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DISCOVERY SCIENTIFIC SOCIETY

Encroachment assessment along Kaduna River in Kaduna Metropolis Nigeria

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ABSTRACT

This study examines the ecological consequences of hydrological alterations imposed on the Kaduna River in Kaduna Metropolis, Nigeria. The research analyzes changes in land cover, river course shape, and urban sprawl using remote sensing, GIS analysis of satellite images, and field surveys. GIS data used to assess encroachment across the region has been visualized using ArcGIS, Google Earth Pro, and ERDAS Imagine software, which are instrumental in both historical and spatial analyses of patterns from 2000 to 2022. The results reveal significant incursions over several river reaches, characterized by considerable urban land, which have major implications for the floodplains. The study shows increased flood risk, habitat fragmentation, and biodiversity loss as consequences of human activities. The results indicate a pattern of increasing encroachment, particularly in the Lower Left Reach Bank Community, where the highest percentage is 47%. The research underscores the need for sustainable urban planning, effective land-use regulations, and community engagement to mitigate the adverse impacts of encroachment. The study's insights are crucial for informing future urban development strategies and preserving the ecological integrity of the Kaduna River and its surroundings.

Keywords: River encroachment, Kaduna River, Urban development, Remote sensing, GIS analysis, Ecological impact, Sustainable urban planning.

1. INTRODUCTION

Background of the Study

One of the primary impacts of encroachment on river banks is altered hydrology. When human activities such as construction, agriculture, or urbanization occur near a river, it can disrupt the natural flow patterns of water. Encroachment often involves the construction of embankments or levees, which can restrict the movement of water and lead to increased flooding during heavy rainfall events. Additionally,

encroachment can result in the narrowing of the river channel, reducing its capacity to carry water and increasing the risk of overflow (Grabowski et al., 2022; Amoateng et al., 2018). Ecologically, encroachment on river banks can have detrimental effects on aquatic habitats and biodiversity. Rivers are home to a wide range of plant and animal species that depend on specific conditions for their survival. When encroachment occurs, it often involves clearing vegetation and altering the natural habitat structure.

This can lead to habitat fragmentation, loss of riparian vegetation, and reduced water quality due to increased sedimentation and pollution from human activities. As a result, many species may lose their habitats or face difficulties in finding suitable conditions for reproduction and survival (Cantonati et al., 2020). Geomorphologically, encroachment on river banks can cause significant changes in the shape and form of rivers. Natural processes such as erosion and sedimentation play a crucial role in maintaining the balance of a river system (Macfall et al., 2014). However, when human activities encroach upon river banks, they can disrupt these processes. For example, removing vegetation along the banks can increase erosion rates as no longer root systems hold the soil together. This erosion can lead to channel widening or shifting, altering the river's course and potentially causing damage to infrastructure and nearby settlements (Macfall et al., 2014; Grabowski et al., 2022).

In terms of human settlements, encroachment on river banks can pose risks to communities living close to rivers. Increased flooding due to altered hydrology can result in property damage, loss of livelihoods, and even loss of life. Encroachment can also lead to the depletion of groundwater resources as the natural recharge mechanisms are disrupted. Furthermore, encroachment on river banks can exacerbate the impacts of climate change, as it reduces the capacity of rivers to absorb and mitigate the effects of extreme weather events. To mitigate the impacts of encroachment on river banks, various measures can be taken. These include implementing strict regulations and land-use planning to prevent further encroachment, promoting sustainable agricultural practices that minimize soil erosion and chemical runoff, restoring riparian vegetation through reforestation efforts, and creating buffer zones along river banks to allow for natural floodplain processes.

Encroachment on river banks has wide-ranging impacts on both the river ecosystem and human settlements. It alters hydrological patterns, disrupts ecological habitats, causes geomorphological changes, and poses risks to nearby communities. Recognizing the importance of rivers as vital ecosystems and valuable resources is crucial in implementing measures to prevent further encroachment and protect these valuable natural assets. The river is a major source of water for communities, providing irrigation, drinking water, and bathing and washing facilities. However, in recent years, the land along the banks of the Kaduna River has been encroached upon, leading to the degradation of the riverside environment and the destruction of important habitats. Siting illegal structures and removal of vegetative cover are some of the activities that have branched out from encroachment along the Kaduna River, with the intent of claiming land for development and illegal activities.

In terms of siting structures, there have been reports of the Kaduna River being sold to people who have no legal claim to the land. Siting of structures along the Kaduna River has resulted in a significant increase in human population density in the area. High levels of human population density are accompanied by high levels of pollution, with human waste, industrial pollution, and untreated sewage flowing into the Kaduna River. Furthermore, there have been reports of illegal structures, such as buildings and houses, being built along the banks of the Kaduna River. These structures can be used for a variety of activities, such as criminal activities. Additionally, illegal construction activities along the Kaduna River can increase pollution levels, as chemicals, debris, and other pollutants are washed into the river. The research aims to assess the encroachment along Kaduna River in Kaduna Metropolis, Nigeria, as a basis for identifying problems and making recommendations for improvement.

The aim of the study is set to be achieved through the following objectives: To investigate the extent of encroachment**,** to assess the causes of encroachment along Kaduna River, **t**o examine the effects of encroachment, and **t**o propose sustainable solutions to mitigate the encroachment problem. Encroachment along the Kaduna River in the Kaduna Metropolis is a major problem, with potentially serious repercussions, including high levels of human population density, increased pollution, and deforestation. An assessment of the encroachment issue is being carried out, identifying viable solutions that need to be implemented to protect the environment and improve the quality of life in Kaduna Metropolis. This assessment will be particularly relevant to several key stakeholders.

For the Kaduna State Government, the study serves as a crucial checkpoint by revealing the need for effective management of river encroachment through stringent enforcement of land use zoning, regulatory planning schemes, and development control in urban river floodplain areas. Such measures will aid physical planners and urban managers in directing and managing growth while ensuring the sustainable provision of infrastructure and services. The findings will also be key inputs for understanding the possible social and economic impacts of flooding in Kaduna. For the people, the assessment provides background information on the importance of

avoiding land grabbing along riverbanks, thereby fostering awareness and community involvement in protecting these areas. Finally, for academia, the study will serve as a foundational baseline for subsequent research, offering valuable material for students and scholars interested in environmental management and urban planning.

The scope of this study encompasses a comprehensive evaluation of the encroachment along the Kaduna River within Kaduna Metropolis, Nigeria. It aims to provide a detailed analysis of the various dimensions of encroachment and its implications on the environment, human settlement patterns, and socio-economic conditions. The study area includes the entire stretch of the Kaduna River within the boundaries of the metropolis, covering both urban and peri-urban zones directly influenced by the river. The assessment will analyze historical data over the past few decades to identify trends and changes in land use patterns along the riverbanks, utilizing satellite imagery, historical maps, and previous studies. Key areas of the study include evaluating the environmental repercussions of encroachment, such as deforestation, loss of biodiversity, soil erosion, and increased pollution levels in the river. It will also assess the impact on water quality and riverine ecosystems.

The socio-economic analysis will investigate the social and economic factors driving the encroachment, studying population density, housing developments, and informal settlements along the riverbanks. The assessment will examine the impact of encroachment on local communities, including health risks, displacement, and livelihood challenges. Additionally, the study will review existing land use policies, zoning regulations, and enforcement mechanisms to evaluate their effectiveness in controlling encroachment and recommend necessary adjustments to strengthen regulatory frameworks. Engagement with key stakeholders, including government agencies, local communities, non-governmental organizations, and academic institutions, will inform a holistic understanding of the issue and ensure inclusive solutions.

The study will utilize Geographic Information Systems (GIS) and remote sensing technologies to map and analyze land use changes along the river, complemented by field surveys, interviews, and focus group discussions to gather qualitative data. The assessment will also identify high-risk areas and propose mitigation strategies to reduce the impact of potential flooding and other natural disasters exacerbated by river encroachment. Finally, the study will propose viable solutions, including sustainable land use management, community awareness programs, and policy recommendations, along with developing a framework for ongoing monitoring and evaluation of encroachment and its impacts to ensure effective implementation and necessary adjustments over time. The study aims to provide valuable insights and actionable recommendations for sustainable urban and environmental management in the Kaduna Metropolis by covering these areas.

Study Area

The study area for "Encroachment Assessment Along the Kaduna River in Kaduna Metropolis" encompasses the city of Kaduna, the capital of Kaduna State, Nigeria, and its adjacent sections along the Kaduna River. This description provides an overview of the geographical, environmental, and urban characteristics of the study area. Kaduna metropolis the capital of Kaduna state lies between 100 39′ 0″ N, 100 24′ 0″ N and 070 33′ 0″ E, 070 21′ 0″ E on the high plains of northern Nigeria with undulating terrain. Figure 1 Kaduna metropolis comprises two urban local government areas (Kaduna North and South) and parts of Igabi and Chikun local governments of Kaduna state. Kaduna metropolis experiences a tropical savanna climate with a hot wet season (March - October) and cool dry season (November - February) with an annual rainfall level of up to 120 mm per hour.

The study area primarily comprises residual landforms of crustal origin, featuring weathered bedrock masses covered by hardened ironstone and tropical ferruginous soil, as documented by. The evolution of urban development in Kaduna Metropolis has brought about significant modifications to its natural features, including changes in vegetation, topography, and soil composition. These transformations stem from alterations in land cover, excavation activities, physical urban construction, and overall development initiatives. The topography within the study area is characterized by undulating terrain, with elevations ranging from 457 meters to 645 meters above sea level (a.s.l). The presence of the River Kaduna bisects the metropolis into nearly equal halves, impacting the city's physical layout and dynamics significantly.

Additionally, the metropolis is traversed by several tributaries, notably the River Romi, Mashi, and Barnawa, which serve as natural drainage channels, conveying surface rain runoff and sediment-laden water from the urban area into the River Kaduna. These tributaries possess wide and steep valleys that intersect the urban landscape. These valleys not only influence the city's physical layout but also present challenges to the spatial expansion of the metropolis, requiring careful planning and management to navigate these natural features effectively.

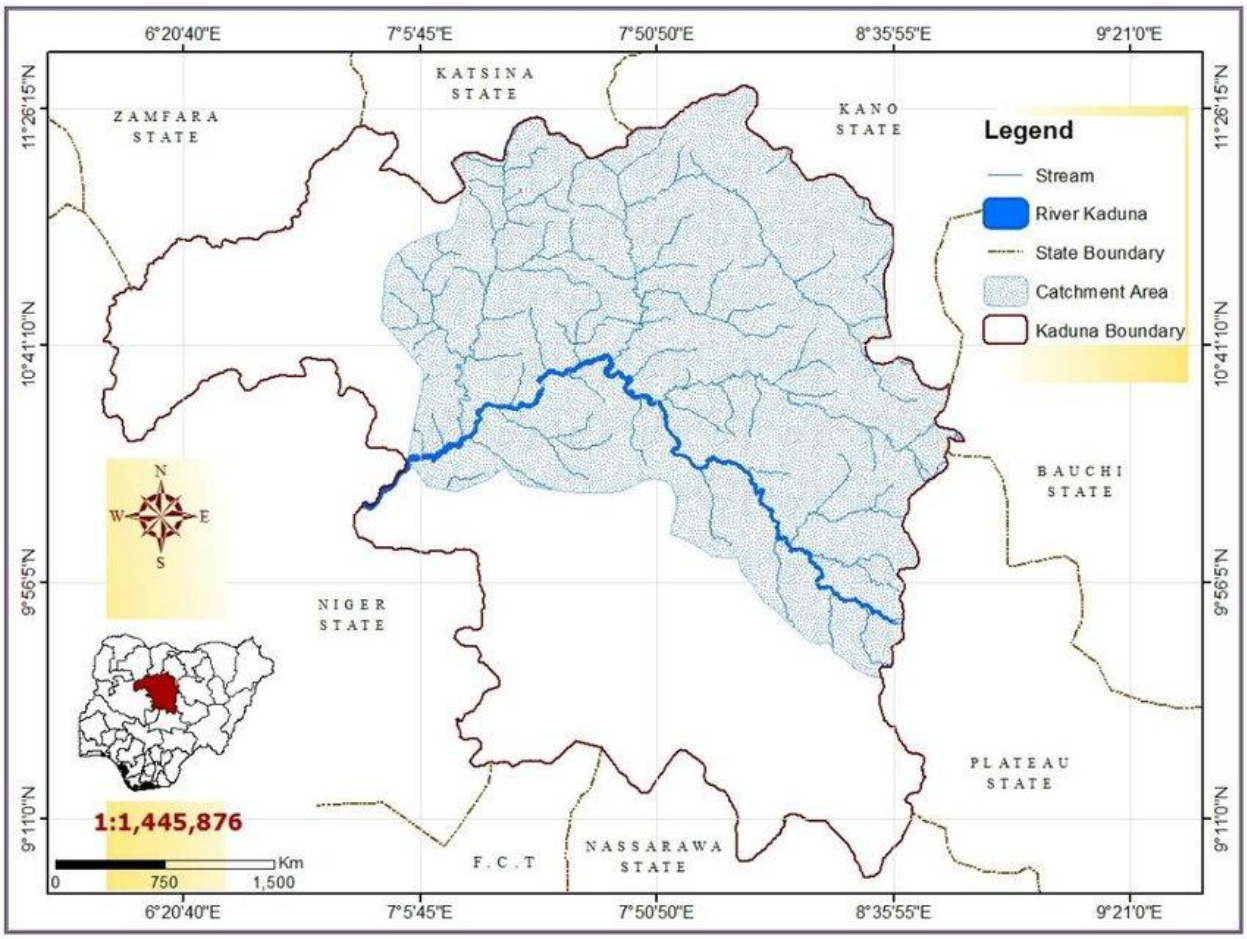

Figure 1 The Study Area (River Kaduna)
Source: Adapted from Administrative Map of Kaduna State

Kaduna Metropolis Development (Population)

Kaduna, originally an indigenous settlement, was established as an administrative center in 1912 under the governance of Lord Lugard, as noted by. Since its inception, the physical expansion of the city has experienced significant growth. In 1967, it covered an estimated land area of 23.18 square kilometers, which has since expanded to approximately 193.24 square kilometers by 2012. Presently, the projected population stands at around 1,731,573 residents, with a growth rate of 3.18%. This remarkable physical and economic expansion of Kaduna Metropolis can be attributed to its multifaceted roles as a military cantonment, a prominent industrial hub in the northern region, and a key center for regional politics and administration. The persistent influx of immigrants into Kaduna over the years has generated an escalating demand for accommodations.

This heightened demand, in turn, has been a driving force behind the spatial expansion of not only Kaduna Metropolis but also its peripheral settlements. To oversee and regulate this growth, the Kaduna Master Plan of 1967, authored by has served as the guiding framework for the city's development. The study area exhibits an undulating topography, with elevations ranging between 457 meters and 645 meters above sea level. This topographical variation influences drainage patterns and urban development. The focal point of the study area is the Kaduna River, which flows through the metropolis. The river is a significant water body in the region and plays a crucial role in the environmental dynamics of the area. The Kaduna River's ecosystem includes riparian vegetation, wetlands, and floodplains.

These natural features are vital for biodiversity, water filtration, and flood regulation. The vegetation in the study area includes a mix of grasslands, savannas, and patches of woodland. However, urbanization and encroachment have led to changes in the landscape.

The region's soil is primarily ferruginous and tropical, with variations in texture and composition. These soils support agriculture and urban development. Urban development in Kaduna Metropolis includes residential areas, commercial districts, industrial zones, educational institutions, and government offices. The city has expanded considerably to accommodate its growing population. The metropolis is equipped with essential urban infrastructure, including road networks, schools, healthcare facilities, markets, and transportation services.

2. RESEARCH METHODOLOGY

Research Design

This research employs a mixed-methods approach, integrating both qualitative and quantitative research methods. This approach allows for a holistic examination of the encroachment phenomenon, capturing both the quantitative data related to physical changes and the qualitative insights into the social and environmental aspects of encroachment. The study primarily falls under the category of descriptive research as it seeks to provide a detailed account and analysis of the extent, causes, impacts, and potential solutions to river encroachment in Kaduna Metropolis.

Primary Data: Primary data was used to collect data through field surveys, satellite imagery analysis, and interviews with stakeholders, such as government officials, local communities, and experts. Field surveys will involve physical measurements, and site observations. Secondary Data: Secondary data was used to gather data from existing sources, including historical maps, satellite images, academic publications, government reports, and environmental databases. These sources provided context and historical data for the study.

Data Collection Methods

Remote Sensing and GIS Analysis: Satellite imagery from sources like LAND-SAT images, Google Earth Pro, and ArcGIS was used to assess changes in land cover, river morphology, and encroachment over time. Geographic Information System (GIS) software will aid in spatial analysis. Field Surveys: Field surveys involved physical measurements of river parameters, such as channel width and depth, as well as observations of encroachment types and impacts. Semi-structured interviews were conducted with key informants, including government officials, environmental experts, and community leaders, to gain insights into policy perspectives and local knowledge.

Data Analytical Tools

The research utilized a combination of analytical tools to conduct comprehensive assessments and analyses:

ArcGIS 10.7: The ArcGIS mapping tool (ArcMap) played a pivotal role in mapping floodplains and tracking the encroachment patterns caused by urban development. The measuring tool within ArcGIS allowed for precise quantification of floodplain areas and the extent of built encroachment. This software facilitated the spatial analysis needed to understand the dynamics of Kaduna Metropolis's growth and its impact on the floodplains.

Google Earth Pro v6.2.2.6613: Google Earth Pro was employed to evaluate the effectiveness of development control measures in managing floodplain encroachment. This tool provided a valuable platform for visualizing and assessing changes in land use and encroachment within the study area. It contributed to the analysis of how well development regulations were enforced and whether they effectively prevented further encroachment.

These analytical tools, in conjunction with remote sensing data and field surveys, were instrumental in generating insights into the extent, causes, and impacts of encroachment along the Kaduna River in Kaduna Metropolis (Grabowski et al., 2022).

Data Analysis and Presentation

In this study, the analysis of river encroachment along the Kaduna River in Kaduna Metropolis involved several key steps. The river floodplain, as generated from the Digital Elevation Model (DEM), was divided into two major reaches. The stadium roundabout bridge, which spans the Kaduna River, served as the reference point for this division. This approach was adopted to facilitate the measurement of built-up encroachment by communities while overcoming the challenge of boundary delineation. The two major reaches considered in the study are as follows: The upper river reach encompasses all flood banks upriver from the stadium

roundabout bridge. Communities situated along the river banks within this reach were grouped into two categories: Upper Right Reach Bank Community (URRBC) and Upper Left Reach Bank Community (ULRBC).

The lower river catchment reach extends from the stadium roundabout bridge downstream along the river's flow. Communities along the river banks in this reach were categorized into two groups: Lower Right Reach Bank Community (LRRBC) and Lower Left Reach Bank Community (LLRBC). To conduct measurements and delineate encroached and un-encroached floodplain areas, ArcGIS 10.7 tools were employed. These tools allowed for the precise measurement of the delineated floodplains and the quantification of encroachment in square kilometers (Km²). The analysis considered five distinct time epochs: 2000, 2005, 2010, 2015, and 2022, enabling the identification of trends in built-up encroachment over time during the spatial growth of Kaduna Metropolis. The utilization of satellite imagery for these various time epochs facilitated the identification of patterns and extents of urban built-up encroachments on floodplains at different points in the city's development.

Additionally, the study assessed the effectiveness of the planning control framework in regulating physical development on floodplains. To present the results of data analysis, various methods were employed, including tables, graphs, charts, and maps where applicable. These visual aids were instrumental in illustrating the encroachment on floodplains and conveying the findings effectively. Inferences were drawn from the data analysis, and the study's conclusions were presented based on the results obtained from maps and graphs, which showcased the encroachment trends on the floodplains (Ndabula et al., 2012).

3. RESULTS AND DISCUSSION

Assessment of Encroachment Extent Kaduna River

The spatial growth of Kaduna Metropolis has encountered physical limitations primarily attributed to the presence of River Kaduna and its associated tributaries encircling the urban area, as well as the existence of gully sites resulting from the natural drainage patterns. Table 1 to 3 provides insights into the scale of river floodplains within Kaduna Metropolis, estimating their total size at approximately 115.80 square kilometers (km²). Figure 2 to 14 gives visually illustration how River Kaduna has been seriously encroached on and the buildings both residential and commercial are cropping up very close to the river bank over the time. Figure 15 to 17 shows the Map of River Kaduna showing communities along its floodplain and the extent of encroachment in year 2000 to 2022 This geographical division significantly influences the urban development patterns and challenges faced by the city.

Figure 2 Kaduna River Tudun Wada Area in 2003

Figure 3 Kaduna River Tudun Wada Area in 2008 Showing beginning of built-up areas and encroachment of River Kaduna

Figure 4 Kaduna River Tudun Wada Area in 2010 Showing beginning of built-up areas and encroachment of River Kaduna

Figure 5 Kaduna River Tudun Wada Area in 2012 Showing beginning of built-up areas and encroachment of River Kaduna

Figure 6 Kaduna River Tudun Wada Area in 2016 showing the encroachment of River Kaduna

Figure 7 Kaduna River Tudun Wada Area in 2018 showing the encroachment of River Kaduna

Figure 8 Kaduna River Tudun Wada Area in 2023 with large scale encroachment into River Kaduna

Consequently, the result for Ugwan Muazu Axis of River Kaduna Area. The trend in the encroachment of River Kaduna was analyzed using google earth.

Figure 9 Kaduna River Ungwan Muazu Axis in 2008 Showing beginning of built-up areas and encroachment of River Kaduna

Figure 10 Kaduna River Ungwan Muazu Axis in 2010 Showing beginning of built-up areas and encroachment of River Kaduna

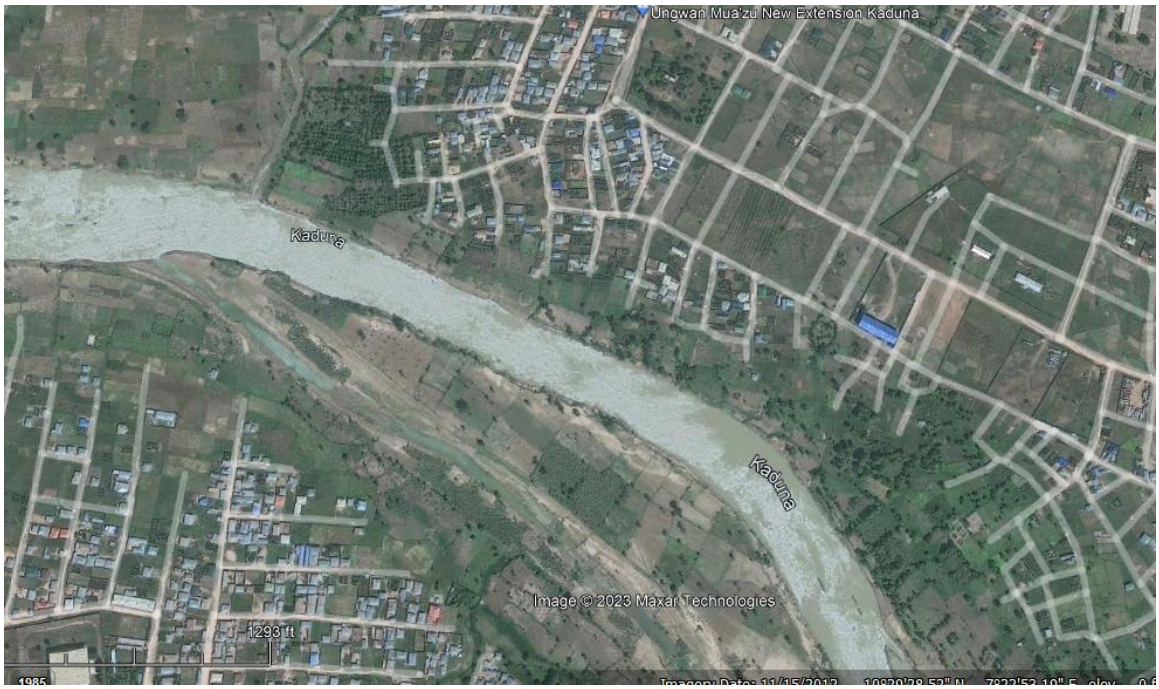

Figure 11 Kaduna River Ungwan Muazu Axis in 2012 showing built-up areas encroachment into River Kaduna

Figure 12 Kaduna River Ungwan Muazu Axis in 2015 with encroachment into River Kaduna

Figure 13 Kaduna River Ungwan Muazu Axis in 2021 with encroachment into River Kaduna

Figure 14 Kaduna River Ungwan Muazu Axis in 2023 with encroachment into River Kaduna

Table 1 serves to pinpoint communities situated along the riverbanks of Kaduna Metropolis that have experienced encroachment onto the river floodplains. This encroachment can be attributed to the continued spatial expansion and growth of the metropolis. This table presents data on the extent of river encroachment in different river reaches along the Kaduna River and the communities or districts affected. The identification of these communities, their encroachment on river floodplains, and the associated data provide critical insights into the evolving dynamics of urbanization and its impact on the ecological integrity of the Kaduna River and its surroundings. This assessment serves as a foundational step in understanding the extent and consequences of river encroachment, ultimately informing sustainable urban planning and management strategies for Kaduna Metropolis (Figure 15). Table 1 is crucial for understanding and interpreting the data in the subsequent (Tables 2 and 3).

Table 1 Communities in which urban development has encroached onto River Kaduna

RIVER REACH	COMMUNITIES OR DISTRICTS	FLOOD LINE AREA ENCROACHMENT (km2)
Kaduna River Upper Right Bank Reach	Kawo, Malali, Ungwan Rimi, Kabala Doki, Kigo Road,	33.7
Kaduna River Upper Left Bank Reach	Barnawa, and Narayi	36.0
Kaduna River Lower Right Bank Reach	Rigasa, Tudun Wada, and Ungwan Muazu	35.2
Kaduna River Lower Left Bank Reach	Kakuri, Nassarawa, Kudandan	10.9

Source: Author, 2023

Kaduna River Upper Right Bank Reach

This reach includes communities such as Kawo, Malali, Ungwan Rimi, Kabala Doki, and Kigo Road. The flood line area affected by encroachment in this reach is approximately 33.7 square kilometers (km²). This means that within these communities, an area of 33.7 km² along the riverbanks has been encroached upon by urban development.

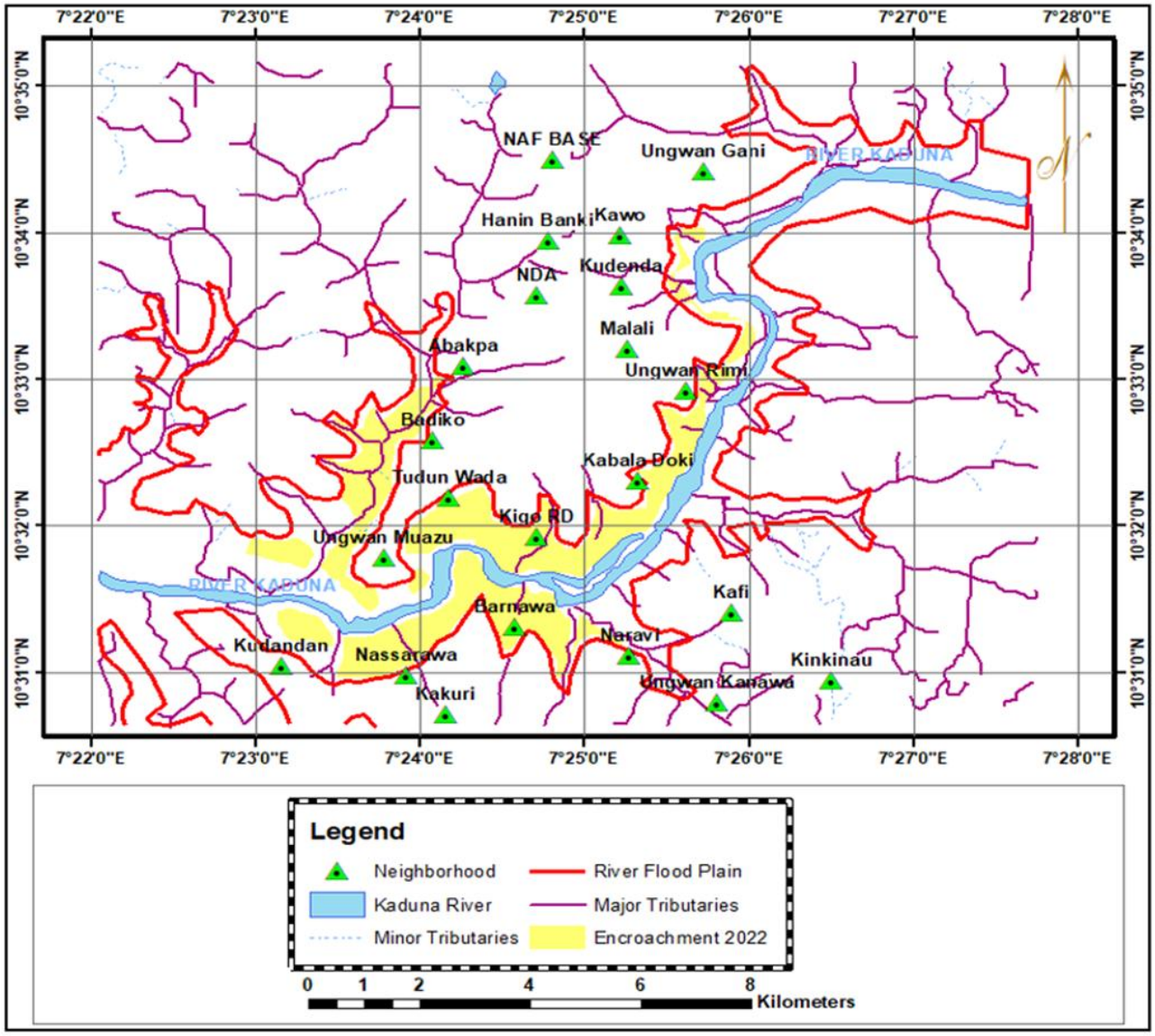

Figure 15 Map of River Kaduna showing communities along its floodplain

Kaduna River Upper Left Bank Reach

In this reach, communities like Barnawa and Narayi are considered. The flood line area affected by encroachment in this reach is larger, estimated at approximately 36.0 km². This indicates that a significant portion of the floodplain in these communities has experienced encroachment.

Kaduna River Lower Right Bank Reach

Communities like Rigasa, Tudun Wada, and Ungwan Muazu fall within this reach. The flood line area affected by encroachment here is about 35.2 km². This suggests that, similar to the upper left bank reach, substantial encroachment has occurred along the riverbanks in these communities.

Kaduna River Lower Right Bank Reach

This reach includes communities like Kakuri, Nassarawa, and Kudandan. The flood line area affected by encroachment in this reach is comparatively smaller, estimated at 10.9 km². While the extent of encroachment is smaller in these communities, it is still a matter of concern. In summary, these results provide a clear breakdown of the extent of river encroachment in different reaches along the Kaduna River, highlighting the communities or districts affected and the corresponding flood line areas that have been encroached upon. This information is crucial for understanding the localized impact of urban development on the river's floodplains and can guide future planning and conservation efforts in these areas.

Table 2 highlights the communities along the riverbanks of Kaduna Metropolis that have encroached onto the river floodplains. This encroachment is due to the ongoing spatial expansion and growth of the metropolis. The table provides data on the extent of river encroachment in various sections of the Kaduna River and the affected communities or districts. Identifying these communities and their encroachment on river floodplains, along with the associated data, offers crucial insights into the changing dynamics of urbanization and its impact on the ecological health of the Kaduna River and its surroundings. This assessment is a key step in understanding the extent and consequences of river encroachment, ultimately guiding sustainable urban planning and management strategies for Kaduna Metropolis (Figure 16).

Table 2 The degree of urban development encroachment on the river floodplain in the year 2000

S/N	AREAS	TOTAL FLOODPLAIN (km2)	EXTENT OF BUILT-UP ENCROACHMENT (km2)	EXTENT OF UNENCROACHED FLOODPLAIN (km2)	% OF FLOODPLAIN	% OF UNENCROACHED FLOODPLAIN
1.	URRBC	33.7	7.8	25.9	23.14	76.86
2.	ULRBC	36.0	5.1	30.9	14.17	85.83
3.	LRRBC	35.2	8.3	26.9	23.58	76.42
4.	LLRBC	10.9	5.0	5.9	45.87	54.13

Upper Right Reach Bank Catchment- URRBC, Upper Left Reach Bank Catchment- ULRBC, Lower Right Reach Bank Catchment- LRRBC, Lower Left Reach Bank Catchment- LLRBC

The Table 2 provides a breakdown of various areas, particularly the communities located along the riverbanks of River Kaduna in year 2015, and their respective floodplain characteristics, including the extent of urban built-up encroachment. This is also illustrated using:

URRBC (Upper Right Reach Bank Community)

Total Floodplain: The entire floodplain area for this community in Kaduna Metropolis is approximately 33.7 square kilometers.
Extent of Built-Up Encroachment: Of the total floodplain, 7.8 square kilometers have been encroached upon by urban development.
Extent of Unencroached Floodplain: This represents the portion of the floodplain that remains unaffected by encroachment, which is 25.9 square kilometers.
% of Floodplain: The percentage of the floodplain that has been encroached upon is 23.14%.

% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached is 76.86%.

ULRBC (Upper Left Reach Bank Community)

Total Floodplain: The entire floodplain area for this community is estimated to be 36.0 square kilometers.

Extent of Built-Up Encroachment: Approximately 5.1 square kilometers of the floodplain has experienced encroachment due to urban development.

Extent of Unencroached Floodplain: This indicates the portion of the floodplain that has not been encroached upon, which measures 30.9 square kilometers.

% of Floodplain: The percentage of the floodplain encroached upon is 14.17%.

% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached is 85.83%.

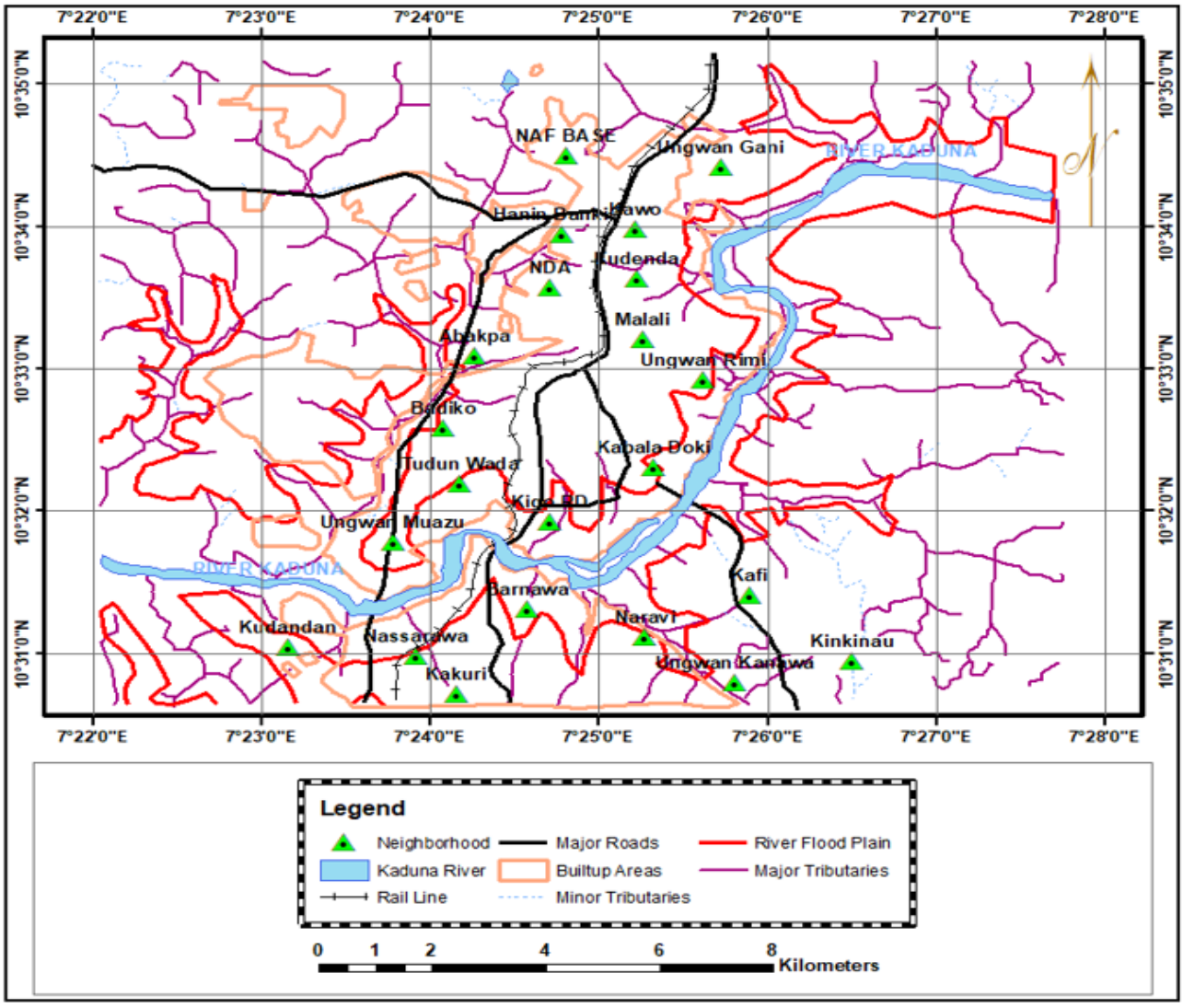

Figure 16 Map of River Kaduna showing communities along its floodplain and extent of encroachment in year 2000

LRRBC (Lower Right Reach Bank Community)

Total Floodplain: The entire floodplain area for this community is approximately 35.2 square kilometers.

Extent of Built-Up Encroachment: About 8.3 square kilometers of the floodplain has been encroached upon by urban development.

Extent of Unencroached Floodplain: This represents the unencroached portion of the floodplain, which measures 26.9 square kilometers.
% of Floodplain: The percentage of the floodplain that has been encroached upon is 23.58%.
% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached is 76.42%.

LLRBC (Lower Left Reach Bank Community)
Total Floodplain: The entire floodplain area for this community is estimated to be 10.9 square kilometers.
Extent of Built-Up Encroachment: Approximately 5.0 square kilometers of the floodplain has experienced encroachment due to urban development.
Extent of Unencroached Floodplain: This indicates the unencroached portion of the floodplain, which measures 5.9 square kilometers.
% of Floodplain: The percentage of the floodplain that has been encroached upon is 45.87%.
% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached is 54.13%.

From table 2, among the four communities or reach bank areas assessed for river encroachment in Kaduna Metropolis, the community with the highest extent of encroachment is "LLRBC" (Lower Left Reach Bank Community). This community has an encroachment percentage of 45.87%, indicating that a significant portion of its floodplain has been encroached upon by urban development. These communities include; Kakuri, Nassarawa, and Kudandan. On the other hand, the community with the lowest extent of encroachment is "ULRBC" (Upper Left Reach Bank Community). This community has an encroachment percentage of 14.17%, suggesting that a relatively smaller portion of its floodplain has been affected by encroachment. These communities are Barnawa, and Narayi.

Table 3 details the communities along the Kaduna Riverbanks that have extended into the river floodplains, driven by the city's ongoing spatial expansion and growth. The table includes data on the extent of encroachment in different sections of the Kaduna River and the affected communities or districts. Identifying these communities and their encroachment on the floodplains, along with the related data, provides essential insights into the evolving urbanization dynamics and its impact on the ecological health of the Kaduna River and its surroundings. This evaluation is crucial for understanding the extent and consequences of river encroachment, ultimately informing sustainable urban planning and management strategies for Kaduna Metropolis (Figure 17).

Table 3 Encroachment extent of River Kaduna floodplain in 2022

S/N	AREAS	TOTAL FLOODPLAIN (km2)	EXTENT OF BUILT-UP ENCROACHMENT (km2)	EXTENT OF UNENCROACHED FLOODPLAIN (km2)	% OF FLOODPLAIN	% OF UNENCROACHED FLOODPLAIN
1.	URRBC	33.7	12.5	21.2	37.09	62.91
2.	ULRBC	36.0	6.6	29.4	18.33	81.67
3.	LRRBC	35.2	15.9	19.3	45.17	54.83
4.	LLRBC	10.9	6.9	4.0	63.3	36.7

Upper Right Reach Bank Catchment- URRBC, Upper Left Reach Bank Catchment- ULRBC, Lower Right Reach Bank Catchment- LRRBC, Lower Left Reach Bank Catchment- LLRBC

Table 3 provides updated data on the extent of river encroachment in the year 2022 for the same communities or reach bank areas along the Kaduna River in Kaduna Metropolis. Here's an analysis of the table:

URRBC (Upper Right Reach Bank Community)
Total Floodplain: The floodplain area for this community remains at 33.7 square kilometers.
Extent of Built-Up Encroachment: The extent of encroachment in 2022 has increased to 12.5 square kilometers, showing a significant rise from the previous measurement.
Extent of Unencroached Floodplain: Unencroached floodplain area is now 21.2 square kilometers, indicating a reduction from the previous assessment.

% of Encroached Floodplain: The percentage of the floodplain that has been encroached upon is 37.09%, demonstrating an increase in encroachment.
% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached has decreased to 62.91%.

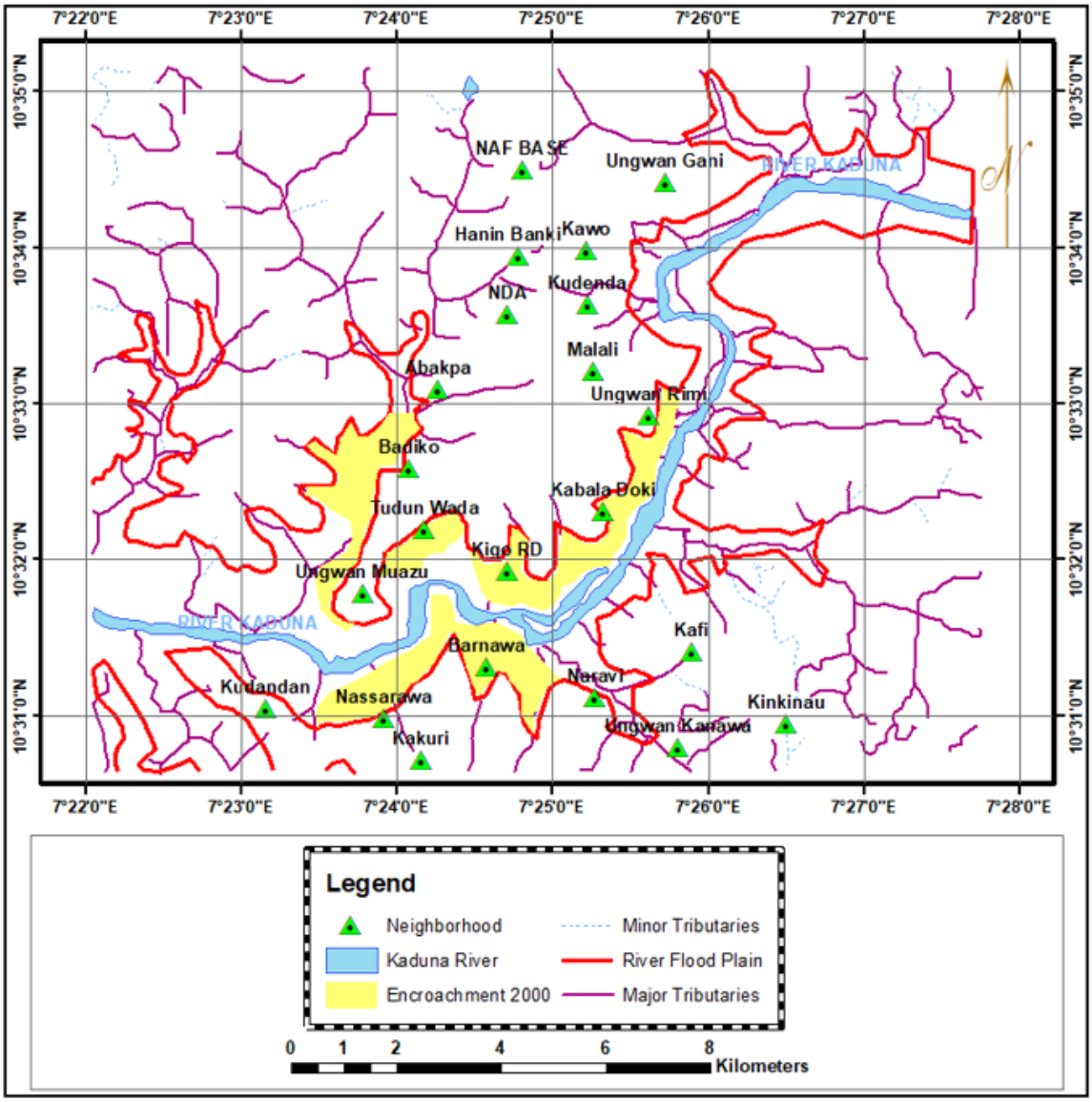

Figure 17 Map of River Kaduna showing communities along its floodplain and extent of encroachment in year 2022

ULRBC (Upper Left Reach Bank Community)
Total Floodplain: The floodplain area for this community remains at 36.0 square kilometers.
Extent of Built-Up Encroachment: The extent of encroachment in 2022 has increased to 6.6 square kilometers, also showing a notable rise from the previous measurement.
Extent of Unencroached Floodplain: Unencroached floodplain area is now 29.4 square kilometers, indicating a reduction from the previous assessment.
% of Encroached Floodplain: The percentage of the floodplain that has been encroached upon is 18.33%, reflecting an increase in encroachment.
% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached has decreased to 81.67%.

LRRBC (Lower Right Reach Bank Community)

Total Floodplain: The floodplain area for this community remains at 35.2 square kilometers.

Extent of Built-Up Encroachment: The extent of encroachment in 2022 has increased to 15.9 square kilometers, indicating a substantial rise from the previous measurement.

Extent of Unencroached Floodplain: Unencroached floodplain area is now 19.3 square kilometers, showing a reduction from the previous assessment.

% of Encroached Floodplain: The percentage of the floodplain that has been encroached upon is 45.17%, demonstrating a significant increase in encroachment.

% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached has decreased to 54.83%.

LLRBC (Lower Left Reach Bank Community)

Total Floodplain: The floodplain area for this community remains at 10.9 square kilometers.

Extent of Built-Up Encroachment: The extent of encroachment in 2022 has increased to 6.9 square kilometers, indicating a substantial rise from the previous measurement.

Extent of Unencroached Floodplain: Unencroached floodplain area is now 4.0 square kilometers, showing a reduction from the previous assessment.

% of Encroached Floodplain: The percentage of the floodplain that has been encroached upon is 63.3%, demonstrating a significant increase in encroachment.

% of Unencroached Floodplain: The percentage of the floodplain that remains unencroached has decreased to 36.7%.

Overall, the data for 2022 reveals a trend of increased encroachment in all four communities, with a notable reduction in the unencroached floodplain areas. This indicates a growing challenge of urban development encroaching onto the river floodplains in Kaduna Metropolis, which has implications for both the environment and urban planning efforts.

4. DISCUSSION

The period from 2000 to 2022 has witnessed significant encroachment along the floodplains of the Kaduna River, driven by rapid urbanization and population growth in Kaduna Metropolis. This heightened demand for land has led to the expansion of both the city and its peripheral settlements. The encroachment has been characterized by the conversion of floodplain areas into residential, commercial, and industrial zones, often without adequate regulatory oversight. Studies by Ndabula et al., (2012), Bahago et al., (2020) highlight the adverse impacts of this encroachment. The transformation of natural floodplains into built-up areas has exacerbated flood risks, leading to more frequent and severe flooding events. These changes have disrupted the natural flow of the river, reduced its capacity to manage floodwaters, and increased the vulnerability of the surrounding communities.

Efforts to manage and regulate this growth have been guided by the Kaduna Master Plan of 1967, which aimed to provide a structured approach to urban development. However, the enforcement of development control measures has often been inadequate, as evidenced by the continued encroachment observed through remote sensing and GIS analysis. Tools like ArcGIS and Google Earth Pro have been instrumental in mapping these changes and assessing the effectiveness of regulatory measures. The analysis of Table 1 and subsequent data from Tables 2 and 3 provides a comprehensive view of the encroachment onto the river floodplains in Kaduna Metropolis. This encroachment is a direct result of the city's spatial expansion and urbanization. The detailed data on the extent of river encroachment across various reaches of the Kaduna River, and the affected communities or districts, underscore the growing challenge of balancing urban development with ecological preservation.

In the Kaduna River Upper Right Bank Reach, which includes communities such as Kawo, Malali, Ungwan Rimi, Kabala Doki, and Kigo Road, the flood line area affected by encroachment is approximately 33.7 square kilometers in 2000. This substantial encroachment indicates significant urban development pressure in these areas. By 2022, the extent of built-up encroachment increased to 12.5 square kilometers, reducing the unencroached floodplain to 21.2 square kilometers. The percentage of the floodplain encroached upon rose to 37.09%, highlighting the escalating impact of urbanization in this reach (Amoateng et al., 2018). In contrast, the Kaduna River Upper Left Bank Reach, which includes communities like Barnawa and Narayi, experienced a different scale of encroachment.

The flood line area affected in this reach is estimated at 36.0 square kilometers, with the extent of built-up encroachment increasing from 5.1 square kilometers in 2000 to 6.6 square kilometers in 2022. Despite this increase, the percentage of encroached floodplain remains relatively lower at 18.33%, indicating that while urban expansion is occurring, it is not as intense as in some other reaches. The Kaduna River Lower Right Bank Reach, encompassing communities such as Rigasa, Tudun Wada, and Ungwan Muazu, saw substantial encroachment, with the affected flood line area being about 35.2 square kilometers in 2000. By 2022, the built-up encroachment had surged to 15.9 square kilometers, with the percentage of encroached floodplain rising significantly to 45.17%. This dramatic increase underscores the critical need for effective urban planning and floodplain management in these areas to mitigate further environmental degradation.

Meanwhile, the Kaduna River Lower Left Bank Reach, which includes communities like Kakuri, Nassarawa, and Kudandan, experienced encroachment over a comparatively smaller area of 10.9 square kilometers. Despite the smaller area, the extent of built-up encroachment grew from 5.0 square kilometers in 2000 to 6.9 square kilometers in 2022. This resulted in an encroachment percentage of 63.3%, the highest among all the reaches analyzed. This indicates a severe impact of urban development on the floodplain in this reach, necessitating urgent intervention. The data from Table 2 and Table 3 reveals a clear trend of increasing encroachment across all four communities or reach bank areas between 2000 and 2022. The Upper Right Reach Bank Community saw an increase in encroachment percentage from 23.14% to 37.09%.

The Upper Left Reach Bank Community's encroachment percentage rose from 14.17% to 18.33%, while the Lower Right Reach Bank Community experienced an increase from 23.58% to 45.17%. The most significant change was observed in the Lower Left Reach Bank Community, with encroachment rising from 45.87% to 63.3%. These findings highlight the urgent need for sustainable urban planning and management strategies in Kaduna Metropolis. The increasing encroachment on river floodplains poses significant risks to the ecological integrity of the Kaduna River and its surrounding areas. Floodplain areas serve critical ecological functions, including flood mitigation, water filtration, and habitat provision. Encroachment not only disrupts these functions but also increases the vulnerability of urban areas to flooding and other environmental hazards.

To address these challenges, comprehensive planning and regulatory measures are essential. This includes enforcing land-use regulations, promoting green infrastructure, and implementing floodplain restoration projects. Additionally, raising awareness among local communities about the importance of preserving floodplain areas and engaging them in conservation efforts can play a crucial role in mitigating encroachment (Grabowski et al., 2022). In conclusion, the data presented in Tables 1, 2, and 3 provides a detailed overview of the extent and impact of urban encroachment on the river floodplains in Kaduna Metropolis. The observed trends of increasing encroachment underscore the pressing need for sustainable urban development practices that balance the demands of growth with the preservation of ecological integrity.

5. CONCLUSION

The assessment of river encroachment along the Kaduna River highlights the dynamic and evolving challenges associated with urban development in riverine environments. The research underscores the urgent need for effective planning and management strategies to strike a balance between urban growth and the preservation of natural ecosystems. The data clearly demonstrate a continuous trend of encroachment, with the urban expansion encroaching further onto river floodplains over the years. This poses a significant threat to the ecological balance and sustainability of the river and its surrounding areas.

The impacts of encroachment, such as changes in channel platforms and altered sediment transport, are tangible and require immediate attention. The proposed sustainable solutions, including afforestation and responsible mining, provide a path forward for mitigating the adverse effects of river encroachment. As Kaduna Metropolis continues to grow and evolve, the findings of this research should serve as a valuable resource for informed decision-making in urban planning, environmental conservation, and sustainable development. The study underscores the importance of balancing urban growth with the preservation of natural resources and ecosystems to ensure the long-term well-being of both the environment and the city's residents.

Recommendation

The assessment of river encroachment along the Kaduna River in Kaduna Metropolis has provided valuable insights into the complex dynamics of urban development in riverine environments. To advance our understanding and develop effective strategies for

sustainable urban planning, future research should prioritize several key areas. Longitudinal studies are essential to monitor trends in river encroachment over time, offering a comprehensive understanding of evolving challenges and assessing the long-term effectiveness of mitigation measures. Additionally, incorporating advanced hydrological modeling and flood risk assessment techniques will help evaluate how encroachment influences flood risk, enabling better prediction of potential consequences and improving flood management strategies.

Investigating the impact of climate change on river encroachment and floodplain dynamics is another crucial area for future research. Understanding how changing climate patterns exacerbate challenges in urban areas will aid in developing adaptation strategies. Alongside this, exploring the socioeconomic implications of river encroachment—such as community displacement, property damage, and economic costs associated with flooding—will provide a holistic view necessary for comprehensive urban planning. In-depth studies on the ecological consequences of encroachment, focusing on aquatic habitats, water quality, and biodiversity, are also vital for creating sustainable solutions that balance human and environmental well-being. Policy and governance analysis is critical to evaluate the effectiveness of existing regulations and governance structures in managing river encroachment.

Identifying gaps and proposing improvements in legal and institutional frameworks will enhance the management of riverine urban development. Community engagement is equally important; involving local communities and stakeholders in research ensures that their perspectives are considered in decision-making processes, fostering sustainable urban development. Comparative studies with other urban areas facing similar challenges can reveal valuable lessons and best practices, contributing to a broader understanding of river encroachment issues. Future research should also explore innovative and sustainable solutions for mitigating river encroachment, such as green infrastructure, smart city technologies, and participatory planning approaches. Disseminating research findings widely to policymakers, urban planners, environmental organizations, and the public ensures practical application of gained knowledge.

Encouraging interdisciplinary collaboration among researchers from various fields—including hydrology, ecology, urban planning, and social sciences—will lead to comprehensive solutions, combining diverse expertise. Securing funding and support for research initiatives is essential to ensure the continuity of studies and the implementation of sustainable strategies. By addressing these recommendations, future research can significantly contribute to understanding the challenges posed by river encroachment in urban areas and facilitate the development of effective, sustainable solutions. These efforts are crucial for the well-being of urban populations and the natural environments they inhabit.

Informed constant

Not applicable

Ethical approval

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

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Data and materials availability

All data associated with this study are present in the paper.

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