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Multivariate Hydrochemical Characterization and Spatial Variability of Groundwater Quality in Kano Region, Nigeria: Insights into Natural Geology and Anthropogenic Influence

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Abstract: This research detailed a hydrochemical investigation and spatial variability examination of the groundwater quality at five principal sites in the Kano Region, Nigeria, namely Hotoro, Kano Municipal, Kumbotso, Kofar Fada, and Gezawa, with a total of Fifty-one (51) water samples collected. Physical, chemical, and biological parameters assessed in the water samples were Electrical Conductivity, Hardness, pH, Total Dissolved Solids (TDS), Temperature, Turbidity, Dissolved Oxygen (DO), major cations (Na^+, K^+, Mg^{2+}, $Ca2^+$), and trace metals (Cr, As, Fe, Zn, Cu, Ni, Pb, Cd). The data demonstrated a high level of spatial heterogeneity that should be considered when examining not only natural geological structures but also anthropogenic factors, particularly in urbanised and peri-urban districts of Kano and certain parts of the surroundings, where elevated Conductivity, TDS, Hardness, and several ion concentrations were observed. The pH was usually in the slightly acidic to slightly alkaline range, with low levels of Dissolved Oxygen indicating possible impacts from organic contaminants or eutrophication. Two multivariate visualisations (box plots, Scatter plots, multiple correlation matrices, PCA, and Piper diagrams) help clarify the complex correlations among the constituents of water quality. The Piper diagram revealed unique hydrochemical facies, primarily Sodium-Chloride and Calcium-Magnesium Bicarbonate, which combined the natural geochemistry of sediments with urban anthropogenic effects. The concentrations of Trace metals were generally low, with little acute risk identified, but periodic increases in iron and Zinc indicated localised areas of potential concern. The inter-area differences were strongly supported by statistical testing, indicating the need for specific water resource management approaches and pollution control strategies. The statistical testing strongly indicated an inter-area difference, necessitating specific approaches to water resources management and pollution control strategies. Overall, the synthesis of spatially resolved hydrochemical measurements with spatial data and its processing has the potential to make an essential contribution to the sustainable monitoring of water quality and environmental management in the Kano region, and to support sound decisions to preserve the health of the overall population and water bodies. In general, the combination of spatially addressed hydrochemical observations with spatial data and its analysis presents an opportunity for a crucial contribution to sustainable monitoring of water quality and environmental management in the Kano area, and to rational decisions to preserve the health of the general population and aquatic ecosystems.

Keywords: Hydrochemical Characterization; Spatial Variability; Groundwater Quality; Anthropogenic Influences; and Multivariate Analysis

Nomenclature:
TDS: Total Dissolved Solids
DO: Dissolved Oxygen
EC: Electrical Conductivity
PCA: Principal Component Analysis
PAC: Polyaluminium Chloride

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I. INTRODUCTION

A. Highlights

- Multi-parameter analysis of groundwater quality was carried out in detail in five selected locations in Kano, showing considerable disparities in the physical, chemical, and biological water quality indicators.
- The results of the study showed that a significant spatial heterogeneity was pronounced due to natural geological provisions and human activities, especially urbanization, where more mineralization and levels of existing pollutants were in Hotoro and some areas within Kumbotso.
- Piper plot and multivariate analyses revealed two different types of water, mainly linked to Sodium-Chloride and Calcium-Magnesium Bicarbonate facies, which showed that there was a combination of natural geochemical processes and contamination sources.
- Statistical and geostatistical results underline the necessity of the localized degree of water quality monitoring and pollution control to secure individual health and aquatic fauna in the Kano area.

What unexplored information about water quality and contamination is contained in the peaks and patterns of ion and trace metal chromatograms of such different locations at Hotoro, Kano Municipal, and Garun Mallam as we can interpret the geochemical fingerprints and footprints of groundwater contamination of groundwater's in critical areas of Nigeria through the deciphering of the complex peaks of chromatogram plots to achieve more intelligent environment management and preservation of resources."

The study by [1] used remote sensing and GIS to analyse the spatial patterns of Electrical Conductivity (EC), Total Dissolved Solids (TDS), and pH in the Gurara Reservoir, Nigeria. The study found that pollution loads increased downstream in the reservoir, with EC and TDS closely related and generally higher in those areas. The upstream regions showed higher pH values, likely due to geological weathering processes. By mapping these parameters using GIS techniques, the research highlighted the impacts of land-use changes and human activities on water quality. The study confirms the critical role of GIS in providing visual insights for ongoing monitoring and effective management of reservoir water resources, underpinning the need for strategic protection plans to safeguard the reservoir's water quality for current and future use. This has led to disproportionate ecological degradation and increased health risks due to the lack of regular risk assessments, underscoring the urgent need for systematic, ongoing monitoring to manage water quality sustainably. The 2025 study published in Frontiers in Water integrates GIS with hydrochemical analyses to model and visualize groundwater quality, focusing on key parameters such as electrical conductivity (EC) and total dissolved solids (TDS). The research demonstrates spatial variations in TDS, ranging from 2,304 to 8,832 mg/L, and in EC, ranging from 3,600 to 13,800 µS/cm, strongly influenced by regional geology and land-use practices. The findings indicate generally poor groundwater quality for both irrigation and drinking purposes due to contamination from agricultural runoff, industrial discharges, and overexploitation. There is a need for comprehensive, continuous, and integrated GIS-based monitoring systems to accurately capture spatial and temporal variations, assess contamination sources, and inform sustainable groundwater management and policy decisions effectively [2].

[3] A study of selected wells in the Taleghan region, Iran, used geospatial analysis to evaluate groundwater quality indicators, primarily electrical conductivity (EC) and total dissolved solids (TDS). The research identified significant correlations between the region's geological characteristics and variations in water chemistry, indicating that local geology strongly influences groundwater quality. These findings emphasize the importance of incorporating geological factors in groundwater management and protection strategies to ensure safe and sustainable water resources, but a limited multi-seasonal and spatially comprehensive groundwater quality data in the Taleghan region. There is a need for ongoing monitoring that incorporates a broader range of hydrochemical parameters and microbial risks to better understand temporal variations and human impacts on groundwater quality. The 2025 study on groundwater quality in polluted hotspots in Nigeria uses geospatial analysis to map key parameters, including electrical conductivity and total dissolved solids. A significant spatial variation driven by anthropogenic activities and geological factors, demonstrating how urbanization and industrial pollution degrade groundwater quality. The study underscores the effectiveness of GIS-based visualization tools in identifying contamination patterns and supporting targeted interventions for groundwater management in urban and peri-urban environments. The survey of groundwater quality assessment in polluted hotspots of Tamil Nadu, India, integrates geospatial and statistical approaches to evaluate key water quality parameters. The research identifies significant spatial variability in contamination levels influenced by industrial activities, agricultural runoff, and geological factors. Using GIS mapping and multivariate statistical analysis, the study effectively highlights areas with elevated electrical conductivity and total dissolved solids, underscoring the combined impact of anthropogenic pressures and natural geology on groundwater quality. The findings provide crucial insights for targeted groundwater management and pollution mitigation strategies in the region. Limited integration of high-resolution temporal data and comprehensive multi-parameter monitoring constrain the understanding of groundwater quality dynamics in Tamil Nadu. Enhanced GIS-based long-term studies are needed to capture seasonal variations and pinpoint pollution sources to support effective groundwater management and policy formulation [5]. The study employed ten vertical electrical soundings (VES) to determine the bedrock depth in the Liji area of Gombe State using geophysical techniques. The majority of geo-electric layers detected by the WINRESIST program displayed three or four layers. Basement rocks with an unlimited thickness were discovered at depths ranging from 5.7 to 24.0 meters. The Western, Northwestern, and Eastern parts exhibited significant resistivity values, and the A-curve was widespread [6]. The deteriorating water quality of the Baitarani River in Odisha, India, highlights pollution from both urban, agricultural, and industrial sectors. He categorises contamination levels, spotlights hotspots, and forecasts water quality most accurately, which calls for actionable interventions, community-level actions, and policy changes to enable sustainable river management [7].

Research on Ain Sefra, located in South West Algeria, is vital amid the arid conditions, especially for water resources and groundwater. They are determined using multivariate statistics, water quality indices, and geochemical modelling, which divide the samples into four hydrochemical groups, primarily suitable for drinking and agricultural use. The prominent processes are mineral dissolution and pollution. Results reiterate the need to incorporate management, as well as constant and GIS-based observation, to ensure sustainable use of groundwater under the pressures of climate and population [8]. In an experiment conducted in Lawspet, India, multivariate analysis found that artificial activities such as waste dumping and waste reuse have a severe negative impact on groundwater quality. Meaningful parameters such as EC, TDS, and Cl- exhibit spatial variation, and the statistical significance of the variance across sites was established; thus, there is a pressing need for management and monitoring of sustainable waste strategies [9]. The analysis examined borehole water quality in Effurun, Nigeria, focusing on contamination from agricultural and industrial activities, including elevated nitrate, sulfate, and lead concentrations. Through hydrochemical, statistical, and geospatial techniques, it targets contamination hotspots. It underlines the necessity of continuous monitoring, mitigation activities, and community participation in the management of healthy drinking water and sustained management of groundwater [10]. The quality of groundwater in Uttarakhand, India, is evaluated and found to be alkaline, rugged, and Ca-Mg-HCO3 weathered, with natural and anthropogenic factors affecting it. Salinity and hardness are the factors of concern, being high, mostly meeting standards. Statistical analysis identifies sources of contamination and indicates that areas are suitable for irrigation. They should sustainably manage.

and monitor it regularly to preserve this critical Himalayan water resource [11]. Shaheed Benazirabad is the city of the Indus River, with a population of 1.613 million and an arid/semi-arid climate. The water samples taken at a depth of 40m are dominated by Calcium chloride, and this was attributed to water-rock interaction. Qualities of groundwater depend largely on soil types and climatic conditions, and spatial variations occur in relation to land-use patterns, vegetation, and urbanisation, making groundwater an imperative area of water management. Groundwater quality in North Bahri City, Sudan, focusing on the Nubian sandstone aquifer using hydrochemical and multivariate analyses. Results show that Ca-Mg-HCO3 water types are influenced by geology and human activities such as agriculture and septic contamination. About 75% of samples are suitable for irrigation, though salinity issues persist, highlighting the need for integrated chemical and statistical monitoring for sustainable groundwater management [12]. The population assessment of groundwater in Sharsa Upazila, Bangladesh, indicates groundwater contamination from agricultural and waste enterprises, with some areas posing a health risk. It depicts variable quality using GIS, indices, and multivariate analyses that necessitate sustainable management, pollution control, and remediation to ensure safe drinking water and agricultural applications against environmental pressures [4]. In the Sharsha Upazila, Jashore District, Bangladesh, 69% of samples exceeded the NH4+ standard, and 100% of samples exceeded the Ca2+ standard. The Water Quality Index (WQI) showed good quality in most of the water to be used for drinking. Contaminants were spatially distributed by using GIS mapping. According to PCA, significant anthropogenic and geogenic impacts on water quality were identified. Groundwater is, in most cases, acceptable to use in irrigation, though there are grounds that pose health hazards because there are excessive levels of the ions.

The primary purpose of this research is to justify and define the spatial nature and multi-parametric processes of groundwater quality across several Nigerian regions, including Hotoro, Kano Municipal, Kumbotso, Kofar Fada, and Gezawa. It seeks to determine and analyse the natural hydro-geochemical processes in these places and the influence of man that interferes with the water chemistry. To this end, various statistical, graphical, and analytical tools, e.g., box plots, scatter plots, violin plots, chromatograms, correlation analyses, principal component analysis (PCA), and calibration curves, were used to provide an accurate overview of water quality. Its outputs are intended for specific decision-making in the management of water resources and the environment, to ensure that management is sustainable and efficient based on solid analysis of data obtained across multiple water quality parameters. The spatial distribution of water quality in the regions under examination is characterised by high variance, leading to spatial heterogeneity caused not only by natural, geological factors but also by the level of anthropogenic impact. Some of these essential physicochemical parameters, including Conductivity, Total Dissolved Solids (TDS), Hardness, and pH, exhibit significant disparities across locations due to differences in mineralisation levels and pollution. Data visualisation of multivariate controls and statistical interpolations shows high correlations between major ions and trace metals, which may help identify geochemical links, sources of contamination, and regions of water-quality importance. By combining chromatograms, Scatterplots, correlation Heatmaps, and Principal Component Analysis (PCA), it is possible to reduce complex contamination compositions into transparent, understandable patterns, helping diagnose contamination, the influence of natural hydro-geochemical processes, and general water quality conditions.

II. MATERIALS AND METHODS

Water samples were systematically collected from various locations in the Kano region of Northern Nigeria, which is geographically restricted, with latitudinal coordinates of 8° 02″ and 8°59″ N and longitudinal coordinates of 11°00″ and 12°14″ E. The sampling locations have been chosen as Hotoro, Kano Municipal, Kumbotso, Kofar Fada, Gezawa, and Garun Mallam, among others, which cover varying degrees of urbanisation, geological environments, and plausible pollution sources. The spatial segregation of sample points and the analysis of sampling point data facilitated comparative studies to determine how geomaterials, anthropogenic activities, and land use affect changes in water quality. Standard environmental sampling procedures were applied to ensure representativeness and minimise contamination. Sterile bottles have been used, and the sampling depth has been adhered to, preserving sample integrity during transport. Temperature, pH, electrical conductivity, turbidity, and dissolved oxygen (DO2) measurements were taken in the field with calibrated portable probes to obtain as precise in situ measurements as possible. Parameters of water quality being monitored included physical, chemical, and biological markers. Physical parameters were temperature (°C), turbidity (Nephelometric Turbidity Units), and dissolved oxygen (mg/L), measured with electrochemical or optical probes. Chemical parameters included electrical conductivity (mS/cm) to measure ionic strength, total dissolved solids (TDS, mg/L) measured gravimetrically after filtration, pH, which indicated acidity or alkalinity, and hardness, which indicated calcium and magnesium concentrations. The measurement of major ions sodium (Na+), Potassium (K+), Magnesium (Mg2+), Calcium (Ca2+), Chloride (Cl+), Sulfate (SO42-), Nitrate (NO3-), and Bicarbonate

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(HCO3-) and the measurement of trace Metals chromium (Cr), Arsenic (As), Iron (Fe), zinc (Zn), and copper (Cu), Nickel (Ni), Lead (Pb) and cadmium (Cd).

Quality assurance was maintained by using standard calibration curves based on certified reference standards across broad concentration ranges, ensuring linearity and accuracy. Precision was validated using multiple replicates and quality-control samples, minimising analytical errors and confirming consistency. Routine blanks were analysed to assess contamination or instrument drift. Quality assurance was performed using standard calibration curves based on certified reference standards over a wide concentration range. It was evaluated for linearity and accuracy. Multiple replicates and quality-control samples validated precision, reduced analytical errors, and assured consistency. Blank runs as part of the routine were investigated to assess contamination or instrument variation. Descriptive statistics and comparative tests, such as t-tests and confidence interval estimates, were used to evaluate significant spatial variation across sampling zones. Statistical methods such as correlation matrices, principal component analysis (PCA), and Piper diagrams provided the basis for understanding complex ionic correspondences, geochemical sources, and facies hydrochemistry. Kriging was used in geostatistical approaches to interpolate spatially and map variability in water quality parameters. Visual representations, such as box plots, scatter plots, violin plots, pairwise correlations, and chromatogram plots, provided multidimensional information on water-chemistry trends and enabled the identification of contamination hotspots. The composite interpretive structure incorporated physical/chemical and biological data to provide a robust evaluation of water quality and ecosystem health across the region. Correlation and geographic analysis separated the naturally occurring geochemical influences from artificial pollution. Positive correlations among essential cations at all points indicated that mineral dissolution and interaction with water occurred, and occasional peak values of trace metals provided evidence of contamination in localised areas. Multivariate analysis condensed complex datasets into patterns that can be recognised to inform specific environmental management, monitoring, and remediation actions. Such methodological design guaranteed accurate and dependable measurement of water quality in spatially heterogeneous urban–peri–urban locations in Kano, as well as data-driven decision-making for the management of water resources and the conservation of ecological integrity.

III. RESULTS

The dataset provides a precise record of water quality as measured at various points along water sampling sites in the Kano region of Nigeria, with all data points centred at latitudes between 8° 02′ and 8° 59′ and longitudes between 11° 00′ and 12° 14′. Parameters monitored include electrical conductivity, hardness, pH, total dissolved solids (TDS), temperature, turbidity, and dissolved oxygen (DO). All these parameters indicate physical, chemical, and biological factors of water quality. Spatial agglomeration of sample points enables a comparative analysis of water quality differences related to the area's geology, urbanisation, and pollution sources.

Electrical conductivity of the water, which measures its capacity to conduct current due to its ionic content, also shows a wide range, from around 176.2 µS/cm to very high values above 2400 µS/cm at certain Hotoro and Ring Road locations, among others. Such high conductivity values will be associated with high TDS and hardness, indicating mineral-rich or possibly polluted water, most likely caused by natural groundwater mineralisation or anthropogenic activities. The majority of pH cases fall within a general range of slightly acidic to slightly alkaline (~5.6 and ~8.7, respectively), and therefore are acceptable for drinking water. However, some cases are borderline and may be considered acidic, contributing to corrosivity and metal leaching in pipes. Moderate changes are recorded in turbidity values, ranging from 8 to 19 NTU, indicating that suspended solids are changing, thereby affecting water clarity and harbouring pathogens, resulting in difficulties in providing water treatment and supporting aquatic organisms.

Temperature fluctuates minimally between 29 and 33 °C, characteristic of a tropical climate, thus having the inverse effect on the solubility of dissolved oxygen. Dissolved oxygen varies between approximately 2.3 mg/L and 6.9 mg/L, but lower levels are often observed where conductivity is high, which may indicate organic contamination, eutrophication, or oxygen depletion. Areas of increased turbidity are usually accompanied by low DO, meaning biologically active waters or heavily sedimented waters. In general, the data indicate substantial heterogeneity in water quality, attributable to a complex interplay among geology, land use, and human activity. Constant monitoring and localised management of these water sources in these peri-urban and urban areas is essential to ensure the quality and the sustainability of water resources and the aquatic ecosystem.

The water quality measurements in the areas of Hotoro, Kano Municipal, Kumbotso, Kofar Fada, and Gezawa show specific spatial and parameter-specific changes that can only be attributed to the possible presence of both natural and anthropogenic factors affecting water quality. Boxplots indicate a disparity in vital characteristics like conductivity, hardness, pH, and total dissolved solids (TDS) among these localities, with the HOTORO zone and some KUMBOTSO locations featuring substantially high values of conductivity and TDS, probably due to the volume of minerals or pollutants related to the climate of urbanization or geographical conditions. It can be seen in the scatter plot of pH against dissolved oxygen (DO2) that, in general, more neutral to slightly alkaline waters have higher oxygen concentrations, which are essential to aquatic life. In contrast, lower pH values are associated with lower DO, which may indicate local contamination and contribute to local oxygen depletion. (Figure 1).

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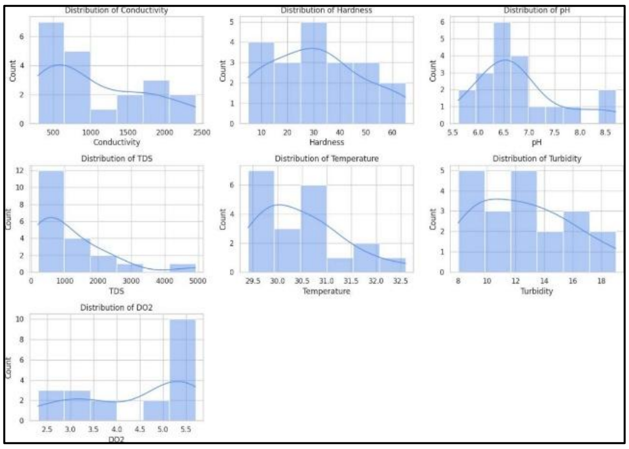
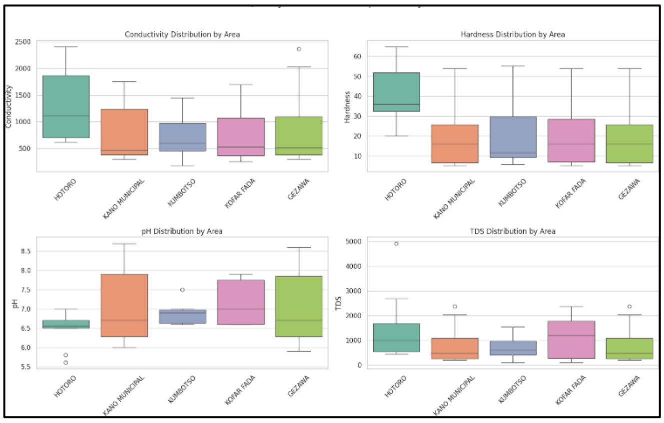
Table I: Showing all the 51 Locations with their Longitudes, Latitudes, Conductivity, Hardness, pH, TDS, Temperature, Turbidity, and DO_2

S/No	Name	Long.	Lat.	Conductivity	Hardness	pH	TDS	Temperature	Turbidity	DO_2
	Sabon bakin zuwo Hotoro		11	8.2	616.5	54	7	525.7	32.6	12
	GRA									
	No. 6 Hotoro Avenue	11.24	8.16	929.6	34	6.7	640.8	29.4	11	5.3
	Hotoro	11.33	8.06	2410	32	6.5	1673	30.5	16	3.4
	No. 1 Sabo Bakin Zuwo Road.	11.11	8.56	1847	20	6.5	1272	31.7	15	3.2
1	No. 13 Sabo Bakin Zuwo	11.18	8.43	2410	36	6.7	1673	29.9	13	2.3
	Road									
	Tarauni	11.01	8.12	651.3	36	6.8	450.4	31.1	10	5.3
	Eastern Bypass Hotoro Kano	11.49	8.71	1289	65	6.6	737.9	30	9	3.6
	No. 70 Ring Road Bypass	113.9	8.22	1871	45	5.6	2700	30.9	19	2.4
	No. 34 Ring Road Bypass	11.19	8.3	702.3	62	5.8	484.3	30.8	10	4.9
	Hotoro Kano	11.22	8.24	715	31	6.5	4917	29.9	9	5.3
2	Kano Municipal 1	11.17	8.31	293.7	6	6.9	202	30	9	5.3
	Kano Municipal 2	11.22	8.3	371.2	16	6.1	256.1	30.9	8	5.2
	Kano Municipal 3	11.46	8.31	346	54	6.5	239	30.8	14	5.6
	Kano Municipal 4	11.19	8.31	753.1	6	7.6	520.1	29.9	12	4.9
	Kano Municipal 5	11.44	8.31	415	8	6.2	286.4	30	13	5.5
	Kano Municipal 6	11.29	8.31	507.7	5	6.5	734.5	29.4	16	5.3
	Kano Municipal 7	11.36	8.31	424.2	16	6	424.2	30.5	9	5.7
	Kano Municipal 8	11.25	8.32	1402	25	8.7	2030	31.7	19	3.2
	Kano Municipal 9	11.46	8.31	1757	26	8	1211	29.9	13	3.6
	Kano Municipal 10	11.48	8.32	1633	35	8.5	2370	29.4	16	2.6
3	Kumbotso 1	12.05	8.54	1365	34.6	6.6	1546	32.1	13	5.6
	Kumbotso 2	12.07	8.55	377.4	54.3	6.9	514.8	30.8	16	5.2
	Kumbotso 3	12.08	8.56	413.1	55.2	6.6	285	29.9	9	4.6
	Kumbotso 4	12.09	8.57	603.1	12.6	7	420.8	30	19	5.2
	Kumbotso 5	12.09	8.59	1452	10.5	6.7	1001	30.9	11	6.9
	Kumbotso 6	12.1	8.59	176.2	15	7.5	115.2	30.8	13	5.6
	Kumbotso 7	12.11	8.1	905.2	9.6	6.9	1308	29.9	11	5.9
	Kumbotso 8	12.12	8.21	610.2	6.1	7	884.9	30	16	6.3
	Kumbotso 9	12.13	8.52	576	9.3	6.6	399	29.4	13	5.5
	Kumbotso 10	12.14	8.03	992.5	5.8	6.9	720.5	30.8	10	6.4
	Aliko Oil Fueling Station	11.38	8.26	323	31	7.8	2030	32.1	10	5.7
	HJRBDA Office	11.38	8.27	257	6	7.1	1211	31.7	9	3.2
	Kadawa Pri. Health Care	11.38	8.27	534	16	7	2370	29.5	9	3.6
4	Tangala	11.38	8.27	1499	54	7.7	1546	32.6	8	2.6
	Kofar Fada Jummat Mosque	11.38	8.24	1704	6	7.9	514.8	30.3	14	5.6
	Makara Huta Borehole	11.38	8.27	1312	8	7.9	225	32.3	12	5.2
	Rijiyar Isha'u	11.39	8.25	727	5	6.6	320.8	29	13	4.6
	Rijiyar Gidan Ganji	11.38	8.27	831	16	6.6	101	29.6	16	5.2
	Maza Waje Borehole	11.39	8.24	367	25	6.6	105.2	30	9	6.9
	Ali Yage Borehole	11.38	8.26	367	26	6.7	1208	31	19	5.6
	Rijiyar Gidan Mallam Kabiru	11.38	8.24	444	35	6.6	2043	32.6	13	5.7
	Babawa 1	12	8.41	293.7	6	6.9	202	29.4	9	5.3
5	Babawa 2	12	8.51	371.2	16	6.1	256.1	32.1	8	5.2
	Kawaji	12	8.52	346	54	6.5	239	30.8	14	5.6
	Babawa 3	12	8.12	753.1	6	7.7	520.1	29.9	12	4.9
	Kano, Gumel Road	12	8.02	415	8	6.2	286.4	30	13	5.5
	Babawa 4	12	8.33	507.7	5	6.5	734.5	30.9	16	5.3
	Gezawa 1	12	8.22	524.2	16	5.9	424.2	30.8	9	5.7
	Gezawa 2	12	8.02	2030	25	8.6	2030	29.9	19	3.2
	Babawa 7	12	8.51	1211	26	7.9	1211	30	13	3.6
	Kawaji 2	12.01	8.1	2370	35	8.5	2370	29.4	16	2.6



[Fig.1: Distribution Patterns of Conductivity, Hardness, pH, TDS, Temperature, Turbidity, and DO2 in the Study Area]

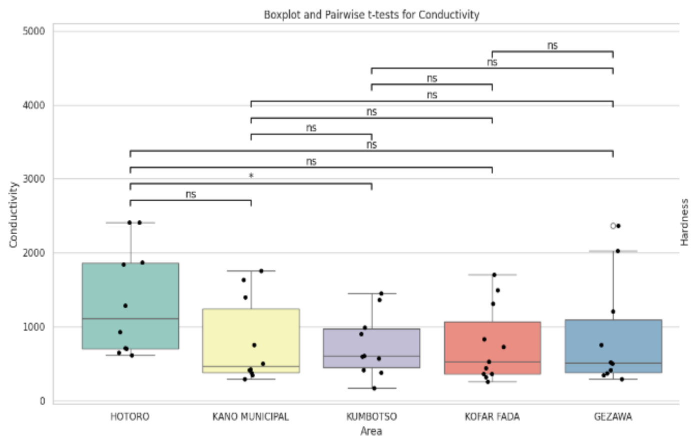


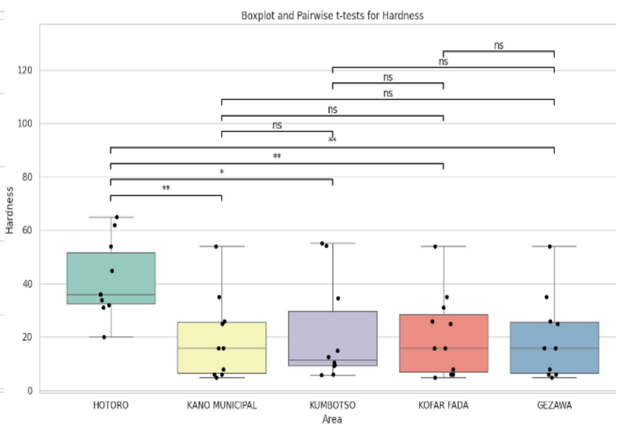
[Fig.2: Violin Plots of Conductivity Hardness, pH, and TDS Distribution in the Study Area]

Where the violin plots indicate scattered patterns of suspended solids across spatial locations, the turbidity plots show greater dispersion in KOFAR FADA, suggesting natural sedimentation or urban waste. The pair plot also shows a positive correlation between conductivity and TDS, confirming that in these water sources, higher dissolved solids concentrations are accompanied by higher ion content. The various visualisation tools, box plots, scatter plots, violins, and pair-wise relationships allow them to come up with a unified picture of how the various parameters of water quality interact spatially and physico-chemically in different locations, thus helping them to be able to monitor and manage the environment in a more targeted fashion. In general, the nature of the plotted data indicates a hydrochemical landscape of great complexity, with localised hotspots in several mineralisation, acidity, and biological oxygen demand parameters, indicative of spatial heterogeneity in land use, pollution sources, and geology. This comprehensive science visualisation highlights the importance of multi-parameter evaluation, which is necessary to accurately represent water quality and support informed planning decisions for the sustainable management of water resources in these Nigerian regions. It is consistent with standard approaches to the analysis of water quality data, in which a combination of physical, chemical, and biological indicators provides strong information on the health of an ecosystem and the effects humans have on it.

A. T-Test Plots Analysis

The plots show that there is a difference in the water quality between HOTORO, KANO MUNICIPAL, KUMBOTSO, KOFAR FADA, and GEZAWA. HOTORO and some areas of KUMBOTSO exhibit a considerably high conductivity, TDS, and hardness, indicating high mineralisation or pollution, possibly due to urban factors. Overall, pH values remain close to neutral, though with some variation that reflects changes in water chemistry and impacts on aquatic health. Dissolved oxygen tends to decline with conductivity and turbidity, indicating that at high-pollutant-load sites, oxygen deficiency occurs, affecting biological feasibility. Statistical testing reveals noticeable inter-area variability in key parameters, attributed to spatial heterogeneity arising from the complex interplay between geological and anthropogenic activities, necessitating exceptional water-quality management.





(a) Boxplot and Pairwise t-test for Conductivity **(b) Boxplot and Pairwise t-test for Conductivity**

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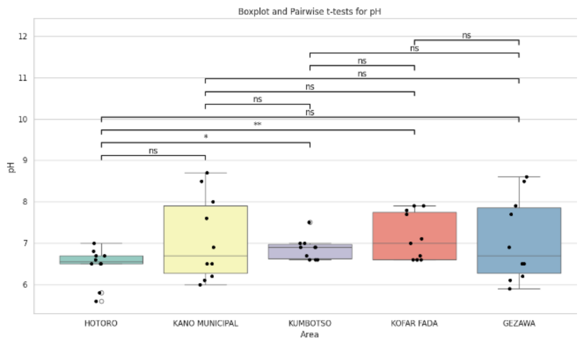
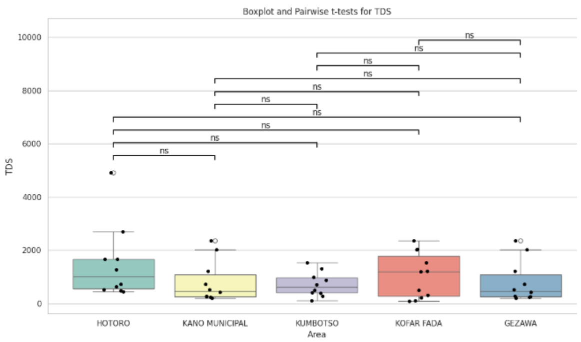
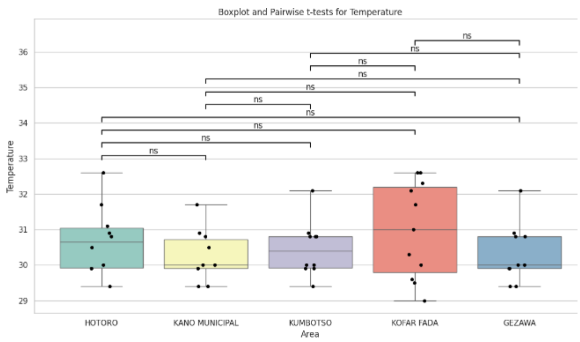


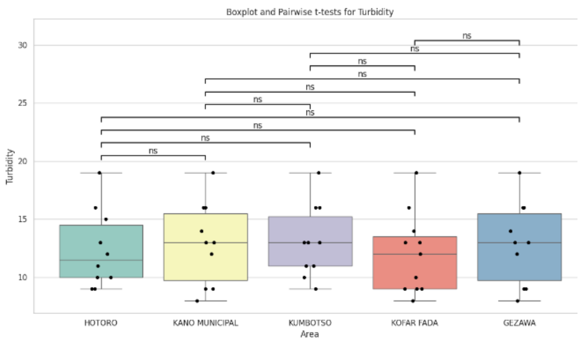
C) Boxplot and Pairwise t-test for pH



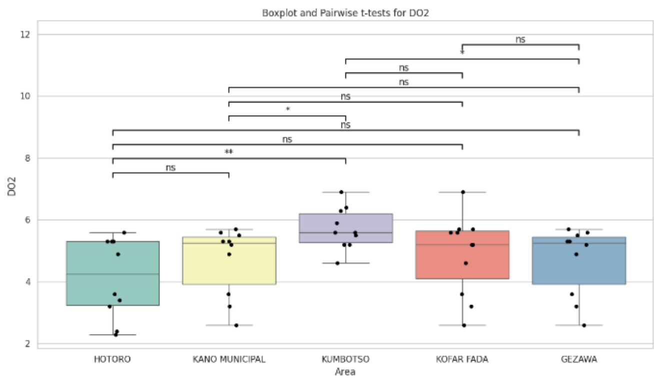
(D) Boxplot and Pairwise t-test TDS



(E) Boxplot and Pairwise t-test for Temperature

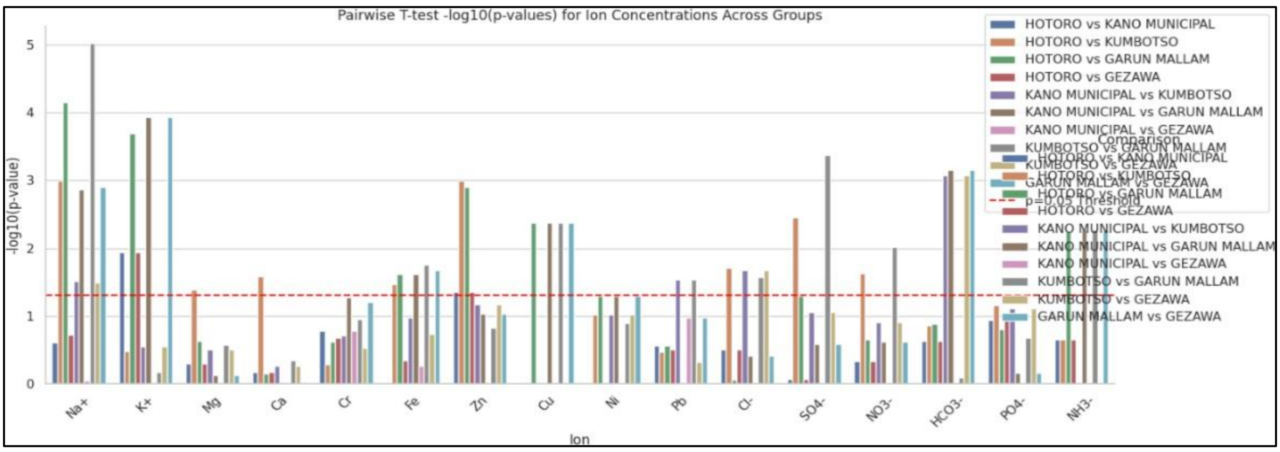


(F) Boxplot and Pairwise t-test for Turbidity



(G) Boxplot and Pairwise t-test for DO_2

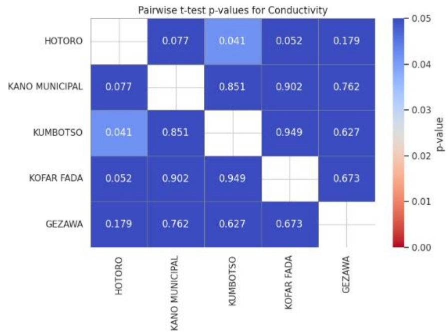
[Fig.3: Showing (a) Boxplot and Pairwise t-test for Conductivity, (b) Boxplot and Pairwise t-test for Conductivity, (C) Boxplot and Pairwise t-test for pH, (d) Boxplot and Pairwise t-test TDS, € Boxplot and Pairwise t-test for Temperature, (f) Boxplot and Pairwise t-test for Turbidity and (G) Boxplot and Pairwise t-test for DO2.]



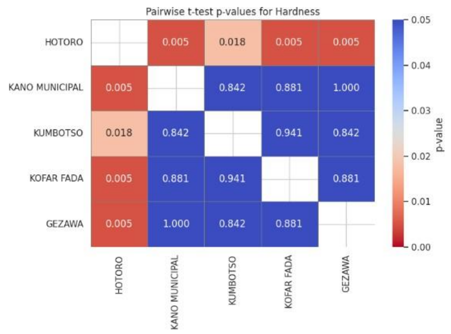
[Fig.4: Boxplot and Pairwise t-Test for all the Cations and Anions in the Study Area]

B. P-Value Plots Analysis

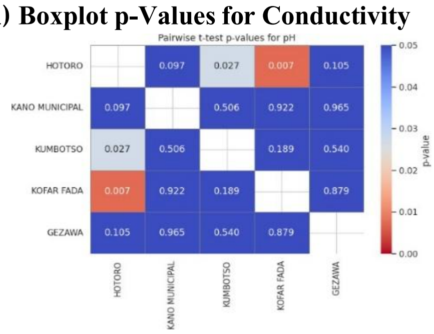
The heat maps of p-value of the pairwise t-tests indicate which parameters of water quality are significantly different between the five regions of HOTORO, KANO MUNICIPAL, KUMBOTSO, KOFAR FADA, and GEZAWA. Statistically significant differences are reported at low p-values (usually <0.05), underscoring the spatial heterogeneity of water quality. Conductivity, TDS, and hardness are parameters that are typically very different in more built-up or industrialized areas (such as HOTORO) compared to the less affected ones. On the other hand, parameters with significant p-values indicate some areas of similarity in water quality. The visualizations assist in setting.



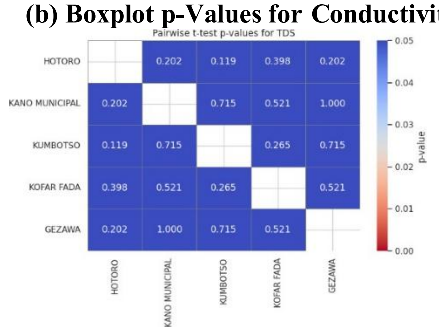
(a) Boxplot p-Values for Conductivity



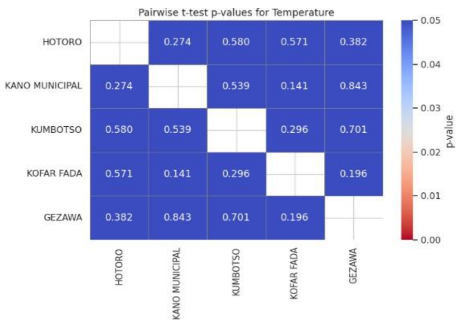
(b) Boxplot p-Values for Conductivity



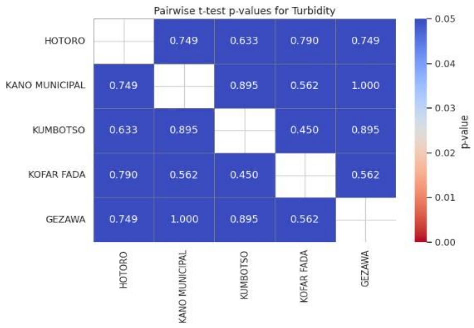
(C) Boxplot p-Values for pH



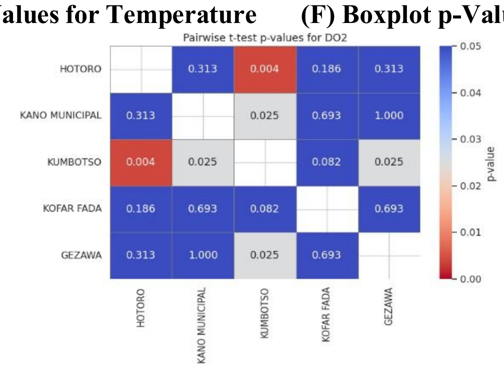
(D) Boxplot p-Values for TDS



(E) Boxplot p-Values for Temperature



(F) Boxplot p-Values for Turbidity



(G) Boxplot p-Values for DO_2

[Fig.5: Showing (a) Boxplot p-Values for Conductivity, (b) Boxplot and p-Values for Conductivity, (C) Boxplot p-Values for pH, (d) Boxplot p-Values for TDS, € Boxplot p-Values for Temperature, (f) Boxplot p-Values for Turbidity, and (G) Boxplot p-Values for DO_2.]

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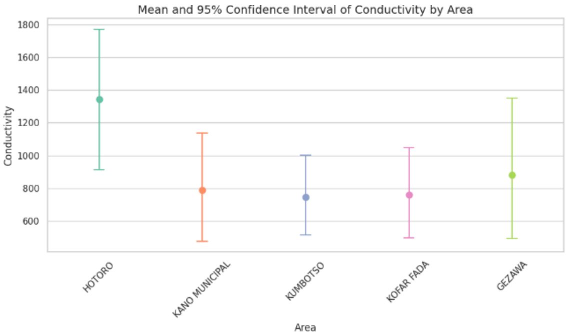
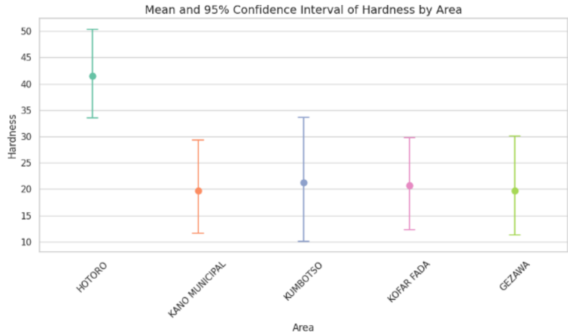
C. Confidence Interval Plots

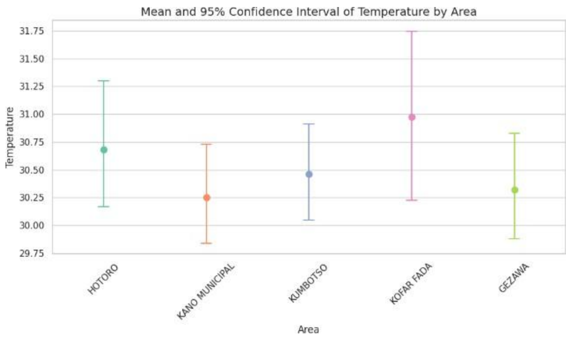
The Confidence interval plot of water quality parameters of HOTORO, KANO MUNICIPAL, KUMBOTSO, KOFAR FADA, and GEZAWA shows the estimate of the mean with the range of uncertainty at a typical 95% confidence level. Narrower intervals indicate consistent, reliable measurements in an area, whereas wider intervals indicate greater variability or fewer data points. Disagreement between the mean values and non-overlapping confidence intervals between areas indicates a statistically significant difference in water quality (e.g., conductivity or TDS), which may be attributed to spatial heterogeneity arising from geology or anthropogenic activity. All in all, these plots provide effective, scientifically robust visual summaries that compare water quality status with greater confidence across regions and enable sharply focused management decisions.



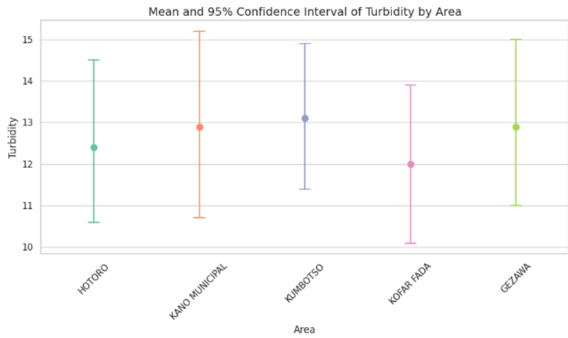
(a) Mean & 95% Confidence Interval of Conductivity



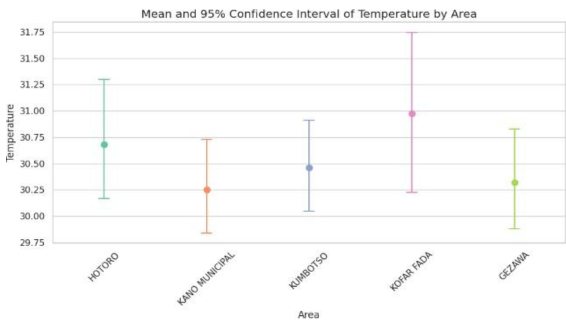
(b) Mean & 95% Confidence Interval of Hardness



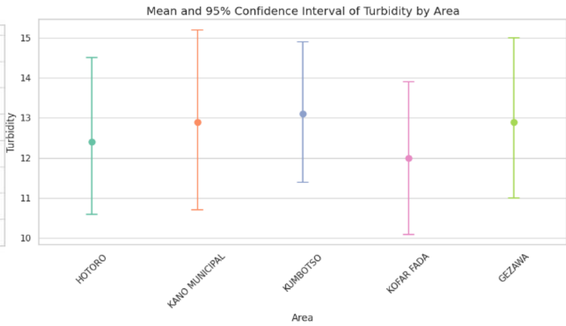
(c) Mean & 95% Confidence Interval of Hardness pH



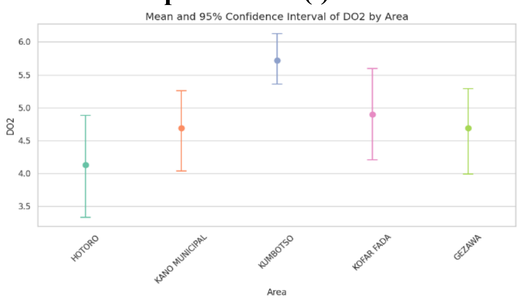
(d) Mean & 95% Confidence Interval of TDS



(e) Mean & 95% Confidence Interval of Temperature



(f) Mean & 95% Confidence Interval of Turbidity



(g) Mean & 95% Confidence Interval of DO_2

[Fig.6: (a) Mean & 95% Confidence Interval of Conductivity, (b) Mean & 95% Confidence Interval of Hardness, (c) Mean & 95% Confidence Interval of Hardness pH, (d) Mean & 95% Confidence Interval of TDS, (e) Mean & 95% Confidence Interval of Temperature, (f) Mean & 95% Confidence Interval of Turbidity and (g) Mean & Confidence Interval of DO_2.]

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Table II: Showing Locations with Cation Concentration in the Study Area

S/No	Name	Na+	K+	Mg2+	Ca2+ (Meq)	Cr	AS	Fe	Zn	Cu	Ni	Pb	Cd
1	Sabon bakin zuwo Hotoro GRA	23.4	0.1	23.2	16.4	0	0	0.01	0	0	0	0	0
	No. 6 Hotoro Avenue	21.6	0.2	9.2	8.5	0	0	0	0	0	0	0	0
	Hotoro	20.4	0	34.2	9.6	0.04	0	0.01	2.51	0.4	0	0.004	0
	No. 1 Sabo Bakin Zuwo Road.	26.6	0	54.2	10.2	0	0	0.02	1.63	0.3	0	0.003	0
	No. 13 Sabo Bakin Zuwo Road	45.9	0	13.2	9.3	0.01	0	0.03	3.31	0.6	0	0.003	0
	Tarauni	54.9	0	15.6	16.1	0	0	0	1.6	0	0	0.1	0
	Eastern Bypass Hotoro Kano	61.3	0.1	11.5	12.2	0	0	0.04	2.61	0.2	0	0.002	0
	No. 70 Ring Road Bypass	34.1	0.2	10.3	16.6	0.01	0	0.04	1.56	0.5	0	0.002	0
	No. 34 Ring Road Bypass	23.6	0.3	9.5	9.5	0	0	0.001	1.23	0	0	0.001	0
	Hotoro Kano	21.6	0.2	15.6	12.9	0	0	0	1.65	0	0	0	0
2	Kano Municipal 1	12	0	4.3	3.5	0	0	0.001	0	0	0	0	0
	Kano Municipal 2	31	0	5.2	9.1	0	0	0.001	0	0	0	0	0
	Kano Municipal 3	15.4	0	6.2	5.5	0	0	0.002	0.04	0.002	0	0	0
	Kano Municipal 4	12.5	0	5.2	4.2	0	0	0.001	0.14	0	0	0	0
	Kano Municipal 5	10.4	0	5.2	6.5	0	0	0.001	0.45	0	0	0	0
	Kano Municipal 6	54.1	0	6.2	4.3	0	0	0.002	0.1	0	0	0	0
	Kano Municipal 7	12.5	0	6.5	3.5	0	0	0.001	0.31	0	0	0.001	0
	Kano Municipal 8	10.6	0	16.3	12.6	0.001	0	0.06	3.01	0	0	0.003	0
	Kano Municipal 9	45.1	0	56.2	34.2	0.004	0	0.04	1.03	0	0	0.002	0
	Kano Municipal 10	43.3	0	36.3	23.4	0.001	0	0.04	1.3	0.001	0	0.005	0
3	Kumbotso 1	12	0.02	6.4	9.1	0	0	0.01	0	0	0	0.001	0
	Kumbotso 2	5.1	0	10.3	15	0.02	0	0	0	0	0	0.005	0
	Kumbotso 3	10.3	0.03	6.6	13.3	0.01	0	0.01	0.01	0.4	0	0.004	0
	Kumbotso 4	16.4	0.54	12.6	6.5	0	0	0	0.01	0.3	0	0.003	0
	Kumbotso 5	12.5	0.65	10	9.3	0	0	0	0.02	0.6	0	0.003	0
	Kumbotso 6	14	0.02	11	6.9	0	0	0	0.1	0	0	0	0
	Kumbotso 7	14.3	0	6.6	5.8	0	0	0	0.02	0	0	0	0
	Kumbotso 8	10.3	9.5	9.5	4.9	0	0	0	0.01	0	0	0	0
	Kumbotso 9	6.5	0.01	6.3	9.4	0	0	0	0.01	0	0	0	0
	Kumbotso 10	6.1	0	8.2	5.3	0	0	0	0.01	0	0	0	0
4	Aliko Oil Fueling Station	0	1.83	6	5.61	0	0	0.1	0.04	0.7	0	0	0
	HJRBDA Office	0	0.96	4	3.21	0.001	0	0	0.02	0.6	0.02	0.001	0
	Kadawa Pri. Health Care	0	1.88	7	6.11	0	0	0.2	0.02	0	0	0	0
	Tangala	0	2.67	31	24.63	0.003	0	0.4	0.02	0	0.02	0.003	0
	Kofar Fada Jummat Mosque	0	2.9	28	31.06	0.002	0	0.8	0.01	0.4	0.03	0.002	0
	Makara Huta Borehole	0	2.05	30	21.08	0.03	0	0.3	0.04	0.2	0.06	0.003	0
	Rijiyar Isha'u	0	0.64	9	5.86	0.004	0	0.2	0.26	0.1	0.01	0.004	0
	Rijiyar Gidan Ganji	0	0.66	8	5.62	0.005	0	0	0	0.2	0	0.005	0
	Maza Waje Borehole	1.4	0.91	6	5.69	0.081	0	0	0.32	0.3	0	0.081	0
	Ali Yage Borehole	0	0.89	4	4.99	0.036	0	0	0.02	0.1	0	0.036	0
Rijiyar Gidan Mallam Kabiru 0.00 1.01 7 6.82 0.018 0.00 0.3 0.04 0.2 0.00 0.018 0.00													
5	Babawa 1	12	0	4.3	3.5	0	0	0.001	0	0	0	0	0
	Babawa 2	31	0	5.2	9.1	0	0	0.001	0	0	0	0	0
	Kawaji	15.4	0	6.2	5.5	0	0	0.002	0.04	0	0	0	0
	Babawa 3	12.5	0	5.2	4.2	0	0	0.001	0.14	0.002	0	0	0
	Kano, Gumel Road	10.4	0	5.2	6.5	0	0	0.001	0.45	0	0	0	0
	Babawa 4	54.1	0	6.2	4.3	0	0	0.002	0.1	0	0	0	0
	Gezawa 1	12.5	0	6.5	3.5	0	0	0.001	0.31	0	0	0.001	0
	Gezawa 2	10.6	0	16.3	12.6	0.001	0	0.006	3.01	0	0	0.003	0
	Babawa 7	45.1	0	56.2	34.2	0.004	0	0.04	1.03	0	0	0.002	0
	Kawaji 2	34.3	0	36.3	23.4	0.001	0	0.04	1.3	0.001	0	0.005	0

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Table III: Showing Locations with Anion Concentration in the Study Area

S/No	Name	Cl-	SO4-	NO3- (Meq)	HCO3-	PO_2 4-	NH3-
1	Sabon bakin zuwo Hotoro GRA	0.34	0.2	0	13	0	0
	No. 6 Hotoro Avenue	1.45	0.5	0.13	12	0	0
	Hotoro	1.21	54	6.9	16	0	0.01
	No. 1 Sabo Bakin Zuwo Road.	1	63	9.6	10	0.6	0.01
	No. 13 Sabo Bakin Zuwo Road	0.46	69	12	116	3.5	0
	Tarauni	0.13	13	0.1	23	0.5	0
	Eastern Bypass Hotoro Kano	0.54	49	16	241	1.6	0.01
	No. 70 Ring Road Bypass	0.21	68	12.9	432	0.3	0
	No. 34 Ring Road Bypass	0.04	23	0.2	13	0.34	0.03
	Hotoro Kano	0.01	16	0.1	14	0.23	0.21
	Kano Municipal 1	0	0.02	0.04	130	0	0
	Kano Municipal 2	0	0	0.6	112.3	0	0
	Kano Municipal 3	0	0	0.3	134	0.02	0
	Kano Municipal 4	0	0	0.5	95.4	0	0
	Kano Municipal 5	1.45	0	0.5	122	0	0
	Kano Municipal 6	2.41	0	0.6	65.3	0	0
	Kano Municipal 7	1.45	0	0.2	56.6	0.03	0
2	Kano Municipal 8	0.34	123.1	34.52	256.3	0.4	0
	Kano Municipal 9	1.68	140.6	56.3	316.2	0.2	0.02
	Kano Municipal 10	1.46	134.3	13.6	255.6	0.4	0
	Kumbotso 1	0.04	0.01	0.51	11	0	0
	Kumbotso 2	0.05	0.63	0.13	16	0	0
	Kumbotso 3	0.01	0.53	0.15	17	0	0
	Kumbotso 4	0.02	0.13	0.46	19	0.1	0
	Kumbotso 5	0.16	0	0.23	13	0	0
	Kumbotso 6	0.13	0.06	0.25	16	0.1	0
	Kumbotso 7	0.06	0.14	0.15	18	1.3	0
3	Kumbotso 8	0.26	0.45	0.16	19	0	0
	Kumbotso 9	0.03	2.33	0.26	14	0	0
	Kumbotso 10	0.05	6.45	0.54	18	0	0
	Aliko Oil Fueling Station	0.7	16.5	0.9	0	0.1	0.9
	HJRBDA Office	0.2	13.1	1.3	0	0	1.3
	Kadawa Pri. Health Care	0	10.4	4.1	8	0.1	4.1
	Tangala	0.1	16.5	1.9	48	1.3	1.9
	Kofar Fada Jummat Mosque	1.4	10.4	1.4	57	0	1.4
	Makara Huta Borehole	1	9.3	9.3	32	0	9.3
	Rijiyar Isha'u	0.6	16.8	2	14	0	2
4	Rijiyar Gidan Ganji	0.1	36	2.9	0	0.1	2
	Maza Waje Borehole	1.9	25.5	6.8	0	0	2.9
	Ali Yage Borehole	0.3	14.1	3.8	0	0.1	6.8
	Rijiyar Gidan Mallam Kabiru	0	0.02	4	0	0	0
	Babawa 1	0	0	0.04	130	0	0
	Babawa 2	0	0	0.6	112.3	0	0
	Kawaji	0	0	0.3	134	0.02	0
	Babawa 3	0	0	0.5	95.4	0	0
	Kano, Gumel Road	1.45	0	0.5	122	0	0
	Babawa 4	2.41	0	0.6	65.3	0	0
	Gezawa 1	1.45	0	0.2	56.6	0.03	0
5	Gezawa 2	0.34	123.1	34.52	256.3	0.4	0
	Babawa 7	1.68	140.6	56.3	316.2	0.2	0.02
	Kawaji 2	1.46	134.3	13.6	255.6	0.4	0

The table contains details of the major cations (Na+, K+, Mg2+, Ca2+) and trace/toxic elements (Chromium, Arsenic, Iron, Zinc, Copper, Nickel, Lead, Cadmium), along with their concentrations at different groundwater sites. The major ion chemistry is primarily dominated by sodium, magnesium, and calcium, whose levels vary widely between sites; sodium is relatively high at Tarauni and Eastern Bypass Hotoro, Kano, whereas magnesium and calcium are high at some Hotoro and Kumbotso locations. There is a generally low value of Potassium that is characteristic of natural waters because of its reactivity in soils. Trace metal and heavy metal analysis shows that most samples have undetectable or extremely low concentrations of chromium, arsenic, copper, nickel, lead, and cadmium, posing little risk of acute toxicity under current circumstances. The presence of iron is sometimes observed at low concentrations, which is not uncommon in groundwater and can be related to the aquifer's mineralogy. Zinc intermittently trends upward, particularly in Hotoro and some of the Kanomunicipal samples, and this could be indicative of localised anthropogenic enrichment or natural fluctuations. Still, there appear to be very low levels of metals that could be considered harmful. Spatial heterogeneity indicates environmental importance when spiked levels of sodium, magnesium, calcium, or zinc occur at specific sites (e.g., No. 13 Sabo Bakin Zuwo Road, Eastern Bypass Hotoro Kano, Babawa 7). Hence, any of these attributes is attributable to the geology, land use, or potential pollution. Nevertheless, the general outline of trace metals indicates that water is generally safe with respect to heavy metal emissions. Persistent monitoring should also be necessary, as occasional surges in metals such as Pb, Fe, and Zn,

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particularly in affected areas, may indicate episodic contamination events or changing land-use demands.

D. Correlation Plot

In Hotoro, the correlation matrix demonstrates linear relationships that suggest familiar sources or geochemical behaviours. Notably, ions such as Na+, Cl-, and SO42- show strong positive correlations, indicating a shared origin, likely from geochemical processes or pollution sources. The heatmap facilitates quick identification of ion groups that co-occur, aiding in understanding water chemistry dynamics and potential environmental impacts.

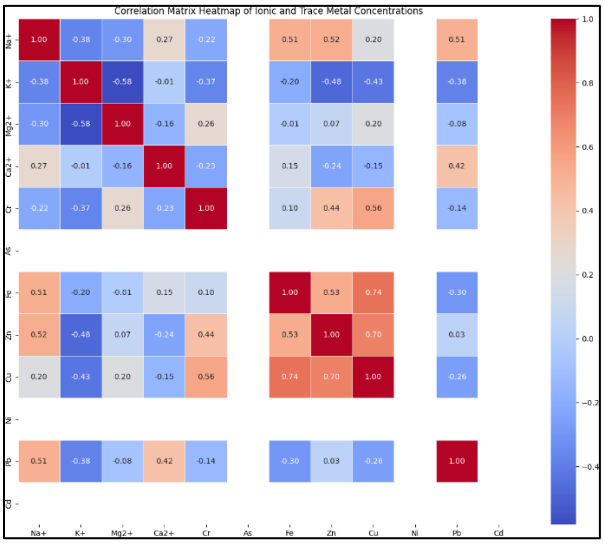
Kano Municipal's correlation plot emphasizes interactions among ions like Na+, Mg, and Ca, which are indicative of mineral dissolution and water-rock interactions. High positive correlations denote shared geochemical controls, while low or zero correlations suggest independent sources or processes. Negative correlations, though less prominent, could highlight contrasting behaviours or contamination influences, guiding resource management and pollution assessment.

In Kumbotso, the correlation analysis underscores the interconnectedness of ions such as Mg and Ca, which tend to vary together due to similar geochemical controls. The heatmap visualises these relationships, assisting in deciphering water chemistry trends and contamination impacts, which are essential for environmental decision-making.

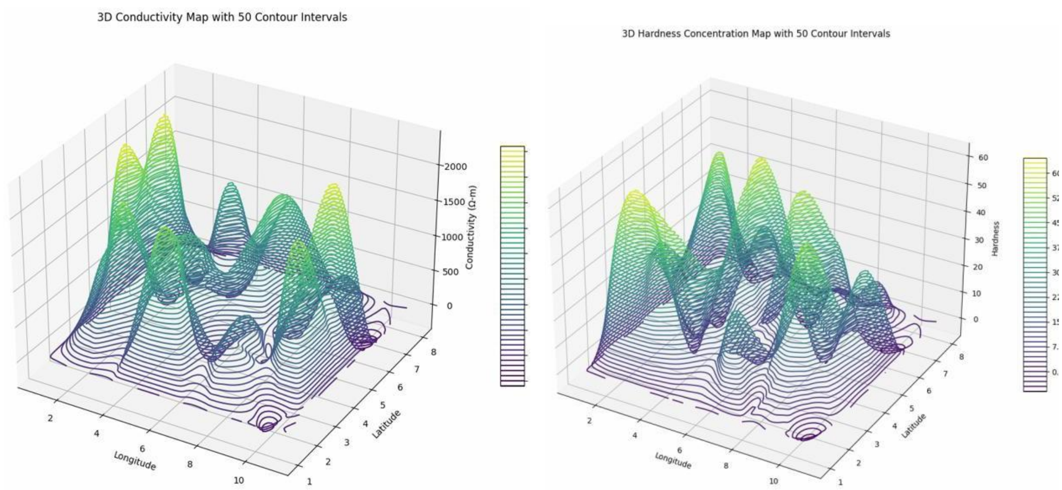
Garun Mallam's data reveal strong positive correlations between alkaline earth metals (Mg, Ca) and major ions such as K+, indicating familiar natural sources, such as mineral dissolution. Conversely, trace metals and some ions exhibit weak or null correlations, suggesting different sources or limited contamination. The correlation matrix supports targeted environmental evaluations and resource management strategies.

Gezawa's correlation plot shows a strong positive relationship among the major cations (Ca, Mg, Na), reflecting their origin from water-rock interactions. Trace metals such as Fe, Zn, and Pb exhibit weaker correlations, suggesting diverse sources or localized contamination. The visualization aids in identifying parameters that co-vary, informing environmental monitoring and pollution control efforts.

Collectively, these correlation analyses across all localities provide a comprehensive understanding of the interactions among water quality constituents. They highlight shared sources, geochemical behaviours, and potential pollution influences, serving as crucial tools for environmental assessment, resource management, and pollution mitigation strategies in the respective communities (Figure 7).



[Fig.7: Correlation Plot in the Study Area]



(a) Conductivity Concentration (b) Hardness Concentration

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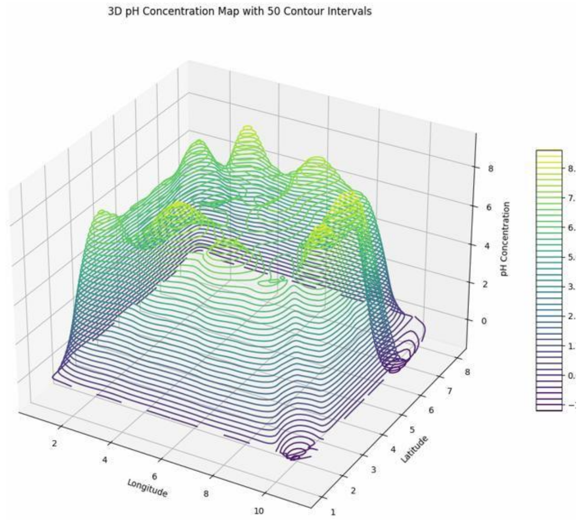
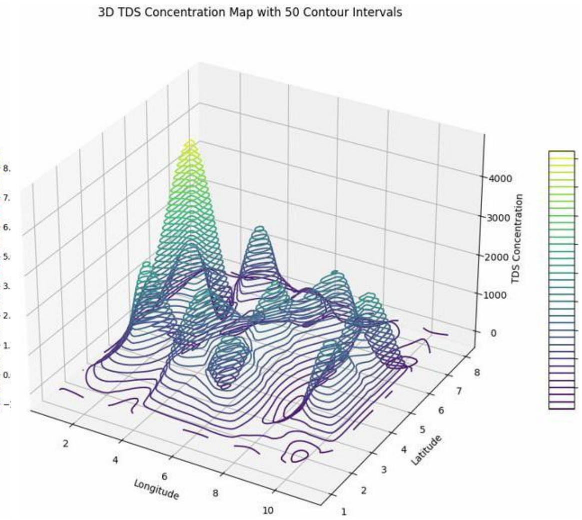
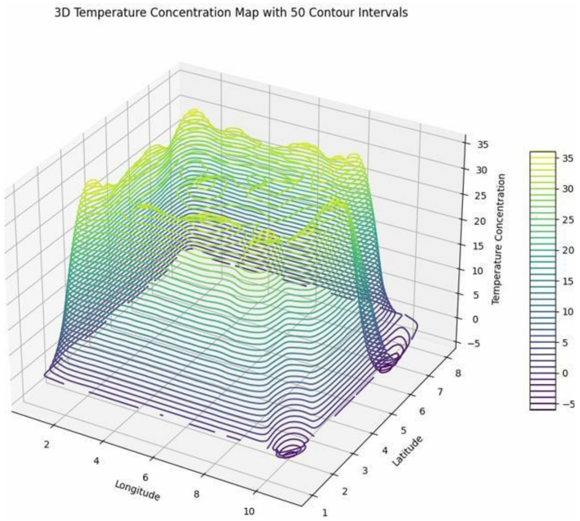


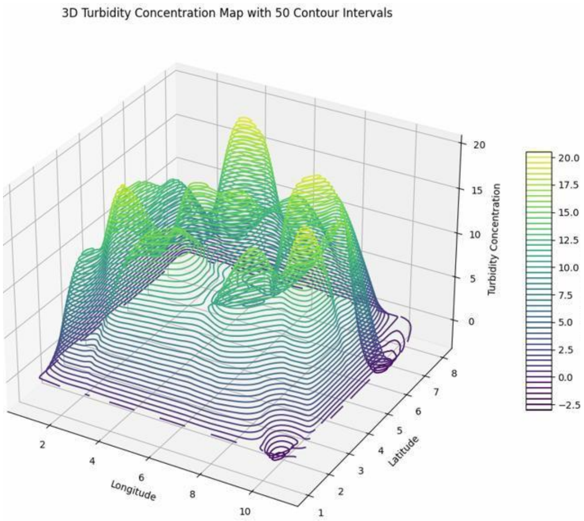
(c) pH Concentration



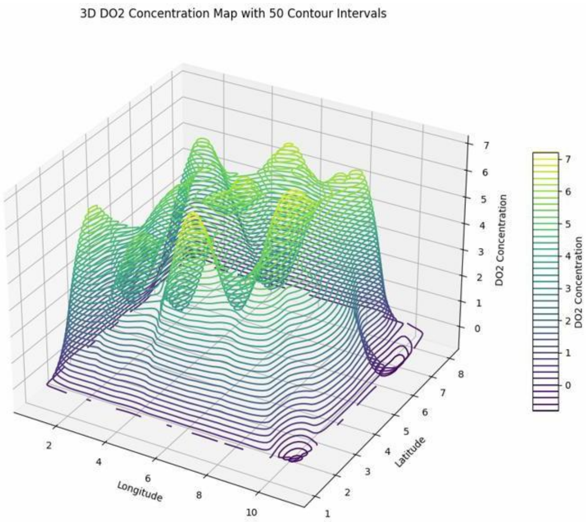
(d) TDS Concentration



(e) Temperature Concentration



(f) Turbidity Concentration

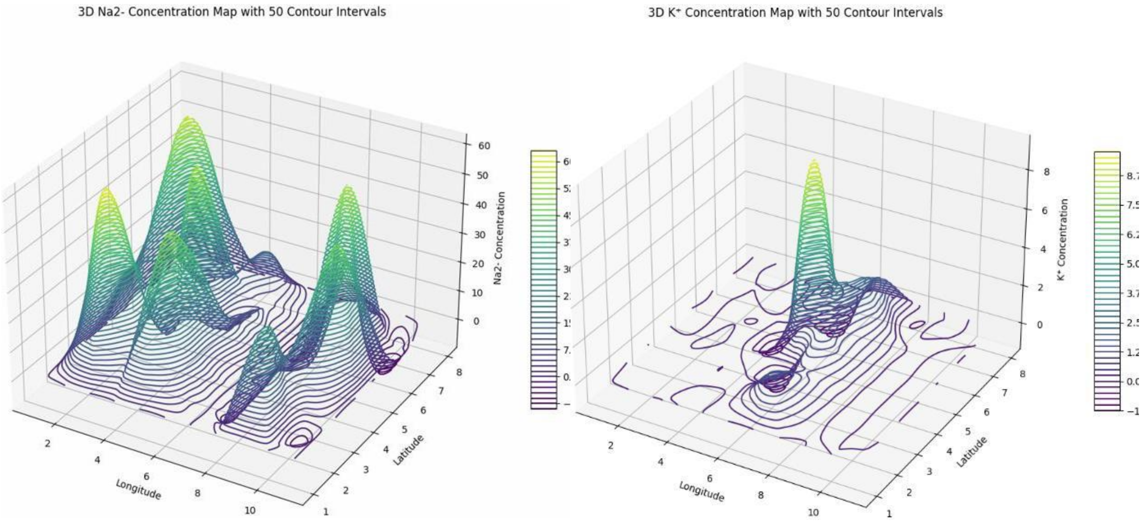


(g) DO_2 Concentration

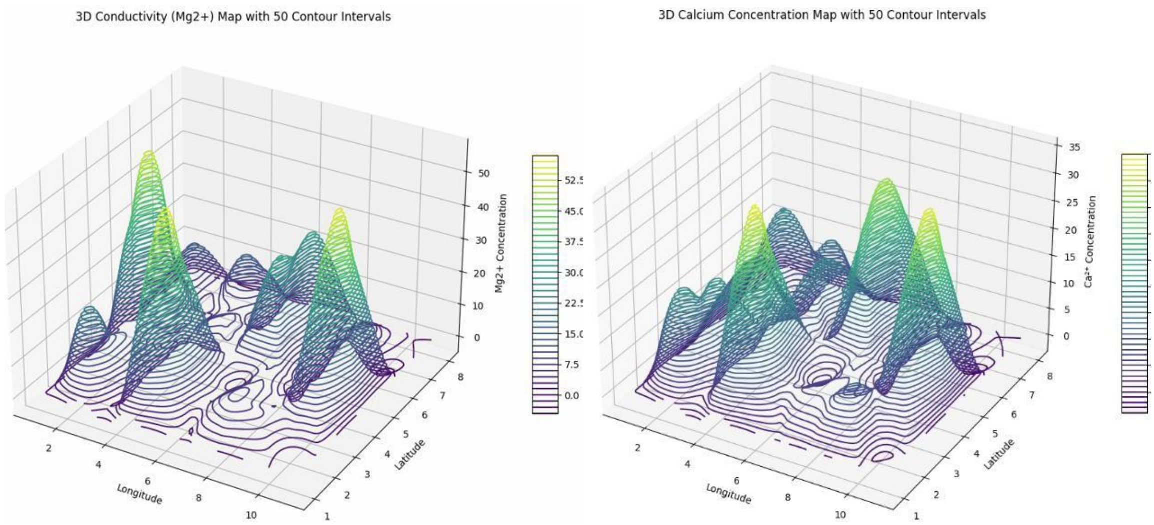
[Fig.8: (a) Conductivity Concentration, (b) Hardness Concentration, (c) pH Concentration, (d) TDS Concentration, (e) Temperature Concentration, (f) Turbidity Concentration, and (g) DO_2 Concentration of the Study Area]

The spatial analysis of environmental parameters reveals significant variability across the surveyed region. Conductivity exhibits high spatial heterogeneity, with zero values at some locations and peaks mainly in central areas, indicating diverse mineral content, soil salinity, and environmental influences. Such variability necessitates advanced geostatistical methods, such as kriging, for accurate mapping and resource assessment. Similarly, pH values range from approximately 5.6 to 8.7, with zero boundary values, reflecting heterogeneous soil and water conditions influenced by mineral weathering, organic matter decomposition, and microbial activity. This heterogeneity, with regions of acidity and alkalinity, impacts nutrient cycling, microbial processes, and environmental health, requiring localised evaluation and geostatistical modelling for effective management. Total Dissolved Solids (TDS) demonstrate substantial spatial variation, with boundary values ranging from 0 to 4917 mg/L, indicating complex geochemical and pollutant distributions that influence water quality and ecological safety. Monitoring is essential to identify sources of mineralisation or contamination. Temperatures remain moderately stable, ranging from 29° C to 33°C, with minor local fluctuations driven by land cover, microclimate, and shading. These temperature patterns influence ecological processes like evapotranspiration and species distribution, informing urban planning and climate mitigation strategies.

Turbidity levels are moderate (8-19 NTU), predominantly along edges, indicating a stable presence of suspended particles that can impair aquatic life by reducing light penetration and conveying pollutants. Elevated turbidity can harm ecosystems, necessitating ongoing monitoring and actions to control erosion and runoff. Dissolved oxygen (DO2) ranges from 2.3 to 6.9 mg/L internally, with boundary values, suggesting generally moderate water quality but localised hypoxia near 2.3 mg/L. These patterns highlight the influence of biological activity, organic matter decomposition, and environmental factors, serving as critical indicators for ecosystem health, pollution detection, and management efforts to preserve aquatic biodiversity and water quality. Overall, these parameters underscore the importance of geostatistical approaches for precise mapping, prediction, and sustainable environmental management (Figure 8).



(a) Sodium Concentration **(b) Potassium Concentration**



(c) Magnesium Concentration **(d) Calcium Concentration**

[Fig.9: Cation Concentration in (Meq) in the Study Area]

The spatial variability of sodium (Na^+) concentrations ranges from 0 to approximately 61.3 mg/L, with many boundary points showing zero values, indicating the influence of geology, mineral weathering, evaporation, and human activities. While most levels are below health-concern thresholds, localised peaks indicate areas requiring monitoring due to potential impacts on water quality, soil health, and ecosystem stability. Potassium (K^+) levels are generally very low, with a maximum of around 9.5 mg/L, suggesting nutrient deficiencies affecting plant

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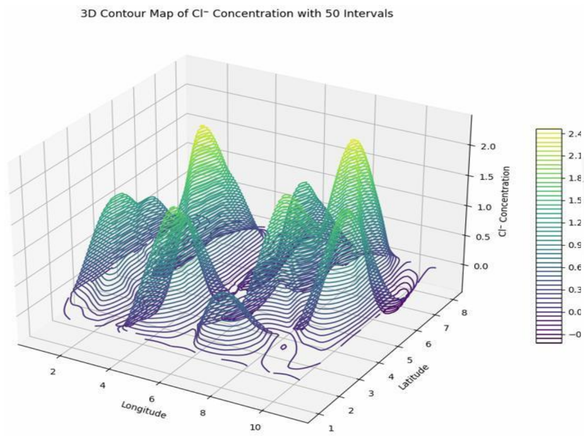
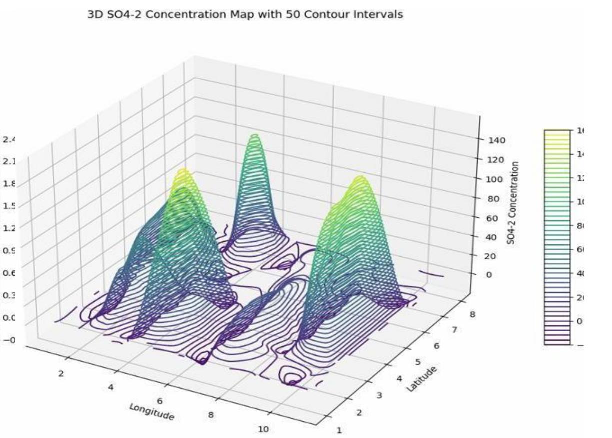
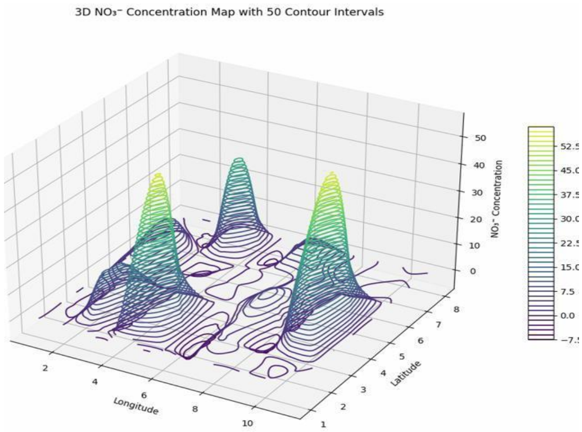
growth and soil fertility, with occasional spikes likely due to mineral weathering or fertiliser use. This diverse distribution emphasizes the need for site-specific soil and water management to address potential agricultural and ecological impacts. Magnesium (Mg^{2+}) concentrations exhibit significant spatial variation, ranging from zero at boundaries to peaks of around 56.2 mg/L, driven by processes such as mineral weathering and water-rock interactions that affect water hardness, alkalinity, and ecological health. Continuous monitoring and geostatistical mapping are essential for managing magnesium's influence on water and soil quality. Similarly, calcium (Ca^{2+}) levels vary from zero to over mg/L, reflecting geochemical and anthropogenic influences. Calcium plays a crucial role in buffering acidity, stabilizing pH, supporting aquatic life, and promoting plant growth. Variations in calcium levels affect ecosystem productivity and stress, underscoring the importance of spatial surveillance and geostatistical analysis for effective management of soil fertility and water quality (Figure 9).



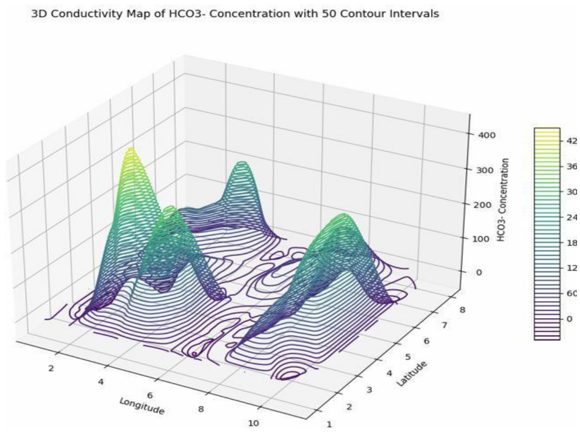
(a) Chlorine Concentration



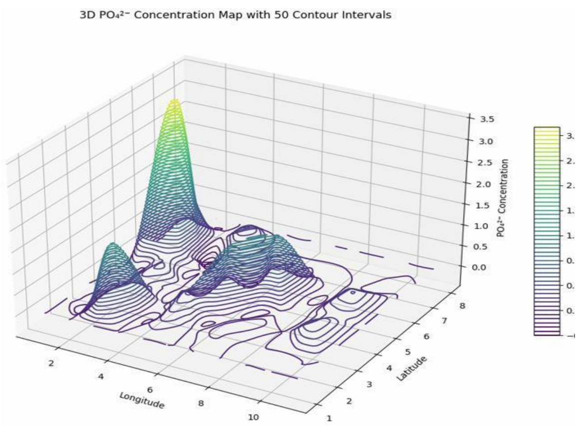
(b) Sulphate Concentration



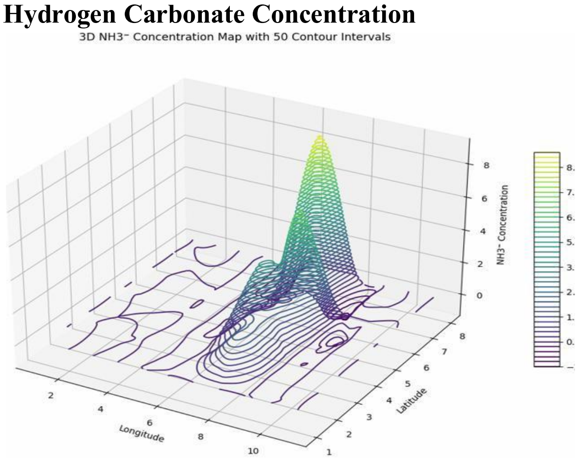
(c) Nitrate Concentration



(d) Hydrogen Carbonate Concentration



(e) Polonium Concentration



(f) Ammonia Concentration

[Fig.10: Anion Concentration in (Meq) the Study Area]

The water quality data across the surveyed area reveal significant spatial variability in key chemical parameters, each with implications for environmental health. Chloride (Cl^-) concentrations are mostly low, generally below 2.5 mg/L, with many boundary points registering zero, suggesting minimal current contamination or salinity intrusion. However, elevated chloride levels can disrupt aquatic osmoregulation, impair reproduction, and

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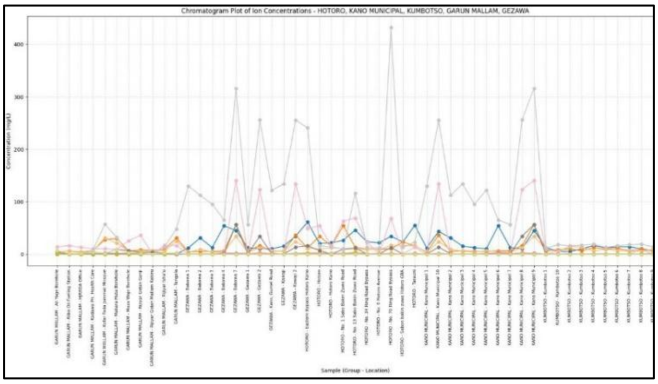
contribute to soil salinization and infrastructure corrosion, highlighting the importance of ongoing geostatistical monitoring to prevent future buildup from sources like wastewater, road salts, or agriculture. Sulfate (SO_4^{2-}) displays a heterogeneous distribution, with concentrations ranging from near zero at edges to over 140 mg/L internally. Elevated sulfate levels, naturally occurring from mineral weathering and volcanism but often intensified by human activities such as mining or industrial waste, can affect water taste, induce biogeochemical changes, and cause eutrophication and oxygen depletion, threatening aquatic ecosystems. Nitrate (NO_3^-) levels vary widely, with most boundary points showing low or zero values, but localized hotspots reaching up to 56.3 mg/L, primarily from agricultural runoff and wastewater. High nitrate levels pose risks of eutrophication, harmful algal blooms, and health issues such as methemoglobinemia, especially in infants. Many readings exceed regulatory limits, emphasizing the need for targeted management guided by geostatistical mapping. Bicarbonate (HCO_3^-) exhibits high spatial heterogeneity, with null values at boundaries and peaks exceeding 400 mg/L centrally, indicating active geochemical processes such as rock erosion and carbonate mineral dissolution. Elevated bicarbonate influences carbon cycling, aquatic photosynthesis, and metal mobility, affecting water chemistry and toxicity risks, necessitating precise monitoring. Ammonia (NH_3) concentrations are predominantly low, but localized hotspots reach up to 9.3 mg/L, suggesting pollution sources like agriculture or wastewater. High ammonia levels can damage aquatic life, especially under elevated pH and temperature, and promote harmful algal blooms, making detailed geostatistical mapping essential for ecosystem protection and water management (Figure 10).

i. *Chromatography:* The chromatogram plot visually displays the concentration profiles of a wide range of ions and trace metals across multiple sampling sites from diverse locations such as HOTORO, KANO MUNICIPAL, KUMBOTSO, GARUN MALLAM, and GEZAWA. Each ion'sconcentration is plotted as a line with markers spanning the various samples, making it straightforward to observe spatial trends, peaks, and relative abundances. This form of visualization highlights how concentrations of major cations (like Na^+, Ca^{2+}, Mg^{2+}), anions (Cl^-, SO_4^-, NO_3^-, HCO_3^-), and trace metals (Fe^{2+}, Zn^{2+}, Pb) vary from site to site, enabling identification of water quality patterns and potential contamination hotspots. The grouped x-axis by geographic areas helps compare water chemistry between regions at a glance. Such chromatogram plots serve as integration tools for complex multi-ion water-quality data, effectively summarising the chemical fingerprints of the sampled waters. Peaks in specific ions suggest elevated levels that may be driven by natural geochemical processes, such as mineral dissolution, or by anthropogenic activities, such as industrial discharge or agricultural runoff. By simultaneously displaying numerous ions, the plot fosters a holistic interpretation of water composition and potential inter-ion relationships, informing environmental monitoring, groundwater resource management, and remediation strategies. Overall, chromatogram plots facilitate a quick assessment of water-chemistry variability and serve as a visual basis for more detailed hydrochemical analysis. This approach is a standard and established method in water quality laboratory analysis and monitoring.



[Fig.11: Chromatography Plot of the Study Area]

The chromatogram plot reveals distinct spatial variation in ion and trace metal concentrations across the sampling sites from HOTORO, KANO MUNICIPAL, KUMBOTSO, GARUN MALLAM, and GEZAWA areas. Major ions such as Na+, Ca, Mg, and HCO3- are consistently present, with noticeable peaks indicating localised geochemical influences or contamination. Trace metals such as Zn and Fe exhibit elevated concentrations at specific locations, suggesting possible anthropogenic inputs or mineralogical differences. Overall, the plot highlights diverse hydrochemical signatures reflecting natural and human impacts on groundwater quality across the different regions (Figure 11).

ii. *Standard Calibration Curve:* The Standard Calibration Curve plot is used to draw the pattern of known anion concentrations and their relative instrument signals; usually, a linear regression is fitted to such data. Considering the validity of your combined water quality data, the curves show that the instrument's responses across the measured ranges of key ions such as Na+, Mg, Ca, Fe, Zn, and Pb increase proportionally with concentration. Linearity supports the assumption that concentration and signal are directly and predictably related, which is the guiding principle of quantitative analysis in unknown samples. Fitted plot lines depict the spread of the data points, and slopes and intercepts are estimated by regression analysis, which aids in computing the sample concentration based on the instrument signals.

- The effectiveness of these calibration curves is evidenced by the low spread of data points about the regression lines, which establishes good measurement accuracy and instrument reproducibility. Well-spaced standard concentrations with a wide range will minimise uncertainty in slope and intercept estimates, thus resulting in higher and better quantifications. These calibration curves can

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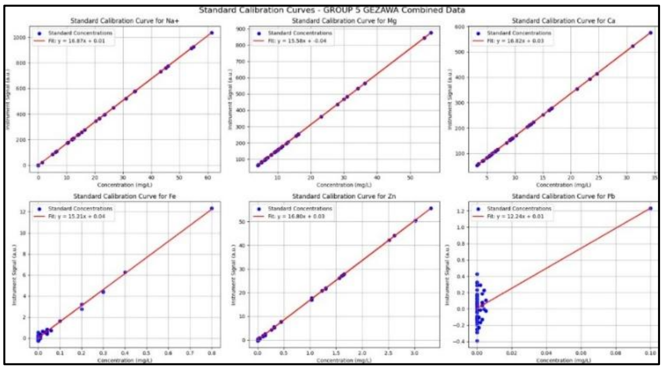
also be used to diagnose deviations from ideal behaviour, i.e., nonlinearity or excessive noise, and further evaluation of the analytical method would then be necessary. On the whole, the Standard Calibration Curve graph is one of the core work instruments in analytical chemistry, as it enables robust, accurate water quality analysis by linking instrumental output to actual ion concentrations.

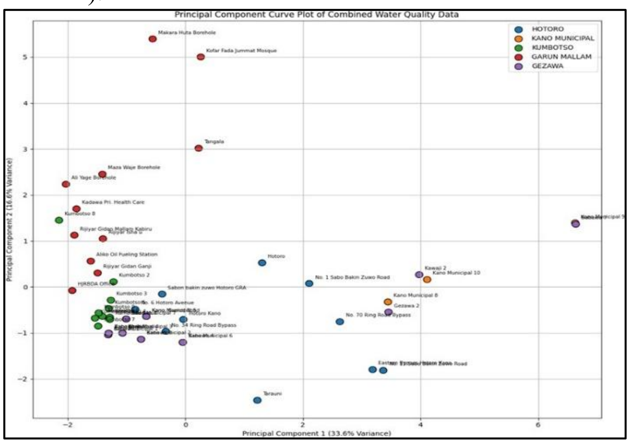


[Fig.12: Standard Calibration Curve]

The Standard Calibration Curve graph shows a high linear correlation between the ion concentrations (Na+, Mg2+, Ca2+, Fe2+, Zn2+, Pb2+) and the instrument signal, thus the quantitative analysis is precise. The small scatter about the lines indicates good precision and consistency in the measurements. Fluctuations in the slope of the ions indicate a disparity in the instrument's sensitivity to both analytes. Overall, the calibration curves confirm the analytical method's suitability for defining water quality across varied sample groups (Figure 12).

iii. *Scatter Plot:* Analysis based on the scatter plot of all generic water quality data of HOTORO, KANO MUNICIPAL, KUMBOTSO, GARUN MALLAM, and GEZAWA shows that the pair of selected ions was linked and had co-variations in varied locations. The scatter diagram can be used to plot major ions, such as Na+ against Mg, Ca vs Mg, and Zn versus Fe, to identify positive correlations between major cations that are most likely due to a common geological or hydrochemical origin, e.g., mineral dissolution and water-rock reactions. At the same time, other trace metals, including Zn and Fe, are variable, highlighting local geochemistry or artificial effects. The clustering of points by location, using different colours, is also helpful for visual identification of regional differences in hydrochemical signatures. The scatter plot can also be used as an exploratory tool to assess water quality, as it can show small groups of samples with similar ionic compositions and possibly outliers that point to contamination or an abnormal geochemical state. The trends noted in these scatterplots can also assist in multivariate analyses, such as principal component analysis, which helps interpret complex data more efficiently. In general, this kind of visualization is the accepted and very effective method of environmental chemistry used to diagnose spatial variability in water chemistry and inform local monitoring or remediation. This is in tandem with conventional wisdom that scatter plots can give a quick look as to whether water quality parameters are linearly or non-linearly related to each other, and that this information can guide holistic planning over water resources

iv. *Principal Component of Curve:* The Principal Component Curve graph prepared using the consolidated data of water quality of HOTORO, KANO MUNICIPAL, KUMBOTSO, GARUN MALLAM, and GEZAWA gives an account of consolidating multidimensional information on ion concentration into two principal components (principal element 1 and principal element 2) that represent the maximum of the variances. This dimensionality reduction reveals essential patterns and clusters in the dataset, and samples that are close together on the plot have comparable water-chemistry profiles. Percentages of explained variance for PC1 and PC2 indicate the proportion of the overall variability in the data that each PC explains, providing insight into the prevailing factors driving variation in water quality across these areas. Also, the spatial distribution of groups by colour samples on the PCA plot shows that each place has its own hydrochemical characteristics and possible natural or artificial factors that may affect it. The closer the two samples are, the more similar their ionic compositions are; conversely, the farther apart they are, the more different their water quality characteristics. The loadings (not included in the plot) behind these principal components typically indicate which ions are most responsible for these variations. They can therefore be used to guide further specific, environmentally geochemically focused studies. On balance, this PCA visualisation provides an efficient overview of complex datasets, improving insights into variations in water chemistry across regions and enabling data-driven decisions in managing water resources (Figure 14).



[Fig.14: Principal Component of Curve]

The PCA plot shows that most of the variance in the compiled water quality data is explained by the first two principal components, which emphasise the overall patterns of ion concentrations across the entire dataset due to the high degree of collinearity between the variables. Clustering samples reports distinct hydrochemical patterns and variations across the regional waters into various geographical clusters. The fact that the groups are

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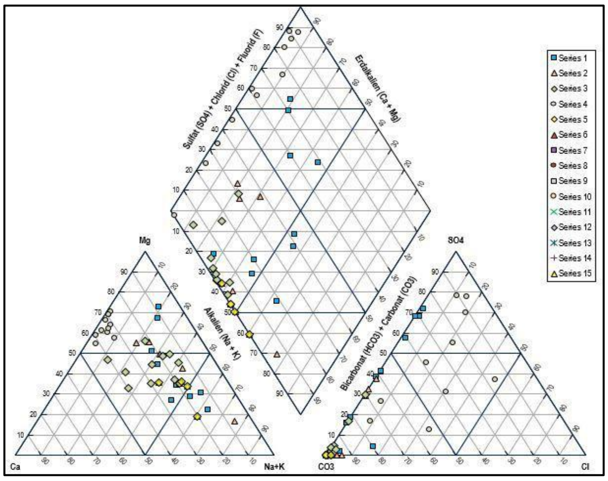
separated indicates that both natural geological effects and potential anthropogenic factors are affecting water quality. Generally, PCA is a good way to distil the complex multi-ion data. The PCA plot shows that most of the variance in the compiled water quality data is explained by the first two principal components, which emphasise the overall patterns of ion concentrations across the entire dataset due to the high degree of collinearity between the variables. Clustering samples reports distinct hydrochemical patterns and variations across the regional waters into various geographical clusters. The fact that the groups are separated indicates that both natural geological effects and potential anthropogenic factors are affecting water quality. Generally, PCA is a good way to distil the complex multi-ion data.



[Fig.15: Piper Trilinear Plot of the Study Area]

The Piper plot analysis of the presented water chemistry data shows the presence of various hydrochemical facies across the sampled locations, as the spatial variability map focuses on ionic composition. The cation triangle indicates the prevalence of Sodium (Na+) and Potassium (K+) in several samples, especially the water types with high Sodium content (e.g., more than 40 meq/L), strongly suggesting the influence of sodium-bearing minerals, a source of high Sodium content due to anthropogenic activities. Mg2+ and Ca2+ reservoirs vary considerably; locations with elevated calcium and Magnesium indicate waters subjected to the dissolution of carbonate rock or groundwater-rock interaction with typical waters of the Calcium-Magnesium bicarbonate or sulfate water variety. The anion triangle reveals an aggregate of areas dominated by bicarbonate (HCO3-), reflecting weak acid sites, and other areas dominated by high concentrations of sulfate (SO42-) and chloride (Cl-), suggesting that acidity is more substantial due to industrial or agricultural contributions. These relative patterns of the various concentrations of these major ions give discrete groups or facies, indicating variations in the influence of geochemical processes such as silicate weathering, ion exchange, or source of contamination (Figure 15).

IV. DISCUSSION

The major geochemical processes in the Kano region that determine the dominance of major ions such as sodium, calcium, and magnesium include mineral dissolution, water-rock interaction, and ion exchange, which together govern groundwater chemistry. These processes indicate the effects of local geology on water composition. Sporadic high levels of trace elements such as iron and zinc are typically associated with localised human activities such as industrial pollution and poor waste disposal. Also, organic matter decomposition influences dissolved oxygen and turbidity, which are biological factors that cause spatial disparities in water quality across sampling locations. The interaction among geological variability, land use, and urbanism is the primary driver of the high spatial heterogeneity in geological parameters, including electrical conductivity, total dissolved solids (TDS), pH, and trace metals. Multivariate statistical methods, such as principal component analysis, correlation matrices, and geostatistical mapping, can be used to find natural geochemical indicators and anthropogenic contamination. These methods identify unique hydrochemical facies and contamination foci, enabling focused groundwater management and pollution control. Continuous spatial monitoring remains essential for sustainable water management in the Kano region amid environmental variability and human-induced pressures.

The overall data on water quality across various sampling sites in the Kano area of Nigeria are characterised by a strongly heterogeneous hydrochemical distribution pattern, resulting from the intricate interplay between the lithological composition of the land and urbanisation and anthropogenic activities. The measured parameters: Electrical Conductivity, Hardness, pH, Total Dissolved Solids (TDS), Temperature, Turbidity, and the Dissolved Oxygen (DO2), are spatially classified or confined between 802°-859° latitudes and 1100°-1214° longitudes, and reflect various physical, chemical, and biological water quality indicators that differ tremendously across the locations, namely: Hotoro, Kano Municipal, Kumbotso, Kofar Fada, and Gezawa. The conductivity values were high, above 2400 µS/cm, in urban areas such as Hotoro and Ring Road, and the results are similar to elevated TDS and Hardness, implying mineralisation or anthropogenic pollution. Most pH values fall within an acceptable pH range for drinking water, but those at the acidic edge are of concern due to corrosivity and metal leaching. Moderate fluctuations in turbidity (8-19 NTU) indicate fluctuating suspended solids that can degrade water clarity and may include disease-causing organisms, making treatment challenging and stressing aquatic life. Temperature is also homogeneous (29-33.39 °C), as per tropical climatic conditions, with opposite effects on Dissolved Oxygen, which has a wide range (2.3-6.9 mg/L) and tends to be lower in locations with high Conductivity and high Turbidity, indicating organic pollution or eutrophication-based hypoxia. Multivariate visualizations (Boxplots, Scatter plots, Violin plots, and Pairwise correlations) help explain parameter-specific spatial heterogeneities. It is shown that the mineral and pollutant loads appear to be higher in areas such as Hotoro and parts of Kumbotso. In contrast, Dissolved Oxygen concentrations are greater in those waters with neutral to alkaline pH, further supporting beneficial aquatic conditions. Further investigations using t-tests

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and p-value heatmaps could also substantiate significant inter-site variations, at least in the conductivity, TDS, and Hardness data, which tend to underscore the influence of urbanisation and geological heterogeneity on these aspects.

The evidence of intervals reflects confidence in these findings and outlines areas of need for water quality interventions. The ion chemistry profile is dominated by Sodium-Magnesium-Calcium, with site variation within the geological bodies and is further affected by anthropogenic effects. As such, Trace metals are present but at low concentrations and do not constitute immediate health hazards, though occasionally Zinc and Iron can be elevated, and hence need monitoring. Correlation matrices among localities strengthen geochemical processes of mineral dissolution and interactions between water and rocks, and also point to local wash-ups of contamination. Geostatistical analyses highlight excessive spatial heterogeneity in the most prominent physicochemical parameters, necessitating refined spatial analyses to inform adaptive management. Chromatogram plots used by the group combine multiple ion datasets to provide a visual representation of spatial trends, which help establish contamination hotspots and natural backgrounds. Calibration curves for the analysis instruments attest to the robustness and precision of the ion quantifications. The significant cation relationships illustrated by scatter plot analyses are consistent, indicating that major ion chemistry is consistent with geological origins; the principal component analysis effectively reduces multivariate variability into clearly observable hydrochemical groupings that relate to geographic and artificial processes. Finally, Piper diagram analyses verify the convergence/divergence of several hydrochemical facies, reflecting different geochemical processes, such as silicate weathering and carbonate dissolution, and anthropogenic enrichment of ions, which drive changes in water chemistry across sites. All these combined results highlight the essential role that real-time, multifactor studies and spatially explicit management and mitigation measures must play in preventing water resource degradation and aquatic living conditions in this fast-growing, highly populated Nigerian environment.

V. CONCLUSION

The high spatial heterogeneity of water quality is clearly evident in the comprehensive study of water quality across various sampling locations in the Kanoregion in the Northern part of Nigeria, due to complex interactions among geological formations, volcanic activity, and anthropogenic pollution sources. Major parameters such as Electrical Conductivity, Hardness, pH, Total Dissolved Solids, Temperature, Turbidity, and Dissolved Oxygen help define the physical, chemical, and biological conditions of the water and reveal localised hotspots of mineralisation and contamination, especially in urban districts like Hotoro and some areas of Kumbotso. High conductivity and TDS are accompanied by increased hardness and ion concentrations, indicating ongoing geochemical processes in the waters (mineral dissolution) and anthropogenic impacts, including industrial effluents and agricultural runoff. The pH values are within acceptable drinking water limits, although borderline acidity at specific sites raises concerns about corrosion and metal leaching. The changes in Turbidity and the reduction of available Dissolved Oxygen in some places signal the possible presence of pathogens and organic contamination, which affect the health of water ecosystems. Multivariate statistical techniques (t-tests, Confidence intervals, Correlation matrices, Principal component analysis, and Piper diagrams) consistently reveal significant disparities in water chemistry across the surveyed localities, whether due to natural geochemical facies or human-induced change. The concentration of trace metals is generally low, and their direct effects on health are limited, but periodic peaks will require constant monitoring. The use of geostatistical techniques lends credence to the argument that, to ensure the spatial differences in these often-changing issues of water quality, monitoring, and management are spatially explicit. In sum, the combined multi-parameter assessment will provide an overall picture of the hydrochemical environment, necessitating long-term and point-specific water-quality assessments, as well as site-specific interventions. The Piper plot analysis of the presented water chemistry data shows the presence of various hydrochemical facies across the sampled locations, as the spatial variability map focuses on ionic composition. The cation triangle indicates the prevalence of Sodium (Na^{+}) and Potassium (K^{+}) in several samples, especially in water types with high Sodium content (e.g., more than 40 meq/L), strongly suggesting the influence of sodium-bearing minerals or a high-Sodium source due to anthropogenic activities. Mg^{2+} and Ca^{2+} reservoirs vary considerably; locations with elevated calcium and Magnesium indicate waters subject to the dissolution of carbon, or rock or groundwater-rock interaction, with typical waters of the Calcium-Magnesium bicarbonate or sulfate variety. The anion triangle reveals an aggregate of areas dominated by bicarbonate (HCO3-), reflecting weak acid sites, and other areas dominated by high concentrations of sulfate (SO42-) and chloride (Cl-), suggesting that acidity is more substantial due to industrial or agricultural contributions. These relative patterns of the various concentrations of these major ions give discrete groups or facies, indicating variations in the influence of geochemical processes such as silicate weathering, ion exchange, or source of contamination (Figure 15).

DECLARATION STATEMENT

As the article's author, I must verify the accuracy of the following information after aggregating input from all authors.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted objectively and without external influence.
- **Ethical Approval and Consent to Participate:** The content of this article

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does not necessitate ethical approval or consent to participate with supporting documentation.

- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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