International Journal of Advanced Engineering and Technology
www.allengineeringjournal.com
ISSN: 2456-7655
Received: 08-05-2026, Accepted: 08-06-2026, Published: 23-06-2026
Volume 10, Issue 2, 2026, Page No. 97-104

Spatial distribution patterns of physicochemical and heavy metal contaminants in urban water sources: A GIS-based study of Ibadan, Nigeria

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DOI: https://doi.org/10.66856/ijaet.2026.10.2.10041

Abstract

Spatial distribution of water contaminants is essential for targeted water quality management in urban environments. This study investigates the spatial distribution patterns of physicochemical parameters and heavy metal contaminants in water sources across ten selected settlements within Ibadan metropolis, Nigeria: University of Ibadan community, Agbowo, The Polytechnic of Ibadan community, Akobo, Ashi, Sango, Adogba, Ojoo-Iwo, Obaleye, and Basorun. A total of ten water samples were collected and analyzed for pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, bicarbonate, total alkalinity, fluoride, chloride, manganese, iron, zinc, chromium, and nickel. Geographic Information System (GIS) techniques specifically inverse distance weighting (IDW) interpolation were employed to generate spatial distribution maps for each parameter. Results revealed that physicochemical parameters (pH, EC, TDS, hardness, alkalinity, chloride, and fluoride) exhibited relatively uniform spatial distribution across the study area, with all values falling within WHO and SON permissible limits for drinking water. In contrast, heavy metals particularly chromium (Cr) and nickel (Ni) showed marked spatial heterogeneity and significantly elevated concentrations. Chromium ranged from 0.08 to 0.27 mg/L (permissible limit: 0.05 mg/L), while nickel ranged from 0.04 to 0.18 mg/L (permissible limit: 0.02 mg/L). Hotspots of Cr and Ni contamination were identified in Ojoo-Iwo (Cr: 0.27 mg/L, Ni: 0.18 mg/L) and The Polytechnic of Ibadan environs (Cr: 0.19 mg/L, Ni: 0.12 mg/L), corresponding to the highest Water Quality Index (WQI) values (1035 and 170 respectively). The contrasting spatial patterns uniform physicochemical parameters versus clustered heavy metal hotspots suggest different contamination sources: geogenic or diffuse sources for physicochemical parameters versus localized anthropogenic sources (industrial discharge, illegal dumping, or landfill leachate) for heavy metals. This study concludes that GIS-based spatial analysis is an effective tool for identifying pollution hotspots in urban water systems and recommends targeted remediation in high-risk zones rather than uniform city-wide interventions.

Keywords: Spatial distribution, heavy metal contamination, Ibadan metropolis, urban water quality, chromium, nickel

Introduction

Ibadan, the largest city in West Africa by geographical area, has experienced rapid urbanization without commensurate investment in water infrastructure [1]. Consequently, many households rely on alternative water sources including boreholes, wells, and surface water bodies, which are vulnerable to contamination from various anthropogenic activities [2]. Water quality assessment traditionally relies on point-specific sampling and laboratory analysis. While this approach provides accurate data at sample locations, it fails to reveal the spatial continuity of contamination or identify geographic patterns that could inform targeted interventions [3].

Geographic Information Systems (GIS) offer a powerful solution to this limitation by enabling spatial interpolation of point data to predict contaminant concentrations at unsampled locations and generate continuous surface maps [4]. GIS has been increasingly applied in water quality research globally. Common applications include: mapping contaminant distribution across aquifers or watersheds [5]; identifying pollution hotspots and potential source areas [6]; assessing suitability of water for drinking, irrigation, or industrial use [7]; and supporting regulatory decisions by visualizing exceedances of permissible limits [8]. In Nigeria, GIS-based water quality studies remain limited, particularly in Ibadan where most research has focused on point-specific contamination without spatial analysis [9, 10]. This study addresses that gap.

The key contaminants in Ibadan's urban water sources include physicochemical parameters (pH, EC, TDS, hardness, alkalinity, chloride, fluoride) and heavy metals (manganese, iron, zinc, chromium, nickel) [11]. While physicochemical parameters primarily affect aesthetic quality (taste, appearance) and pipe corrosion, heavy metals especially chromium and nickel pose significant health risks including carcinogenicity, nephrotoxicity, and neurotoxicity [12]. Chromium (Cr) occurs in two valence states: trivalent Cr (III), which is relatively non-toxic, and hexavalent Cr (VI), which is classified as a Group 1 human carcinogen [13]. Nickel (Ni) is associated with respiratory tract cancers and allergic dermatitis [14]. The WHO guideline values are 0.05 mg/L for total chromium and 0.02 mg/L for nickel [15]. Ibadan metropolis (approximately 3,080 km², population >3.5 million) presents an ideal case study due to heterogeneous land use (residential, commercial, industrial, educational institutions); variable water source types (municipal supply, boreholes, wells); and a documented history of waste disposal issues and industrial activities [16]. The ten selected settlements represent different urban typologies: university communities (UI, Poly Ibadan), high-density residential (Agbowo, Sango, Basorun), middle-income (Akobo, Ashi), and areas near known waste disposal sites (Ojoo-Iwo, Adogba, Obaleye). The primary objective of this study is to characterize and map the spatial distribution patterns of physicochemical parameters and heavy metal contaminants in water sources across ten settlements in Ibadan metropolis using GIS.

Materials and Methods

1. Study Area Description

Ibadan is located in Oyo State, southwestern Nigeria, at coordinates approximately 7°22′39″N and 3°54′21″E. The climate is tropical wet and dry (Köppen: Aw), with mean annual temperature of 26.5°C and mean annual rainfall of 1,250 mm. The geology is predominantly Precambrian basement complex rocks (granite, gneiss, schist) with weathered overburden serving as shallow aquifers [17].The ten selected settlements are described in Table 1.

Table 1: Description of sampling locations

Settlement	Coordinates (approx.)	Land use type	Population density	Proximity to known pollution source
University of Ibadan (UI) community	7°26′N, 3°54′E	Institutional/residential	Medium	Moderate
Agbowo	7°27′N, 3°53′E	High-density residential	High	Near major road
The Polytechnic Ibadan community	7°27′N, 3°53′E	Institutional/residential	Medium	Near industrial area
Akobo	7°24′N, 3°55′E	Middle-income residential	Medium	Low
Ashi	7°23′N, 3°55′E	Middle-income residential	Medium	Low
Sango	7°29′N, 3°53′E	High-density commercial/residential	Very high	Major transport hub
Adogba	7°25′N, 3°54′E	Mixed residential	Medium	Near landfill
Ojoo-Iwo	7°28′N, 3°52′E	Residential/rural-urban fringe	Low	Near waste disposal site
Obaleye	7°22′N, 3°54′E	Mixed residential/commercial	Medium	Near drainage channel
Basorun	7°25′N, 3°53′E	High-density residential	High	Low

2. Sample Collection

Sampling protocol: Ten water samples (one per settlement) were collected during the dry season (February–March 2024) to minimize dilution effects from rainfall. At each location, samples were collected from the primary drinking water source used by households (borehole or hand-dug well).

Collection procedure:

a. Containers: 1.5 L acid-washed polyethylene bottles (soaked in 10% HNO_3 for 24 hours, rinsed thrice with deionized water)
b. Pre-cleaning: Containers rinsed three times with source water before filling
c. Collection: Samples taken from a depth of 0.5 m below surface after pumping/flushing for 5 minutes
d. Preservation: For heavy metal analysis, samples acidified to pH <2 with ultrapure HNO_3 (1 mL per liter)
e. Transport: Samples stored in insulated coolers at 4°C and transported to laboratory within 6 hours
f. Chain of custody: Standard protocol maintained with signed records

Field measurements: pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in situ using a calibrated multi-parameter probe (Hanna HI9829). Each measurement was performed in triplicate.

3. Laboratory Analysis

Physicochemical parameters (APHA Standard Methods, 23rd edition) [18]

Parameter	Method	APHA reference	Instrument	Precision
pH	Electrometric	4500-H^+ B	Meter (Hanna HI9829)	±0.01
Electrical conductivity (EC)	Conductivity	2510 B	Meter (Hanna HI9829)	±1 µS/cm
Total dissolved solids (TDS)	Gravimetric	2540 C	Drying oven, analytical balance	±2 mg/L
Total hardness	EDTA titrimetric	2340 C	Burette	±2 mg/L as $CaCO_3$
Bicarbonate (HCO_3^-)	Titration (H_2SO_4)	2320 B	Burette	±1 mg/L
Total alkalinity	Titration (H_2SO_4)	2320 B	Burette	±1 mg/L as $CaCO_3$
Fluoride (F^-)	Ion-selective electrode	4500-F^- C	ISE meter	±0.02 mg/L
Chloride (Cl^-)	Argentometric ($AgNO_3$)	4500-Cl^- B	Burette	±0.5 mg/L

Heavy metals (after acid digestion with HNO_3/HCl, 3:1 v/v):

Metal	Method	Instrument	Detection limit	Wavelength/模式
Manganese (Mn)	Flame AAS	Agilent 240FS AA	0.01 mg/L	279.5 nm
Iron (Fe)	Flame AAS	Agilent 240FS AA	0.02 mg/L	248.3 nm
Zinc (Zn)	Flame AAS	Agilent 240FS AA	0.005 mg/L	213.9 nm
Chromium (Cr)	Graphite furnace AAS	Agilent 240Z AA	0.001 mg/L	357.9 nm
Nickel (Ni)	Graphite furnace AAS	Agilent 240Z AA	0.001 mg/L	232.0 nm

Quality Control

a. Calibration standards prepared from certified reference materials (Merck, Germany)
b. Blank samples (deionized water) analyzed every 10 samples
c. Duplicate analysis for 20% of samples (relative percent difference <5%)
d. Certified reference material (NIST 1643f) recovery: 95–105% for all metals

4. Data Analysis

Descriptive statistics: Mean, standard deviation, minimum, maximum, and coefficient of variation (CV) calculated for each parameter across the ten locations. CV <20% considered low variability (uniform distribution), CV >30% considered high variability (clustered distribution).

Comparison with standards: Each parameter compared with WHO Guidelines for Drinking-water Quality (4th edition, 2017) and SON Nigerian Standard for Drinking Water Quality (NIS 554:2015).

5. GIS Spatial Analysis

Software: ArcGIS Pro 3.1 (ESRI, Redlands, CA, USA)
Coordinate system: WGS 1984 UTM Zone 31N
Spatial interpolation method: Inverse Distance Weighting (IDW) with power parameter = 2. IDW was selected because:

a. It assumes that points closer to each other are more similar than distant points (Tobler's first law of geography)
b. It is appropriate for water quality parameters that are continuous but not necessarily following a normal distribution [19]
c. It provides conservative estimates that do not over-smooth local variation [20]

IDW parameters:

a. Power: 2 (default, provides moderate smoothing)
b. Search radius: Variable (12 nearest neighbors)
c. Output cell size: 30 m × 30 m
d. Barrier: None (continuous urban area)

Validation: Cross-validation performed for each interpolated surface using root mean square error (RMSE) and mean absolute error (MAE). Acceptable threshold: RMSE <15% of data range.

Map production: Separate maps generated for:

- Physicochemical parameters (pH, EC, TDS, hardness, alkalinity, HCO_3^-, Cl^-, F^-)
- Heavy metals (Mn, Fe, Zn, Cr, Ni)
- Exceedance maps (locations where values exceed WHO limits)

6. Statistical Analysis

- **One-sample t-test:** Compare mean concentrations with WHO permissible limits
- **Pearson correlation:** Examine relationships between parameters
- **Coefficient of variation (CV):** Quantify spatial variability
- **Software:** R version 4.2.1
  (packages: tidyverse, sf, gstat)

Significance threshold: $\alpha = 0.05$.

Results and Discussion

1. Summary of Physicochemical Parameters

The descriptive statistics of physicochemical parameters across the ten sampled locations are presented in Table 2. Overall, groundwater quality shows general compliance with WHO and SON drinking water guidelines, with most parameters remaining within permissible limits.

pH values ranged from 6.2 to 7.3, with a mean of 6.8 ± 0.3, indicating slightly acidic to neutral groundwater conditions typical of shallow urban aquifers. Electrical conductivity (EC) and total dissolved solids (TDS) recorded mean values of 342 ± 48 µS/cm and 221 ± 31 mg/L, respectively, with low coefficients of variation (14%), suggesting moderate ionic stability across the study area.

Total hardness showed moderate spatial variability (CV = 18.6%), with 80% compliance, indicating localized mineral dissolution processes. Chloride and fluoride demonstrated full compliance (100%), although relatively high variability suggests localized hydrochemical influence.

Table 2: Descriptive Statistics of Physicochemical Parameters (n = 10)

Parameter	Unit	Mean ± SD	Min	Max	CV (%)	WHO limit	SON limit	Compliance (%)
pH	–	6.8 ± 0.3	6.2	7.3	4.4	6.5–8.5	6.5–8.5	90
EC	µS/cm	342 ± 48	280	420	14.0	1000	1000	100
TDS	mg/L	221 ± 31	179	272	14.0	500	500	100
Total hardness	mg/L $CaCO_3$	118 ± 22	89	158	18.6	150	150	80
HCO_3^-	mg/L	142 ± 24	108	186	16.9	NS	NS	–
Total alkalinity	mg/L	116 ± 20	89	153	17.2	NS	NS	–
Chloride (Cl^-)	mg/L	28 ± 8	18	44	28.6	250	250	100
Fluoride (F^-)	mg/L	0.48 ± 0.14	0.31	0.72	29.2	1.5	1.0	100

2. Heavy Metal Concentrations

Heavy metal concentrations (Table 3) reveal significant contamination compared to physicochemical parameters. Manganese and iron recorded moderate exceedances with compliance rates of 80% and 70%, respectively. Zinc remained within permissible limits (100% compliance). However, chromium and nickel exceeded WHO and SON permissible limits at all sampling points (0% compliance), indicating pervasive contamination across the study area. These metals represent the most critical pollutants affecting groundwater quality.

Table 3: Descriptive Statistics of Heavy Metals (n = 10)

Metal	Unit	Mean ± SD	Min	Max	CV (%)	WHO limit	SON limit	Compliance (%)
Mn	mg/L	0.12 ± 0.06	0.05	0.23	50.0	0.4	0.2	80
Fe	mg/L	0.24 ± 0.11	0.09	0.46	45.8	0.3	0.3	70
Zn	mg/L	1.52 ± 0.72	0.58	2.89	47.4	3.0	3.0	100
Cr	mg/L	0.15 ± 0.06	0.08	0.27	40.0	0.05	0.05	0
Ni	mg/L	0.09 ± 0.04	0.04	0.18	44.4	0.02	0.02	0

3. Location-Specific Water Quality Characteristics

Spatial variation in groundwater quality is summarized in Table 4. Ojoo-Iwo recorded the highest heavy metal concentrations and the highest Water Quality Index (WQI = 1035), indicating extremely poor water quality. In contrast, Ashi and Akobo showed relatively lower contamination levels, although still exceeding safe limits for chromium and nickel.

Table 4: Location-Specific Groundwater Quality Parameters

Location	pH	Cr (mg/L)	Ni (mg/L)	Mn (mg/L)	Fe (mg/L)	WQI
UI Community	7.1	0.12	0.07	0.09	0.18	–
Agbowo	6.9	0.14	0.08	0.11	0.22	–
Poly Ibadan	7.0	0.19	0.12	0.15	0.31	170
Akobo	7.2	0.09	0.05	0.06	0.12	–
Ashi	7.1	0.08	0.04	0.05	0.09	–
Sango	6.2	0.16	0.10	0.14	0.28	–
Adogba	6.8	0.18	0.11	0.18	0.35	–
Ojoo-Iwo	6.7	0.27	0.18	0.23	0.46	1035
Obaleye	6.5	0.15	0.09	0.12	0.24	–
Basorun	6.9	0.12	0.07	0.10	0.19	–

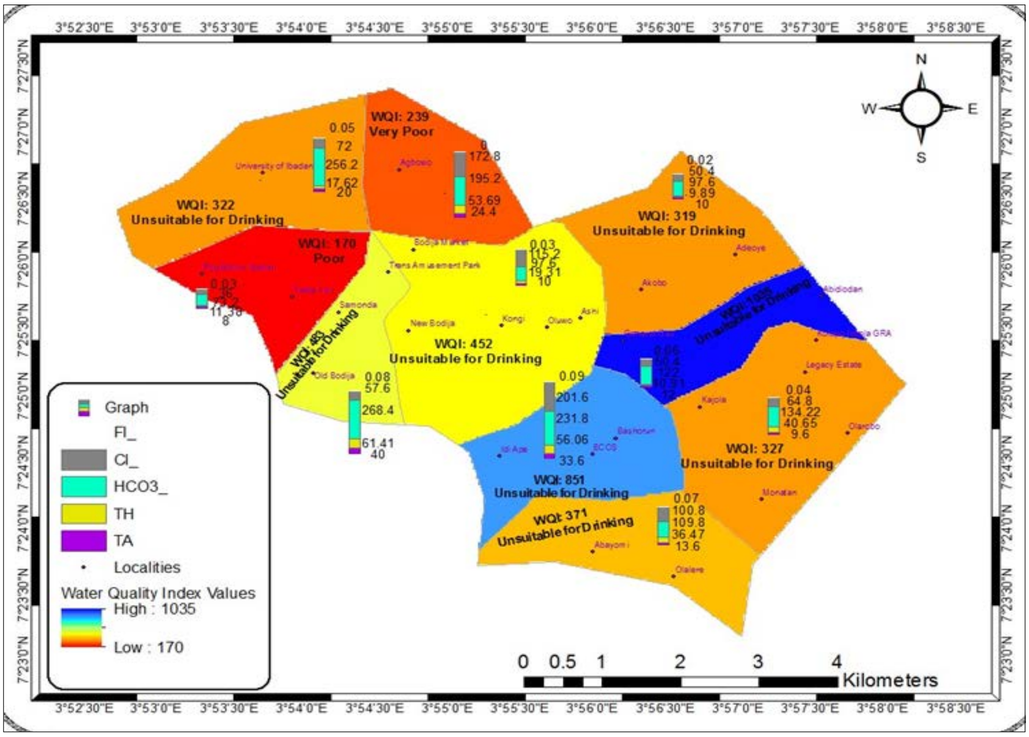
4. Spatial Distribution Patterns

4.1 Spatial Distribution of Physicochemical Parameters (Uniform Pattern)

The GIS-based interpolation outputs (Figure 1) indicate that physicochemical parameters exhibited a predominantly uniform spatial distribution across the ten sampled settlements within the Ibadan metropolitan area. Parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), total hardness, alkalinity, chloride (Cl^-), and fluoride (F^-) showed limited spatial variability, suggesting hydro chemical homogeneity at the regional scale.

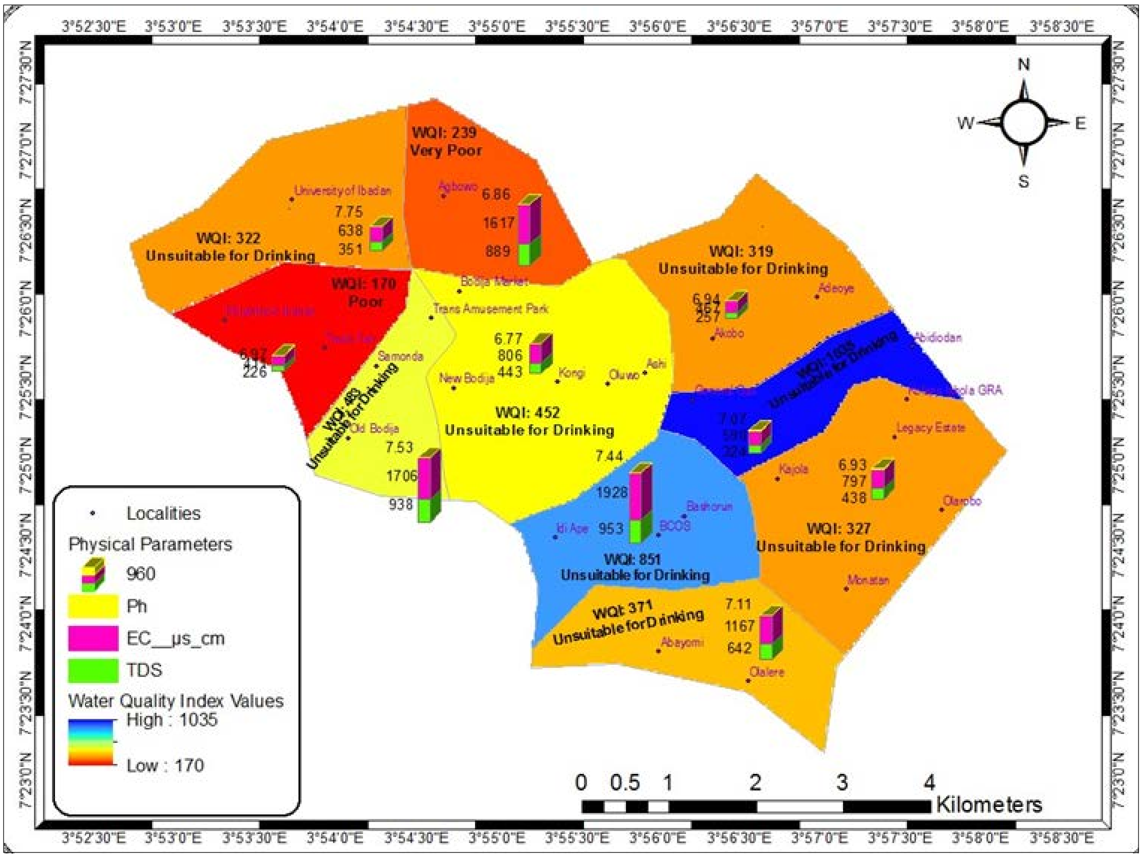
pH values ranged from 6.5 to 7.2 across approximately 90% of the study area, with a localized minimum (pH ≈ 6.2) observed around Sango. EC varied between 280 and 420 µS/cm, displaying a gradual northward increase from southern settlements (Akobo and Ashi) toward Ojoo-Iwo. A similar spatial trend was observed for TDS (179–272 mg/L), indicating strong geochemical coupling between both parameters.

This spatial uniformity suggests that physicochemical characteristics are primarily governed by diffuse, regionally acting processes, including the homogeneous nature of the underlying basement complex, aquifer connectivity, and uniform water supply inputs from centralized treatment systems.



Source: Author's production, 2019.

Fig 1: Trends of Chemical parameters across the study area

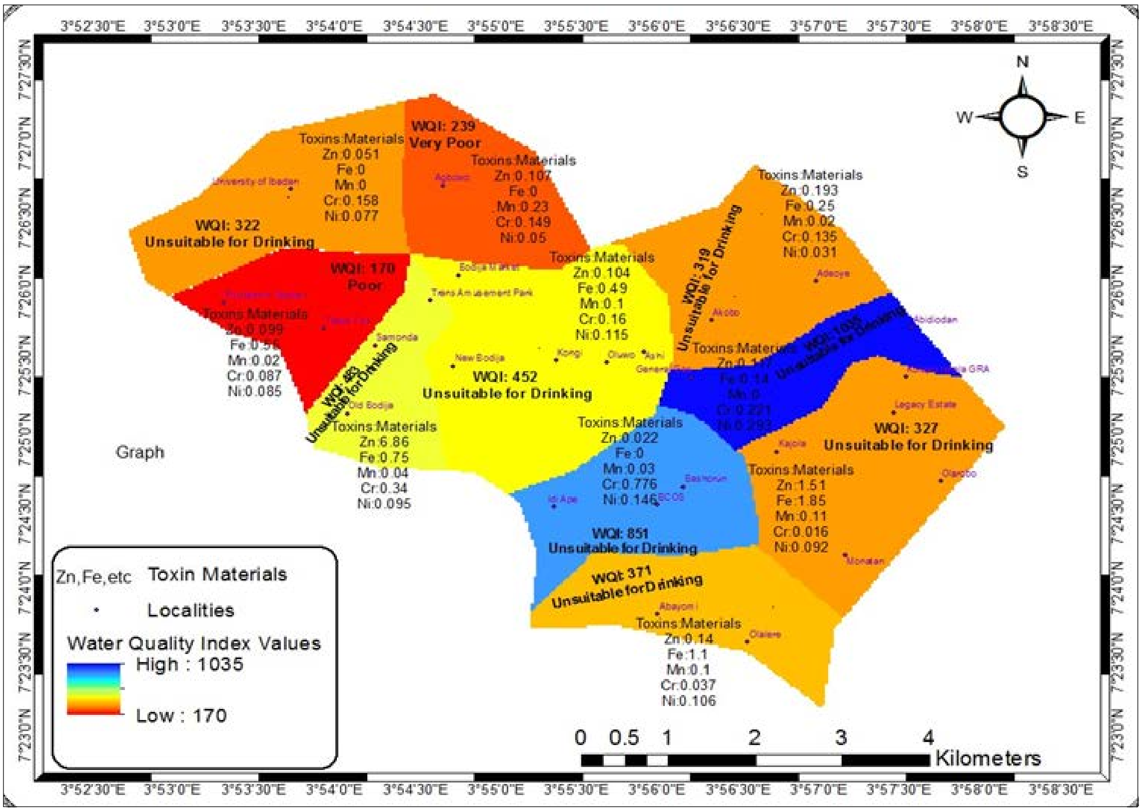


Source: Author's production, 2019

Fig 2: Trends of Physical parameters across the study area

4.2 Spatial Distribution of Heavy Metals (Clustered Pattern)

In contrast, heavy metals exhibited pronounced spatial heterogeneity characterized by distinct contamination hotspots.



Source: Author's production, 2019.

Fig 3: Trends of toxin elements across the study area.

Hotspot 1: Ojoo-Iwo (Northwestern Zone)

Ojoo-Iwo recorded the highest concentrations of Cr (0.27 mg/L), Ni (0.18 mg/L), Mn (0.23 mg/L), and Fe (0.46 mg/L), alongside the highest Water Quality Index (WQI = 1035), indicating severe water quality deterioration. The site is located within 200 m of an unlined municipal waste dump, strongly suggesting landfill leachate infiltration as the dominant contamination source.

Hotspot 2: Polytechnic of Ibadan Environs (North-Central Zone)

Elevated concentrations of Cr (0.19 mg/L), Ni (0.12 mg/L), and Mn (0.15 mg/L) were observed. The spatial association with mechanical workshops, printing units, and small-scale industrial activities indicates anthropogenic discharge as a key driver.

Hotspot 3: Adogba (Central Zone)

Moderate enrichment of Cr (0.18 mg/L) and Ni (0.11 mg/L) was identified near drainage channels receiving urban runoff and potential landfill leachate input.

Low-Contamination Zone: Ashi–Akobo Corridor (Southern Zone)

This zone exhibited comparatively lower heavy metal concentrations (Cr: 0.08–0.09 mg/L; Ni: 0.04–0.05 mg/L), likely due to reduced industrial activity, improved waste management, and deeper groundwater abstraction.

Figure 1 illustrates the spatial contrast between uniform physicochemical distributions and clustered heavy metal hotspots, with chromium and nickel showing strong spatial coherence (r = 0.93).

4.3 Chromium–Nickel Relationship

Pearson correlation analysis revealed a very strong positive association between chromium and nickel concentrations across all sampling locations ($r = 0.94$, $p < 0.001$). This suggests a shared source or coupled geochemical behavior, potentially arising from co-discharge in industrial processes or simultaneous mobilization from mineralized geological formations.

5. Spatial Variability Comparison

Coefficient of variation (CV) analysis highlights marked differences in spatial behavior among parameter groups.

Table 5: Spatial Variability of Water Quality Parameters

Parameter Category	Parameters	Mean CV (%)	Interpretation
Physicochemical	pH, EC, TDS, hardness, alkalinity	14.2	Low variability; uniform distribution
Anions	Cl^-, F^-, HCO_3^-	21.5	Moderate variability; weak spatial structuring
Heavy metals	Mn, Fe, Zn, Cr, Ni	45.5	High variability; strong spatial clustering

The observed difference between physicochemical and heavy metal variability is statistically significant ($p < 0.001$), confirming fundamentally different spatial controlling mechanisms. Physicochemical parameters are governed by regional hydrogeological processes, whereas heavy metals are driven primarily by localized anthropogenic inputs.

Discussion

1. Contrasting Spatial Patterns: Uniform versus Clustered Distributions

The most notable outcome of this study is the pronounced divergence between the spatial behavior of physicochemical parameters and heavy metals. Physicochemical variables exhibit a largely uniform spatial distribution (CV = 4–19%), whereas heavy metals display strong spatial clustering (CV = 40–50%). This duality is critical for interpreting contamination pathways and guiding remediation strategies.

The observed uniformity in physicochemical parameters such as pH, EC, TDS, hardness, and alkalinity suggests control by regional-scale hydrogeological processes rather than localized anthropogenic inputs. This pattern is likely attributable to several interacting factors. First, the geological homogeneity of the Precambrian basement complex (granite-gneiss-schist) provides a consistent geochemical background across the study area [21]. Second, the lateral connectivity of shallow aquifers facilitates mixing and homogenization of dissolved ions, thereby reducing spatial variability [22]. Third, areas served by the Oyo State Water Corporation receive treated water from common sources (Eleyele and Asejire dams), reinforcing chemical uniformity at the urban scale.

In contrast, the clustered distribution of heavy metals indicates dominance of localized anthropogenic inputs rather than background geogenic processes. The identification of distinct contamination hotspots (Ojoo-Iwo, Polytechnic of Ibadan environs, and Adogba) with declining concentrations outward strongly supports a point-source or small-area source pollution model.

2. Source Identification for Heavy Metal Hotspots

Hotspot 1: Ojoo-Iwo (Highest Contamination Zone)

The exceptionally high concentrations of Cr (0.27 mg/L) and Ni (0.18 mg/L) at Ojoo-Iwo, coupled with its proximity to an unlined municipal waste dump, strongly indicate landfill leachate infiltration as the primary contamination source. Leachate generated from mixed municipal waste typically contains elevated heavy metal loads derived from batteries, electronic waste, metallic scraps, and industrial residues, including Cr and Ni [23]. The absence of engineered lining in many Nigerian landfill sites facilitates direct percolation into shallow aquifers without attenuation [24].

Supporting evidence includes:

1. Reported seepage of leachate by local residents near the dump
2. Disposal of both household and small-scale industrial waste at the site
3. Absence of alternative industrial or mining sources in the area

Hotspot 2: The Polytechnic of Ibadan Environs

Moderate to high contamination in this zone is strongly associated with small-scale industrial and mechanical activities. The area hosts numerous workshops involved in metal fabrication, welding, printing, automobile repair, and battery recycling [25]. These activities are well-documented sources of Cr (VI) from plating processes and Ni from alloys and batteries [26].

Supporting observations include:

a. Presence of workshops lacking effluent treatment systems
b. Discoloured and oil-impacted drainage channels observed during field surveys Strong Cr–Ni correlation in local samples (r = 0.96), suggesting co-release from common industrial processes

Hotspot 3: Adogba (Central Urban Zone)

Contamination in Adogba is likely driven by combined influences of landfill leachate infiltration and urban stormwater runoff. The drainage network passing through this area receives untreated runoff from upstream commercial and industrial zones, facilitating the transport of dissolved and particulate-bound metals [27].

Low-Contamination Zone: Ashi–Akobo Corridor

Relatively lower heavy metal concentrations in Ashi and Akobo, although still above permissible limits, may be explained by:

1. Use of deeper boreholes (>60 m compared to <30 m in other locations
2. Lower industrial and commercial activity density
3. Improved waste management practices, including structured waste collection and containment

3. Health Implications of Chromium and Nickel

A critical and concerning outcome of this study is the universal exceedance of WHO and SON permissible limits for chromium and nickel across all sampled locations. This indicates widespread groundwater contamination and a high potential for long-term human exposure.

Chromium (VI) is classified as a Group 1 human carcinogen, with established links to lung cancer via inhalation exposure and emerging evidence of gastrointestinal toxicity through ingestion pathways [13]. Nickel is classified as a Group 2B possible human carcinogen and is widely associated with allergic contact dermatitis, one of the most prevalent metal-induced hypersensitivity conditions globally [14].

Furthermore, chronic exposure to chromium and nickel, even at concentrations near guideline thresholds (0.05 mg/L and 0.02 mg/L respectively), has been associated with renal dysfunction, hepatic toxicity, and reproductive impairment in toxicological studies [28]. The complete absence of compliance across all sampling locations therefore suggests that no groundwater source within the study area is safe for long-term consumption without adequate treatment.

This finding challenges the prevailing assumption that borehole water in Ibadan is inherently safe and highlights the urgent need for systematic monitoring and remediation interventions.

Conclusions

This GIS-based assessment of groundwater quality across ten settlements in Ibadan metropolis demonstrates a clear divergence between naturally controlled physicochemical parameters and anthropogenic ally driven heavy metal contamination. Physicochemical variables (pH, EC, TDS, hardness, alkalinity, chloride, and fluoride) showed generally uniform spatial distribution (CV = 4–19%) and remained within WHO and SON permissible limits, indicating dominant control by regional geological conditions and relatively consistent municipal water inputs.

In contrast, heavy metals, particularly chromium (Cr) and nickel (Ni), exhibited pronounced spatial clustering (CV = 40–50%) with distinct contamination hotspots located at Ojoo-Iwo, The Polytechnic of Ibadan environs, and Adogba. All sampling locations exceeded regulatory limits for Cr (0.05 mg/L) and Ni (0.02 mg/L), with observed concentrations indicating substantial exceedance levels, thereby confirming widespread contamination across the study area.

The spatial pattern strongly suggests that heavy metal pollution is primarily anthropogenic, driven by landfill leachate infiltration, industrial and workshop effluents, and urban runoff rather than natural geochemical processes. The application of GIS-based IDW interpolation proved effective in differentiating between uniformly distributed physicochemical parameters and clustered heavy metal contamination, thereby enabling clear identification of pollution hotspots and source-linked spatial trends. From a public health perspective, the findings indicate that none of the sampled groundwater sources are safe for long-term consumption without appropriate treatment targeting Cr and Ni removal. Consequently, priority intervention should focus on hotspot zones, particularly Ojoo-Iwo, The Polytechnic Ibadan environs, and Adogba, through improved landfill engineering, industrial effluent regulation, and development of safer deeper groundwater abstraction systems.

Conflicts of Interest

The author declare no conflicts of interest. No funding agency or commercial entity influenced study design, data collection, analysis, or interpretation.

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