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Assessing the Impact of Land Use Land Cover (LULC) and Climate Change on Groundwater Quality in Awka Agricultural Zone

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Abstract
This study investigates the combined impacts of land use/land cover (LULC) changes, topographic variability, and climate-induced stressors on groundwater quality in the Awka Agricultural Zone, southeastern Nigeria. Over the past decades, rapid urbanization, agricultural intensification, and climate variability have increasingly degraded groundwater resources in sub-Saharan Africa. To address this, the study integrated physicochemical data, satellite-derived LULC classifications (2017, 2020, 2023 and 2024), and climate records of Awka Agricultural Zone from 2017 to 2024 within a GIS-based framework. Findings reveal that urban expansion and agricultural encroachment significantly reduce infiltration and elevate pollutant loads, while declining rainfall and rising temperatures intensify solute concentrations such as nitrates, TDS, and heavy metals. Statistical analyses show strong correlations between groundwater parameters and environmental variables, confirming the interactive nature of anthropogenic and climatic pressures. This research offers a spatial-temporal approach for identifying contamination hotspots and recharge-limiting zones, providing critical insights for adaptive groundwater governance, spatial planning, and climate resilience in data-scarce agro-ecological regions.

Keywords: Groundwater Quality, GIS, LULC, Climate, Awka Agricultural Zone.

1. Introduction

Over the past six decades, the Earth has undergone an unprecedented acceleration in environmental transformation, largely driven by explosive population growth, increased resource extraction, and intensified consumption. These forces have accelerated land-use changes, fertilizer application, and water withdrawals for agriculture, urbanization, and industrial expansion. Collectively, these processes have ushered humanity into the Anthropocene - a new epoch marked by significant and often irreversible human impact on Earth's systems. One of the most critical consequences of this shift is the widespread degradation of water quality, now recognized as a global environmental crisis. Recent studies have reported increasing contamination of freshwater systems by recalcitrant chemicals, nutrient over-enrichment, harmful algal blooms, and microbiological pollutants, including antibiotic-resistant pathogens (Abdelfattah, Gaber and Geriesh, 2021; Maurizio et al., 2023). This degradation poses threats to ecosystem stability, biodiversity, and human health. Furthermore, climate change—manifested through rising temperatures, shifting precipitation patterns, and extreme weather events—exacerbates water quality issues by intensifying pollution transport and altering hydrological cycles. Climate change introduces significant variability into the global water cycle (Saito, Taniguchi and Shimada, 2016). Changes in rainfall regimes, evapotranspiration rates, and temperature extremes affect both the quantity and reliability of freshwater resources. The frequency and severity of hydrometeorological events—such as flash floods, prolonged droughts, and heat waves—have increased in many parts of the world, leading to aquifer depletion, river desiccation, and compromised soil moisture and recharge rates (Abbass et al., 2022; Beckmann and Winkelmann, 2022; Santos, Ferreira and Pedersen, 2022). Historical climatological records indicate that at least twenty major climate anomalies since 1700 have significantly disrupted global water systems, often causing socio-economic and ecological crises (Costa, Zhang and Levison, 2021; Easterbrook, 2016). Presently, these impacts are particularly severe in regions with fragile water balances or insufficient infrastructure.

In the face of climate-induced variability, groundwater is increasingly seen as a critical buffer and a reliable source of water. It constitutes about 30% of global freshwater and supplies over two billion people for domestic, agricultural, and industrial needs. However, despite its importance, groundwater remains poorly monitored and vulnerable to overexploitation and contamination. Rapid urban growth, population increase, and the declining reliability of surface water sources have intensified groundwater dependence—especially in developing regions like sub-Saharan Africa. In urban centers such as Ibadan, Nigeria, residents increasingly rely on boreholes and shallow wells, which are often exposed to contamination due to poor sanitation, unregulated land use, and inadequate waste disposal (Balogun, Anumah, Adegoke and Maxakato, 2022; Barbieri et al., 2023; Usman, Lawal and Ajayi, 2021). Land use and land cover (LULC) changes directly influence hydrological processes, including infiltration, runoff, evapotranspiration, and aquifer recharge. While land cover denotes the physical features of the Earth's surface—such as vegetation, croplands, or impervious surfaces—land use refers to how humans manage and modify these landscapes (Giri, 2021; Sawant, Garg, Meshram and Mistry, 2023). Deforestation, urban sprawl, and agricultural intensification disrupt groundwater systems by altering surface permeability, increasing runoff, and reducing infiltration (Sulamo, Kassa and Roba et al., 2021). The removal of vegetation also accelerates erosion and sediment transport, degrading both surface and groundwater quality.

There is an urgent need to examine how these interacting drivers shape groundwater recharge dynamics, flow systems, and pollution risks. Identifying vulnerable zones, assessing contamination hotspots, and integrating spatial and temporal datasets are essential steps toward sustainable groundwater management leveraging on the physicochemical data and spatial GIS-based LULC classification to produce an understanding of groundwater vulnerability. Topographic factors, particularly slope, also modulate infiltration and recharge potential. Steep terrains tend to generate higher surface runoff and reduced recharge, while flat or undulating areas promote water percolation into aquifers (Quillet et al., 2017; Sertel, Imamoglu, Cuceloglu and Erturk, 2019; Yuan, Jin and Lee, 2020). Therefore, groundwater vulnerability is governed by the interplay between LULC patterns and geomorphological conditions. Interactions between climate change and LULC dynamics further complicate groundwater sustainability (De Giglio et al., 2016). Shifts in land cover influence evapotranspiration and soil moisture retention, while climate variability alters recharge timing, rainfall intensity, and evaporation rates. These processes affect the chemical and biological properties of groundwater, often leading to elevated concentrations of nitrates, heavy metals, salts, and pathogens in aquifers (Aladejana, Kalin, Sentenac and Hassan, 2020; Cochand, Molson and Lemieux, 2019 Wilopo, Putra and Hendrayana, 2021). Extreme climatic events such as flooding can mobilize surface pollutants, while droughts reduce aquifer dilution, resulting in higher contaminant concentrations. These shifts pose increasing risks to groundwater-dependent communities and ecosystems, particularly in semi-arid zones where paleo-hydrological records indicate high sensitivity to climate change, and by bridging hydrology, climatology, and land system science, it offers an innovative spatial-temporal framework to identify groundwater pollution hotspots and recharge-limiting factors. (Amanambu et al., 2020; Mousazadeh, Eftekhari and Ostovari, 2019). Groundwater plays a critical role in sustaining domestic, agricultural, and ecological functions, especially in regions affected by climate stress and poor water infrastructure (Doulgeris, Nikolaidis, and Karatzas, 2023). Yet, the combined effects of land use change, topographic variation, and climate variability on groundwater quantity and quality remain poorly understood particularly in rapidly urbanizing and agriculturally intensive areas.

This study seeks to fill this critical knowledge gap by investigating the hydrological and environmental consequences of LULC and climatic interactions, with the goal of supporting evidence-based groundwater governance, spatial planning, and climate adaptation in vulnerable landscapes in Awka Agricultural Zone. The findings will contribute to the growing body of interdisciplinary groundwater research and provide practical implications for adaptive water resource governance, land use planning, and climate resilience strategies in vulnerable agro-ecological zones such as Awka Agricultural Zone.

2.0 Materials and methods

2.1 Study Area

Awka agricultural zone is one of the four agricultural zones operational in Anambra state, it comprises of five Local government areas (LGAs) namely: Awka-North, Awka-South, Anaocha, Njikoka and Dunukofia local government areas which are largely involved in agricultural production and rural development. Awka agricultural zone is within the derived savanna vegetative zone and experiences a tropical climate with two distinct seasons: the rainy season (March to April) and the dry season (October to November), the topography is hilly and in many parts flood erosion is a major problem. The soil is classified as deep porous ferralithic which is easy to till but subject to excessive leaching because it is formed from sandstone (Nweke and Winch, 1980).

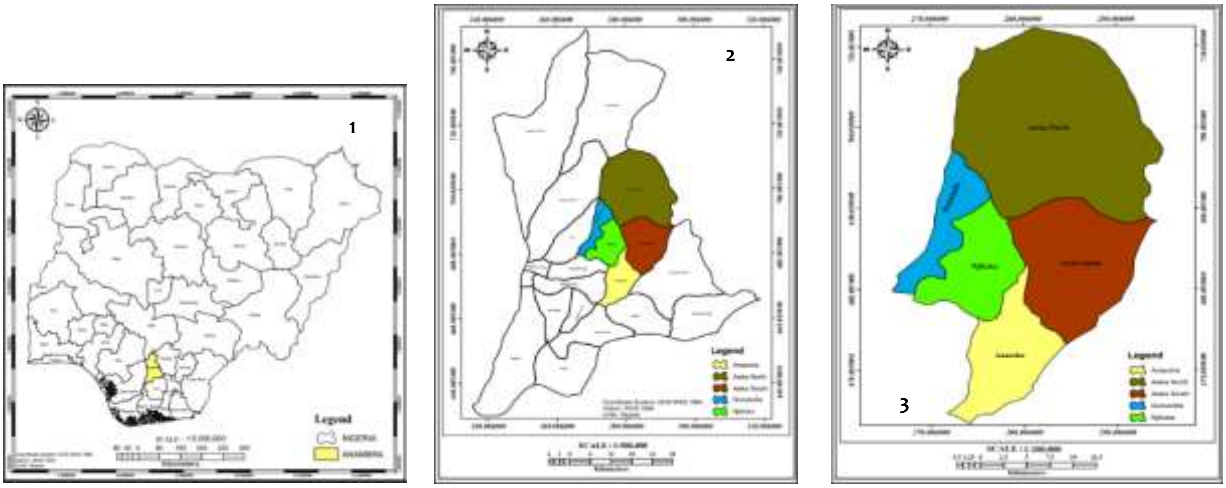

Fig. 1: Map of Nigeria showing Anambra State; **Fig. 2:** Map of Anambra State showing Awka Agricultural Zone; **Fig. 3:** Map showing Awka Agricultural Zone. (***Source:*** *ArcGIS 10.8)*

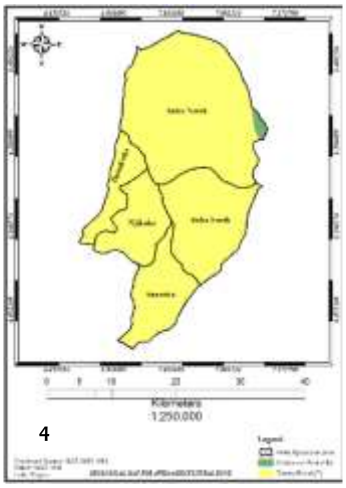

Fig. 4: Geological Map showing Awka Agricultural Zone. (***Source:*** *ArcGIS 10.8)*

2.2 Sample Collection and Data Processing:

Twenty water samples were collected in duplicate from selected boreholes in five Local Government Areas of the Awka Agricultural Zone, the depth of the selected boreholes ranges within 200ft – 500ft. Samples were divided into filtered (A) for cation analysis and unfiltered (B) for anion analysis, collected with pre-cleaned plastic cans after flushing the taps for five minutes. The cans were filled without airspace, kept in ice packs, and delivered to the lab, where batch A was acidified to preserve cations. On-site pH and electrical conductivity measurements were taken with appropriate meters, and laboratory analyses followed APHA (1998) guidelines. Land Use and Land Cover (LULC) data from Sentinel-2 satellite imagery for 2017, 2020, 2023, and 2024 were processed in ArcGIS 10.8, using the Maximum Likelihood Algorithm to classify into six categories, classification accuracy was validated with ground truth data. Climate data of Awka Agricultural Zone from 2017 to 2024 were sourced from NiMet's Awka Station. All data were integrated in ArcGIS 10.8 to map LULC changes and identify vulnerable zones, aiding recommendations for sustainable groundwater quality management.

3.0 Result and Discussion

Groundwater quality in the Awka Agricultural Zone of southeastern Nigeria is increasingly impacted by anthropogenic activities and climatic shifts. Recent research highlights that heavy metal concentrations and other pollutants in Nigerian groundwater are rising due to mining, industrialization, socioeconomic development, and notably, land use and land cover (LULC) changes (Ajala et al., 2022; Obasi and Akudinobi, 2020; Omeka and Igwe, 2023). The region's geological diversity, rainfall variability, soil types, and topographical features further shape groundwater vulnerability (Agbasi et al., 2023; Aryal, Wang and Yeung, 2021; Ayejoto et al., 2023; Unigwe, Egbueri and Omeka, 2022). GIS-based LULC analysis from 2017 to 2024 as shown in Figures 5-8 reveals marked urban expansion across Anaocha, Awka South, and Njikoka LGAs, red-coded built-up zones increasingly replaced vegetated and open areas. Between 2017 and 2020, vegetated areas, including flood-prone wetlands, declined significantly, with further reductions observed by 2023 in central and northern zones. This LULC transformation has reduced permeable surfaces, hindering aquifer recharge and amplifying surface runoff. Urbanization introduces direct threats to groundwater through increased impervious surfaces, which reduce infiltration and elevate pollutant loads. Sources include domestic waste, leaking septic systems, industrial discharges, and hydrocarbon spills (Akhtar, Bhat and Wani, 2021; Xu, Yin and Zhang, 2019; Zhang, Zhang, Wang and Cheng, 2018). Additionally, peri-urban communities with poor sanitation pose risks of leachate percolation, vegetation loss is especially concerning because such areas act as natural filtration buffers that protect aquifers. Their degradation increases vulnerability to contamination. Meanwhile, agricultural encroachment particularly in previously open spaces has contributed to heightened nitrate, phosphate, and heavy metal concentrations through fertilizer and pesticide applications (FAO, 2016; Singh, Roshni and Singh, 2024; Zhang et al., 2021). Poorly drained agricultural land also contributes to salinization and nutrient leaching. Flooded vegetation in low-lying areas, while potentially beneficial for recharge and filtration, also acts as a sink for agrochemicals and waste, particularly during the rainy season (Nnaemeka-Okeke, Eze-Steven and Ugwu, 2019; Okeke, Chukwu and Agu, 2024; Rahman, Hossain and Rahman, 2019).

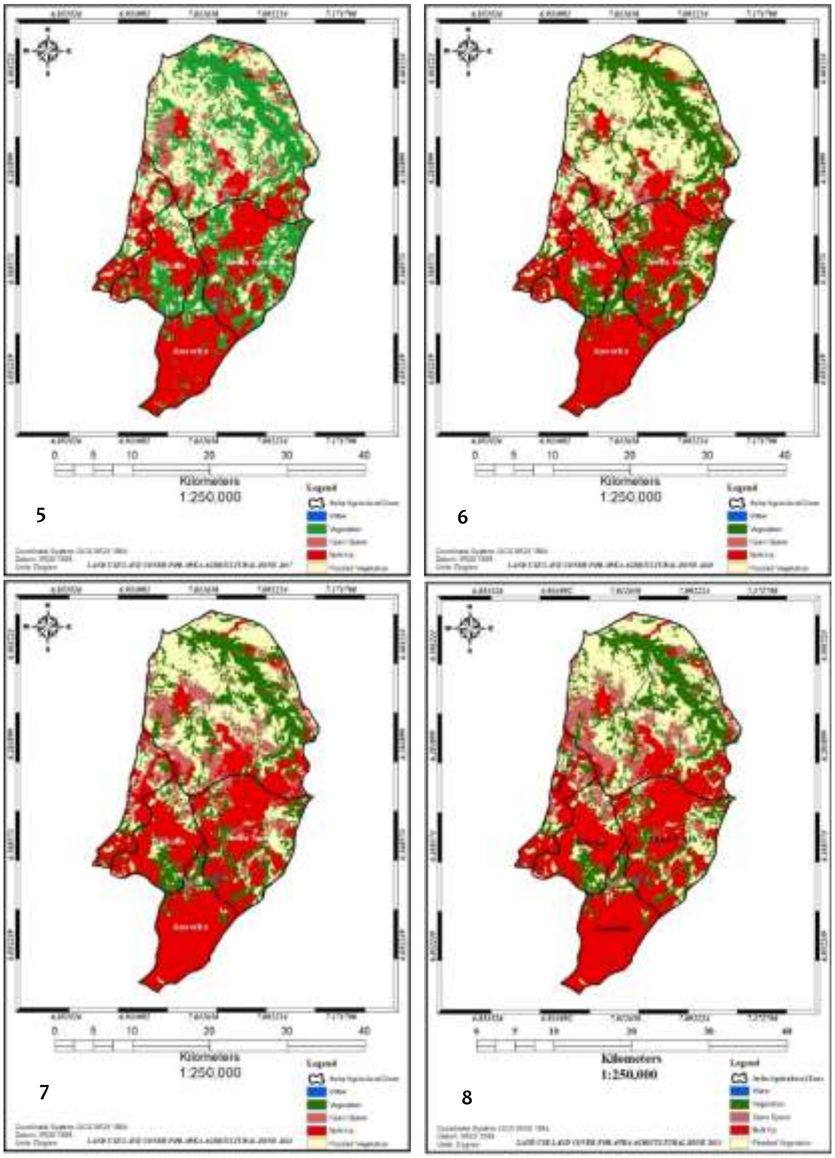

Fig. 5: 2017 LULC Map of Awka Agricultural Zone; **Fig. 6:** 2020 LULC Map of Awka Agricultural Zone; **Fig. 7:** 2023 LULC Map of Awka Agricultural Zone; **Fig. 8:** 2024 LULC Map of Awka Agricultural Zone.

Source: *ArcGIS 10.8 – (Sentinel 2.10m imagery)*

Table 1: Overall Classification Accuracy and Kappa Coefficient

Year	Overall Accuracy (%)	Kappa Coefficient (%)	Product Matrix	Total
2017	94.87	82.19	74	78
2020	94.59	82.56	70	74
2023	97.26	89.85	71	73
2024	95.83	85.12	92	96

The classification accuracy achieved between 2019 and 2024 (Table 1) indicates a consistently high and progressively improved performance in land use/land cover (LULC) mapping. Overall classification accuracies ranged from 94.59% to 97.26%, while Kappa coefficients varied between 82.19% and 89.85%. These metrics surpass the commonly accepted 85% benchmark for reliable remote sensing-based LULC analysis (Akinbile, Oni and Abegunde, 2023; Congalton and Green, 2019; Malakar et al. 2021). This reflects the robustness of the applied classification techniques and underscores their suitability for spatial-temporal land cover change detection, landscape interpretation, and environmental monitoring. The classification for the year 2023 demonstrated the highest performance, with a 97.26% overall accuracy and a Kappa of 89.85%, suggesting near-perfect agreement beyond random chance. This improvement is likely due to advancements in classification algorithms, more accurate training sample collection, or enhanced image quality—possibly obtained during seasons that reduce spectral overlap (Zhang, Guo and Zhang, 2021). Across the entire period, flooded vegetation consistently proved to be the most difficult class to distinguish, years such as 2019, 2020, and 2024 show notable misclassification between flooded vegetation and both water and terrestrial vegetation. This confusion is well-recognized in remote sensing literature, as flooded vegetation and water surfaces often share similar reflectance characteristics in the shortwave infrared (SWIR) and near-infrared (NIR) wavelengths (Bamal, Sondhi, Singh and Saxena, 2022; Roy et al., 2020). Over time, distinct LULC trends emerge, built-up areas expanded modestly from 2019 to 2023, followed by a notable decrease in 2024. In contrast, vegetation-cover more than doubled between 2023 (38) and 2024 (71), which may reflect environmental recovery, reforestation, or seasonal variation associated with image capture during the rainy season (Asoka, Gleeson, Wada and Mishra, 2021; Ayanlade and Jegede, 2022; Rahmati, Pourghasemi and Kalantari, 2022). Water bodies remained largely unchanged over the study period, suggesting stability or controlled hydrological conditions in the area. Water features were consistently well classified, demonstrating clear spectral separability, particularly for static water bodies like lakes or reservoirs (Liu, Liu, Tian and Wang, 2022).

Table 2: Classification Trends over Time

Class	2017	2020	2023	2024	Trend Summary
Water	4	4	3	4	Relatively stable
Vegetation	44	36	39	71	Sharp increase in 2024
Open Source	2	3	1	1	Decreasing
Built-up	24	26	28	17	Dropped in 2024
Flooded Vegetation	4	5	2	3	Slight variations

In Table 2, the consistently high classification accuracies across all years support the effectiveness of supervised classification techniques such as Random Forest or Maximum Likelihood Estimation in multi-year LULC studies (Ansari, Raza and Kant, 2016; Wu, Li and Huang, 2020). The results are valuable for decision-making in land use planning, environmental management, ecosystem service evaluation, and disaster risk reduction (Adeoye, Ayeni and Akinpelu, 2024; Kassawmar, Dube and Adelabu, 2023). However, recurring misclassifications—especially between vegetation and flooded vegetation—highlight the need for more sophisticated classification strategies. Incorporating ancillary datasets, such as elevation models, soil moisture maps, or hydrological data, could significantly enhance class separability. Additionally, the sharp drop in built-up areas seen in 2024 may result from misclassification, possibly caused by vegetation overgrowth in developed plots, insufficient or biased training samples, or limitations in spectral differentiation (Mishra, Singh and Yadav, 2021; Schmitt and Brisco, 2022). The classification results from 2019 through 2024 demonstrate a high level of accuracy and reliability, making them suitable for long-term land cover change monitoring.

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Table 3: Showing the Physicochemical Parameters results with the maximum permissible limits by FAO Water quality for agriculture – **(FAO) 2016**, World Health Organization - Water quality for drinking **(WHO) 2017**, and Nigerian Standard for Drinking Water Quality **(NSDWQ)**/Nigerian Industrial Standards **(NIS) 2012**.

		AWKA AGRICULTURAL ZONE (AWKA-NORTH, AWKA-SOUTH, DUNUKOFIA, ANAOCHA AND NJIKOKA LGAs)																				FAO 2016	WHO 2017	NSDWQ NIS 2012 NIS-306-2008
S/N	**PARAMETERS**	**AN01**	**AN02**	**AN03**	**AN04**	**AS01**	**AS02**	**AS03**	**AS04**	**DN01**	**DN02**	**DN03**	**DN04**	**AN01**	**AN02**	**AN03**	**AN04**	**NJ01**	**NJ02**	**NJ03**	**NJ04**	**MPL**	**MPL**	**MPL**
1	**Temperature (◦C)**	24	23.3	22.8	22.7	23.7	22.9	22.4	22.6	23.6	22.9	22.4	22.3	23.4	22.9	22.8	23	25	21	22	22	**25.0 (Ambient)**	**25.0 (Ambient)**	**Unobjectionable**
2	**pH**	6	5.6	5.3	6.2	6.5	5.7	4.5	6.2	5.3	5.7	5.7	7.2	5.8	6	6.6	6.3	5.5	5.9	5.8	6.28	**6.50-8.50**	**6.50-8.50**	**6.50-8.50**
3	**TDS (mg/L)**	52.51	11.02	128.5	65.4	263.31	157.4	225.1	284.8	21.14	14.55	14.6	120.2	29.5	22.01	118.2	174.8	34.3	267.1	30.18	3.5	**2000**	**500**	**500**
4	**Total Hardness (mg/L)**	15	3.8	39.2	19.01	85.4	48.1	69.7	85	5.7	4.01	5	37.2	9.4	7.8	53.4	55.01	9	10.1	27.5	15.28	**-**	**100**	**150**
5	**Calcium (Ca^{2+}) (mg/L)**	12.14	2.45	30.1	14.76	63.77	7.28	34.7	51.88	4.43	3.56	3.56	26.8	5.98	4.98	40.73	38.85	7.9	7.19	13.82	3.99	**20**	**75**	**75**
6	**Magnesium (Mg^{2+}) (mg/L)**	4.22	0.69	9.51	3.89	21.67	12.55	18.05	16.44	1.46	1.26	1.26	7.08	2.39	1.4	13.58	13.6	2.65	1.11	6.25	0.454	**5**	**50**	**20**
7	**Nitrate ($N0_3^{2-}$) (mg/l)**	24.56	29.32	23.97	17.13	35.15	19.07	23.92	17.04	16.24	25.16	11.05	12.33	21.37	19.16	14.78	12.94	24.37	13.98	13.98	10.55	**10**	**50**	**50**
8	**Electrical Conductivity (µS)**	85.17	17.63	206.9	103.45	407.6	246.7	351.8	438.5	31.98	25.42	25.42	190.8	46.42	35.35	276.5	273.5	49.74	135.7	126.7	71.25	**-**	**1200**	**1000**
9	**Alkalinity (mg/L)**	11.6	2.35	28.8	14.25	59.59	34.9	50.4	63.2	4.6	3.4	5.4	26.6	6.4	4.8	39.1	38.6	7.8	6.9	18.8	16.2	**50**	**50**	**50**
10	**Chloride (Cl^{-}) (mg/l)**	22.6	17.5	22.2	19.9	11.5	30.31	44.73	17.5	24.6	25.5	28.7	9.2	18.7	17.2	27.2	31.4	33.1	18.3	26.05	58.18	**30**	**250**	**250**
11	**Bicarbonate HCO3-(mg/l)**	25.4	21.8	28.65	24.76	80.54	74.89	76.78	75.43	20.56	25.77	30.45	44.6	40.6	25.75	40.55	48.6	100.25	88.1	75.45	78.9	**-**	**250**	**100**
12	**Sulphate ($SO4^{2-}$) (mg/l)**	17.08	19.03	13.85	18.11	18.74	32.18	14.82	11.76	9.86	21.08	19.35	14.56	21.93	19.03	30.09	28.92	24.51	12.94	24.13	60.28	**20**	**250**	**100**
13	**Sodium (Na^{2+}) (mg/l)**	6.78	4.9	6.24	5.99	6.18	6.28	6.88	1.92	1.66	0.9	0.49	1.92	0.9	0.49	4.95	4.68	4.89	1.66	4.95	4.5	**40**	**50**	**200**
14	**Potassium (K) (mg/l)**	4.92	4.89	4.83	4.78	5.94	4.99	5.84	2.45	3.54	3.12	2.8	12.45	23.12	22.8	3.22	3.26	4.89	13.54	3.12	2.88	**2**	**10**	**10**
15	**Iron (Fe^{2+}) (mg/l)**	0.08	0.1	0.32	0.06	0.08	0.11	0.05	0.05	0.087	0.095	0.075	0.19	0.08	0.086	0.28	0.02	0.12	0.11	0.16	0.18	**0.5**	**0.5**	**0.3**
16	**Lead (pb)**	0	0	0	0	0	0.002	0	0	0	0	0	0	0	0	0	0.001	0.001	0.001	0	0.001	**0.01**	**0.01**	**0.01**

Table 4: ANOVA Table by LGAs in Awka Agricultural Zone

		ANOVA **Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Temperature ◦C	Between Groups	.934	4	.233	.024	.999
	Within Groups	343.138	35	9.804		
	Total	344.071	39			
pH	Between Groups	.909	4	.227	.766	.554
	Within Groups	10.378	35	.297		
	Total	11.286	39			
TDS mgL	Between Groups	121586.016	4	30396.504	5.121	.002
	Within Groups	207767.784	35	5936.222		
	Total	329353.799	39			
Total Hardness mgl	Between Groups	17571.098	4	4392.775	16.657	.000
	Within Groups	9229.959	35	263.713		
	Total	26801.057	39			
Calcium Ca^{2+} mgl	Between Groups	5635.473	4	1408.868	6.047	.001
	Within Groups	8155.023	35	233.001		
	Total	13790.496	39			
Magnesium Mg^{2+} mgl	Between Groups	1228.509	4	307.127	21.789	.000
	Within Groups	493.342	35	14.095		
	Total	1721.851	39			
Nitrate NO_3^{2-} mgl	Between Groups	594.994	4	148.749	4.739	.004
	Within Groups	1098.665	35	31.390		
	Total	1693.659	39			
Electrical Conductivity µS	Between Groups	448551.051	4	112137.763	16.385	.000
	Within Groups	239542.028	35	6844.058		
	Total	688093.080	39			
Alkalinity mgl	Between Groups	9575.584	4	2393.896	17.213	.000
	Within Groups	4867.502	35	139.071		
	Total	14443.086	39			
Chloride Cl^{-} mgl	Between Groups	875.059	4	218.765	2.004	.115
	Within Groups	3820.955	35	109.170		
	Total	4696.014	39			
Bicarbonate HCO_3 mgl	Between Groups	24901.465	4	6225.366	108.227	.000
	Within Groups	2013.253	35	57.522		
	Total	26914.718	39			
Sulphate SO_4^{2-} mgl	Between Groups	1145.986	4	286.496	2.963	.033
	Within Groups	3384.006	35	96.686		
	Total	4529.992	39			
Sodium Na^{2+} mgl	Between Groups	119.001	4	29.750	11.958	.000
	Within Groups	87.078	35	2.488		
	Total	206.078	39			
Potassium K mgl	Between Groups	398.158	4	99.540	3.229	.023
	Within Groups	1078.984	35	30.828		
	Total	1477.142	39			
Iron Fe^{2+} mgl	Between Groups	.016	4	.004	.535	.711
	Within Groups	.259	35	.007		
	Total	.275	39			
Lead Pb mgl	Between Groups	.000	4	.000	.935	.455
	Within Groups	.000	35	.000		
	Total	.000	39			

Table 5: Climatic Data of Awka Agricultural Zone 2017 – 2024 (Nigerian Meteorological Agency (NiMet), Awka)

	2017	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Max. Temp. ⁰C	35.1	30.2	30.4	28.8	30.7	33.6	33.1	32.7
Min. Temp. ⁰C	23.7	23.7	23	23	24.2	23.5	23	22.7
Rainfall (mm)	132.4	131.8	130.4	132.1	129.8	131.6	128.8	127.4
Relative Humidity (%)	71.6	70.3	81.2	70.5	82.6	71.2	72.8	76.4

Climatic data of Awka Agricultural Zone (Table 5) from 2017 to 2024 show slight declines in annual rainfall of Awka Agricultural Zone from 132.4 mm in 2017 to 127.4 mm in 2024 alongside temperature fluctuations. Maximum temperatures peaked at 35.1°C in 2017 and 32.7°C in 2024, while minimum temperatures remained fairly constant between 22.7°C and 24.2°C. Relative humidity peaked at 82.6% in 2021, sustaining levels above 70% through 2024, higher temperatures promote mineral dissolution, thereby increasing Total Dissolved Solids (TDS), Electrical Conductivity (EC), and hardness. For example, AS03 recorded TDS of 284.8 mg/L and EC of 438.5 µS. Reduced rainfall slows recharge, concentrating ions such as Ca^{2+}, Mg^{2+}, SO_4^{2-}, and NO_3^{-} in groundwater. Intense rainfall events, though infrequent, increase runoff, transporting pollutants into aquifers—as reflected in elevated nitrate levels (e.g., 36.7 mg/L in AS03) (Eze, Nnaemeka-Okeke and Ugwu, 2024; Yahaya et al., 2021). High humidity fosters organic decay and microbial activity, possibly contributing to low pH (e.g., pH 4.5 in AS03) from leachates and soil acidification (IIETA, 2023; Oyeku, Adeyemi and Omole, 2024). Using GIS overlays and hydrochemical data, spatial relationships between groundwater quality parameters and dominant LULC classes were identified across sampling sites in Awka North, Anaocha, Awka South, Njikoka, and Dunukofia in Table 6. The parameters in Table 3 vary significantly across Awka Agricultural Zone as shown in ANOVA table (Table 4), suggesting strong spatial correlation with environmental factors (e.g. LULC, rainfall etc.). the following parameters TDS (0.002), Total Hardness (0.000), Calcium (0.001), Magnesium (0.000), Nitrate (0.004), Electrical Conductivity (0.000), Alkalinity (0.000), Bicarbonate (0.000), Sulphate (0.033), Sodium (0.000), and Potassium (0.023) have shown significant p-values ($p<0.05$), while Temperature (0.999), pH (0.554), Chloride (0.115), Iron (0.711), and Lead (0.455) have shown non-significant p-values ($p>0.05$). Based on the p-values TDS and EC (both being related to ionic concentration in water) showed a strong positive correlation, TDS and Total Hardness/Calcium/Magnesium showed a strong positive correlation, Nitrate and Land Use (agricultural runoff is a likely cause of variations) showed a moderate to strong correlation, Alkalinity and Bicarbonate (bicarbonates dominates alkalinity) showed very strong correlation, Sulphate and Land Use (industrial use causing leaching of waste or fertilizers), and Sodium and Potassium (anthropogenic activities) showed moderate correlation due to urban waste and agricultural practices.

Table 6: Spatial Relationships between Groundwater Quality Parameters and Dominant LULC Classes of Awka Agricultural Zone

				Spatial Pattern	
	Parameters	**LULC Link**	**Cause:**	**Built-up zones:**	**Agriculture:**
1	Total Dissolved Solids (TDS) and Electrical Conductivity (EC)	Built-up (AS03, AS04) and Agricultural (NJ02, NJ04)	Domestic waste discharge, urban runoff, and fertilizer leaching	EC > 300 μS, TDS > 250 mg/L	EC between 125–275 μS
2	Nitrate (NO_3^{2-})	Agricultural Land and Open Spaces (AN01–AS02, NJ01)	Excessive fertilizer/manure application and septic leakage	Built-up zones (e.g., AS03) with poor sanitation also show moderate nitrate	$NO_3^- > 25$ mg/L
3	Total Hardness, Calcium (Ca^{2+}), and Magnesium (Mg^{2+})	Built-up (AS03, AS04) and Flooded Vegetation (DN04, NJ04)	Leaching from concrete/rocks, industrial effluent, decaying biomass	i. AS03/AS04: Hardness > 69 mg/L, $Ca^{2+} > 51$ mg/L ii. DN04/NJ04: $Mg^{2+} > 13$ mg/L	-
4	Alkalinity and Bicarbonate (HCO_3^-)	Agricultural and Vegetated Zones (AN03, NJ01)	Soil CO_2 interactions, organic matter decay	Moderate in built-up zones (e.g., AS01: 80.5 mg/L)	$HCO_3^- > 75$ mg/L
5	Chloride (Cl^-)	Built-up and Flooded Vegetation (NJ04, DN03)	Urban runoff, wastewater seepage, water stagnation	$Cl^- > 30$ mg/L	$Cl^- < 20$ mg/L
6	Sulphate (SO_4^{2-})	Agricultural and Built-up Zones (AS03, AN03, NJ04)	Fertilizer, pesticide residue, industrial discharges	-	i. AS03: > 30 mg/L ii. AN03, NJ04: ~25 mg/L
7	Sodium (Na^+) and Potassium (K^+)	Built-up (AS03) and Agricultural (AN02, AN03)	Road runoff, soil salinization, fertilizer/manure use	AS03 – 6.88 mg/L	AN02 and AN03 – $K^+ > 20$ mg/L
8	Iron (Fe^{2+}) and Lead (Pb)	Built-up and Flooded Vegetation (AS02, NJ04)	Corroded pipelines, industrial residues, organic-rich soils	Pb > 0.001 mg/L in urban zones	Slightly elevated Fe^{2+} in organic/flooded soils

Table 7: Summary of LULC Effect on Groundwater Quality of Awka Agricultural Zone (2017, 2020, 2023 and 2024)

LULC Class	Trend (2017 – 2024)	Groundwater Quality Impact	Explanation
Water/Water Bodies	Relatively Stable	Mixed – Recharge and Contamination Potential, if polluted sources mix with recharge areas	Mixed – Clean Water Helps, Polluted Water Harms. While surface water didn’t change much, its proximity to contaminated areas may affect shallow groundwater quality
Vegetation	Decreased (especially in Awka-South, Njikoka and Anaocha)	Negative – Reduced recharge, filtration capacity and increased erosion	Vegetation loss limits aquifer recharge and natural pollutant filtering, while increasing erosion and contamination transport
Open Space	Increased (linked to land clearing and bare lands in Awka-South, Njikoka and Anaocha)	Variable – Potential increase in runoff and sediment load	Open lands may lack cover, promoting runoff of pollutants and reducing percolation
Built-up	Significantly Increased (especially in Awka-South, Njikoka and Anaocha)	Negative – Increased contamination from sewage, waste, used-oils, and impermeable surfaces	Urbanization leads to reduced infiltration, more runoff, and increased contamination from domestic and industrial sources
Flooded Vegetation	Slight Increase (especially in Awka-North and Dunukofia)	Negative – High risk of microbial and chemical leaching	Stagnant water areas act as pollutant sinks and often contribute to microbial contamination during infiltration
Agricultural/Converted Areas	Expanded (indicated by open space and reduced vegetation in Awka-South, Njikoka and Anaocha)	Negative – Agrochemical runoff (nitrates , phosphates and pesticides)	Intensive farming contributes significantly to groundwater nitrate and pesticide contamination in groundwater

4.0. Conclusion

This study examined the combined effects of land use/land cover (LULC) changes, topographic variability, and climate-induced stressors on groundwater quality in the Awka Agricultural Zone, southeastern Nigeria. By integrating hydrochemical analysis, GIS-based LULC classification, topographic slope data, and climate records (2017–2024), the research revealed that urban expansion and agricultural intensification have significantly reduced infiltration capacity, increased pollutant loadings, and altered recharge patterns. Key findings include elevated concentrations of nitrates, TDS, sulphates, and heavy metals in areas with intensive land use and poor topographic drainage. Climate variability—particularly declining rainfall and rising temperatures—has further exacerbated groundwater degradation by reducing recharge and increasing solute concentrations. Significant correlations were observed between groundwater quality parameters and environmental drivers, highlighting the interactive nature of these stressors. This study provides a spatial-temporal framework for identifying groundwater contamination hotspots and recharge-limiting zones, contributing novel insights to interdisciplinary water resource management. It emphasizes the importance of integrated land-climate-groundwater monitoring and offers practical implications for groundwater governance, spatial planning, and climate adaptation in vulnerable

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