

# Assessment of Pavement Failures Along Flood-Prone Highways in The Niger Delta, Nigeria

AKWENUKE, O. M.<sup>1</sup>

<sup>1</sup>Department of Civil and Water Resources Engineering  
Southern Delta University, Ozoro, Nigeria.

Date of Submission: 08-03-2026

Date of Acceptance: 20-03-2026

## ABSTRACT

### Background

Flood-induced pavement deterioration represents one of the most persistent infrastructure challenges in the Niger Delta, Nigeria. The region's low-lying terrain, high rainfall intensity, weak deltaic soils, and inadequate drainage systems make highways highly vulnerable to recurrent flooding and structural damage. Major transportation corridors frequently experience cracking, rutting, potholes, depressions, and structural collapse, disrupting economic activities and posing safety risks. Integrated assessment of environmental, geotechnical, and engineering factors is essential for understanding the mechanisms driving these failures and for developing sustainable mitigation strategies.

### Methods

Field observations were conducted along selected flood-prone highway segments in the Niger Delta. Pavement conditions were evaluated using visual distress surveys, while environmental factors such as drainage adequacy, waterlogging, and soil characteristics were assessed. Failure types were classified into cracking, rutting, potholes, depressions, edge failure, and washout. Engineering factors including construction quality, traffic loading, and maintenance status were also examined.

### Results

Flood-affected highway sections exhibited extensive structural deterioration characterized by severe potholes, alligator cracking, rutting, and localized pavement collapse. Subgrade soils were predominantly clayey with high moisture retention, leading to loss of bearing capacity under prolonged saturation. Inadequate drainage infrastructure resulted in persistent water accumulation on pavement surfaces and shoulders. Sections subjected to heavy truck traffic showed accelerated failure rates.

### Conclusion

Flooding significantly compromises pavement integrity in the Niger Delta by reducing subgrade strength, promoting erosion, and accelerating fatigue damage under traffic loads. Engineering deficiencies

such as poor drainage design, inadequate soil stabilization, and delayed maintenance exacerbate vulnerability. Sustainable highway performance in the region requires climate-resilient design approaches, improved drainage systems, soil improvement techniques, and routine monitoring.

**Keywords:** Pavement failure, Flooding, Niger Delta, Highway infrastructure, Subgrade soils, Drainage

## I. Introduction

The Niger Delta region of Nigeria constitutes one of the largest coastal wetland systems in Africa, characterized by extensive river networks, floodplains, mangrove swamps, and low-lying sedimentary terrain. The region plays a critical role in Nigeria's economy due to its petroleum resources, agriculture, fisheries, and transportation networks (Edo & Albrecht, 2021; Obi, 2023). However, road infrastructure in the Niger Delta is highly vulnerable to environmental degradation, particularly flooding, which frequently damages highways and disrupts mobility (Akinwumijuet *al.*, 2020; Jacob *et al.*, 2024).

Pavement failures along flood-prone highways manifest in various forms, including potholes, rutting, cracking, depressions, and structural collapse. These failures reduce road serviceability, increase vehicle operating costs, and elevate accident risk (Adlinge & Gupta, 2013; though foundational, recent studies confirm similar patterns) (Ukureboret *al.*, 2023). In many cases, affected roads serve as major corridors connecting oil-producing communities and industrial facilities, making their deterioration economically significant (Nanadeinboemiet *al.*, 2024).

Flooding is widely recognized as a major factor influencing pavement performance in deltaic environments. When pavement layers become saturated, the underlying subgrade loses shear strength and stiffness, making the structure incapable of supporting traffic loads (Osinubiet *al.*, 2018; Salau *et al.*, 2019). Clayey soils common in the Niger Delta exhibit swelling, softening, and reduced bearing capacity under wet conditions,

leading to differential settlement and surface deformation (Nwankwoala, 2019; Adebangbe *et al.*, 2025). Prolonged water exposure also weakens pavement materials, promotes stripping of asphalt binder, and accelerates fatigue cracking (Huang *et al.*, 2017; O’Flaherty *et al.*, 2018).

Anthropogenic factors further compound the problem. Poor construction practices, inadequate geotechnical investigations, substandard materials, overloading by heavy trucks, and insufficient maintenance contribute to premature deterioration (Federal Ministry of Works, 2017; Salau *et al.*, 2019). Drainage systems are often poorly designed or blocked, preventing efficient removal of surface water and increasing infiltration into pavement layers (Akinbami & Adeyemi, 2021). Climate variability, including increased rainfall intensity and extreme weather events, has intensified flooding, thereby exacerbating infrastructure vulnerability in the region (Adebangbe *et al.*, 2025; Nanadeinboemiet *et al.*, 2024).

The socioeconomic implications of pavement failures in the Niger Delta are substantial. Damaged roads hinder movement of goods and people, disrupt oil and gas operations, increase transportation costs, and restrict access to healthcare, education, and markets (Obi, 2023; Isukuru, 2024). Communities may become isolated during severe flood events, affecting livelihoods and emergency response capabilities (Jacob *et al.*, 2024).

Despite the importance of reliable transportation networks, comprehensive assessments of flood-related pavement failures in the Niger Delta remain limited. Many existing studies focus on isolated engineering aspects without integrating environmental and operational factors. A holistic evaluation is therefore necessary to identify the underlying causes of recurrent failures and to inform sustainable infrastructure planning (Ukureboret *et al.*, 2023; Akinbami & Adeyemi, 2021).

This study aims to assess pavement failures along flood-prone highways in the Niger Delta by examining environmental conditions, geotechnical characteristics, engineering deficiencies, and traffic influences. The findings are expected to support the development of resilient highway design and maintenance strategies suited to deltaic environments.

## II. Materials and Methods

### Study Area

The study was conducted along selected highways located in flood-prone zones of the Niger Delta, including areas adjacent to rivers, wetlands, and coastal plains. The region experiences a humid tropical climate with annual rainfall exceeding 2,000 mm and a prolonged rainy season, resulting in frequent flooding and waterlogging (Edo & Albrecht, 2021; Akinwumijuet *et al.*, 2020).

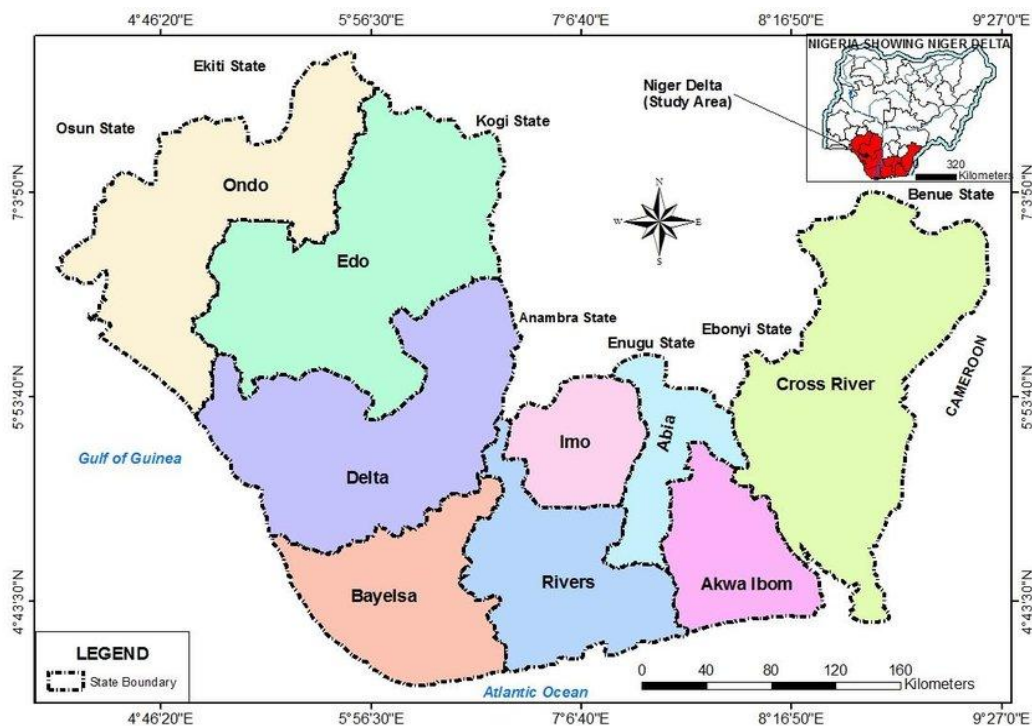


Fig. 1: Map of Niger Delta

### Pavement Condition Survey

Pavement distress was evaluated using visual inspection methods commonly employed in road engineering assessments. Observed failure types included alligator cracking, longitudinal cracking, rutting, potholes, depressions, edge failure, and washout (Osinubiet *al.*, 2018).

### Environmental Assessment

Environmental conditions influencing pavement performance were assessed, including drainage adequacy, presence of standing water, flood history, soil type, and moisture conditions (Akinbami & Adeyemi, 2021).

### Evaluation of Engineering Factors

Engineering characteristics such as pavement thickness, embankment height, construction quality, and maintenance status were examined. Traffic conditions, particularly heavy truck movement associated with petroleum transport, were also considered (Ukureboret *al.*, 2023).

## III. Results and Discussion

### Pavement Distress Characteristics

Field observations revealed that flood-prone highway sections in the Niger Delta exhibit multiple forms of pavement distress occurring simultaneously, indicating systemic structural weakness rather than isolated defects. The most prevalent failures included extensive potholes, alligator (fatigue) cracking, rutting, depressions,

edge failures, and localized pavement collapse. Potholes were particularly widespread, often coalescing into large failed patches that severely reduced ride quality and traffic safety. Such deterioration typically results from progressive disintegration of the surface layer following water infiltration through cracks and joints (Osinubiet *al.*, 2018).

Alligator cracking was frequently observed in wheel paths, suggesting repeated traffic loading on weakened pavement layers. This pattern of interconnected cracks indicates structural failure of the base or subgrade rather than superficial surface distress. Rutting depths were pronounced in heavily trafficked lanes, in some cases exceeding 40 mm, reflecting plastic deformation of saturated subgrade soils under sustained loading (Huang *et al.*, 2017). Depressions and undulations were common in areas with prolonged waterlogging, indicating differential settlement due to uneven soil consolidation.

Edge failures were particularly severe along road shoulders where erosion had removed lateral support. In extreme cases, entire pavement sections had collapsed, rendering the roadway impassable. These failures were most prominent in low-lying segments lacking adequate embankment height or drainage infrastructure. Similar patterns of multi-modal distress have been reported in deltaic environments where prolonged moisture exposure accelerates structural degradation (Salau *et al.*, 2019).



Plate 1: Cracking and Potholes

### Influence of Flooding and Water Saturation

Persistent flooding emerged as the dominant environmental factor influencing pavement performance in the study area. Water accumulation on road surfaces and shoulders was observed across most failure locations, often persisting long after rainfall events due to inadequate drainage. Prolonged inundation allows water to infiltrate pavement layers, saturating the base and subgrade and drastically reducing their load-bearing capacity (Akinbami & Adeyemi, 2021).

When clayey subgrade soils become saturated, their shear strength decreases while compressibility increases, making them highly susceptible to deformation under traffic loads. Hydrostatic pressure and seepage forces further destabilize the pavement structure, promoting upward movement of fines and weakening interlayer bonding (Nwankwoala, 2019). In some locations,

standing water had penetrated through cracks to form subsurface voids, eventually leading to sudden pavement collapse.

Floodwaters also caused erosion of embankments and removal of shoulder materials, undermining the structural support of the roadway. In coastal areas, tidal influences compounded the effects of rainfall-induced flooding, resulting in prolonged submergence of infrastructure. Climate variability, including increasing rainfall intensity and frequency of extreme events, has intensified such conditions in recent years (Adebangbe *et al.*, 2025; Nanadeinboemiet *et al.*, 2024).

Prolonged moisture exposure additionally accelerates stripping of asphalt binder from aggregates, reducing cohesion within the surface layer and facilitating rapid disintegration. This explains the widespread occurrence of potholes and surface raveling observed across the study sites.



Plate 2: Effect of Flood and Water Saturation

### Role of Subgrade Soil Properties

Geotechnical conditions in the Niger Delta play a critical role in pavement failure mechanisms. The region is dominated by soft, compressible sediments such as clay, silt, and peat, which possess poor engineering properties. These soils exhibit high plasticity, low permeability, and significant volume change behavior when exposed to moisture (Osinubiet *et al.*, 2018).

During flooding, clayey soils absorb large quantities of water and undergo swelling, reducing their strength and stiffness. As the soil later dries, shrinkage occurs, creating voids and cracks that weaken the pavement foundation. This cyclical swelling and shrinkage contributes to differential settlement and surface deformation (Adebangbe *et al.*, 2025).

High groundwater levels further exacerbate the problem by maintaining the subgrade in a near-

saturated state even during dry periods. In some surveyed areas, seepage from adjacent wetlands continuously supplied moisture to the roadbed, preventing adequate drainage. Such conditions render conventional pavement designs ineffective unless appropriate soil stabilization or reinforcement measures are implemented (Nwankwoala, 2019).

Peaty soils encountered in certain locations were particularly problematic due to their extremely low bearing capacity and high compressibility. Without ground improvement techniques, these materials cannot sustain heavy traffic loads, leading to rapid structural failure.

### Engineering Deficiencies and Drainage Failures

Engineering shortcomings significantly amplified the vulnerability of highways to flooding. Many surveyed sections lacked functional side drains, culverts, or cross-drainage structures. In

some cases, existing drains were blocked by sediment, vegetation, or solid waste, preventing efficient water evacuation. Poor drainage design allowed water to accumulate on pavement surfaces and infiltrate underlying layers (Federal Ministry of Works, 2017).

Insufficient pavement thickness and poor compaction of subgrade and base layers were also evident in several locations. These deficiencies reduce structural capacity and accelerate deterioration when exposed to moisture. Low embankment elevations relative to surrounding floodplains further increased susceptibility to inundation.

Conversely, highway segments constructed with elevated embankments, stabilized subgrades, and well-maintained drainage systems demonstrated comparatively better performance. This contrast highlights the importance of proper engineering design tailored to deltaic environments.

#### Traffic Loading and Maintenance Factors

Operational factors such as heavy traffic loading played a significant role in accelerating pavement deterioration. Highways in the Niger Delta serve as major corridors for petroleum transportation, exposing them to frequent movement of heavy trucks with axle loads often exceeding design limits (Ukureboret *et al.*, 2023). Repeated loading on weakened pavement structures accelerates fatigue cracking and rutting.

Maintenance practices were generally inadequate across the surveyed routes. Minor defects such as small cracks and potholes were rarely repaired promptly, allowing water infiltration to continue and structural damage to progress. Preventive maintenance is critical in flood-prone environments because early intervention can significantly extend pavement life (Salau *et al.*, 2019).

#### Socioeconomic Implications

The widespread pavement failures observed have substantial socioeconomic consequences for the Niger Delta region. Damaged highways increase travel time, fuel consumption, and vehicle repair costs, placing financial burdens on individuals and businesses. Disruptions to transportation networks affect the movement of petroleum products, agricultural produce, and commercial goods, thereby impeding economic activities (Obi, 2023).

Access to essential services such as healthcare, education, and emergency response is also compromised, particularly for rural communities dependent on road connectivity.

During severe flooding events, some communities become completely isolated, exacerbating vulnerability and hindering disaster management efforts (Isukuru, 2024).

Furthermore, deteriorated roads contribute to higher accident rates due to uneven surfaces, water-filled potholes, and reduced vehicle control. The cumulative effect of these impacts underscores the urgent need for resilient infrastructure development in the region.

#### IV. Conclusion

This study has demonstrated that pavement failures along flood-prone highways in the Niger Delta are the result of complex and interrelated environmental, geotechnical, engineering, and operational factors. Persistent flooding emerged as the dominant driver of structural deterioration, primarily through prolonged saturation of pavement layers and underlying soils. When subgrade materials particularly clayey and organic deltaic sediments become saturated, their shear strength and stiffness decline substantially while compressibility increases. This condition leads to excessive deformation under traffic loads, manifesting as rutting, cracking, potholes, depressions, and eventual structural collapse.

The geotechnical characteristics of the Niger Delta significantly amplify vulnerability. The prevalence of highly plastic clays, silts, and peat with low bearing capacity makes conventional pavement designs inadequate without appropriate soil improvement measures. Cyclic swelling and shrinkage associated with wetting and drying further contribute to differential settlement and surface irregularities. High groundwater levels maintain near-saturated conditions even during dry periods, reducing the effectiveness of natural drainage and prolonging recovery after flood events.

Engineering deficiencies were found to play a critical enabling role in failure development. Inadequate drainage systems often characterized by insufficient capacity, poor design, or blockage allow water to accumulate on pavement surfaces and infiltrate structural layers. Low embankment elevations relative to surrounding floodplains increase the likelihood of overtopping during heavy rainfall or river overflow. Insufficient pavement thickness, poor compaction, and substandard materials further reduce structural resilience. Conversely, road sections constructed with elevated embankments, stabilized subgrades, and effective drainage exhibited noticeably better performance, highlighting the importance of context-specific design.

Operational factors also contribute significantly to deterioration. Heavy truck traffic associated with petroleum extraction and industrial activities imposes loads that frequently exceed design specifications, accelerating fatigue damage in already weakened pavements. Inadequate maintenance practices exacerbate the problem, as minor defects such as cracks and small potholes are not repaired promptly, allowing water infiltration and progressive structural degradation. Preventive maintenance is particularly critical in flood-prone environments, where early intervention can substantially extend pavement life.

Beyond technical considerations, the socioeconomic consequences of recurrent pavement failures are profound. Damaged highways disrupt mobility, increase transportation costs, and reduce accessibility to essential services such as healthcare, education, and markets. In oil-producing regions, deterioration of key transport corridors can impede industrial operations and national revenue generation. Communities located in remote or riverine areas are especially vulnerable, as road failures during flood events may lead to temporary isolation and hinder emergency response efforts. Safety risks also increase due to uneven road surfaces, water-filled potholes, and reduced vehicle control.

Climate change is likely to intensify these challenges. Projections indicate increasing rainfall intensity, more frequent extreme weather events, and potential sea-level rise in coastal regions, all of which will exacerbate flooding and infrastructure vulnerability. Consequently, traditional pavement design approaches based on historical climate conditions may no longer be adequate. Adaptation strategies must incorporate climate projections, hydrological modeling, and risk-based planning to ensure long-term infrastructure resilience.

To address these challenges, a holistic and multidisciplinary approach is required. Sustainable solutions should integrate improved drainage infrastructure, soil stabilization techniques (such as lime or cement treatment), geosynthetic reinforcement, elevated embankments, and the use of moisture-resistant pavement materials. Routine inspection and preventive maintenance programs must be institutionalized to detect and repair early signs of distress. Additionally, enforcement of axle load regulations and adoption of asset management systems can reduce operational stresses on vulnerable roads.

In conclusion, flood-induced pavement failures in the Niger Delta represent not merely an engineering problem but a broader environmental and developmental challenge. Ensuring resilient

transportation infrastructure is essential for economic stability, social well-being, and regional integration. Future infrastructure planning in the Niger Delta and similar deltaic environments worldwide must prioritize climate-resilient design, integrated water management, and sustainable maintenance practices. Without such measures, recurrent failures will continue to undermine the reliability of transportation networks and impede long-term development in flood-prone regions.

### Recommendations

Based on the findings of this study, comprehensive and coordinated interventions are required to mitigate flood-induced pavement failures and enhance the resilience of highway infrastructure in the Niger Delta. The recommendations below address engineering design, maintenance practices, policy measures, and climate adaptation strategies.

### Improvement of Drainage Infrastructure

Effective drainage is the most critical requirement for sustaining pavement performance in flood-prone environments. Highway designs should incorporate adequately sized side drains, culverts, and cross-drainage structures to facilitate rapid removal of surface runoff and prevent water accumulation. Existing drainage systems should be routinely inspected, cleared of debris, and rehabilitated where necessary. In areas with high groundwater levels, subsurface drainage systems such as perforated pipes and filter layers should be installed to reduce moisture infiltration into the pavement structure.

### Elevation of Road Embankments

Many highways in the Niger Delta are constructed at elevations lower than surrounding flood levels, making them highly susceptible to inundation. Raising road embankments above anticipated flood levels can significantly reduce the risk of overtopping and prolonged submergence. Embankment design should consider hydrological data, flood frequency analysis, and projected climate scenarios to ensure long-term resilience. Protective measures such as slope stabilization, vegetation cover, or erosion-control materials should also be implemented to prevent washout during high-flow events.

### Soil Stabilization and Ground Improvement

Weak deltaic soils with low bearing capacity require improvement before pavement construction. Stabilization techniques such as lime treatment, cement stabilization, bituminous stabilization, or the use of industrial by-products

(e.g., fly ash) can enhance strength and reduce moisture susceptibility. In severely weak zones, partial replacement of unsuitable soil with well-graded granular materials may be necessary. Geosynthetic materials—including geotextiles and geogrids—should be employed to reinforce the subgrade, improve load distribution, and minimize deformation.

#### **Adoption of Climate-Resilient Pavement Design**

Traditional pavement design approaches based on historical climate conditions are insufficient for regions experiencing changing rainfall patterns. Future highway projects should integrate climate projections, hydrological modeling, and risk-based design principles. Materials with improved resistance to moisture damage, temperature variation, and repeated loading should be prioritized. Flexible pavement systems may require thicker structural layers, improved binder formulations, or modified asphalt mixes to enhance durability under wet conditions.

#### **strengthening Construction Quality Control**

Poor construction practices significantly contribute to premature pavement failure. Strict quality control measures should be enforced during construction, including proper compaction of subgrade and base layers, adherence to material specifications, and adequate curing of stabilized soils. Pre-construction geotechnical investigations should be mandatory to identify soil characteristics and groundwater conditions, ensuring that design decisions are site-specific.

#### **Implementation of Preventive Maintenance Programs**

Routine inspection and timely repair of minor defects are essential for preventing catastrophic failures. Maintenance programs should prioritize sealing of cracks, patching of potholes, clearing of drainage channels, and stabilization of eroded shoulders. Adoption of pavement management systems can support data-driven decision-making and optimize maintenance scheduling. Preventive maintenance is particularly cost-effective in flood-prone environments, where early intervention can significantly extend pavement life.

#### **Regulation of Traffic Loading**

Heavy axle loads associated with petroleum transport and industrial activities accelerate pavement deterioration. Enforcement of vehicle weight regulations through weigh stations and monitoring systems is necessary to reduce

structural stress on vulnerable highways. Where heavy traffic is unavoidable, pavement design should account for anticipated load intensities.

#### **Integrated Flood Management and Land-Use Planning**

Road infrastructure resilience cannot be achieved without addressing broader watershed and land-use issues. Integrated flood management strategies—such as river channel improvement, wetland conservation, and controlled development in floodplains—can reduce the frequency and severity of roadway inundation. Coordination between transportation agencies, environmental authorities, and urban planners is essential for sustainable outcomes.

#### **Community Engagement and Monitoring**

Local communities play an important role in maintaining infrastructure integrity. Public awareness programs should encourage reporting of drainage blockages, erosion, and emerging road defects. Community-based monitoring can provide early warning of potential failures, especially in remote areas where formal inspection may be infrequent.

#### **Policy and Institutional Strengthening**

Government agencies should develop and enforce policies that promote climate-resilient infrastructure development. Adequate funding mechanisms must be established for construction, rehabilitation, and maintenance of highways. Collaboration with research institutions can support continuous innovation in materials, design methods, and monitoring technologies.

#### **REFERENCES**

- [1]. Adebangbe, S. A., Dixon, D., & Barrett, B. (2025). Geo-computation techniques for identifying spatio-temporal patterns of environmental hazards in the Niger Delta. *International Journal of Digital Earth*, 18(1), 1–20.
- [2]. Akinbami, J. F. K., & Adeyemi, O. (2021). Oil industry impacts on infrastructure and water resources in Nigeria's Niger Delta. *Resources Policy*, 72, 102061. <https://doi.org/10.1016/j.resourpol.2021.102061>
- [3]. Akinwumiju, A. S., Adelodun, A. A., & Ogundej, S. E. (2020). Geospatial assessment of environmental degradation in the Niger Delta of Nigeria. *Environmental Pollution*, 267, 115545. <https://doi.org/10.1016/j.envpol.2020.115545>

- [4]. Edo, M., & Albrecht, C. (2021). Wetland ecosystem services and conservation challenges in the Niger Delta. *Wetlands Ecology and Management*, 29, 115–129. <https://doi.org/10.1007/s11273-020-09754-3>
- [5]. Federal Ministry of Works. (2017). *Highway design manual*. Federal Government of Nigeria, Abuja.
- [6]. Huang, Y. H., Bird, R. N., & Heidrich, O. (2017). Development of a life-cycle assessment tool for pavement maintenance and rehabilitation. *Journal of Cleaner Production*, 142, 2147–2154. <https://doi.org/10.1016/j.jclepro.2016.11.093>
- [7]. Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate change 2021: The physical science basis*. Cambridge University Press. <https://doi.org/10.1017/9781009157896>
- [8]. Isukuru, E. J. (2024). Nigeria's infrastructure challenges under environmental change. *Environmental Science & Policy*, 154, 103560. <https://doi.org/10.1016/j.envsci.2023.103560>
- [9]. Jacob, O. J., Amadike, M. P., Nwanesi, F. O., Ogbonna, C. G., Ibeneme, S. I., & Okeke, O. C. (2024). Environmental impacts of flooding in Nigeria's coastal regions: Implications for infrastructure sustainability. *IIARD Journal of Geography and Environmental Management*, 10(3), 370–412.
- [10]. Nanadeinboemi, O. A., Modebe, L. U., Chukwurah, N. C., Olabimtan, O. H., & David, D. S. (2024). Environmental and socioeconomic effects of climate hazards in Niger Delta communities. *Journal of Health and Environmental Research*, 10(2), 29–40.
- [11]. Nwankwoala, H. O. (2019). Geotechnical properties of soils in the Niger Delta region and their implications for engineering construction. *Environmental Earth Sciences*, 78, 1–12. <https://doi.org/10.1007/s12665-019-8258-7>
- [12]. Obi, C. I. (2023). Environmental degradation and resource governance in the Niger Delta. *Global Environmental Change*, 78, 102627. <https://doi.org/10.1016/j.gloenvcha.2022.102627>
- [13]. Osinubi, K. J., Yohanna, P., & Eberemu, A. O. (2018). Stabilization of tropical soils for road construction using chemical additives. *Transportation Geotechnics*, 17, 1–12. <https://doi.org/10.1016/j.trgeo.2018.08.001>
- [14]. Salau, O. A., Adeyemi, G. O., & Oke, S. A. (2019). Maintenance challenges of road infrastructure in developing countries: The Nigerian experience. *Journal of Construction Engineering and Management*, 145(6), 04019022. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001640](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001640)
- [15]. Ukurebor, K. E., Olayiwola, O. A., Adekanmbi, A. O., & Adebayo, S. A. (2023). Environmental impacts of petroleum exploration on host communities in the Niger Delta. *Energy Reports*, 9, 1045–1058. <https://doi.org/10.1016/j.egy.2023.01.056>