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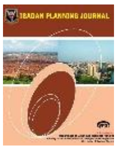

Mapping Climate Change Vulnerability of Transportation Infrastructure in Nigeria Using Gis and Remote Sensing

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Abstract

Climate change poses unprecedented threats to transportation infrastructure in Nigeria, with rising temperatures, intensified rainfall, flooding, coastal erosion, and changing precipitation patterns threatening roads, bridges, railways, airports, and seaports. This study employs Geographic Information Systems (GIS) and remote sensing techniques to systematically map and assess the climate change vulnerability of Nigeria's transportation network. Using multi-temporal satellite imagery, climate projection data, digital elevation models, and infrastructure databases, we analyze exposure to multiple climate hazards including flood risk from intensified precipitation and sea-level rise, erosion susceptibility from extreme rainfall events, heat stress impacts on pavement and railway infrastructure, and coastal inundation threatening maritime and aviation facilities. Our vulnerability assessment integrates hazard exposure, infrastructure sensitivity based on design standards and age, and adaptive capacity considering maintenance regimes and institutional resources. Results reveal that approximately 35% of Nigeria's federal road network faces high or very high vulnerability to climate-related hazards, with critical corridors including Lagos-Ibadan Expressway (flooding), East-West Road (coastal erosion and flooding), and northern routes (heat stress and drought impacts). Over 60% of railway infrastructure exhibits moderate to high vulnerability, while 12 of 22 major airports and 4 of 6 seaports face significant flood or inundation risks. This research provides critical spatial intelligence for climate adaptation planning and infrastructure investment prioritization, contributing to Nigeria's climate resilience objectives and sustainable development goals and therefore concludes that the economic implications are substantial, hence strategies for maintaining transportation infrastructures should be developed.

Keywords
Climate change vulnerability, Transportation infrastructure, GIS, Remote sensing, Flood risk, Coastal erosion

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1. Introduction

1.1 Background and Context

Climate change represents one of the most significant challenges to sustainable development in the 21st century, with developing nations disproportionately vulnerable to its impacts despite contributing least to greenhouse gas emissions (IPCC, 2021). Transportation infrastructure, fundamental to economic activity, social connectivity, and emergency response, faces multiple climate-related threats including flooding from intensified precipitation, sea-level rise threatening coastal facilities, extreme heat damaging pavement and rail infrastructure, erosion undermining road foundations, and changing precipitation patterns affecting drainage systems (Koetse & Rietveld, 2009; Meyer et al., 2014).

Nigeria, Africa's most populous nation with over 220 million inhabitants and a rapidly growing economy, possesses an extensive transportation network including approximately 195,000 kilometres of roads, 3,505 kilometres of railways, 22 airports with paved runways, and 6 major seaports (Federal Ministry of Transportation, 2021). This infrastructure underpins internal commerce, regional trade, and connectivity essential for national development. However, Nigeria's geographic and climatic characteristics create profound climate vulnerability (Nkwunonwo, Whitworth, & Baily, 2020). Nigeria’s geographic diversity, ranging from low-lying coastal plains in the south to arid and semi-arid regions in the north, exposes its transportation networks to a wide spectrum of climate-related hazards.

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Intensifying rainfall has increased the frequency and severity of flooding, often washing away roads, damaging bridges, and disrupting rail operations, particularly in urban and coastal areas. Rising temperatures contribute to pavement deterioration and rail deformation, while sea-level rise and coastal erosion threaten critical transport corridors in states such as Lagos, Bayelsa, and Rivers. These impacts highlight the urgent need for systematic assessment tools that can identify vulnerable transportation assets and support climate-resilient planning

Transportation infrastructure in Nigeria already experiences climate-related challenges. Annual flooding affects major highways, isolating communities and disrupting commerce (Aderogba, 2012). The 2012 floods, Nigeria's worst in decades, damaged over 1,000 kilometres of federal roads, numerous bridges, and rail infrastructure, costing an estimated ₦2.6 trillion in economic losses (Nkwunonwo, Whitworth, & Baily, 2016). Coastal erosion threatens the Lagos-Badagry Expressway and Escravos-Warri Road, requiring repeated emergency interventions (Awosika et al., 1992). Heat-induced pavement failure occurs frequently on northern routes, while inadequate drainage systems result in road deterioration during rainy seasons (Aderamo, 2012).

Despite these evident vulnerabilities, a comprehensive spatial assessment of climate risks to Nigeria's transportation infrastructure remains limited. Existing vulnerability assessments have been largely qualitative, lacking the spatial precision necessary for targeted adaptation planning (Building Nigeria's Response to Climate Change (BNRCC, 2011). Geographic Information Systems (GIS) and Remote Sensing (RS) offer powerful tools for overcoming these limitations by enabling the integration, analysis, and visualization of diverse spatial datasets. Remote sensing provides timely and consistent information on land use and land cover, surface temperature, flood extents, and terrain characteristics, while GIS facilitates multi-criteria analysis, spatial modeling, and vulnerability classification. Together, these technologies allow for the identification of high-risk zones, assessment of infrastructure exposure to multiple climate stressors, and production of decision-support maps at national and sub-national scales. (Chinowsky et al., 2013; Jaroszweski et al., 2010).

1.2 Research Problem and Significance

Despite growing scholarly recognition of climate change as an existential threat to transportation infrastructure, a critical analytical void persists in the Nigerian context. Existing studies have been geographically narrow, concentrating predominantly on Lagos and a handful of southern urban centres, examining discrete hazards such as coastal inundation, flooding, and storm disruptions in isolation. A systematic review of climate change impact research across Nigeria confirmed this imbalance, revealing that research effort remains heavily skewed toward a small number of cities, while the road, rail, and bridge networks spanning the country's six geopolitical zones each defined by sharply contrasting climate hazard profiles, from the arid Sahelian North-East to the tropical coastal South-South remain almost entirely unmapped from a vulnerability standpoint (Matemilola et al., 2021).

Although GIS and remote sensing technologies have advanced flood risk delineation in several Nigerian cities, their application has been largely confined to hazard mapping, with minimal translation into infrastructure policy, investment planning, or governance reform. A recent systematic review of GIS-based flood risk studies in Nigeria found a persistent gap between analytical outputs and practical implementation, noting that spatial knowledge rarely informs infrastructure design or urban decision-making (Nwogu et al., 2025). This knowledge deficit carries direct fiscal consequences. The Climate Policy Initiative's Landscape of Climate Finance in Nigeria reported that despite a 32% rise in total climate finance to USD 2.5 billion in 2021/22, adaptation investment continues to lag significantly behind mitigation, with data gaps further obscuring where climate-resilient transport infrastructure investment is most urgently needed (CPI, 2025). Globally, the UNEP Adaptation Gap Report (2025) found that international public adaptation finance fell to USD 26 billion in 2023 approximately twelve to fourteen times below estimated needs leaving infrastructure-dependent economies like Nigeria dangerously underprotected.

At the methodological frontier, Koks et al. (2019) demonstrated through a landmark global analysis that roughly 27% of all road and railway assets are exposed to at least one natural hazard, with flooding driving nearly 73% of expected annual damages, yet this global-scale assessment cannot substitute for the country-specific, multi-hazard composite analysis that national transport planning requires. While GIS-based vulnerability frameworks have been successfully piloted for road networks in other sub-Saharan African contexts (Kamara et al., 2025), no comparable study has been applied to Nigeria's national transport system.

These literatures also reveals that no study has produced a spatially explicit, GIS and remote sensing based, multi-hazard composite vulnerability assessment of Nigeria's transportation infrastructure at the national scale one that integrates hazard exposure, infrastructure sensitivity, and adaptive capacity across all six geopolitical zones into actionable vulnerability maps. This study directly addresses that gap.

1.3 Research Objectives

This study aims to develop a comprehensive GIS-based climate vulnerability assessment framework for Nigeria's transportation infrastructure. Specific objectives include: (1) mapping the spatial distribution of climate hazards (flooding, heat stress, coastal inundation, erosion) affecting transportation infrastructure; (2) assessing infrastructure exposure and sensitivity to identified climate hazards; (3) evaluating adaptive capacity of transportation authorities and maintenance systems; (4) producing integrated vulnerability maps identifying priority areas for adaptation intervention; and (5) recommending adaptation strategies and climate-resilient design standards for different infrastructure types and geographic contexts.

1.4 Study Area

Nigeria covers 923,768 km^2 between latitudes 4°N and 14°N and longitudes 3°E and 15°E Shown in figure 1. Climate ranges from equatorial in the coastal south (annual rainfall exceeding 3,000mm) through tropical savanna in the central belt to semi-arid in the north (annual rainfall below 500mm). Temperature varies from 25-28°C in coastal areas to 28-35°C in northern regions, with extreme temperatures exceeding 45°C during the dry season. The country experiences distinct wet and dry seasons, with the rainy season typically lasting April-October in the south and June-September in the north.

Nigeria's transportation network includes federal highways connecting major cities, state roads providing regional connectivity, and local roads serving rural areas. The railway system includes both the legacy narrow-gauge network and new standard-gauge lines under construction. Twenty-two airports with paved runways serve domestic and international traffic, with Lagos, Abuja, Port Harcourt, and Kano handling the majority of passenger and cargo movements. Six major seaports at Lagos (Apapa and Tin Can Island), Port Harcourt, Calabar, Warri, and Onne facilitate international trade, handling over 90 million tons of cargo annually.

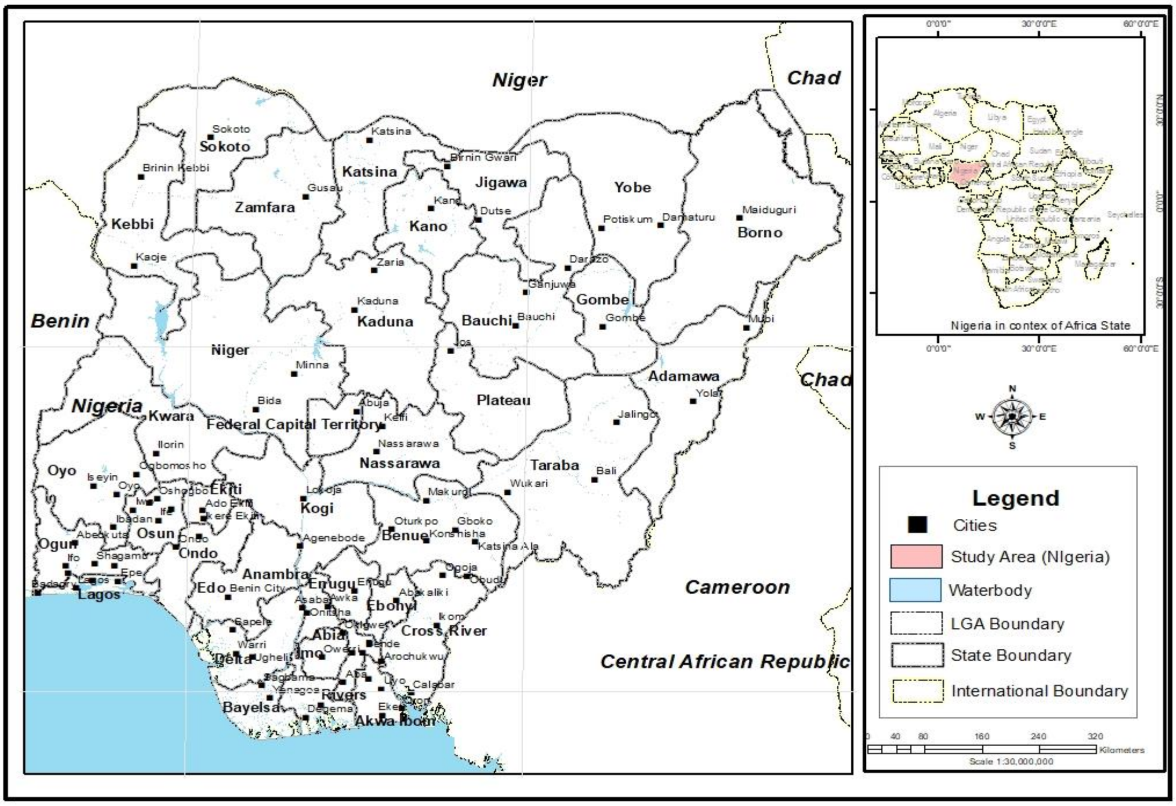

Figure 1: The study area map

2. Literature Review

2.1 Climate Change Impacts on Transportation

Transportation infrastructure faces multiple direct and indirect climate change impacts. Flooding, the most immediate threat, results from intensified precipitation events that overwhelm drainage systems and inundate low-lying routes (Mallakpour & Villarini, 2015). Climate models project 10-30% increases in extreme precipitation frequency across Nigeria by mid-century. Heat stress affects pavement through accelerated aging, rutting, and cracking when temperatures exceed design thresholds (Qiao et al., 2013). Northern Nigerian highways already experience temperatures 5-10°C above original design assumptions. Railway infrastructure faces track buckling, signal failures, and overhead wire sagging during extreme heat events. Sea-level rise threatens coastal infrastructure through direct inundation, increased storm surge, and saltwater intrusion affecting foundations and drainage systems (Nicholls et al., 2007). Nigeria's 853 kilometres coastline includes major transportation corridors and port facilities vulnerable to a projected 0.3-0.6 metre sea-level rise by 2050.

Extreme weather events including windstorms, dust storms, and intense rainfall cause immediate infrastructure damage and operational disruptions. Meyer et al. (2014) documented transportation disruptions from extreme weather increasing globally, with developing nations experiencing disproportionate impacts due to infrastructure age and maintenance limitations. Indirect impacts include changing soil moisture affecting road foundations, altered groundwater levels undermining infrastructure stability, and changing vegetation patterns affecting erosion control and drainage (Koetse & Rietveld, 2009).

2.2 Vulnerability Assessment Frameworks

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC, 2014). This framework integrates three components: exposure (presence of people, infrastructure, or assets in places that could be adversely affected), sensitivity (degree to which a system is affected by climate-related stimuli), and adaptive capacity (ability of systems to adjust to climate change, moderate potential damages, or cope with consequences).

For transportation infrastructure, exposure analysis identifies which facilities face which climate hazards at what intensities. Sensitivity depends on design standards, materials, age, condition, and inherent susceptibility to specific hazards. Adaptive capacity reflects maintenance quality, institutional capacity, financial resources, and governance effectiveness. Schweikert et al. (2014b) developed the Infrastructure Planning Support System integrating these dimensions for road vulnerability assessment across multiple countries. Their framework employs multi-criteria decision analysis combining weighted hazard layers with infrastructure characteristics. Malczewski (2006) reviews GIS-based multicriteria approaches, emphasizing the importance of explicit criteria weighting and sensitivity analysis.

2.3 GIS and Remote Sensing Applications

Geographic Information Systems provide essential tools for integrating diverse spatial datasets required for comprehensive vulnerability assessment. GIS enables spatial analysis including overlay analysis, proximity analysis, network analysis, and spatial modeling (Malczewski, 2006). Remote sensing complements GIS by providing consistent, repeatable observations of land surface characteristics, land use patterns, surface temperatures, and flood extents. Satellite imagery from platforms including Landsat, Sentinel, and MODIS supports change detection, hazard monitoring, and infrastructure mapping.

Flood hazard assessment combines digital elevation models, precipitation data, drainage networks, and land cover information. Schumann and Moller (2015) demonstrate radar remote sensing for flood extent mapping, particularly valuable during cloud-covered rainy seasons. Heat stress assessment employs thermal infrared imagery from Landsat and MODIS to map land surface temperatures. Coastal vulnerability assessment integrates elevation data, shoreline change analysis, and storm surge modeling. Ma et al. (2019) review deep learning applications in remote sensing, highlighting improved classification accuracy for land cover and infrastructure mapping. These technological advances enable more precise vulnerability assessments than previously possible.

2.4 Transportation Vulnerability in Sub-Saharan Africa

African transportation infrastructure faces particular vulnerability due to infrastructure age, limited maintenance budgets, rapid urbanization, and institutional capacity constraints (Kumar & Barrett, 2008). Transport infrastructure across low-income countries in Africa remains highly susceptible to the effects of climate change, with surveys of stakeholders across multiple nations consistently identifying poor implementation of resilience policies and lack of knowledge exchange as critical barriers to adaptive capacity.

Several studies have examined climate impacts on African transportation at a regional scale. Chinowsky et al. (2013) assessed road climate vulnerability across multiple African countries, projecting substantial adaptation costs. Extending this line of inquiry, Chinowsky et al. (2015) applied a stressor-response methodology to road infrastructure in Malawi, Mozambique, and Zambia, running 425 climate scenarios and estimating that these three southern African countries face a potential $596 million cost to maintain and repair roads from temperature and precipitation changes through 2050. Springer However, these studies typically employed coarse spatial resolution inadequate for project level planning.

Country specific assessments remain limited. Climate related disasters are increasingly damaging road infrastructure through washouts, erosion, and structural failures, resulting in accidents, traffic disruptions, economic losses, and escalating maintenance costs, yet locally adapted vulnerability assessment tools remain scarce, leaving critical research gaps in climate-resilient infrastructure planning across the continent. Frontiers Nkwunonwo et al. (2020) reviewed flood modeling in developing countries, identifying data limitations as a primary constraint. Even where country level economic assessments have been attempted, such as analyses projecting cumulative costs exceeding $473 million for Ghana's road network under a non-adaptation scenario through 2100, the findings underscore how little work has been done to assess the economic impact of climate change on road infrastructure at the national scale across Sub-Saharan Africa. (Twerefou,et al 2014)

3. Methodology

3.1 Data Sources and Processing

Climate data were obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6), specifically temperature and precipitation projections from multiple General Circulation Models under Shared Socioeconomic Pathway scenarios SSP2-4.5 (moderate emissions) and SSP5-8.5 (high emissions). We utilized outputs from five climate models selected for their performance in West African climate simulations. Historical climate data (1981-2020) from the Nigerian Meteorological Agency provided baseline conditions. Climate data were downscaled from native model resolution to 10 km using statistical methods. Ensemble means from five climate models reduces the individual model uncertainties while preserving the range of projected outcomes.

Satellite imagery included Landsat 8 and 9 providing 30-metre resolution optical and thermal imagery acquired every 16 days, enabling land cover classification and urban heat assessment. Sentinel-1 Synthetic Aperture Radar at 10-meter resolution proved particularly valuable during the rainy season when cloud cover limits optical imagery, supporting flood extent mapping and all-weather infrastructure monitoring. Sentinel-2 multispectral imagery at 10-metre resolution complemented Landsat for detailed land cover mapping. MODIS sensors provided 250-500 metre resolution data valuable for broad-scale temperature trends and vegetation dynamics. Digital elevation data from the Shuttle Radar Topography Mission (SRTM) at 30-metre resolution and ALOS PALSAR at 12.5-meter resolution supported terrain analysis, slope calculation, drainage network delineation, and flood modeling. The higher-resolution ALOS data proved particularly valuable in low-relief coastal areas. Infrastructure data came from the Federal Ministry of Transportation, State Ministries of Works, OpenStreetMap community mapping, and field GPS surveys conducted from 2022 to 2024. Field surveys validated infrastructure locations, documented current conditions, and identified segments not in existing databases.

Socioeconomic data from WorldPop provided gridded population estimates at 100-metre resolution, while the Nigerian National Bureau of Statistics contributed economic indicators and demographic statistics supporting assessment of infrastructure importance based on populations served and economic activities.

3.3 Hazard Assessment Methods

3.3.1 Flood Hazard

Flood hazard assessment integrated multiple factors: precipitation intensity (current and projected), drainage density, slope gradient, elevation, and land cover. We employed the Height above Nearest Drainage (HAND) method for identifying flood-prone areas, combined with rainfall-runoff modeling using the SCS Curve Number method. Areas with

HAND values below 5 metres and high precipitation exposure received high flood hazard ratings. Urban areas with impervious surfaces exceeding 40% received additional weighting due to increased runoff. Historical flood extent mapping from Sentinel-1 SAR imagery during 2012, 2018, and 2022 flood events validated the hazard model.

3.3.2 Heat Stress

Heat stress assessment employed land surface temperature (LST) derived from Landsat thermal bands and MODIS thermal products. We calculated maximum annual temperatures, frequency of extreme heat events (LST > 45°C), and projected temperature increases under climate scenarios. Areas experiencing current maximum LST above 42°C or projected increases exceeding 3°C by 2050 received high heat hazard classifications. Urban heat island effects were quantified by comparing urban versus rural temperature differentials.

3.3.3 Coastal Vulnerability

Coastal vulnerability integrated elevation (areas below 5 metres above sea level), slope are (gentle slopes more vulnerable), shoreline change rates from multi-temporal imagery analysis (1984-2024), and storm surge modeling. We applied the Coastal Vulnerability Index methodology combining these factors with coastal geomorphology and wave exposure. Sea-level rise scenarios of 0.3m, 0.5m, and 0.8m by 2050, 2070, and 2100 respectively identified areas at risk of permanent inundation versus episodic flooding during storm events.

3.3.4 Erosion Risk

Erosion risk assessment employed the Revised Universal Soil Loss Equation (RUSLE) integrating rainfall erosivity (R-factor calculated from precipitation intensity), soil erodibility (K-factor from soil surveys), slope length and steepness (LS-factor from DEM), land cover (C-factor from satellite imagery), and conservation practices (P-factor). Areas with estimated annual soil loss exceeding 20 tons per hectare per year received high erosion risk classifications. Gully erosion susceptibility received additional analysis in southeastern states where this hazard is particularly severe.

3.4 Infrastructure Vulnerability Assessment

Infrastructure exposure was determined through the spatial intersection of infrastructure networks with hazard zones. Each infrastructure segment received exposure scores for each hazard type based on hazard intensity at that location. Sensitivity assessment considered design standards (older infrastructure designed to lower standards received higher sensitivity scores), age (infrastructure older than 20 years received increased sensitivity), materials (some materials are more vulnerable to specific hazards), and current condition ratings from inspection reports where available.

Adaptive capacity assessment evaluated maintenance frequency and quality, institutional capacity of responsible agencies (staffing, budget, technical expertise), availability of climate information and early warning systems, and existence of adaptation plans or climate-resilient design guidelines. These factors were scored and combined into an adaptive capacity index. The overall vulnerability index combined these components: $V = (E \times S) / AC$, where V is vulnerability, E is exposure, S is sensitivity, and AC is adaptive capacity. Results were classified into five categories: very low (0-0.2), low (0.2-0.4), moderate (0.4-0.6), high (0.6-0.8), and very high (0.8-1.0) vulnerability.

3.5 Economic Impact Assessment

Economic impact assessment integrated infrastructure replacement costs, repair costs for different damage levels, business disruption costs, and indirect economic impacts. We employed damage functions relating hazard intensity to expected damage levels, combined with infrastructure asset values from government databases and engineering cost estimates. Disruption costs considered traffic volumes, economic value of transported goods, and duration of service interruptions. Monte Carlo simulation with 10,000 iterations captured uncertainties in climate projections, damage functions, and economic parameters.

4. Results

4.1 Climate Hazard Exposure Patterns

4.1.1 Flood Hazard Distribution

Flood hazard mapping (Figure 2) reveals that approximately 42% of Nigeria's federal road network experiences moderate to very high flood hazard (Figure 2). The spatial distribution exhibits clear patterns related to topography, drainage, and precipitation. Highest flood hazards occur in:

Niger Delta region: The East-West Road connecting Warri, Yenagoa, and Port Harcourt faces very high flood hazard along 68% of its 338-kilometre length, with extensive low-lying terrain, high rainfall (>2,500mm annually), and poor drainage creating chronic flooding (consistent with findings by Nkwunonwo, Whitworth, & Baily, 2020). The Aba-Port Harcourt and Calabar-Itu routes exhibit similar vulnerability. Analysis shows that under current conditions, these routes experience flood disruption affecting traffic flow during 45-60 days annually during the rainy season, with complete road closure occurring 8-15 days per year.

Coastal Lagos: Major routes including Lagos-Badagry Expressway, Ikorodu Road, and coastal sections of Lekki-Epe Expressway face high flood hazard from both riverine flooding and poor urban drainage. Lagos Island and Victoria Island experience compound flooding from heavy rainfall, high water tables, and tidal influences. The Lagos-Ibadan Expressway, Nigeria's busiest corridor carrying over 15,000 vehicles daily, experiences moderate to high flood hazard along 35% of its length, particularly in the Ogun State portion where poor drainage combines with intense rainfall. Climate projections indicate that by 2050, areas currently experiencing 10-year return period floods will face such events every 5-7 years under RCP 4.5 (Akinsanola & Zhou, 2019).

Middle Belt river crossings: Major bridges crossing the Niger, Benue, Kaduna, and tributaries face flood hazard from increasing river flows. The Niger Bridge at Onitsha, critical for east-west connectivity, experiences high flood hazard with projections indicating 15-25cm increases in flood levels by 2050. Analysis of 24 major river crossings finds that 18 (75%) were designed for flood return periods that climate change is reducing, meaning century floods in design specifications may become 30–50-year events.

Northern urban centers: Cities including Kano, Kaduna, Jos, and Maiduguri experience flash flood hazard in urbanized valleys where inadequate drainage combines with intense rainfall events. The Kano-Kaduna and Kaduna-Abuja highways traverse areas prone to seasonal flooding affecting multiple segments totaling 45 kilometres.

Railway infrastructure exhibits even higher flood vulnerability, with 63% of existing track facing moderate to very high flood hazard. The Lagos-Ibadan railway crosses multiple flood-prone areas, requiring 18 elevated sections and numerous drainage structures. The Abuja-Kaduna railway faces moderate flood hazard along 28% of its length. Historical narrow-gauge railways were often built in floodplains using inadequate engineering standards, contributing to their abandonment. New standard-gauge construction incorporates some climate considerations including elevated sections and improved drainage, though comprehensive climate-resilient design remains inconsistent.

Airport flood vulnerability assessment identifies 12 of 22 (54.5%) major airports facing moderate to high flood hazard. Lagos Murtala Muhammed International Airport, handling 60% of Nigeria's air passenger traffic, experiences regular flooding of access roads and occasional runway drainage challenges during intense rainfall. Port Harcourt International Airport has experienced multiple closure events due to flooding. Abuja Nnamdi Azikiwe Airport faces a moderate hazard from inadequate drainage in some areas.

Coastal inundation analysis projects that with a 0.5-metre sea-level rise (mid-range scenario for 2050), approximately 75 kilometres of coastal roads will face regular inundation, affecting Lagos-Badagry Expressway, coastal sections in Rivers and Bayelsa States, and access roads to ports. Four of six major seaports (Lagos, Tin Can Island, Onne, Calabar) face significant flood risk from storm surge and sea-level rise, though port facilities are generally elevated above immediate risk. Access roads and rail connections to ports are more vulnerable.

4.1.2 Erosion Hazard Patterns

Erosion hazard assessment using RUSLE methodology identifies 12,450 kilometres (35.6%) of federal roads experiencing high to very high erosion hazard within adjacent areas (within 100m of roadway). Spatial patterns reflect rainfall intensity, topography, land cover, and soil characteristics:

Southeastern erosion corridor: Anambra, Enugu, Imo, and Abia States exhibit extensive erosion hazards from intense rainfall (1,500-2,500mm annually), hilly terrain, and erodible soils. Major gully erosion systems threaten numerous road segments, with the Enugu-Onitsha, Owerri-Umuahia, and Onitsha-Owerri routes particularly affected. Analysis identifies 234 active gully erosion sites within 100 meters of federal roads in these states, with erosion rates averaging 2.5-4 metres per year. The Agulu-Nanka gully system in Anambra State, among the largest in West Africa, threatens highway segments and settlements (Igwe, 2012).

Southwestern routes: Roads in Ondo, Ekiti, Osun, and Oyo States traverse areas with moderate to high erosion hazard, particularly routes crossing through older geological formations with weathered parent material. The Akure-Owo-Benin and Ile-Ife-Ilesa routes experience erosion challenges affecting road shoulders and drainage systems.

Northern regions: While generally lower rainfall reduces erosion intensity in northern states, localized high erosion hazard occurs in areas including Jos Plateau with steep topography and intense rainfall concentrated in short wet season, Sokoto-Zamfara areas with erodible sandy soils vulnerable to wind and water erosion, and river valleys where concentrated runoff creates erosion.

Coastal erosion: Shoreline change analysis from 1990 to 2020 Landsat imagery reveals erosion rates averaging 1.8 meters per year along Nigeria's coast, with hotspots experiencing higher than >10 metres per year. Critical infrastructure threatened includes Lagos-Badagry Expressway with segments less than 50 metres from eroding shoreline, Escravos-Warri Road in Delta State facing severe erosion, and coastal segments of East-West Road in Rivers and Bayelsa States. Projection of historical erosion rates to 2050, accelerated by sea-level rise, indicates that 28 kilometres of coastal roadway will be directly threatened without intervention (consistent with projections by Awosika et al., 1992).

Railway erosion vulnerability assessment identifies 380 kilometres (10.8% of the total network) facing high erosion hazard, primarily in southeastern states and along river valleys. The Coastal railway corridor planned from Lagos to Calabar will traverse extensive erosion-prone areas requiring significant protective measures.

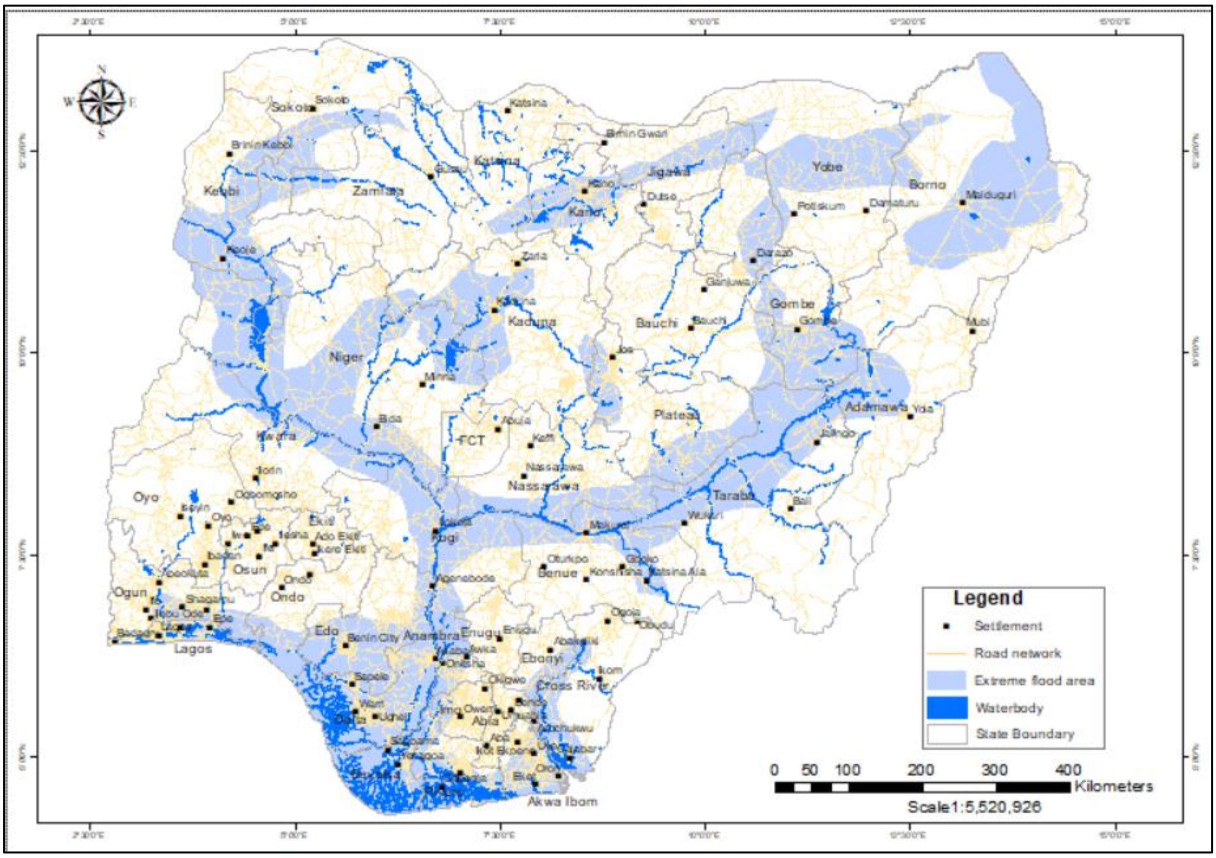

Figure 2: Flood Hazard Area

4.1.3 Heat Stress Patterns

Temperature analysis and projection reveal that northern states experience the most severe heat stress. Historical data (1990-2020) shows that states including Borno, Yobe, Sokoto, Zamfara, Kebbi, and Kano regularly experience maximum temperatures exceeding 40°C during the March to May hot season, with some locations recording 45°C. Climate projections indicate temperature increases of 1.8-2.5°C by 2050 under RCP 4.5, meaning areas currently experiencing 40-50 days per year above 40°C will see 70-100 such days (Akinsanola & Zhou, 2019).

Infrastructure exposure analysis identifies 8,200 kilometres (23.4%) of federal roads in northern states facing high to very high heat stress. Critical corridors include the Kano-Katsina-Sokoto route experiencing very high heat with projections indicating more than 100 days annually above 40°C by 2050, the Maiduguri-Damaturu and Maiduguri-Bama routes in the northeast with extreme heat, and the Kano-Kaduna-Abuja highway with high heat stress in northern sections.

Field observations and ministry reports document heat-induced pavement failure including rutting (permanent wheel-path deformation) requiring frequent resurfacing, bleeding (bitumen rising to the surface) creating slick conditions, and cracking from thermal expansion-contraction cycles. These failures occur despite specifications supposedly accounting for high temperatures, suggesting either inadequate design standards or poor construction quality. Climate projections indicate conditions will exceed current design specifications more frequently and with longer duration.

Railway heat vulnerability focuses on rail buckling risk. While Nigerian railways have not systematically documented buckling incidents, international research indicates that rail buckling risk increases substantially when rail temperatures exceed 50°C, which can occur when air temperatures reach 40°C with solar heating (Dobney et al., 2009). Projected increases in extreme heat days suggest buckling risk will increase, particularly for new standard-gauge railways using continuous welded rail more susceptible than legacy narrow-gauge jointed rail.

Airport pavement faces similar heat challenges, with northern airports including Kano, Maiduguri, and Sokoto experiencing conditions approaching or exceeding design specifications during the hot season.

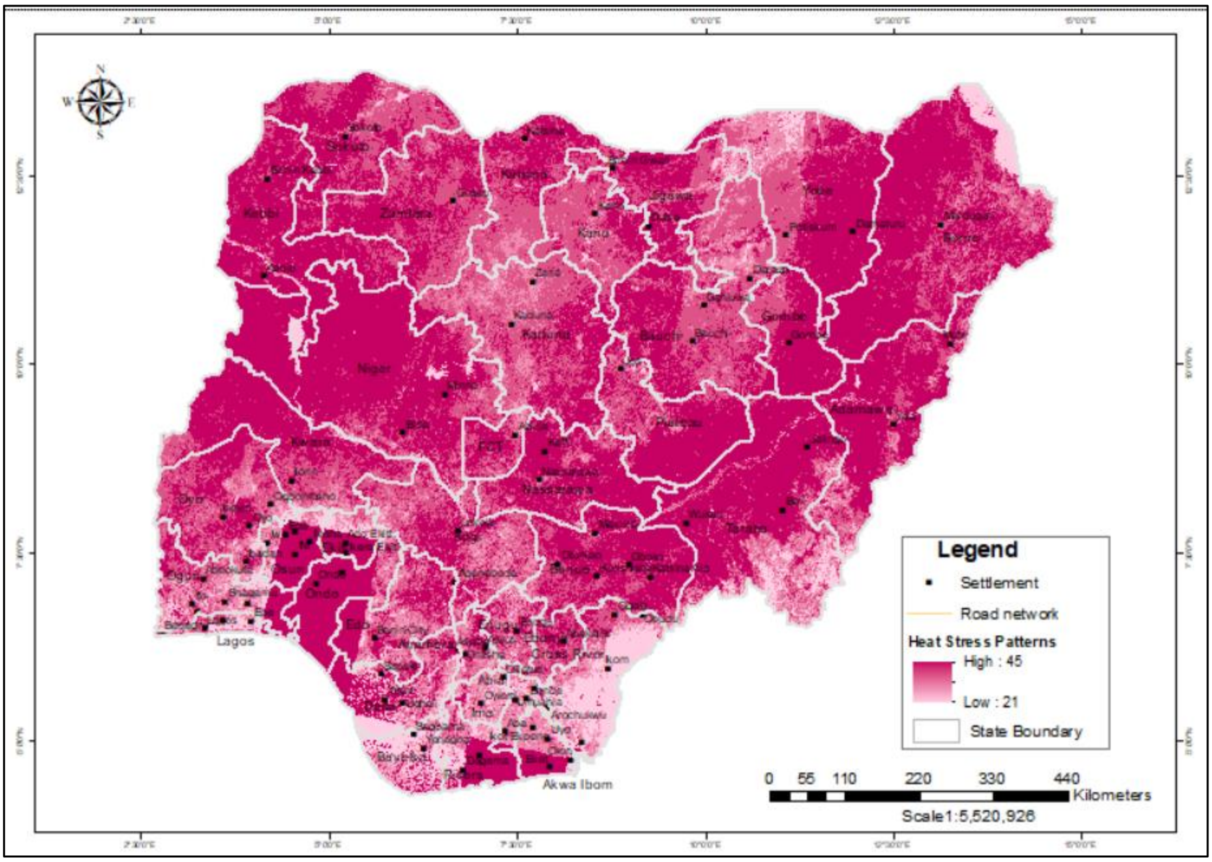

Figure 3: Heat Stress Patterns in Nigeria

4.1.4 Integrated Multi-Hazard Assessment

The multi-hazard composite analysis reveals that 15-20% of transportation infrastructure as shown in Figure 3 faces high exposure to multiple concurrent climate hazards, creating compound vulnerability. Key multi-hazard zones include:

- **Niger Delta:** Combined flooding, coastal erosion, and intense rainfall erosion create extreme vulnerability. The East-West Road faces all three hazards along extended segments.

- **Lagos coastal corridors:** Combined flooding from rainfall and tidal influences, sea-level rise and storm surge, and coastal erosion create compound hazards for Lagos-Badagry Expressway and Lekki coastal routes.
- **Southeastern highlands:** A combination of intense rainfall flooding and severe erosion creates a high hazard for routes in Anambra, Enugu, and Imo States.
- **Northern routes:** Combined heat stress and occasional intense rainfall create pavement stress, while some areas face both heat and drought-induced foundation instability.
- Infrastructure in multi-hazard zones requires comprehensive adaptation addressing multiple threats, increasing intervention costs but also potential benefits from avoiding repeated climate-related damage.

4.2 Infrastructure Sensitivity Assessment

Sensitivity analysis reveals substantial variation in transportation infrastructure vulnerability based on age, condition, design standards, and structural characteristics. Age distribution of federal roads shows that 38% were constructed before 1990, 41% during 1990-2010, and only 21% since 2010, with older infrastructure generally exhibiting higher sensitivity due to deterioration and outdated design standards.

Condition assessment from the Federal Ministry of Works inspection data (supplemented by field verification) classifies federal roads as: Excellent/Good condition (28%), Fair condition (35%), Poor condition (37%). Poor-condition infrastructure exhibits dramatically higher climate sensitivity through compromised drainage from clogged or damaged systems, weakened pavement susceptible to flood and heat damage, eroded shoulders and slopes increasing failure risk, and inadequate maintenance amplifying climate impacts.

Design standard analysis comparing infrastructure specifications to climate projections reveals systematic inadequacies. Drainage systems on 67% of assessed road segments have capacity below projected peak rainfall intensities for the 2030-2050 period under RCP 4.5. Bridge designs from pre-2000 typically used flood return periods (50-100 years) that climate change is reducing, with century floods in original designs potentially becoming 30–50-year events. Pavement specifications are often based on historical temperature ranges that projections indicate will be exceeded increasingly frequently.

Material vulnerability assessment identifies that flexible asphalt pavements dominating Nigerian roads (85% of the network) exhibit higher heat sensitivity than rigid concrete pavements, with rutting and bleeding occurring at high temperatures. Concrete pavements, more expensive initially but more heat-resistant, comprise only 15% of the network, primarily in Lagos and Abuja. Railway track specifications vary, with new standard-gauge lines using continuous welded rail offering operational advantages but greater buckling sensitivity than legacy jointed rail.

Structural characteristics affecting vulnerability include roadway elevation, with at-grade construction in low-lying areas highly flood-vulnerable while elevated sections reduce flood exposure but increase construction costs. Drainage density and capacity vary substantially, with newer roads generally having better drainage than older routes. Bridge characteristics including span lengths, pier spacing, and elevation above design flood level determine flood and debris vulnerability. Coastal protection measures remain limited, with most coastal roads lacking seawalls or natural buffer zones, increasing erosion and inundation vulnerability.

Sensitivity scores normalized to 0-1 scale show mean sensitivity of 0.58 for federal roads (indicating moderate-high sensitivity), 0.64 for existing railways (high sensitivity reflecting age and condition), 0.48 for new standard-gauge railways (moderate sensitivity from modern design), 0.52 for airports (moderate sensitivity with variation by facility age), and 0.55 for ports (moderate-high sensitivity).

The combination of high hazard exposure and high sensitivity creates critical vulnerability for substantial infrastructure proportions, particularly older roads in flood or erosion-prone areas, railways traversing floodplains or coastal zones, and aging airport facilities with inadequate drainage.

4.3 Adaptive Capacity Assessment

Adaptive capacity assessment at the state level reveals as shown in Figure 5 substantial geographic variation reflecting differences in government resources, institutional capacity, and governance quality. States classified by adaptive capacity quintiles show:

Very High Adaptive Capacity (5 states): Lagos, Rivers, Delta, Edo, and Federal Capital Territory exhibit the highest capacity from strong revenue bases, significant federal infrastructure investment, relatively strong institutions, and technical expertise. These states have resources for infrastructure maintenance and climate adaptation, though actual implementation varies. Lagos has developed climate adaptation strategies and invested in drainage improvements, though challenges remain substantial given the extent of infrastructure and growth pressures (Building Nigeria's Response to Climate Change, 2011).

High Adaptive Capacity (7 states): Kano, Oyo, Kaduna, Akwa Ibom, Ogun, Enugu, and Anambra exhibit high capacity from moderate revenues, federal presence, and institutional capacity. These states can undertake adaptation measures but face resource constraints limiting comprehensive responses.

Moderate Adaptive Capacity (12 states): Includes Ondo, Osun, Imo, Abia, Bayelsa, Katsina, Sokoto, Plateau, Bauchi, Cross River, Kwara, and Benue. These states face more significant resource constraints and institutional limitations, with adaptation capacity limited to priority segments and emergency responses.

Low Adaptive Capacity (8 states): Including Ekiti, Gombe, Adamawa, Taraba, Nasarawa, Kogi, Niger, and Ebonyi. Limited state revenues, weaker institutions, and competing development priorities constrain adaptation capacity, with infrastructure maintenance often deferred.

Very Low Adaptive Capacity (5 states): Yobe, Borno, Zamfara, Jigawa, and Kebbi exhibit the lowest capacity from limited revenues, institutional weaknesses, and in some cases security challenges diverting resources. Infrastructure in these states faces high climate vulnerability with minimal adaptive capacity.

The adaptive capacity distribution creates equity concerns, as states with the highest hazard exposure (Niger Delta, southeastern erosion zones) do not always have the highest adaptive capacity. Federal intervention becomes critical for ensuring climate adaptation in lower-capacity states.

Institutional factors affecting adaptive capacity include limited integration of climate considerations in transportation planning and design, inadequate technical guidelines for climate-resilient infrastructure, weak monitoring systems for infrastructure condition and climate hazards, and limited coordination among agencies responsible for transportation, water resources, environment, and emergency management.

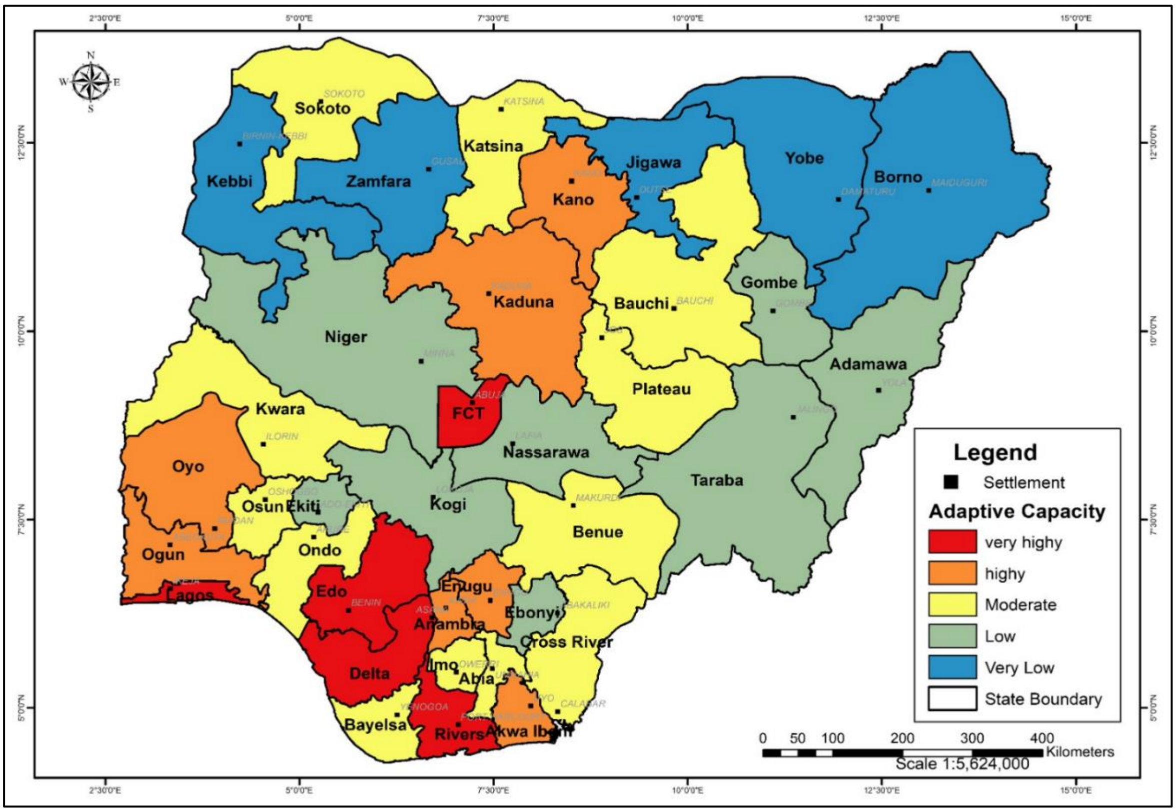

Figure 4: Adaptive Capacity Assessment map of the study Area

4.4 Integrated Vulnerability Index

The integrated vulnerability assessment combining hazard exposure, sensitivity, and adaptive capacity produces a spatial vulnerability map identifying priority infrastructure segments requiring adaptation intervention (Figure 5). Results show:

Federal roads: 35% (12,250 km) face high or very high vulnerability, 28% (9,800 km) face moderate vulnerability, and 37% (12,950 km) face low to very low vulnerability. High vulnerability corridors include:

- East-West Road (212 km of 338 km high/very high vulnerability)
- Lagos-Badagry Expressway (78% high vulnerability)
- Southeastern routes in Anambra, Enugu and Imo (multiple segments totaling 890 km)
- Northern routes Kano-Katsina-Sokoto (156 km high vulnerability from heat stress)
- Lagos-Ibadan Expressway (48 km high vulnerability from flooding)

Railways: 61% of existing track length exhibits moderate to high vulnerability, with southeastern routes and coastal segments most vulnerable. New standard-gauge railways show lower vulnerability from modern design, though flood-prone segments require monitoring.

Airports: 12 of 22 major airports face moderate to high vulnerability primarily from flooding, including Lagos (high), Port Harcourt (high), Benin (moderate), Calabar (high), Asaba (high) and Warri (moderate). Northern airports face moderate vulnerability from heat stress affecting pavements.

Seaports: All six major ports exhibit moderate to high vulnerability. Lagos and Tin Can Island ports face high vulnerability from flooding and sea-level rise. Onne, Port Harcourt, Warri, and Calabar ports face high vulnerability from flooding, coastal erosion, and sea-level rise.

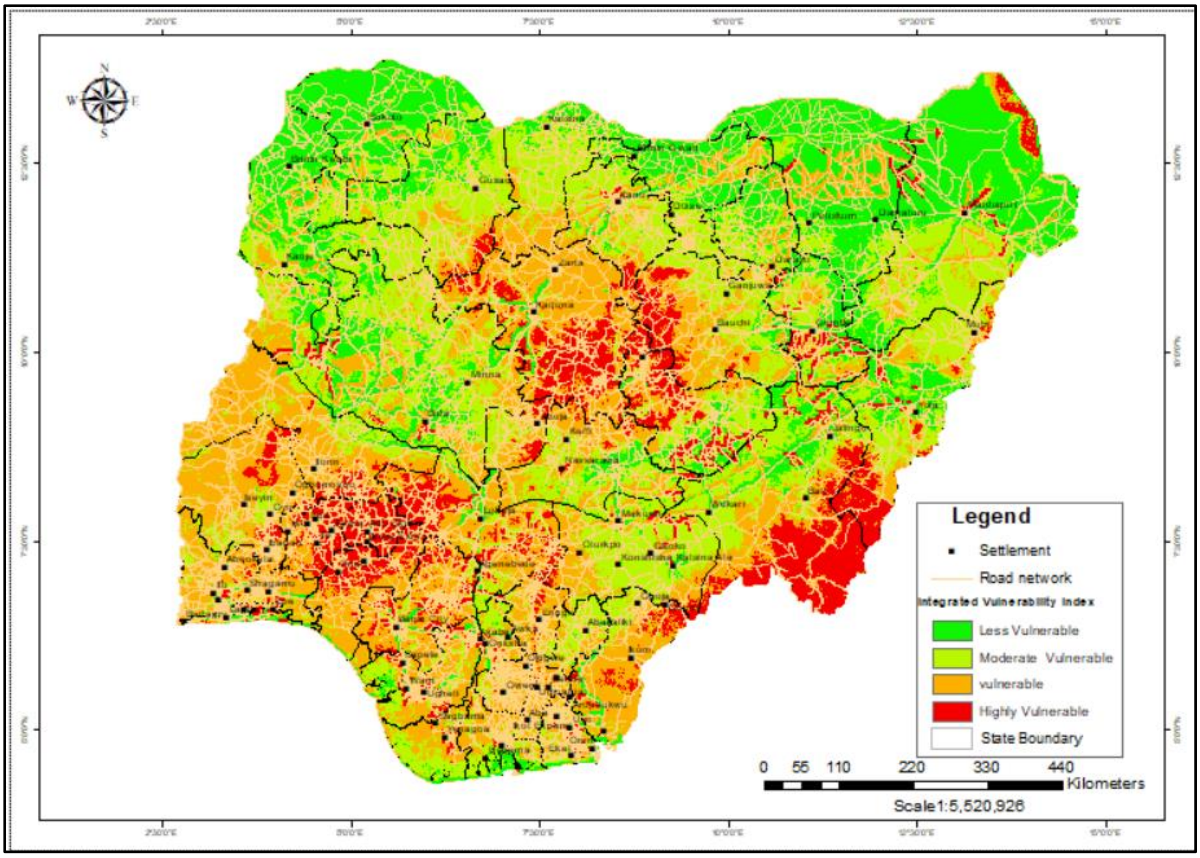

Figure 5: Integrated Vulnerability Index of Nigeria

Critical bridges: Assessment of 847 major bridges identifies 234 (28%) facing high vulnerability from increasing flood levels, debris loading, and in some cases scour. The Niger Bridge at Onitsha, the second Niger Bridge (under construction), Benue crossings, and numerous smaller bridges require climate adaptation consideration.

The spatial pattern of vulnerability reveals concerning concentrations in economically critical areas. The Lagos-Ibadan corridor, Nigeria's most important economic axis, contains extensive high-vulnerability infrastructure. The Niger Delta, source of 90% of foreign exchange earnings, faces extreme vulnerability across road, pipeline, and coastal infrastructure. Southeastern states, economically dynamic but heavily dependent on road transport, face severe vulnerability from flooding and erosion. Regression analysis examining vulnerability determinants finds that hazard exposure and sensitivity are significant predictors while adaptive capacity shows weaker but still significant relationships, suggesting that even well-resourced states struggle to fully compensate for high hazard exposure through adaptation. Infrastructure age emerges as a critical predictor, with pre-1990 infrastructure exhibiting vulnerability scores 35-45% higher than post-2010 infrastructure, controlling for hazard exposure.

4.5 Economic Impact Assessment

4.6 Priority Infrastructure and Adaptation Needs

Integration of vulnerability assessment and economic analysis identifies priority infrastructure segments requiring immediate adaptation intervention:

Tier 1 Priorities (Immediate intervention, 0-3 years):

i. Lagos-Ibadan Expressway flood-prone segments (48 km): Drainage enhancement, elevation of chronic flood points, improved bridge drainage. Estimated cost ₦85 billion.
ii. East-West Road critical segments (120 km): Comprehensive reconstruction with elevation, drainage, and bank stabilization. Estimated cost ₦180 billion.
iii. Lagos-Badagry Expressway coastal protection (35 km): Seawall construction, drainage improvement, road elevation. Estimated cost ₦95 billion.
iv. Major bridge climate adaptation (Niger Bridge, key Benue crossings, 15 priority bridges): Scour protection, increased clearance, debris barriers. Estimated cost ₦125 billion.
v. Lagos Airport access and drainage: Comprehensive drainage system upgrade, road elevation. Estimated cost ₦18 billion.

Tier 2 Priorities (Short-term intervention, 3-7 years):

vi. Southeastern erosion-vulnerable corridors (580 km in Anambra, Enugu, Imo and Abia): Gully stabilization, improved drainage, slope protection. Estimated cost ₦285 billion.
vii. Northern heat-vulnerable routes (450 km): Pavement rehabilitation with heat-resistant materials, maintenance program. Estimated cost ₦95 billion.
viii. Railway flood adaptation: Elevation of flood-prone segments, drainage improvement, and bridge upgrades. Estimated cost ₦145 billion.
ix. Port access road climate resilience (Lagos, Port Harcourt, Onne and Calabar): Elevation, drainage, coastal protection. Estimated cost ₦75 billion.
x. Secondary airports drainage and access: Nine priority airports requiring drainage upgrades. Estimated cost ₦42 billion.

Tier 3 Priorities (Medium-term, 7-15 years):

xi. Comprehensive coastal protection for vulnerable road segments (180 km): Engineered and nature-based solutions. Estimated cost ₦265 billion.
xii. Systematic drainage system enhancement across federal road network: Prioritized by vulnerability and traffic volume. Estimated cost ₦420 billion over 10 years.
xiii. Railway heat adaptation: Rail cooling systems, maintenance protocols, monitoring. Estimated cost ₦35 billion.
xiv. Bridge systematization: Climate assessment and adaptation across all federal bridges. Estimated cost ₦180 billion.
xv. Climate monitoring and early warning systems: Hydrological monitoring, road weather information systems, prediction models. Estimated cost ₦28 billion initial, ₦8 billion annually operations.

Total estimated cost for all priority adaptations: ₦2.85 trillion over 15 years, with ₦503 billion required for Tier 1 immediate priorities. While substantial, this represents less than 20% of current national development plan transportation allocation (₦5 trillion over 2021-2025), suggesting fiscal feasibility if climate adaptation is prioritized (National Planning Commission, 2021).

5. Discussion

5.1 Spatial Patterns of Vulnerability

Transportation infrastructure vulnerability shows distinct spatial patterns reflecting Nigeria's climate gradient and infrastructure distribution. Three primary vulnerability zones emerge: coastal areas facing flooding, erosion, and sea-level rise; the Niger Delta region with extreme flood exposure; and northern regions experiencing severe heat stress.

This spatial distribution requires differentiated adaptation strategies tailored to dominant hazards in each zone. Urban areas show higher absolute vulnerability due to infrastructure density and exposure, while rural areas often face greater relative vulnerability due to limited adaptive capacity, lower design standards, and minimal maintenance.

5.2 Adaptation Strategy Priorities

Priority adaptation interventions for Nigeria's transportation infrastructure should prioritise climate-resilient design standards based on projected mid-century climate conditions rather than historical data. Existing standards relying on past precipitation, temperature, and sea-level records are increasingly inadequate as climate conditions exceed historical ranges. Updated standards should incorporate projected rainfall intensities, higher temperature thresholds, sea-level allowances for coastal assets, and revised wind-load specifications, while remaining flexible for future climate adjustments.

Enhanced drainage systems are critical, particularly in urban areas and flood-prone corridors. Much existing drainage infrastructure is undersized, even for historical rainfall. Priority actions include increasing culvert and bridge capacities, improving road camber and cross-drainage, developing retention and detention facilities, and strengthening routine maintenance. Green infrastructure such as permeable pavements, bio swales, and constructed wetlands can complement conventional drainage while delivering environmental co-benefits.

Coastal protection should integrate hard engineering with nature-based solutions. While seawalls and revetments provide immediate defense, mangrove restoration, dune stabilisation, wetland conservation, and beach nourishment offer cost-effective, multifunctional protection, particularly in Lagos, the Niger Delta, and along the East-West Road.

Additional priorities include heat-resilient pavement and railway materials for northern regions, early warning systems supported by emergency response protocols, and institutional capacity building to sustain long-term climate resilience.

5.3 Policy and Planning Implications

Research findings support key policy recommendations to enhance climate resilience in Nigeria's transportation sector. Climate vulnerability assessment should be mandatory in transportation planning and Environmental Impact Assessment processes, with all new projects evaluating exposure to current and projected climate conditions. Design codes and standards must be updated to reflect future climate scenarios rather than outdated historical data. Dedicated adaptation funding mechanisms, including national climate funds, international climate finance, and climate resilience bonds, are essential. Improved coordination among transportation, environmental, and meteorological agencies will strengthen climate data integration. Finally, institutional frameworks and capacity-building programmes are needed to guide adaptation implementation and sustain long-term infrastructure resilience

5.4 Implementation Challenges

Several challenges hinder climate adaptation in Nigeria's transportation sector. Limited financial resources constrain adaptation investments amid competing demands for expansion and maintenance, creating a gap between funding needs and available resources. Institutional capacity limitations, such as technical expertise gaps, limited climate data access, and weak inter-agency coordination, reduce adaptation effectiveness. Uncertainty in climate projections complicates infrastructure design, requiring adaptive management approaches that allow periodic adjustments. Political and governance challenges, including short political cycles and weak enforcement of standards, further impede progress. Weak land-use planning enables development in high-risk areas, while limited community engagement undermines acceptance. Addressing these constraints requires institutional reform, innovative financing, stronger regulation, and participatory planning.

6. Conclusion

This study presents the first comprehensive, spatially explicit assessment of climate change vulnerability affecting Nigeria's transportation infrastructure using integrated GIS and remote sensing techniques. The findings demonstrate that climate change poses serious risks to transport systems critical for economic development and social connectivity. Approximately 35% of federal roads (about 68,000 km), over 60% of railway infrastructure, twelve major airports, and four of Nigeria's six seaports face high vulnerability to flooding, heat stress, coastal erosion, and sea-level rise, threatening national mobility and trade.

The potential economic consequences are substantial and could undermine development gains if unaddressed. Annual climate-related infrastructure damage may reach ₦450–680 billion by 2050 under moderate emissions scenarios and ₦620–950 billion under high-emissions pathways. Cumulative losses between 2025 and 2050 could total ₦12-17 trillion without adaptation. Beyond direct repair costs, impacts include business disruption, supply chain interruptions, reduced agricultural productivity due to market access constraints, and limited access to essential social services, disproportionately affecting vulnerable populations reliant on public transport.

These risks, however, are not inevitable. Proactive adaptation can significantly reduce vulnerability and long-term costs, with benefit–cost ratios ranging from 4:1 to 6:1. Priority measures include climate-resilient design standards based on projected conditions, enhanced drainage capacity, integrated coastal protection using engineering and nature-based solutions, heat-resistant materials for high-temperature regions, early warning systems, and strengthened institutional capacity.

The GIS-based vulnerability framework and maps developed provide vital decision-support tools for targeted investment and adaptation. Integrating climate considerations into all stages of transportation planning is imperative for achieving Nigeria’s development goals, Paris Agreement commitments, and long-term infrastructure resilience, while offering transferable lessons for other climate-vulnerable developing regions.

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