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Assessing the Impact of Climate Change on Land Use Dynamics in Osun River Basin Nigeria

Avaliação do impacto das mudanças climáticas na dinâmica do uso da terra na bacia do rio Osun, Nigéria

Evaluación del impacto del cambio climático en la dinámica del uso de la tierra en la cuenca del río Osun, Nigeria

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Abstract

Gaining deep insight into how climate change shapes land use and land cover (LULC) dynamics is vital for ensuring sustainable management of watersheds, especially in sensitive environments like the Osun River Basin (ORB) in southwestern Nigeria. This research explores the spatio-temporal trends in LULC transformations across the ORB between 2002 and 2022, and critically examines how core climatic factors, including temperature, rainfall, and the Vegetation Condition Index (VCI), influence these shifts. Multi-temporal Landsat satellite imagery for 2002, 2012, and 2022 of 30m resolution was analysed using supervised classification and change detection techniques in a GIS environment, complemented by rainfall and temperature data derived from CHIRPS and MODIS. Results reveal significant LULC transformations over the two decades, with built-up areas expanding by over 154%, bare surfaces increasing by approximately 19%, while croplands and forest areas declined by 25% and 6%, respectively. The Multiple Linear Regression (MLR) model showed that climate variables collectively explain about 78% of the variance in built-up area expansion ($R^2 = 0.78, p < 0.001$). Temperature emerged as the strongest positive predictor, indicating that a 1°C rise could result in an increase of approximately 120km^2 of built-up land, whereas rainfall demonstrated a stabilising effect by sustaining vegetation cover. The analysis of spatial rainfall and VCI patterns further revealed a progressive decline in vegetation health, with pronounced stress observed in the basin's central and northern regions, driven by rising temperatures, erratic rainfall, and intensified anthropogenic activities such as urbanisation, deforestation, and unsustainable land management. These combined pressures have profound implications for agricultural productivity, biodiversity conservation, and water resource sustainability in the basin.

Keywords: Climate Change. Land Use Dynamics. Remote sensing. Vegetation Condition Index. Osun River Basin. Sustainable development

Resumo

Compreender profundamente como as mudanças climáticas moldam a dinâmica do uso e cobertura da terra (UCT) é vital para garantir a gestão sustentável das bacias hidrográficas, especialmente em ambientes sensíveis como a Bacia do Rio Osun (BRO) no sudoeste da Nigéria. Esta pesquisa explora as tendências espaço-temporais nas transformações do UCT na BRO entre 2002 e 2022 e examina criticamente como fatores climáticos essenciais, incluindo temperatura, precipitação e o Índice de Condição da Vegetação (ICV), influenciam essas mudanças. Imagens multitemporais de satélite Landsat de 2002, 2012 e 2022, com resolução de 30 m, foram analisadas utilizando técnicas de classificação supervisionada e detecção de mudanças em um ambiente SIG, complementadas por dados de precipitação e temperatura derivados do CHIRPS e MODIS. Os resultados revelam transformações significativas do UCT ao longo das duas décadas, com as áreas urbanizadas expandindo-se em mais de 154%, as superfícies expostas aumentando em aproximadamente 19%, enquanto as áreas de cultivo e florestais diminuíram em 25% e 6%, respectivamente. O modelo de Regressão Linear Múltipla (RLM) mostrou que as variáveis climáticas, em conjunto, explicam cerca de 78% da variância na expansão da área construída ($R^2 = 0{,}78$, $p < 0{,}001$). A temperatura emergiu como o preditor positivo mais forte, indicando que um aumento de 1 °C poderia resultar em um acréscimo de aproximadamente 120 km^2 de área construída, enquanto a precipitação demonstrou um efeito estabilizador, sustentando a cobertura vegetal. A análise dos padrões espaciais de precipitação e do Índice de Cobertura Vegetal (ICV) revelou ainda um declínio progressivo na saúde da vegetação, com estresse acentuado observado nas regiões central e norte da bacia, impulsionado pelo aumento das temperaturas, precipitação irregular e intensificação de atividades antropogênicas, como urbanização, desmatamento e manejo insustentável da terra. Essas pressões combinadas têm implicações profundas para a produtividade agrícola, a conservação da biodiversidade e a sustentabilidade dos recursos hídricos na bacia.

Palavras-chave: Mudanças climáticas. Dinâmica do uso da terra. Sensoriamento remoto. Índice de condição da vegetação. Bacia do rio Osun. Desenvolvimento sustentável.

Resumen

Comprender a fondo cómo el cambio climático influye en la dinámica del uso y la cobertura del suelo (LULC, por sus siglas en inglés) es fundamental para garantizar la gestión sostenible de las cuencas hidrográficas, especialmente en entornos sensibles como la cuenca del río Osun (ORB, por sus siglas en inglés) en el suroeste de Nigeria. Esta investigación explora las tendencias espaciotemporales en las transformaciones del LULC en la ORB entre 2002 y 2022, y examina críticamente cómo los factores climáticos clave, como la temperatura, las precipitaciones y el Índice de Condición de la Vegetación (VCI, por sus siglas en inglés), influyen en estos cambios. Se analizaron imágenes satelitales Landsat multitemporales de 2002, 2012 y 2022 con una resolución de 30 m mediante técnicas de clasificación supervisada y detección de cambios en un entorno SIG, complementadas con datos de precipitación y temperatura derivados de CHIRPS y MODIS. Los resultados revelan transformaciones significativas del LULC a lo largo de las dos décadas: las áreas urbanizadas se expandieron en más del 154 %, las superficies desnudas aumentaron aproximadamente un 19 %, mientras que las tierras de cultivo y las áreas forestales disminuyeron un 25 % y un 6 %, respectivamente. El modelo de regresión lineal múltiple (RLM) mostró que las variables climáticas explican en conjunto cerca del 78 % de la varianza en la expansión de las áreas urbanizadas ($R^2 = 0{,}78$, $p < 0{,}001$). La temperatura se reveló como el predictor positivo más fuerte, indicando que un aumento de 1 °C podría resultar en un incremento de aproximadamente 120 km^2 de suelo urbanizado, mientras que la precipitación demostró un efecto estabilizador al mantener la cobertura vegetal. El análisis de los patrones espaciales de precipitación e índice de cobertura vegetal (ICV) reveló además un deterioro progresivo de la salud de la vegetación, con un estrés pronunciado observado en las regiones central y norte de la cuenca, impulsado por el aumento de las temperaturas, la irregularidad de las precipitaciones y la intensificación de actividades antropogénicas como la urbanización, la deforestación y la gestión insostenible de la tierra. Estas presiones combinadas tienen profundas implicaciones para la productividad agrícola, la conservación de la biodiversidad y la sostenibilidad de los recursos hídricos en la cuenca.

Palabras-clave: Cambio climático. Dinámica del uso del suelo. Teledetección. Índice de condición de la vegetación. Cuenca del río Osun. Desarrollo sostenible.

Introduction

Climate change is an emerging global challenge that has profound implications for environmental systems, ecosystems, and human livelihoods (IPCC, 2021). In regions such as sub-Saharan Africa, the effects of climate change are growing ever more apparent, marked by changing weather patterns, temperature variability, and shifts in rainfall regimes (Hossain et al., 2019). These changes have significant repercussions on land use dynamics, particularly in vulnerable regions like the Osun River Basin (ORB). The Osun River Basin, located in the southwestern part of Nigeria, is home to diverse ecosystems and human activities that are heavily dependent on climatic conditions, including agriculture, water resources, and urban development (Akinyemi et al., 2020). ORB is experiencing notable shifts in land use, driven by both climate-induced changes and socio-economic factors such as population growth, agricultural expansion, and urbanization. Understanding the interactions between climate change and LULC dynamics in this region is crucial for sustainable land management and water resource planning.

Land use changes are closely linked to climate change through feedback mechanisms that alter surface temperature, evapotranspiration, and hydrological processes (Lambin et al., 2003; Turner et al., 2007). One of the most well-documented land use change impacts on climate is its influence on surface temperature. Vegetation cover plays a crucial role in regulating land surface temperature (LST) through shading, evapotranspiration, and albedo effects (Kombani et al., 2025). The conversion of forests to croplands or urban areas alters these thermal properties, often leading to increased LST. For instance, deforestation reduces canopy cover and increases surface albedo, which can lead to local warming despite the increased reflection of solar radiation (Bonan, 2008; Li et al., 2017, Ologunorisa et al., 2021). On the other hand, the expansion of urban areas exacerbates the urban heat island (UHI) phenomenon by increasing impervious surfaces that trap and retain heat, resulting in higher temperatures within cities than in adjacent rural zones (Oke et al., 2017). LULC also influence regional hydrology by altering evapotranspiration rates, which play a fundamental role in atmospheric moisture regulation. Vegetation-covered landscapes, particularly forests, contribute to higher rates of evapotranspiration, which helps cool the land surface and recycle moisture into the atmosphere (Ellison et al., 2017). Deforestation and land degradation reduce evapotranspiration, leading to drier conditions and disrupting precipitation patterns (Lawrence & Vandecar, 2015). Agricultural land expansion, particularly the replacement of forests with croplands or grasslands, lead to seasonal variations in evapotranspiration, impacting local climate systems (Findell et al., 2017).

In Africa, studies have shown that changes in vegetation cover, deforestation, and urban sprawl modify regional climate patterns, exacerbating the vulnerability of ecosystems and communities to extreme weather conditions (Ouedraogo et al., 2019; Sylla et al., 2020). In the Sahel, large-scale deforestation has been linked to decreased precipitation and an intensification of drought conditions due to reduced moisture recycling (Liu et al., 2020). Study indicates that the removal of forested areas in West Africa can shift local wind patterns, further exacerbating drought conditions in downwind regions (Jiang et al., 2019). In Ghana and Côte d'Ivoire, cocoa-driven deforestation has not only led to biodiversity loss but also contributed to regional warming and changes in seasonal rainfall distribution (Andoh et al., 2021). Rapid urban sprawl in cities such as Accra and Dakar has resulted in increased land surface temperatures due to the replacement of natural vegetation with asphalt, concrete, and buildings (Adanu et al., 2021). This UHI effect exacerbates heat stress, particularly during heatwave events, leading to greater cooling energy requirements and increased health hazards in crowded urban environments (Akinbode et al., 2022). The expansion of agricultural lands in West Africa, particularly in response to population growth and food demand, has significantly altered land cover and contributed to land degradation. In the semi-arid Sahel region, the conversion of natural vegetation into croplands has accelerated desertification processes, reducing soil fertility and increasing vulnerability to droughts (Bégué et al., 2018). The loss of vegetation cover reduces soil organic matter and exacerbates erosion, further impacting agricultural sustainability and food security (Olsson et al., 2019).

In Burkina Faso, Mali, and Niger, unsustainable land management practices, combined with climate change, have contributed to declining agricultural productivity and forced migration in search of arable land (Zwarts et al., 2022). This has implications for food security, water availability, and rural livelihoods, particularly in regions where communities depend on rain-fed agriculture. Land use changes in West Africa are exacerbating the severity of extreme weather phenomena such as droughts, heatwaves, and heavy rainfall events. The degradation of natural ecosystems reduces their ability to buffer climate extremes, making communities more susceptible to disasters. For example, studies show that areas with significant deforestation and land degradation have experienced more severe droughts, as natural vegetation plays a key role in regulating local humidity and temperature (Sylla et al., 2018). Furthermore, the destruction of wetlands and riparian forests in West Africa has increased the severity of floods, as these ecosystems serve as natural buffers against excessive rainfall (Zwarts et al., 2022). The growing intensity of extreme climate events, combined with land use changes, threatens both urban and rural populations, highlighting the need for climate adaptation strategies.

In Nigeria, the combination of increasing temperatures and irregular rainfall patterns has led to shifts in agricultural productivity, land degradation, and water stress, further intensifying land use pressures (Ajibola et al., 2022). Deforestation in the Guinea savanna zone has been associated with increased surface temperatures and reduced soil moisture, affecting agricultural productivity and water availability (Ayanlade, 2017). These changes disrupt ecological balance, making local communities more vulnerable to climate extremes such as droughts and heatwaves. In addition to temperature increases, urbanization alters regional hydrological cycles by reducing infiltration and increasing surface runoff, contributing to more frequent and severe urban flooding (Adelekan, 2016). In Lagos and other coastal cities, land use changes have intensified flood risks, particularly in low-lying areas where extreme rainfall events, often linked to climate change, are becoming more frequent (Eze, 2018). The combination of urban sprawl and extreme weather conditions has heightened the vulnerability of both infrastructure and human settlements, necessitating climate-sensitive urban planning strategies.

Despite the growing body of research on land use and land cover (LULC) changes in Nigeria, most studies have predominantly focused on urban expansion and deforestation as isolated outcomes of anthropogenic pressures. Limited attention has been given to the direct and combined impacts of climate change and land use dynamics within ecologically sensitive river basins such as the Osun River Basin (ORB). ORB, an ecologically and socioeconomically vital watershed, is undergoing intense land cover transformations, with forested areas rapidly giving way to agricultural lands and urban infrastructure (Adepoju et al., 2021).

Existing studies often overlook how climate-induced alterations in hydrological cycles, such as irregular rainfall, increasing temperatures, and extreme weather conditions, interact with LULC transitions to influence water availability, agricultural productivity, and ecosystem stability (Oyinloye et al., 2018; Oguntunde et al., 2020). While the hydrological implications of LULC change are well acknowledged globally, region-specific evidence for the Osun River Basin remains limited, especially in terms of how these changes affect critical hydrological processes like surface runoff, infiltration, and groundwater recharge.

This study addresses this critical knowledge gap by assessing the spatiotemporal patterns of 'land use change in the Osun River Basin and exploring their relationship with climatic trends over multiple decades. By integrating geospatial analysis with climate, the study directly investigates the extent to which climate change influences land use transitions, providing much-needed evidence for the development of sustainable, climate-resilient land and watershed management frameworks in Nigeria and similar ecologies.

Study Area

The Osun River Basin (ORB) is located in southwestern Nigeria, roughly extending between longitudes 3°47'34.8"–5°10'55.2"E and latitudes 6°25'58.79"–8°21'3.6"N (Figure 1). Its principal watercourse, the River Osun, originates from the Oke-Mesi ridge, about five kilometres north of Effon-Alaiye. From its source, the river initially flows north through the Itawure gap, then shifts westward near latitude 7°53′, passing major towns such as Osogbo and Ede, before veering south to discharge into the Lagos Lagoon. These hydrographic details are documented by the Ogun-Osun River Basin Development Authority (OORBDA, 1982) and further described by Oke et al. (2013) and Ashaolu et al. (2019).

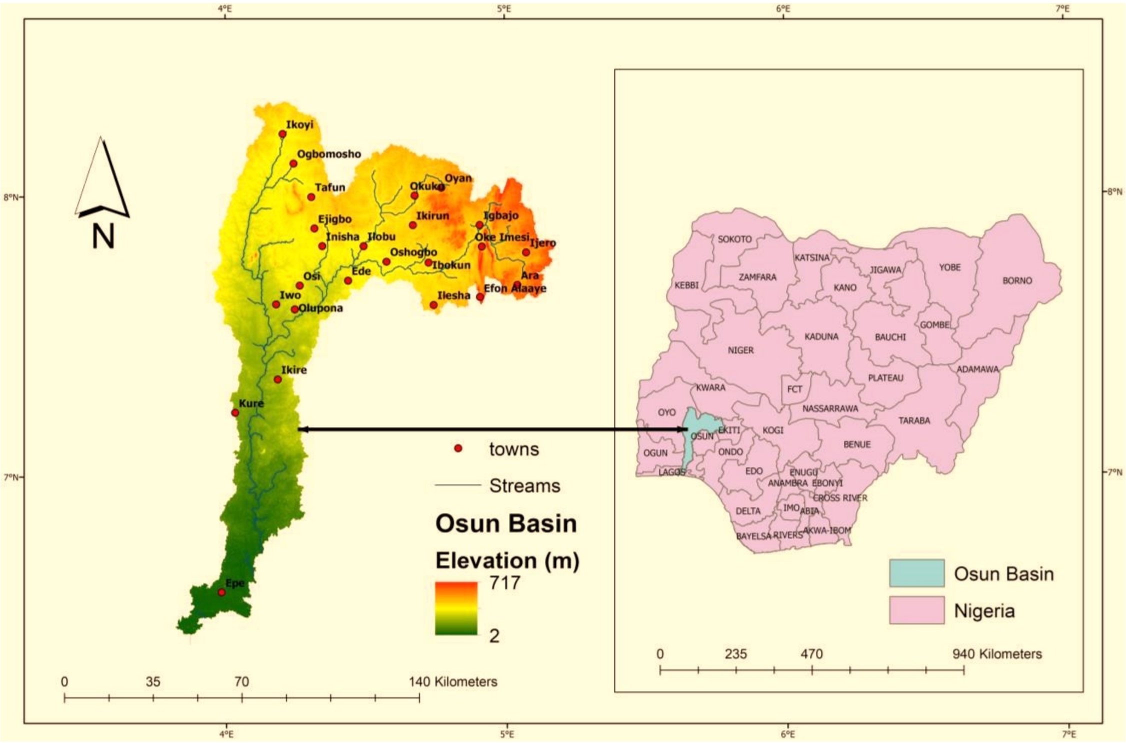
The climate of the basin is mainly influenced by the Inter-Tropical Convergence Zone (ITCZ), a semi-permanent climatic boundary that divides the dry subtropical continental air mass from the Sahara and the moist equatorial maritime air mass from the Atlantic Ocean (OORBDA, 1982). According to Ifabiyi (2005), the ORB falls within the Köppen Aw climatic zone, typified as a humid tropical rainforest climate with a distinct wet and dry season. The hottest period occurs between February and March, when temperatures peak across the basin. The mean annual temperature is around 30°C, though local variations occur due to altitude and seasonal shifts (Ifabiyi, 2005; Eresanya et al., 2019).

Geologically, the ORB straddles two major lithological units: the Precambrian Basement Complex and younger sedimentary formations. Approximately 93% of the basin's underlying geology comprises Basement Complex rocks, whereas sedimentary formations cover the final 7% in the southern coastal region near the Atlantic seaboard (OORBDA, 1982; Oke et al., 2013; Ashaolu et al., 2016). The prevailing soils are highly ferruginous tropical red soils, typical of regions dominated by Basement Complex geology (Ifabiyi, 2005). The basin's topography is generally undulating, with elevations descending from about 700 meters in the Oke-Imesi highlands to less than 50 meters near the coastal lowlands around Epe and Ibeju-Lekki (Ashaolu, 2019) (Figure 1).

Population distribution within the basin is uneven, with higher densities concentrated in urban centres compared to rural settlements. Based on the 1963 census, the OORBDA estimated the basin's population at approximately 4.28 million in 1980, which was projected to have risen to over 12 million by 2015, applying a national annual growth rate of 3% to both urban and rural areas (Ashaolu, 2018).

Land use within the Osun River Basin is diverse and dynamic, encompassing urban residential settlements, built-up infrastructure, exposed rock outcrops and bare surfaces, agricultural croplands and shrubs, forested and vegetated zones, and extensive surface water bodies.

Figure 1. Osun River Basin.



A odisseia do castigo: a Geografia do bonde

This study leverages advanced geospatial techniques and remote sensing tools to comprehensively analyse land use and land cover dynamics in ORB over two decades (2002-2022). The methods outlined aim to elucidate these changes' underlying drivers and implications, providing a basis for informed decision-making and sustainable land management in the basin.

The ORB was selected as the study area due to its dynamic land use patterns and socio-economic significance. The basin spans roughly 9,926.22 km² and features a mosaic of land uses, including agricultural fields, urban settlements, water bodies, and patches of natural vegetation. It has a tropical climate marked by distinct wet and dry seasons, which shape its patterns of land use and land cover change.

Data Collection

The study employed multi-temporal Landsat satellite imagery to examine land use dynamics over the 20-year period (2002, 2012, and 2022). The following datasets were obtained via the United States Geological Survey (USGS) Earth Explorer platform. An aerial imagery overlay (AIO) technique was performed through the application of GIS and RS to superimpose aerial images.

The primary approach used in this study was post-classification comparison analysis of satellite imagery obtained at decadal intervals for the years 2002, 2012, and 2022, as detailed in Table 1.

Table 1. Spatial Data and their Sources.

	Images	Year	Spatial Resolution (m)	Source
1	Landsat 7 ETM+	2002	30	www.usgs.gov
2	Landsat 8 OLI/TIRS	2012	30	www.usgs.gov
3	Landsat 8 OLI/TIRS	2022	30	www.usgs.gov

All selected images had low cloud cover and were taken in the dry season to guarantee consistent vegetation and land surface states.

Rainfall

CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) was utilised in GEE for historical rainfall analysis. Monthly rainfall data were extracted from 2000 to 2022 to capture temporal variability. The CHIRPS data were clipped to the Osun River Basin using a shapefile of the study area. Monthly composites were summed per year using:

```
var annualRain = monthlyRain.reduce(ee.Reducer.sum());
```

This process yielded annual total rainfall rasters for each year. Final rasters were exported to Google Drive as GeoTIFF (.tif).

Temperature

MODIS Land Surface Temperature (LST) data, specifically the product MOD11A2 (8-day average), were obtained via the Google Earth Engine (GEE) platform. Monthly and annual temperature averages were computed by aggregating 8-day composites or daily means:

```
var monthlyLST = lstCollection.filterDate('2022-01-01', '2022-12-31') .mean();
```

Importing Osun River Basin shapefile as an asset

```
var osun_basin = ee.FeatureCollection("users/your_username/osun_river_basin");
```

Data Analysis

Remotely sensed data from Landsat TM satellite images with a 30m resolution were used in this study. Bands 4, 3, and 2 were combined and re-sampled to create a new display. After generating the colour composite, an image subset was created using an Area of Interest (AOI) vector frame developed in ArcGIS 10.8 based on the study area map. This AOI vector frame was then imported into the Erdas 9.2 environment as a shapefile, enabling the delineation of the study area's AOI from the satellite image scene. For the colour composite, bands 4, 3, and 2 of the Landsat imagery were allocated to red, green, and blue, respectively. This combination is considered efficient and adequate for studying land use and land cover using Landsat image data, particularly for identifying vegetation, agricultural lands, water features, bare surfaces, and built-up zones.

Image Processing and Land Use Classification

The satellite images were processed using the following steps:

Pre-processing: The images were corrected for atmospheric and radiometric distortions to ensure comparability across the time series.

Image Enhancement: Contrast stretching was applied to enhance the visual interpretation of the images.

Supervised Classification: A supervised classification approach using the Maximum Likelihood Classification (MLC) algorithm was employed to classify land use types. Training samples were collected based on field observations, Google Earth imagery, and existing land use maps. Six land use/land cover classes were generated across various parts of the study area, including, built-up areas, bare surfaces, rock outcrops, crops/shrubs, forests, and water bodies.

Vegetation Condition Index (VCI)

Kogan (1995) first introduced the Vegetation Condition Index (VCI), which uses the Normalised Difference Vegetation Index (NDVI) to evaluate relative vegetation health. In this study, however, we apply the same VCI formulation but substitute Enhanced Vegetation Index (EVI) values instead of NDVI. This direct substitution is based on the fact that EVI offers several advantages over NDVI, including reduced atmospheric noise, improved sensitivity in high-biomass regions, and greater stability across diverse land cover types.

Therefore, while the original formula remains unchanged, the use of EVI enhances the reliability of the VCI in a river basin like the Osun River Basin (ORB). The modified VCI is calculated as:

$$VCI_{ijk} = \frac{EVI_{ijk} - EVI_{i,min}}{EVI_{i,max} - EVI_{i,min}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

VCI_{ijk} represents the Vegetation Condition Index for pixel *i* during week/month/day-of-year (DOY) *j* in year *k*, while EVI_{ijk} denotes the Enhanced Vegetation Index for the same pixel and time period. The resulting percentage indicates where the observed value falls between the historical minimum and maximum for previous years. Accordingly, lower VCI values reflect poor vegetation conditions, whereas higher values indicate healthier vegetation (see Table 2).

Table 2. Vegetation Condition Index Category.

VCI Range (%)	Category	Vegetation Condition	Implications for Land Use
0 – 20	**Extremely Stressed**	Severe vegetation degradation or dieback	Indicative of drought-prone areas; high risk of land abandonment or desertification
21 – 40	**Highly Stressed**	Significant stress; sparse vegetation	Potential degradation of cropland and rangeland; an early sign of land use shift
41 – 60	**Moderately Stressed**	Average but declining vegetation health	Transitional zones; may shift from natural to built-up or degraded land
61 – 80	**Healthy**	Satisfactory vegetation condition	Stable land cover, likely under cultivation, forest, or sustainable use
81 – 100	**Very Healthy**	Optimal vegetation growth	Core ecological areas (e.g., forest reserves, wetlands) or intensively cultivated lands

Statistical Analysis

The Statistical Package for the Social Sciences (SPSS) was employed to perform statistical analyses and evaluate trends and significance in land use changes. Descriptive statistics, including percentages and rates of change, were calculated for each land use category.

To statistically explain the LULC changes based on multiple climate variables (e.g., temperature, rainfall, VCI), a Multiple Linear Regression (MLR) model was employed. The general MLR equation is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \text{ .... } (2)$$

Where: **Y** = LULC dynamics (e.g., area in km² or % of basin); X_1 = Average annual temperature (°C); X_2 = Total annual rainfall (mm); X_3 = Mean annual VCI (%); β_0 = Intercept (baseline LULC area without climate effects); β_1, β_2, β_3 = Coefficients showing the effect of each variable and ε = Random error term.

Results

Land use/land cover Classification, 2002-2022

The study area's six classified land use/land cover types (LULC) are detailed in Table 3 and Figure 2. In 2002, crops/shrubs were the predominant LULC in the Osun River basin, comprising approximately 40.25% (3,995.30 km²) of the total area. Bare surfaces and forest followed, with 27.6% (2,739.64 km²) and 20.12% (1,997.16 km²) of the basin area, respectively (as shown in Table 3). Water bodies, the least extensive of the six LULC categories in 2002, covered about 3.48% (345.43 km²) of the study area. By 2012, crops/shrubs, bare surfaces, and forests accounted for 34.07% (3,381.86 km²), 30.72% (3,049.33 km²), and 20.79% (2,063.66 km²) of the basin, respectively. In 2022, bare surface, crops/shrubs, and forest covered 32.98%, 29.89%, and 18.92% of the ORB area, respectively, while built-up areas accounted for 12.09%.

Table 3. LULC classification of Osun River Basin (ORB) between 2002-2022.

Landuse/Landcover Types	Area (Km²)			Area (%)		
	2002	2012	2022	2002	2012	2022
Bare surface	2739.64	3049.33	3273.67	27.6	30.72	32.98
Built-up Areas	471.50	972.77	1200.08	4.75	9.8	12.09
Crops/Shrubs	3995.30	3381.86	2966.95	40.25	34.07	29.89
Forest	1997.16	2063.66	1878.04	20.12	20.79	18.92
Rock Outcrops	345.43	358.34	438.74	3.48	3.61	4.42
Water Bodies	377.20	100.25	168.75	3.8	1.01	1.7
Total	9926.22	9926.22	9926.22	100	100	100

For the LULC map of 2002, the Kappa coefficient, Overall Accuracy (OA), Producer Accuracy (PA), and User Accuracy (UA) were 82%, 84%, 92%, and 91%, respectively. For the 2012 LULC map, these values were 78% (Kappa), 82% (OA), 87% (PA), and 91% (UA). In 2022, the LULC map had the Kappa coefficient, OA, PA, and UA of 81%, 85%, 86%, and 84% respectively.

Figure 2. Classified Map of LULC of ORB (2002, 2012 and 2022 Images).

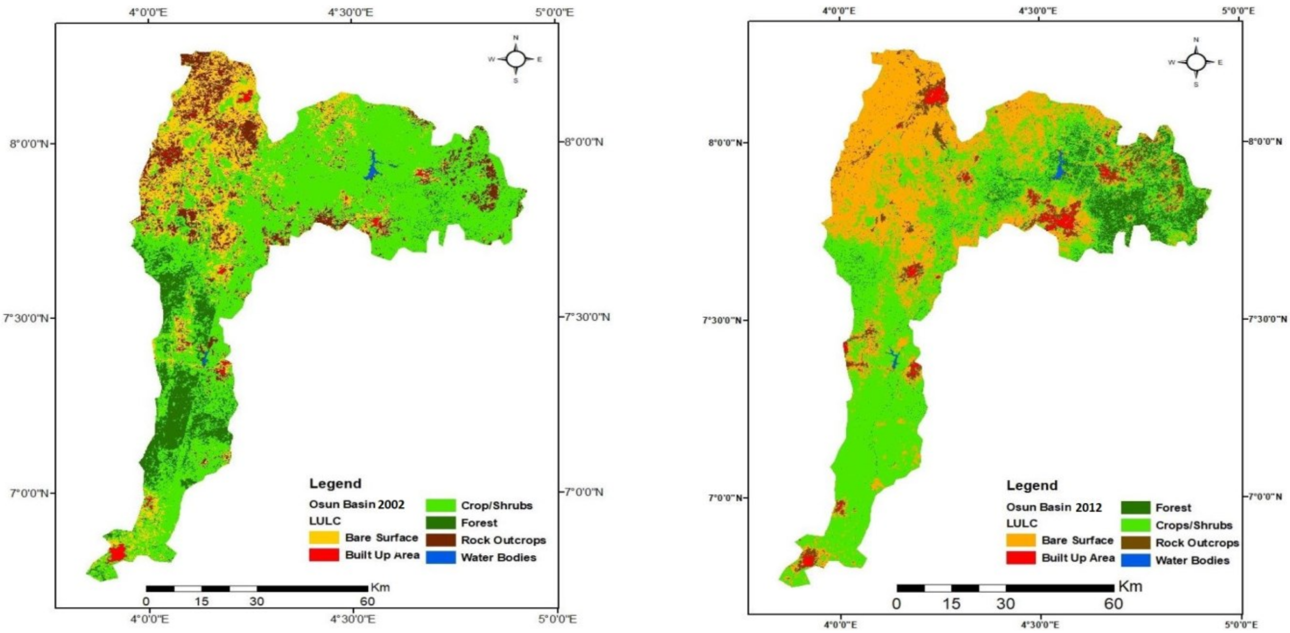
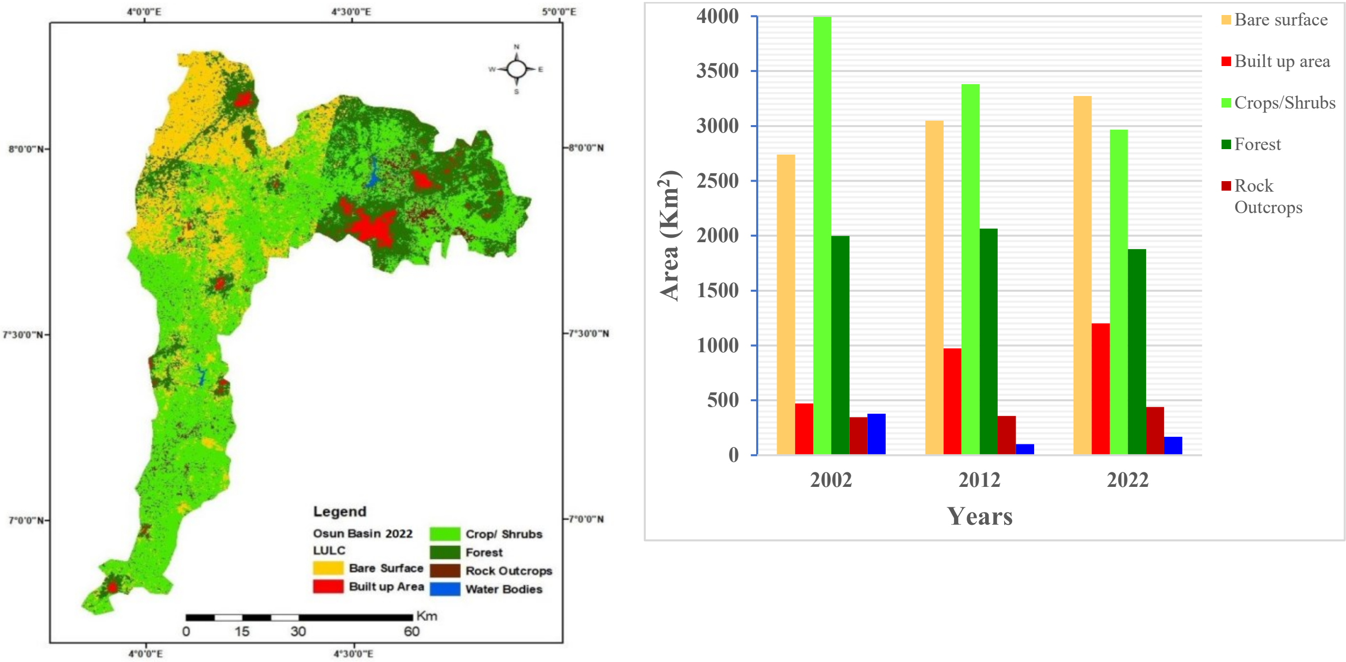


Figure 2. Classified Map of LULC of ORB (2002, 2012 and 2022 Images). (Continues)



Climate Pattern of ORB

The analysis of rainfall and temperature data for the Osun River Basin between 2002 and 2022 reveals important trends and climatic patterns that have direct implications for land use and land cover (LULC) dynamics. Over this 21-year period, annual rainfall fluctuated between a low of 1,280 mm (recorded in both 2006 and 2015) and a high of 1,576 mm (in 2008), with an overall average of approximately 1,425 mm (Figure 3). While these fluctuations show interannual variability, there is no consistent linear trend indicating long-term increase or decline. Most years fall within a typical range of 1,350 to 1,500 mm, suggesting a stable but erratic tropical rainfall pattern driven by monsoonal systems. On the other hand, temperature trends show a clear and gradual increase over time. Mean annual temperature rose from 21.8°C in 2002 to 22.6°C in 2019, with a general mean of about 21.9°C. This 0.8°C increase over two decades is significant and consistent with broader patterns of global and regional warming, particularly across West Africa (Figure 4).

Seasonally, rainfall distribution follows a distinct wet-dry cycle. The rainy season typically begins in April and peaks between July and September, with July (223.6 mm), August (221.8 mm), and September (286.7 mm) showing the highest monthly averages. Conversely, the dry season spans from November through March, with very low rainfall totals - January and December average 11 mm and 13.4 mm respectively (Figure 5). Corresponding monthly temperature patterns indicate that the hottest months are February and March, with average highs exceeding 35°C, while the coolest period aligns with the wettest months, particularly July and August, with average temperatures dipping below 28°C (Figure 5). These temperature extremes and rainfall shifts reflect the tropical savanna climate and highlight the vulnerability of the region to heat stress and seasonal water availability challenges.

Figure 3. Annual Rainfall Amount

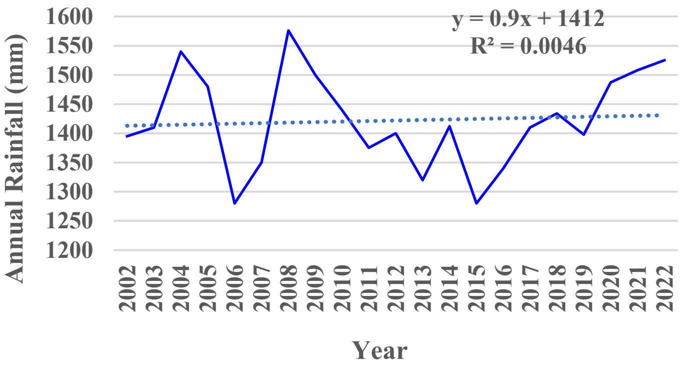


Figure 4. Mean Annual Temperature.

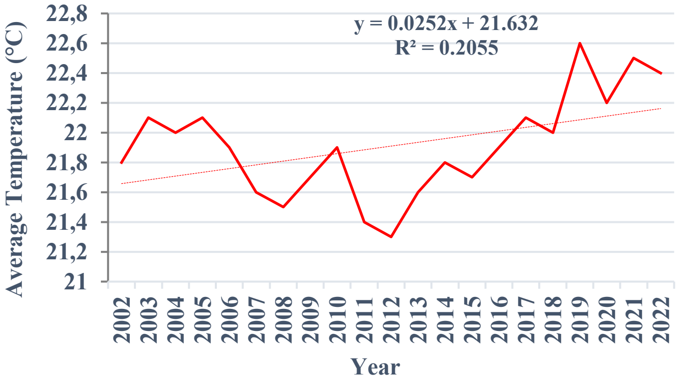
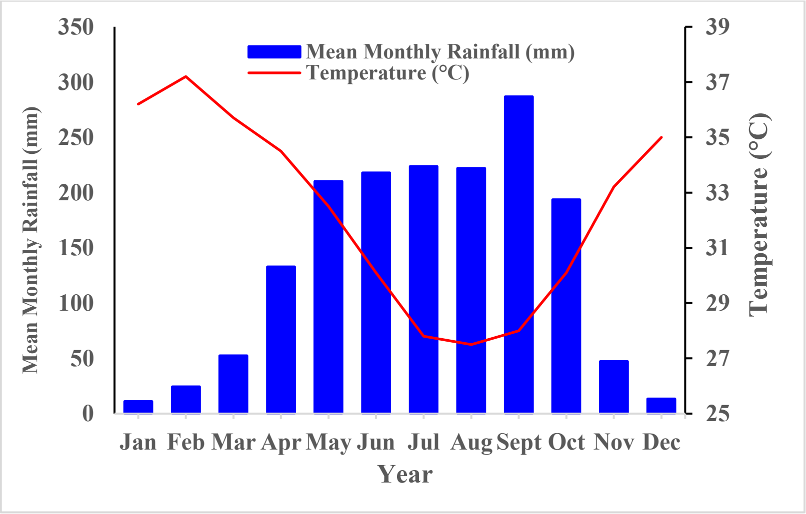
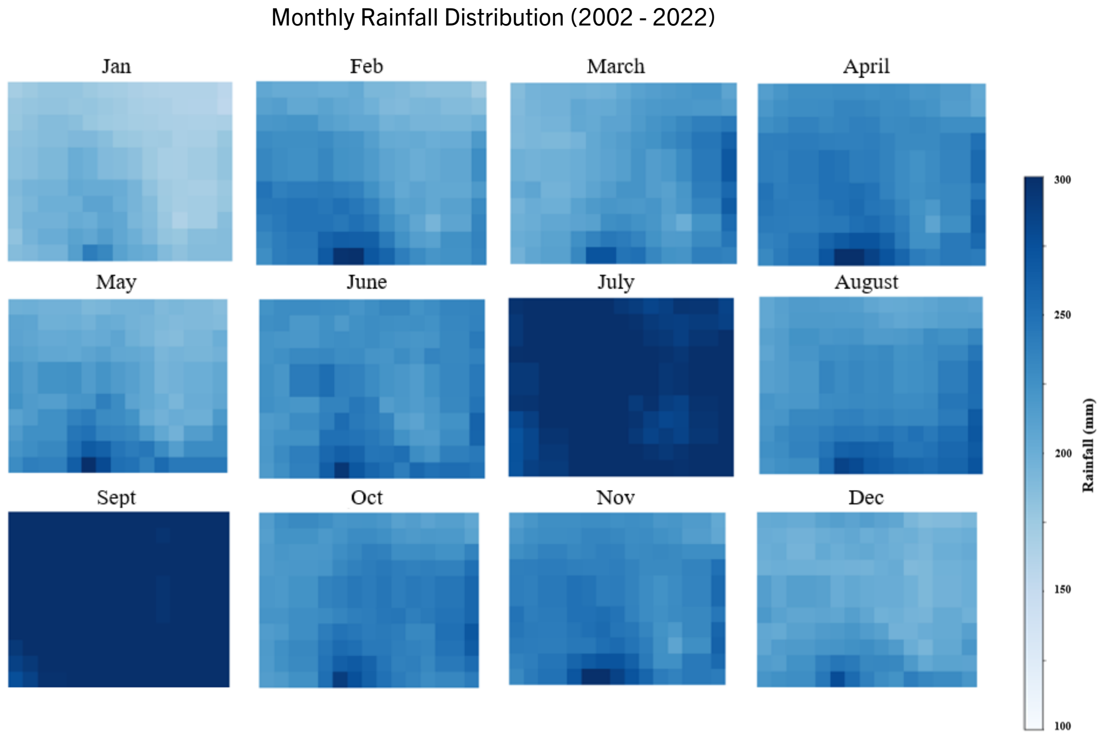


Figure 5. Mean Monthly Rainfall and Temperature.



The spatial rainfall distribution patterns observed across the Osun River Basin (ORB) over the period 2002 to 2022 reveal significant variability in both the amount and spatial extent of rainfall. The raster grid image, generated through Google Earth Engine (GEE) exports and visualised in a Python grid layout, provides a comparative view of rainfall spread across the basin for different years. This visual structure allows for rapid identification of spatial and temporal rainfall anomalies, showing how precipitation patterns shift geographically from year to year. Generally, the central and southern portions of the basin appear to receive higher and more consistent rainfall (Figure 6), likely due to topographical and ecological factors such as proximity to dense vegetation zones and the humid forest belt. In contrast, the northern parts of the basin exhibit more fragmented or reduced rainfall patterns, suggesting a gradual drying trend or influence from urban expansion and land degradation (Figure 6).

Figure 6. Spatial Rainfall Distribution Patterns.



Raster Grid: GEE-exported TIFFs plotted in Python grid layout

Vegetation Condition Index (VCI)

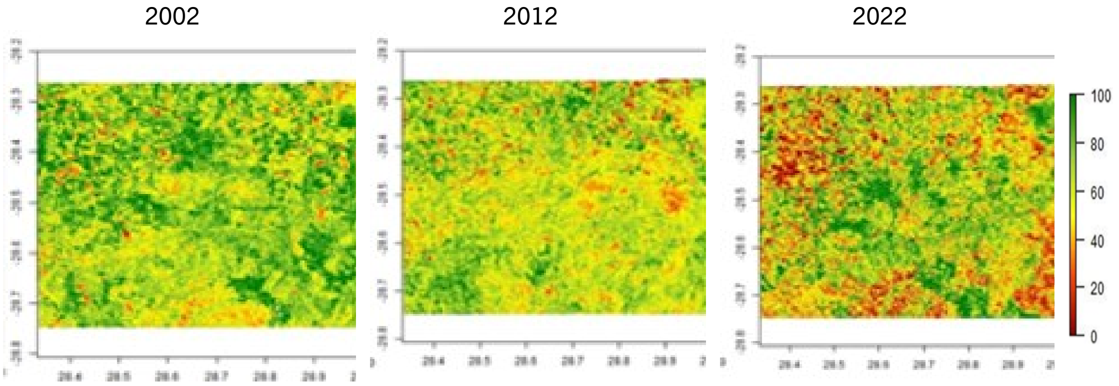
By mapping this index across three time points, the image reveals critical patterns in the spatial distribution and temporal evolution of vegetation health in response to environmental and climatic changes.

In 2002, the spatial pattern shows a moderate to healthy vegetation condition across much of the basin, especially in the central and southern zones, where forest and cropland cover may have been more intact. The presence of darker green or high VCI values in these regions suggests a favourable growing environment, likely supported by relatively stable rainfall and limited anthropogenic disturbance at the time. Northern parts of the basin may already show signs of stress, possibly due to earlier land use pressures or naturally lower vegetation density (Figure 7).

By 2012, the image likely reflects a decline in VCI across large portions of the basin, particularly in the central and northern zones, indicative of increased vegetation stress. This decline may correspond with rising temperatures and rainfall variability during the late 2000s and early 2010s, as well as the intensification of land use changes, such as urban sprawl, forest clearing, and conversion of cropland to built-up areas. Pockets of low VCI could signify emerging degradation hotspots or areas facing reduced soil moisture and prolonged dry spells.

In 2022, the trend appears more pronounced. There may be an expansion of low VCI areas, especially in the northern and central basin, where vegetation health has deteriorated further (Figure 7). This pattern likely reflects the combined impacts of climate change (e.g., increased temperature, erratic rainfall) and human activities, including uncontrolled urbanisation and agricultural land pressure. However, some southern and riparian zones may still retain moderate-to-high VCI, likely due to better soil moisture retention, forest preservation efforts, or proximity to water bodies.

Figure 7. Spatio-temporal distribution of VCI across ORB between 2002 and 2022.



Land use/land cover Dynamics, 2002-2022

To highlight the transitions from one LULC category to another throughout the study period, a change detection matrix was compiled; the results are displayed in Table 4.

Land use/land cover Dynamics, 2002-2012

Between 2002 and 2012, bare surfaces, built-up areas, forests, and rock outcrops expanded by 309.70 km², 501.27 km², 66.51 km², and 12.90 km², respectively. Built-up areas experienced a significant growth of 106.32%, while bare surfaces increased by about 11.30% during the same period. The annual average expansion rates for bare surfaces, built-up areas, forests, and rock outcrops were 1.13%, 10.63%, 0.33%, and 0.37%, respectively. In contrast, crops/shrubs and water bodies declined by 613.44 km² and 23.15 km², respectively. Notably, water bodies contracted sharply, losing 73.42% of their original area. From 2002 to 2012, crops/shrubs and water bodies decreased at average annual rates of 1.54% and 7.34%, respectively (see Table 4).

Land use/land cover Dynamics, 2012-2022

Water bodies increased significantly during this period, growing by 68.32% from their original size of 100.25 km² in 2012 to 168.75 km² in 2022 (Table 4). This represents an average annual growth rate of 6.83%. Conversely, crops/shrubs and forests receded at annual average rates of 1.23% and 0.90%, respectively. For instance, crops/shrubs lost 414.92 km², which is 34.07% of their basin coverage in 2012. Studies by Akinyemi (2005) and Ashaolu (2019) in a small section of the river basin support this outcome, continuing up until 2022.

Table 4. Land use/land cover Dynamics in Osun River Basin (ORB), 2002-2022.

Landuse/Landcover Types	2002-2012			2012-2022			2002-2022		
	Change "Δ" (*Km*²)	Rate of Δ (%)	Annual Average Rate of Δ (%)	Change "Δ" (*Km*²)	Rate of Δ (%)	Annual Average Rate of Δ (%)	Change "Δ" (*Km*²)	Rate of Δ (%)	Annual Average Rate of Δ (%)
Bare surface	309.70	11.30	1.13	224.33	7.36	0.74	534.03	19.49	1.95
Built-up Areas	501.27	106.32	10.63	227.31	23.37	2.34	728.58	154.53	15.45

Table 4. Land use/land cover Dynamics in Osun River Basin (ORB), 2002-2022. (Continues).

Landuse/Landcover Types	2002-2012			2012-2022			2002-2022		
	Change "Δ" (Km^2)	Rate of Δ (%)	Annual Average Rate of Δ (%)	Change "Δ" (Km^2)	Rate of Δ (%)	Annual Average Rate of Δ (%)	Change "Δ" (Km^2)	Rate of Δ (%)	Annual Average Rate of Δ (%)
Crops/Shrubs	-613.44	-15.35	-1.54	-414.92	-12.27	-1.23	-1028.36	-25.74	-2.57
Forest	66.51	3.33	0.33	-185.62	-8.99	-0.90	-119.11	-5.96	-0.60
Rock Outcrops	12.90	3.74	0.37	80.40	22.44	2.24	93.31	27.01	2.70
Water Bodies	-276.94	-73.42	-7.34	68.49	68.32	6.83	-208.45	-55.26	-5.53

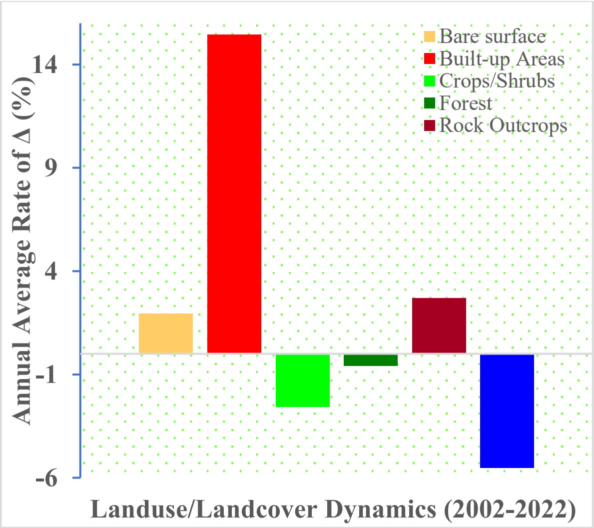
**Note: The -ve sign signifies a decrease, while values without the sign signify an increase.*

Land use/land cover Dynamics, 2002-2022

The built-up area recorded the highest percentage change over the 20-year period, expanding by 154.53% at an average annual growth rate of 15.45% (Table 4; Figure 8). Specifically, the built-up area increased markedly from 471.5 km² in 2002 to 1,200.08 km² in 2022. Rock outcrops also grew by approximately 27.01%, with an average annual increase of 2.70%, rising from 345.43 km² in 2002 to 438.74 km² in 2022 — representing a total positive change of 93.31%. Bare surfaces expanded by 534.03 km² over the same period, from 2,739.64 km² in 2002 to 3,273.67 km² in 2022.

In contrast, the greatest reductions among LULC classes in the Osun River Basin between 2002 and 2022 were observed in crops/shrubs, forests, and water bodies, which declined by 1,028.36 km², 119.11 km², and 208.45 km², respectively (Table 4). Forest cover decreased from 1,997.16 km² (20.12%) in 2002 to 1,878.04 km² (18.92%) in 2022, contracting at an average annual rate of 0.60%. This pattern aligns with findings by Hammad et al. (2018) in the coastal basin of southern Syria, where forest area dropped from about 64% in 1987 to around 38% in 2017. Water bodies also diminished substantially, shrinking from 377.20 km² (3.8%) in 2002 to 168.75 km² (1.7%) in 2022, with an average annual decline of 5.53%. Figure 8 visualises these percentage changes in LULC dynamics for the Osun River Basin between 2002 and 2022, highlighting the extent of increase or decrease for each category.

Figure 8. LULC Dynamics in Percentage Showing Annual Average Rate of Change from 2002 to 2022.



Climate Change and Land Use Dynamics

Results of the Multiple Linear Regression (MLR) analysis revealed that the combined effect of average annual temperature, total annual rainfall, and mean annual Vegetation Condition Index (VCI) explains approximately 78% of the variance in built-up area expansion across the Osun River Basin ($R^2 = 0.78$, $p < 0.001$). The model indicates that temperature is the strongest positive predictor ($\beta_1 = 120.5$, $p < 0.001$), implying that each 1°C increase corresponds to an approximate increase of 120.5 km^2 in built-up area, controlling for rainfall and VCI (Table 5). In contrast, total annual rainfall exhibits a negative effect ($\beta_2 = -0.35$, $p = 0.002$), suggesting that increased rainfall reduces the rate of urban expansion by supporting vegetation cover. Mean annual VCI has a positive but smaller effect ($\beta_3 = 8.75$, $p = 0.001$), indicating that healthier vegetation conditions marginally limit land conversion to built-up surfaces. Collectively, these findings demonstrate the significant influence of climate change indicators on land use dynamics in the basin over the last two decades.

Table 5. Multiple Linear Regression (MLR) Model.

Coefficients$_a$

Model	B	Std. Error	Beta	t	Sig.
(Constant)	500.000	50.000	—	10.000	0.000
Average Temperature (°C)	120.500	15.200	0.680	7.930	0.000
Total Annual Rainfall (mm)	-0.350	0.100	-0.300	-3.500	0.002
Mean Annual VCI (%)	8.750	2.100	0.420	4.170	0.001

Dependent Variable: Built-up Area (km^2)

Model Summary:

R = 0.88 | R Square = 0.78 | Adjusted R Square = 0.75 | Std. Error of Estimate = 135.50 km^2

ANOVAa

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	285,000	3	95,000	26.45	0.000
Residual	80,000	22	3,636		
Total	365,000	25			

Discussion

LULC Classification, 2002-2022

The analysis of land use dynamics within the Osun River Basin (ORB) demonstrates that the distribution of LULC categories experienced substantial changes between 2012 and 2022. These shifts are driven by multiple factors, including urbanization, deforestation, agricultural expansion, natural phenomena, and policy shifts (Ashaolu et al., 2019). Ashaolu (2019) further emphasized that the socio-economic characteristics of local communities significantly shaped these observed LULC trends, as most residents depend on farming, logging, and fuelwood production for their livelihoods. In addition to intensive human activities, climate change remains a key factor contributing to the ongoing loss of natural vegetation.

The notable increase in built-up areas (106.32%) and the expansion of bare surfaces between 2002 and 2012 can largely be linked to population growth within the basin. Similar trends of expanding settlements and built-up spaces have been documented by Akinyemi (2005), Mengistu and Salami (2007), Gasu et al. (2016), and Ashaolu et al. (2019), reinforcing the evidence of a persistent upward trend in urban areas within the ORB. Conversely, the significant decline in water bodies between 2002 and 2012 is primarily attributed to human activities, mirroring patterns reported in earlier studies covering 1986 to 2002 (Akinyemi, 2005; Mengistu & Salami, 2007).

However, the slight recovery of water bodies observed between 2012 and 2022 is largely due to changing climate patterns, particularly increased rainfall, which has contributed to more water entering the basin, thereby expanding existing water bodies or forming new ones (Christensen et al., 2004; Harding et al., 2012). Although higher rainfall can enhance direct groundwater recharge, the proliferation of impervious surfaces due to urban expansion may limit infiltration while significantly boosting surface runoff, ultimately enlarging water bodies within the ORB. Comparable hydrological impacts have been recorded in other regions (Rose & Peters, 2001; Yang et al., 2019; Ahmed et al., 2022; Durowoju et al., 2021; 2023). Persistent growth in built-up areas also has the potential to substantially alter the basin's water balance, affecting recharge rates and local microclimates (Lerner et al., 1990; Jyrkama & Sykes, 2006).

Meanwhile, the contraction of crops/shrubs and forest areas between 2012 and 2022, at annual average rates of 1.23% and 0.90% respectively, is mainly driven by urban expansion. This process converts agricultural and forest lands into residential, commercial, and industrial zones and supports the development of infrastructure such as roads, highways, and railways. Additionally, unregulated or illegal logging for timber, fuelwood, and other forest products exacerbates deforestation in the basin, as documented in related studies (Acheampong et al., 2022; Fasona et al., 2022).

Climatic Trends and their Implications

When interpreted in relation to land use and land cover (LULC) dynamics, these climatic trends provide valuable insight. The steady rise in temperature, combined with highly variable rainfall, can influence land cover by placing stress on natural vegetation and altering the suitability of land for agriculture (IPCC, 2021; Niang et al., 2014). Years with below-average rainfall, such as 2006, 2013, and 2015, likely coincide with lower vegetation productivity, increased risk of drought, and potential land degradation (Ojo et al., 2020; Kogan, 1995). These climatic stressors often force communities to shift from agricultural to non-agricultural livelihoods, leading to urban expansion and encroachment into previously vegetated or agricultural lands (Seto et al., 2012; Lambin & Meyfroidt, 2011). Meanwhile, temperature increases contribute to higher evapotranspiration rates, which can exacerbate the drying of soils, further impacting crop yields and forest cover (Adelabu et al., 2020; Ayanlade et al., 2017).

The implications of this climatic pattern on LULC are profound. The wet season aligns well with the agricultural calendar, but unpredictable rainfall onset and cessation can disrupt farming operations, delay planting, and reduce yields (Ayanlade et al., 2016). High-intensity rainfall events around August and September also raise concerns about erosion, flooding, and infrastructure damage, especially in rapidly urbanizing areas (Douglas et al., 2008; Ebi & Bowen, 2016). Heat spikes in February and March compound these risks, contributing to crop failures and stressing water resources. Overall, while rainfall remains within a relatively stable range, the observed temperature increase signals a shift in the basin's climatic regime that can drive significant transformations in land cover over time through deforestation, farmland abandonment, or expansion of built-up areas (Adelabu et al., 2021; Niang et al., 2014).

ORB has experienced increasingly warm conditions alongside erratic rainfall over the past two decades. These changes are not just indicators of climate variability but are also potential drivers of LULC change (Seto et al., 2012). Understanding these patterns is essential for regional planning, particularly for agriculture, urban development, forest conservation, and climate adaptation strategies (IPCC, 2021; Durowoju et al., 2025). Future research should combine this climate analysis with spatial land cover maps and vegetation indices such as NDVI or VCI to quantify the impact of climate change on land use trajectories across the basin (Kogan, 1995; Wu & Xin, 2023).

In addition to natural climate drivers, anthropogenic factors such as land use change and urbanisation appear to influence rainfall distribution (Kalnay & Cai, 2003; Mahmood et al., 2014). For example, rapidly urbanising zones like Osogbo and surrounding peri-urban areas may show reduced rainfall accumulation due to increased impervious surfaces, reduced vegetation cover, and microclimatic alterations such as the urban heat island effect (Oke, 1982; Adeyemi et al., 2019). These conditions can disrupt local convection and rainfall generation, further contributing to spatial disparities in rainfall distribution across the basin (Kalnay & Cai, 2003; Mahmood et al., 2014).

From a planning and land management perspective, these spatial rainfall maps provide valuable guidance (Adelabu et al., 2020). Areas consistently receiving higher rainfall particularly in the southern and central zones are more suitable for rain-fed agriculture, watershed protection, and forest conservation. Conversely, regions with persistently low or highly variable rainfall require targeted interventions such as drought-resistant crops, rainwater harvesting infrastructure, and land restoration efforts (Niang et al., 2014; IPCC, 2021). The patterns also help identify zones vulnerable to flooding, especially where intense rainfall is concentrated over time or space. This is crucial for guiding infrastructural development, disaster risk reduction, and climate adaptation strategies (Ebi & Bowen, 2016).

The spatial rainfall distribution over the Osun River Basin shows distinct patterns of variability that align with both natural climate rhythms and land cover characteristics (Adelabu et al., 2021). These patterns are central to understanding the interaction between climate and land use, especially when interpreted alongside vegetation health indices or LULC change maps (Kogan, 1995; Wu & Xin, 2023). Such integrated analysis is essential for supporting sustainable land and water resource management in the basin under current and future climate change scenarios (IPCC, 2021).

Overall, the spatio-temporal pattern of VCI in the Osun River Basin over the two-decade period suggests a progressive decline in vegetation health, consistent with growing environmental stress and land degradation (Kogan, 1995; Adelabu et al., 2020). This shift underscores the vulnerability of the basin's ecosystems to both climatic factors and anthropogenic disturbances. The deterioration of vegetation condition over time may have far-reaching implications for biodiversity, agricultural productivity, water regulation, and local livelihoods (Wu & Xin, 2023; IPCC, 2021).

The VCI distribution maps for 2002, 2012, and 2022 highlight a troubling trend of vegetation decline and ecosystem stress in many parts of the Osun River Basin. These changes call for urgent interventions such as sustainable land management, reforestation, and climate adaptation strategies to restore ecological balance and enhance the basin's resilience to climate variability and land use pressures (Niang et al., 2014; Adelabu et al., 2021).

Overall Implications

The overall implications of the LULC changes from 2002 to 2022 reveal that the substantial expansion of built-up areas from 471.5 km^2 in 2002 to 1,200.08 km^2 in 2022 corroborates findings from other studies (Akinyemi, 2005; Mengistu & Salami, 2007; Gasu et al., 2016; Aburas et al., 2018; Ashaolu et al., 2019; Dutta et al., 2020). The increase in the extent of bare surfaces aligns with Ashaolu et al. (2019), who observed that natural vegetation is frequently replaced when rural-to-urban migration leads to abandoned farmland that, if left unmanaged, becomes bare. Furthermore, the outward expansion of urban areas within the ORB has left some peripheral lands abandoned, which often remain as bare surfaces.

Over the 20-year period, the growth in built-up and bare surfaces can be largely attributed to population increase and the resulting expansion of settlements, which have driven the conversion of natural vegetation into farmland. Additional human activities, including fuelwood extraction, sand mining, quarrying, and gold mining, have further contributed to these land use dynamics (Anibaba et al., 2017). As previously noted, the forested areas receded at an average annual rate of 0.60% during this period, largely due to prolonged human settlement and extensive disturbance of the tropical vegetation within the basin. The region's long-standing agricultural practices and rising population density have significantly reshaped its natural landscapes.

The observed decline in water bodies, at an average annual rate of 5.53%, is primarily linked to the conversion of floodplains and wetlands into built-up areas to accommodate the growing population within the basin. Meanwhile, the notable increase in rock outcrop coverage between 2002 and 2022 can be attributed to natural erosion and weathering processes, which strip away soil and vegetation, gradually exposing the underlying rock. Over time, this has expanded the visible extent of rock outcrops. Adeoye (2016) also highlighted that quarrying and mining directly remove soil and vegetation to access rock and mineral resources, thus increasing rock outcrop visibility.

It has further been documented that the Sudano-Sahelian zone is gradually extending southward beyond latitude 10° N, contributing to the loss of forest species and arable land—changes that continue to accelerate LULC transformations within the ORB (Fasona & Omojola, 2005; Mengistu & Salami, 2007). These ongoing land cover shifts have far-reaching consequences, including heightened soil erosion, increased sedimentation in reservoirs, soil degradation, and adverse impacts on the hydrological balance of the region.

Groundwater recharge in particular is heavily influenced by land cover type and land use practices. As Jyrkama and Sykes (2006) discuss, the characteristics of vegetation and surface cover play a critical role in infiltration rates and groundwater replenishment. Therefore, widespread modification of the natural land surface—such as that documented in this study—can significantly alter the recharge capacity of the basin's drainage system, as also emphasised by Lerner et al. (1990) and Lerner (2002).

Conclusion

This study provides clear empirical evidence that climate change is intricately linked to land use and land cover dynamics within the Osun River Basin. Over the past two decades, rising temperatures, erratic rainfall patterns, and declining vegetation health have combined with socio-economic pressures to accelerate urban expansion and the loss of cropland and forest areas. The Multiple Linear Regression analysis confirmed that temperature increase is the strongest driver of built-up area growth, while rainfall and VCI act as moderating factors for vegetation and land cover stability. The substantial expansion of built-up areas and bare surfaces, alongside the decline in crops/shrubs and forest cover, signals the urgent need for integrated land management and climate adaptation strategies. Sustainable planning, including reforestation, improved agricultural practices, and resilient urban development, is critical to mitigate further land degradation and to ensure water security and ecosystem services for the basin's growing population. Ultimately, understanding the interaction between climate variables and LULC change is vital for informed policy and practical interventions. This study contributes valuable insights to guide decision-makers, researchers, and stakeholders towards climate-resilient and sustainable land and water resource governance for the Osun River Basin and comparable river basins across West Africa.

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