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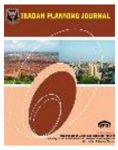

Climate Change and Vulnerabilities of Critical Infrastructure in Africa: A Systematic Review

[1]Sunday Adenrele Adeniyi and [2]Olusegun Ekanade

Abstract
Worldwide, climate change presents one of the most pressing challenges of the 21st century, with Africa emerging as one of the regions most exposed to its impacts. Rising temperatures, extreme weather events, sea-level rise, droughts, and flooding threaten not only ecosystems and livelihoods but also the integrity of critical infrastructure needed for socio-economic development. This review paper examines the nexus between climate change and vulnerabilities of critical infrastructure in Africa, with a focus on key sectors such as energy, transportation, water supply, sanitation, and information and communication technologies. The review synthesizes current literature to highlight patterns of exposure and vulnerabilities across different sectors, which underscores the need for integrated adaptation strategies or resilience. A city-scale assessment of climate change impact was carried out based on studies from Lokoja, Kogi State in Nigeria. Annually, the city experiences significant flooding events, leading to serious fatalities, the destruction of livelihoods, and damage to critical infrastructure. Ultimately, the paper argues that safeguarding Africa's critical infrastructure against the evolving threats of climate change is essential for ensuring economic stability, public safety, and long-term sustainable development. Strategic pathways for building resilience suggested in the paper include strengthening institutional frameworks, mainstreaming climate risk assessments into infrastructure planning, enhancing local or community participation, and enhancing regional cooperation, among others.

Keywords
Climate change; Critical infrastructure; Vulnerability; Resilience; Adaptation; Africa

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Contact
Sunday Adenrele Adeniyi

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1. Introduction

Climate change is among the more recent issues affecting the entire world and is recognized to be the major environmental risk for the 21st century (Okolie *et al.,* 2025). It presents a profound threat to global food security and sustainable development. Nowhere is this threat more acute than in Africa, which is a continent characterized by high climate sensitivity, low adaptive capacity, and endemic developmental challenges (IPCC, 2022). The Intergovernmental Panel on Climate Change (IPCC) in its fourth assessment report concluded that the sub-Saharan nations will be particularly hit hard by the consequences of climate change in the form of floods from heavy rains, droughts, decrease in agricultural yield, increased heat waves, and higher average temperatures, among others (IPCC, 2007). Obviously, these climatic shifts present profound threats to livelihoods, agriculture, infrastructure, and overall socio-economic stability across the African continent (Eze *et al.,* 2024; Gaegane, 2024; Onyeaka *et al.,* 2024; Luhunga, 2025).

A critical review of historical climate trends suggests that surface temperatures have been rising rapidly over Africa by approximately 0.7°C over the last five decades compared to the global rate of temperature increase (Niang *et al.,* 2014; Engelbrecht, 2015), with statistically significant impacts on several sectors. These sectoral impacts, however, occur not only through increases in average temperature, but also through a range of climate-related extreme events such as heat-waves, wildfires, and agricultural drought, among others (Engelbrecht, 2015). Consequently, climate change impacts on natural ecosystems, sustainable livelihood, and Africa's critical infrastructure have continued to attract the attention of scholars and policymakers in the more recent times (Engelbrecht, 2015; Bayeroju *et al.,* 2024; Gaegane, 2024; Das, 2025; Luhunga, 2025).

[1,2]Department of Geography, Osun State University, Osogbo

Critical infrastructure refers to the physical and digital assets, systems, and networks essential to a society and its economy. These include transportation networks, power grids, water and sanitation facilities, healthcare institutions, financial services, and communication systems.

The functionality of these systems is vital for national security, economic stability, and public safety (Andrea *et al.,* 2025). Since critical infrastructure is fundamental to any country's economic growth and social well-being (Indrajit *et al.,* 2023; Walter *et al.,* 2024; Andrea *et al.,* 2025), any disruption to these systems, whether from natural disasters or systemic failures, can seriously affect human security, economic activities, public safety, and sustainable development. As human societies grow, increasingly interconnected and technologically dependent, the protection and resilience of critical infrastructure have become paramount in global policy discourse (Udie *et al.,* 2018; Eze *et al.,* 2024; Andrea *et al.,* 2025; Nhamo *et al.,* 2025).

A cursory review of available literature reveals that what has been regarded as critical infrastructure varies widely from country to country (Walter *et al.,* 2024; Nhamo *et al.,* 2025), and the degree to which various infrastructural types become vulnerable to climate change differs based on geographic location and regional setting (Indrajit *et al.,* 2023). Unfortunately, critical infrastructure in Africa is still limited, unevenly distributed, poorly maintained, and sometimes located in high-risk areas (AfDB, 2021; Nhamo *et al.,* 2025), with recent climate change impacts becoming more pronounced in several areas, particularly in coastal cities (Ekanade *et al.,* 2011; Adelekan, 2020; Nhamo *et al.,* 2025). For instance, Udie *et al.* (2018) reported on the damaging impact of climate change on critical oil/gas infrastructure in the Niger Delta region of Nigeria. Again, Wesam *et al.* (2024) reported that cities of Lagos, Lokoja, and Port Harcourt in Nigeria regularly experience severe floods that disrupt traffic, damage highways, and isolate entire communities. In Mozambique, Cyclone Idai in 2019 caused catastrophic flooding that destroyed over 3,000 kilometers of roads, more than 90 bridges, and halted supply chains for months (World Bank, 2020).

Currently, much of Africa's infrastructural development planning was not done with climate resilience in mind, making it susceptible to both acute shocks (e.g., floods, storms) and chronic stressors (e.g., rising temperatures, droughts) (Hallegatte *et al.,* 2019). To these ends, this paper synthesizes current literature to improve knowledge and understanding of climate change impacts on critical infrastructure vulnerability in Africa. Specifically, the paper focuses on key infrastructure and discusses how they are affected by recent climate change, with a view to arguing for the need to integrate climate risk assessments into infrastructure planning. Key critical infrastructure examined in the paper includes energy, water, transportation, telecommunications, and healthcare. These sectors are interdependent, and the failure of one can escalate negative effects across others, leading to widespread societal disruption. For instance, the energy sector provides the power needed to operate businesses, homes, and essential services such as hospitals and water treatment plants. The water sector ensures the availability of clean water for drinking, sanitation, agriculture, and industrial processes. The transportation sector facilitates the movement of people and goods, connecting communities and enabling trade. The telecommunications sector provides the communication networks essential for business operations, emergency services, and social interactions. The healthcare sector provides medical care and public health services, protecting the health and well-being of the population.

2. Scope and Objectives of the Review

This paper examines the vulnerabilities of key critical infrastructure in Africa to the impacts of climate change. It seeks to provide a comprehensive assessment of the risks posed by climate change. The review identifies key climate-related threats, such as extreme weather events, sea level rise, and gradual environmental changes, and assesses their potential impacts on infrastructure systems. These impacts range from direct physical damage to infrastructure assets to disruptions in service delivery and other negative effects on other sectors. Furthermore, the review explores adaptation strategies and policy recommendations aimed at enhancing the resilience of critical infrastructure in the face of climate change in Africa. These strategies encompass a range of measures, including infrastructure hardening, early warning systems, disaster preparedness, and policy and institutional reforms. The review also highlights best practices and case studies of successful adaptation initiatives in Africa and other regions. The ultimate objective of the paper is to inform policymakers, infrastructure operators, and other stakeholders about the risks posed by climate change and to provide guidance on how to build more resilient infrastructure systems that can withstand the impacts of a changing climate

3. Conceptual Clarification

Conceptually, critical infrastructure refers to systems and assets that are essential for the functioning of a society and economy. What constitutes critical infrastructure varies by country and institution but generally encompasses assets whose incapacitation would have a debilitating impact on human security, national defence, economic security, public health, or safety (Andrea *et al.,* 2025). The European Union (EU) defines critical infrastructure as "an asset, system, or part thereof located in Member States which is essential for the maintenance of vital societal functions" (European Commission, 2006, cited in Harasta, 2018). In 2008, however, the EU refined the term critical infrastructures as: assets, systems, or parts of systems that, if they suffered a disruption or were destroyed, would have a major impact on the citizens of the Member State. Globally, the lists of critical infrastructure are typically unending and heterogeneous, and these may include electricity and energy provision, heating systems, water supply, drainage and sewerage systems, transportation and logistics, telecommunications and information technologies and systems, banking and finance, national and municipal governments, emergency and rescue services, health services, and so on (Brunner & Suter, 2008; Harasta, 2018). Whereas the United States identifies 16 critical infrastructure sectors, including energy, water, and transportation, among several others. With regards to climate change impacts, the energy sector, which includes electricity generation, transmission, and distribution systems, is highly sensitive to changing rainfall patterns and drought (Conway & Schipper, 2011). Healthcare infrastructure is, however, strained by climate-induced disease outbreaks and weather-related disruptions (WHO, 2021). The water and the Sanitation sector are at risk from both water scarcity and contamination due to climate-induced floods (Niang *et al.,* 2014). With regards to transportation sector, climate change can cause several physical and operational impacts on railway networks and common physical impacts often mentioned in the literature include track buckling, landslides, coastal erosion, overhead line and signalling failures, erosion and washouts of track materials, corrosion of metal components, cracking, creep, and shrinkage in concrete structures, submergence of tracks, track subsidence, drainage system failures, and switch/crossing malfunctions (Jiang *et al.,* 2015; Chen & Wang, 2019; Hansel *et al.,* 2022;; Liu *et al.,* 2021; Wang *et al.,* 2020). Other operational impacts include traffic disruptions, accidents, temporary restrictions, and delays within the railway sector (Khosro *et al.,* 2024).

4. Materials and Methods

The literature for this study was gathered using the Scopus database as the primary source. Scopus is a comprehensive multidisciplinary abstract and citation database that covers a wide range of scientific disciplines, including those relevant to the study of climate change (CC) and critical infrastructure (CI). Scopus' vast array of peer-reviewed journals, conference proceedings, and other scholarly literature gives researchers the confidence to conduct comprehensive research and access relevant publications from various fields, setting it apart from more restricted databases such as Google Scholar and Web of Science. For this study, the Scopus database was searched for peer-reviewed articles, books, and research reports. Search terms included combinations of: ("climate change" OR "extreme weather events") AND ("critical infrastructure" OR "energy infrastructure" OR "water infrastructure" OR "transport infrastructure") AND ("vulnerability" OR "resilience" OR "adaptation") AND "Africa. Additionally, reports from intergovernmental bodies (e.g., the IPCC, World Bank, and African Development Bank) were also incorporated to provide policy and regional context. The selected literature was analysed thematically to identify consistent patterns of vulnerability, major knowledge gaps, and emerging pathways to adaptation.

5. Climate Change Trends and Manifestations in Africa

Climate change can be defined as long-term changes in precipitation patterns, weather events, and temperature due to human activities and natural systems that release CO_2 and other greenhouse gases (GHG), which alter the composition of Earth's atmosphere. (Temte *et al.,* 2019; Fawzy *et al.,* 2020, Shivanna, 2022; Okolie *et al.,* 2025). The increase in CO_2 and other anthropogenic greenhouse gases (GHG) within the Earth's atmosphere is responsible for the observed global warming (Franco *et al.,* 2025). Such an astronomical increase in CO_2 and GHG is the main driver of rising temperatures, responsible for the current rapid warming of the Earth's climate on a global scale (Barral *et al.,* 2017). Rising temperatures, melting ice caps, sea-level rise, and extreme weather events like wildfires, hurricanes, droughts, and floods are the most common manifestations of climate change at the global scale.

Studies have shown that Africa is warming more quickly than the global average, particularly in the Sahel and southern regions (Engelbrecht *et al.,* 2015). Another study conducted by Niang *et al.* (2014) revealed that surface temperatures across Africa have increased by approximately 0.7°C over the 20th century and further projected to rise faster than the global average in the 21st century. Recent climate projection for Africa anticipates that average temperatures in many regions could rise by 2°C to 4°C by 2100 (Engelbrecht *et al*., 2015). In terms of climate change manifestation, Opoku *et al.* (2021) reported that surface temperature increases in Africa have led to prolonged dry seasons and intensified desertification in the Sahel region. In contrast to the situation in the Sahel region, heavy rainfall has resulted in serious floods in the West and Central Africa sub-region, as evidenced by river overflows, population displacement, and a rise in disease burdens and fatalities in Niger, Ghana, Nigeria, Burkina Faso, Sierra Leone, Guinea, and Mali (Opoku *et al.,* 2021). In addition, rainfall variability is increasing, with several African countries experiencing more intense droughts. For instance, the Horn of Africa has witnessed alternating periods of severe drought in recent years (UNEP, 2021). Additionally, there has been a noticeable increase in the frequency and severity of extreme events such as cyclones, floods, and heatwaves. For example, Cyclone Idai devastated Mozambique, Zimbabwe, and Malawi, affecting over 3 million people in 2019 (World Bank, 2020). In general, Africa's climate is known to be highly diverse, and the continent is universally identified as a hotspot for increased climate variability and extreme events (IPCC, 2022).

6. How Climate Change Affects Key Critical Infrastructure in the African Context

This section of the paper discusses the specific ways that climate change affects key critical infrastructure in the African context. The section focuses on climate-related activities that include flooding, extreme weather events, drought, and general environmental changes.

6.1 Extreme Weather Events

The increasing frequency and intensity of extreme weather events present a significant and growing threat to critical infrastructure across Africa. These events, exacerbated by climate change, can cause widespread damage, disrupt essential services, and lead to significant economic losses. Increased frequency and intensity of floods can damage transportation networks, energy facilities, and water infrastructure (Lumbroso, 2020; Salam *et al.,* 2023; Chirisa, 2024). These floods can inundate roads and bridges, making them impassable and disrupting transportation and trade. Energy facilities, such as power plants and substations, can be damaged by floodwater, leading to power outages. Water infrastructure, including dams, water treatment plants, and pipelines, can also be damaged or destroyed by floods, disrupting water supply and sanitation services.

Droughts, on the other hand, lead to water scarcity, affecting hydropower generation and water supply systems (Benjamin & Dieudonn, 2024; Etukudoh *et al.,* 2024). Reduced rainfall and increased evaporation rates diminish water availability for hydroelectric power generation, leading to power shortages. Water supply systems are also affected, leading to water rationing and economic losses. Heatwaves strain energy grids and transportation infrastructure, causing disruptions and failures (Kinney *et al.,* 2015; Li *et al.,* 2022). The increased demand for electricity during heatwaves can overload power grids, leading to blackouts. Transportation infrastructure, such as roads and railways, can also be affected by heatwaves, as extreme temperatures can cause road surfaces to degrade and railway tracks to buckle. The impacts of these extreme weather events are often compounded by existing vulnerabilities, such as aging infrastructure, inadequate maintenance, and limited adaptive capacity. Concerted efforts to address these challenges will require a comprehensive approach that includes investing in climate-resilient infrastructure, strengthening early warning systems, and enhancing disaster preparedness and response plans, among several others.

6.2 Sea Level Rise and Coastal Impacts

Sea level rise poses a particularly acute threat to coastal infrastructure in Africa, where many major cities, ports, and industrial facilities are located. Coastal infrastructure, including ports, oil and gas installations, and transportation hubs, is vulnerable to inundation and erosion from sea level rise (Horton *et al.,* 2010; Udie *et al.,* 2018). The gradual rise in sea levels can submerge low-lying coastal areas, inundating ports, roads, and other critical infrastructure. Erosion, caused by rising sea levels and increased wave action, can damage coastal infrastructure and undermine its structural integrity. Again, saltwater intrusion contaminates freshwater sources, impacting water supply and agriculture (Udie *et al.,* 2018; Musarurwa *et al.,* 2025). As sea levels rise, saltwater can intrude into coastal aquifers and rivers, contaminating freshwater sources used for drinking water and irrigation. This salinization of water resources can have devastating consequences for human health and agricultural productivity. Increased storm surges exacerbate coastal flooding and damage infrastructure assets (Horton *et al.,* 2010; Lumbroso, 2020). Storm surges, which are temporary increases in sea level during storms, can inundate coastal areas and cause widespread damage to infrastructure. The combination of sea level rise and storm surges increases the risk of coastal flooding and erosion, threatening the viability of coastal communities and economies. Obviously, efforts to address these challenges will require a range of adaptation measures, including constructing seawalls and other coastal defenses, relocating infrastructure away from vulnerable areas, and implementing sustainable land use planning practices. It also requires a global effort to reduce greenhouse gas emissions and mitigate the long-term effects of climate change.

6.3 Gradual Environmental Changes

In addition to extreme weather events and sea level rise, gradual environmental changes associated with climate change also pose significant threats to infrastructure in Africa. Rising temperatures can degrade infrastructure materials, such as roads and pipelines, leading to premature failure (Chirisa, 2024; Eze *et al.,* 2024). The increased heat can cause road surfaces to soften and buckle, requiring frequent repairs. Pipelines can also be affected, as increased temperatures can cause them to corrode and leak. Changes in precipitation patterns affect water availability and agricultural productivity, impacting food security and related infrastructure (Mukamana 2024; Onyeaka *et al.,* 2024). Reduced rainfall and increased evaporation rates can lead to water scarcity, affecting irrigation systems and food processing facilities. Altered ecosystems and biodiversity loss can undermine natural infrastructure and ecosystem services (Tietjen *et al.,* 2023; Musarurwa *et al.*, 2025). The degradation of wetlands and forests can reduce their ability to provide flood control, water purification, and other essential services. Addressing these gradual environmental changes requires a long-term perspective and a focus on building resilient infrastructure systems. This includes using climate-resilient materials in infrastructure construction, implementing sustainable land management practices, and promoting biodiversity conservation.

7. Critical Infrastructure Deficit and Vulnerability to Climate Change in Africa

Critical infrastructure in Africa is highly deficient, underdeveloped, or poorly maintained. For instance, the current road infrastructure deficit in Africa is estimated between $68 billion and $108 billion (Mtweve *et al.,* 2025), leading to heavy reliance on external funding, particularly from China and international financial institutions (Laurance *et al.,* 2015; Thorn *et al.,* 2022). This financing strategy often creates complex dynamics in project selection, implementation, and governance (Müller-Mahn, 2020; Müller-Mahn *et al.,* 2021), with several infrastructural provision prioritizing resource extraction routes over local connectivity needs (Damania *et al.,* 2018).

Compared to other continents, what constitutes critical infrastructure is less complex in Africa, though more vulnerable to the impacts of anthropogenically-induced climate change (Aiyetan, 2025). This stems not only from projected climate change signals, which are relatively strong for Africa, but also from a relatively low adaptive capacity (Engelbrecht, 2015). Several studies have reported on heatwaves, degrading roads in the Sahel, flooding disrupting networks in Nigeria and Mozambique, sea level rise threatening coastal cities like Dakar and Lagos, and droughts affecting hydropower in Ethiopia and Namibia. Additionally, Mozambique experienced devastating cyclones in 2019 that damaged thousands of kilometres of roads. All these research works illustrate the urgent need for climate-resilient infrastructure investment.

7.1 Sector-specific Vulnerabilities of Critical Infrastructure to Climate Change in Africa

This section of the paper focuses on sector-specific vulnerabilities of key critical infrastructure to climate change.

7.1.1 Transportation Infrastructure

African transportation networks, such as roads, railways, ports, and airports, are highly vulnerable to climate extremes. Roads are often unpaved or poorly maintained. Examples include the East-West Road in Nigeria's Niger Delta and highways in Tanzania and Ethiopia that suffer recurring flood and landslide damage. Flooding, exacerbated by poor drainage and informal urban planning, damages roads and bridges, particularly during the rainy season in countries like Nigeria and Kenya (Adelekan, 2020). In many coastal cities such as Dar es Salaam and Lagos, sea level rise and storm surges threaten major roadways and port infrastructure (Ekanade *et al.,* 2011; Hallegatte *et al.,* 2019). Conversely, drought and heat waves have degraded road surfaces, limiting transport access in arid regions.

7.1.2 Energy Systems

Energy infrastructure across Africa is already constrained, with many countries facing significant electricity access deficits. Unfortunately, climate change intensifies these challenges. Presently, hydropower supplies a substantial portion of Africa's electricity, making energy systems particularly vulnerable to climate-induced fluctuations in river flows (Conway *et al.,* 2017). Available statistics show that hydropower accounts for over 90% of electricity generation in the Democratic Republic of Congo (DRC), Ethiopia, Malawi, Mozambique, Namibia, and Zambia, and it provides 20% of energy generation across the entire Southern Africa region (Conway *et al.,* 2017). Three of the largest rivers in the world (Congo, Zambezi, and Nile) power the majority of this electrical generating capacity, with even more untapped potential of these rivers attracting much of the focus for future development.

Unfortunately, prolonged droughts have reduced hydropower capacity, which accounts for more than 60% of electricity generation in many African countries. For instance, Zambia and Zimbabwe experienced major power shortages during the 2015–2016 El Niño drought, which severely depleted water levels in Lake Kariba. Hydropower-dependent countries like Zambia and Uganda are vulnerable to drought-induced blackouts. Additionally, extreme weather events also threaten transmission lines and renewable energy installations, increasing the risk of grid failure. For instance, South Africa faced overheating of transmission systems, and Nigeria's gas plants are frequently submerged during floods. In Nigeria, the national grid is vital to economic development but highly unstable, frequently failing due to overload and poor maintenance.

7.1.3 Water and Sanitation Infrastructure

Africa's water infrastructure is deeply affected by shifting rainfall patterns and increasing temperatures. Climate-induced droughts exacerbate water scarcity in regions like the Sahel and the Horn of Africa, straining urban water supply systems and rural irrigation schemes (Niang *et al.,* 2014). Intense rainfall events can overwhelm outdated drainage systems, leading to flash floods and water contamination, as seen in Accra, Ghana, and Kampala, Uganda (Douglas *et al.,*2008). Sea level rise also threatens coastal aquifers and wastewater treatment facilities. Water scarcity and flooding present twin challenges. Cape Town nearly ran out of water in 2018. Northern Nigeria's drying Lake Chad affects millions. Urban flooding overwhelms sewers in Sierra Leone and Ghana. Inadequate infrastructure in countries like Chad and Niger has contributed to recurrent cholera outbreaks.

7.1.4 Healthcare Facilities

Healthcare systems in Africa are especially vulnerable to climate-related disruptions. Extreme weather events can damage health facilities and prevent access for both patients and medical personnel. Moreover, rising temperatures and altered rainfall patterns are expanding the geographic range of climate-sensitive diseases such as malaria, dengue fever, and cholera (WHO, 2021). For example, malaria is now found at higher elevations in East African countries like Ethiopia and Kenya, straining under-resourced health systems. Mozambique and Malawi have seen health infrastructure destroyed by tropical storms. Nigeria's health centres in flood-prone zones have become inaccessible, compounding disease outbreaks like cholera and malaria. COVID-19 exposed major weaknesses in the health infrastructure across many African countries.

7.1.5 Digital and Communication Infrastructure

The reliability of digital and communication systems, crucial for modern economies and emergency response, is increasingly compromised by climate impacts. Floods and landslides damage fibre-optic cables and mobile networks, while high temperatures stress data centre operations. In rural and peri-urban Africa, where digital infrastructure is often limited, such disruptions can isolate communities during emergencies and impede disaster response coordination (African Development Bank [AfDB], 2022). In Kenya, digital networks are vulnerable to floods, Nigeria's electricity to electrical surges, and Uganda's rural regions lose connectivity during storms.

Table 1: Summary of Studies on Climate Change Impact on Key Critical Infrastructure in Africa

Infrastructure Sector	Climate-Related Vulnerabilities	References
Transport	Floods, landslides, heat damage, seaport erosion, and disruption of trade	Egbinola et al. 2017 Lumbroso, 2020
Energy (Hydropower)	Droughts are causing energy shortages, rainfall variability, sedimentation	Conway et al., 2017
Water & Sanitation	Water scarcity, service degradation, social inequality, and health risks	Aiyetan, 2025
Urban & Coastal Systems	Flooding, sea-level rise, erosion, and disaster-related infrastructure loss	Ekanade et al. 2011 Adelekan, 2020
Data & Planning Systems	Poor monitoring, weak risk assessments, neglect of local insights	Argyroudis et.al, 2022 Anya et al. 2024
Equity & Justice	Marginalized communities face disproportionate impacts and displacement	Satterthwaite et al., 2020 Mukamana 2024

8. A City Scale Perspective from Lokoja, Nigeria

Lokoja (latitude 7°45′27″–7°51′04″N and longitude 6°41′55″–6°45′36″E) is the capital of Kogi State, Nigeria. As shown in Figure 2, the city sits at the confluence of two great rivers: the Niger and the Benue. The majority of administrative wards in Lokoja are located along the channels of the river Niger and Benue. Again, Figure 3 revealed that annual rainfall in the area is between 1016 mm and 1524 mm with a peak in 2012. The annual average maximum temperature is 37^0C and the annual average minimum temperature of 20^0C. The mean annual temperature does not fall below 27^0C (Adeoye 2012). Whereas the geography of the city made it a hub of trade and connectivity, the location makes the city vulnerable to the growing impacts of climate change. Over the years, the city has experienced increased flooding episodes due to climate variability, rapid urban growth, and poor urban planning, jeopardizing critical infrastructure such as transport networks, power supply, water, and sanitation systems (Lumbroso, 2020). In fact, the story of climate change in the city is not only about damaged infrastructure (roads and power lines), but disrupted families, displaced communities, and a location struggling to keep pace with rising water.

The most important and devastating climate-related threat to human lives and critical infrastructure in Lokoja is flooding, triggered by heavy rainfall (greater than 8mm per hour), and often worsened by the release of water from Cameroon's Lagdo Dam into the River Benue (Ahmed *et al.,* 2024; Okosun *et al.,* 2025). As a result, roads that link the city to Abuja and other states are often submerged, cutting residents off from healthcare, markets, and schools. During the 2012 flood experience, over 363 persons were reported dead, and over 2,000 persons were rendered homeless with property worth millions of naira destroyed (Ahmed *et al.,* 2024). Additionally, stranded travellers slept on highways for days, while trucks carrying food and fuel could not move (Ahmed *et al.,* 2024; Okosun *et al.,* 2025). Again, thousands of residents watch their homes swallowed by water, forcing them into temporary shelters or Internally Displaced Persons (IDP) camps.

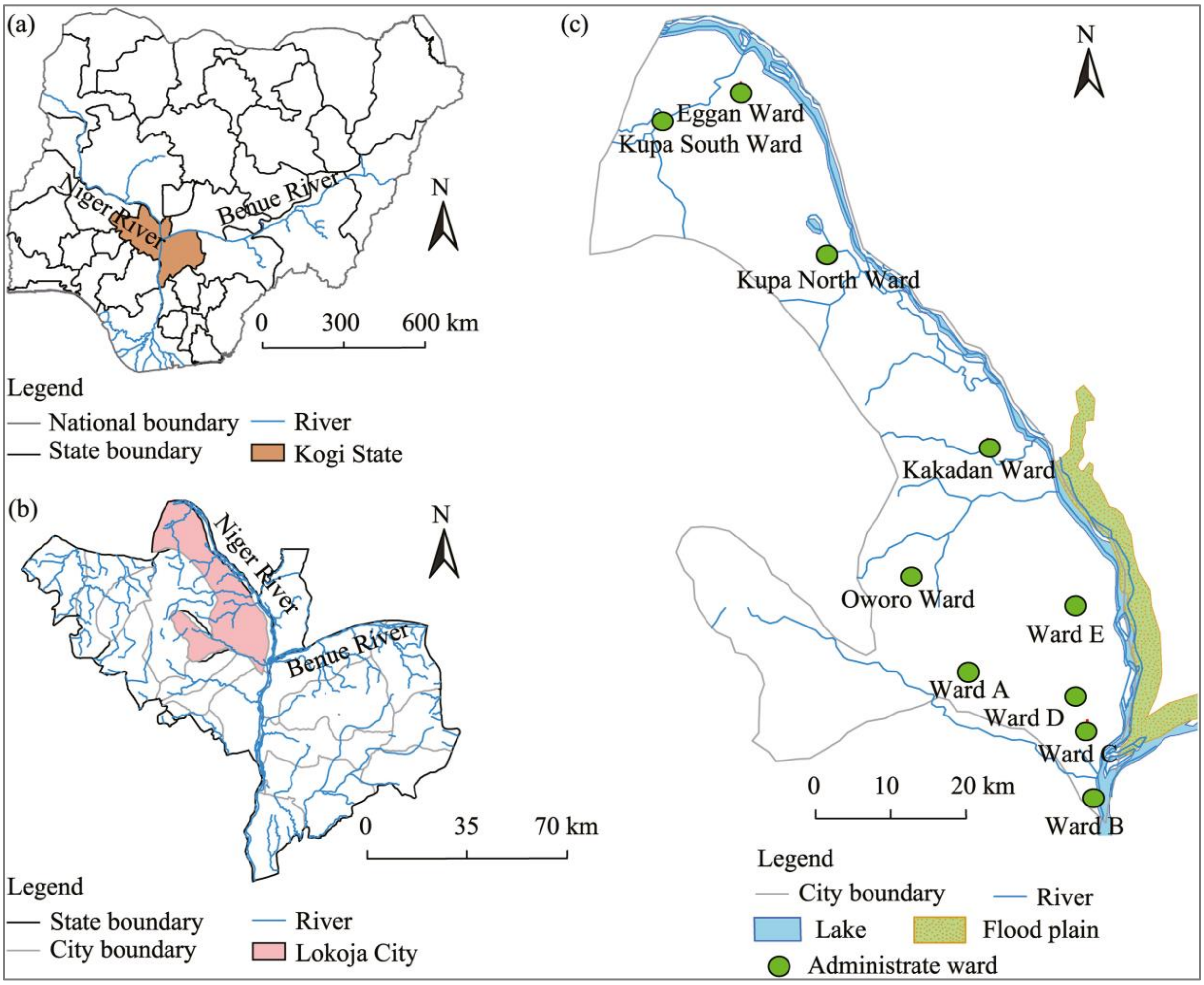

Figure 2: Location of Lokoja City at the Confluence of Niger-Benue Rivers
Source: Oluwatimilehin *et al.* (2022)

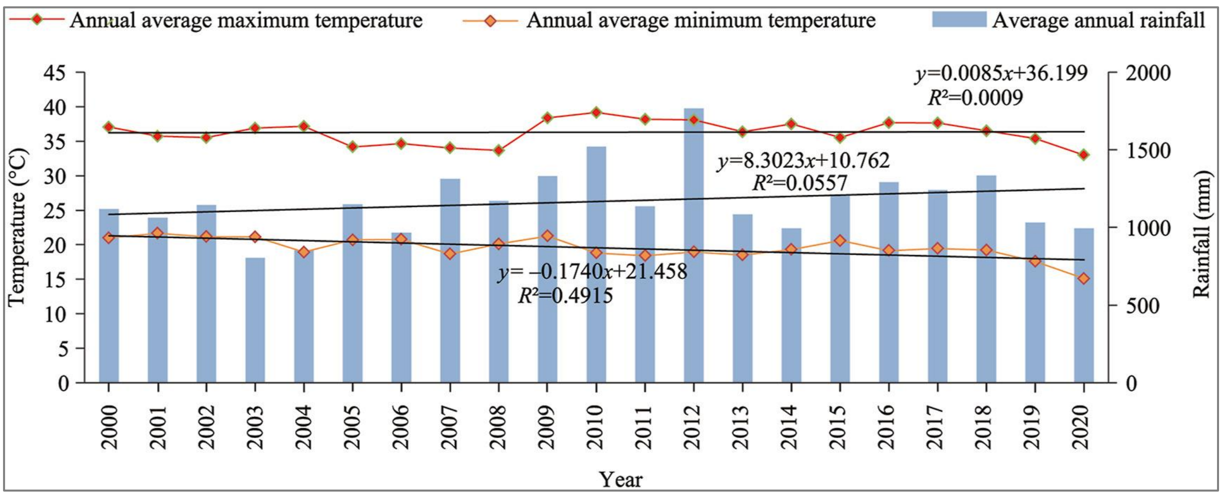

Figure 3: Variations of the Average Annual Rainfall, Annual Average Minimum Temperature, and Annual Average Maximum Temperature in Lokoja City (2000–2020)
Source: Oluwatimilehin *et al.* (2022)

In their paper, Samuel *et al.* (2017) give an insight into the impacts of the 2012 flooding on the city of Lokoja in Nigeria. A survey of residents in Lokoja, carried out as part of this work, illustrates the devastating impact that floods have on life and properties in the city. Major flood impacts reported by respondents in the study included disruption of movement (14.5%), damage to roads (13.9%), loss of valuable properties (13.7%), loss of farmland (13.1%), and environmental pollution (11.5%). According to Samuel *et. al.* (2017), these statistics attest to the severity 2012 flood event, as significant proportions of households reported impacts that cut across virtually all aspects of their livelihoods. With regards to water and sanitation systems**,** burst water pipes affected the water quality, and many families had to use unsafe water. Outbreaks of cholera and other waterborne diseases followed, placing unbearable pressure on already stretched hospitals. In terms of power and communication, entire neighbourhoods were thrown into darkness when floodwater destroyed electrical infrastructure. In some cases, mobile networks and internet services collapse, cutting people off from relatives and emergency information at the time they need it most.

The climate-related failure of critical infrastructure in Lokoja is not just a technical issue, but a general reshaping of life. Residents are often reported to fall ill from unsafe water, leading to a high incidence of malaria, pneumonia, meningitis, and cholera diseases (Oluwatimilehin *et al.,* 2022), and clinics often struggle with surges in patients after annual and recurrent floods. Expectedly, farmers lose crops and fishing livelihoods with each flood, while traders face destroyed shops and inaccessible markets. Families displaced from their homes often endure crowded camps, loss of dignity, and psychological stress. For residents, displacement is no longer temporary but a recurring feature of life in Lokoja. Meanwhile, some initiatives are underway to address the negative impacts of climate change on critical infrastructure in the city. For instance, the Kogi State government noted that "flooding has continued to threaten livelihoods, displace communities, and damage infrastructure, particularly in low-lying areas along the River Niger". Accordingly:

> The State Government has not only recognized the urgency of this challenge but has also taken concrete steps to address it. From the construction of drainage systems and flood embankments to community sensitization and early warning mechanisms, the state is actively working to build resilience against the recurring flood menace" (The Honourable Commissioner for Environment and Ecological Management, Engr. Joseph Oluwasegun**,** 2025).

Recently, the government of Kogi State has engaged in early warning sensitisation campaigns against the 2025 flood season. Additionally, drainage projects and embankment construction have begun, though implementation is slow and sometimes inconsistent. Notwithstanding the above, our extensive review of literature suggests that local actions or strategies can be adopted to mitigate the effects of climate change in the city. These include a combination of green and grey solutions such as enforcing building codes to discourage construction in floodplains, developing comprehensive flood vulnerability and risk assessments using integrated GIS and machine learning tools to map susceptibility and flood-vulnerable areas, investing in nature-based solutions like reforestation, riverbank restoration, and wetland protection to buffer floodwaters, community engagement and education to improve risk awareness and adaptive capacities, securing funding and technical support for sustainable infrastructure projects in line with Nigeria's climate adaptation policies (Egbelakin *et al.,* 2023; Adeyemi *et al.,* 2024). Additionally, several stakeholders, including the Nigerian Senate, have suggested the immediate dredging of the River Niger as a crucial step toward reducing the risk of future floods. Dredging is a key river management practice that involves removing accumulated sediments, silt, debris, and vegetation from riverbeds and channels. Over time, these materials reduce a river's depth and capacity to carry water, increasing the likelihood of overflow during heavy rains. By clearing sediment and widening river channels, dredging restores natural water flow and enhances the river's ability to contain large volumes of runoff. (Raj, 2025). According to Raj (2025), dredging not only prevents flooding but also contributes to improved navigation, better water quality, and healthier aquatic ecosystems.

In summary, climate change-induced flooding is not a distant forecast in Lokoja; it is an annual disaster that tests the resilience of people and infrastructure alike. Each flood season disrupts lives, weakens development, and erodes confidence in institutions. Protecting critical infrastructure is not only about roads, power, or drainage; it is about protecting families, sustaining livelihoods, and safeguarding the future of a city at Nigeria's heart.

9. Strategic Pathways to Building Infrastructure Resilience in Africa

Building resilience in Africa's critical infrastructure systems in the face of climate change requires the implementation of integrated, multi-dimensional strategies that combine technological innovation, ecosystem-based approaches, strong governance, inclusive finance, and active community engagement. These suggested strategies are briefly discussed below:

9.1 Integration of Climate-Resilient Design and Technology

A fundamental pathway to guarantee infrastructure resilience lies in the integration of climate-responsive design principles and the adoption of modern technologies (Bayeroju *et al.,* 2024). Accordingly, Bayeroju *et al.* (2024) advocate for the upgrading of aging infrastructure assets, incorporating adaptive engineering practices, and deploying digital tools for real-time monitoring and informed decision-making. This proactive approach will enable infrastructure systems to better withstand the stresses and shocks associated with climate change. For instance, the implementation of Internet of Things (IoT) sensors and the creation of digital twins can facilitate rapid condition assessment and enable proactive maintenance, ensuring that infrastructure remains robust and functional even under adverse climate conditions (Argyroudis *et al.,* 2022). In South Africa, for example, strategic plans have increasingly emphasised the importance of upgrading water infrastructure with climate-resilient technologies, improving management capacity, and enhancing financial mechanisms to address potential supply disruptions (Aiyetan 2025). The more recent work conducted by Aiyetan (2025) concluded that these measures are essential for ensuring the reliable provision of water resources in the face of climate-related challenges. Furthermore, the application of process systems engineering approaches can aid in vulnerability assessment and optimization of infrastructure to withstand a range of predicted climate scenarios (Besigomwe 2025). These engineering methodologies offer a structured framework for identifying weaknesses, assessing adaptation strategies, and informing decision-making processes (Besigomwe 2025).

9.2 Nature-Based and Ecosystem-Based Solutions

Complementing traditional "gray" infrastructure with nature-based solutions represents a promising strategy for enhancing ecological and social resilience in the face of climate change (Bayeroju *et al.,* 2024). Therefore, Bayeroju *et al.* (2024) advocate for the implementation of measures such as wetland restoration, the creation of urban green spaces, the use of permeable surfaces, and the adoption of natural flood management techniques to reduce vulnerabilities to floods, heatwaves, and droughts. These nature-based solutions not only mitigate the impacts of climate change but also provide a multitude of co-benefits, including improved air and water quality, enhanced biodiversity, and increased recreational opportunities (Das 2025). Furthermore, Das (2025) emphasizes that integrating nature-based solutions into urban infrastructure planning can create more sustainable and resilient cities. Today, urban planning initiatives in many African cities are increasingly incorporating green infrastructure to mitigate urban heat island effects and manage stormwater runoff, although challenges in governance and financing often persist (Dossa & Miassi 2024).

9.3 Strengthening Governance, Policy Coordination and Community Engagement

Effective frameworks for integrating climate resilience into infrastructure planning necessitate the establishment of robust governance structures, including participatory policymaking processes, and the promotion of cross-sectoral coordination (Bayeroju *et al.,* 2024). Sodje *et al.* (2025) opined that good governance is essential for ensuring that climate resilience is effectively mainstreamed into infrastructure development. The Sendai Framework for Disaster Risk Reduction and alignment with the SDGs provide valuable guidance for integrating resilience into policies and practices (Sodje *et al.,* 2025). Multi-level governance approaches can enhance the capacity to address complex interdependencies and mobilize resources across various levels of government (Anya *et al.,* 2024). Additionally, Usman (2022) notes that fostering stronger transnational cooperation is also crucial for addressing the transboundary impacts of climate change.

Community-based adaptation strategies, particularly in informal settlements that are disproportionately vulnerable to climate impacts, can foster local empowerment, reduce risks, and support inclusive resilience-building (Satterthwaite *et al.,* 2020). In consequence, Satterthwaite *et al.* (2020) highlight the importance of engaging local communities in the design and implementation of adaptation measures. Again, public awareness campaigns are critical for promoting adaptive behaviours and fostering a culture of resilience within communities (Anya *et al.,* 2024). Empowering communities to take ownership of adaptation efforts is essential for achieving sustainable resilience.

9.4 Mobilizing Finance and Investment

Securing adequate financial resources and directing investments towards low-carbon, climate-resilient infrastructure is equally of paramount importance for building resilience in Africa (Adisa *et al.,* 2024). Innovative financing mechanisms, such as public-private partnerships, can help increase the flow of capital to resilience-building projects across the continent (Aiyetan *et al.,*2025). For instance, Aiyetan *et al.* (2025) research concludes that improving funding mechanisms and enhancing financial oversight are critical for ensuring the sustainability of water infrastructure projects in South Africa. Whereas financial constraints often remain significant challenges in Africa, Usman (2022) notes that addressing these financial and capacity-related barriers is crucial for accelerating the implementation of climate-resilient infrastructure projects.

9.5 Enhancing Data and Predictive Analytics

Availability of large data can play a crucial role in supporting evidence-based decision-making through climate risk assessment, early warning systems, and scenario planning. Anya et al. (2024) highlight that predictive insights can aid in anticipating vulnerabilities, prioritizing interventions, and optimizing adaptive responses in critical sectors such as water, agriculture, and infrastructure. The integration of climate data into disease surveillance systems can enhance early warning capabilities and enable more effective responses to climate-sensitive health risks (Musarurwa *et al.,*2025). As a result, Musarurwa *et al.* (2025) suggested that strengthening disease surveillance systems is essential for protecting public health in the face of climate change. Furthermore, the development and utilization of climate models can help policymakers and planners better understand the potential impacts of climate change on infrastructure systems and inform the design of more resilient solutions (Bornemann *et al.,* 2019).

9.6 Capacity Building and Knowledge Transfer

Investing in the development of local technical capacity, fostering innovation, and promoting knowledge exchange among African countries are essential for ensuring sustainable resilience in the long term (Sodje *et al.,* 2025). To achieve this, Sodje *et al.* (2025) highlight the importance of building local expertise to support the design, construction, and maintenance of climate-resilient infrastructure. Pilot projects can serve as valuable platforms for co-creating solutions that are tailored to the specific needs and contexts of different regions, although scaling up these initiatives often poses a significant challenge (Amorim *et al.,* 2022). Amorim *et al.* (2022) note that addressing the barriers to scaling up successful pilot projects is crucial for achieving widespread adoption of resilience-building practices. Furthermore, promoting knowledge transfer and collaboration among African countries can facilitate the sharing of best practices and the development of innovative solutions to common challenges.

Case Examples

- *South Africa's Water Infrastructure Resilience*: South Africa has implemented strategies that include upgrading aging water networks, adopting climate-resilient technologies, and enhancing governance and financial management practices to counter climate-related threats to its water supply (Aiyetan 2025). These comprehensive measures are essential for ensuring the reliable provision of water resources in the face of climate change.
- *Informal Settlements Adaptation*: Community participation and infrastructure upgrading projects in various African cities have demonstrated the potential for mitigating flood risks and improving access to essential services

in vulnerable informal settlements (Satterthwaite *et al.,* 2020). Therefore, local communities must be empowered to take ownership of adaptation efforts.

- *Use of Digital Technologies*: The deployment of IoT and AI-driven systems for infrastructure monitoring has shown promise in boosting resilience and facilitating proactive risk management across various sectors (Argyroudis *et al.,* 2022). These digital technologies can enable rapid condition assessment and informed decision-making, ensuring that infrastructure remains robust and functional even under adverse climate conditions (Argyroudis *et al.,* 2022).

10. Conclusion

Given the urgency for studies that evaluate the impacts of climate change on critical infrastructure in Africa with a view to informing policymakers, this review paper focused on key critical infrastructure such as roads, water, and the energy sector, among others. Our review shows that climate change poses a systemic risk to selected critical infrastructure across African countries. Therefore, resilience must be embedded into the design and planning of critical infrastructure to ensure sustainable development in Africa. To this end, collaboration across sectors and countries is considered very crucial to protect the fragile continent's critical infrastructure systems. In order to strengthen infrastructure resilience in Africa, key actions must include mandatory climate risk assessments, integration of adaptation into national planning, greater access to climate finance, training for professionals, and regional cooperation on transboundary infrastructure systems. The exposed relationship between climate change and vulnerabilities of critical infrastructure suggests the need for enhanced environmental safeguards in investment frameworks, particularly in countries with lower institutional capacity. By highlighting both the progress made and the critical gaps remaining in our understanding of climate change impacts on critical infrastructure, this review provides a foundation for exploring more sustainable pathways to critical infrastructural development in the face of climate change in Africa.

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