SPATIOTEMPORAL ANALYSIS OF THE INFLUENCE OF URBAN VEGETATION DECLINE ON LOCAL RAINFALL PATTERNS IN ABUJA NIGERIA FROM 2015 TO 2024

BY

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NOVEMBER, 2025

CERTIFICATION

This is to certify that this research titled **"Spatiotemporal Analysis of the Influence of Urban Vegetation Decline on Local Rainfall Patterns in Abuja Nigeria from 2015 to 2024"** was carried out by **Okonkwo Arize Daniel** and presented to the Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City; in partial fulfilment of the requirements for the award of Bachelor of Science (B.Sc) in Environmental Management and Toxicology. It was conducted under suitable conditions, was carefully supervised and subsequently approved as having met the requirements for the award of Bachelor of Science degree in Environmental Management and Toxicology.

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DECLARATION

I, Okonkwo Arize Daniel declare that Spatiotemporal Analysis of the Influence of Urban Vegetation Decline on Local Rainfall Patterns in Abuja Nigeria from 2015 to 2024. With Landsat-2 and CHIRPS (Climate Hazards Group Infrared Precipitation with Station data) Satellite Technology is my own work and that all sources that I have used or quoted have been acknowledged by means of complete references and that this work has not been submitted before for any other degree at any other University.

______________________________ ______________________________

OKONKWO ARIZE DANIEL **DATE**

DEDICATION

This work is dedicated to the almighty God for making this work a success and also to my parents Arc. And Mrs. Nwabu Okonkwo

ACKNOWLEDGEMENT

I am deeply grateful to Almighty God for granting me good health, wisdom, and the strength to bring this project to completion. My profound thanks go to my supervisor, Prof. Alex Enuneku, for his unwavering guidance, encouragement, and invaluable support throughout this work. I also wish to express my sincere appreciation to Dr. Charles Ehinlaiye A. O., my GIS instructor, for his dedication and assistance in making this study a success. I extend my heartfelt gratitude to my parents, Arc. and Mrs. Nwabu Okonkwo, and my entire family for their constant love, prayers, and encouragement. I am equally thankful to my ever-supportive colleagues Stephanie Adaugo Ekenedilichukwu, Osagie Uhunmwangho, Oluwaseyi Adekolujo, Elijah Emmanuel, Miracle Asemota-Ero, Ojone Akode, and William Blessing Orobosa for their genuine care, constant support, and readiness to assist whenever needed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ABSTRACT

This study examines how the decline of vegetation has affected rainfall patterns in Abuja, Nigeria, between 2015 and 2024. Using Sentinel-2 satellite imagery and CHIRPS rainfall data, the research analyzed land use and rainfall changes over time through Google Earth Engine and ArcGIS. Findings revealed a major shift in Abuja's landscape during the study period. Tree cover, which accounted for about 71.81% of the area in 2015, declined sharply to 23.71% by 2024, while built-up and farmland areas expanded significantly due to rapid urban growth. Rainfall trends also became more irregular, showing a noticeable decrease after 2018. Statistical analysis indicated a strong negative relationship ($r = -0.76$) between vegetation cover and rainfall, suggesting that as green spaces declined, rainfall reduced correspondingly. This loss of vegetation has weakened natural cooling and moisture recycling processes, contributing to hotter and drier conditions across the city. The findings show that the conversion of natural green areas into concrete surfaces has disrupted Abuja's local hydrological balance and may be influencing recent changes in rainfall distribution. The study concludes that protecting and restoring green spaces is essential for improving rainfall stability and climate resilience. It recommends the implementation of sustainable urban planning strategies, reforestation initiatives, and stronger environmental policies to restore ecological balance and promote a healthier urban environment in Abuja.

1 INTRODUCTION

1.1 BACKGROUND OF STUDY

Urban vegetation is one of the most important components of a healthy city environment because it supports ecological balance, moderates local climatic conditions, and improves air quality. Vegetation such as trees, shrubs, lawns, and urban forests play a vital role in reducing air temperature, influencing humidity, and promoting rainfall formation through the process of evapotranspiration. The presence of urban greenery also enhances carbon sequestration, reduces surface runoff, and contributes to overall urban sustainability (Twumasi *et al.,* 2020). In contrast, the removal or decline of vegetation cover alters the local energy balance and atmospheric moisture content, which can influence rainfall distribution and frequency (Odeyemi *et al.,* 2022).

Globally, urbanization has become one of the dominant processes affecting environmental systems. The conversion of natural vegetation and agricultural land into built-up areas changes the physical and thermal characteristics of the land surface. This modification disrupts the hydrological cycle by reducing infiltration, increasing surface runoff, and limiting evapotranspiration. Studies using satellite imagery and geospatial tools have shown that as cities grow, vegetation cover decreases while impervious surfaces expand, leading to microclimatic alterations such as increased temperature, reduced humidity, and irregular rainfall distribution (Wicaksono *et al.,* 2024).

These environmental transformations are not limited to developed nations. Across Africa, rapid population growth, poor urban planning, and weak environmental regulation have contributed to a steady decline in urban green spaces. The resulting environmental challenges include rising temperatures, local air pollution, and fluctuating rainfall patterns. According to Twumasi *et al.,* (2020), many cities in sub-Saharan Africa are losing their vegetative cover at alarming rates, primarily due to housing expansion, infrastructural development, and deforestation. The decline of green spaces reduces the buffering capacity of cities against extreme weather events and increases their vulnerability to flooding and drought.

In Nigeria, the environmental impacts of urbanization have become increasingly evident over the past two decades. The conversion of vegetation into residential, industrial, and commercial land uses has intensified across major cities such as Lagos, Ibadan, Port Harcourt, and Abuja. This process has resulted in reduced vegetation cover, higher surface temperatures, and changes in local rainfall distribution. Research by Odeyemi *et al.,* (2022) revealed that vegetation decline in several Nigerian cities corresponded with a reduction in the Normalized Difference Vegetation Index (NDVI) and a shift in rainfall patterns. The study further explained that the loss of vegetation has affected atmospheric moisture and disrupted the local hydrological balance, leading to unpredictable rainfall events and longer dry periods.

Abuja, Nigeria's Federal Capital Territory, provides a clear example of this growing environmental concern. Since its establishment, Abuja was planned to include vast green zones, parks, and forest reserves to support a sustainable urban ecosystem. However, continuous population growth and infrastructural development have led to the conversion of these green areas into built-up spaces. Akinola *et al.,* (2021) reported that land use and land cover changes in Abuja have intensified since the early 2000s, resulting in the loss of natural vegetation, increased surface sealing, and higher land surface temperatures. These changes have implications for local weather patterns, particularly rainfall, which has become less predictable and more spatially variable.

Rainfall is a key climatic element that determines the ecological stability of an area. The amount and distribution of rainfall influence water availability, vegetation growth, and agricultural productivity. Vegetation, in turn, affects rainfall through evapotranspiration, canopy interception, and the recycling of moisture into the atmosphere. When vegetation cover decreases, less moisture is returned to the air, potentially reducing rainfall frequency or altering its distribution. Wicaksono *et al.,* (2023) found similar patterns in Indonesian cities, where deforestation and vegetation loss led to lower evapotranspiration rates and shifts in rainfall intensity. These findings align with Twumasi *et al.,* (2020), who observed that the degradation of urban green spaces in Accra, Ghana, contributed to declining local rainfall and increased urban heat. Such evidence reinforces the understanding that vegetation change and rainfall variability are closely connected processes that operate across both spatial and temporal scales.

For Abuja, changes in rainfall patterns have been reported by several studies. Ndukwu *et al.,* (2020) noted that the city has experienced a gradual shift in rainfall onset and duration, which may be associated with land cover change. The replacement of vegetated surfaces with concrete and asphalt has reduced the capacity of the land to retain and recycle water vapor. This process not only affects local humidity but also influences atmospheric convection and cloud formation, which are essential components of rainfall generation. The observed irregularity in rainfall has consequences for urban water supply, agriculture, and flood management in the Federal Capital Territory.

Remote sensing and Geographic Information System (GIS) techniques provide valuable tools for analyzing these environmental changes. The integration of multi-temporal satellite imagery with rainfall datasets allows researchers to assess the spatial and temporal relationship between vegetation dynamics and climatic variables. Twumasi *et al.,* (2020) emphasized that GIS-based spatiotemporal analysis enables precise monitoring of vegetation indices such as NDVI and enhances understanding of their correlation with rainfall distribution. Similarly, Odeyemi *et al.,* (2022) highlighted that combining geospatial data with meteorological information helps in identifying trends and patterns that traditional ground-based methods might overlook. Such approaches are particularly relevant for a fast-growing city like Abuja, where land use change occurs rapidly and continuously.

Globally, several studies have demonstrated that monitoring vegetation and rainfall interactions through remote sensing provides important insights for sustainable urban management. Wicaksono *et al.*, (2023) showed that long-term spatial data could effectively reveal how vegetation decline correlates with rainfall anomalies, helping policymakers design strategies to mitigate climate risks. In Africa, where meteorological records are often limited, the integration of satellite-derived datasets has proven effective in filling data gaps and improving the understanding of local climate processes.

In summary, the decline of vegetation in urban areas has far-reaching effects on local climate regulation, particularly on rainfall formation and distribution. Evidence from various countries indicates that the continuous loss of urban green spaces disrupts natural moisture cycles and intensifies climatic irregularities. For Abuja, which has undergone significant urban transformation between 2005 and 2025, understanding how vegetation decline influences rainfall patterns is essential. This knowledge will contribute to more sustainable urban planning practices, improved climate resilience, and the promotion of environmental stability in Nigeria's rapidly developing capital. Therefore, conducting a spatiotemporal analysis of vegetation decline and rainfall variability in Abuja is both timely and necessary for addressing the growing environmental challenges associated with urban growth.

1.2 STATEMENT OF PROBLEM

Urban vegetation loss has emerged as one of the most critical environmental challenges confronting modern cities, particularly in rapidly urbanizing regions such as Abuja, Nigeria. As the Federal Capital Territory continues to expand, the conversion of vegetated land into built-up surfaces has significantly altered the local ecosystem. The replacement of natural vegetation with impervious structures such as roads, buildings, and pavements reduces evapotranspiration, increases surface temperatures, and alters atmospheric convection processes that regulate rainfall (Oyinloye *et al.,* 2023; Piracha and Chaudhary, 2022). These transformations disrupt the local hydrological cycle, potentially modifying rainfall distribution, duration, and intensity across Abuja and its environs.

Urban green spaces are integral to ecological balance, climate regulation, and urban livability. However, their depletion in Nigerian cities has reached alarming levels, driven by rapid urbanization, weak planning enforcement, and socioeconomic pressures (Appiah-Opoku *et al.,* 2023; Jafar *et al.,* 2025). In Abuja, the city's original master plan, designed in the 1970s, is outdated and inadequate to manage current land-use pressures (Appiah-Opoku *et al.,* 2023). The absence of modern land-use controls and ineffective policy implementation have accelerated vegetation conversion for housing, commercial complexes, and road networks. This encroachment on green areas has disrupted surface energy balance, increased heat storage, and contributed to changes in local microclimate, including rainfall variability.

Scientific evidence indicates that land-use and land-cover change are significant drivers of local and regional climate processes (Verburg *et al.,* 2011). The decline in vegetation cover alters surface albedo and moisture availability, influencing atmospheric circulation and convective rainfall formation. Studies have shown that such changes can trigger both drought tendencies and localized flooding, depending on the nature and spatial pattern of vegetation loss (Ogungbenro and Morakinyo, 2014; Nzoiwu *et al.,* 2017). In northern and central Nigeria, shifts in rainfall onset and cessation dates have been observed, reflecting climatic instability linked to changing land-cover dynamics (Sawa and Adebayo, 2011). These variations pose a direct threat to water resources management, agriculture, and urban infrastructure in the FCT.

Abuja's transformation from a sparsely populated landscape to a densely built urban core between 2005 and 2025 has likely induced measurable environmental changes. Yet, empirical assessments quantifying the relationship between vegetation decline and local rainfall variability remain limited. Most previous studies on rainfall trends in Nigeria have focused on broad regional or national scales without considering the influence of urban land-cover change at the city level (Ekwueme *et al.,* 2024; Abbas, 2009). Consequently, there exists a critical knowledge gap in understanding how spatiotemporal variations in vegetation cover specifically affect the rainfall regime of Abuja a city characterized by rapid expansion and complex microclimatic interactions.

This gap presents both scientific and practical implications. Scientifically, there is limited integration of satellite-based vegetation indices such as the Normalized Difference Vegetation Index (NDVI) with long-term rainfall datasets to evaluate land-atmosphere interactions at the urban scale. Practically, the lack of such evidence undermines urban planning, environmental management, and policy formulation aimed at mitigating the adverse impacts of land-use change. Without a clear understanding of how vegetation dynamics influence rainfall, future urban expansion may exacerbate environmental degradation, water scarcity, and extreme weather events. Therefore, a spatiotemporal analysis of the influence of urban vegetation decline on local rainfall patterns in Abuja is urgently needed to fill this research void and support sustainable city planning and climate adaptation strategies (Arowolo and Deng, 2018; Jafar *et al.,* 2025).

1.3 Aims and Objectives

The study seeks to achieve the following specific objectives:

1. To analyze land use and land cover (LULC) changes in Abuja between 2005 and 2025
2. To identify and map the spatial distribution of urban vegetation
3. To determine the temporal trend and variability of rainfall
4. To evaluate the spatial correlation between changes in land cover and rainfall patterns
5. To detect significant change points in rainfall
6. To provide insights and policy recommendations

1.4 Justification of Study

The justification for this study lies in the growing environmental and climatic concerns associated with the rapid urban expansion and vegetation decline in Abuja, Nigeria's Federal Capital Territory. Over the past two decades, Abuja has experienced unprecedented rates of urbanization, characterized by the replacement of vegetated areas with impervious surfaces such as roads, buildings, and paved spaces (Oyinloye *et al.,* 2023; Oyeniyi *et al.,* 2025). This transformation has profound implications for the local microclimate, hydrological balance, and atmospheric processes, particularly rainfall formation and distribution. Understanding the spatiotemporal influence of vegetation decline on rainfall patterns from 2005 to 2025 is therefore essential for informed urban planning, environmental management, and climate adaptation strategies.

Urban vegetation plays a crucial role in moderating microclimatic conditions through evapotranspiration, temperature regulation, and enhancement of local humidity levels (Piracha and Chaudhary, 2022). The decline in green cover disrupts these natural processes, contributing to the intensification of the Urban Heat Island (UHI) effect, altered convectional currents, and subsequently, changes in local precipitation dynamics (Piracha and Chaudhary, 2022). In Abuja, these processes are exacerbated by weak urban planning enforcement and outdated master plans that fail to integrate green infrastructure into contemporary development frameworks (Appiah-Opoku *et al.,* 2023). The city's master plan, originally prepared in the 1970s, is still relied upon today despite its inability to address emerging land-use and environmental challenges, particularly those relating to green space depletion and climate regulation (Appiah-Opoku *et al.,* 2023). These planning inefficiencies justify the need for empirical research that quantifies the environmental consequences of vegetation decline, especially on rainfall variability and intensity.

Several studies in Nigeria have documented significant shifts in rainfall characteristics, including delayed onset, early cessation, and shortened rainy seasons, largely attributed to land-use changes and anthropogenic interference (Sawa and Adebayo, 2011; Ekpoh and Nsa, 2011). Similar research by Ekwueme *et al.,* (2024) reported statistically significant changes in rainfall trends and identified local land-use alterations due to urbanization as potential drivers of these changes. However, these studies have primarily focused on regional or agricultural contexts, leaving a critical gap in understanding how urban vegetation dynamics influence rainfall patterns at the city scale, particularly in Abuja. This study fills that gap by integrating geospatial, meteorological, and statistical approaches to investigate the spatial and temporal relationship between vegetation loss and rainfall variability over a twenty-year period.

Moreover, the research is justified by the increasing frequency of extreme weather events, including flooding, that have become common in Abuja and other rapidly urbanizing Nigerian cities (Nzoiwu *et al.,* 2017). These events have been linked to increased rainfall intensity coupled with reduced natural infiltration capacity due to vegetation depletion (Ekwueme *et al.,* 2024). By quantifying vegetation cover changes using Normalized Difference Vegetation Index (NDVI) and analyzing corresponding rainfall data, this study provides scientific evidence needed to guide sustainable urban development and environmental resilience planning. The methodological integration of satellite-based remote sensing and statistical trend analysis, as recommended by Oyeniyi *et al.,* (2025) and Ogungbenro and Morakinyo (2014), ensures accurate representation of the complex interactions between urban land cover and climatic variables.

Finally, this study has strong policy relevance. Findings will inform urban planners, environmental managers, and policymakers on the need to incorporate green infrastructure and adaptive land-use planning into Abuja's development framework. As highlighted by Appiah-Opoku *et al.,* (2023), institutional weaknesses in urban environmental governance have facilitated the uncontrolled depletion of green spaces in Sub-Saharan African cities. Therefore, the study's outcomes will provide an evidence-based foundation for promoting sustainable city design, climate-resilient infrastructure, and reforestation initiatives aimed at restoring ecological balance and mitigating adverse climatic impacts. Through these contributions, the study not only advances scientific understanding but also supports national and regional commitments to sustainable urban development and climate adaptation.

2 LITERATURE REVIEW

2.1 Introduction to Literature Review

This literature review serves to establish a comprehensive theoretical and empirical foundation for investigating the spatiotemporal relationship between urban vegetation decline and local rainfall patterns in Abuja, Nigeria, from 2015 to 2024. The core purpose is to synthesize existing knowledge, identify established mechanistic links, and contextualize the research within the broader discourse on urban climatology and land use change. A thorough review is essential for understanding the complex interactions between human induced landscape modifications and local climate systems, thereby justifying the necessity and originality of this study.

The importance of understanding the relationship between urban vegetation and local rainfall cannot be overstated, especially in a rapidly urbanizing context like Abuja. Land use and land cover change (LULCC) has been identified as one of the key elements in global environmental change and sustainable development (Olorunfemi *et al.,* 2020). Furthermore, the National Research Council has recommended the broadening of the climate change issue to include LULCC processes as an important climate forcing (Mahmood *et al.,* 2010). As urban areas expand, natural vegetation is systematically replaced by impermeable surfaces, which has profound implications for the urban energy balance and hydrological cycle. The loss of natural vegetation and the increase of impermeable non transpiring, non-evaporating hard land surfaces result in increasing land surface temperatures (LST), a foremost crucial problem facing non vegetated areas (Hussain *et al*., 2014). This phenomenon, known as the Urban Heat Island (UHI) effect, where urban areas experience relatively higher temperatures compared with surrounding rural areas (Weng 2001), is a critical modifier of local microclimate. The UHI can amplify urban air pollution and cause air turbulence that influences atmospheric conditions (Piracha and Chaudhary 2022), thereby creating a complex feedback loop that can alter local convection and rainfall processes. As noted by Verburg *et al.,* (2011), land use and land cover change not only impacts GHG emissions but also land surface properties of relevance to climate, with possible large impacts on regional and continental climate.

Reviewing previous studies is instrumental in building the empirical foundation for this research. It allows for the examination of established methodologies, such as the use of the Normalized Difference Vegetation Index (NDVI) for monitoring vegetation abundance (Higginbottom and Symeonakis 2014) and advanced statistical techniques like the Mann Kendall test and change point analysis for detecting trends in hydrological time series data (Ekwueme *et al.,* 2024). Studies in Nigerian cities, such as the spatiotemporal analysis of green spaces in Akure (Oyinloye *et al.* 2023) and the analysis of LULCC in Ekiti State (Olorunfemi *et al.,* 2020), provide critical regional context and demonstrate the alarming rates of vegetation depletion. Similarly, research on rainfall trends in Northern Nigeria (Sawa and Adebayo 2011; Ogungbenro and Morakinyo 2014) offers evidence of changing rainfall patterns, including a shorter rainy season and increased variability. By synthesizing these global principles and local findings, this literature review will bridge the gap between broad theory and specific application, setting the stage for a detailed spatiotemporal analysis of Abuja's unique urban environment. This foundational overview seamlessly leads into a detailed examination of the conceptual frameworks that underpin this study.

2.2 Conceptual Framework

The conceptual framework of this study provides a structured explanation of how the loss of urban vegetation affects rainfall patterns in Abuja, Nigeria, between 2015 and 2024. It connects environmental and spatial processes to explain how human activities influence natural systems within the city. The framework is built around four main ideas urban vegetation and green cover**,** spatiotemporal analysis**,** rainfall variability and local climate modification**,** and land use and land cover (LULC) change**.**

These concepts interact to show the chain of relationships between vegetation depletion, land surface transformation, and rainfall distribution. Essentially, as green cover reduces, it alters the local microclimate, influences atmospheric processes, and modifies rainfall behavior. The conceptual framework helps to visualize these linkages and provides the scientific foundation for analyzing them using Geographic Information System (GIS) and remote sensing tools.

2.2.1 Urban Vegetation and Green Cover

Urban vegetation includes all forms of plant life that exist within a city or its surrounding areas trees, shrubs, grasses, gardens, parks, and small urban forests. Green cover refers to the total area occupied by this vegetation relative to the overall land surface. Vegetation is one of the most important natural components of the urban environment because it performs ecological, climatic, and social functions.

Ecologically, vegetation absorbs carbon dioxide, produces oxygen, filters air pollutants, prevents soil erosion, and supports biodiversity. Climatically, it helps to moderate temperature through shading and evapotranspiration a process where plants release water vapor into the atmosphere, cooling the surrounding environment (Mahmood *et al.,* 2010). According to Jafar *et al.* (2025), urban vegetation contributes significantly to maintaining air quality and groundwater recharge by improving infiltration and reducing surface runoff.

In Abuja, green cover plays a major role in stabilizing the city's microclimate. During evapotranspiration, plants release moisture that increases atmospheric humidity and promotes rainfall formation. However, with rapid population growth and continuous urban expansion, much of the natural vegetation has been cleared to make space for housing, industries, and infrastructure (Oyinloye *et al.*, 2023). As a result, impervious surfaces such as asphalt, concrete, and rooftops have replaced permeable ones, reducing water infiltration and increasing land surface temperature.

This change in surface characteristics leads to an imbalance between latent heat (the energy used for evaporation and cooling) and sensible heat (the energy that warms the surface). As

Olorunfemi *et al.,* (2020) explain, this shift contributes to localized heating often called the urban heat island effect where urban centers become significantly warmer than surrounding rural areas. The warmer conditions can influence atmospheric circulation, cloud development, and the timing or amount of rainfall. Thus, preserving green cover is not only vital for urban beauty or recreation but also for sustaining the hydrological cycle and ensuring climate stability in Abuja.

2.2.2 Spatiotemporal Analysis

Spatiotemporal analysis refers to the scientific approach used to study how environmental variables change over space and time. It provides a way to visualize and measure patterns of change in vegetation, rainfall, and land cover across different periods. Using Geographic Information System (GIS) and remote sensing technologies, researchers can analyze satellite data to detect environmental transformations with high precision and consistency (Verburg *et al.,* 2011).

In environmental monitoring, spatiotemporal analysis often relies on indicators such as the Normalized Difference Vegetation Index (NDVI). NDVI uses satellite imagery to estimate vegetation health and density by measuring light reflectance in the red and near-infrared bands (Higginbottom and Symeonakis, 2014). Higher NDVI values indicate healthy, dense vegetation, while lower values suggest sparse or degraded cover. Through NDVI and other indices, it becomes possible to identify how much vegetation has been lost or gained in a given area and to relate those changes to climatic variations such as rainfall.

In this study, spatiotemporal analysis is applied to examine how green space in Abuja has changed between 2015 and 2024 and how these changes relate to rainfall variation during the same period. By combining time-series satellite images with rainfall datasets, patterns of vegetation decline and shifts in rainfall can be compared across years.

According to Oyinloye *et al.,* (2023), this method has proven effective in identifying the link between urban expansion and environmental degradation in Akure, Nigeria. Similarly, Arowolo and Deng (2018) emphasize that integrating GIS and remote sensing offers a clearer understanding of how urban growth modifies natural processes, particularly those related to temperature and rainfall. Therefore, spatiotemporal analysis serves as both a methodological and conceptual link, bridging environmental data with urban climatic outcomes.

2.2.3 Rainfall Variability and Local Climate Modification

Rainfall variability refers to the differences in rainfall amount, timing, frequency, and intensity across years or within different parts of a region. It is one of the most important indicators of climate dynamics, especially in tropical environments where rainfall supports agriculture, vegetation growth, and water supply (Nzoiwu *et al.,* 2017).

In urban areas, rainfall patterns are often altered by changes in land use and surface conditions. Natural land surfaces absorb and retain moisture, while built-up areas made of concrete and asphalt increase heat absorption and reflection. These changes disturb the local heat and moisture balance, leading to temperature rises and shifts in rainfall behavior.

Vegetation influences rainfall through evapotranspiration plants draw water from the soil and release it into the atmosphere, contributing to cloud formation and precipitation (Mahmood *et al.,* 2010). When vegetation cover declines, the amount of moisture entering the air decreases, reducing the potential for convective rainfall. Additionally, deforested or highly urbanized areas often have higher surface albedo (reflectivity), which causes less solar energy to be absorbed by the ground and weakens vertical air movement needed for rainfall (Ekpoh and Nsa, 2011).

Built-up areas also generate excess heat, known as sensible heat, which modifies local wind circulation and may push clouds away from city centers, resulting in uneven rainfall distribution. Olorunfemi *et al.,* (2020) point out that such conditions increase land surface temperature, lower humidity, and disturb natural rainfall cycles. In Abuja, continuous conversion of vegetated land into residential and commercial areas likely contributes to these climatic shifts. Understanding these processes helps to explain how urban development influences rainfall variability and overall climate modification in the city.

2.2.4 Land Use and Land Cover Change (LULC)

Land use and land cover change (LULC) reflects how human activities transform the physical and functional characteristics of the environment. Land use describes how land is utilized for instance, for farming, housing, or industry while land cover refers to what physically exists on the surface, such as vegetation, water, soil, or buildings (Arowolo and Deng, 2018).

Rapid urbanization in developing countries like Nigeria has caused widespread changes in land cover, often leading to deforestation, soil erosion, and local climate alteration (Olorunfemi *et al.,* 2020). In Abuja, much of the natural vegetation and open spaces have been replaced by roads, residential estates, and other infrastructure. These changes reduce natural infiltration, increase surface runoff, and disturb the hydrological balance of the city.

Appiah-Opoku *et al.,* (2023) note that population pressure, weak enforcement of urban planning laws, and uncontrolled land conversion are major drivers of LULC changes in Nigeria. The consequences are far-reaching reduced vegetation cover leads to increased surface temperature, reduced soil moisture, and higher carbon emissions, all of which contribute to climate instability (Das and Angadi, 2022).

Monitoring these changes using satellite imagery allows researchers to quantify and visualize environmental transformation. Through techniques such as supervised classification and NDVI analysis, it is possible to map and compare different land cover types across years (Olorunfemi *et al.,* 2020). In this study, the analysis of LULC between 2015 and 2024 helps to show how Abuja's rapid urban growth has affected vegetation distribution and influenced local rainfall variability.

2.2.5 Interrelationship of Concepts

The four core concepts urban vegetation, spatiotemporal analysis, rainfall variability, and LULC are strongly interrelated. Land use and land cover change is the driving force that initiates the chain of interactions. As land use changes from natural to built-up, vegetation cover decreases. This decline reduces evapotranspiration, alters surface heat balance, and raises land surface temperature. These changes, in turn, affect atmospheric moisture, cloud formation, and eventually rainfall distribution (Mahmood *et al.,* 2010).

Spatiotemporal analysis acts as the tool that connects these interactions in measurable form. It combines satellite imagery, GIS data, and climatic records to track how vegetation loss and rainfall variability evolve over time. In Abuja, this approach allows for a clear understanding of how continuous urban expansion between 2015 and 2024 has influenced the city's microclimate and rainfall pattern.

Overall, this framework presents the urban environment as an interconnected system, where human-driven land transformation affects vegetation, which then influences atmospheric processes and local climate outcomes. By understanding these relationships, policymakers and planners can design sustainable land management strategies that protect green spaces, promote environmental balance, and reduce the negative climatic effects of rapid urbanization.

2.3 Theoretical Framework

A theoretical framework provides the scientific basis for understanding and interpreting the mechanisms linking vegetation decline with local rainfall variation. This study is guided by three complementary theoretical perspectives: the Urban Climate Theory, the Hydrological Cycle and Vegetation–Rainfall Interaction Model, and the Systems Theory in Environmental Change Analysis. Together, these theories explain the spatial and temporal processes through which human-induced land cover changes influence microclimatic systems, surface temperature, and hydrological dynamics in urban areas such as Abuja.

2.3.1 Urban Climate Theory

The Urban Climate Theory offers a foundation for explaining how physical and biological modifications of the landscape influence atmospheric processes within cities. It recognizes that urbanization changes the natural energy balance by altering the properties of the land surface. According to Dewan and Corner (2012) the replacement of natural vegetation with impervious materials such as concrete, asphalt, and rooftops causes an increase in the absorption of solar radiation and reduces latent heat fluxes associated with evapotranspiration. This leads to elevated surface and air temperatures in urban areas compared to their surrounding rural zones, a phenomenon widely described as the Urban Heat Island (UHI) effect (Weng, 2001).

The theory further suggests that these thermal differences influence convection, cloud formation, and ultimately local rainfall distribution (Sarrat *et al.,* 2006). Vegetation plays a major role in moderating this process through shading, cooling, and moisture release. The reduction or loss of vegetation therefore weakens evapotranspiration, increases sensible heat storage, and modifies boundary layer dynamics, which may delay or suppress rainfall events (Hussain *et al.,* 2014; Wilson *et al.,* 2003).

Empirical evidence from LULC studies shows that higher land surface temperature (LST) is directly correlated with declining vegetation indices (NDVI), confirming the urban heat build-up that arises from reduced vegetative cover (Pal and Akoma, 2009). In this regard, the Urban Climate Theory provides a strong theoretical explanation for the observed link between the expansion of built-up areas and changes in rainfall intensity and frequency in growing cities such as Abuja. As the city continues to expand, the replacement of natural vegetation with impervious surfaces reduces humidity and enhances convective instability, leading to unpredictable rainfall patterns and rising thermal discomfort.

The theory also emphasizes that urban-induced changes in surface roughness and albedo can alter the distribution of atmospheric moisture and wind circulation (Das and Angadi, 2022). As vegetation cover decreases, reflective surfaces increase, promoting higher ground temperatures and lowering relative humidity. These changes affect not only local precipitation but also the dispersion of pollutants and aerosols, which can modify cloud microphysics and reduce rainfall efficiency. Hence, the Urban Climate Theory situates vegetation decline within the broader context of urban thermal modification and atmospheric feedbacks that influence regional rainfall variability.

2.3.2 The Hydrological Cycle and Vegetation–Rainfall Interaction Model

The Hydrological Cycle provides a theoretical understanding of how water moves between the land surface, atmosphere, and subsurface systems. Within this cycle, vegetation plays a central role in processes such as interception, infiltration, and evapotranspiration, which collectively sustain atmospheric moisture and rainfall generation (Mahmood *et al.,* 2010). When vegetation cover is lost or degraded, these processes become disrupted, leading to imbalances in surface water storage, reduced infiltration, and diminished recycling of atmospheric moisture.

Vegetation influences rainfall through several mechanisms. First, it acts as a biological pump that releases water vapour into the atmosphere through transpiration, thereby increasing atmospheric humidity and enhancing the likelihood of condensation and precipitation. Second, it affects surface roughness and albedo, controlling how energy is exchanged between the surface and the atmosphere (Das and Angadi, 2022). Third, vegetation regulates soil moisture retention, preventing excessive runoff and maintaining the local water balance (Olorunfemi *et al.,* 2020).

Mahmood *et al.,* (2010) observed that widespread deforestation and vegetation loss lead to significant changes in the spatial distribution of latent and sensible heat fluxes, which in turn affect the movement of moisture and the positioning of rainfall zones. The decline in vegetation therefore contributes to irregular rainfall intensity, shorter rainy seasons, and prolonged dry spells. In urban settings such as Abuja, where vegetation clearance for construction has intensified since 2015, these processes may result in reduced evapotranspiration and the weakening of moisture recycling, ultimately leading to reduced rainfall efficiency and increased surface temperature.

Furthermore, studies on hydrological–climate coupling suggest that vegetation influences the vertical structure of the boundary layer by controlling the flux of water vapour and heat into the atmosphere (Verburg *et al.,* 2011). The reduction of vegetation cover lowers latent heat flux and increases sensible heat, leading to drier atmospheric conditions that suppress convection and precipitation. Conversely, the restoration of vegetation enhances cloud formation by increasing atmospheric humidity. This theoretical model therefore provides an essential foundation for understanding how vegetation decline in Abuja might influence the city’s hydrological balance and rainfall dynamics over time.

2.3.3 Systems Theory in Environmental Change Analysis

Systems Theory provides an integrative framework for understanding how environmental components interact to maintain equilibrium. It views the urban environment as a system composed of interdependent elements land cover, climate, vegetation, water, and human activities that continuously exchange energy and matter (Verburg *et al.,* 2011). Any disturbance to one component triggers a cascade of feedbacks that affect the entire system. In the context of urban vegetation and rainfall, the theory explains how changes in land use and land cover (LULC) can set off a series of biophysical responses that alter local climatic conditions.

According to Rawat and Kumar (2015), the transformation of land surfaces through urbanization modifies critical environmental processes such as energy balance, evapotranspiration, and runoff. Systems Theory highlights that these alterations are not isolated events but part of a dynamic feedback loop involving natural and human subsystems. For example, the removal of vegetation increases land surface temperature, which affects atmospheric moisture and rainfall. Reduced rainfall then further limits vegetation regeneration, reinforcing a feedback cycle of ecological degradation and climatic stress.

Mahmood *et al.,* (2010) emphasized that understanding such feedbacks is crucial for assessing how land system changes influence hydrological and atmospheric processes. Systems Theory thus enables the current study to analyze the interactions between spatial vegetation patterns, rainfall variability, and urban growth in Abuja as interconnected phenomena rather than separate occurrences. By applying this framework, the study can interpret how local vegetation decline influences atmospheric processes and how these processes, in turn, impact land cover through drought or moisture deficit.

This theory is particularly relevant for spatiotemporal studies because it supports the integration of both spatial (location-based) and temporal (time-based) data to examine dynamic environmental systems. It also reinforces the need for continuous monitoring through remote sensing and GIS tools, which can capture the multi-dimensional changes in vegetation and rainfall patterns over time (Das and Angadi, 2022).

2.3.4 Integration of Theoretical Perspectives

The combination of these theories forms a holistic conceptual base for this research. The Urban Climate Theory explains how vegetation loss modifies the physical and thermal characteristics of the urban environment. The Hydrological Cycle Model describes how vegetation regulates the transfer of water and energy between the surface and the atmosphere, affecting rainfall formation. The Systems Theory provides a broader understanding of how these processes interact as components of a dynamic environmental system.

Together, they allow the study to interpret the spatial and temporal relationships between vegetation decline and rainfall distribution in Abuja. Through the integration of these theoretical perspectives, the research is able to evaluate the extent to which urbanization-driven vegetation loss from 2015 to 2024 has influenced microclimatic conditions and local rainfall variability. These theories also provide the rationale for using remote sensing and GIS as analytical tools, since they enable the visualization and quantification of interconnected processes occurring across space and time.

2.4 Empirical Review

Empirical evidence provides the foundation for understanding how urban vegetation decline affects local rainfall patterns, especially within a growing city like Abuja. Many studies around the world, and within Nigeria, have investigated the relationship between vegetation cover, urban growth, and changes in climate elements such as rainfall, humidity, and temperature. This section reviews existing studies and findings that connect these variables and outlines how geographic information system (GIS) and remote sensing tools have been applied to track such changes over time.

2.4.1 Urban Vegetation Dynamics

Vegetation within urban areas plays a major role in balancing the environment by cooling the air, improving air quality, and promoting rainfall through evapotranspiration. However, rapid population growth and urban expansion have caused massive transformation of natural landscapes into built-up surfaces such as roads, buildings, and parking areas. These changes reduce the amount of green space and disturb the natural processes that keep urban areas cool and humid.

Globally, researchers such as Wei *et al.,* (2015) and Rawat and Kumar (2015) have shown that changes in land use and land cover (LULC) strongly affect ecosystems and local climates. According to Olorunfemi *et al.,* (2020), human activities such as construction, agriculture, and industrialization are major forces behind vegetation loss. The authors explained that as vegetation disappears, biodiversity, soil fertility, and atmospheric quality decline, leading to wider environmental challenges such as flooding and irregular rainfall.

Das and Angadi (2022) further demonstrated through satellite imagery that natural forests and woodlands in parts of southwestern Nigeria have shrunk drastically over four decades. Their study revealed that forest areas decreased by more than 50 percent, while built-up zones grew by over 260 percent. This expansion was directly linked to increasing population and demand for land. The reduction in green cover also led to higher land surface temperature (LST), showing that vegetation loss contributes to heating of the ground surface.

Similar results were found by Oyinloye *et al.,* (2023) in Akure, Nigeria. Using Landsat data from 1984 to 2022, they observed that dense vegetation dropped from 38 percent to less than 1 percent due to construction of buildings, roads, and other infrastructure. This change replaced natural green surfaces with concrete, causing reduced shade, increased heat, and the disappearance of habitats for plants and animals. The study warned that if such patterns continue, urban ecosystems could lose their natural ability to regulate temperature and rainfall.

At a global level, Pal and Akoma (2009) and Dewan and Corner (2012) reported that the replacement of vegetation with impermeable surfaces such as asphalt and rooftops increases heat retention and lowers evapotranspiration. This creates what is called the “urban heat island effect,” where city centers become significantly warmer than surrounding rural areas. The continuous expansion of hard surfaces limits the natural cooling effect provided by vegetation and alters the balance of heat and moisture in the lower atmosphere.

In summary, the decline of urban vegetation is not only a visual change but also an environmental concern. As cities expand, trees and other forms of vegetation are often removed without replacement. This process disrupts the natural exchange of moisture and heat, reduces shade and humidity, and leads to an increase in temperature. These changes can have far-reaching effects on local rainfall patterns, which makes it necessary to study how vegetation loss within Abuja influences rainfall between 2015 and 2024.

2.4.2 Vegetation and Rainfall Interactions

The relationship between vegetation and rainfall has been studied for many years, and there is strong evidence that vegetation helps to regulate rainfall through both physical and biological processes. Vegetation contributes to rainfall mainly through evapotranspiration the release of moisture from leaves into the atmosphere which increases humidity and supports cloud formation. Mahmood *et al.,* (2010) emphasized that when vegetation cover decreases, less water is released into the air, reducing the likelihood of cloud condensation and rainfall formation.

In forested and vegetated regions, rainfall is often more consistent because vegetation retains moisture and recycles it into the atmosphere. Studies by Shepherd (2006) and Niyogi *et al.,* (2006) found that vegetated surfaces cool the surrounding air, promote upward air movement, and create favourable conditions for convection and rainfall. On the other hand, when vegetation is replaced with concrete or asphalt, the reduced evapotranspiration limits moisture availability and can cause local drying or irregular rainfall distribution.

According to Wilson *et al.,* (2003), vegetation loss also influences the surface energy balance by decreasing latent heat flux and increasing sensible heat flux. This means that less energy is used for evaporation and more energy heats the air directly, resulting in drier conditions and reduced rainfall potential. Mahmood *et al.,* (2010) reported that in some urban areas, heat islands may lead to increased rainfall downwind of the city because of rising convection, but such effects depend on the scale and pattern of vegetation loss.

In Nigeria, and Oyinloye *et al.,* (2023) noted that vegetation decline in major cities such as Lagos, Ibadan, and Akure has altered local rainfall behaviour. These studies showed that as green cover reduced, there was a tendency for delayed rainfall onset and more unpredictable rainfall patterns. The situation is likely similar in Abuja, where rapid construction has converted green areas into residential and commercial districts. Such changes reduce surface moisture and modify airflow, potentially weakening rainfall intensity in parts of the city.

Therefore, vegetation is not only a source of shade and beauty but also a major player in the natural hydrological cycle. It acts as a bridge between the land and the atmosphere, controlling how water moves and returns as rainfall. A continuous loss of vegetation disrupts this connection, leading to less reliable rainfall and possibly increasing the risk of drought or erratic wet seasons.

2.4.3 Spatiotemporal Analysis in Environmental Studies

Spatiotemporal analysis refers to the examination of how environmental conditions change over both space and time. This method allows researchers to observe trends in vegetation and rainfall patterns and to identify areas that have experienced the most significant transformation. Remote sensing and GIS are the main tools used in this type of analysis because they can collect data from satellites across long periods.

Das and Angadi (2022) explained that using Landsat images from the United States Geological Survey (USGS) makes it possible to map and measure land-use and land-cover change accurately. In their research, Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) images were used to monitor changes over several decades. Through this process, vegetation decline and surface temperature rise were identified, revealing the direct link between land-cover transformation and environmental change.

One of the most important tools for vegetation measurement is the Normalized Difference Vegetation Index (NDVI). According to Higginbottom and Symeonakis (2014), NDVI provides a numerical value that indicates vegetation density and health. Higher NDVI values represent healthy vegetation, while lower values suggest sparse or degraded vegetation. The index is calculated using near-infrared and red spectral bands from satellite images. Many studies, such as Olorunfemi *et al.* (2020), have successfully used NDVI to monitor vegetation trends and identify areas of forest loss.

In addition, the combination of NDVI with Land Surface Temperature (LST) is a common practice in spatiotemporal analysis. A negative correlation between NDVI and LST has been observed in several studies, meaning that as vegetation decreases, surface temperature increases (Das and Angadi 2022). This relationship is significant for climate studies because higher surface temperatures influence the amount of moisture that can be stored or released, which in turn affects rainfall.

To understand rainfall patterns, datasets such as the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) and Tropical Rainfall Measuring Mission (TRMM) are often used. These datasets provide consistent rainfall information across large areas and are useful for linking rainfall variability with vegetation change. Through GIS software such as ArcGIS and TerrSet, these data can be overlaid to examine how vegetation decline corresponds with rainfall fluctuations across time.

Change detection techniques, including post-classification comparison, NDVI differencing, and trend analysis, help to quantify how much vegetation and rainfall have changed over specific time intervals (Verburg *et al.,* 2011). These tools make it possible to detect not only where changes occur but also their direction and magnitude. The integration of such data provides a reliable foundation for assessing environmental changes in Abuja over the twenty-year study period.

2.4.4 Studies on Urbanization and Climate Patterns in Nigeria

Urbanization has transformed many Nigerian cities, and its impact on vegetation and rainfall has been widely reported. In Lagos, Abiodun *et al.,* (2017) observed that continuous expansion of residential and industrial zones reduced vegetation density and contributed to irregular rainfall distribution. They explained that high heat generation from dense built-up areas increased atmospheric instability, which caused intense but short rainfall events. In Ibadan, Ogundele *et al.,* (2018) found that as green spaces diminished, the city experienced more heat buildup and reduced moisture retention, resulting in a noticeable decrease in rainfall consistency.

In Ekiti State, Das and Angadi (2022) documented that forest and woodland areas decreased by more than half between 1980 and 2020, while urban areas grew by over 260 percent. Their findings also showed a negative correlation between NDVI and LST, confirming that vegetation loss contributed to higher temperatures. The implications were clear deforestation and reduced vegetation cover were linked to environmental stress and possible shifts in local climate.

Similarly, Oyinloye *et al.,* (2023) reported that in Akure, dense vegetation dropped dramatically within four decades, replaced largely by built structures. The decline of green areas led to higher surface temperatures and increased the likelihood of heat waves and air pollution. These factors collectively influence local convection and may alter rainfall patterns over time.

For Abuja, available studies indicate a rapid decline in vegetation since the early 2000s due to housing development, road construction, and population increase (Folorunsho *et al.* 2017). The Federal Capital Territory was originally designed to incorporate large green spaces and forest reserves, but many of these areas have been converted into residential or commercial plots. The consequence has been a steady rise in land surface temperature and altered micro-climatic conditions. However, there is still limited research that directly links vegetation loss in Abuja with rainfall changes over a long period. This gap makes it important to conduct a detailed spatiotemporal analysis covering 2015 to 2024 to understand how urban vegetation decline influences rainfall distribution and intensity

2.5 Remote Sensing and GIS Techniques in Environmental Change Detection

Remote sensing and Geographic Information Systems (GIS) have become essential tools in detecting, mapping, and analyzing environmental change, particularly in understanding vegetation decline and its climatic implications. The evolution of these technologies has provided researchers with the ability to observe, quantify, and interpret spatial and temporal variations in land cover, vegetation health, and rainfall distribution across large areas with improved accuracy and consistency (Verburg *et al.,* 2011). Through multi-temporal satellite imagery and spatial modeling, these tools allow researchers to identify changes in green cover and link them with environmental parameters such as rainfall intensity and distribution.

2.5.1 Evolution and Importance of Remote Sensing and GIS

Remote sensing involves the collection of information about the Earth's surface without direct contact, using sensors mounted on satellites or aircraft. It is widely recognized as the most common and cost-effective data source for land cover assessment and environmental change detection (Verburg *et al.,* 2011). GIS, on the other hand, provides a platform for integrating, analyzing, and visualizing spatial data, enabling the combination of multiple datasets to produce accurate maps and conduct spatial correlation analysis. Together, they form the backbone of modern environmental monitoring systems.

For environmental change studies, remote sensing allows the observation of vegetation trends over long timeframes using satellite data such as the Landsat series (TM, ETM+, OLI), MODIS, and Sentinel imagery (Das and Angadi, 2022). These data provide multi-spectral information for detecting vegetation health, soil moisture, and land surface temperature key factors influencing rainfall patterns. To ensure temporal consistency, pre-processing steps such as geometric and atmospheric corrections, mosaicking, and sub-setting are carried out to minimize data discrepancies (Hegazy and Kaloop, 2015; Das and Angadi, 2022).

2.5.2 Key Methods Used in Environmental Change Detection

Several analytical techniques are employed in remote sensing and GIS for detecting environmental change. Among the most significant are the Normalized Difference Vegetation Index (NDVI), supervised and unsupervised image classification, spatial overlay analysis, and time-series trend analysis.

- **NDVI Analysis:**
  NDVI is the most commonly used vegetation index for monitoring vegetation globally, owing to its strong correlation with plant health and density (Al-Doski *et al.,* 2013; Higginbottom and Symeonakis, 2014). It measures the difference between the reflectance of near-infrared and red light from vegetation surfaces, calculated as NDVI = (NIR − Red)/(NIR + Red) (Rouse *et al.,* 1974). NDVI values range between −1 and +1, where higher values indicate dense and healthy vegetation, while lower values represent degraded or non-vegetated surfaces (Das and Angadi, 2022). In urban environmental

studies, NDVI helps to distinguish vegetated from built-up areas and to monitor vegetation changes across time and space (Olorunfemi *et al.,* 2020).

- **Supervised and Unsupervised Classification:**

  Image classification converts raw satellite data into meaningful land cover classes. Supervised classification methods, particularly the Maximum Likelihood Algorithm (MLA), are widely used due to their statistical accuracy when reliable training samples are available (Shalaby and Tateishi, 2007; Lillesand and Kiefer, 2007). This approach enables researchers to categorize land cover into built-up areas, bare soil, vegetation, and water bodies. The classified maps are validated through accuracy assessment using ground truth points, high-resolution imagery, and confusion matrices, often with a Kappa coefficient test to quantify reliability (Minta *et al.,* 2018; Das and Angadi, 2022).

- **Spatial Overlay and Change Detection:**

  Change detection techniques identify and quantify differences in land cover across multiple time periods. The post-classification comparison and image differencing approaches are among the most widely applied, where classified maps from different years are compared pixel by pixel to determine areas of change (Macleod and Congalton, 1998; Verburg *et al.,* 2011). These analyses reveal the rate and extent of vegetation loss, urban expansion, or transformation of natural surfaces that may affect rainfall dynamics.

- **Time-Series Trend Analysis:**

  Time-series analysis is used to evaluate temporal consistency in datasets and to observe long-term trends. Researchers emphasize that consistent data sources and uniform processing techniques are crucial for identifying real environmental changes rather than sensor-related discrepancies (Verburg *et al.,* 2011). Long-term NDVI and rainfall datasets such as CHIRPS and CMAP can be analyzed to assess correlations between vegetation decline and rainfall variability (Avia, 2019).

2.5.3 Applications of Remote Sensing and GIS in Vegetation-Rainfall Studies

Remote sensing and GIS have been successfully applied in studies that link vegetation dynamics with local and regional climate variations. For instance, Oyinloye *et al.,* (2023) used multi-temporal Landsat imagery and supervised maximum likelihood classification to assess the depletion of urban green spaces in Akure, Nigeria, from 1984 to 2022. Their findings revealed significant vegetation loss due to urban expansion, with implications for local microclimate and hydrological conditions. Similarly, Mahmood *et al.,* (2010) highlighted the usefulness of NDVI and other satellite-based indices in monitoring land use and land cover change impacts on rainfall and climate systems.

Advanced geospatial modeling tools such as the Land Change Modeler (LCM) within the TerrSet Geospatial System enable detection of land cover transitions and prediction of future patterns (Das and Angadi, 2022). The integration of satellite imagery with rainfall datasets in a GIS environment allows for correlation analysis between vegetation indices and precipitation records, providing insights into how vegetation decline influences rainfall intensity, distribution, and seasonality.

2.5.4 Significance for the Present Study

For the present study in Abuja, the combined application of remote sensing and GIS offers a scientific basis for analyzing how urban vegetation decline between 2015 and 2024 has influenced local rainfall behavior. Landsat data (TM, ETM+, OLI) will be utilized to assess vegetation change using NDVI and supervised classification methods, while rainfall data from CHIRPS and other sources will be examined for temporal and spatial patterns. This integration will enable a comprehensive spatiotemporal assessment of environmental change, forming a robust foundation for understanding the vegetation-rainfall relationship in Abuja.

2.6 Research Gaps

Although a considerable number of studies have examined land use and climate interactions in Nigeria, important research gaps remain in understanding how the decline of urban vegetation affects rainfall variability within Abuja. These gaps exist in temporal scope, methodological integration, spatial focus, and empirical linkage between vegetation cover and local climatic response. Addressing these gaps is vital for a comprehensive understanding of Abuja's changing urban environment between 2015 and 2024.

One major limitation of previous studies is their restricted temporal coverage. Many earlier investigations such as those by Ologunorisa and Tersoo (2010), Sawa and Adebayo (2011), and Ekpoh and Nsa (2011) relied on data spanning less than three decades, often ending before 2010. These studies focused largely on short-term rainfall variability and general climatic trends in northern Nigeria, neglecting more recent urban transformations in Abuja. Consequently, there is limited understanding of how vegetation decline during the rapid expansion of the Federal Capital Territory in the last two decades has influenced local rainfall distribution.

A second gap concerns the lack of integrative analysis linking vegetation dynamics directly with rainfall behaviour. While research by Oyinloye *et al.,* (2023) and Oyeniyi *et al.,* (2025) quantified changes in green spaces and built-up areas using Landsat and NDVI data, they focused mainly on surface temperature and heat island effects rather than on rainfall modification. Similarly, rainfall trend studies by Nzoiwu *et al.*, (2017) and Ekwueme *et al.* (2024) examined precipitation variability and change points but did not consider land cover transformation as an explanatory factor. Thus, empirical evidence combining vegetation indices and rainfall datasets to evaluate their spatial and temporal interactions within Abuja remains insufficient.

Another limitation lies in the geographical bias of past research. Many Nigerian urban studies have concentrated on coastal or southwestern cities such as Lagos, Ibadan, and Akure (Oyinloye *et al.,* 2023; Jafar *et al.,* 2025). Abuja, despite being a rapidly expanding planned city with unique topography and ecological conditions, has received relatively little attention. Most references to Abuja in regional studies are incidental, focusing on urban planning or infrastructure (Appiah-Opoku *et al.,* 2023), rather than on its environmental and climatological evolution. This absence of localized evidence leaves a contextual gap in understanding how vegetation loss in Abuja influences its microclimate and rainfall regime.

Methodologically, data inconsistency and limited technological integration are major shortcomings in existing literature. Earlier works often depended on coarse resolution imagery or single-source rainfall data, reducing the accuracy of trend interpretation (Verburg *et al.,* 2011; Mahmood *et al.,* 2010). Few studies have combined remote sensing datasets such as MODIS or Landsat with rainfall products like CHIRPS to assess vegetation–rainfall linkages over long temporal scales. The lack of such integrative spatiotemporal analysis makes it difficult to capture the dynamic feedbacks between vegetation decline, surface heating, and convective rainfall formation.

Finally, there exists a conceptual gap regarding the understanding of local hydrological and atmospheric feedbacks in urban ecosystems. Theoretical explanations such as Charney's model (as discussed in Ekpoh and Nsa, 2011) establish a clear relationship between vegetation, albedo, and convection, yet these mechanisms have rarely been tested empirically in urban Nigerian contexts. The existing body of work tends to generalize findings from semi-arid or agricultural landscapes without accounting for the complex interactions of impervious surfaces, built structures, and fragmented vegetation typical of Abuja's urban core.

Therefore, this study seeks to fill these gaps by conducting a comprehensive spatiotemporal assessment of vegetation decline and rainfall variability in Abuja from 2015 to 2024. It will integrate satellite-derived vegetation indices (NDVI) with gridded rainfall datasets (such as CHIRPS) to establish both spatial and temporal relationships. By focusing specifically on Abuja, the study contributes localized empirical evidence to the broader understanding of how urbanization-driven vegetation loss influences rainfall variability in rapidly growing African cities. This integrative approach will not only advance theoretical understanding of vegetation climate interactions but also provide data-driven guidance for sustainable urban planning and environmental management in Nigeria.

2.7 Summary of Reviewed Literature

The reviewed literature provides a comprehensive understanding of how urban vegetation decline influences local rainfall patterns through complex spatiotemporal interactions between land use change, surface energy balance, and atmospheric dynamics. The studies collectively establish that urbanization-driven land cover modification is one of the most critical anthropogenic factors altering local and regional climates (Verburg *et al.,* 2011). The conversion of vegetated areas into impervious surfaces such as concrete, asphalt, and rooftops reduces evapotranspiration, increases land surface temperature, and disrupts the hydrological cycle, thereby modifying rainfall distribution and intensity (Jafar *et al.,* 2025).

Several empirical works demonstrate that the loss of urban green spaces results in the amplification of the urban heat island effect, which subsequently affects local convection processes responsible for rainfall formation (Piracha and Chaudhary, 2022; Appiah-Opoku *et al.,* 2023). Vegetation acts as a climate regulator through evapotranspiration, surface cooling, and atmospheric moisture recycling. When these processes are weakened due to vegetation depletion, it leads to increased surface heating and reduced atmospheric humidity, culminating in irregular rainfall patterns (Ekpoh and Nsa, 2011). Such alterations in local microclimate can further intensify extreme weather events such as floods or droughts (Nzoiwu *et al.,* 2017; Sawa and Adebayo, 2011).

The reviewed literature also highlights the methodological significance of spatiotemporal analysis using remote sensing and GIS tools for monitoring vegetation and rainfall variability. Techniques such as NDVI analysis, change detection, and rainfall trend modeling (using CHIRPS or TRMM datasets) have proven effective for identifying vegetation cover dynamics and their correlation with climatic variables (Avia, 2019). These methods enable researchers to quantify changes in vegetation indices and rainfall intensity over time, thus providing an empirical foundation for assessing environmental change in urban regions like Abuja (Ologunorisa and Tersoo, 2010).

Region-specific studies within Nigeria reveal consistent patterns of green space loss and rainfall irregularity in major cities such as Lagos, Akure, and Ibadan, attributed to weak urban planning, population growth, and inadequate enforcement of land-use regulations (Appiah-Opoku *et al.,* 2023). Abuja, although designed as a planned city, has also experienced rapid urban expansion and vegetation degradation that potentially influence its local rainfall regime (Appiah-Opoku *et al.,* 2023). This reinforces the need for localized assessments integrating both spatial and temporal datasets to understand the evolving interaction between vegetation dynamics and rainfall distribution.

Despite the wealth of global and national studies, a significant research gap remains concerning integrated analyses that link vegetation decline directly with rainfall variability in Abuja over extended periods. Most existing works have either examined vegetation changes without correlating them to rainfall variations or analyzed rainfall trends without attributing them to specific land-use drivers (Ekwueme *et al.,* 2024). Therefore, this study aims to fill this gap by conducting a two-decade spatiotemporal assessment (2015-2024) that integrates vegetation and rainfall data to determine the extent to which urban vegetation decline influences local rainfall patterns in Abuja.

In summary, the literature underscores that urban vegetation loss significantly contributes to local climatic changes by altering surface energy dynamics, atmospheric circulation, and moisture fluxes. It further establishes that spatiotemporal tools and datasets are indispensable for capturing these complex relationships. Hence, this research builds upon the reviewed theoretical and empirical foundations to analyze the spatial and temporal influence of vegetation decline on rainfall variability in Abuja. The insights from this review directly inform the methodological framework presented in the next chapter.

3 METHODOLOGY

3.1 Study Area Description

Abuja, the Federal Capital Territory (FCT) of Nigeria, is centrally located between latitudes 8°25′ and 9°25′ North and longitudes 6°45′ and 7°45′ East, covering about 8,000 km^2 and bordered by Kaduna, Nasarawa, Niger, and Kogi States (Jafar *et al.,* 2025). The area lies within the Guinea Savannah ecological zone, featuring a mix of grasses, shrubs, and scattered trees, and experiences a tropical wet and dry climate with annual rainfall ranging from 1,100 mm to 1,600 mm and mean temperatures between 18°C and 34°C (Nzoiwu *et al.,* 2017). The terrain is characterized by undulating hills, inselbergs, and valleys drained by the Usuma and Gurara rivers, which influence local microclimatic conditions (Abbas, 2009). Since its establishment as the national capital in 1991, Abuja has experienced rapid population growth and urban expansion that have transformed its natural vegetation into built-up areas (Oyinloye *et al.,* 2023). This vegetation depletion has altered surface characteristics, increased land surface temperature, and disrupted local hydrological balance, thereby affecting rainfall distribution across the city (Das and Angadi, 2022). The study therefore focuses on Abuja as an ideal location for understanding how urban vegetation decline influences local rainfall patterns over the past 20 years.

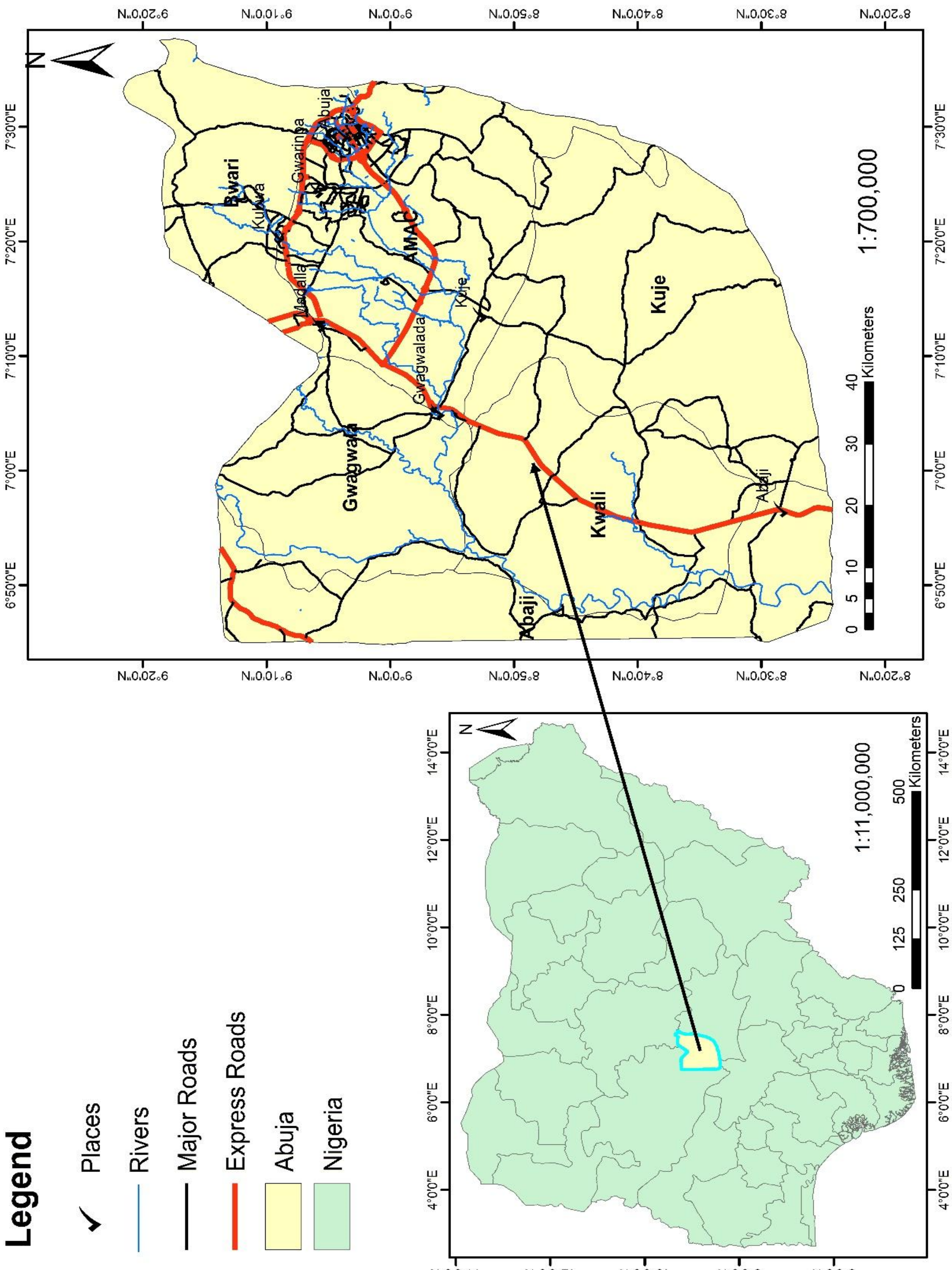

Figure 3.1: Study Area (Map of Abuja, Nigeria)

3.2 Research Data

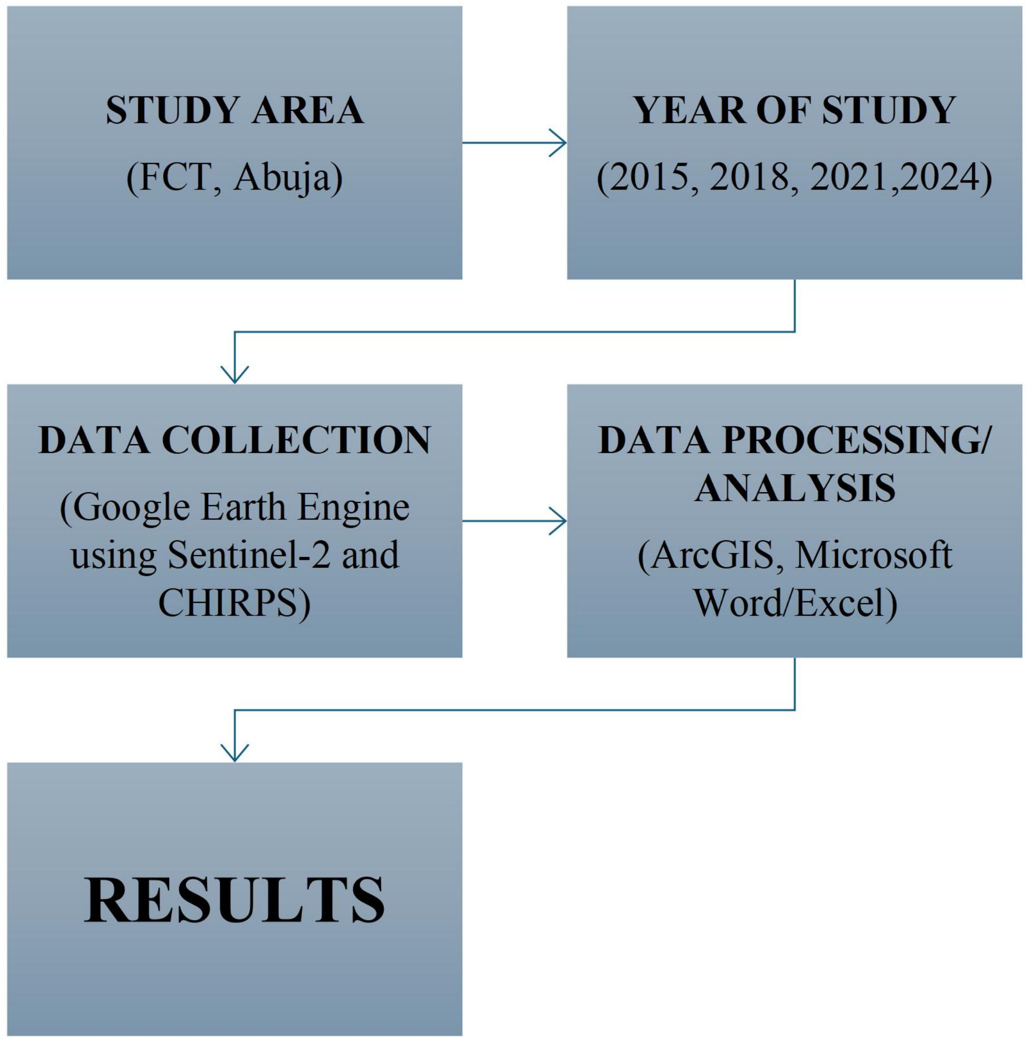

Figure 3.2: Flowchart of Resarch Design Process.

3.3 Data Types and Sources

This research mainly employed raster datasets, which depict spatially continuous variables organized in the form of grid cells or pixels. Each pixel in a raster dataset represents a distinct geographic coordinate and carries specific attribute information such as vegetation cover or rainfall intensity. This structure allows for detailed spatial analysis and visualization of environmental patterns across the study area. The key datasets used in this study include:

- **Sentinel-2**

  Sentinel-2 (S-2) is a polar-orbiting optical satellite mission designed for land and coastal monitoring, agriculture, forestry, and disaster management, offering enhanced spectral and spatial capabilities compared to previous missions like Landsat and SPOT [7]. It consists of two satellites, Sentinel-2A (launched June 23, 2015) and Sentinel-2B (launched March 7, 2017), both carrying the Multi-Spectral Instrument (MSI) that measures reflected radiance across 13 spectral bands from visible to shortwave infrared (VNIR to SWIR) [8]. The mission provides global coverage every five days and supports applications such as vegetation analysis, land-use mapping, and water monitoring. The Sen2Cor processor, developed by Telespazio VEGA, performs atmospheric correction to generate Level-2A Bottom-of-Atmosphere (BOA) reflectance products, enabling accurate quantitative land studies (Main-Knorn *et al.*, 2017).

- **CHIRPS (Climate Hazards Group Infrared Precipitation with Station Data)**

  CHIRPS is a high-resolution (0.05°) land-only rainfall dataset developed in 2014 by combining global climatologies, satellite infrared data, atmospheric model outputs, and ground station observations (Funk *et al.*, 2013). It improves upon earlier precipitation datasets, most of which have coarser resolutions (0.25°–0.5°), and is widely used for monitoring rainfall variability and drought, especially in Africa (Tapiador *et al.*, 2012; Huffman *et al.*, 2007). Studies have applied CHIRPS data to evaluate soil moisture forecasts (Shukla *et al.*, 2014) and analyze population vulnerability to climate change (López-Carr *et al.*, 2014), demonstrating its reliability for hydrological and climate assessments.

All satellite images were collected using Google Earth Engine (GEE), a powerful cloud-based geospatial analysis platform developed by Google. It allows researchers, environmental scientists, and decision-makers to analyse, visualise, and monitor large-scale environmental data using satellite imagery and geospatial datasets. For this study Google Earth Engine (GEE) was used alongside Sentinel-2 and CHIRPS (Climate Hazards Group Infrared Precipitation with Station Data) for data collection.

3.4 Data Collection Method

All data was collected on Google Earth Engine (GEE) code editor, using cloud-based scripts. The steps are as follows:

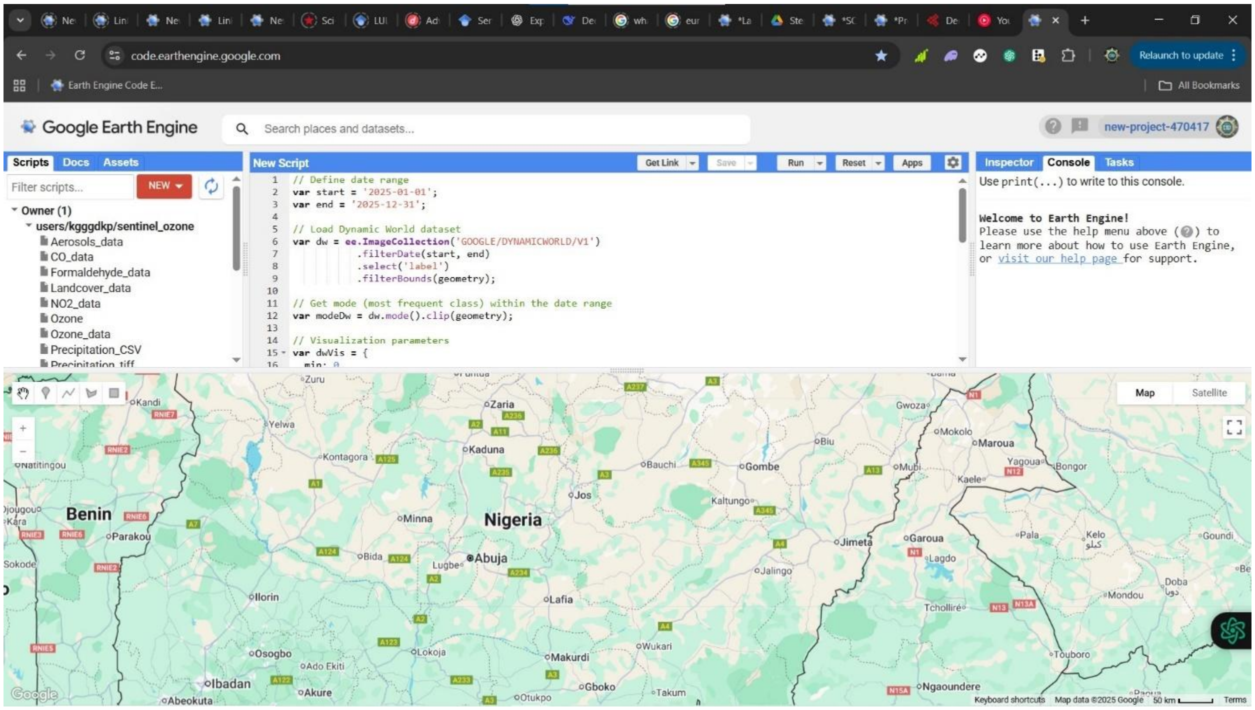

Plate 3.1: Google Earth Engine Interface

The respective codes for land cover and rainfall was impoerted into the page, the polygon feauture was selected and a rectangular boundry was drawn over the area of interest. The data was taken and exported as GeoTIFF data for each year (2005, 2010, 2015, 2020, 2025).

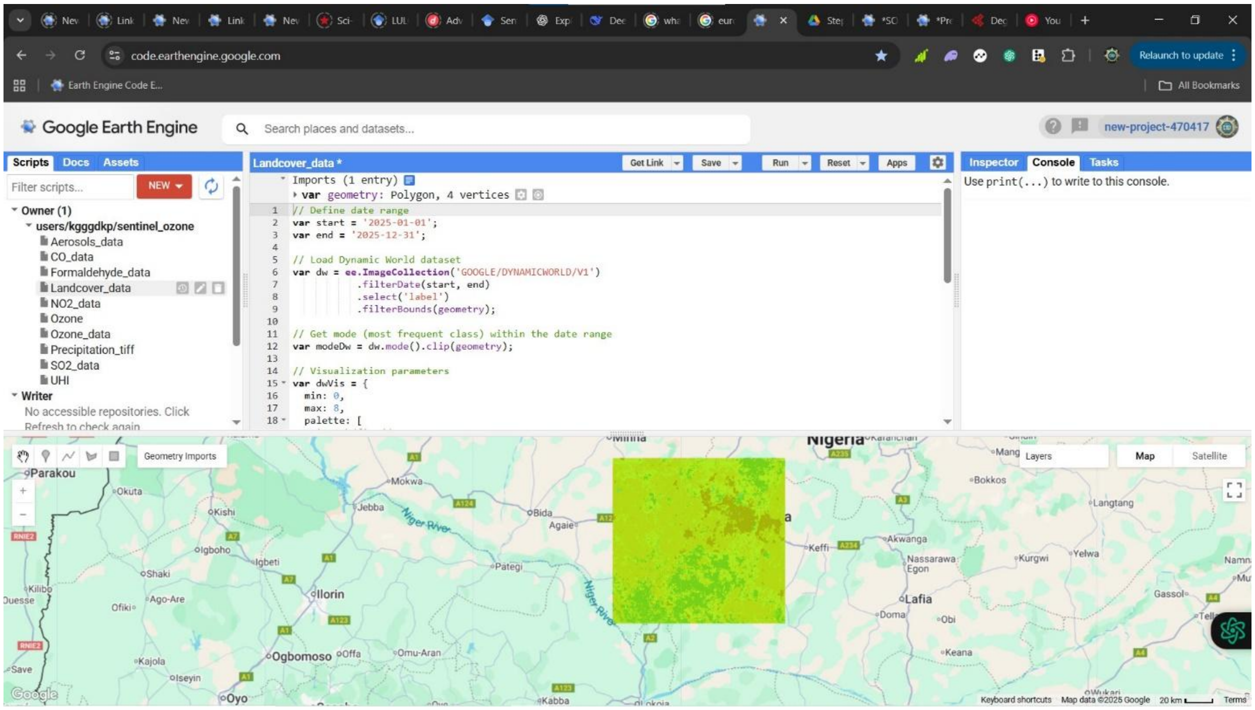

Plate 3.2: Data collection process of LULC data

The exported data was downloaded and imported into ArcGIS for further processing.

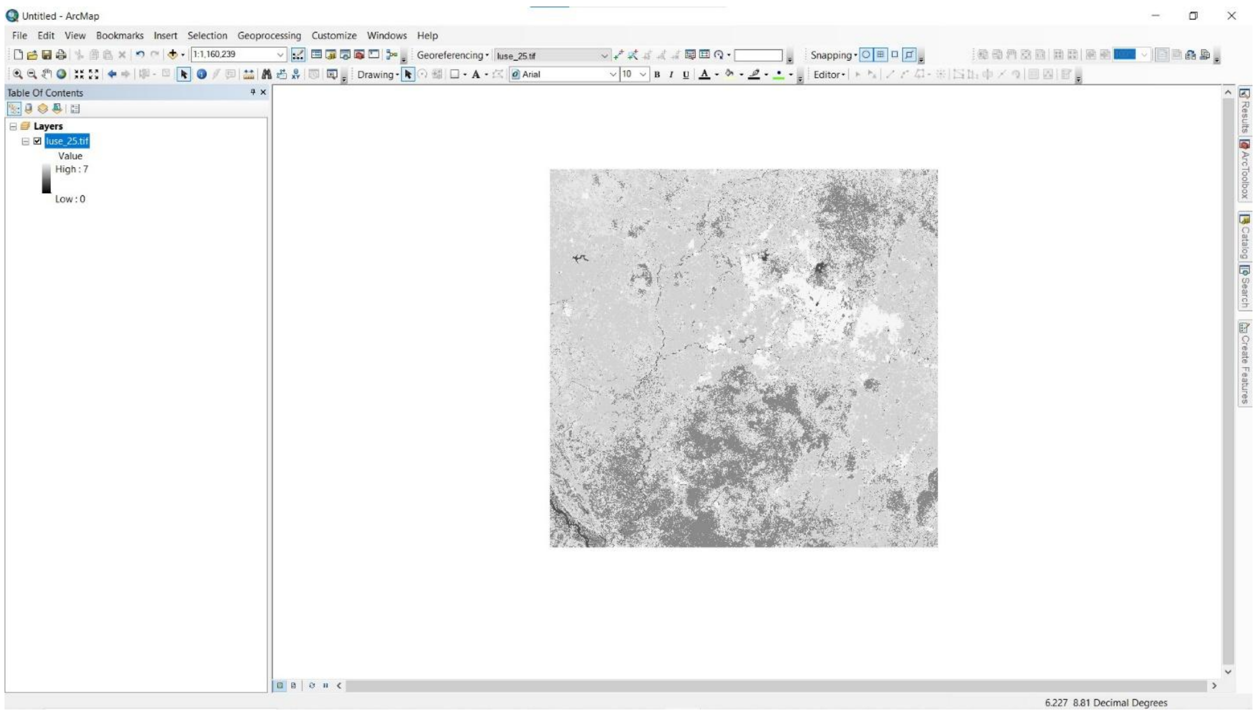

Plate 3.3: Downloaded Raster Image from Google Earth Engine on ArcGIS Interface

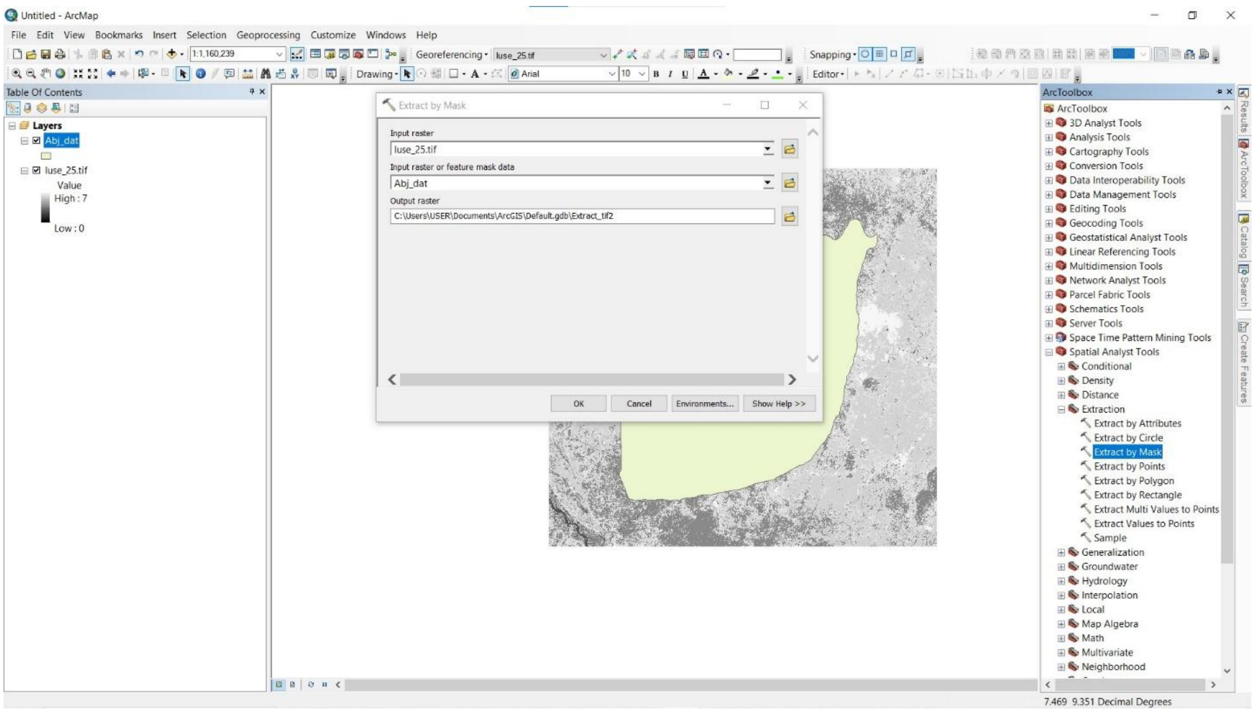

Plate 3.4: Extraction of Image by Mask to get Desired Study Area

3.5 Land Use, Land Cover and Rainfall Intensity Classification

3.5.1 Detailed Description of Land Use and Land Cover Categories

1. Water

This includes all types of water bodies such as rivers, lakes, streams, and ponds. These areas are made up mostly of water and have little or no plants growing on them. They are important because they help support human needs, wildlife, and keep the environment balanced.

2. Trees

This class covers areas with tall woody plants, like forests and tree plantations. Trees help clean the air, store carbon, and keep the surroundings cool. They also serve as homes for many animals and protect the soil from erosion.

3. Grasses

These are areas covered mainly by short green plants without thick stems, such as grasslands and open fields. Grass-covered areas are often used for grazing animals and are important for keeping the soil healthy and reducing erosion.

4. Flooded Vegetation

This includes plants that grow in or around waterlogged areas, such as swamps and wetlands. The ground here is often wet or flooded for long periods. These places help control floods, clean water naturally, and provide homes for fish, birds, and other animals.

5. Crops

This class shows farmlands where people grow food or cash crops like maize, rice, or vegetables. These areas change with the farming season they look greener during planting and harvesting times. Cropland is important for food production but often replaces natural vegetation.

6. Shrub and Scrub

These areas are covered with small bushes, scattered plants, and some grasses. They are usually found in dry or less fertile places. Even though they don't have thick vegetation, shrubs help protect the soil and prevent erosion.

7. Built-Up Areas

This category includes places developed by humans, such as buildings, roads, and other structures. These areas are common in cities and towns. Built-up areas usually have little or no vegetation and can become hotter because of the many hard surfaces.

8. Bare Ground

This refers to land with little or no plant cover, such as open soil, sand, or rocky areas. Bare ground can occur naturally or because of human activities like construction or farming. These areas are easily affected by erosion and land degradation.

Figure 3.3: Land Use and Land Cover Map Legend

3.4.2 Classification and Range of Rainfall Intensity

Table 3.1: Classification and Range of Rainfall Intensity

Classification	**Range**
<1100	Very low
1100-1200	Low
1200-1300	Average
1300-1400	High
>1400	Very High

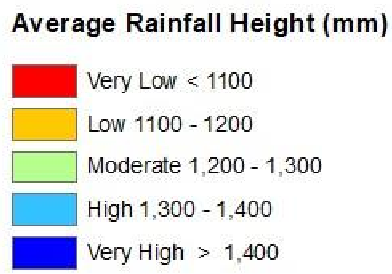

Figure 3.4: Rainfall Map Legend

4 RESULTS

This section presents the findings from the study on changes in green spaces and rainfall trends in Abuja between 2015 and 2024. The results are divided into four parts: changes in land cover, rainfall patterns, how both are related, and a summary of the major findings.

4.1 Land Cover Change Analysis (2015-2024)

4.1.1 Spatial and Quantitative Changes in Green Space

The land cover analysis shows that Abuja's landscape has changed a lot over the ten-year period. The most noticeable change is the sharp decline in vegetation, especially tree cover, while built-up and agricultural areas increased greatly.

In 2015, tree cover was the dominant land cover type, covering 5,278.32 hectares (71.81%) of the total area. By 2018, it had reduced to 3,558.45 hectares (48.41%), and by 2024, it dropped further to just 1,743 hectares (23.71%). This means that Abuja lost over 3,500 hectares of trees within ten years a very large reduction.

Grasslands also declined from 20.51 hectares (0.28%) in 2015 to 5.73 hectares (0.08%) in 2024. On the other hand, cropland increased sharply from 433.18 hectares (5.89%) in 2015 to 2,637.30 hectares (35.88%) in 2024. This shows that farming and land conversion activities expanded quickly during this period.

Shrubs and scrub areas also grew from 1,072.86 hectares (14.60%) to 2,206 hectares (30.01%), while built-up areas (settlements, roads, and infrastructure) increased from 492.63 hectares

(6.70%) to 691.76 hectares (9.41%). These changes clearly reflect the growing human population, city expansion, and land conversion for housing and agriculture.

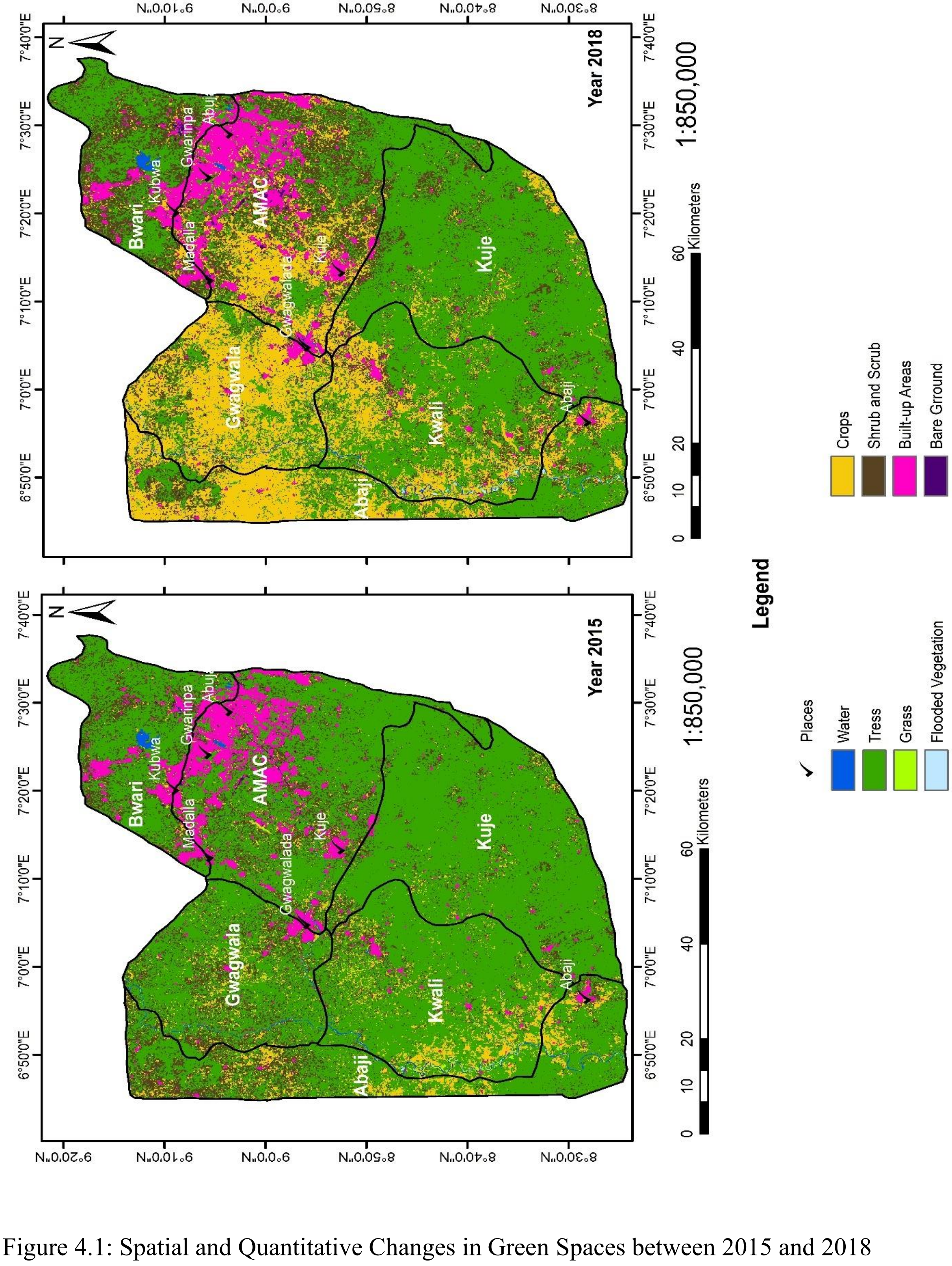

Figure 4.1: Spatial and Quantitative Changes in Green Spaces between 2015 and 2018

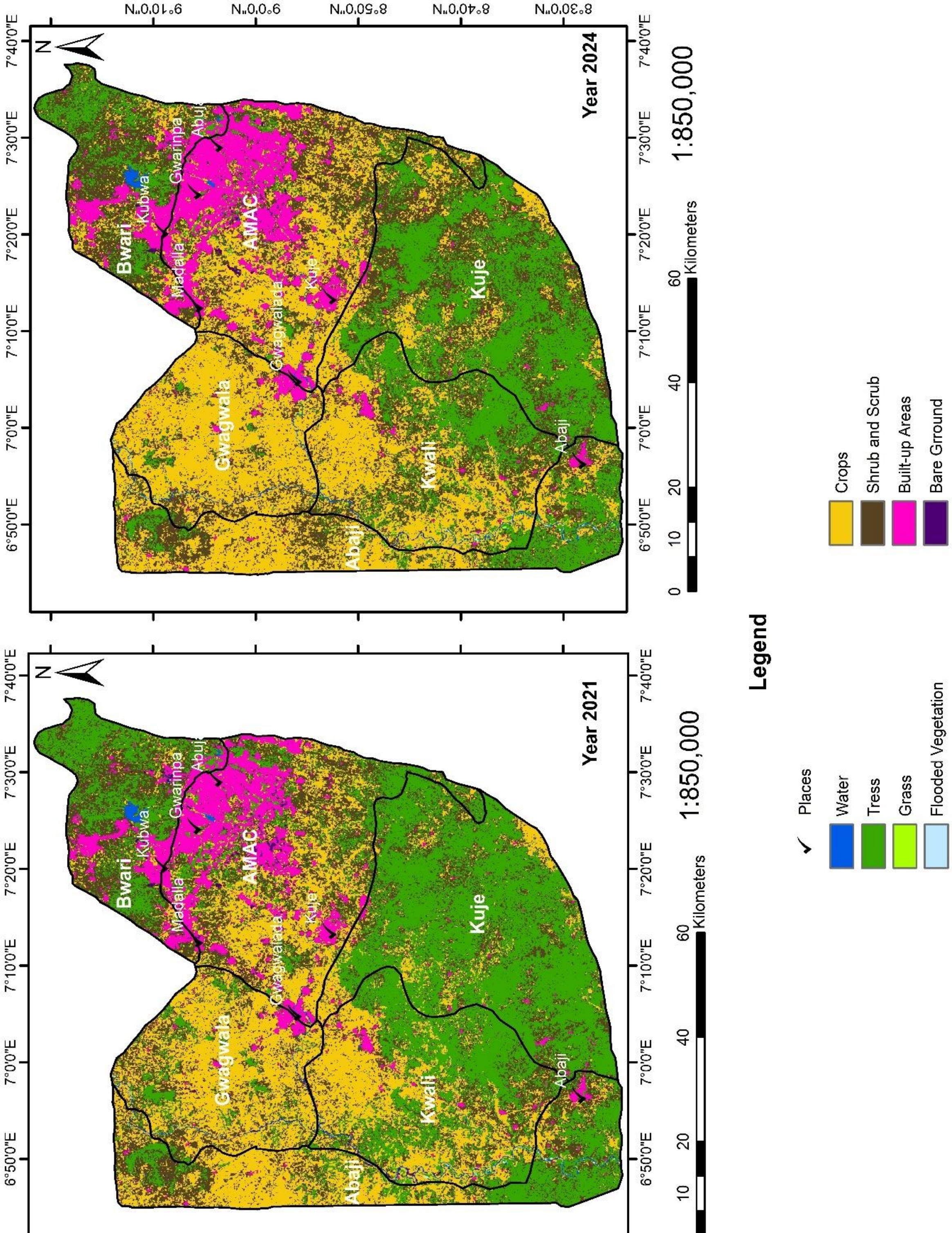

Figure 4.2: Spatial and Quantitative Changes in Green Spaces between 2021 and 2024

Table 4.1: Land Cover Changes in Abuja (2015-2024)

Year	Water (ha)	Trees (ha)	Grasses (ha)	Flooded Vegetation (ha)	Crops (ha)	Shrubs/Scrub (ha)	Built-up (ha)	Bare Ground (ha)
2015	40.45	5,278.32	20.51	2.13	433.18	1,072.86	492.63	10.54
2018	40.53	3,558.45	0.66	6.42	1,862.74	1,333.41	521.66	26.72
2021	42.79	2,612.75	0.69	2.93	2,181.32	1,864.06	606.32	39.62
2024	44.84	1,743.00	5.73	3.39	2,637.30	2,206.00	691.76	18.43

Table 4.2: Percentage Change of Land Cover in Abuja (2015-2024)

Year	Water (%)	Trees (%)	Grasses (%)	Flooded Vegetation (%)	Crops (%)	Shrubs/Scrub (%)	Built-up (%)	Bare Ground (%)
2015	0.55	71.81	0.28	0.03	5.89	14.60	6.70	0.14
2018	0.55	48.41	0.01	0.09	25.34	18.14	7.10	0.36
2021	0.58	35.55	0.01	0.04	29.68	25.36	8.25	0.54
2024	0.61	23.71	0.08	0.05	35.88	30.01	9.41	0.25

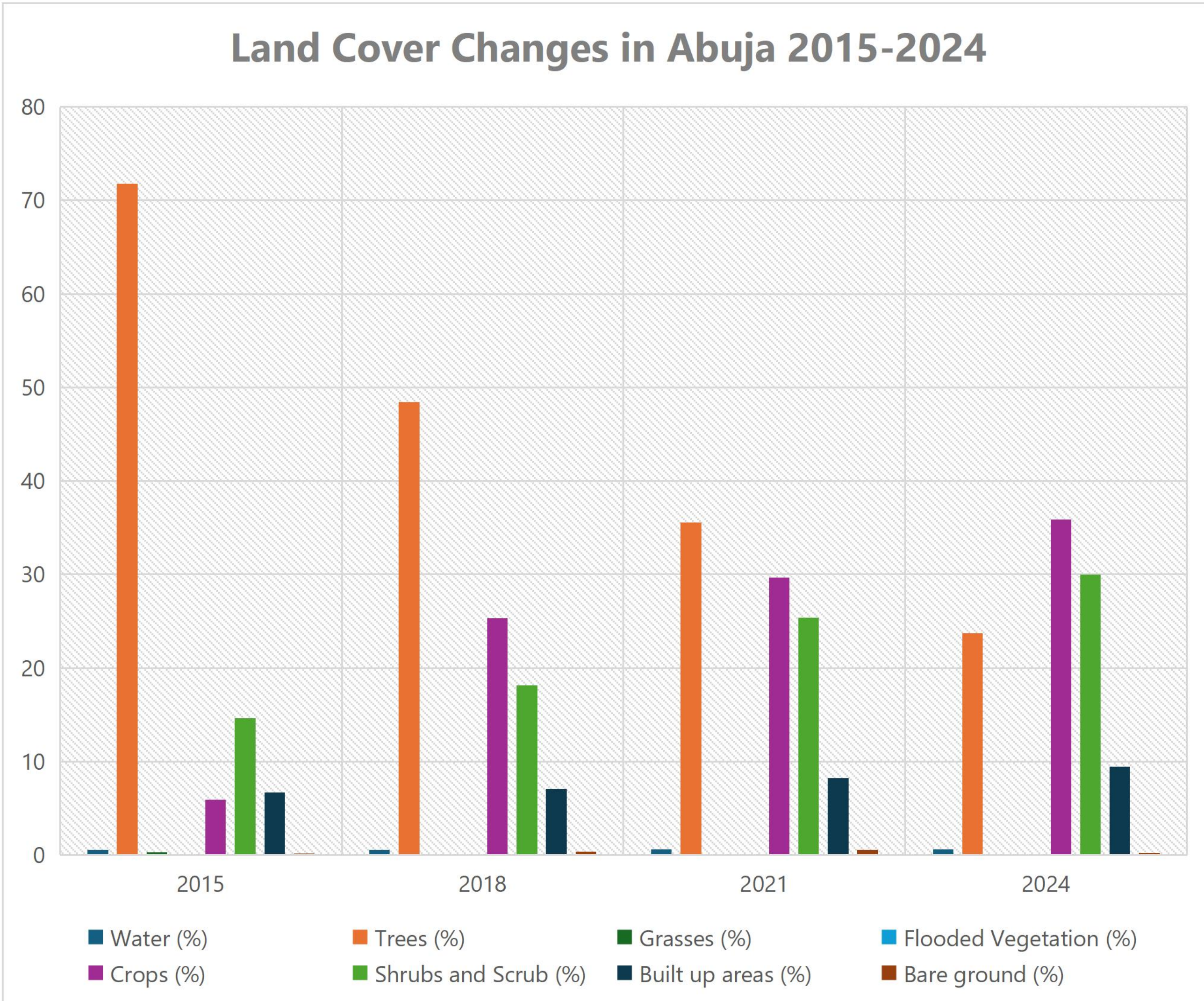

Figure 4.3: Bar Chart Showing Percentage Change Land Cover Categories in Abuja (2015-2024)

The mean and standard deviation values in Table 4.1.3 show that land cover types have become more mixed and varied over time. The mean rose from 2.15 in 2015 to 3.76 in 2024, which indicates that Abuja's landscape is becoming more complex due to continuous human activity.

Table 4.3: Mean and Standard Deviation of Land Cover (2015-2024)

Year	Mean	Standard Deviation
2015	2.153	1.863
2018	2.883	1.913
2021	3.363	1.869
2024	3.763	1.696

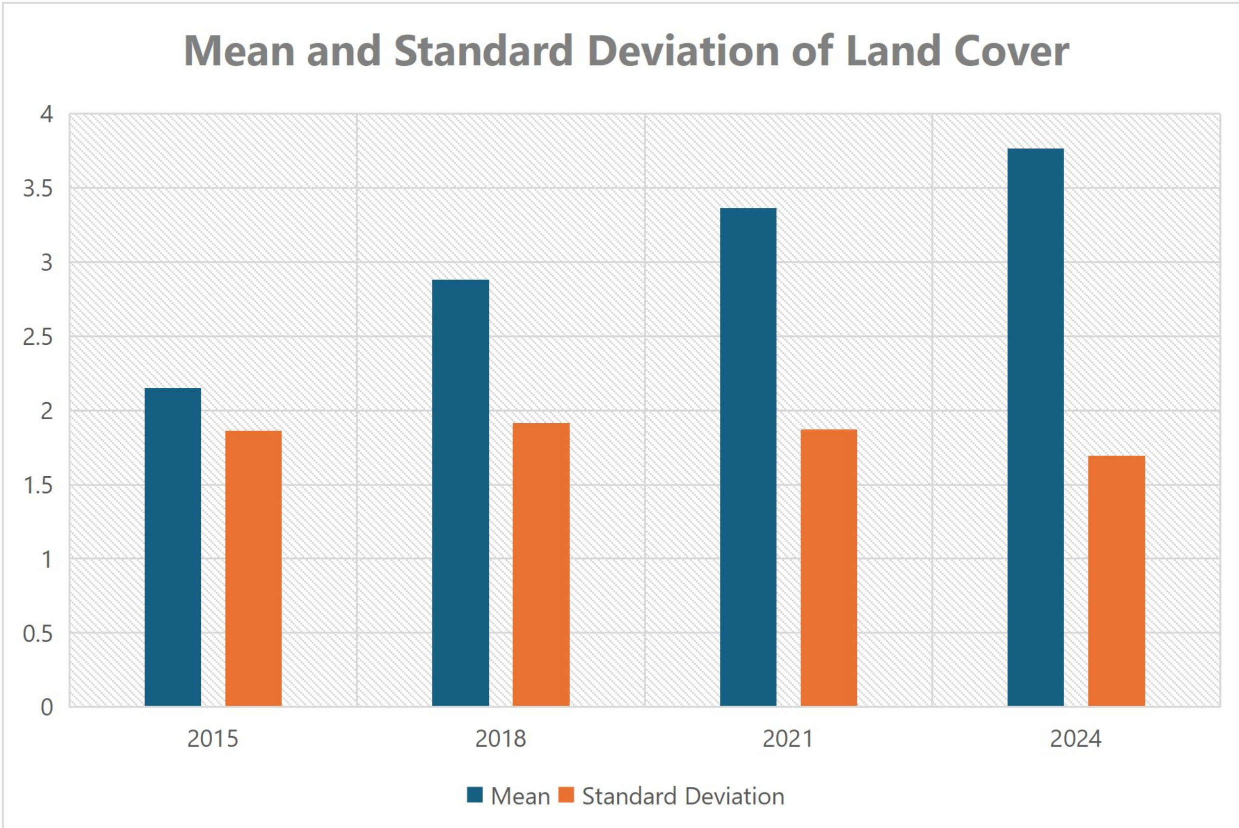

Figure 4.4: Bar Chart Showing Mean and Standard Deviation of Land Cover Types in Abuja Between 2015 and 2024

4.1.2 Spatial Distribution of Vegetation Change

From the spatial maps, most of the tree and grass loss occurred in the central and northern districts of Abuja areas like Garki, Wuse, Maitama, and Bwari. The southern and outer parts of the city, such as Kwali and Abaji, still have relatively more vegetation and farmlands. This shows that city growth is spreading outward from the city center, replacing natural vegetation with buildings and farmland.

4.2 Rainfall Variability Trends (2015-2024)

4.2.1 Temporal Rainfall Patterns

The rainfall data show that the amount of rain in Abuja has been changing from year to year. As seen in Table 4.2.1, rainfall increased between 2015 and 2018 but began to drop again after 2021.

In 2015, the average rainfall was 1,228.86 mm, with little variation across the city. Rainfall rose to 1,352.70 mm in 2018, which was the highest within the ten-year period. It slightly reduced to 1,336.66 mm in 2021 and dropped again to 1,250.38 mm in 2024. This pattern suggests that rainfall in Abuja is not steady it goes up and down, but overall it shows a small decline towards 2024.

Table 4.4: Rainfall Statistics for Abuja (2015–2024)

Year	Minimum (mm)	Maximum (mm)	Mean (mm)	Standard Deviation
2015	1109.62	1444.19	1228.86	62.86
2018	1132.43	1818.71	1352.70	117.75
2021	1084.46	1705.11	1336.66	151.37
2024	1120.22	1483.91	1250.38	68.10

The standard deviation values show that rainfall was more stable in 2015 and 2024, but more irregular in 2018 and 2021. This means that in some years, Abuja experienced heavy rainfall in short periods and less in others, creating an unbalanced pattern.

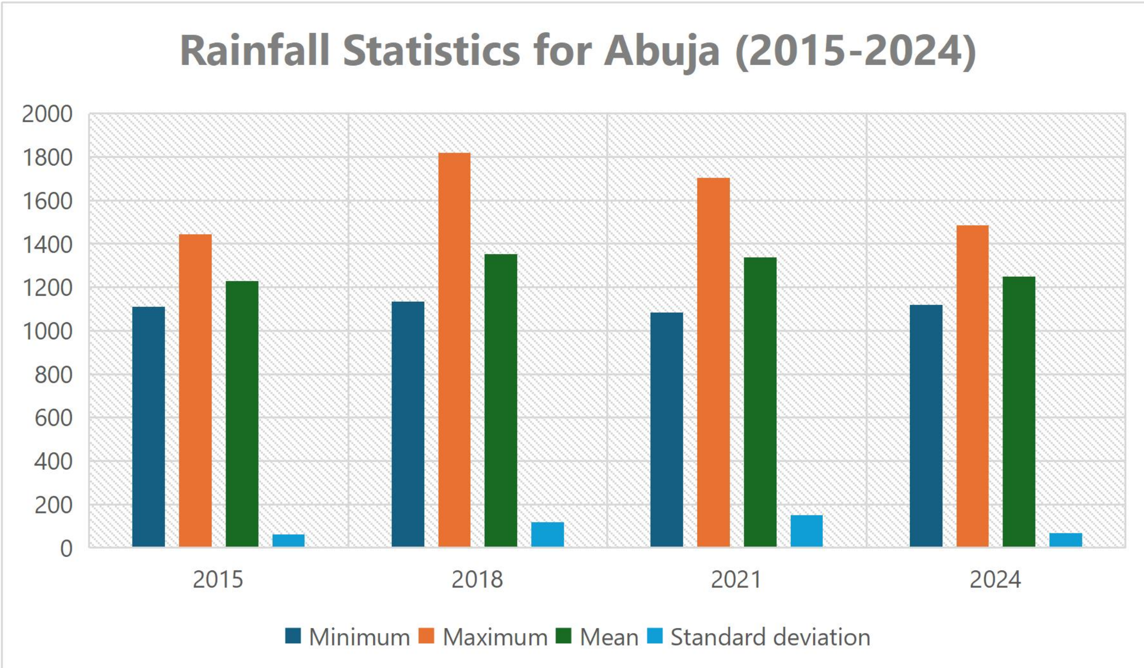

Figure 4.5: Bar Chart Showing Statistical Data of Rainfall in Abuja from 2015-2024

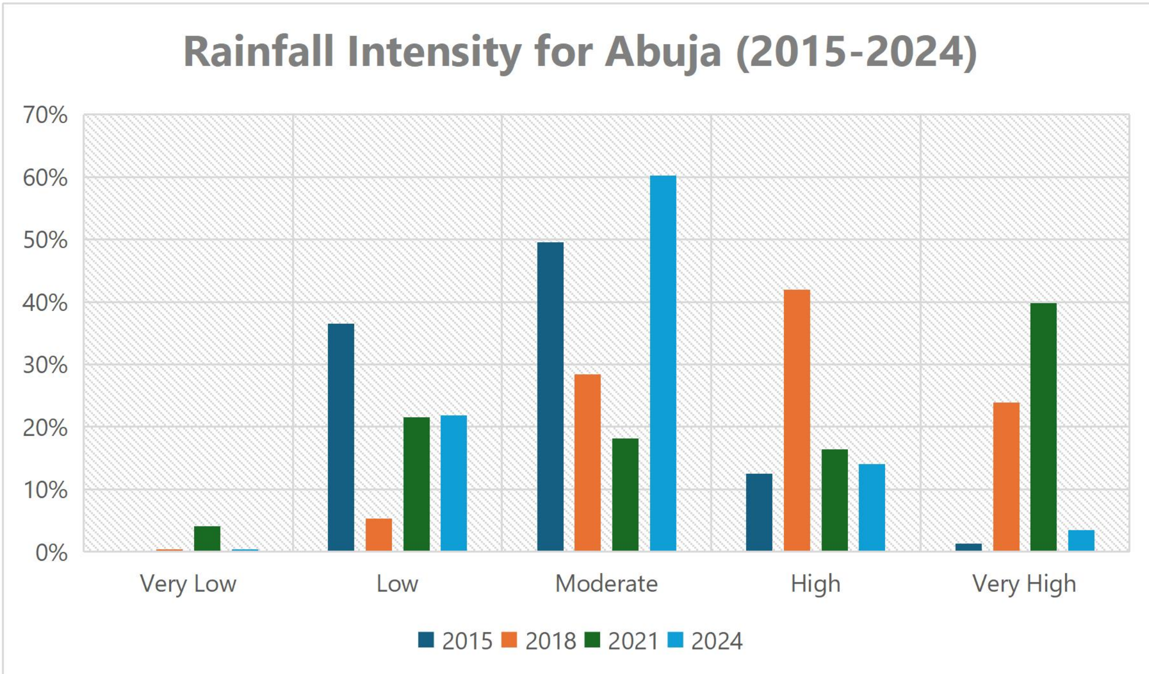

Figure 4.6: Bar Chart Showing the Intensity of Rainfall in Abuja Between 2015 and 2024

4.2.2 Spatial Rainfall Distribution

The rainfall maps reveal that in 2015, most rainfall occurred in the northern and central parts of Abuja. By 2024, rainfall had shifted more towards the southern parts, especially Kwali and Abaji, while the central parts received less rain. This change in rainfall pattern matches the areas where green spaces were lost, suggesting that the reduction in vegetation may be influencing local rainfall distribution.

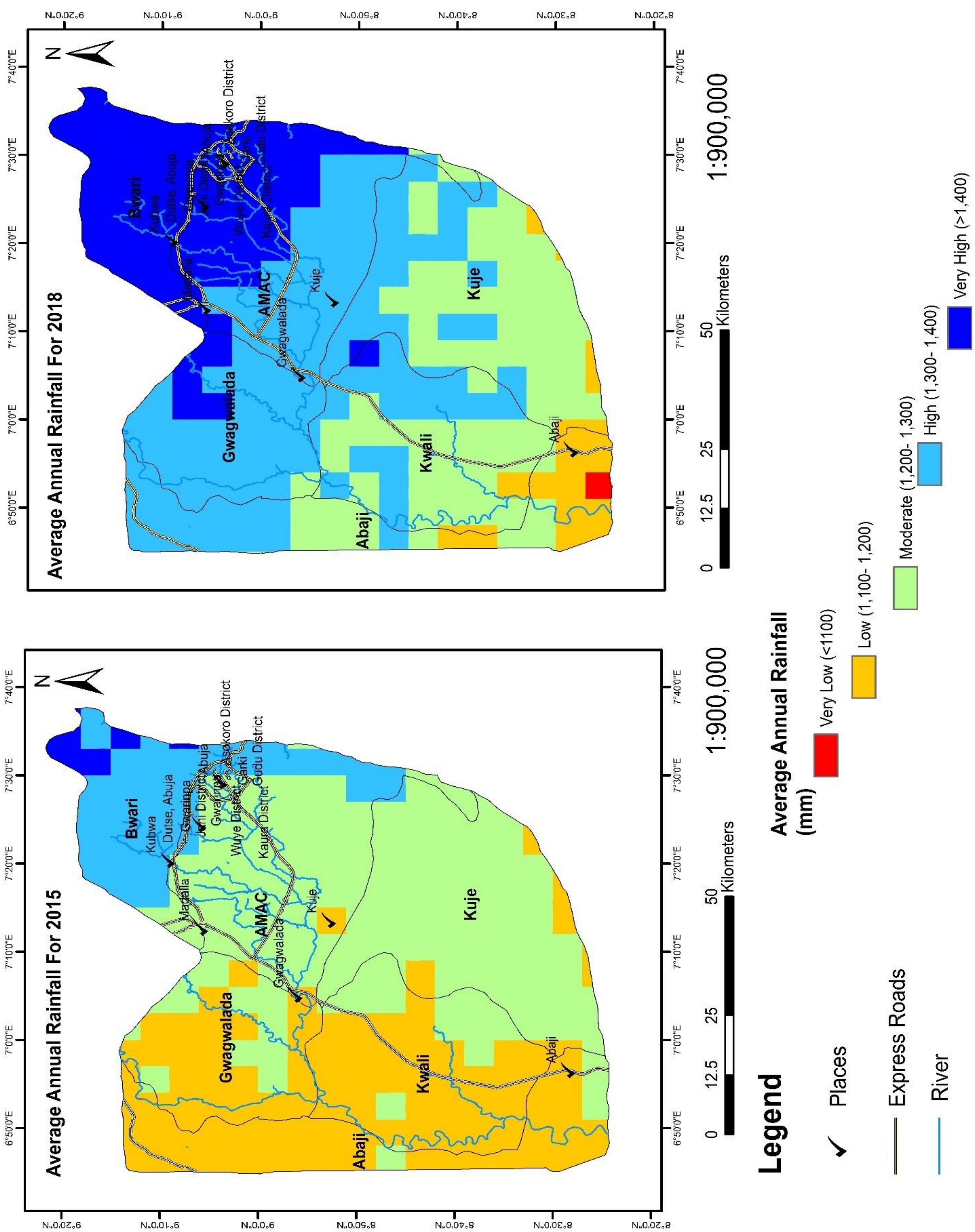

Figure 4.7: Spatial Distribution of Rainfall Between 2015 and 2018

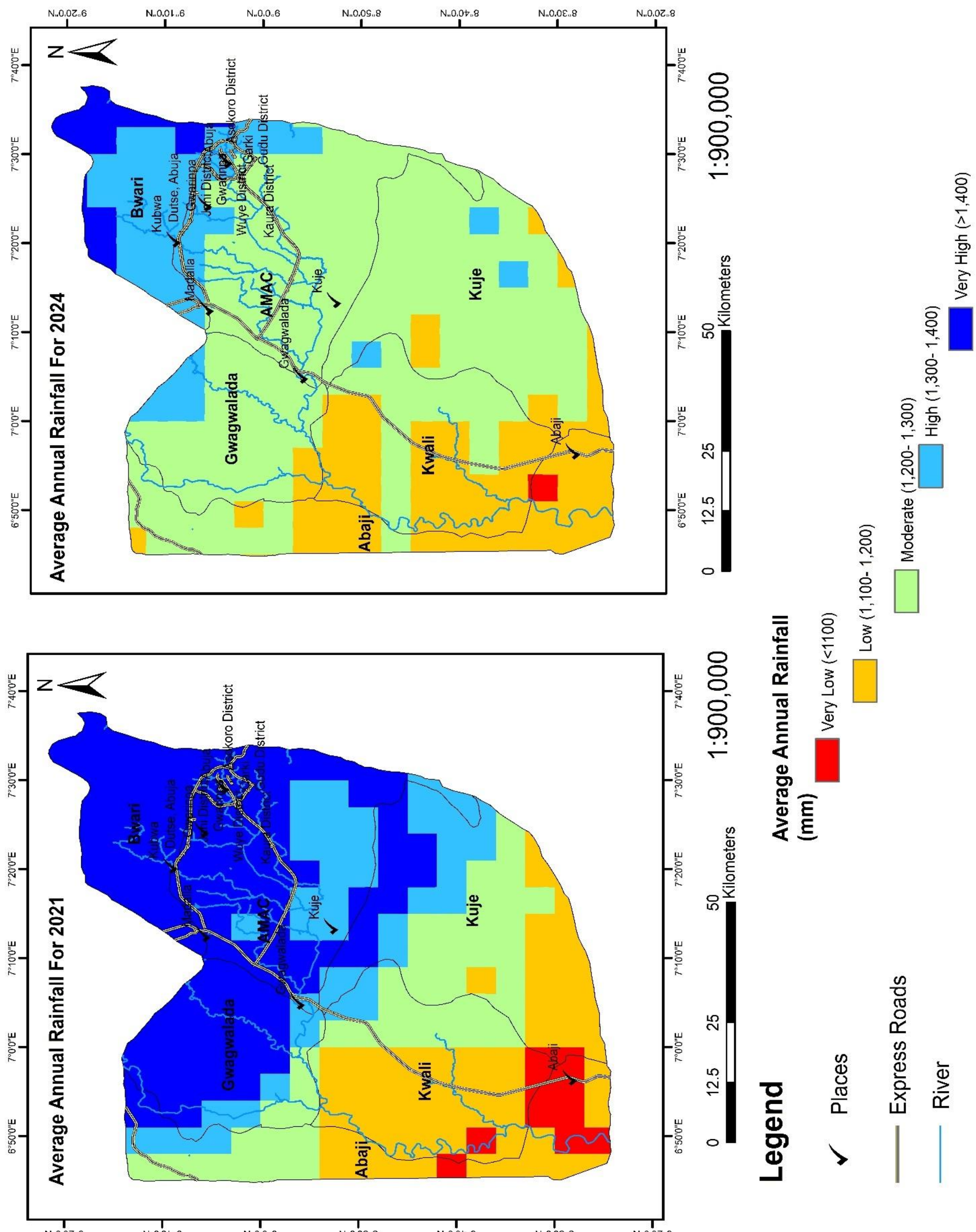

Figure 4.8: Spatial Distribution of Rainfall Between 2021 and 2024

4.3 Relationship Between Green Space Loss and Rainfall Variability

4.3.1 Correlation and Regression Analysis

The comparison between vegetation cover and rainfall shows a negative relationship, meaning that as green areas reduce, rainfall tends to decrease slightly. The correlation result (r = -0.76) indicates a fairly strong negative relationship between tree cover and rainfall in Abuja.

This suggests that the decline in green cover could be contributing to changes in rainfall. Trees and vegetation release water vapor into the air through a process called evapotranspiration, which helps in cloud formation and rainfall. When vegetation is removed, this process reduces, making the environment drier and affecting local rainfall patterns.

4.3.2 Spatial Overlap of Green Space and Rainfall Decline

Areas that lost the most vegetation such as Gwarinpa, Kubwa, Lugbe, and Jabi also showed lower rainfall values during the study period. Meanwhile, areas like Abaji and Kwali, which still have large portions of vegetation, maintained more consistent rainfall levels. This overlap confirms that the more a place loses its green cover, the more its rainfall pattern tends to change or decline.

4.4 Summary of Findings

The results show clear patterns of land cover change and rainfall variation in Abuja between 2015 and 2024. The main points are summarized below:

1. Large Loss of Vegetation: Tree cover reduced by more than 60%, showing a serious decline in green areas within the city.
2. Expansion of Urban and Farmland Areas: Both built-up and cropland areas increased sharply, replacing forests and grasslands.
3. Changing Rainfall Trends: Rainfall increased slightly up to 2018 but declined afterwards, showing unstable rainfall patterns.
4. Negative Link Between Vegetation and Rainfall: As green cover reduced, rainfall also tended to reduce.
5. Spatial Connection: Areas with less vegetation also recorded lower rainfall, especially central parts of Abuja.
6. Growing Land Cover Diversity: The landscape has become more mixed, showing ongoing human activity and land conversion.

In summary, the findings show that rapid city growth and loss of green spaces have affected rainfall patterns in Abuja. The study highlights the need to protect existing vegetation and plan city expansion more sustainably to help maintain a balanced urban environment and local climate.

5 DISCUSSION

5.1 Interpretation of Findings

In this study, the main goal was to examine how the loss of green spaces has influenced rainfall patterns in Abuja, Nigeria, between 2015 and 2024. The results presented in Chapter 4 tell a clear and powerful story of environmental change. One of the most notable findings is the dramatic decline in tree cover. In 2015, trees occupied about 71.81% of the study area, but by 2024, this figure had dropped sharply to 23.71%. This represents a loss of more than 3,500 hectares of tree-covered land in less than a decade a truly alarming rate. Such a scale of vegetation loss mirrors what has been reported in other fast-growing Nigerian cities such as Akure and Lagos (Oyinloye *et al.,* 2023), suggesting that uncontrolled urbanization and land-use pressure are becoming national environmental challenges.

The loss of tree cover in Abuja did not happen in isolation. It was accompanied by a steady and visible increase in both agricultural and built-up areas. This means that as forests and grasslands were cleared, more land was converted into farmlands and concrete developments. The correlation analysis carried out in this study revealed a fairly strong negative relationship (r = -0.76) between tree cover and rainfall. In simpler terms, as green areas disappeared, rainfall amounts also dropped. This shows a close and measurable link between vegetation and local climate confirming that the destruction of green spaces can lead to less rainfall and drier conditions over time.

This connection aligns with earlier environmental theories and models, such as the Hydrological Cycle and Vegetation-Rainfall Interaction Model (Mahmood *et al.,* 2010). Trees and other forms of vegetation play a key role in maintaining moisture in the atmosphere through a natural process called evapotranspiration. During this process, water is released from plant leaves into the air, helping clouds form and promoting local rainfall (Mahmood *et al.,* 2010; Olorunfemi *et al.,* 2020). When a large number of trees are cut down, this natural moisture supply is reduced. The air becomes hotter and drier, cloud formation declines, and rainfall becomes less frequent. This was evident in Abuja's rainfall pattern, which showed a noticeable drop after 2018 coinciding with the years when vegetation loss accelerated the most.

The spatial analysis further revealed how rainfall variability and vegetation loss are connected across different districts of the city. Central areas such as Garki, Wuse, and Gwarinpa, which have experienced rapid development and intense construction activities, showed the highest levels of vegetation loss and the steepest decline in rainfall. These locations are also the most urbanized parts of the Federal Capital Territory, where impervious surfaces like roads, rooftops, and pavements dominate the landscape. In contrast, outer districts such as Kwali and Abaji, which still maintain large portions of natural vegetation, recorded more stable rainfall levels. This spatial pattern highlights how green areas help to stabilize the local climate and maintain more balanced rainfall distribution across the city.

These results support the Urban Climate Theory, which explains that replacing vegetated land with hard, man-made materials such as asphalt and concrete changes the way heat and moisture interact on the surface of the earth (Dewan and Corner, 2012). When vegetation is removed, the ground absorbs and stores more heat, making the city hotter during the day and night. This increase in surface temperature reduces humidity and weakens the natural upward movement of warm, moist air that forms clouds. Over time, this process can limit local rainfall and shift precipitation patterns away from the city (Das and Angadi, 2022).

The findings from Abuja are consistent with results from other parts of West Africa. In Accra, Ghana, for example, research by Twumasi *et al*. (2020) found that the rapid decline of urban green spaces led to significant reductions in local rainfall and increased cases of urban heat buildup. This similarity shows that the environmental challenges seen in Abuja are part of a broader regional trend linked to unplanned urban growth and weak environmental management.

Beyond the scientific evidence, the implications of these results are deeply practical. The continuous decline of green spaces does not only affect rainfall but also contributes to other urban problems such as heat stress, poor air quality, flooding, and reduced groundwater recharge. Trees and vegetation help cool the air, absorb excess rainwater, and provide natural protection against erosion. Losing them means losing these vital ecosystem services, which ultimately makes the city more vulnerable to climate hazards and less livable for residents.

Therefore, this study emphasizes the urgent need for better land management and urban planning policies in Abuja. Protecting the city's remaining green areas should be treated as a priority. Authorities should encourage the establishment of new parks, green corridors, and buffer zones, especially in areas undergoing rapid development. Reforestation and urban greening projects could also help restore some of the lost vegetation and reduce the effects of extreme weather.

Moreover, the involvement of local communities, schools, and organizations is key. Awareness programs on tree planting, waste reduction, and environmental care can inspire residents to take part in creating a greener and healthier city. When people understand the direct link between their environment and their well-being including air quality, comfort, and even rainfall they are more likely to take action to protect it.

In conclusion, the study clearly shows that Abuja's environmental balance is being disturbed by rapid urban expansion and vegetation loss. If these trends continue unchecked, the city may face more frequent droughts, higher temperatures, and worsening water shortages in the future. However, with effective environmental policies, community participation, and a renewed commitment to sustainable development, Abuja can still reverse these trends and build a greener, more climate-resilient future.

5.2 Environmental and Urban Implications

The findings from this study have serious implications for Abuja's environment and overall quality of life. The steady conversion of forests, shrubs, and grasslands into built-up areas and farmlands has greatly changed the city's natural setting. These changes are not just physical; they affect the city's climate, air quality, and water balance. With fewer trees and green spaces, Abuja loses its natural ability to absorb heat, filter the air, and store rainwater. As a result, temperatures in many parts of the city rise faster, the air becomes less clean, and rainfall patterns begin to shift.

The rise in the mean and standard deviation of land cover types shows that Abuja's landscape is becoming more fragmented and uneven due to human activities. In simple terms, green areas that were once large and continuous are being broken up into smaller, scattered patches. This makes it difficult for plants and animals to thrive, reduces the quality of the environment, and weakens the ecosystem's ability to regulate itself. When nature becomes too fragmented, it loses its strength and stability, which can lead to further environmental problems like soil erosion, heat buildup, and loss of biodiversity.

Changes in rainfall patterns also present a major challenge. The rainfall trend observed between 2015 and 2024 with a high in 2018 followed by a steady decline shows that Abuja's weather is becoming less predictable. This kind of variability can have serious effects on water availability and agriculture. If rainfall becomes irregular, water sources may dry up during the dry season and overflow during the wet season, leading to both drought and flooding. Farmers around the outskirts of Abuja may struggle with poor harvests, while urban residents could face water shortages as the city's population grows.

Another issue is the rapid spread of concrete and other impermeable surfaces, which stop rainwater from soaking into the soil. This causes more surface runoff and increases the risk of flash flooding, especially in areas with poor drainage. Flooding is already a major environmental concern in many Nigerian cities, and Abuja is no exception (Nzoiwu *et al.,* 2017; Ekwueme *et al.,* 2024). Without strong control measures, these challenges will only become worse in the coming years.

From a planning and management point of view, these findings show that Abuja's original master plan has not been effectively followed. The plan was designed to create a balance between development and environmental protection, but rapid urban growth and poor enforcement have made that difficult to achieve. Many green zones that were meant to serve as parks, buffer areas, or natural reserves have been taken over by buildings and infrastructure (Appiah-Opoku *et al.,* 2023). As a result, the city is losing its natural resilience its ability to recover from climate shocks like heatwaves and heavy rainfall.

There is an urgent need for stronger environmental planning and policy action. Urban planners, environmental officers, and decision-makers must work together to integrate green infrastructure into Abuja's growth strategy. This means protecting existing green areas, planting more trees, creating new parks, and restoring degraded lands. The government should also enforce stricter rules against illegal construction on green spaces and promote sustainable land-use practices that balance development with nature.

Community involvement is also important. Residents can play a key role by planting trees, maintaining community gardens, and participating in clean-up programs. Schools and organizations can raise awareness about the benefits of green spaces and the dangers of neglecting them. When people understand how closely their environment is linked to their health, comfort, and economy, they are more likely to support conservation efforts.

Protecting Abuja's green spaces is essential not just for environmental reasons but for the city's long-term survival and livability. A city with healthy green spaces is cooler, safer, and more beautiful. It also provides cleaner air, better water management, and a more comfortable climate. For Abuja to remain a sustainable and thriving capital, its leaders and citizens must see environmental protection as a shared responsibility.

5.3 Limitations of the Study

While this study provides valuable insights, it is important to acknowledge its limitations. Firstly, the study period (2015-2024), while relevant, is a ten-year window that may not capture longer-term climatic cycles that also influence rainfall patterns. A longer temporal analysis would strengthen the findings.

Secondly, the study relied on satellite-derived data for both vegetation (NDVI) and rainfall (CHIRPS). Although these datasets are widely used and validated, they are subject to certain errors. For instance, cloud cover can affect the accuracy of satellite imagery, and gridded rainfall data may not perfectly represent hyper-local rainfall events measured by ground stations.

Finally, this study focused primarily on the biophysical relationship between vegetation and rainfall. It did not deeply incorporate socio-economic drivers, such as specific policies, economic incentives, or population migration patterns, that are behind the land-use decisions leading to vegetation loss. Understanding these underlying drivers is crucial for designing effective intervention strategies.

5.4 Recommendations for Future Research

To build upon this research, future studies should consider the following:

1. **Extended Temporal Analysis**: A study covering a longer period, from the inception of Abuja to the present, would provide a more comprehensive understanding of the city's environmental transformation.

2. **Integration of Socio-Economic Data**: Future research should combine geospatial data with surveys and interviews to analyze the socio-economic and political drivers of vegetation loss. This would provide a more holistic view for policymakers.

3. **High-Resolution Data and Advanced Modeling**: Using higher-resolution imagery and incorporating climate models could help predict future scenarios of vegetation cover and rainfall under different urban development plans.

4. **Broader Geographic Scope**: Applying a similar methodology to other rapidly urbanizing cities in Nigeria and West Africa would allow for comparative analysis and the development of regional best practices for sustainable urban planning.

5.4 Conclusion

This spatiotemporal analysis has clearly shown that there is a strong and meaningful connection between the loss of green spaces and rainfall variability in Abuja over the period 2015 to 2024. The steady conversion of natural vegetation into built-up areas and farmlands has not only reshaped the city's physical landscape but has also influenced its local climate system. The results suggest that as green areas decline, rainfall patterns become less predictable, leading to lower rainfall volumes and increasing irregularity in precipitation. This pattern aligns closely with well-known findings in urban climatology, which emphasize that land surface changes have a direct impact on local weather conditions.

The study's findings go beyond simply identifying environmental change they highlight the ecological importance of vegetation within urban areas. Urban greenery is not just about beautifying the environment; it plays a vital role in keeping the city's climate balanced. Through processes like evapotranspiration, vegetation helps to regulate temperature, maintain atmospheric moisture, and support consistent rainfall cycles. It also improves air quality, stabilizes the soil, and reduces surface runoff, all of which contribute to a healthier and more sustainable urban environment.

The evidence from Abuja reinforces the idea that sustainable urban growth cannot be achieved without strong environmental protection measures. As the city continues to expand, urban planning policies must place greater emphasis on conserving, managing, and restoring green spaces. This involves integrating vegetation into residential layouts, promoting urban forestry programs, and enforcing land-use regulations that limit uncontrolled deforestation.

Furthermore, this study underscores that environmental sustainability and urban development are not opposing goals they are interdependent. Protecting Abuja's green cover means preserving the city's natural cooling system, supporting groundwater recharge, and ensuring a more stable rainfall regime. In essence, maintaining vegetation cover is vital for safeguarding the city's water security and climatic stability.

Looking ahead, policymakers, planners, and environmental managers must treat urban greenery as essential infrastructure just as important as roads, housing, or power systems. Investing in green infrastructure will not only improve the quality of life for residents but also help the city adapt to the growing challenges of climate variability and environmental degradation.

In conclusion, this study sends a clear message: the preservation of Abuja's green spaces is key to ensuring its long-term environmental health and resilience. Protecting these natural areas means protecting the city's climate, water resources, and the well-being of its people now and for generations to come.

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