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RESEARCH ARTICLE

ASSESSING THE IMPACT OF LAND USE ON HYDROLOGICAL VARIABLES USING THE SWAT MODEL: A CASE STUDY OF ANAMBRA RIVER BASIN

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ABSTRACT

Climate change and land use/ land cover (LULC) dynamics had critically alter hydrological processes, yet their combined impacts on water resources in tropical basins remain poorly quantified. This study employs the Soil Water Assessment Tool (SWAT) model to evaluate the effects of LULC changes (2017–2024) on hydrological components in Nigeria's Anambra River Basin (ARB), a region crucial for agriculture and water supply. Using a 30 m DEM, 235 subbasins and 2,626 Hydrological Response Units (HRUs) were delineated, integrating climate data from NASA POWER and LULC maps from Sentinel-2. Results reveal significant LULC shifts, forest cover declined by 24.9 percent, while built-up areas and rangeland expanded by 79.1 percent and 45.3 percent, respectively. These changes drove spatially heterogeneous hydrological responses: surface runoff increased by 5.7 percent in flooded vegetation but decreased in agricultural lands (−4.4 percent), while groundwater recharge was highest in forests (791.57 mm) and lowest in urban areas (472.34 mm). Evapotranspiration (ET) varied sharply, with flooded vegetation experiencing a 13.4 percent decline due to reduced water retention. Drought resilience analysis ranked forested areas as most resilient (high AWC and GWQ), whereas urban and agricultural lands exhibited high vulnerability. The study underscores the compounding effects of LULC change and climate variability, highlighting the urgent need for integrated water management strategies to mitigate flood risks and sustain groundwater recharge in tropical monsoonal basins such as the Anambra River Basin.

Keywords: Hydrological variable, SWAT model, Land use change, Anambra River basin

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1.0. INTRODUCTION

Climate change is significantly altering global hydrological cycles, impacting water availability, increasing the frequency of extreme weather events, and destabilizing ecosystems (IPCC, 2021). Understanding how key hydrological components such as evapotranspiration (ET), baseflow, and surface runoff respond to these changes is critical for sustainable water resource management. The Soil and Water Assessment Tool (SWAT) has emerged as a widely used hydrological model for simulating these processes under various climate scenarios (Arnold et al., 1998).

Evapotranspiration, a key water cycle component, is highly sensitive to temperature and precipitation changes. Studies have indicated that rising temperatures due to climate change are increasing potential ET, leading to greater water loss from ecosystems (Zhang et al., 2019). However, actual ET may decrease in water-limited regions due to reduced soil moisture (Milly & Dunne, 2016). SWAT has been widely used to model these dynamics, incorporating climate projections to assess future ET trends (Gassman et al., 2007).

Baseflow, the sustained flow of groundwater into streams, is critical for maintaining river ecosystems during dry periods. Climate change is expected to alter baseflow through shifts in precipitation patterns and increased ET (Price, 2011). Some studies using SWAT predict reduced baseflow in arid regions due to higher evaporation rates, while others suggest increased baseflow in wetter climates due to more intense rainfall recharge (Eckhardt & Ulbrich, 2003).

Changes in precipitation intensity and land use significantly influence surface runoff. Increased extreme rainfall events under climate change are projected to enhance runoff, leading to higher flood risks (Trenberth, 2011). SWAT simulations have demonstrated that urbanization and deforestation exacerbate runoff, reducing infiltration and groundwater recharge (Neitsch et al., 2011).

SWAT is a semi-distributed, process-based model integrating climate, soil, and land-use data to simulate hydrological processes (Arnold et al., 2012). Its ability to incorporate future climate scenarios from General Circulation Models (GCMs) makes it valuable for assessing long-term hydrological changes (Ficklin et al., 2017). From literature, studies have applied the SWAT model to evaluate the impacts of temperature and precipitation changes on ET and water balance (Wu & Chen, 2013), assess future baseflow variability under different emission scenarios (Ahiablame et al., 2013) and predict increased surface runoff and flood risks due to altered rainfall patterns (Wang et al., 2016). Although this tool is robust, uncertainties can arise from input data quality, mostly precipitation and temperature projections (Abbaspour et al., 2015), model parameterization and calibration challenges in diverse basins (Moriasi et al., 2007), and simplifications in representing groundwater processes (Sophocleous, 2002).

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The SWAT model has been instrumental in assessing hydrological responses to climate change, particularly in evaluating ET, baseflow, and surface runoff dynamics. However, uncertainties in climate projections and model parameterization necessitate further research, including ensemble modeling and improved data integration. Future studies should focus on region-specific adaptations to ensure sustainable water management in a changing climate.

The study area is an important River basin in Nigeria that drains about five States and sustains agricultural and other activities. The present study aimed to assess land use influence on hydrological parameters and trends derived from the SWAT model and their implications in a changing climate in the Anambra River basin. The objectives will include analyzing hydrological variables' response to land use, effects of urbanization on hydrological parameters when compared to natural grounds, assessing significant differences in water balance components between years, and recommending adaptation strategies for water resource management and flood hazard mitigation.

2.0. DESCRIPTION OF THE STUDY AREA

2.1. The Study Area

The Anambra River Basin (ARB) is located between Latitude: 5° 50' N to 7° 00' N and Longitude: 6° 30' E to 7° 30' E. The key states drained by the Anambra River and its tributaries include Anambra State, Enugu State, Kogi State, Delta State, and Imo State as seen in Figure 1. The highest elevation ranges from 500 to 700 m above the sea level around the Udi-Nsukka Plateau and the lowest elevation ranging from 20 to 50 m above the sea level near the Niger River confluence.

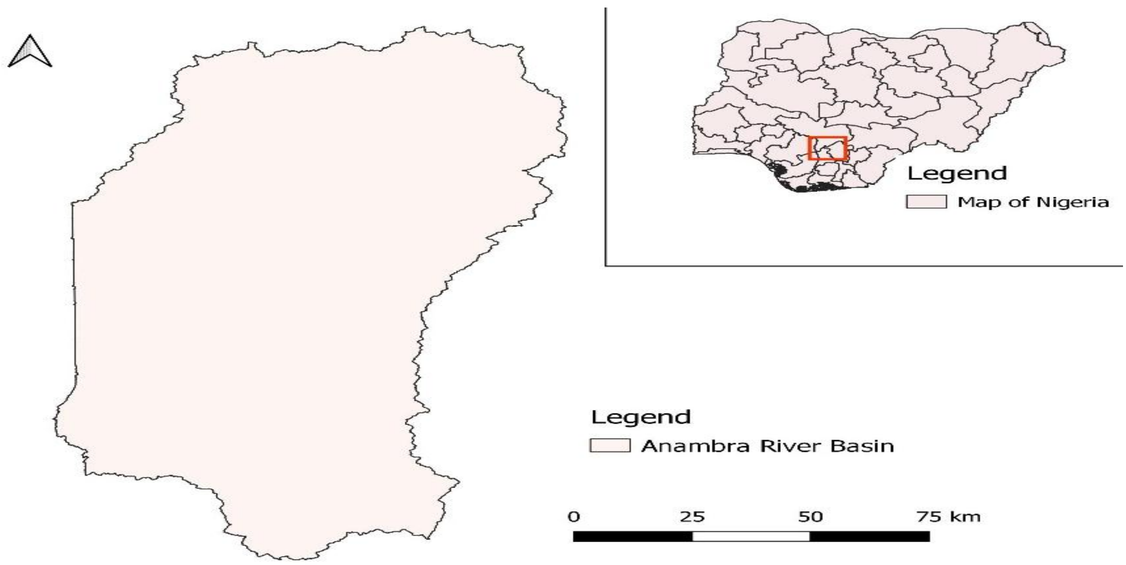

Figure 1: The Study Area

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According to the Köppen-Geiger climatic classification, ARB is within the Tropical Monsoon Climate (Am) or Tropical Savanna (Aw). The basin has a distinct wet season between April and October and dry season between November and March, with a mean annual rainfall average ranging from 1,800 to 2,500 mm/year and a mean annual temperature of 27 to 28°C (Nwaogazie *et al.*, 2018).

3.0. MATERIALS AND METHODS

3.2. Data Set

The data set used is from different sources, as shown in Table 1, and they are further formatted to suit SWAT input data.

Table 1: Data and Source

DATA TYPE	SOURCES
Soil	Digital Soil Map of the World (DSMW)
Land Use / Land Cover	Sentinel – 2
Digital Elevation Model (DEM)	SRTM
Measured Climatic Data	NASA power data

3.3. SWAT Model Setup

Watershed delineation was performed in QGIS 3.18.3 using a 30 m Digital Elevation Model (DEM). A flow accumulation threshold of 30 km² was applied to derive the stream network, resulting in the delineation of 235 sub-basins (Figure 2) within the Anambra River Basin (ARB), which encompasses a total drainage area of 11,818.81 km².

For hydrological modeling, soil and land use maps were integrated with slope class divisions (0–5%, 5–10%, 10–20%, and 20–9999%) to generate 2,626 Hydrological Response Units (HRUs). Meteorological data (2005–2024) from seven gauging stations across the basin were utilized as input for the Soil and Water Assessment Tool (SWAT) simulation.

Figures 2, 3, and 4a, b show Maps of the DEM with stream network, soil, and land use of the study area in 2017 and 2024, respectively.

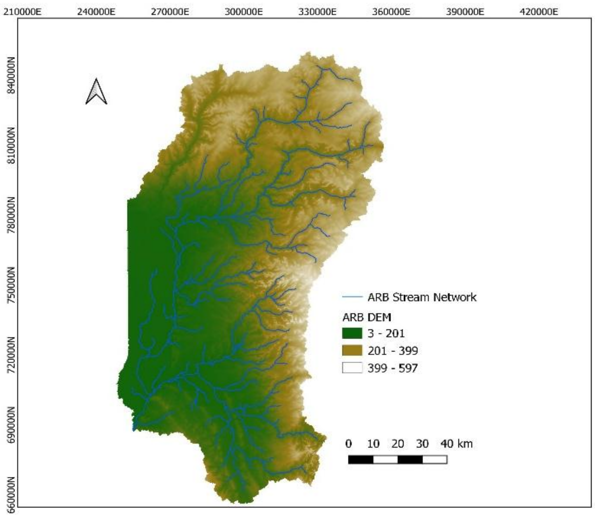

Figure 2: DEM and Stream network

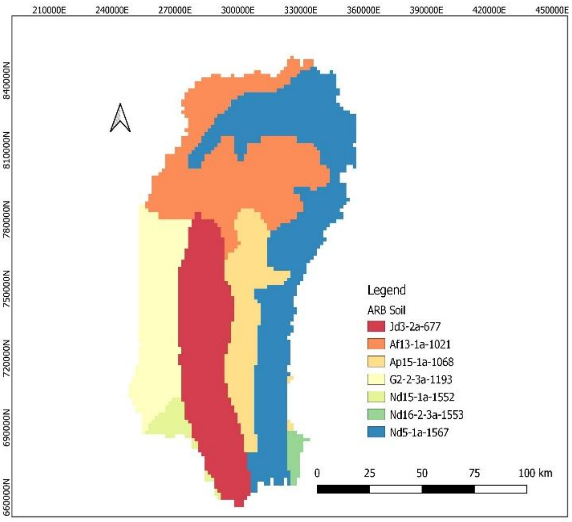

Figure 3: Soil map

4.0. RESULTS AND DISCUSSION

4.1. Assessment of Land Use and Land Cover Change

The interaction between hydrological variables and land use is a major indicator of a resilient environment to climate change. Several factors influence these variables, including land use, terrain formation, soil types, and weather patterns. Table 2 shows land use area coverage in hectares and percentage change in land use type in ARB in 2017 and 2024, derived from the SWAT model.

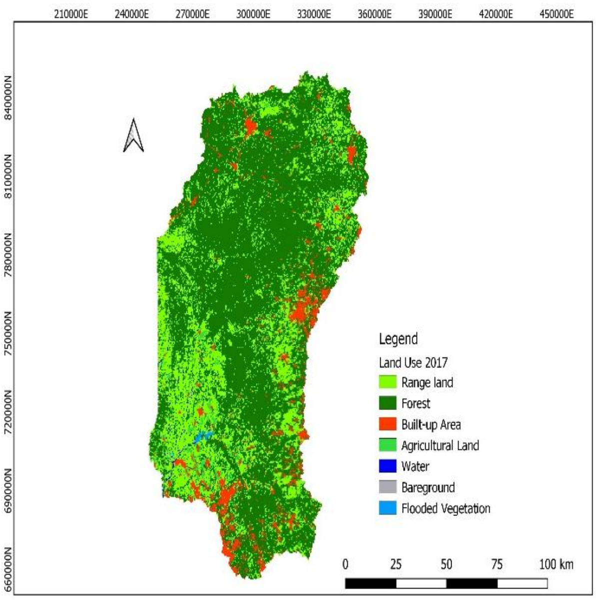

Figure 4a: 2017 Land use map

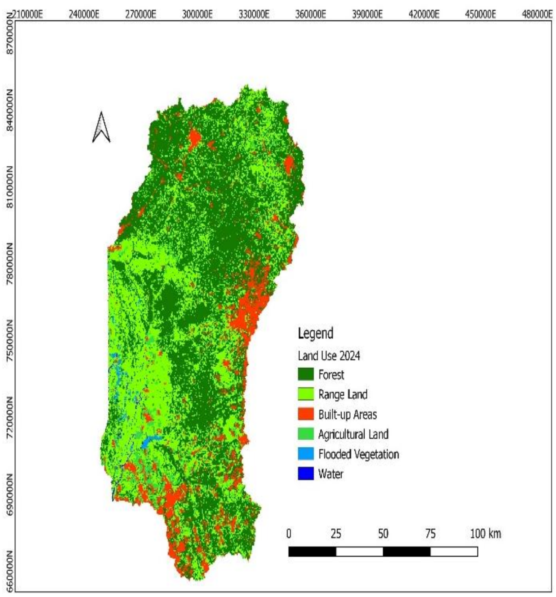

Figure 4b: 2024 Land use map

The result showed that forest land use had the highest land area of 8,033.17 in 2017 and 6,030.41 in 2024, covering 68 percent and 51.02 percent respectively. Rangeland covered 20 percent of the land area in 2017 but increased to 36.92 percent in 2024; built-up areas, agricultural, water, and flooded vegetation are all under 20 percent in the period under investigation. The change analysis showed a significant expansion of farmland, rapid urbanization, expansion of rangeland, large-scale deforestation, minor reduction in water bodies, and a dramatic increase in wetland. This implies that there may be an increase in surface runoff and a decrease in biodiversity due to the loss of forest area to other land use types, also local hydrology, like the groundwater recharge, could be altered due to flooded vegetation changes.

Table 2: Anambra River Basin Land Use Change 2017-2024

LULC Class	2017 Area (ha)	2024 Area (ha)	Change (ha)	% Change
Agriculture	139.22	254.22	+115.00	+82.6%
Built-up area	617.31	1,105.77	+488.46	+79.1%
Forest	8,033.17	6,030.41	-2,002.76	-24.9%
Rangeland	3,002.89	4,363.55	+1,360.66	+45.3%
Water	9.28	8.86	-0.42	-4.5%
Flooded vegetation	16.97	56.32	+39.35	+231.9%

Source: Author's Analysis (2025).

4.2. Evaluation of Water Balance Components

The SWAT model simulates the water balance parameters of the Anambra River basin. The average curve number CN for 2017 and 2024 is 75.13 and 76.31, respectively, which aligns with the literature. The potential evapotranspiration (PET) for the period under investigation is 1066.30. Figures 5a and b show a schematic representation of the average water balance components in the study area during the period under investigation.

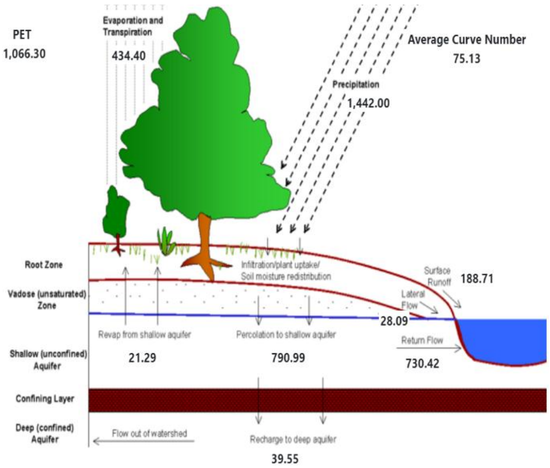

Figure 5a: 2017 Water Balance

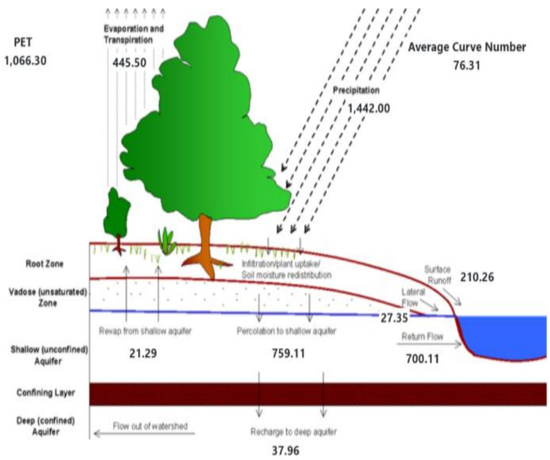

Figure 5b: 2024 Water Balance

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During the period under investigation, the precipitation values, ranging from 1,412.73 mm in forest areas to 1,593.09 mm in water, indicate spatial variability. Higher precipitation in water bodies suggests accurate representation, while forests show lower values, possibly due to interception losses. Surface Runoff (SURQ) is highest in built-up areas with a value of 415.77 mm, and agricultural areas with 367.05 mm, likely due to reduced infiltration in agricultural and built-up areas. The lowest in forest areas with a value of 139.91 mm due to higher infiltration and canopy interception, while water with 0 mm logically has no runoff since it is water itself. Groundwater Flow (GWQ) showed the highest values in forest area and rangeland, 791.57 mm and 705.68 mm, respectively, indicating good infiltration in forested and rangeland areas, and the lowest in built-up areas with a value of 472.34 mm, possibly due to compacted soils or impervious surfaces. Evapotranspiration (ET) is highest in built-up areas and range land with 537.34 mm and 457.71 mm, respectively suggesting higher water use by vegetation, and the lowest value is from agricultural land with a value of 428.69 mm, possibly due to less dense vegetation and the type of crop planted as compared to forest areas.

Table 3: Comparative Analysis of Water Balance/ Uses under Different Land Use Type

LULC	CN	AWC mm		USLE_LS		PREC mm		SURQ mm		GWQ mm		ET mm	
		2017	2024	2017	2014	2017	2024	2017	2024	2017	2024	2017	2024
Agriculture	83	133.84	122.54	0.77	0.84	1,587.89	1,560.43	384	367.05	714.37	706.3	430.57	428.69
Built-up area	81.88	118.79	115.35	1.04	1.08	1,480.66	1,471.30	420.83	415.77	474.37	472.34	539.4	537.34
Forest	73	109.55	109.38	1.21	1.27	1,421.93	1,412.73	144.07	139.91	798.2	791.57	417.31	419.39
Rangeland	79	97.99	102.5	1.07	1.06	1,479.80	1,466.52	251.3	245.21	715.06	705.68	455.17	457.71
Water	92	10	10.97	0.07	0.07	1,593.09	1,593.09	0	0	0	0	1,543.08	1,543.72
Flooded vegetation	79	134.66	45.62	0.55	0.56	1,593.09	1,544.89	307.6	325.14	777.75	771.79	445.51	385.96

Source: Author's Analysis (2025).

4.3. Trend Analysis of LULC / Hydrologic Variables

This analysis examined temporal changes in hydrologic variables across different land use/land cover (LULC) classes to identify significant trends, anomalies, and potential drivers. The paired observations for 2017 and 2024 across 6 LULC classes were used to calculate (a) percentage Change (Δ%) for each variable, (b) annual rate of change (per year), and statistical significance (Paired t-test/Wilcoxon test).

The Percentage Change (Δ%) by LULC Class of the study area was calculated using the formula below:

Formula: $\Delta\% = \left(\frac{2024\ values - 2017\ values}{2017\ values}\right) x\ 100$

Table 4: **Percentage Change in Hydrological Variables by LULC Class (2017–2024)**

LULC Class	CN (%)	AWC (%)	USLE_LS (%)	PREC (%)	SURQ (%)	GWQ (%)	ET (%)
Agriculture	+8.5	−8.4	+9.1	−1.7	−4.4	−1.1	−0.4
Built-up	+3.0	−2.9	+3.8	−0.6	−1.2	−0.4	−0.4
Forest	+0.2	−0.2	+5.0	−0.6	−2.9	−0.8	+0.5
Rangeland	+4.6	+4.6	−0.9	−0.9	−2.4	−1.3	+0.6
Water	+9.7	+9.7	0.0	0.0	0.0	0.0	+0.04
Flooded Vegetation	−66.1	−66.1	+1.8	−3.0	+5.7	−0.8	−13.4

Source: Author's Analysis (2025).

Note. CN = Curve Number; AWC = Available Water Capacity; USLE_LS = Slope Length and Steepness Factor; PREC = Precipitation; SURQ = Surface Runoff; GWQ = Groundwater Recharge; ET = Evapotranspiration.

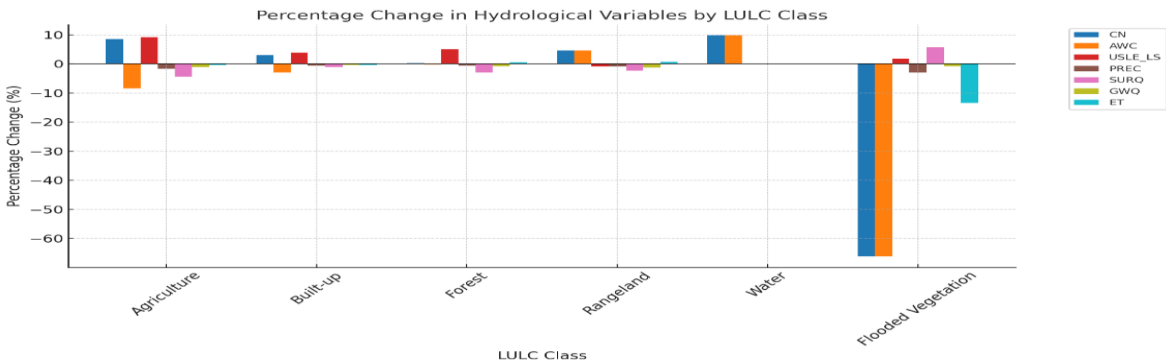

Figure 6: Percentage Change Graph

The computed results showed a decline in flooded vegetation CN and AWC by 66 percent, ET by 13.4 percent, and Agriculture AWC by 8.4 percent. However, there is an increase in rangeland AWC by 4.6 percent and forest/rangeland ET by 0.5 – 0.6 percent, respectively. Built-up areas had minimal changes, while water bodies' hydrology was static and no change in PREC/SURQ/GWQ.

The annual rate of change was calculated on some of the hydrological variables in selected land use classes with the following formula:

$$\text{Annual Rate} = \frac{\Delta\%}{Years\ (7)}$$

A yearly reduction of 9.4 % and 1.9% of AWC and ET in the flooded vegetation represents a rapid loss of water retention and declining evapotranspiration within the study area. Surface runoff reduction of 0.63% on agricultural land use shows a slight decrease over time, and CN increase in the water land use represents a slight increase in surface runoff potential.

Spatial-Temporal Patterns showed that the Climate-Driven Variables (PREC, ET) vary across the land use classes, with PREC slightly decreasing by 1.7% across all classes except water, with a 0 percent, and ET increased in forests/rangelands with 0.5 and 0.6% respectively but dropped sharply in flooded vegetation by 13.4 percent. However, the Land Use-Driven Variables (CN, SURQ, GWQ) also varied with CN increase in water by 9.7 percent and agriculture by 8.5 percent, suggesting higher runoff risk, and SURQ decreased in most classes except in flooded vegetation that has an increase of 5.7 percent.

Climate Change Impacts on Water Availability

Groundwater recharge within the land use types showed climate risk in agricultural land (706.3 mm) and built-up (472.34 mm) areas. If the precipitation becomes more erratic, such as fewer but heavier storms, these land use types may lose recharge capacity due to increased runoff (Trenberth, 2011). Among the land use types in the study area, flooding vulnerability will be higher in built-up areas and agricultural lands due to high surface runoff of 415.77 and 367.05, respectively. Despite similar rainfall in the built-up areas and the forest areas, the ET of the built-up area is greater than that of the forest areas, due to having shallow-rooted crops and exposed soil, which increases water loss within the built-up areas (Zhang et al., 2019). Higher temperatures will mean high ET, leading to a reduction in surface water and groundwater (Milly & Dunne, 2016).

The catchment area drought resilience was analyzed for the best to worst performers based on available water capacity (AWC) and groundwater recharge (GWQ) results from each land use type. AWC is the amount of water the soil can store and make available for plants to use. It represents the difference between the soil's field capacity, which is the maximum water held after drainage, and its permanent wilting point, which is the leftover water when plants can no longer extract it. It depends on the soil texture and is critical for irrigation planning, drought assessment, and crop management (Sophocleous, 2002). It can be calculated by:

AWC = Field Capacity − Permanent Wilting Point

The result shows that the forest areas are the most resilient to drought, mostly due to the deep-rooted trees and vegetation cover. The rangeland showed moderate resilience as grasslands hold moisture well. The agricultural land and built-up areas are highly vulnerable because of low groundwater recharge and high evapotranspiration; in case of drought, both land use types will suffer first.

Table 7: Drought Resilience by Land Use Type Based on Available Water Capacity (AWC) and Groundwater Recharge (GWQ)

Land Use Type	AWC (mm)	GWQ (mm)	Drought Resilience
Forest Area	109.38	791.57	High
Rangeland	102.50	705.68	Moderate
Agricultural Land	122.54	706.30	Low
Built-up Area	115.35	472.34	Very Low

Note. AWC = Available Water Capacity; GWQ = Groundwater Recharge.

5.0. CONCLUSION

This study assesses the impact of climate change and land use/land cover (LULC) changes on key hydrological components, particularly evapotranspiration (ET), surface runoff, and groundwater recharge, in the Anambra River Basin (ARB), Southeast Nigeria. Using the Soil and Water Assessment Tool (SWAT), simulations were conducted for 2017 and 2024 to understand hydrological responses to LULC shifts and evolving climate patterns.

The results indicate significant changes in land use, including an 82.6 percent increase in agricultural land, a 79.1 percent increase in built-up areas, and a 231.9 percent rise in flooded vegetation, accompanied by a 24.9 percent loss in forest cover. These changes contributed to a notable increase in surface runoff, particularly in urban and agricultural zones, and reduced groundwater recharge. ET was found to be highest in built-up areas (537.34 mm) and rangelands (457.71 mm), agricultural areas had the lowest ET (428.69 mm), suggesting less dense vegetation and higher vulnerability to water stress.

Further, the study revealed that forest and rangeland areas maintained higher drought resilience due to greater available water capacity (AWC) and groundwater recharge potential. In contrast, built-up and agricultural areas exhibited increased hydrological vulnerability due to low infiltration and high ET. Climate-induced reductions in precipitation (~1.7 percent) and potential temperature increases could intensify these vulnerabilities, particularly in water-scarce seasons.

To address these challenges, the study recommends sustainable land management strategies such as conservation tillage, reforestation, rainwater harvesting, and the use of drought-resistant crops. Forest preservation and wetland restoration are especially critical for enhancing ecosystem resilience and mitigating flood and drought risks.

Overall, the findings demonstrate the SWAT model's utility in evaluating hydrological responses to LULC and climate change, offering insights for climate-adaptive watershed management and policy planning in tropical river basin

Competing Interest

The author declares that no conflicting interest exist in this paper.

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