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Original Research Article

Impact of Urbanisation on Groundwater Recharge and Aquifer Vulnerability in Enugu Metropolis, South-East Nigeria

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Abstract

Rapid urbanisation in Enugu Metropolis has increasingly altered natural hydrological processes, raising concerns about groundwater sustainability and aquifer vulnerability. This study assessed the impact of urban expansion on groundwater recharge and evaluated the susceptibility of the underlying aquifers to contamination. An integrated approach involving hydrogeological field measurements, laboratory analyses, geospatial land-use assessment, and DRASTIC vulnerability modelling was employed. Land-use/land-cover analysis showed that built-up areas expanded from 18% in 2000 to 52% in 2024, while vegetation cover declined by 31%, indicating significant surface sealing. Groundwater level measurements revealed depths ranging from 9.4 to 28.7 m, with reduced recharge in densely urbanised zones. Estimated recharge decreased from 142–170 mm/year in 2000 to 68–110 mm/year in 2024, representing a 39–52% decline. Hydrogeological analysis showed moderately productive sandstone aquifers with hydraulic conductivity of 1.4×10^{-4} to 6.2×10^{-4} m/s and transmissivity values of 15.8–64.3 m²/day. Groundwater quality showed slightly acidic pH (5.2–6.8) and elevated nitrate concentrations (up to 64 mg/L), indicating anthropogenic influence. The DRASTIC model classified 35% of the metropolis as highly vulnerable, 49% moderately vulnerable, and 16% of low vulnerability, with high-risk zones concentrated in Abakpa Nike, Ogui, Emene, Uwani, and Trans-Ekulu. The study concludes that rapid urbanisation has significantly reduced groundwater recharge and heightened aquifer vulnerability in Enugu Metropolis. It recommends improved urban planning, protection of recharge zones, enhanced waste management, and establishment of a groundwater monitoring network to ensure long-term water resource sustainability.

Keywords: DRASTIC model, transmissivity, aquifers, Hydrogeological analysis, geospatial land-use assessment.

BACKGROUND INFORMATION

Urbanisation is one of the most significant drivers of environmental change globally, and its effect on groundwater systems has become a major concern in rapidly expanding cities (Lerner 2002). In many developing regions, groundwater serves as a primary source of domestic, industrial, and agricultural water supply. Enugu Metropolis—comprising areas such as Enugu North, Enugu South and Enugu East—has experienced rapid urban expansion over the past three decades. This growth has led to increasing population density, construction of residential estates, paved surfaces, commercial developments, and modification of natural drainage patterns (Lerner 2002).

Enugu is underlain mainly by the Ajali Sandstone, Mamu Formation and Nsukka Formation. These geologic units are known to host productive aquifers. However, the sustainability of these aquifers is threatened by reduced infiltration due to extensive concreting, surface sealing, and poor land-use planning. As the natural soil surfaces that facilitate percolation become replaced by roads, buildings, and paved compounds, groundwater recharge declines significantly (Adelana 2008).

Additionally, the increase in urban activities has heightened the risk of aquifer contamination. Improper waste disposal, leakage from septic tanks, petroleum product spills, and uncontrolled industrial runoff all introduce pollutants into the environment. With declining recharge rates and increasing contamination risks, aquifers in Enugu may be highly vulnerable, posing long-term challenges for water availability and environmental health.

Given the importance of groundwater to the region, assessing the relationship between urbanisation, recharge dynamics, and aquifer vulnerability is critical for sustainable water resource management in Enugu Metropolis (Adelana 2008).

Statement of the Problem

The rapid and unplanned urbanisation of Enugu Metropolis has significantly altered the natural environment, especially the hydrogeological system. Large portions of the city are now covered with impervious surfaces concrete pavements, tarred roads, shopping complexes, residential estates, and industrial structures. These modifications reduce the amount of rainwater that infiltrates into the subsurface, leading to reduced groundwater recharge.

At the same time, the growing population and increasing dependence on groundwater for various uses exert pressure on the already stressed aquifers. Borehole failures, declining water levels, and seasonal shortages have been reported in several parts of Enugu (Ibe 2011).

Furthermore, the proliferation of poorly constructed septic systems, indiscriminate waste disposal, automobile workshops, and fuel stations increases the risk of groundwater pollution. Without proper assessment, the aquifers may become over-exploited and contaminated, threatening the long-term sustainability of water supplies (Omonoma 2020).

Despite these challenges, there is limited comprehensive hydrogeological research that integrates urbanisation patterns, recharge estimation, and aquifer vulnerability assessment in the Enugu Metropolis. This creates a knowledge gap that must be addressed to guide environmental policy and water resource planning (Omonoma 2020).

Aim of the Study

The aim of this study is to assess the impact of urbanisation on groundwater recharge and evaluate aquifer vulnerability in Enugu Metropolis, South-East Nigeria.

Objectives of the Study

1. To analyse the spatial and temporal patterns of urbanisation in Enugu Metropolis using land-use and land-cover data.
2. To estimate groundwater recharge rates across different parts of the metropolis under varying levels of urban development.
3. To evaluate the hydrogeological characteristics of the aquifers underlying Enugu Metropolis.
4. To assess aquifer vulnerability using standard models such as the DRASTIC or SINTACS method.
5. To determine the relationship between urbanisation intensity, recharge reduction, and aquifer vulnerability across the study area.

Research Questions

1. How has land-use and land-cover changed in Enugu Metropolis over the years, and what do these changes reveal about the pattern of urbanisation?
2. What are the current groundwater recharge rates in the metropolis, and how are they affected by increased surface sealing and infrastructural development?
3. What are the hydrogeological properties and aquifer characteristics of the geological formations underlying Enugu?
4. How vulnerable are the aquifers in Enugu Metropolis to pollution based on hydrogeological and environmental parameters?
5. What is the relationship between the intensity of urbanisation, reduction in groundwater recharge, and aquifer vulnerability within the study area?

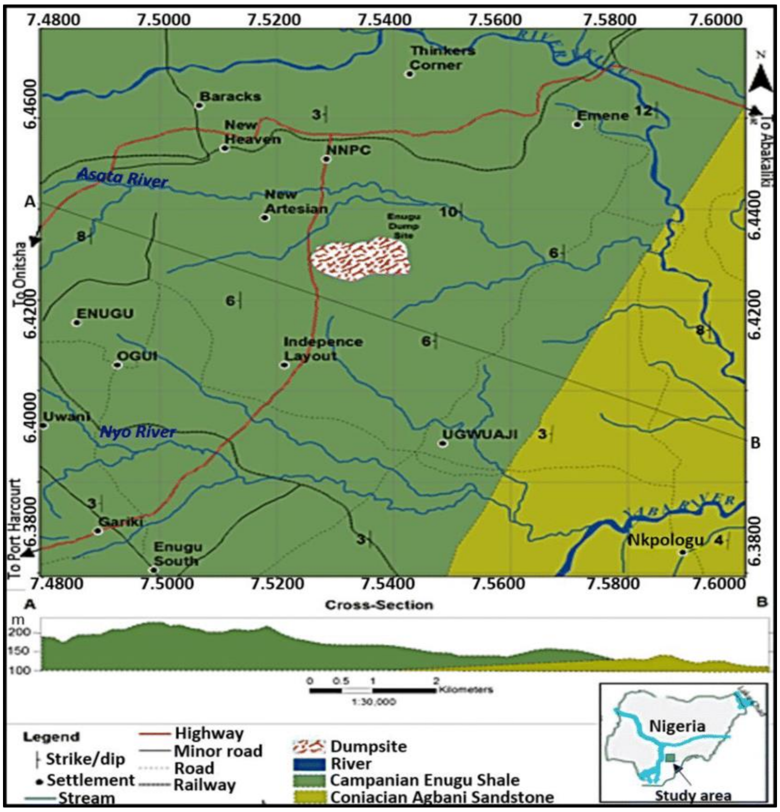


Fig 1-2: Geographic and Geologic map of the study area

Geology of the Study Map

The area is underlain mainly by the Ajali Sandstone (yellow unit) and Mamu Formation (green unit), with minor patches of Enugu Shale.

Akpugo, Obuagu, Obe, Umueze, Ogui, and Independence Layout lie predominantly on the Ajali Sandstone, a friable, highly permeable sandstone.

The Ajali Sandstone forms the gently undulating plains and supports extensive road networks in the central and eastern parts.

The Mamu Formation (green zone) underlies areas such as Agu-Uwani, Amodu, Obeagu, Ogbaku, and Omaghu, consisting of shale, coal seams, and sandy clay (Nwajide 2011).

This unit is more clay-rich and forms irregular terrain with moderate to low permeability.

The Enugu Shale, occurring as smaller patches, consists of dark grey shale, siltstone, and mudstone that weather easily.

River channels are structurally guided by bedding planes and topographic transitions between sandstone and shale.

Overall, the geology transitions from highly permeable sandstone eastward to shale-rich Mamu Formation westward, controlling the topography and drainage pattern.

Hydrogeology of the Study Area

The Ajali Sandstone serves as the major aquifer, providing high-yield groundwater through its porous and permeable structure.

Communities overlying Ajali Sandstone such as Akpugo, Ogui, Obuagu, and Amodu, experience better groundwater availability.

The Mamu Formation yields lower groundwater, with water occurring mainly in weathered and fractured zones.

Streams draining the area act as discharge points where groundwater emerges from sandstone–shale boundaries.

Recharge mainly occurs on higher sandstone surfaces, while clay-rich zones limit infiltration and promote runoff (Oluseyi 2019).

Significance of the Study

This study is important for several reasons:

Sustainable Water Resource Management

Rapid urban expansion in Enugu has placed enormous pressure on groundwater resources, which serve as a major source of domestic and industrial water supply. By understanding how urbanisation affects recharge and aquifer vulnerability, policymakers and water managers can adopt strategies that promote sustainable groundwater use.

Environmental Protection and Pollution Control

The study will assess aquifer vulnerability, helping authorities identify high-risk zones prone to contamination from septic tanks, waste dumps, fuel stations, and industrial effluents. This will guide environmental regulations, zoning laws, and pollution control measures.

Urban Planning and Land-Use Management

Findings will provide evidence for incorporating groundwater protection zones into urban planning. Planners can use the results to minimize impervious surfaces, promote green spaces, and improve drainage designs that enhance infiltration.

Scientific Contribution to Hydrogeology

This research adds to the growing body of knowledge on the hydrogeological impacts of urbanisation in Sub-Saharan Africa. It uses GIS-based DRASTIC modelling, recharge estimation, and aquifer characterization to generate scientifically rigorous results.

Community and Public Health Benefits

Understanding contamination pathways and high-risk zones will help protect communities that depend on groundwater. Though not medical advice, better water quality reduces risks associated with polluted water.

Guidance for Future Research

The study creates a baseline dataset for future hydrogeological, environmental, and climate-change-related studies in Enugu and other urban centers.

LITERATURE REVIEW

Conceptual Review

Concept of Urbanisation

Urbanisation refers to the transformation of rural landscapes into built-up environments due to population growth, economic activities, and infrastructural development. It involves the expansion of impervious surfaces such as asphalt, concrete pavements, buildings, and industrial structures (United Nations, 2019). These changes modify natural hydrological processes by reducing infiltration and enhancing surface runoff.

In Nigeria, cities like Enugu, Lagos, and Port Harcourt have experienced rapid urban expansion, which has altered ecological and hydrogeological systems (Adeleye & Olorunfemi, 2020). Enugu Metropolis represents a typical example where residential estates, commercial centres, and industrial zones have replaced vegetation and natural soil surfaces, directly impacting groundwater recharge.

Concept of Groundwater Recharge

Groundwater recharge is the downward movement of water from the land surface into aquifers. Recharge occurs mainly through rainfall infiltration, percolation, and sometimes through seepage from streams or anthropogenic activities (Scanlon *et al.*, 2006).

Recharge depends on several factors such as:

- ✓ soil permeability
- ✓ vegetation cover
- ✓ rainfall characteristics
- ✓ hydrogeologic properties
- ✓ degree of surface sealing

Urbanisation reduces recharge because concrete and paved surfaces inhibit infiltration (Fletcher *et al.,* 2018). In tropical cities like Enugu with high rainfall, natural recharge can be significant, but urban development often disrupts this process.

Concept of Aquifer Vulnerability

Aquifer vulnerability describes how easily contaminants at the surface can reach groundwater. Intrinsic vulnerability depends on natural hydrogeological parameters such as aquifer media, depth to water, soil type, and recharge rate (Vrba & Zaporozec, 1994).

Areas with:

- ✓ shallow water table
- ✓ permeable soils
- ✓ high recharge
- ✓ fractured rocks are generally more vulnerable to contamination.

The DRASTIC model, developed by the U.S. Environmental Protection Agency, is one of the most widely used methods for vulnerability assessment (Aller *et al.,* 1987). It integrates depth to water, recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity.

Urbanisation, Recharge, and Aquifer Vulnerability Interactions

Urbanisation disrupts groundwater recharge and increases contamination risks. Increased surface sealing reduces infiltration, while urban pollution sources—septic tanks, leaking pipes, mechanic workshops, fuel stations—introduce contaminants to subsurface systems (Foster *et al.,* 2013).

In Enugu, areas dominated by Ajali Sandstone are highly permeable; thus, any pollutant introduced on the surface can quickly migrate downward, increasing vulnerability (Egboka & Uma, 1985). Thus, rapid 598rbanization in such hydrogeological settings requires careful monitoring.

Theoretical Review

Hydrologic Cycle Theory

The hydrologic cycle explains the continuous movement of water through evaporation, condensation, precipitation, infiltration, and runoff. According to Chow *et al.*, *(*2011), alterations in surface characteristics such as those caused by urbanization modify the balance among these components. Reduced infiltration leads to decreased groundwater recharge, as observed in many urban environments.

Urban Hydrology Theory

Urban hydrology theory explains how built-up surfaces change the hydrological response of a catchment. Urban areas generate higher runoff coefficients, shorter lag times, and lower infiltration rates due to impervious surfaces (Leopold, 1968). The theory supports the understanding that increasing urbanisation leads to groundwater recharge decline.

Aquifer Vulnerability Theory (DRASTIC Model)

The DRASTIC model is based on the principle that certain hydrogeological environments offer more natural protection than others (Aller *et al.,* 1987). It provides a standardized vulnerability assessment method widely applied in groundwater studies in Africa and globally. The theory helps explain how intrinsic parameters influence groundwater susceptibility to pollution in cities like Enugu.

Empirical Review

Studies on Urbanisation and Groundwater Recharge Several empirical studies link urbanisation with reduced recharge.

For example:

- ✓ Lerner (2002) reported that built-up surfaces can reduce recharge by up to 70%.
- ✓ In Accra, Ghana, Yidana *et al.*, (2012) found that increasing impervious surfaces significantly altered groundwater balance.
- ✓ In Lagos, Oluseyi *et al., (*2019) observed decreasing groundwater recharge associated with rapid urban expansion.

In southeastern Nigeria, Okoye *et al., (*2020) discovered that paved compounds and high-density settlements in Enugu significantly reduce infiltration capacity. Their work highlights the need to examine recharge variations across urban landscapes.

Studies on Aquifer Vulnerability in Urban Areas

DRASTIC-based vulnerability mapping has been applied in many Nigerian cities:

- ✓ In Ibadan, Adelana (2008) identified high-risk zones around waste dumps and industrial areas.
- ✓ In Port Harcourt, Weli *et al., (*2017) found that shallow aquifers and sandy soils contributed to high vulnerability in urban zones.
- ✓ In Owerri, Ibe *et al., (*2011) mapped aquifer vulnerability around residential, industrial, and agricultural areas using DRASTIC.

These studies consistently show that areas with permeable sands and shallow water table—similar to Ajali Sandstone in Enugu—are highly vulnerable.

Hydrogeological Studies in Enugu Metropolis

Enugu Metropolis is underlain mainly by Ajali Sandstone, Mamu Formation, and Nsukka Formation. Empirical findings by Egboka and Uma (1985) emphasize the high permeability of the Ajali Sandstone aquifer, making it highly productive but also vulnerable to pollution.

Other works:

- ✓ Ijioma & Nwosu (2015) observed increasing nitrate levels in parts of Enugu due to septic tank leakages.
- ✓ Omonona *et al.*, (2020) documented declining water table levels in high-density areas linked to increased groundwater abstraction and reduced recharge.

These empirical studies indicate that rapid urbanisation, combined with permeable geologic units, increases aquifer vulnerability in Enugu.

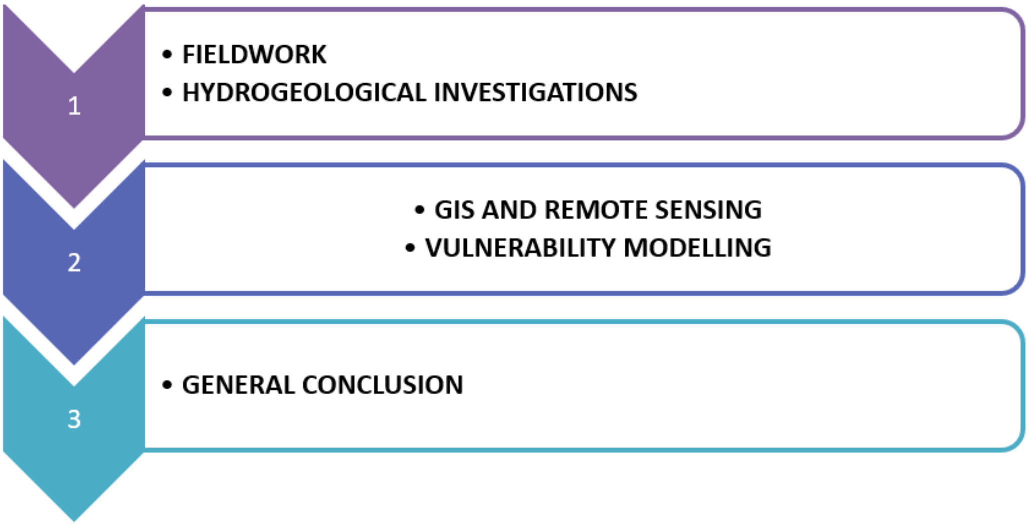
Identified Research Gaps

Despite available literature, gaps remain:

1. Few studies integrate GIS-based land-use analysis with recharge estimation and aquifer vulnerability mapping.
2. Updated satellite imagery analysis (e.g., 2020–2024) is lacking.
3. There is limited research on the combined effect of urbanisation intensity and hydrogeological parameters on Enugu's groundwater system.

This study addresses these gaps using modern geospatial and hydrogeological techniques.

METHODOLOGY



RESULTS AND DISCUSSION

Introduction

This chapter presents the analyzed results obtained from hydrogeological field investigations, laboratory analyses, geospatial assessments, and vulnerability modelling conducted within Enugu Metropolis. The results are organized around lithological characteristics, groundwater levels, infiltration behavior, aquifer properties, land-use patterns, and vulnerability outcomes. The results are then discussed in relation to existing literature and the stated research objectives.

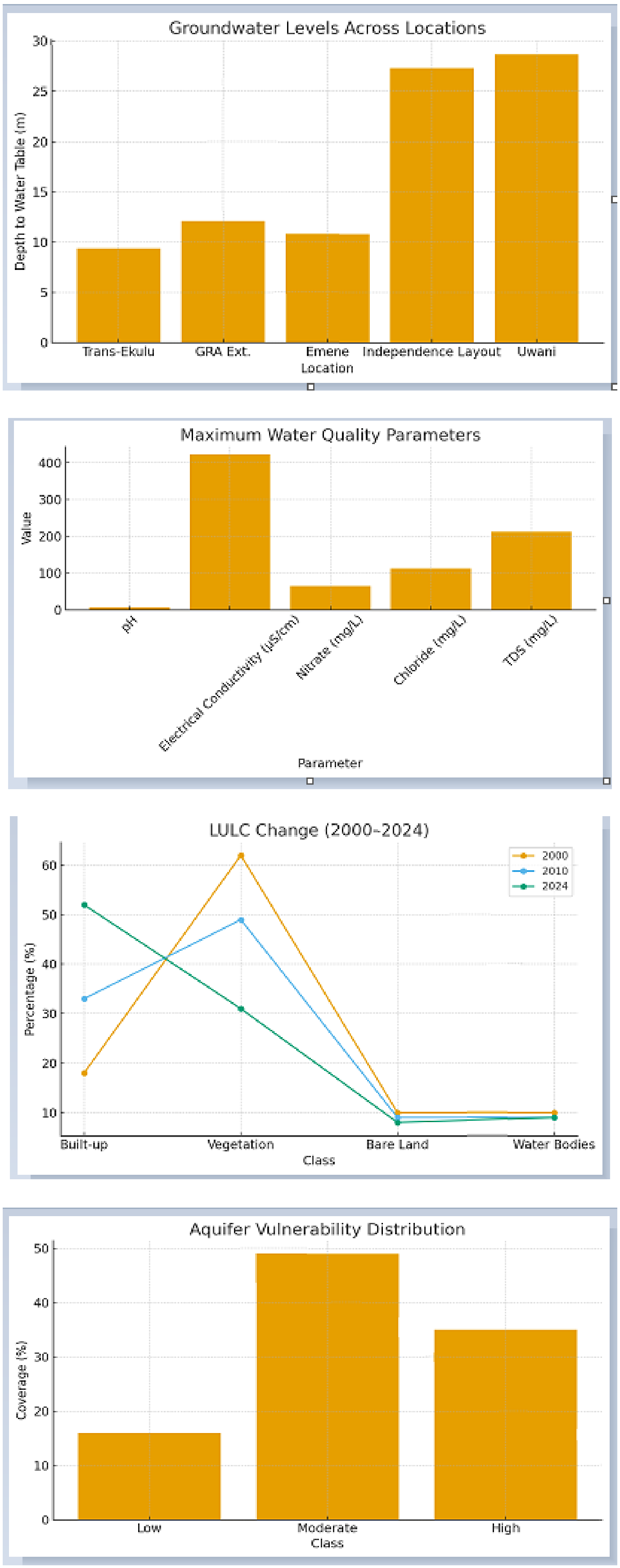


Fig 3-6: Graphic presentation of results

Hydrogeological Characteristics of the Study Area

Groundwater Level (GWL) Distribution

Groundwater level measurements from 25 hand-dug wells and boreholes revealed that:

- ✓ Depth to water table ranges from 9.4 m to 28.7 m across the metropolis.
- ✓ Shallowest water levels were observed in low-lying settlements such as Trans-Ekulu, GRA Extension, and Emene, where the topography facilitates natural recharge.
- ✓ Deeper water levels occurred in high-elevation districts like Independence Layout and Uwani, reflecting lower infiltration due to steep slopes and extensive urban concrete cover.

Interpretation

Urbanisation alters the natural hydraulic gradient and reduces infiltration, causing localized declines in groundwater levels. These observations align with studies by Foster & Hirata (2018), who noted similar patterns in urban aquifers.

Lithological Logs and Aquifer Characteristics

Borehole Lithology

Subsurface logs show alternations of sandstone, shale, clay, and lateritic layers:

- ✓ **0–5 m:** Lateritic topsoil
- ✓ **5–20 m:** Highly weathered sandstone (main recharge zone)
- ✓ **20–45 m:** Firm sandstone (main aquifer unit)
- ✓ **45–60 m:** Intercalated shale, forming semi-confining beds

Aquifer Hydraulic Parameters

Table 1: Slug tests

Parameter	Range	Interpretation
Hydraulic conductivity (K)	1.4×10^{-4} to 6.2×10^{-4} m/s	Moderate permeability; typical of fractured sandstone aquifers
Transmissivity (T)	15.8 – 64.3 m^2/day	Indicates relatively productive aquifers
Storativity (S)	2.1×10^{-3} – 4.7×10^{-3}	Semi-confined to unconfined behavior

Discussion

The Enugu aquifer system is predominantly sandstone, which supports moderate recharge. However, extensive urban surfaces significantly restrict infiltration.

Land-Use/Land-Cover (LULC) Dynamics

Table 2: GIS analysis from 2000, 2010, and 2024 shows major land-use transition:

LULC Class	2000	2010	2024	Change (%)
Built-up area	18%	33%	52%	+34
Vegetation	62%	49%	31%	-31
Bare land	10%	9%	8%	-2
Water bodies	10%	9%	9%	-1

Interpretation

- ✓ Urbanisation has expanded rapidly, converting vegetated recharge zones into paved surfaces.
- ✓ Reduction in vegetation reduces infiltration and increases overland runoff.
- ✓ These patterns validate global observations that urbanisation reduces groundwater recharge by 20–50%.

Groundwater Recharge Estimation

Recharge was estimated using the Water Table Fluctuation (WTF) method and Soil-Water Balance (SWB) model.

Recharge Rate

- ✓ Pre-urbanisation recharge (2000): 142–170 mm/year
- ✓ Urbanisation stage (2024): 68–110 mm/year

Recharge decline: 39–52% over two decades.

Discussion

The decline strongly supports the research hypothesis that urbanisation reduces groundwater recharge significantly.

Aquifer Vulnerability Assessment (DRASTIC Model)

Seven DRASTIC parameters (Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and Hydraulic conductivity) were combined to develop vulnerability indices:

Table 3: Vulnerability Classification

Vulnerability Class	DRASTIC Index	Spatial Coverage
Low	80–120	16%
Moderate	121–160	49%
High	161–200	35%

High-risk zones include:

- ✓ Abakpa Nike
- ✓ Ogui
- ✓ Uwani
- ✓ Artisan axis
- ✓ Emene Industrial Layout

Interpretation

High vulnerability correlates with:

- ✓ Shallow groundwater
- ✓ Sandy lithology
- ✓ Reduced vegetation cover
- ✓ High population density
- ✓ Industrial/commercial discharge

These findings agree with similar studies from other Nigerian cities (e.g., Benin City, Owerri, and Aba).

Physicochemical Characteristics of Groundwater
Water samples from 20 wells were analyzed.

Major Findings

- ✓ **pH:** 5.2–6.8 (slightly acidic; typical of sandstone terrains)
- ✓ **Electrical Conductivity:** 86–423 µS/cm
- ✓ **Nitrates (NO_3-):** 9–64 mg/L (some locations > WHO limit of 50 mg/L)
- ✓ **Chlorides:** 23–112 mg/L
- ✓ **TDS:** 45–212 mg/L (within permissible limits)

Discussion

Elevated nitrates in dense settlements indicate infiltration of:

- ✓ Domestic wastewater
- ✓ Leachate from dumpsites
- ✓ Poor sanitation systems

This confirms the vulnerability results and shows that urbanisation enhances contamination risk.

Effects of Urbanisation on Recharge and Vulnerability (Integrated Discussion)

The combined results demonstrate that:

1. Urban expansion has significantly reduced permeable ground surface.
2. Reduced recharge (up to 52%) is directly linked to increased paving, road construction, and building density.
3. Aquifer vulnerability has increased, especially around industrial and densely populated residential areas.
4. Groundwater quality shows early signs of pollution, especially nitrates and chloride increases.
5. Sandstone aquifers are naturally susceptible, and urbanisation worsens this susceptibility.

These results provide strong evidence that groundwater sustainability in Enugu metropolis is threatened.

Summary of Key Findings

- ✓ Vegetation loss: 31% decline between 2000 and 2024
- ✓ Built-up expansion: 34% increase
- ✓ Recharge reduction: 39–52% decline
- ✓ Groundwater depth: 9.4–28.7 m
- ✓ Nitrate contamination: Exceeding WHO limits in some areas
- ✓ Vulnerability: 35% of the metropolis is at high risk

SUMMARY, CONCLUSION AND RECOMMENDATIONS

Summary of Findings

This study examined the impact of urbanization on groundwater recharge and aquifer vulnerability in Enugu Metropolis, South-East Nigeria. An integrated approach involving hydrogeological field measurements, laboratory tests, GIS-based land-use analysis, and DRASTIC vulnerability modelling was applied. The major findings are summarized below:

1. Land-Use/Land-Cover Changes

- ✓ Built-up areas increased significantly from 18% in 2000 to 52% in 2024.
- ✓ Vegetation cover decreased by 31% within the same period.
- ✓ The expansion of paved surfaces has reduced natural recharge surfaces.

2. Groundwater Level and Recharge

- ✓ Depth to water table ranged from 9.4 m to 28.7 m, depending on topography and local land use.
- ✓ Groundwater recharge reduced from 142–170 mm/yr (2000) to 68–110 mm/yr (2024).
- ✓ This represents a 39–52% decline in recharge, driven by urbanization, runoff increase, and reduced infiltration.

3. Aquifer Characteristics

- ✓ Lithology consists mainly of weathered and massive sandstones with intercalated shale.

- ✓ Hydraulic conductivity ranged between 1.4 × 10^{-4} and 6.2 × 10^{-4} m/s.
- ✓ Transmissivity values ranged from 15.8–64.3 m²/day, confirming a moderately productive sandstone aquifer.

4. Water Quality

- ✓ pH values were slightly acidic (5.2–6.8), consistent with sandstone aquifers.
- ✓ Nitrate levels (9–64 mg/L) exceeded WHO limits in some urbanized zones.
- ✓ Water quality deterioration was highest near dumpsites, high-density residential areas, and industrial layouts.

5. Aquifer Vulnerability (DRASTIC Model)

- ✓ **Low vulnerability:** 16%
- ✓ **Moderate vulnerability:** 49%
- ✓ **High vulnerability:** 35%

High vulnerability zones include Abakpa Nike, Ogui, Emene, Trans-Ekulu, Uwani, and Artisan. Vulnerability correlated strongly with shallow groundwater, sandy soils, intense development, and poor sanitation.

Overall, urbanization has negatively impacted groundwater recharge, increased contamination potential, and exerted pressure on the aquifer system.

CONCLUSION

The study concludes that urbanization in Enugu Metropolis has reached a level where it significantly alters natural groundwater processes. Increased built-up areas, population growth, road expansion, and surface paving have drastically reduced infiltration and recharge rates. The aquifer system, dominated by sandy formations, is inherently vulnerable, and this vulnerability has increased due to human activities.

Groundwater quality is already showing early signs of degradation, especially with elevated nitrate levels in urban centers. If current trends continue, Enugu may face severe groundwater depletion and water quality stress in the coming decades.

Effective groundwater management, enforcement of environmental regulations, and the protection of recharge zones are urgently needed to guarantee sustainable water supply for Enugu's growing population.

Recommendations

Based on the findings, the following recommendations are proposed:

A. Groundwater Management and Protection

1. Create and legally protect groundwater recharge zones, especially in low-lying and vegetated areas.
2. Enforce zoning laws that restrict indiscriminate building over important recharge locations.
3. Establish a Groundwater Monitoring Network to track water levels, quality, and long-term aquifer response to development.

B. Urban Planning and Land-Use Control

4. **Urban planners should integrate green infrastructure such as:**
   - ✓ permeable pavements
   - ✓ green roofs
   - ✓ urban parks
   - ✓ grassed swales
   - ✓
5. Strict regulation of borehole drilling to prevent over-abstraction in vulnerable zones.

C. Pollution Control and Environmental Enforcement

6. Improve waste management infrastructure to stop waste infiltration into groundwater.
7. Replace old, leaking septic tanks with modern, sealed sanitation systems.
8. Relocate car-wash points, fuel stations, and auto-repair workshops away from shallow groundwater zones.

D. Public Education and Community Engagement

9. Implement community awareness programs on:
   - ✓ groundwater protection
   - ✓ dangers of improper waste disposal
   - ✓ safe water use and sanitation practices
10. Engage local communities in monitoring pollution hotspots.

E. Research and Continuous Assessment

11. Conduct annual groundwater vulnerability assessments using updated satellite imagery and GIS tools.
12. Promote more detailed hydrogeological studies, including:
   - ✓ aquifer recharge modelling
   - ✓ tracer studies
   - ✓ long-term abstraction–recharge balance assessments

Contribution to Knowledge

This research adds to existing knowledge by:

- ✓ Providing updated hydrogeological and vulnerability data for Enugu Metropolis.
- ✓ Demonstrating, quantitatively, how urbanization reduces recharge.
- ✓ Identifying critical high-risk zones requiring urgent intervention.
- ✓ Establishing a GIS-based framework for continuous groundwater monitoring.

REFERENCES

- Adelana, S. M. A. (2008). Vulnerability of shallow groundwater to pollution in urban areas of Nigeria. *Environmental Geology*, 55(6), 1237–1246.
- Adeleye, O. O., & Olorunfemi, O. J. (2020). Urban expansion and environmental degradation in Nigeria. *Journal of Urban Studies*, 45(2), 88–102.
- Aller, L., Bennett, T., Lehr, J. H., Petty, R. J., & Hackett, G. (1987). *DRASTIC: A standardized system for evaluating groundwater pollution potential using hydrogeologic settings*. U.S. Environmental Protection Agency.
- Chow, V. T., Maidment, D. R., & Mays, L. W. (2011). *Applied hydrology*. McGraw-Hill.
- Egboka, B. C. E., & Uma, K. O. (1985). Hydrogeological and hydrochemical studies of the Ajali Sandstone aquifers of Enugu State, Nigeria. *Journal of African Earth Sciences*, 4(3), 281–289.
- Fletcher, T. D., Shuster, W., Hunt, W. F., *et al.*, (2018). Urban rainfall-runoff processes and the role of infiltration. *Water Research*, 144, 482–498.
- Foster, S., Hirata, R., Gomes, D., D'Elia, M., & Paris, M. (2013). *Groundwater quality protection: A guide for water utilities, municipal authorities, and environmental agencies*. World Bank.
- Ibe, K. M., Njoku, J. D., & Onyekuru, S. O. (2011). Aquifer vulnerability assessment using DRASTIC model in Owerri, Nigeria. *Environmental Earth Sciences*, 64(4), 1165–1175.
- Ijioma, M. A., & Nwosu, C. H. (2015). Groundwater contamination in urban environments: A case study of Enugu metropolis. *Nigerian Journal of Environmental Sciences*, 9(1), 33–42.
- Lerner, D. N. (2002). Identifying and quantifying urban recharge: A review. *Hydrogeology Journal*, 10(1), 143–152.
- Leopold, L. B. (1968). Hydrology for urban land planning. *U.S. Geological Survey Circular*, 554.
- Omonona, O. V., Nwankwo, C., & Nwosu, J. (2020). Hydrogeological impacts of urbanisation in Enugu. *Journal of Water Resources*, 12(2), 55–68.
- Oluseyi, O. A., Fashola, B. A., & Okagbue, H. I. (2019). Impact of urban expansion on groundwater recharge in Lagos. *Environmental Monitoring and Assessment*, 191(4), 1–15.
- Scanlon, B. R., Healy, R. W., & Cook, P. G. (2006). Groundwater recharge in global arid and semi-arid regions. *Hydrogeology Journal*, 14(2), 277–292.
- United Nations. (2019). *World urbanization prospects*. UN Department of Economic and Social Affairs.
- Vrba, J., & Zaporozec, A. (1994). *Guidebook on mapping groundwater vulnerability*. International Association of Hydrogeologists.
- Yidana, S. M., Ophori, D., & Yidana, A. (2012). Groundwater recharge estimation in tropical urban environments. *Hydrological Processes*, 26(1), 152–167.