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Impact of Land Use and Land Cover Changes on Groundwater Dynamics in Selected Local Government Areas of Anambra State, Nigeria

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INFORMATION

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ABSTRACT

This research investigates the shifts in Land Use and Land Cover (LULC) patterns from 2017 to 2023 and their impact on groundwater resources. The objective is to evaluate how these changes affect groundwater recharge, quality, and availability. Utilizing LULC data sourced from Sentinel-2 imagery and Digital Elevation Models (DEMs) from the Shuttle Radar Topography Mission (SRTM), the study employs supervised classification methods to categorize LULC classes. Terrain slope analysis offers insights into water flow dynamics and soil stability. The findings reveal substantial alterations in LULC types during the study period, predominantly driven by urban expansion and agricultural intensification. Notable changes include declines in tree cover and flooded vegetation, alongside expansions in built-up and agricultural areas. These shifts have significant implications for groundwater recharge, impacting both its availability and quality. Urbanization and agricultural growth emerge as key drivers of change, leading to diminished natural recharge zones, heightened surface runoff, and increased contamination risks. Moreover, the influence of terrain slope adds complexity to groundwater dynamics, affecting water movement and soil integrity. The study emphasizes the critical importance of adopting sustainable land management practices and strategic urban planning to safeguard groundwater resources. It underscores the intricate relationship between land use alterations, terrain characteristics and groundwater dynamics, highlighting the necessity for targeted management approaches to enhance groundwater recharge and preserve its quality amidst evolving environmental challenges.

1. Introduction

Land use and land cover (LULC) changes are fundamental to comprehending environmental dynamics, particularly concerning groundwater systems (Akaolisa et al., 2023; Rowland and Agbasi, 2024). Groundwater, a crucial resource for drinking water, agriculture, and industry, is significantly influenced by alterations in land use and cover. These changes can dramatically affect groundwater recharge, quality, and availability, which in turn have far-reaching impacts on socio-economic activities and ecosystem health (George et al., 2022).

In the past few decades, the acceleration of urbanization, agricultural expansion, and deforestation has led to considerable alterations in landscapes worldwide. These transformations are not merely superficial; they deeply influence hydrological processes by altering the natural infiltration and runoff patterns of water (Li et al., 2020).

Urbanization, for instance, replaces permeable land surfaces with impermeable ones like concrete and asphalt, which hinders the natural infiltration of rainwater into the ground, thus reducing groundwater recharge (Ifeanyichukwu et al., 2021). This process also increases surface runoff, which can lead to erosion, flooding, and the transport of pollutants into water bodies.

Agricultural expansion, while essential for food security, often involves the conversion of forests and grasslands into cropland. This change affects the soil's ability to absorb and retain water, impacting the recharge of aquifers. Agricultural practices frequently involve the use of fertilizers and pesticides, which can percolate into the groundwater system, leading to contamination (Chinye-Ikejiunor et al., 2021). Deforestation, another significant LULC change, removes the vegetation cover that plays a crucial role in maintaining the hydrological cycle. Trees and plants facilitate the infiltration of water into the soil, and their removal leads to increased surface runoff and reduced groundwater recharge (Omoyemi, 2023).

Hydrological processes, including precipitation, infiltration, evapotranspiration, and runoff, are all influenced by LULC changes. When forests are cleared or urban areas expand, the balance of these processes is disrupted. Infiltration, the process through which water permeates the soil and recharges aquifers, is particularly affected. Natural vegetation, with its root systems, enhances soil structure and porosity, promoting the infiltration of water (Onanuga et al., 2021). The removal of this vegetation cover reduces the soil's permeability, leading to lower rates of groundwater recharge. Urbanization introduces impervious surfaces that prevent water from seeping into the ground. Instead, water runs off these surfaces quickly, often overwhelming drainage systems and leading to urban flooding. This rapid runoff can carry pollutants from urban areas into water bodies, posing a threat to water quality. The lack of infiltration means that less water is available to recharge aquifers, leading to a decline in groundwater levels over time (Chinye-Ikejiunor et al., 2021). Agricultural practices can also disrupt natural hydrological processes. Intensive irrigation, necessary to support crop growth, often relies heavily on groundwater extraction. This practice can lead to the over-extraction of groundwater, reducing the levels of aquifers and threatening the sustainability of the water supply. The application of chemical fertilizers and pesticides can result in the leaching of these substances into the groundwater system, contaminating the water and posing risks to human health and the environment.

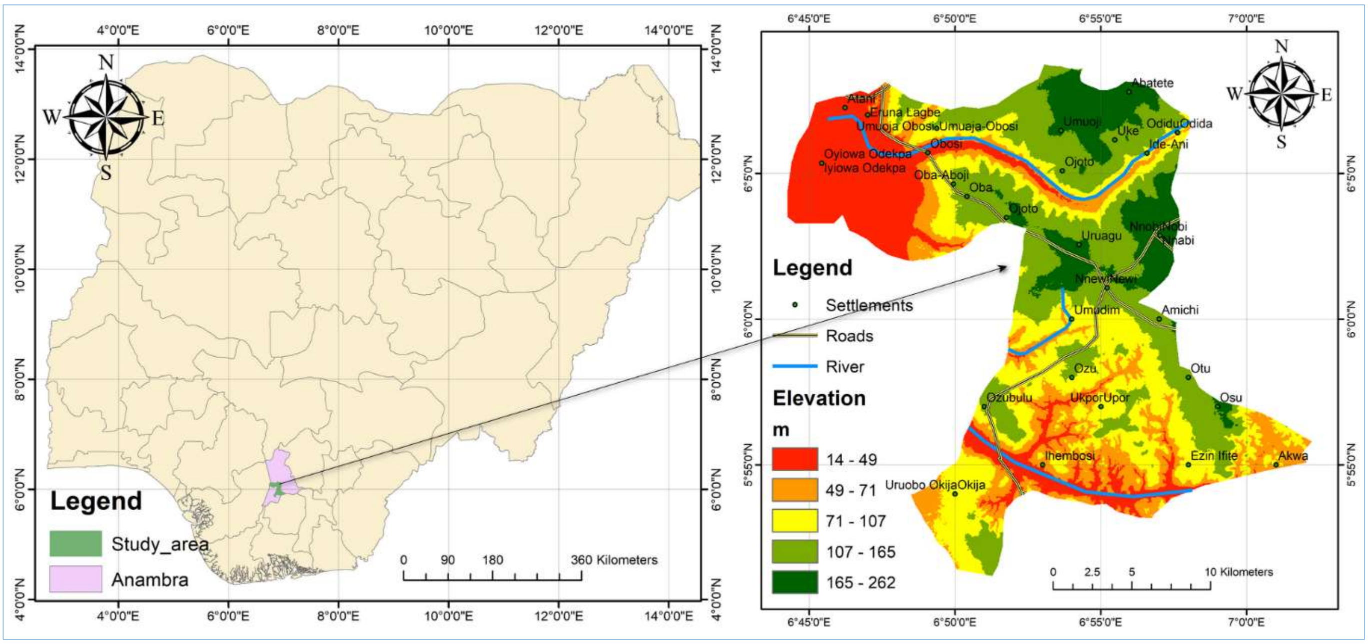

Fig. 1. Map of the study area

Groundwater dynamics have profound socio-economic implications. Groundwater is a vital resource for drinking water, particularly in areas where surface water resources are inadequate or unreliable. It also supports agricultural activities, which are crucial for food production and livelihoods, especially in rural areas (Akaolisa et al., 2022). In many parts of the world, including Anambra State in Nigeria, groundwater is also essential for industrial activities, providing water for manufacturing processes, cooling, and other industrial uses (Ifeanyichukwu et al., 2021).

Changes in LULC that affect groundwater recharge and quality can therefore have significant impacts on socio-economic activities. A reduction in groundwater recharge due to urbanization or deforestation can lead to declining groundwater levels, threatening water security for households, agriculture, and industry (Wudineh, 2023). This scarcity of water can drive up costs, making it more expensive to access clean water for drinking and irrigation. In regions where agriculture is a primary economic activity, this can threaten food security and reduce incomes, exacerbating poverty and social inequality. Contamination of groundwater due to agricultural runoff, industrial discharges, or inadequate waste management in urban areas poses serious health risks. Pollutants such as nitrates from fertilizers, pesticides, heavy metals, and industrial chemicals can contaminate drinking water supplies, leading to a range of health problems including gastrointestinal illnesses, reproductive issues, and neurological disorders (Zacchaeus et al., 2020; Ibe et al., 2021). The economic costs associated with treating contaminated water and addressing health issues can be substantial, placing additional burdens on communities and healthcare systems.

Groundwater is a vital resource in Anambra State, providing water for domestic use, agriculture, and industry. The reliance on groundwater has increased due to the inadequacy of surface water resources and the unreliability of public water supply systems. Many communities depend on wells and boreholes for their water supply, making the sustainability and quality of groundwater critically important (Ifeanyichukwu et al., 2021). Changes in LULC, driven by urbanization, deforestation, and agricultural practices, directly impact the groundwater system by altering recharge rates, runoff patterns, and contamination risks.

Urbanization in Anambra State has led to the expansion of impervious surfaces, reducing the areas available for groundwater recharge. The construction of roads, buildings, and other infrastructure has increased surface runoff, often leading to erosion and the transport of pollutants into water bodies. This process not only reduces the recharge of aquifers but also threatens the quality of groundwater (Chukwura and Igwe, 2021; Ukpai et al., 2021).

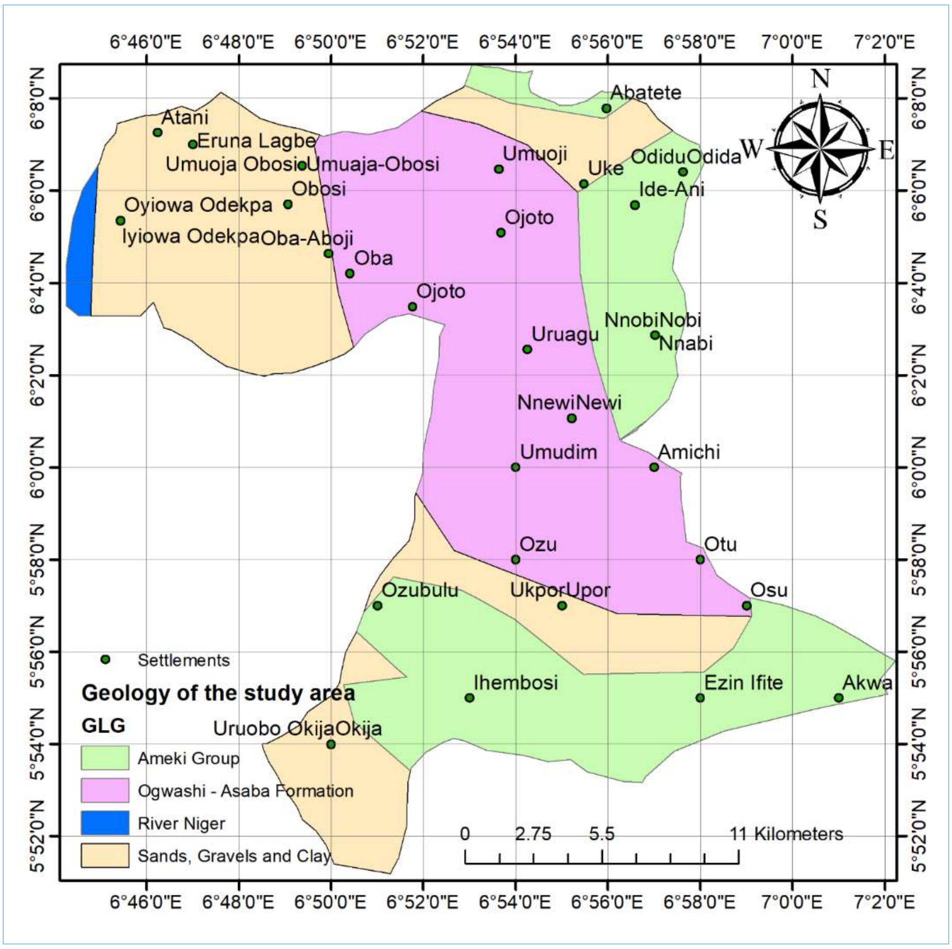

Fig. 2. Geology map of the study

Deforestation and agricultural expansion in Anambra State further exacerbate the challenges to groundwater management. The removal of natural vegetation for farming reduces the soil's ability to absorb and retain water, leading to increased runoff and decreased infiltration (Egbueri et al., 2020). The use of chemical fertilizers and pesticides in agriculture poses additional risks to groundwater quality, as these substances can leach into the water system, contaminating it.

Given the critical role of groundwater in supporting socio-economic activities and maintaining ecosystem health, it is essential to understand and manage the impacts of LULC changes on groundwater dynamics. Sustainable land use practices, including reforestation, the adoption of conservation agriculture, and the implementation of green infrastructure in urban areas, can help mitigate the adverse effects of LULC changes on groundwater systems (Ijioma, 2021). Reforestation and afforestation can restore the natural vegetation cover, enhancing the soil's ability to absorb and retain water, thus promoting groundwater recharge.

Conservation agriculture practices, such as minimal tillage, crop rotation, and the use of cover crops, can improve soil health and water retention, reducing the need for chemical inputs and minimizing their impact on groundwater quality

(Ogar et al., 2022). In urban areas, the integration of green infrastructure, such as green roofs, permeable pavements, and rain gardens, can enhance infiltration and reduce surface runoff, contributing to the sustainability of groundwater resources.

Effective groundwater management in Anambra State requires a comprehensive understanding of the complex interactions between LULC changes and hydrological processes. It also necessitates the collaboration of various stakeholders, including government agencies, local communities, and non-governmental organizations, to develop and implement policies and practices that promote sustainable land use and groundwater management (Naz et al., 2020). Through informed decision-making and the adoption of sustainable practices, it is possible to safeguard the groundwater resources that are vital for the well-being and prosperity of Anambra State.

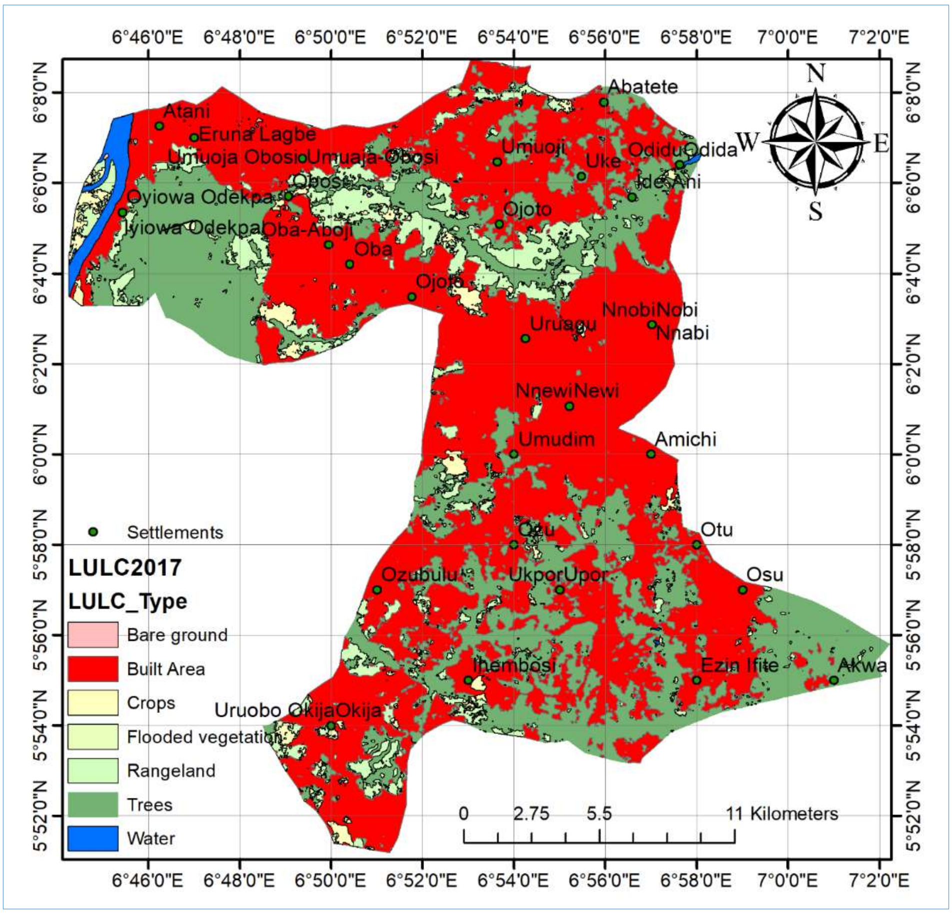

Fig. 3. LULC 2017 of the study area

This study aims to investigate the effects of land use and land cover changes on groundwater dynamics in Onitsha North, Onitsha South, Nnewi North, Nnewi South, Idemili North, and Idemili South Local Government Areas of Anambra State, Nigeria. By analyzing DEM data to calculate slope and Sentinel-2 imagery data from 2017-2023, the research seeks to identify patterns of groundwater contamination, over-extraction, and seasonal fluctuations, offering insights into sustainable groundwater management practices in the region.

This study is significant for Onitsha North and South, Nnewi North and South, and Idemili North and South due to their diverse land uses, including industrial, residential, and agricultural activities. These areas face critical groundwater issues like contamination, over-extraction, and pollution, making it essential to understand and manage groundwater dynamics to ensure sustainable water resources and environmental health.

Table 1. Area of various LULC type in 2017

LULC Type	Area (km^2)
Water	4.77
Trees	148.38
Flooded vegetation	0.44
Crops	11.65
Built Area	269.18
Bare ground	0.40
Rangeland	41.05

2. Study Area

Anambra State, situated in southeastern Nigeria, boasts a diverse landscape characterized by various topographical features, climate patterns, and land use practices. The state is located approximately between latitudes 5° 53' and 7° 00' North and longitudes 6° 50' and 7° 42' East. Specifically, the capital city of Anambra, Awka, is positioned at approximately 6° 12' North latitude and 7° 04' East longitude.

The selected study area within Anambra State encompasses three Local Government Areas (LGAs) that exemplify the varied land use dynamics within the state. These LGAs include Onitsha, Awka, and Nnewi, each offering unique characteristics representative of different urbanization levels, agricultural practices, and natural vegetation.

Onitsha, a prominent urban center, is renowned for its bustling commercial activities and high population density. Situated at approximately 6° 09' North latitude and 6° 47' East longitude, Onitsha features extensive built-up areas indicative of rapid urbanization and economic vibrancy. Awka, the capital of Anambra State, serves as a pivotal hub with a blend of urban and semi-urban attributes. Located at approximately 6° 12' North latitude and 7° 04' East longitude, Awka embodies administrative significance alongside evolving urban developments and infrastructural advancements. Nnewi, celebrated for its industrial prowess, stands out as a key player in the economic landscape of Anambra State.

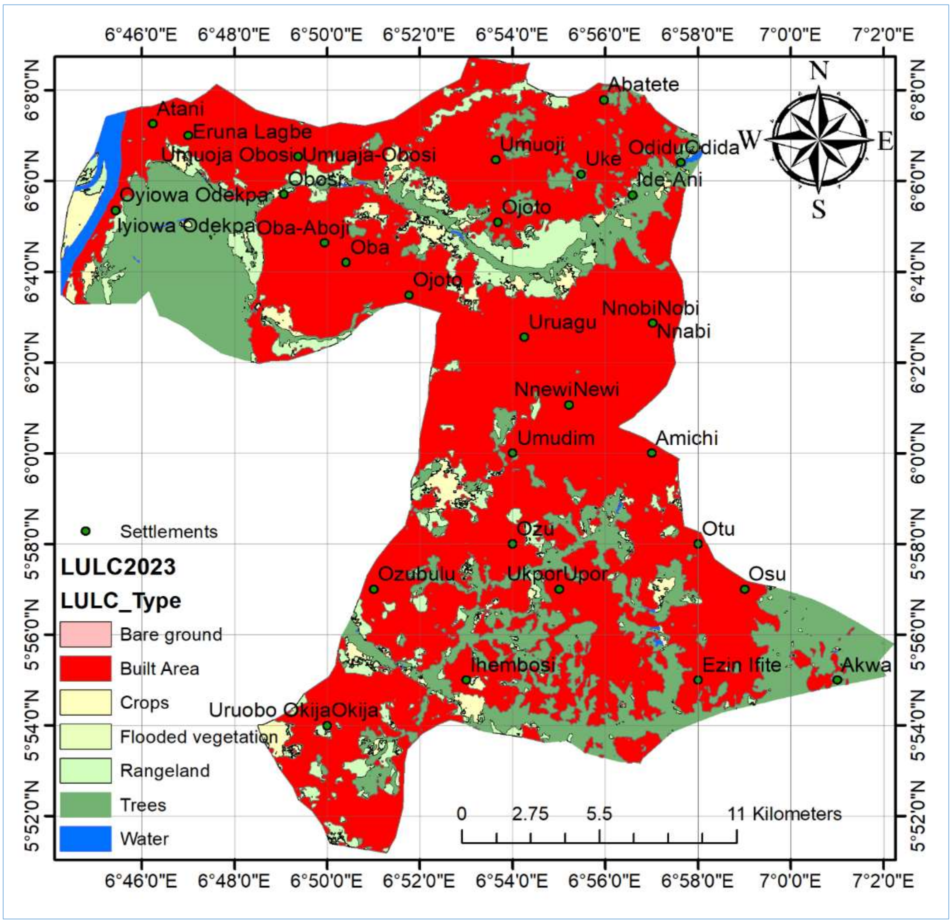

Fig. 4. LULC 2023 of the study area

Positioned at approximately 6° 01' North latitude and 6° 55' East longitude, Nnewi boasts a thriving industrial sector amidst its distinctive land use patterns. Fig. 1 illustrates the spatial distribution of these selected LGAs within Anambra State, highlighting their respective roles in shaping the overall land use dynamics of the region (Ifeanyichukwu et al., 2021).

Table 2: Area of various LULC type in 2023

LULC Type	Area (km^2)
Water	4.82
Trees	107.90
Flooded vegetation	0.10
Crops	19.65
Built Area	305.07
Bare ground	0.05
Rangeland	38.26

The geological composition of the study area, illustrated in Fig. 2, encompasses a rich variety of formations that significantly contribute to its distinctive landscape features. Among these formations are the Ameki Group and the Ogwashi-Asaba Formation, each with its unique characteristics and geological significance. The Ameki Group, known for its sedimentary deposits, plays a pivotal role in shaping the topography and soil composition of the study area (Ogbe and Osokpor, 2021).

These sedimentary rocks, formed over millions of years, provide valuable insights into the geological history and evolution of the region. The Ogwashi-Asaba Formation, characterized by its geological diversity and stratigraphic complexity, further enriches the geological profile of the study area (De Andrade Caxito et al., 2020). The presence of deposits such as sands, gravels, and clay underscore the diverse nature of the geological landscape. These deposits, formed through various geological processes including erosion, weathering, and sedimentation, contribute to the overall soil fertility and mineral composition of the region. Geological constituents of the study area exert a profound influence on land use patterns, agricultural practices, and natural resource availability. For instance, areas with fertile soils derived from sedimentary deposits are often conducive to agricultural activities, while regions with clay-rich soils may be suitable for pottery and brick-making industries. The presence of sand and gravel deposits may facilitate construction and infrastructure development within the study area.

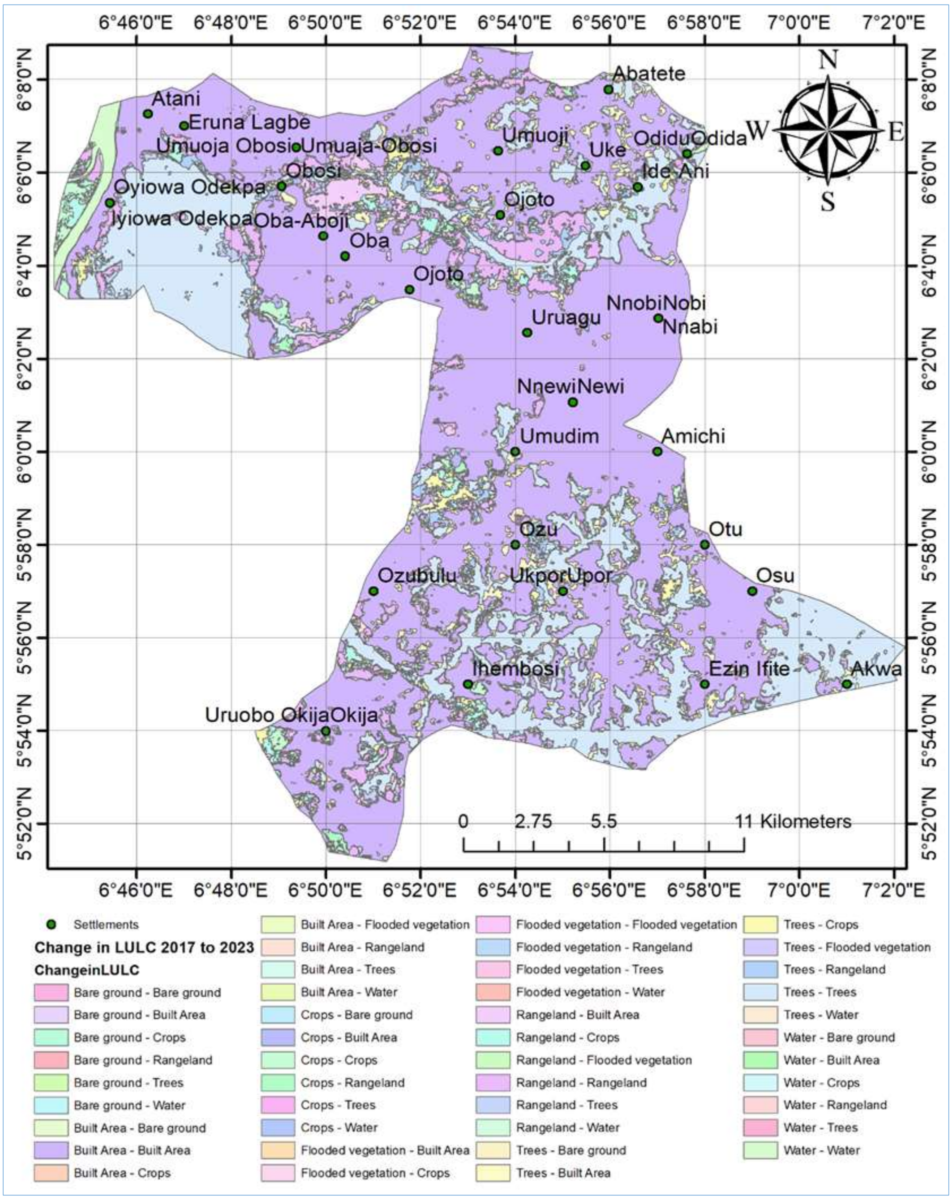

Fig. 5. LULC change between 2017 to 2023 of the study area

3. Materials and Methods

The study utilized a comprehensive dataset comprising four Digital Elevation Models (DEMs) sourced from the Shuttle Radar Topography Mission (SRTM) and Land Use and Land Cover (LULC) data derived from Sentinel-2 imagery. These datasets were pivotal for characterizing the topography and land cover dynamics of the study area. The SRTM DEMs were acquired from the United States Geological Survey (USGS) Earth Explorer platform, offering a spatial resolution of 30 meters for the year 2021. These DEMs provided essential information regarding elevation variations, slope gradients, and terrain features, which are fundamental for understanding landscape dynamics and processes such as erosion, sediment transport, and hydrological modeling (Eludoyin and Adewole, 2019; Khan et al., 2020).

In addition to the DEMs, LULC data obtained from Sentinel-2 imagery played a crucial role in the study. Spanning the temporal range from 2017 to 2023 (Fig. 5), Sentinel-2 imagery provided high spatial resolution (10 meters) multispectral data, enabling detailed land cover classification and change detection analysis (Rahman et al., 2020). Prior to analysis, the Sentinel-2 imagery underwent preprocessing to eliminate atmospheric distortions and enhance image quality. Subsequently, supervised classification techniques were employed to delineate various land cover classes including urban areas, agricultural lands, water bodies, and natural vegetation.

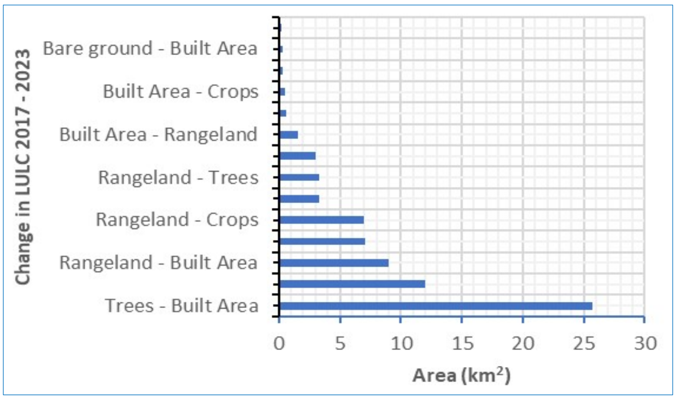

Fig. 6. Cluster bar of major LULC change between 2017 to 23023 of the study area

Table 3: Area and percentage area of major LULC change type

Change in LULC	Area Change (km^2)
Trees - Built Area	25.67
Trees - Rangeland	11.95
Rangeland - Built Area	9.03
Trees - Crops	7.08
Rangeland - Crops	6.97
Crops - Built Area	3.27
Rangeland - Trees	3.26
Crops - Rangeland	3.03
Built Area - Rangeland	1.52
Built Area - Trees	0.64
Built Area - Crops	0.55
Crops - Trees	0.29
Bare ground - Built Area	0.28
Rangeland - Water	0.20

The integration of SRTM DEMs and Sentinel-2-derived LULC data allowed for a comprehensive assessment of landscape characteristics and dynamics over the study period. This approach facilitated the identification of trends in land cover change, assessment of landscape fragmentation, and examination of potential drivers influencing landscape dynamics. Overall, the combined use of these datasets provided valuable insights into the interactions between topography and land cover, contributing to a better understanding of landscape processes and their implications for environmental management and planning.

4. Results and Discussion

4.1. LULC 2017

In 2017, the study area exhibited diverse LULC types, which are critical in understanding groundwater dynamics. The LULC types in the study area included water bodies, tree cover, flooded vegetation, crops, built-up areas, bare ground, and rangeland as shown in Fig. 3 and Table 1. Each of these LULC types plays a distinct role in influencing groundwater recharge, quality, and availability.

Water bodies, though covering a relatively small area, are essential for groundwater recharge. They facilitate the percolation of water into the aquifers, maintaining the groundwater levels. However, in the context of Onitsha and surrounding areas, water bodies can also be sources of contamination if polluted by industrial or domestic waste, thereby affecting the groundwater quality adversely. Tree cover represents a significant portion of the study area. Forested regions are crucial for sustaining groundwater as they enhance infiltration and reduce surface runoff. Trees also help in maintaining the ecological balance, reducing erosion, and improving soil moisture content, which collectively contribute to groundwater recharge (Lasisi et al., 2022). The presence of extensive tree cover is beneficial for the health of the groundwater system in these LGAs.

Flooded vegetation, though minimal in area, plays a role in groundwater dynamics by providing temporary storage of surface water which can eventually seep into the ground. This LULC type helps in moderating the effects of floods and can support groundwater recharge during high precipitation periods (Abdullateef et al., 2021).

However, if these areas are polluted, they can introduce contaminants into the groundwater system. Agricultural lands, comprising 11.65 km², are critical in the study of groundwater dynamics. Crops require significant amounts of water, which is often sourced from groundwater, leading to potential over-extraction. Moreover, the use of fertilizers and pesticides in farming can lead to groundwater contamination. Therefore, sustainable agricultural practices are necessary to balance the water needs and protect groundwater quality.

The built-up area is the most extensive LULC type in the study region, covering 269.18 km². Urbanization significantly impacts groundwater dynamics by reducing the land available for natural recharge. Impervious surfaces such as roads, buildings, and pavements prevent water infiltration, leading to increased surface runoff and reduced groundwater recharge. Urban areas are often sources of various pollutants, contributing to groundwater contamination (Weatherl et al., 2021).

Bare ground areas are sparse but play a role in groundwater recharge by allowing direct infiltration of rainwater. However, these areas are also prone to erosion and can quickly become sources of sediment that may clog waterways and affect groundwater recharge rates negatively. Rangelands, covering 41.05 km², are utilized for grazing and other pastoral activities. These areas can contribute to groundwater recharge through infiltration. However, overgrazing and poor land management practices can lead to soil degradation and reduced infiltration capacity, thereby affecting groundwater levels and quality.

4.2. LULC 2023

The LULC data for 2023 illustrates the distribution of various land cover types within the study area as shown in Fig. 4 and

Table 2. This updated information is essential for understanding how land use practices have evolved over the six-year period and how these changes may influence groundwater dynamics.

The conversion of 25.67 km² of tree cover to built-up areas represents the most significant LULC change. This shift is primarily driven by urban expansion and industrial development. The reduction in tree cover impacts groundwater recharge negatively, as trees facilitate infiltration and reduce surface runoff. Urban areas, with impervious surfaces, hinder water infiltration, leading to decreased groundwater recharge. Urbanization increases the risk of groundwater contamination from industrial and residential pollutants (Zacchaeus et al., 2020).

The transformation of tree-covered areas to rangeland, accounting for 11.95 km², also affects groundwater dynamics. Trees play a crucial role in maintaining soil structure and promoting infiltration. The conversion to rangeland, often associated with grazing activities, can lead to soil compaction and reduced infiltration rates, thereby impacting groundwater recharge negatively. The shift of 9.03 km² from rangeland to built-up areas signifies further urban expansion. Like the conversion of trees to build areas, this change reduces the land available for natural recharge. Rangelands, although less effective than forests, still contribute to groundwater recharge. Their loss to urban development exacerbates the challenges of maintaining sustainable groundwater levels. The conversion of 7.08 km² of tree cover to agricultural land indicates an expansion in farming activities. While agriculture is vital for food security, this change can lead to increased groundwater extraction for irrigation, posing a risk of over-extraction. Moreover, the use of fertilizers and pesticides in agriculture can contaminate groundwater sources.

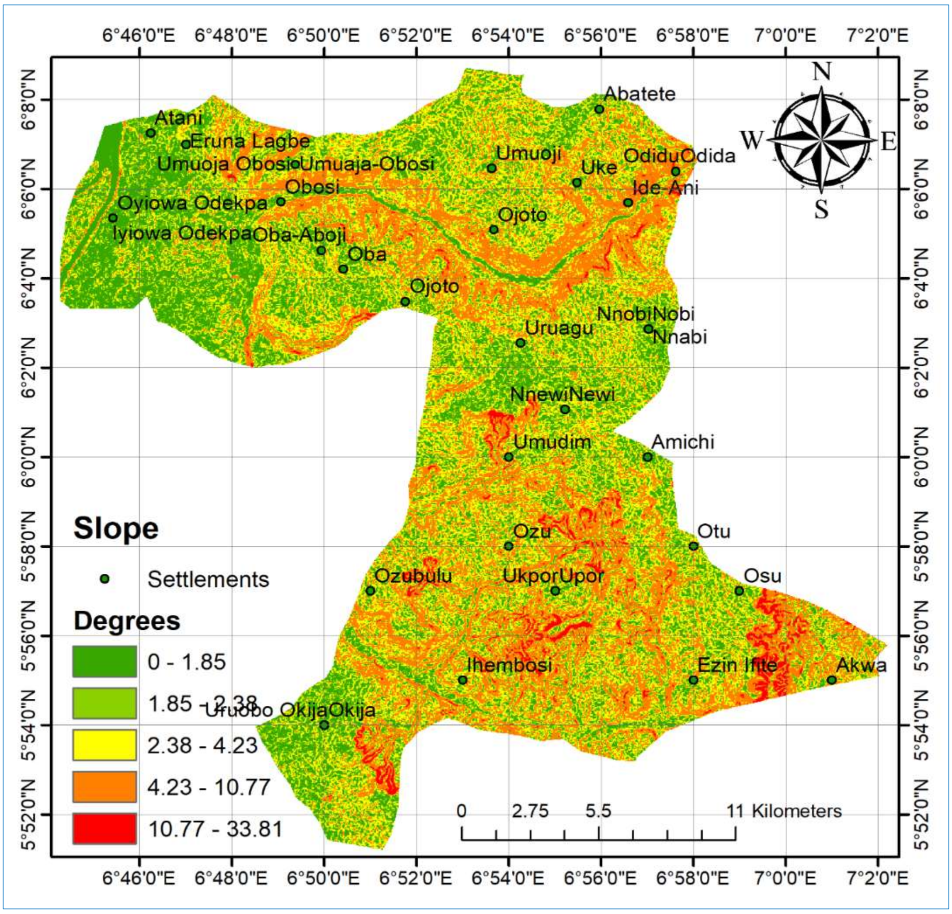

Fig. 7. Slope map of the study area

Similarly, the conversion of 6.97 km² of rangeland to cropland reflects agricultural intensification. This change can strain groundwater resources due to higher water demands for irrigation. Sustainable agricultural practices are needed to balance groundwater use and prevent contamination from agricultural runoff. The conversion of 3.27 km² of cropland to built-up areas further highlights urban growth. As with other urbanization-related changes, this shift reduces groundwater recharge areas and increases the risk of contamination. Proper urban planning and the inclusion of green spaces can help mitigate these impacts. The transformation of 3.26 km² of rangeland to tree cover is a positive change for groundwater dynamics. Reforestation enhances infiltration and reduces runoff, contributing to improved groundwater recharge. The shift of 3.03 km² from cropland to rangeland might indicate a reduction in agricultural activities. While rangelands are less effective in promoting infiltration than forests, they still support groundwater recharge better than croplands. This change could have neutral to positive impacts on groundwater dynamics, depending on land management practices.

The conversion of 0.55 km² of built-up areas to cropland, although minimal, indicates a shift towards agricultural use. This change could have mixed impacts on groundwater, depending on the intensity of agricultural practices and water management strategies. The shift of 0.29 km² from cropland to tree cover is beneficial for groundwater recharge. Trees improve soil structure and infiltration, thereby enhancing groundwater recharge rates and improving water quality. The conversion of 0.28 km² of bare ground to built-up areas is a relatively minor change but still contributes to reduced recharge areas and increased surface runoff, characteristic of urbanization impacts. The change of 0.20 km² from rangeland to water bodies can positively affect groundwater recharge if the new water bodies are managed to prevent contamination.

4.4. Slope of the Study Area

The slope map as shown in Fig. 7 provides a detailed representation of the terrain's gradient across the study area. Different slope ranges can have varying impacts on groundwater dynamics due to their influence on water movement and soil stability.

Table 4: Area and percentage area of slope range in the study area

Slope (º)	**Area (km²)**	**Area (%)**
0 - 1.85	125.12	26.29
1.85 - 2.38	56.69	11.91
2.38 - 4.23	150.84	31.70
4.23 - 10.77	133.66	28.09
10.77 - 33.81	9.56	2.01

This slope range of 0 - 1.85° with 26.29% of the study area represents relatively flat terrain, which is conducive to high infiltration rates as water has more time to percolate into the soil. Consequently, areas with these gentle slopes are likely to contribute significantly to groundwater recharge. However, flat terrains can also be prone to waterlogging and the accumulation of pollutants, which may lead to groundwater contamination if not properly managed (Awomeso et al., 2020).

This slope range of 1.85 - 2.38° with 11.91% of the study area represents slightly steeper slopes compared to the first category. These slopes can still facilitate good infiltration rates while moderately increasing surface runoff. The balance between infiltration and runoff makes these areas important for both groundwater recharge and surface water management (Ashaolu et al., 2020). This category (2.38 - 4.23° with 31.70%), representing the largest area, has moderately steep slopes that generate more surface runoff compared to flatter areas. While infiltration is reduced, these slopes can still support groundwater recharge in areas where soil permeability is high (Garba and Abubakar, 2023).

Steeper slopes (4.23 - 10.77° with 28.09%) in this range contribute significantly to surface runoff and are less favorable for groundwater recharge due to rapid water movement. These areas are also more susceptible to soil erosion, which can further reduce infiltration and introduce sediments into water bodies (Prancevic et al., 2020). These (10.77 - 33.81° with 2.01%) are the steepest slopes in the study area and cover the smallest area. High runoff and low infiltration characterize these terrains, making them poor contributors to groundwater recharge. The steepness also poses a high risk of soil erosion and landslides.

5. Discussion

The research delves into the intricate relationship between LULC types and their impact on groundwater dynamics within the study area from 2017 to 2023. It elucidates how various LULC categories, including water bodies, tree cover, flooded vegetation, crops, built-up areas, bare ground, and rangeland, exert distinct influences on groundwater recharge, quality, and availability.

Urban expansion and agricultural intensification emerge as the primary drivers of change in LULC patterns over the study period. The expansion of built-up areas and agricultural lands results in notable alterations in the landscape, with significant implications for groundwater recharge dynamics (Abdullateef et al., 2021; Ijioma, 2021). As built-up areas encroach upon natural habitats and permeable surfaces are replaced with impervious materials, such as concrete and asphalt, the ability of the land to absorb and recharge groundwater diminishes. Consequently, there is an increase in surface runoff, leading to reduced infiltration rates and heightened risks of groundwater contamination from pollutants carried by runoff (Zacchaeus et al., 2020; Chinye-Ikejiunor et al., 2021).

Similarly, agricultural intensification contributes to changes in LULC patterns, particularly through the conversion of natural land covers such as tree cover and rangeland into agricultural fields. While agricultural activities are essential for food production, the use of fertilizers and pesticides poses risks to groundwater quality through leaching and runoff (He et al., 2019; Jabir et al., 2022). Moreover, the extraction of groundwater for irrigation purposes further exacerbates the pressure on groundwater resources, potentially leading to overdrafting and depletion of aquifers.

The conversion of tree cover to built-up areas represents a significant shift in LULC patterns with profound implications for groundwater recharge. Trees play a crucial role in enhancing infiltration and reducing surface runoff by intercepting rainfall and promoting soil permeability through root systems. However, the replacement of tree cover with impervious surfaces impedes infiltration, leading to increased runoff and reduced groundwater recharge rates (Csicsaiova et al., 2020). Efforts to mitigate these impacts may include reforestation initiatives and the implementation of green infrastructure strategies to enhance permeability and water retention in urban areas.

Conversely, shifts towards sustainable land management practices, such as reforesting rangeland areas, demonstrate positive effects on groundwater dynamics. Rangelands contribute to groundwater recharge through infiltration, but overgrazing and poor land management practices can lead to soil degradation, reducing infiltration capacity (Ashaolu et al., 2020; Ijioma, 2021). Restoring these areas with vegetation helps improve soil structure, increase infiltration rates, and reduce surface runoff, thereby enhancing groundwater recharge and quality.

Moreover, terrain slope emerges as a critical factor influencing groundwater dynamics. Flatter terrains are conducive to high infiltration rates, making them significant contributors to groundwater recharge (Sikakwe, 2020; George et al., 2022; Ogungbade et al., 2022). However, steeper slopes generate more surface runoff and are prone to soil erosion, posing challenges for groundwater recharge and soil stability (Li et al., 2020; Abdullateef et al., 2021). Understanding these terrain characteristics is essential for implementing targeted management strategies to enhance groundwater recharge and protect groundwater quality.

This study underscores the urgent need for adopting sustainable land management practices and effective urban planning to safeguard groundwater resources. It emphasizes the interconnectedness between land use changes, terrain characteristics, and groundwater dynamics, highlighting the importance of holistic approaches to preserve groundwater sustainability in the study area. By addressing the drivers of change and implementing targeted management strategies, stakeholders can work towards ensuring the long-term viability of groundwater resources for current and future generations.

6. Conclusion

The study area displayed a rich array of LULC types in 2017, each intricately linked to groundwater dynamics. These LULC categories, including water bodies, tree cover, flooded vegetation, crops, built-up areas, bare ground, and rangeland, collectively influenced groundwater recharge, quality, and availability. However, the period from 2017 to 2023 witnessed substantial alterations in the landscape, predominantly driven by urban expansion and agricultural intensification, profoundly impacting groundwater dynamics.

The expansion of built-up areas, representing the most extensive LULC type, significantly reduced natural recharge areas, increased surface runoff, and heightened contamination risks. Conversely, reductions in tree cover and flooded vegetation diminished the capacity for groundwater recharge, exacerbating issues related to water availability and flood management. Agricultural land expansion intensified groundwater extraction for irrigation, raising concerns about contamination from agricultural inputs.

Moreover, the conversion of LULC types, such as tree cover to built-up areas and cropland, further strained groundwater resources, highlighting the interconnectedness between land use changes and groundwater sustainability. Notably, shifts towards sustainable land management practices, such as the conversion of rangeland to tree cover, demonstrated positive impacts on groundwater recharge, emphasizing the importance of environmental restoration efforts.

The terrain's slope also emerged as a crucial factor influencing groundwater dynamics, with varying slope ranges exhibiting distinct contributions to groundwater recharge and susceptibility to erosion. Flatter terrains facilitated high infiltration rates, enhancing groundwater recharge, while steeper slopes posed challenges due to increased surface runoff and erosion risks.

In conclusion, the study underscores the intricate relationship between land use changes, terrain characteristics, and groundwater dynamics. The findings emphasize the imperative for sustainable land management practices and effective urban planning to mitigate adverse impacts on groundwater resources. Targeted strategies, including green infrastructure development and conservation measures, are essential for enhancing groundwater recharge and safeguarding groundwater quality in the face of evolving land use patterns and terrain conditions.

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