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Hydrological modelling of flood risk and watershed response to land use change: A case study of the Anambra Watershed, Nigeria

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Abstract
Land use and land cover (LULC) changes significantly influence watershed hydrological processes and flood risk. This study assessed the effects of long-term LULC change on the hydrological response of the Anambra Watershed between 1995 and 2025 using Remote Sensing (RS), Geographic Information Systems (GIS), and HEC-HMS hydrological modelling. Satellite imagery was analyzed to quantify historical land cover changes, while HEC-HMS was employed to simulate rainfall–runoff responses under varying land use conditions. The results revealed a 184.2% increase in built-up areas and substantial declines in forest cover (34.1%) and wetlands (34.0%) over the study period. Hydrological simulations showed that these changes reduced infiltration by 45.4%, increased surface runoff by 36.0%, and increased peak discharge by 38.6% under a 100-year rainfall event. The time-to-peak also decreased from 14.2 to 11.8 hours, indicating a faster watershed response to storm events. Flood susceptibility mapping further revealed that approximately 73% of the watershed falls within medium to very high flood-risk categories, with the highest vulnerability concentrated in the southern floodplain regions. The findings demonstrate that long-term land use change has significantly altered the hydrological behaviour of the watershed and increased flood vulnerability. The study highlights the importance of riparian restoration, wetland conservation, and sustainable urban drainage strategies for effective flood-risk management within the watershed.

1. Introduction

Flooding events continue to be one of the most detrimental environmental crises of human habitation, infrastructure and agriculture across the world (Smith & Ward, 2015). The volume of water entering a watershed system is primarily dependent on the intensity and duration of the rainfall (Chow et al., 1988), but the hydrological response of a watershed is greatly influenced by the land surface characteristics and the land use conditions (SCS-USDA, 1986). In natural environments, vegetation cover, forest ecosystems and wetlands can improve infiltration, slow water flow and provide temporary water storage to help reduce the rapid surface runoff and generation of peak discharges (Balarabe et al., 2025). On the other hand, anthropogenic changes like urbanization, deforestation, increase in agriculture and reclamation of wetlands have a marked influence on the hydrodynamics of the watersheds, by decreasing the infiltration capacity and increasing the impervious surface coverage (Weng, 2012; Herold et al., 2003).

Population growth and careless land development has led to an increasing rate of land use and land cover (LULC) changes in many developing areas, especially in sub-Saharan Africa (SSA) (Ward & Shukla, 2017). Land use changes such as the installation of impermeable surfaces (asphalt, concrete, compacted soils) affect the hydrology of watersheds (Weng, 2012). During heavy rainfall, these low permeability surfaces cause an increase in the amount of runoff in a shorter lag time, thus increasing the discharge of the river, flood frequency and flood intensity (Chow et al., 1988; SCS-

USDA, 1986). Hence, the recurrent flood disasters, deterioration of infrastructure, soil erosion and agriculture losses in urban and peri-urban communities are escalating with time (Nkwunonwo et al., 2020).

Flooding is now a recurring environmental problem in Nigeria that has significant socio-economic impacts (Nkwunonwo et al., 2020). Several decades ago, there have been a rise in the frequency of flooding in the south-eastern part of the country with the Anambra Watershed being highly susceptible to such flooding (Chukwuma et al., 2021; Tella & Balogun, 2020). The entire Anambra Watershed which occupies an area of about 11010km^2 within the lower Niger drainage basin is a significant hydrological and agricultural basin, and is crisscrossed by major urban centres including Onitsha and its attendant rural areas. However, the hydrologic behaviour of the watershed has been significantly altered due to rapid urban expansion, deforestation, settlement development and agricultural encroachment into natural floodplains (Okafor & Agunwamba, 2024). These changes have led to significant flooding that was observed during the years 2012, 2022 and 2024, causing heavy displacement, destruction of infrastructural facilities, disruptions in transportation and heavy losses in agricultural productivity (Okafor & Agunwamba, 2024; Tella & Balogun, 2020).

Most of the previous studies on flooding in south-eastern Nigeria have concentrated on flood mapping, climate variability or disaster impact assessment with little attention paid to quantifying the relationship between long-term land use change and watershed hydrological response through the use of integrated geospatial and hydrological modelling techniques (Chukwuma et al., 2021; Nkwunonwo et al., 2020). This means that there is still a lack of clarity on the effects of land cover changes on runoff generation, peak discharge characteristics and flood susceptibility in the Anambra Watershed (Okafor & Agunwamba, 2024).

Revolutions in geospatial technologies and hydrological simulation models now allow for effective consideration of the dynamics of a watershed and flood risk patterns (Youssef et al., 2011). Multi-temporal monitoring of LULCC can be done with RS through platforms and historical data portals such as satellite platforms and historical data portals (Jensen, 2005; Lillesand et al., 2015; NASA, 2023; USGS, 2023). In the meantime, Geographic Information Systems (GIS) environments enable sophisticated spatial analysis of topography, drainage networks, soil attributes, and rainfall patterns (Esri, 2023; Shrestha et al., 2021). These systems can be used in combination with multi-criteria decision-making systems for comprehensive hazard mapping (Saaty, 1980; Shrestha et al., 2021). The United States Army Corps of Engineers (USACE) developed hydrological models including the Hydrologic Engineering Centre–Hydrologic Modelling System (HEC-HMS) which offer a solid basis for modelling the rainfall–runoff processes and evaluating the watershed responses across different land use scenarios (HEC, 2022).

Thus, this study has incorporated the application of Remote Sensing, GIS and HEC-HMS hydrological modelling techniques to assess the impact of land use change on flood risk and watershed response onto the Anambra Watershed (Balarabe et al., 2025; HEC, 2022). The purpose of the study therefore is to examine how land use has changed over time, model watershed responses to various land use scenarios, and to determine sustainable approaches to flood mitigation and watershed management for the area. This study is vital for developing targeted flood mitigation and sustainable land-management frameworks in a region heavily impacted by rapid urbanization. The Anambra Watershed faces escalating environmental vulnerabilities, yet current regional literature exhibits a severe thematic gap.

While understanding a watershed's hydrological response requires rigorous environmental modeling, local academic output remains heavily skewed toward educational pedagogy and classroom instruction rather than environmental or fluid dynamics. For instance, recent regional research focuses extensively on gamification and computer-based studies (Enem et al., 2025; Muogbo et al, 2025), and AI integration (Muogbo et al, 2026). Furthermore, empirical studies in the area frequently target student psychology and science demographics (Ezeanyagu et al., 2023; Okafor, 2018), leaving a deficit in physical geography research. Even when examining technical skill acquisition, literature is restricted to process skills, literacy and scientific perspectives (Okafor, 2017; Nneka & Okafor, 2013; Okafor, 2019; Ugonwa, 2015). Consequently, by applying HEC-HMS and geospatial modeling to map physical flood risks, this study directly addresses a critical gap, shifting regional data from classroom mechanics to urgent environmental resource management.

The main objective of this study is to evaluate the effects of long-term land use and land cover (LULC) change on the hydrological response and flood risk of the Anambra Watershed between 1995 and 2025 using Remote Sensing (RS), Geographic Information Systems (GIS), and HEC-HMS hydrological modelling techniques. Specifically, this study aims to determine the extent and pattern of land use and land cover changes within the Anambra Watershed between 1995 and 2025, with particular emphasis on the conversion of forests and wetlands into agricultural and built-up areas. It also aims to assess the impact of land use and land cover changes on watershed hydrological response by evaluating variations in surface runoff generation, peak discharge, and time-to-peak during severe rainfall events. In addition, the study seeks to identify and map flood-prone communities and zones within the Anambra Watershed based on topographic, soil, drainage, and land use characteristics using GIS-based flood susceptibility analysis. Therefore, this study focuses on examining the extent to which natural forests and wetlands have been converted into farms and towns within the Anambra Watershed between 1995 and 2025, analyzing the increase and acceleration of floodwater flow through the river network during severe storms compared to conditions 30 years ago, and identifying the specific communities and zones within the watershed that are currently at the highest risk of flooding based on local terrain, soils, and land use.

2. Method

Study Area Description: This study was conducted within the Anambra Watershed, located in south-eastern Nigeria. The watershed covers an area of approximately 11,010 km^2 and forms an important component of the lower Niger drainage basin. The basin exhibits considerable variations in topography, soil characteristics, and hydrological conditions. The northern portion is characterized by undulating terrain and predominantly sandy loam soils with relatively high infiltration capacities, which promote groundwater recharge and reduce surface runoff. In contrast, the southern section consists mainly of low-lying floodplains underlain by alluvial clay soils with low permeability. These conditions limit infiltration and increase the susceptibility of the area to waterlogging and flood inundation during periods of intense rainfall.

Land Use and Land Cover Change Analysis: To evaluate historical land use and land cover (LULC) dynamics within the watershed, cloud-free satellite imagery for the years 1995, 2010, and 2025 was obtained from the United States Geological Survey (USGS) Earth Explorer database. Image processing and classification were performed using ArcGIS Pro.

The watershed was classified into five major land use categories, namely built-up areas, agricultural land, forest/riparian vegetation, wetlands/water bodies, and bare land. Built-up areas include urban settlements, transportation infrastructure, and other developed surfaces, while agricultural land consists of cultivated fields and farming areas. Forest/riparian vegetation refers to natural forests and vegetation found along river corridors. Wetlands/water bodies include swamps, marshes, rivers, streams, and permanent water bodies. Bare land refers to exposed soil surfaces, degraded lands, and sparsely vegetated areas.A supervised classification approach was employed to generate land cover maps for each study year. Classification accuracy was assessed through confusion matrix analysis using reference data obtained from historical records and available validation sources. The resulting classifications achieved an overall accuracy greater than 90%, ensuring the reliability of the generated LULC maps for subsequent analyses.

Hydrological Modelling Using HEC-HMS: The hydrological response of the watershed under different land use scenarios was simulated using the Hydrologic Engineering Centre–Hydrologic Modelling System (HEC-HMS). A Digital Elevation Model (DEM) with a spatial resolution of 30 m was used to delineate the watershed boundary, extract drainage networks, and subdivide the basin into 24 hydrologically connected sub-basins. Surface runoff estimation was performed using the Soil Conservation Service Curve Number (SCS-CN) method. This method integrates land use characteristics and hydrologic soil groups to estimate rainfall losses and determine the proportion of precipitation converted into direct runoff. Historical rainfall records were incorporated into the model to simulate watershed responses under 10-year, 50-year, and 100-year rainfall return periods. Model calibration was conducted using observed streamflow data obtained from the Otuocha hydrological gauging station to improve the accuracy and reliability of the simulated runoff and discharge estimates. The calibrated model was subsequently used to evaluate the effects of long-term land use change on runoff generation, peak discharge, and overall watershed hydrological response.

Flood Susceptibility Assessment: Flood susceptibility mapping was carried out using a Geographic Information System (GIS)-based multi-criteria evaluation approach. Six environmental and hydrological factors known to influence flood occurrence were selected for analysis: Elevation, Slope, Distance from rivers, Drainage density, Soil type, Land use and land cover (2025). These factors were converted into thematic spatial layers and standardized within the GIS environment. The relative importance of each factor was determined using the Analytic Hierarchy Process (AHP), a widely applied decision-support technique for multi-criteria analysis.

Weighted overlay analysis was then performed to integrate the selected factors and generate a flood susceptibility map of the watershed. The resulting map classified the study area into different flood-risk categories, thereby identifying communities and locations most vulnerable to flooding based on prevailing topographic, hydrological, soil, and land use conditions.

3. Results and Discussion

Over the past 30 years, satellite data revealed that human activities have profoundly reshaped the landscape of the Anambra Watershed, with the detailed changes presented in Table 1.

Table 1. Landscape Change from 1995 to 2025

Land Cover Type	1995 Area (km^2)	1995 %	2025 Area (km^2)	2025 %	Net Change (%)
Built-Up (Towns/Concrete)	412.5	3.75%	1,172.4	10.65%	+184.2% (Grew)
Agricultural (Farms)	3,415.2	31.02%	5,125.8	46.56%	+50.1% (Grew)
Forest / Trees	4,110.8	37.34%	2,710.2	24.61%	-34.1% (Lost)
Wetlands / Swamps	1,812.4	16.46%	1,195.4	10.86%	-34.0% (Lost)
Bare / Cleared Soil	1,259.1	11.43%	806.2	7.32%	-36.0% (Lost)

The trends show clear environmental pressure. Concrete towns and cities expanded by a massive 184.2%. Farmland grew by 50.1% to feed the growing population. To make room for this growth, communities cleared away 34.1% of the region's forests and drained 34.0% of the natural swamps. This represents a massive loss of the environment's natural "sponges."

By incorporating the 1995 and 2025 land use maps into the HEC-HMS model, the study simulated the response of both landscapes to the same heavy 100-year rainstorm, and the structural changes in water behaviour are detailed in Table 2.

Table 2. Simulated Changes in Flood Water Behaviour

Flood Metric	1995 Landscape	2025 Landscape	Net Change	What This Means
Water Sunk into Ground	62.4mm	34.1mm	-45.4%	The ground can no longer absorb rainwater.
Water Turning into Runoff	78.6mm	106.9mm	+36.0%	Massive amounts of extra water pour into rivers.
Peak River Flow (Qp)	2,850.4 m3/s	3,950.8m3/s	+38.6%	Rivers rise significantly higher, bursting banks.
Flood Metric	1995 Landscape	2025 Landscape	Net Change	What This Means

Because the natural forests and swamps are gone, the watershed's capacity to absorb rainwater dropped by 45.4%. Instead of soaking into the earth, that water turns into instant surface runoff, causing a 38.6% increase in peak river flow. Furthermore, because concrete allows water to slide forward effortlessly, the floodwaters reach their maximum, dangerous peak 2.4 hours faster than they did 30 years ago. This compression of time turns predictable river rises into dangerous, rapid-onset flash floods.

The results indicate a strong shift toward human-dominated land use within the watershed. Built-up areas and agricultural land expanded substantially, while forest cover and wetlands declined significantly. These changes reflect increasing urbanization and agricultural demand driven by population growth and economic activities. The reduction in forests and wetlands is particularly important because these ecosystems naturally regulate hydrological processes through rainfall interception, infiltration enhancement, and water storage. Their continuous decline reduces the watershed's ability to absorb rainfall, thereby increasing the likelihood of surface runoff generation and flood occurrence.

The hydrological results show a marked increase in runoff generation and peak discharge under the 2025 land use scenario. This is primarily due to increased impervious surfaces and reduced vegetative cover, which limit infiltration and accelerate surface flow. The reduction in time-to-peak indicates that runoff is being conveyed more rapidly through the drainage network, resulting in faster flood development. This shortened response time reduces the opportunity for early warning and increases flood risk for downstream communities.

The results confirm that land use change has intensified the hydrological response of the watershed. The spatial distribution of flood risk is strongly controlled by topography, soil characteristics, and drainage patterns. Low elevation, flat terrain, and clay-rich soils in the southern floodplain reduce infiltration capacity and promote water accumulation. In addition, the convergence of major river channels increases the volume of water received from upstream sub-basins, further intensifying flood risk. When combined with ongoing land use changes, these physical factors significantly increase the vulnerability of communities located in these zones.

The final GIS multi-criteria map combined terrain and land cover data to identify the areas where future floods are likely to have the greatest impact. The analysis shows that 73% of the entire Anambra Watershed faces medium to very high flood risk, with the danger heavily concentrated in the low-lying southern plains. Local Government Areas such as Anambra West and Ogbaru are in extreme danger because these areas are flat, located less than 25 meters above sea level, dominated by heavy clay soils with poor drainage capacity, and positioned directly where major rivers converge. In contrast, upland areas with steep slopes generate high-velocity runoff but face a lower risk of localized water pooling because gravity directs the water downward into the more vulnerable lowland areas.

4. Conclusion

This study assessed the impact of long-term land use and land cover change on the hydrological response and flood risk of the Anambra Watershed between 1995 and 2025 using Remote Sensing, GIS, and HEC-HMS modelling. The results showed a marked increase in built-up areas and agricultural land, alongside significant reductions in forest cover and wetlands. Hydrological simulations revealed that these changes reduced infiltration by 45.4%, increased surface runoff by 36.0%, and increased peak discharge by 38.6%. The decrease in time-to-peak further indicates a faster watershed response to rainfall events, thereby increasing flood vulnerability. Flood susceptibility analysis showed that about 73% of the watershed lies within medium to very high-risk zones, particularly in the southern floodplain areas. These findings confirm that land use change has significantly altered the watershed's natural hydrological processes and increased flood risk across the basin. Therefore, it is recommended that riparian vegetation along river channels be restored to improve infiltration and reduce runoff, wetlands and floodplains be protected through strict land-use regulations to preserve natural flood storage capacity, sustainable urban drainage systems such as permeable surfaces and retention structures be adopted in urban areas, and flood risk maps be integrated into planning decisions to guide development away from high-risk zones.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

Author in this publication declare no conflict of interest regarding the title, data, location, and results of the research.

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Supplementary Materials

This study does not include any supplementary materials.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript. AI were used only to improve readability and language under strict human oversight; no content, ideas, analyses, or conclusions were generated by AI.

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