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Spatial Temporal Dynamics of Hydrological Systems in Part of River Benue Makurdi, Benue State: A GIS Analysis of Critical Environmental Resource Management in Makurdi, Nigeria

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Abstract

This study explores the complex dynamics of land use and land cover (LULC) transformations along and within the River Benue in Makurdi, Nigeria, with particular focus on seasonal variations of water resources and alluvial deposits. Using advanced remote sensing and Geographic Information System (GIS) technologies, multi-temporal Landsat satellite imagery from 1976 to 2024 was analyzed to assess environmental changes and their implications for sustainable resource management. The research employed a 6 km buffer zone along the River Benue, utilizing QGIS, ArcGIS, ERDAS Imagine, and Terrset 2020 for supervised classification and change detection analyses. Five distinct land cover classes were identified: Built-Up, Farmland, Water Body, Vegetation, and Alluvial Deposits. Key findings revealed significant transformations over the 48-year period. Water bodies declined drastically during dry seasons, shrinking from 79.19 km² in 1976 to 42.43 km² in 2024. Conversely, alluvial deposits exhibited consistent growth from 18.03 km² to 54.98 km², reflecting changes in sedimentation patterns. Urbanization was a pronounced driver of LULC changes, with built-up areas expanding dramatically from 13.23 km² to 94.03 km², coinciding with vegetation decline from 412.28 km² to 262.90 km². Seasonal variations highlighted the basin's dynamic nature, with wet seasons showing significant water body expansions (304.85 km² in 2012 and 236.61 km² in 2022) attributed to dam releases and precipitation. Predictive modelling projected continuing reductions in vegetation and water bodies coupled with increases in built-up and agricultural areas unless targeted conservation efforts are implemented.

Keywords: *Remote Sensing; GIS; Land Use/Land Cover; River Benue; Predictive Modelling; Hydrological Dynamics.*

I. INTRODUCTION

Natural resources form the fundamental basis of human civilization, providing essential elements for life and economic development. However, increasing pressures from population growth, urbanization, and industrialization have led to widespread exploitation and depletion of these vital resources (Hula & Ukpong, 2013). The River Benue, a major tributary of the Niger River, represents a critical water resource in Nigeria, supporting millions of people through provision of water for domestic, agricultural, and industrial purposes.

Remote sensing and Geographic Information Systems (GIS) have revolutionized resource mapping, offering unprecedented capabilities in monitoring and analyzing natural resources over vast areas with high accuracy and efficiency (Weng & Wang, 2014). These technologies provide unique opportunities to assess spatial and temporal variations of water bodies, vegetation, and land use patterns. The integration of remote sensing data with GIS allows for sophisticated spatial analysis and modeling, revealing complex interrelationships between various natural resources (Cohen & Goward, 2004).

The Benue River basin has experienced substantial environmental challenges due to rapid population growth and urbanization, resulting in environmental degradation, water pollution, and habitat loss (Ezekwe et al., 2015). Traditional methods of resource mapping are often limited in spatial coverage and temporal resolution, while remote sensing techniques enable comprehensive analysis of natural resource dynamics through multi-temporal and multi-spectral data acquisition (Ramona et al., 2016).

Climate change adds complexity to natural resource management in the region. Rising temperatures, altered precipitation patterns, and extreme weather events exacerbate existing challenges such as water scarcity, soil degradation, and habitat loss (Musetsho et al., 2021). Understanding these dynamics is crucial for developing proactive strategies ensuring long-term sustainability of the region's ecological and economic resources.

Despite the region's abundant endowment of water bodies, vegetation, mineral deposits, and agricultural lands, these resources face mounting pressure from anthropogenic activities and environmental factors. Uncontrolled urbanization, agricultural expansion, deforestation, and industrial activities have led to resource degradation and depletion, jeopardizing ecological integrity and inhabitants' livelihoods (Ezekwe et al., 2015). A major challenge is the lack of comprehensive, up-to-date information on spatial distribution, abundance, and dynamics of natural resources around River Benue.

This study aims to contribute to sustainable development and environmental management of the River Benue region through comprehensive natural resource mapping. By creating a spatial database and examining trends within the river catchment area from 1976 to 2024, this research attempted to promote sustainable management strategies that would help to facilitate the river's ecological integrity. The specific objectives are to: (1) identify, locate, and demarcate various natural resources within the River Benue basin, emphasizing water sources and alluvial deposits; (2) assess transformations between alluvial deposits and water bodies over the study period; and (3) predict future trends in the River Benue system.

II. STUDY AREA

The study focuses on the River Benue region in Makurdi, Nigeria, situated between latitudes 6°25'E and 8°8'E and longitudes 7°47'N and 10°0'N. Benue State shares borders with five Nigerian states and Cameroon, reinforcing its cultural and agricultural significance as the "Food Basket of the Nation."

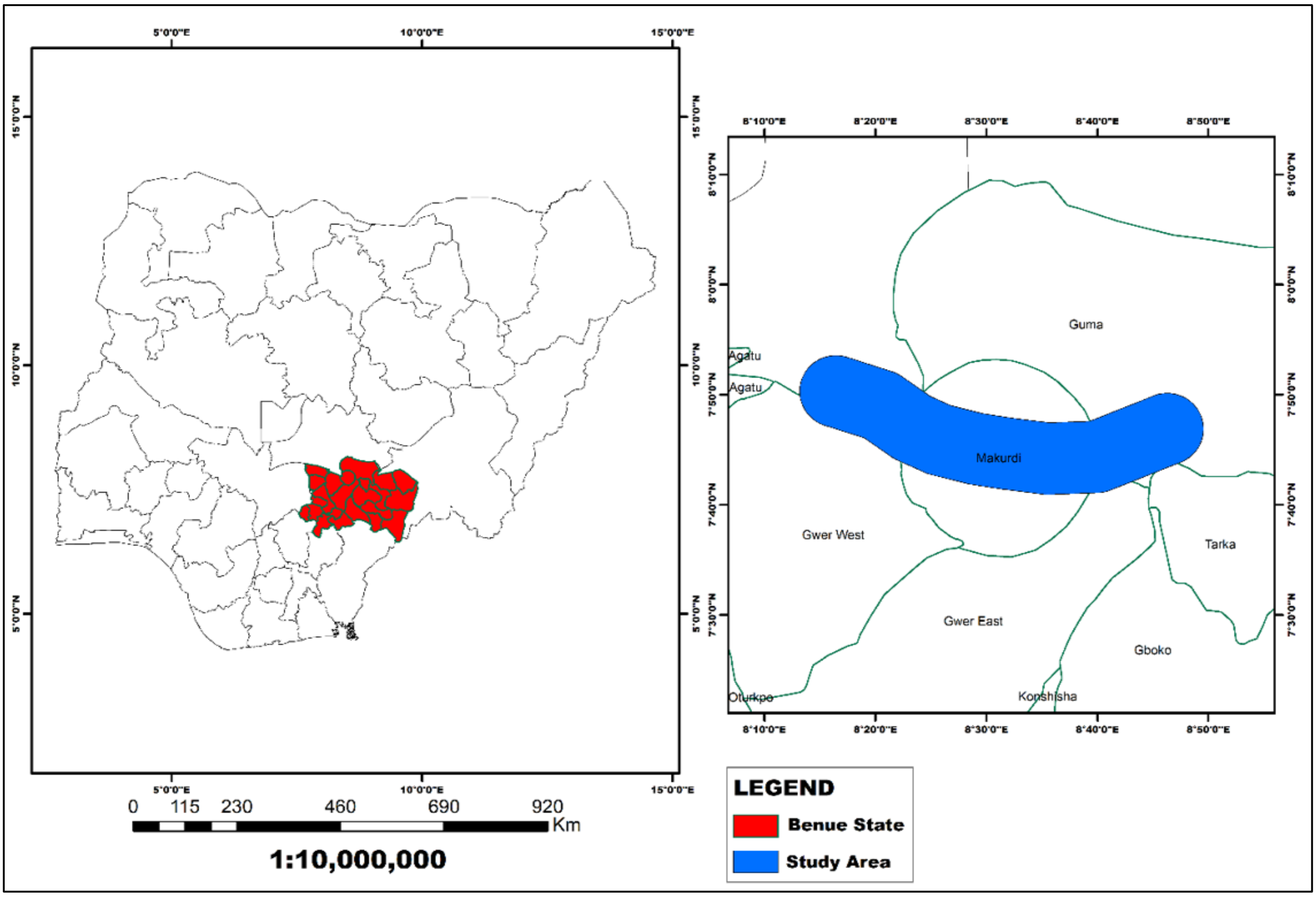

Fig 1 Map of the Study Area Showing the River Benue Catchment in Makurdi, Benue State, Nigeria

The study area encompasses a 6 km stretch north and south of the river and a 25 km radius on both sides of the Makurdi Bridge (Figure 1). This zone spans parts of five Local Government Areas (LGAs) in Benue State—Makurdi, Guma, Tarka, Gwer East, and Gwer West and Doma LGA in neighbouring Nasarawa State, capturing diverse climatic, geological, and socio-economic factors.

Benue's tropical sub-humid climate is characterized by a rainy season (April to October) and dry season (November to March), influenced by the Intertropical Convergence Zone (ITCZ). Annual rainfall varies between 1,200 mm and 1,500 mm, with peak precipitation in August and September. Temperatures average 27.5°C but range from 16°C to 38°C. The area experiences harmattan, a dry, dusty wind causing hazy conditions between November and March.

Geologically, the region lies in the Lower Benue Trough, characterized by sedimentary rocks of Cretaceous age. The River Benue significantly shapes local geology, depositing fertile alluvial soils ideal for agriculture. Key formations include Makurdi Sandstone, known for aquifers and mineral deposits.

Agriculture dominates the local economy, with fertile alluvial soils supporting staple crops like yams, cassava, maize, and rice, alongside cash crops including soybeans, sesame, and groundnuts. Vegetable farming thrives near the river with irrigation supporting crops such as tomatoes and peppers. Livestock rearing and fishing complement farming, though overfishing and pollution challenge the latter.

III. MATERIALS AND METHODS

- *Data Sources*

The research employed satellite imagery from multiple Landsat missions spanning several decades for comprehensive land cover change analysis. Data sources included Landsat 1-5 Multispectral Scanner (MSS) images from 1976 (dry season), Landsat 7 Enhanced Thematic Mapper (ETM) images from 2012 (rainy season) and 2013 (dry season), Landsat 8 Operational Land Imager (OLI) images from 2022 (rainy season), and Landsat 9 Operational Land Imager 2 (OLI 2) images from 2024 (dry season).

Table 1 Satellite Data Specifications Used in the Study.

Types	Sources of data	Years
Landsat 1-5 (MSS)	WGS(GLCF)	1976 (dry season)
Landsat 7 (ETM)	WGS(GLCF)	2012 (rainy season)
Landsat 7 (ETM)	WGS(GLCF)	2013 (dry season)
Landsat 8 (OLI)	WGS(GLCF)	2022 (rainy season)
Landsat 9 (OLI)	WGS(GLCF)	2024 (dry season)

IV. METHODOLOGY

The research methodology employed a multi-stage approach analyzing land cover changes and river dynamics using satellite imagery and advanced geospatial technologies. Four specialized GIS and Remote Sensing software packages were utilized: QGIS for cleaning satellite images and addressing scan line errors in Landsat 7 ETM imagery; ArcGIS for creating composite images, managing spatial data, and producing cartographic outputs; ERDAS Imagine 2015 for supervised classification; and Terrset 2020 for change detection analysis and predictive modelling.

The area of interest was defined using ArcGIS's Measuring and Buffer Tools, creating a shapefile for focused analysis. Composite images were clipped to this area to reduce computational complexity. Supervised classification was performed defining five distinct land cover classes: Built-Up, Farmland, Water Body, Vegetation, and Alluvial Deposits. Accuracy assessment was conducted generating overall accuracy and kappa coefficients.

Terrset 2020 performed image crossing analysis between 1976 and 2024, identifying and quantifying land cover changes. The study extended analysis into the future, projecting potential land cover changes for 2024-2034 through predictive modeling generating transition potential maps. Outputs included classified images, change detection results, transition potential maps, and projected land cover classifications exported in standard formats for further analysis.

V. RESULTS AND DISCUSSION

- *Land Use Land Cover Analysis*

The study revealed intricate transformations in land use and land cover from 1976 to 2024, with particular significance in water bodies and alluvial deposits evolution. Using advanced satellite imagery and GIS techniques, comprehensive mapping and analysis examined spatial and temporal changes across five primary land cover classes.

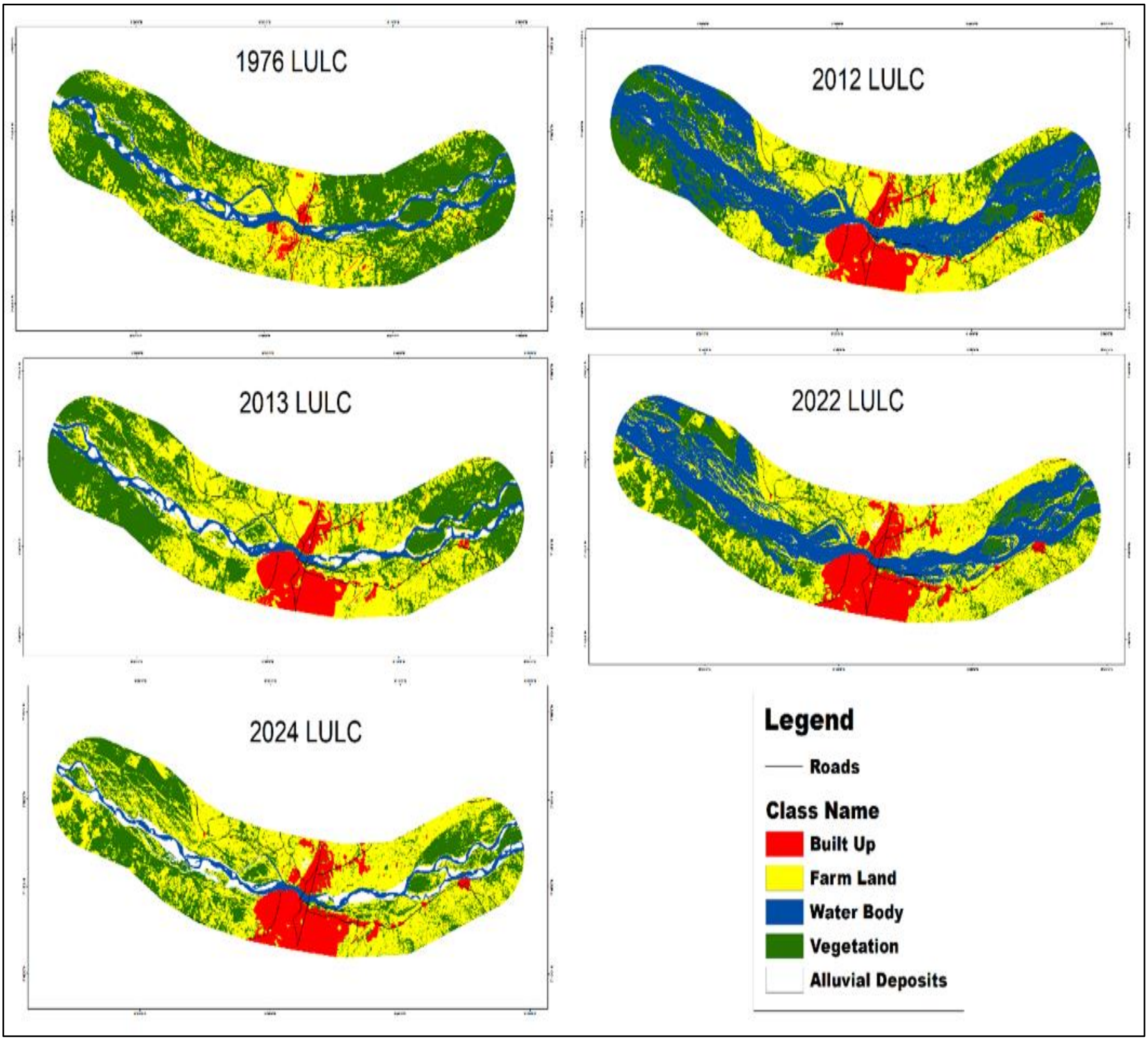

Fig 2 Land Use Land Cover Maps Showing Temporal Changes from 1976 to 2024 Across Different Seasons

Table 2 Land Use Land Cover Statistics (km²) for Different Time Periods

Class Names	1976 Dry Season		2012 Wet Season		2013 Dry Season		2022 Wet Season		2024 Dry Season	
	(Area Km2)	%	(Area Km2)	%	(Area Km2)	%	(Area Km2)	%	(Area Km2)	%
Built Up	13.23	1.63	72.84	9.0	73.13	9.03	93.96	11.61	94.03	11.61
Farm Land	286.68	35.42	244.59	30.1	325.12	40.16	298.39	36.86	355.29	43.88
Water Body	79.19	9.78	304.85	37.1	54.52	6.73	236.61	29.23	42.43	5.24
Vegetation	412.28	50.94	183.48	22.7	318.77	39.38	177.7	21.95	262.9	32.47
Alluvial Deposits	18.03	2.23	3.26	1.1	38.01	4.70	2.81	0.35	54.98	6.79
TOTAL	809.41	100.00	809.54	100.0	809.55	100.00	809.47	100.00	809.63	100.00

➢ *Dry Season LULC Comparison (1976, 2013, and 2024)*

The analysis revealed significant landscape transformations during dry seasons over the past decades (Figure 3). Built-up areas expanded dramatically from 13.23 km² in 1976 to 93.96 km² in 2024, attributed to population growth, rural-urban migration, and infrastructure development. Makurdi, as Benue State's capital, experienced surge in demand for residential, commercial, and industrial areas.

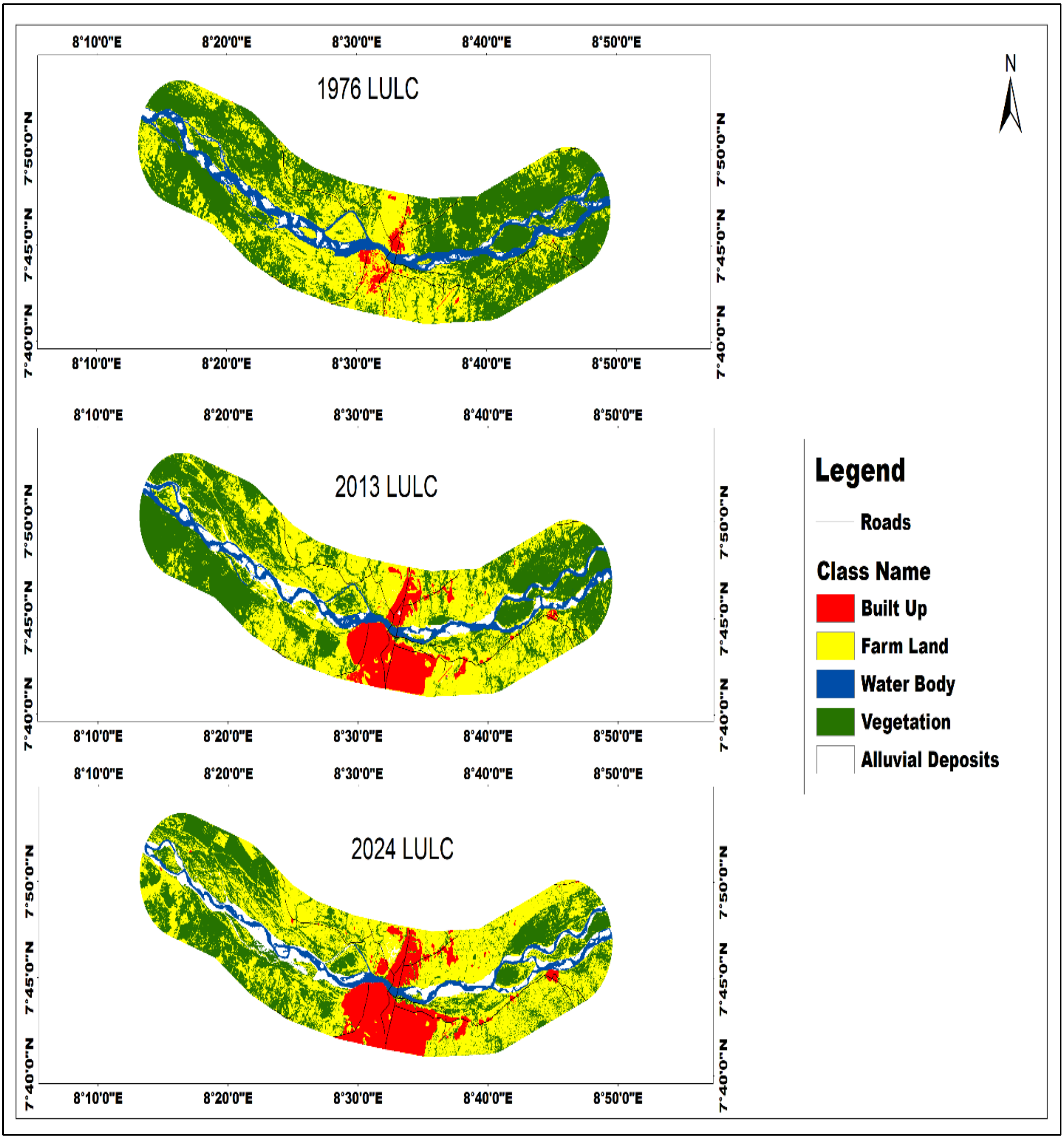

Fig 3 Land Use Land Cover Comparison for Dry Seasons (1976, 2013, and 2024).

Built-up expansion occurred largely at vegetation expense, which decreased significantly from 412.28 km² in 1976 to 262.90 km² in 2024, raising concerns about deforestation, habitat fragmentation, and biodiversity loss. Farm land area increased from 286.68 km² to 355.29 km², reflecting growing demand for agricultural production but potentially leading to soil degradation and ecosystem service loss.

Water body area reduction from 79.19 km² in 1976 to 42.43 km² in 2024 represents a concerning trend attributed to climate change-induced precipitation variations, increased water consumption, and potential encroachment by other land uses. Alluvial deposits showed consistent increase from 18.03 km² to 54.98 km², influenced by natural processes and human activities requiring careful management.

➢ *Wet Season LULC Comparison (2012 and 2022)*

Wet season analysis revealed significant changes reflecting the region's dynamic landscape (Figure 4). Built-up areas increased from 72.84 km² in 2012 to 94.03 km² in 2022, demonstrating continued urbanization pressure.

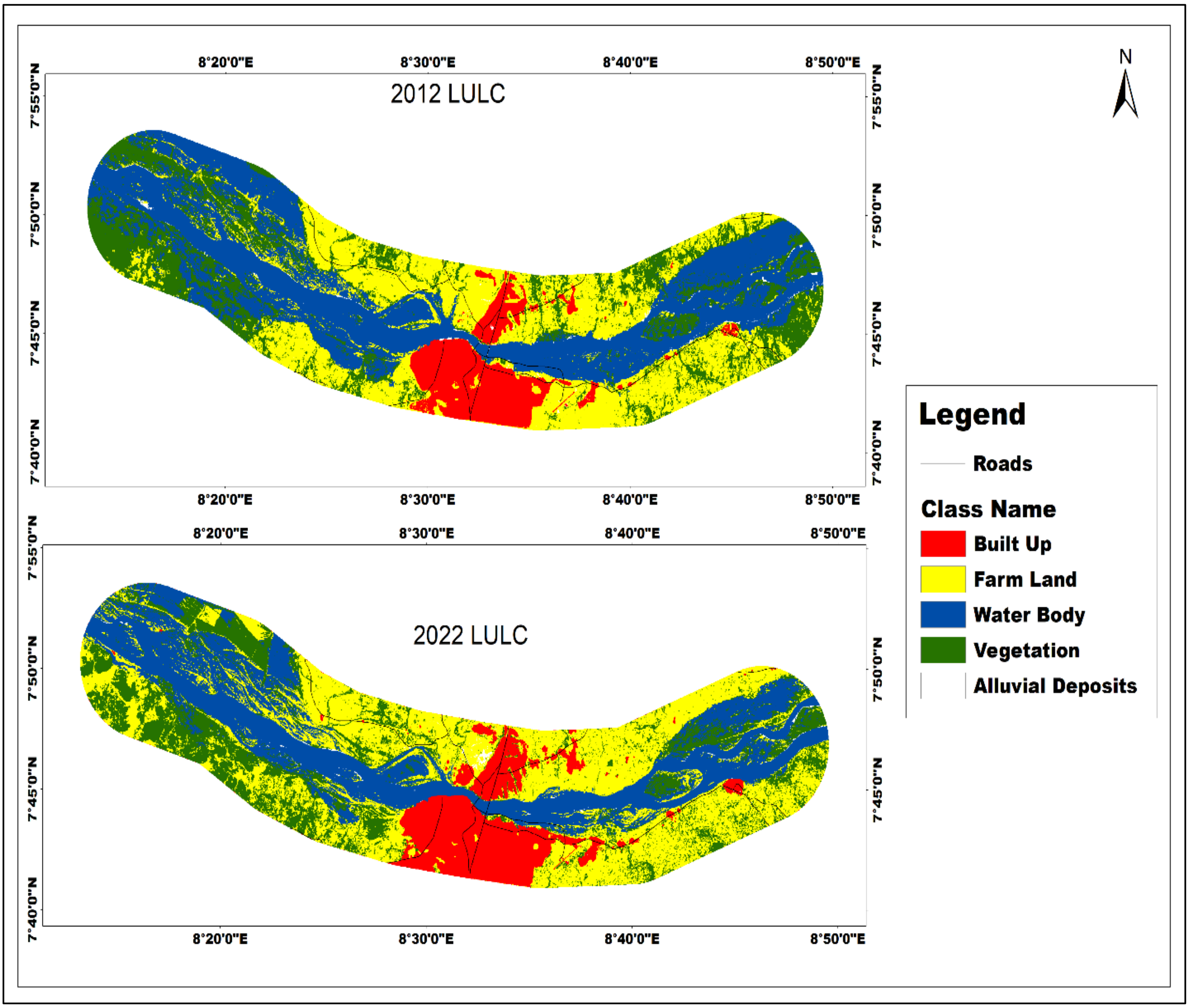

Fig 4 Land Use Land Cover Comparison for Wet Seasons (2012 and 2022).

In 2012, water body coverage expanded substantially to 304.85 km² due to Lagdo Dam water releases and high precipitation, causing widespread flooding. This expansion reduced farmland to 244.59 km² and vegetation to 183.48 km² due to inundation. In 2022, water body area covered 236.61 km², smaller than 2012 but still significant compared to dry seasons, allowing farmland expansion to 298.39 km² and vegetation partial recovery to 177.70 km².

Alluvial deposits showed minor increase from 2.26 km² in 2012 to 2.81 km² in 2022, with smaller coverage during wet seasons due to expanded water bodies from flooding.

➢ *Water Body Dynamics*

Water body landscape demonstrated remarkable temporal variability characterized by dramatic seasonal fluctuations and long-term transformative trends. During dry seasons, water body area contracted substantially from 79.19 km² in 1976 to 42.43 km² in 2024, while wet seasons showed contrasting expansions reaching 304.85 km² in 2012 and 236.61 km² in 2022.

The shrinking trend was attributed to complex environmental and anthropogenic factors including climate change disrupting precipitation patterns, unsustainable water management practices, and land use transformations altering basin hydrological characteristics. Factors contributing to water body reduction include natural seasonal variations, climate change impacts on precipitation patterns, overextraction for various purposes, land use changes affecting hydrological cycles, and sedimentation processes reducing water depth and surface area.

➢ *Alluvial Deposits Transformation*

Parallel to water body changes, alluvial deposits exhibited distinct developmental trajectory with progressive increase from 18.03 km² in 1976 to 54.98 km² by 2024 during dry seasons. This growth reflected complex geological and environmental interactions involving reduced water flow facilitating sediment accumulation, increased sediment transport from surrounding catchments, land use modifications influencing erosion processes, and climate change-induced precipitation variations.

The region's high rainfall intensity over loose soil with minimal vegetation creates high runoff carrying particles into waterways. When water flow is stronger on river bend outsides, it erodes banks while depositing sand and gravel on the inside bends and around riverbanks.

➢ *Projection Probability Analysis*

Projection probability analysis predicted future land cover change likelihood based on historical data and trends from 1976 to 2024. The analysis provided quantitative measures of future event probabilities for decision-making, risk assessment, and planning.

Table 3 Projection Probability Statistics Showing Transition Probabilities Between Land Cover Classes

Class Name	Built Up	Farm Land	Water Body	Vegetation	Alluvial Deposits
Built Up	0.8459	0.1355	0.0013	0.013	0.0043
Farm land	0.1102	0.7256	0.0034	0.151	0.0099
Water Body	0	0.0369	0.7016	0.0473	0.2141
Vegetation	0	0.2723	0.0063	0.715	0.0064
Alluvial Deposits	0.0007	0.0453	0.1699	0.0474	0.7368
First landcover image: 1976 LULC					
Second landcover image: 2024 LULC					
Output prefix: Prediction Two					
Time interval 1: 48					
Time interval 2: 10					
Background cell option: 1					
Proportional error: 0.15					
Confident interval: 15 -25%					

The projection shows probability that 0.0007 built-up, 0.0453 farmland, 0.1699 water body, and 0.0474 vegetation will convert to alluvial deposits with 25% probability (confidence interval 15-25%). Water body coverage trend shows increasing and decreasing patterns based on wet and dry seasons, while alluvial deposit coverage demonstrates significant increase.

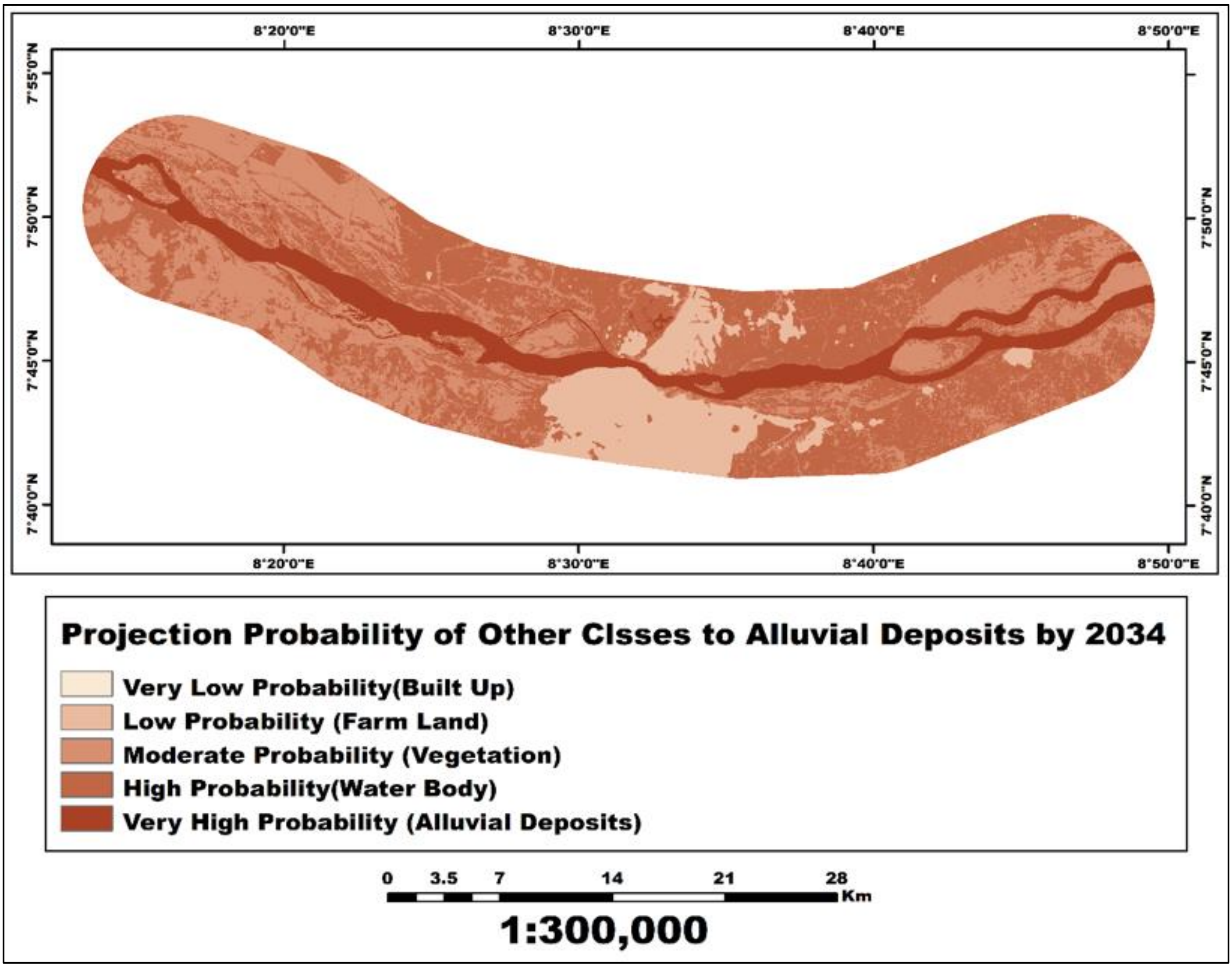

Fig 5 Projection Probability of Other Classes Converted to Alluvial Deposits

The probability projection map (Figure 5) shows land uses converting to alluvial deposits between 1976 and 2024, demonstrating various transformation shapes appearing in River Benue. This conversion proves that land use changes within the river basin can be analyzed and show transitions based on 10-year projection probability from 2024 land cover.

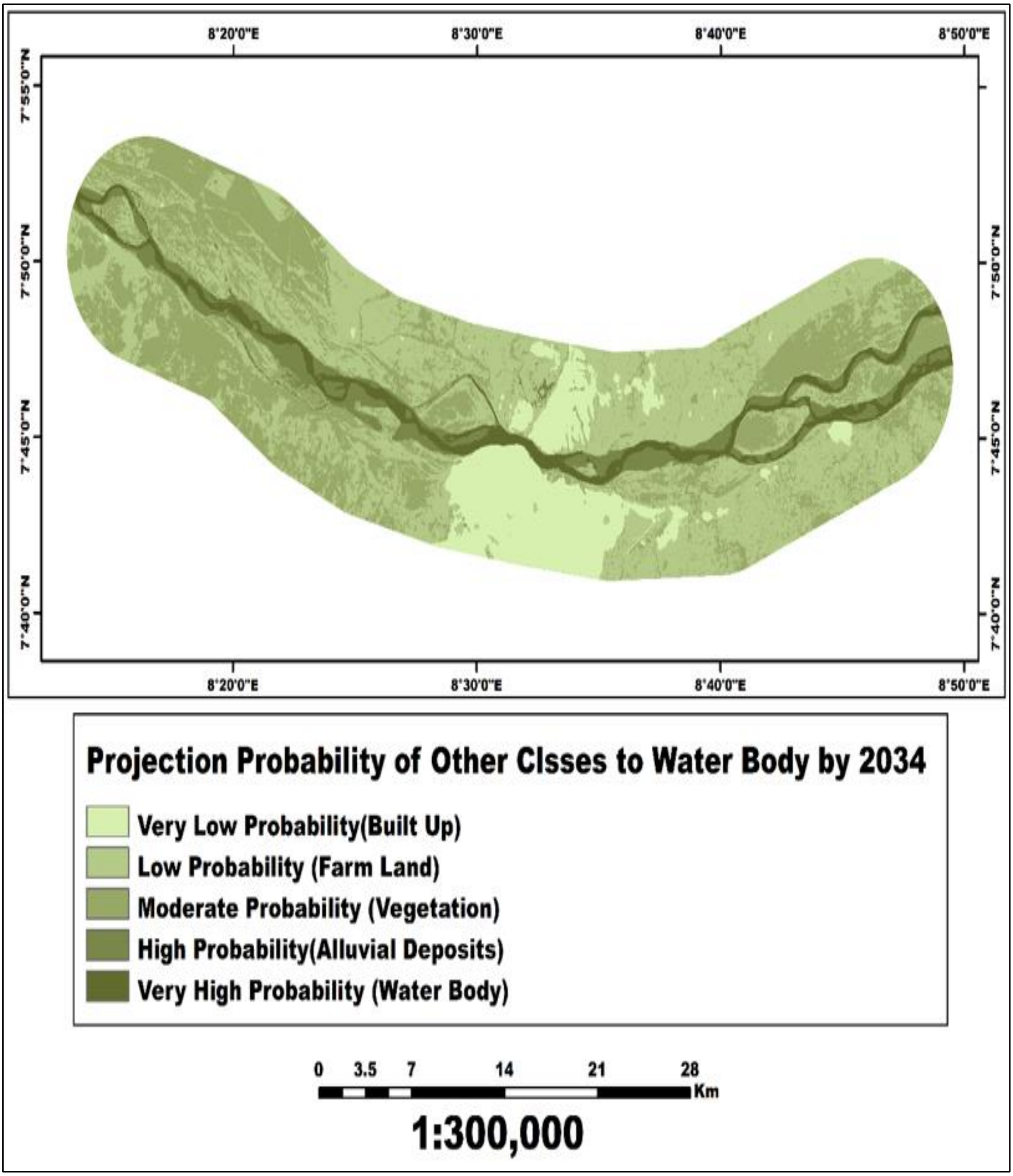

Fig 6 Projection Probability of Other Classes Converted to Water Body

Water body gain probability in River Benue shows transformation potential during 2034 rainy seasons (Figure 6). The conversion probability demonstrates that built-up, farmland, vegetation, and alluvial deposits may transform to water body, showing increased water body probability appearing in research findings.

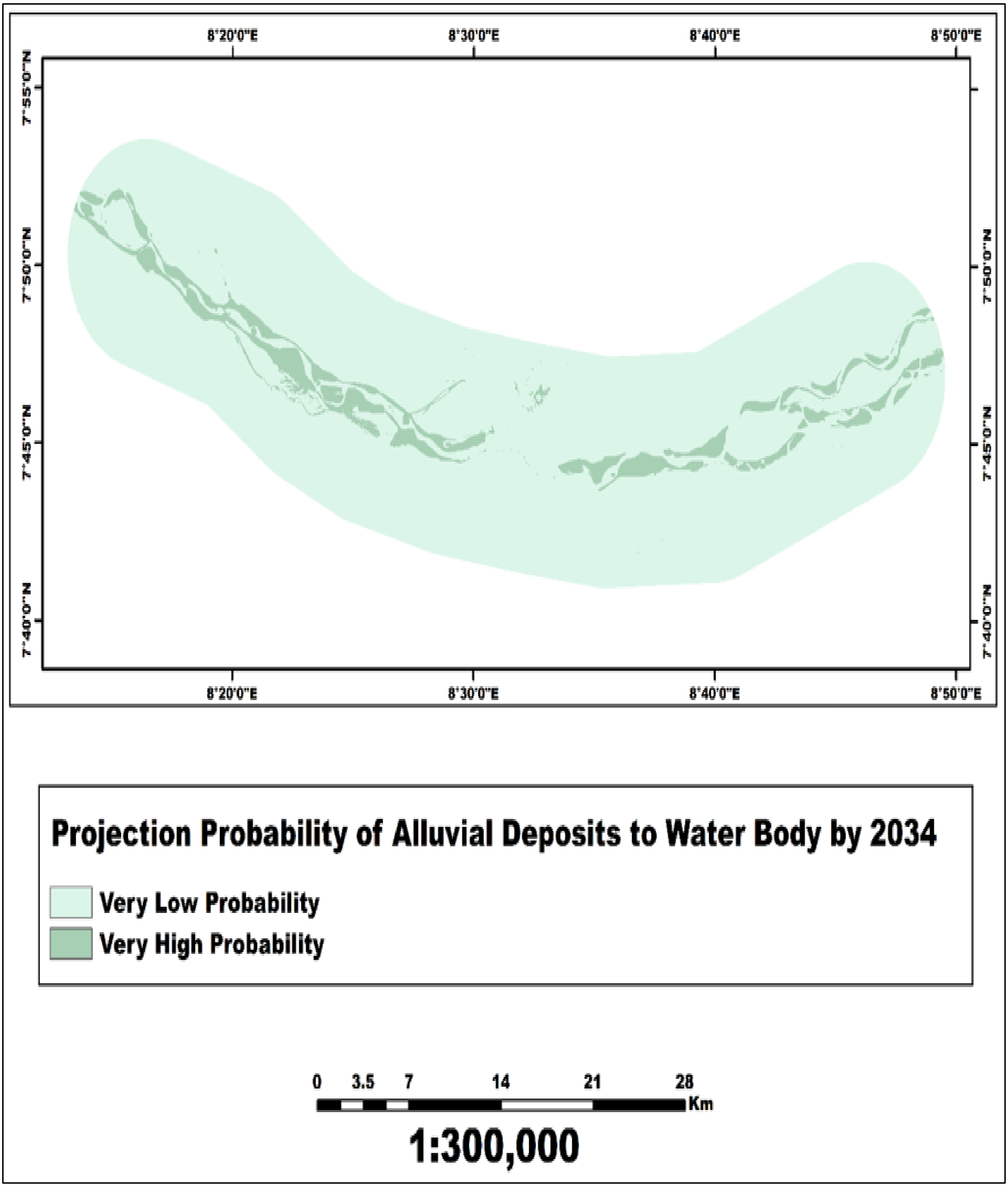

Fig 7 Projection Probability of Alluvial Deposits Converted to Water Body

The low probability projection areas are non-alluvial deposit areas in 2024 with low probability of becoming alluvial deposits by 2034. High and very high probability areas are already alluvial deposits in 2024, maintaining very high probability of remaining as such by 2034.

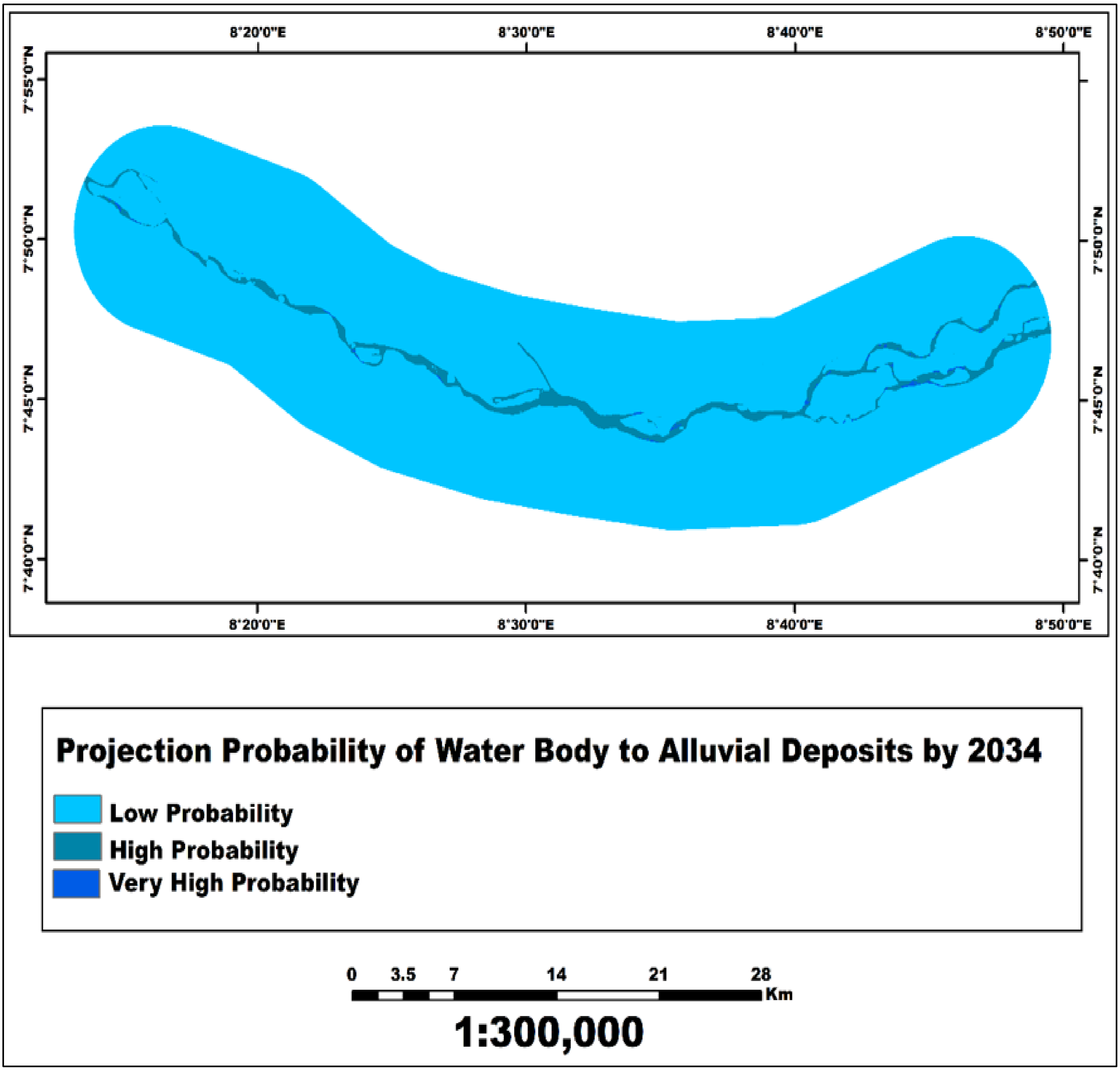

Fig 8 Projection Probability of Water Body Converted to Alluvial Deposits

The transformation probability of water bodies into alluvial deposits shows significant variation depending on seasonal factors, with very low to very high probability ranges reflecting the gradual nature of geological processes occurring over decades while being influenced by human activities and natural events.

VI. CONCLUSION

This comprehensive analysis of the River Benue reveals a landscape influx, shaped by both natural processes and human activities over the 48-year study period. Key findings demonstrate significant urbanization with built-up areas expanding exponentially, agricultural intensification with 24% farmland increase, while water body decline during dry seasons with 46% reduction, substantial alluvial deposit of about 205% increase, and marked seasonal variations highlighting basin dynamics.

These transformations reflect complex interactions between climate change, population growth, urbanization, and land management practices. The rapid urban expansion, while indicating economic development, tremendous challenges to environmental sustainability. The declining water bodies during dry seasons, coupled with increasing alluvial deposits, signal altered hydrological processes with significant implications for water resource management and ecosystem health.

Projection probability analysis suggests continued trends of water body reduction and alluvial deposit increase unless targeted conservation measures are implemented. The study underscores urgent need for integrated sustainable management approaches addressing both development pressures and environmental conservation requirements.

RECOMMENDATIONS

Based on the findings, the following recommendations are proposed:

- *Sustainable Water Management:*
  Implement comprehensive water resource management strategies including sedimentation control, source protection, and equitable access mechanisms.

- *Conservation Efforts:*
  Establish protected areas preserving remaining water bodies, wetlands, and floodplains while creating buffer zones around critical habitats.

- *Land Use Planning:*
  Promote sustainable practices including agroforestry and reforestation to reduce deforestation and soil erosion while implementing zoning regulations controlling urban expansion.

- *Monitoring and Enforcement:*
  Develop regular monitoring systems for land use changes and strengthen enforcement of environmental regulations preventing illegal activities.

- *Community Engagement:*
  Educate and involve local communities in conservation efforts, promoting sustainable livelihoods and environmental stewardship through capacity building programs.

- *Climate Change Adaptation:*
  Implement strategies reducing greenhouse gas emissions and developing adaptation measures for climate change impacts on the River Benue ecosystem.

- *Interagency Collaboration:*
  Foster cooperation among government agencies, NGOs, and stakeholders ensuring coordinated approaches to natural resource management.

These recommendations aim to balance development needs with environmental conservation, ensuring long-term sustainability of this vital ecosystem and supporting communities.

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