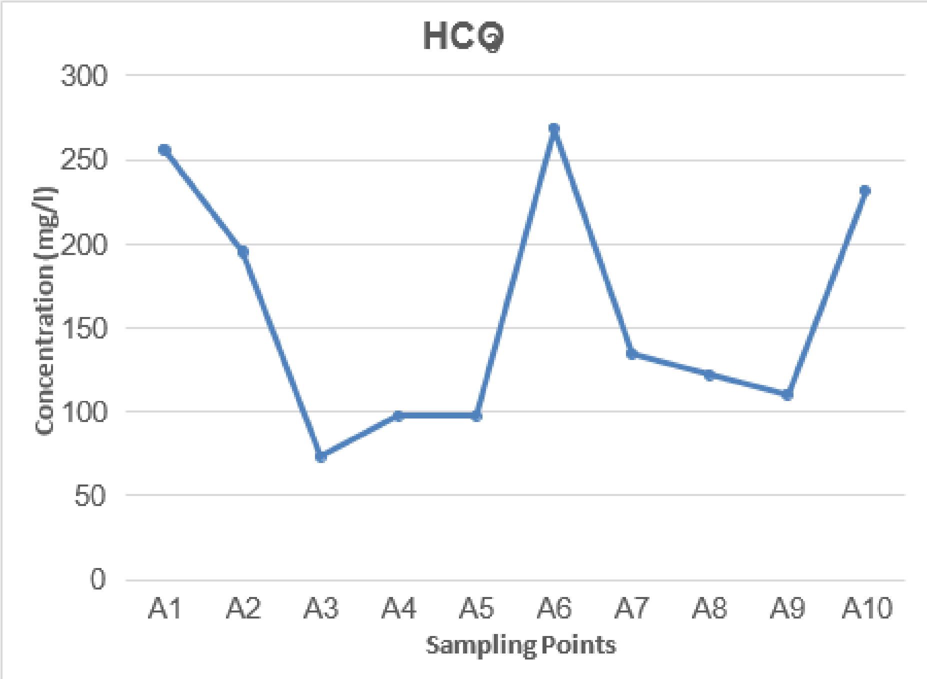

Figure 7: Spatial Variation of Bicarbonate Concentration in Groundwater Samples

The total hardness results illustrated in Figure 8 reveal that concentrations across all sampling points remained within the acceptable limit of 150 mg/L. The lowest total hardness value of 9.89 mg/L was observed at point A4, while the highest concentration of 61.41 mg/L was recorded at point A6. These findings indicate relatively low to moderate hardness levels within the study area and suggest a moderate dissolution and presence of hardness-forming ions, particularly calcium, magnesium, bicarbonates, and related mineral constituents in the groundwater system.

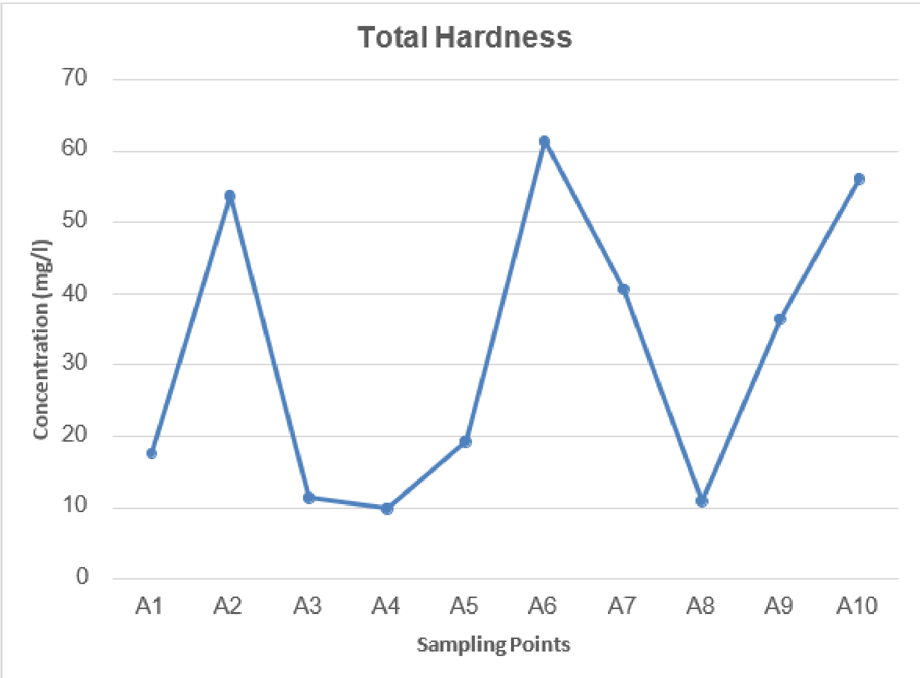

Figure 8: Total Hardness Concentration across Sampling Points

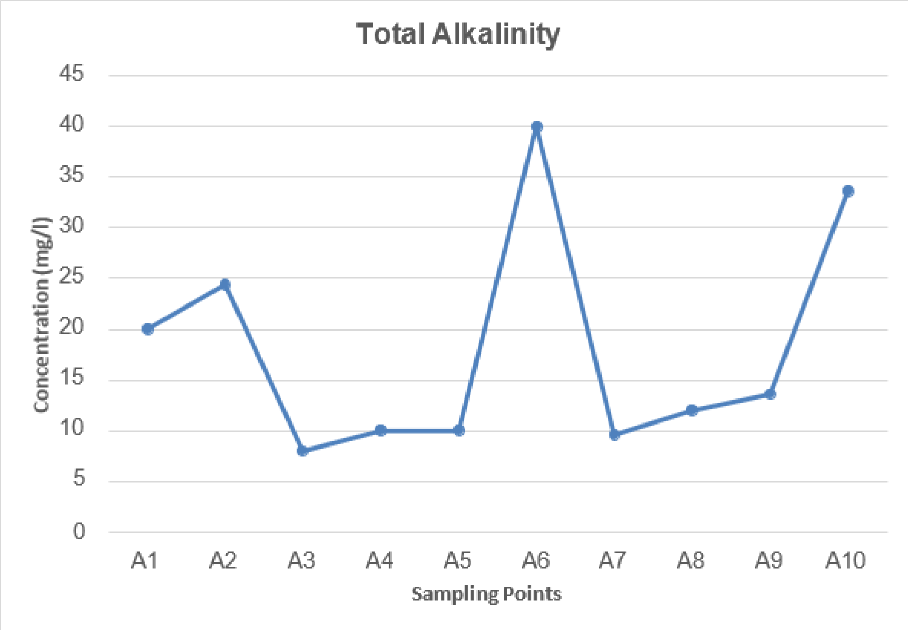

Figure 9: Total Alkalinity Concentration across Sampling Points

The total alkalinity results presented in Figure 9 indicate that all sampled locations within the study area were within the permissible drinking water quality limit of 40 mg/L. The highest concentration of 40 mg/L was recorded at sampling point A6, while the lowest concentration of 33.60 mg/L was observed at point A10. Although these values comply with the recommended standard, locations approaching the threshold require periodic monitoring to ensure continued water quality compliance. Total alkalinity plays an important role in aquatic systems by providing buffering capacity that stabilizes pH through the neutralization of acidic substances. However, excessive alkalinity may alter water chemistry by shifting pH conditions toward alkalinity (basicity).

The fluoride concentrations shown in Figure 10 reveal that all sampling points recorded values below the permissible limit. Sampling point A2 recorded no detectable fluoride concentration, whereas the highest value of 0.09 mg/L was measured at point A10. These concentrations are considerably lower than the recommended range for optimal human health. Fluoride is regarded as a critical trace element in drinking water because both deficiency and excess may result in adverse health outcomes. According to Daskalaki et al. (2019), fluoride concentrations below 0.8 mg/L may contribute to dental caries, while elevated concentrations may lead to dental fluorosis. Consequently, the recommended fluoride concentration in drinking water is generally maintained within the range of 0.8 to 1.0 mg/L to achieve beneficial health effects while minimizing associated risks.

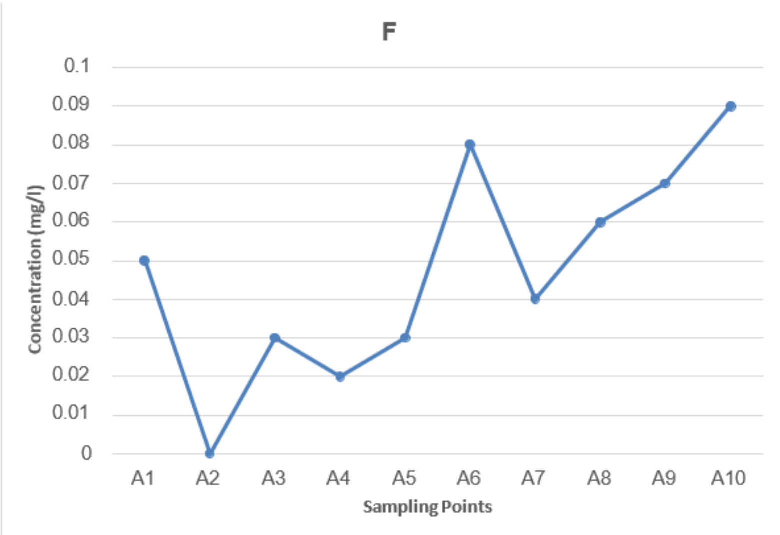

Figure 10: Spatial Distribution of Fluoride Concentration in Water Samples

The chloride concentration results presented in Figure 11 indicate variations across the sampling locations within the study area, with all measured values remaining within the permissible limit of 250 mg/L for drinking water quality. Sampling points A2 and A3 recorded relatively elevated chloride concentrations of 172.80 mg/L and 201.60 mg/L, respectively, while the lowest concentration of 36.00 mg/L was observed at another sampling location. Chloride is a naturally occurring constituent of groundwater and is commonly introduced through the dissolution of salt-bearing geological formations and soil deposits.'

The observed chloride levels suggest that groundwater within the study area has not experienced excessive chloride enrichment and remains suitable with respect to chloride standards. Nevertheless, the relatively higher concentrations recorded at A2 and A3 may reflect moderate chloride input from both natural processes and anthropogenic influences such as domestic activities, land use practices, or localized contamination sources.

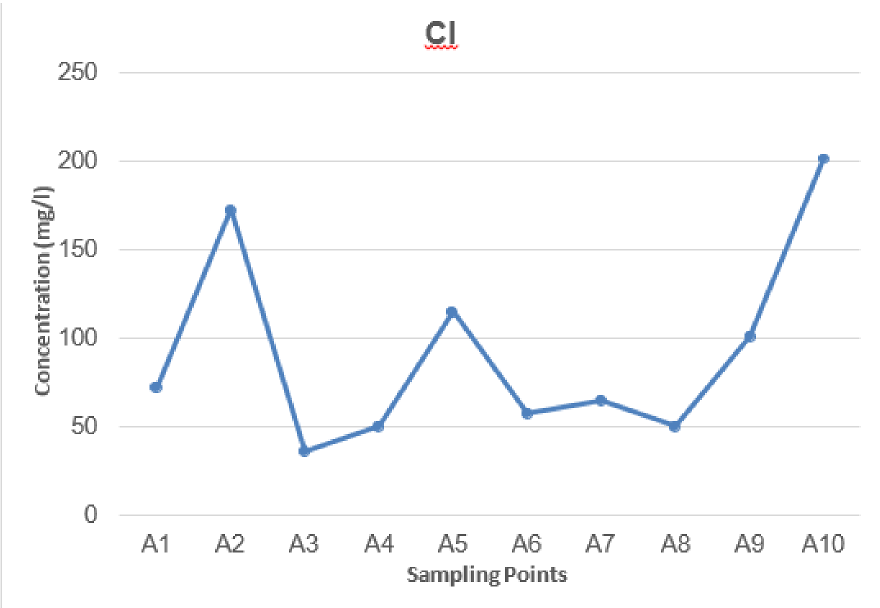

Figure 11: Distribution of Chloride Concentration in Collected Water Samples

3.3 Heavy Metals Content

The manganese results presented in Figure 12 show spatial variability across the sampling points within the study area. Sampling locations A1 and A8 recorded no detectable manganese ions, indicating absence or levels below analytical detection limits at those points. In contrast, sampling point A2 exhibited a concentration of 0.23 mg/L, which slightly exceeds the permissible limit of 0.2 mg/L for drinking water quality.

The presence of manganese in groundwater is typically associated with natural geochemical processes, particularly the dissolution of manganese-bearing crustal rocks and minerals, especially manganese in its divalent form (Mn^{2+}), as noted by Howe et al. (2004). The elevated concentration observed at A2 may therefore be linked to localized geological formations, including manganese-containing mineral deposits within the subsurface strata, potentially associated with marble formations influencing groundwater chemistry in that area.

From a health perspective, prolonged ingestion of manganese at concentrations above recommended limits is of concern. Excess exposure has been associated with toxicological effects, particularly neurological impairment and disruption of normal muscular function, as reported by Ravindra et al. (2014). Overall, while most sampling points remain within safe limits, the exceedance at A2 suggests the need for targeted monitoring of that location.

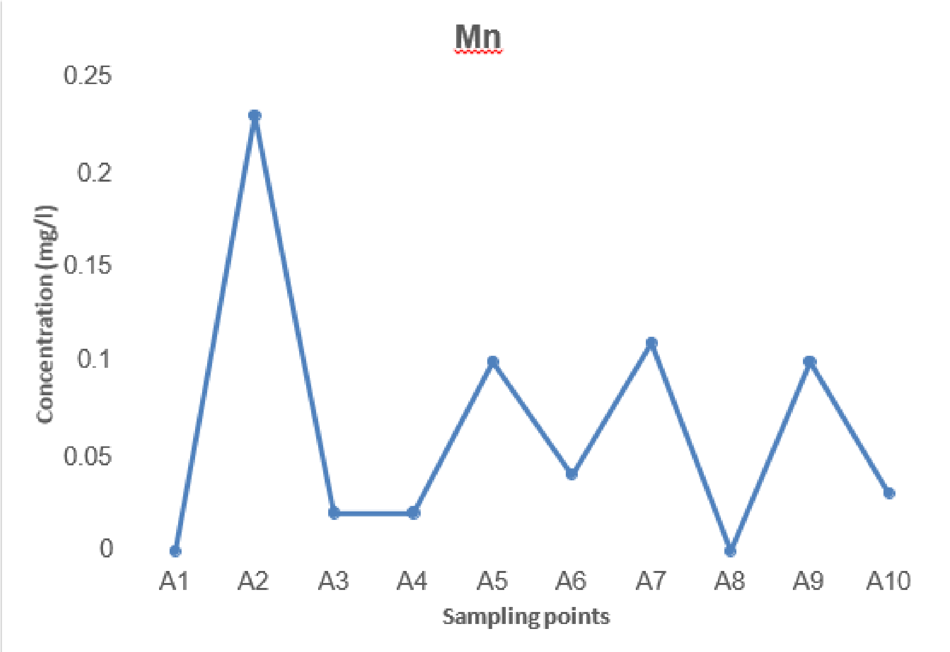

Figure 12: Variation of Manganese Concentration in the Study Area

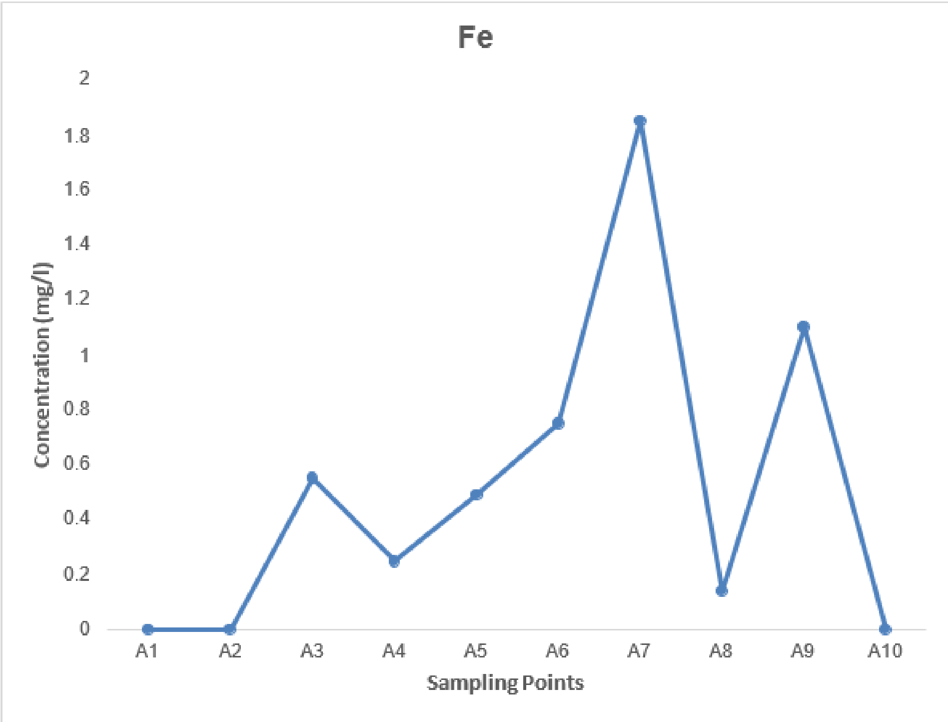

Figure 13: Iron Concentration across Sampling Points

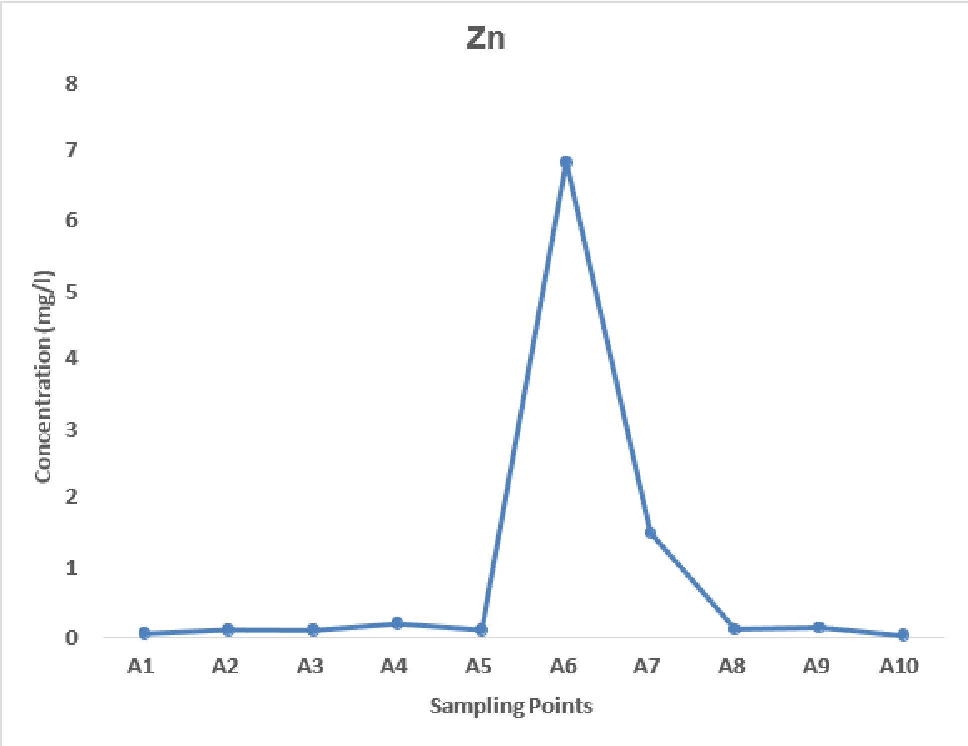

Figure 14: Zinc Concentration across Sampling Points

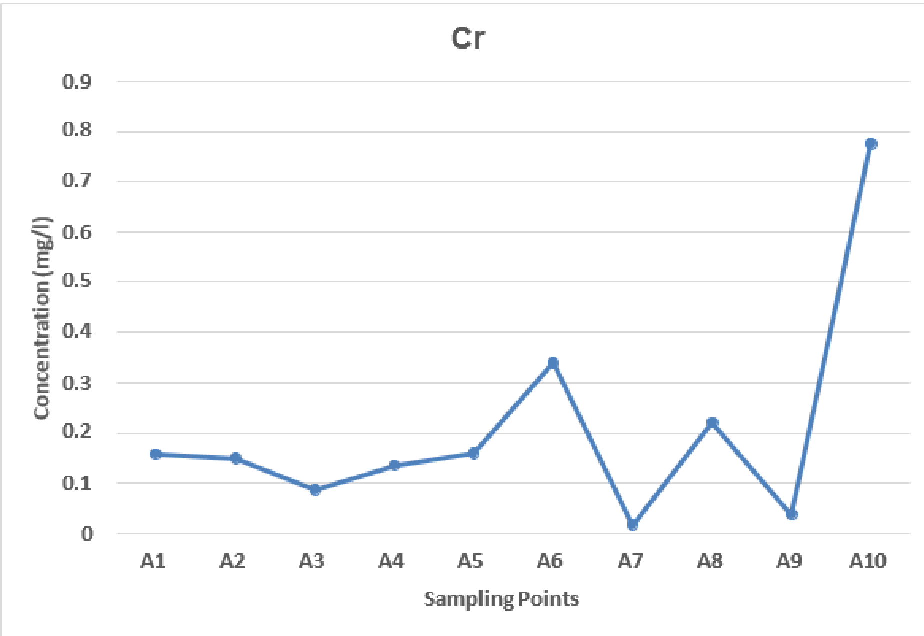

Figure 15: Chromium Concentration across Sampling Points

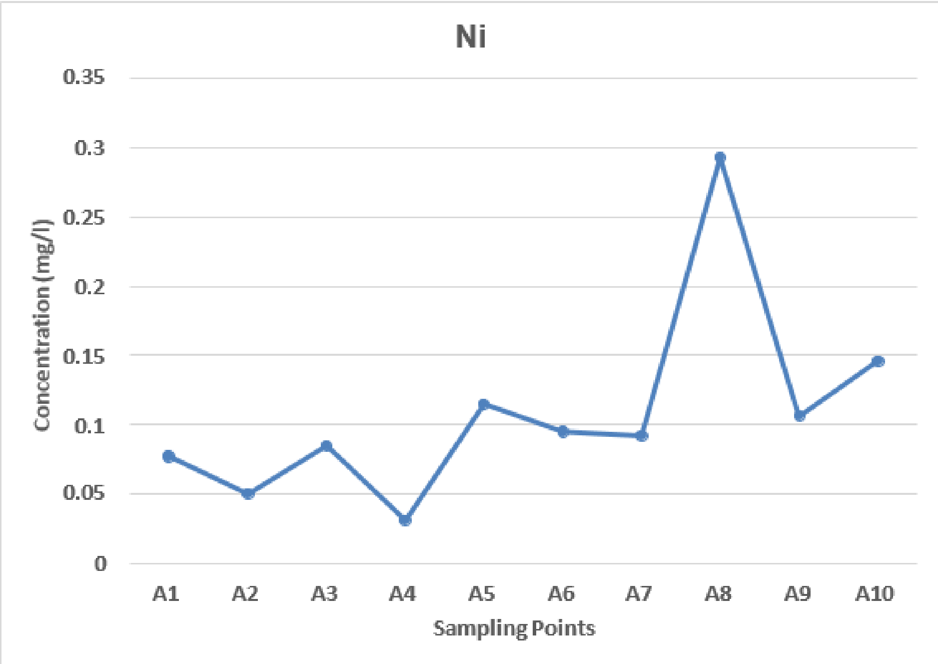

Figure 16: Nickel Concentration across Sampling Points

The iron concentration results presented in Figure 13 reveal notable spatial variability across the study area. Sampling points A1, A2, and A10 recorded no detectable iron, suggesting minimal contamination or absence of iron influence within the aquifer at these locations. In contrast, points A4 and A8 recorded concentrations of 0.25 mg/L and 0.14 mg/L respectively, values which remain within the permissible limit of 0.3 mg/L stipulated by WHO and SON drinking water standards.

However, elevated iron concentrations were observed at sampling points A3, A5, A6, A7, and A9, all of which exceeded the recommended threshold. The highest concentration of 1.85 mg/L was recorded at point A7, indicating a pronounced enrichment of iron in the groundwater at that location. This pattern suggests a higher degree of interaction between groundwater and iron-bearing geological materials within these zones. Elevated iron levels in drinking water are of concern due to their potential adverse health effects, particularly on the liver, kidneys, and cardiovascular system (Ravindra K. et al., 2014).

Similarly, the zinc concentration results in Figure 14 indicate that most sampling points fall within acceptable limits except for point A6, which recorded a concentration of 6.860 mg/L, exceeding the WHO and SON permissible limit of 3 mg/L. This elevated value may be attributed to the dissolution of zinc-rich minerals present in the surrounding soil and geological formations, which subsequently leach into the groundwater system. Such conditions may also contribute to undesirable metallic taste in the water.

Although zinc is an essential trace element in human nutrition, excessive intake can be harmful. High concentrations have been associated with adverse health outcomes such as nausea, vomiting in children, as well as disruptions in lipid metabolism leading to anaemia and cholesterol-related complications (Ravindra K. et al., 2014).

The chromium concentration results presented in Figure 15 indicate that sampling points A7 and A9 recorded values of 0.016 mg/L and 0.037 mg/L respectively, both of which remain within the permissible limit of 0.05 mg/L for drinking water. In contrast, the remaining sampling locations exhibited concentrations exceeding the recommended threshold, with point A10 recording the highest value of 0.776 mg/L. Chromium is recognized as a toxic heavy metal in groundwater systems, and prolonged exposure to elevated levels has been associated with serious health risks, including carcinogenic effects, particularly lung cancer (WHO, 2003).

Similarly, the nickel concentration results shown in Figure 16 reveal that all sampling points exceeded the recommended guideline value of 0.02 mg/L for potable water. The lowest concentration of 0.031 mg/L was recorded at point A4, while the highest concentration of 0.293 mg/L was observed at point A8. According to WHO (2005), nickel contamination in drinking water is commonly linked to leaching from metallic plumbing materials such as pipes and fittings, although natural geological sources, particularly the dissolution of nickel-bearing ore formations, also contribute significantly to its presence in groundwater.

In the context of the study area, the elevated nickel concentrations across both borehole and well water sources suggest a dominant geogenic influence arising from mineral dissolution rather than localized infrastructure contamination alone. Exposure to excessive nickel intake has been associated with a range of adverse health outcomes, including cellular damage, weight loss, carcinogenic effects, and impairment of the nervous system, as reported by Ravindra K. et al. (2014).

3.4 Water Quality Index (WQI)

WQI values ranged from 170 (Polytechnic Ibadan, A3) to 1035 (Ojoo-Iwo, A8) (Table 3). All sampling points were classified as Poor, Very Poor, or Unsuitable (Toxic). Heavy metals particularly Cr and Ni were identified as the dominant drivers of the high WQI values. The exceptionally high WQI at Ojoo-Iwo (1035) indicates severe multi-parameter contamination requiring urgent intervention.

Table 3. Water Quality Index values and classification

Sample Point	Settlement	WQI	Classification	Suitability
A3	Polytechnic Ibadan	170	Poor	Unsuitable without treatment
A4	Akobo	215	Very Poor	Requires significant treatment
A5	Ashi	218	Very Poor	Requires significant treatment
A1	UI community	235	Very Poor	Requires significant treatment
A2	Agbowo	265	Very Poor	Requires significant treatment
A7	Adogba	312	Unsuitable (Toxic)	Toxic for consumption
A9	Obaleye	328	Unsuitable (Toxic)	Toxic for consumption
A6	Sango	345	Unsuitable (Toxic)	Toxic for consumption
A10	Basorun	358	Unsuitable (Toxic)	Toxic for consumption
A8	Ojoo-Iwo	1035	Unsuitable (Toxic)	Toxic for consumption

3.5 Health Implications

The elevated concentrations of chromium (Cr) and nickel (Ni) detected in the study area present significant implications for public health. Hexavalent chromium (Cr VI) is recognized as a Group 1 carcinogen and has been strongly associated with increased risks of lung and gastrointestinal cancers (World Health Organization, 2017). In comparison, nickel is classified as a Group 2B carcinogen and has been linked to respiratory tract cancers, neurological disorders, and reproductive toxicity (International Agency for Research on Cancer, 2012).

The fact that nickel contamination was recorded across all sampling locations (100%) indicates a widespread occurrence, suggesting that no groundwater source within the study area can be considered entirely safe for long-term direct consumption without appropriate treatment. This pattern further implies a dominant geogenic influence, potentially compounded by prolonged exposure risks to the local population.

Furthermore, low fluoride concentrations may increase the risk of dental caries, as insufficient fluoride intake weakens enamel structure and reduces resistance to tooth decay (World Health Organization, 2004).

IV. CONCLUSIONS

i. The pH of groundwater samples remained within acceptable limits; however, electrical conductivity (EC) and total dissolved solids (TDS) exceeded permissible standards at Agbowo, Sango, Obaleye, and Basorun, indicating elevated ionic content in these locations.
ii. Fluoride concentrations were consistently deficient across all sampling points (0–0.09 mg/L). This widespread deficiency suggests a heightened risk of dental caries and indicates the need for controlled fluoridation.
iii. The groundwater quality is significantly impacted by heavy metals. Chromium exceeded permissible limits at approximately 80% of sampling locations, with a maximum concentration of 0.776 mg/L, while nickel exceeded regulatory limits at all sampling points, ranging from 0.031 to 0.293 mg/L.
iv. The computed WQI values ranged from 170 to 1035, classifying the groundwater as poor to toxic in quality. Chromium and nickel were identified as the principal contributors to the observed deterioration in water quality.
v. The groundwater within the study area is generally unsuitable for direct human consumption without prior treatment, although it may still be considered for certain non-potable domestic uses and irrigation purposes, subject to quality control.

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