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Sustainable Soil-Structure Interaction for Road Infrastructure in Flood-Prone Regions of Nigeria

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Abstract - **This research applies sustainable soil-structure interaction (SSI) principles to enhance the resilience of Nigerian road infrastructure to floods in certain regions. Given the socio-economic importance of road networks, the study highlights the challenges posed by extreme weather events, soil instability, hydrological stress, and design deficiencies. By focusing on the use of innovative materials, including recycled low-density polyethylene (LDPE) and bioengineered additives that improve tensile strength and moisture resistance, the research acknowledges that these challenges cannot be addressed without incorporating these materials. The study also explores nature-based solutions, such as permeable pavements and raised embankments, to mitigate waterlogging and erosion. The review synthesizes global and local research by identifying key mechanisms contributing to infrastructure failure, including subgrade erosion in sandy soils and foundation destabilization in clay-rich regions due to moisture fluctuations. It emphasizes the importance of advanced geospatial methods, climate-adaptive strategies, and multidisciplinary approaches for assessing and managing flood risks. Transferable practices from other flood-prone regions, such as the use of salinity-resistant materials and GIS-based risk modeling, are highlighted, along with the need for local adaptation to Nigeria's specific geographic and socio-economic context. The review advocates for a paradigm shift in policy and practice through sustainable road design that integrates ecological, economic, and technological considerations. The study aims to bridge advancements in theory with practical applications, contributing to the development of a resilient road network that will support economic growth and mitigate the impact of climate-induced disasters in Nigeria.**
Keywords: **Soil-Structure Interaction (SSI), Flood Resilience, Innovative Materials, Nature-Based Solutions, Climate-Adaptive Strategies**

I. INTRODUCTION

Nigeria's road infrastructure is key for socioeconomic development, particularly in promoting interlinkages between rural and urban areas, which are important for commerce, health, and education. Studies show that the development of road networks considerably reduces poverty and enhances economic development, while also demonstrating that infrastructure investment raises intra-regional trade and total economic activity to a substantial magnitude [22], [4]. However, Nigeria's road infrastructure faces tremendous challenges, especially in flooded regions (Fig. 1), which are affected by extreme weather events that adversely impact transportation systems, causing structural damage and endangering public safety [38], [37]. With climate change leading to more frequent flooding in Nigeria, innovative road design and maintenance are required to sustain road resilience against hydrological stresses. Research indicates that among Nigeria's coastal states, Delta and Bayelsa are among the most at risk from floods [7]. Improvements in drainage systems and partnerships for sustainable practices are proposed as adaptation strategies that can strengthen transportation infrastructure against extreme weather events [8].

Past flooding incidents in Lagos, for instance, contributed to the displacement of more than 120,000 individuals and caused substantial development losses [24]. Vulnerabilities to these must be addressed with innovative adaptation strategies, such as improved drainage systems and partnerships for sustainable practices [8]. Resilience to flooding is also enhanced by integrating soil-structure interaction (SSI) principles into construction methods [8], [3]. In the design of road infrastructure situated in flood-prone areas, SSI is essential since it encompasses the complex relationships between soil properties and structural demands. The stability and performance of roads are affected by several factors, predominantly soil type, water infiltration, and loading conditions. Variations in structural responses resulting from different loading scenarios for a particular soil condition can have a profound impact on soil dynamic behavior, particularly in ensuring reliability and integrity [15], [17]. More accurate predictions of the dynamic performance of both soil and structures can be made using advanced modeling techniques, such as finite element analysis, as the time-dependent behavior of soil and structure can be modeled appropriately. Additionally, SSI analysis is improved with new innovative ground improvement methods and high-performance computing, which enhances the infrastructure's resilience to environmental challenges [29].

To improve infrastructure resilience in hydrologically extreme environments, SSI principles must be incorporated into road engineering. Pavement distress in expansive soil zones can result from a lack of SSI in road design [11], [39], where moisture can have a significant impact on road integrity. An eco-friendly road design seeks to control or mitigate ecological impacts and decrease maintenance costs by implementing innovative materials and recycling practices, thereby enhancing long-term durability [9]. Additionally, quantifying road network robustness to flooding is essential to prepare for and recover more proactively from climate-induced disasters [35]. Creating more resilient environments is crucial for integrating sustainable infrastructure (SSI) principles in road design, particularly in flood-prone regions such as Nigeria. Road performance has been improved with innovative materials, including recycled low-density polyethylene (LDPE) and bioengineered additives. For instance, tensile strength ratio is found to be 85.7% for simulating flood conditions for LDPE-modified specimens [18].

Another advantage of nature-based solutions is the use of permeable pavements and raised embankments, which effectively mitigate waterlogging and improve the durability and environmental benefits of 100% recycled asphalt pavement [19], [6]. However, a holistic approach that considers socioeconomic and environmental factors overcomes the discussed issues and helps develop infrastructure that is effective for flooding and sustainable urban planning [9]. Nigeria's flood-prone geographical and climatic regions present unique challenges for road infrastructure development, as they involve a mix of clayey and sandy soils that behave differently under water saturation, presenting various engineering challenges [7], [28]. Poor urban planning, as well as variations in rainfall patterns, exacerbate ineffective flood impact prediction and management [23]. Consequently, current road construction practices often rely on generic standards that fail to consider such regional nuances, leading to infrastructure ill-suited for local conditions [30]. These challenges require a multidisciplinary approach, where geotechnical expertise is complemented by hydrological modeling and climate-adaptive strategies [34]. Advanced geospatial techniques can improve flood risk assessment, as well as predictive models for saturation profiles, serving as tools for pavement resilience and management during floods [7], [34]. In fact, the implementation of resilient infrastructure strategies is essential for successful flood risk management in Nigeria [30].

This review aims to bridge the gap between theoretical advancements in soil-structure interaction and its practical application in road infrastructure design. The manuscript synthesizes existing research, identifying sustainable strategies to enhance the resilience of roads in Nigeria's flood-prone areas. The study also stresses the importance of shifting the paradigm for policy and practice to integrate sustainability and resilience into national infrastructure planning. Ultimately, this review aims to contribute to the development of a more robust and flexible road network that will promote the economic growth of Nigeria while protecting communities from the impact of flooding.

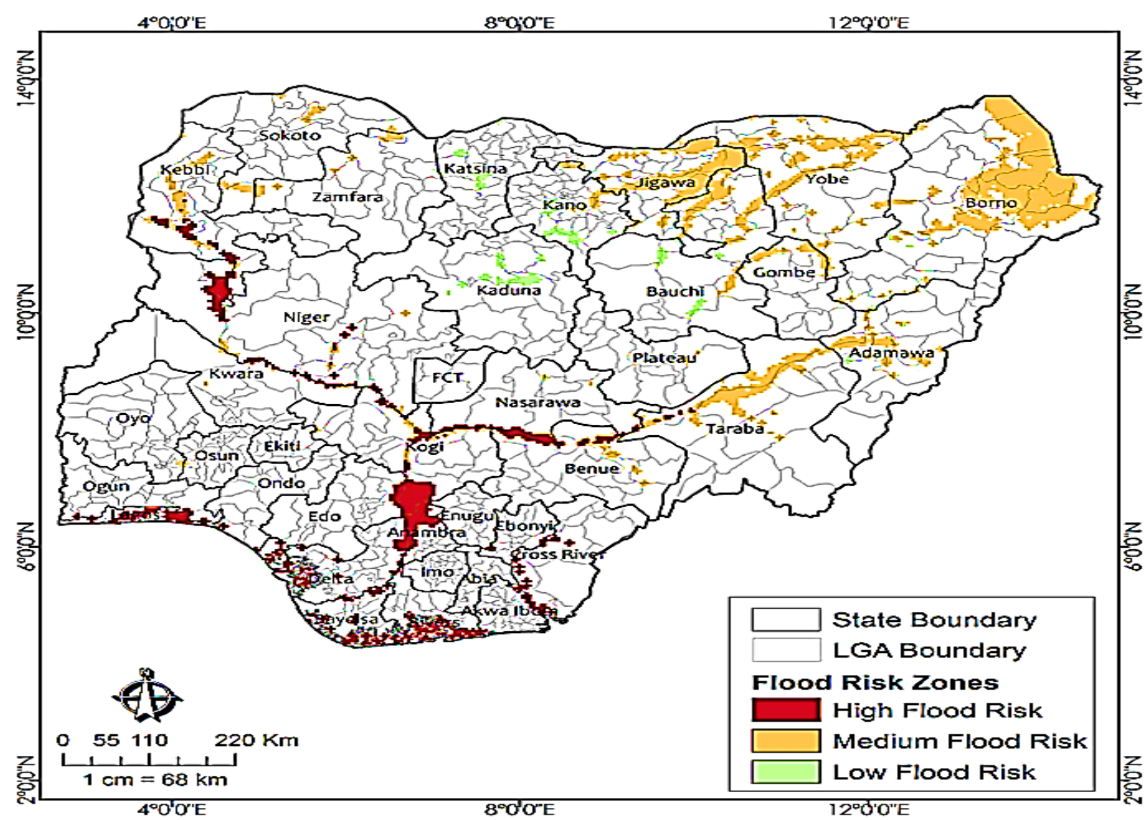

Fig. 1 Flood risk map of Nigeria from [26]

II. METHODOLOGY

This research review employs a structured methodology to synthesize research on sustainable soil-structure interaction (SSI) in road infrastructure in flood-prone areas of Nigeria. It includes strict criteria for the selection of literature, a systematic search plan, and analytical methods to ensure appropriateness and excellence. The selection criteria focus on SSI studies applicable to road infrastructure, particularly in flood-prone areas, and the sustainability of tropical construction and maintenance. Peer-reviewed articles from 2000 to 2023 were included, balancing both empirical and theoretical studies, while seminal works prior to 2000 were excluded. The search strategy was implemented using reputable academic databases such as Scopus, Web of Science, Google Scholar, ScienceDirect, and the ASCE Library. Key terms included “soil-structure interaction,” “road infrastructure,” “flood-prone regions,” “Nigeria,” and “sustainability,” with Boolean operators and synonyms applied for better search results. Only English-language studies within the specified timeframe were used.

III. RESULTS AND DISCUSSION

This analysis of the studies summarized in Table I highlights important lessons concerning the challenges, mechanisms, and solutions for achieving the resilience of road infrastructure in flood-prone regions. The failure of infrastructure is found to be influenced by a primary set of contributing factors, which include soil and geotechnical properties, hydrological dynamics, and design flaws. For example, sandy soils with low cohesion but high permeability are especially vulnerable to seepage-induced subgrade erosion, as found in [1], which can result in pavement collapses in the coastal area of Akwa Ibom. Expansive clay soils, documented by [27] and [20], also exhibit swelling and shrinking cycles, which destabilize pavement foundations due to seasonal moisture variations (Fig. 2). Issues in underground environments are exacerbated by heavy rainfall, waterlogging, and poor drainage systems, as shown in [8] in Lagos City and [28] in Edo State, leading to urban flooding that disrupts the transportation system and threatens infrastructure stability. As studied by [16], severe erosion and slope instability (Fig. 2) occur in rural areas where inadequate drainage and unprotected embankments exist.

The current studies also identify pervasive deficiencies in the design and maintenance of road infrastructure in urban and coastal areas. Researchers such as [2, 33] cite inadequate foundation reinforcement and drainage systems as primary causes of structural weakening in Lagos and Port Harcourt under tidal flood conditions. Road failures are exacerbated by poor subgrade compaction and the lack of salinity-resistant materials. Additionally, [36] identifies the absence of robust embankment stabilization measures for hilly regions that accelerate road degradation during seasonal rains. Innovative methods are proposed in several studies aimed at improving the sustainability and resilience of road infrastructure. [1] suggests that geotextiles and impermeable barriers are effective means for subgrade stabilization in flood-prone coastal areas. [8] calls for city planning that incorporates climate change considerations, including flood barriers and permeable pavements to mitigate the effects of rising sea levels and erratic rainfall. Bioengineering techniques, also explored by [16], provide low-cost options for controlling erosion and stabilizing slopes.

Fig. 2 (A & B) Pictures showing road infrastructure failure caused by flooding and erosion from [16] and [20]

The use of salinity-resistant materials and improved compaction techniques, as proposed by [33], is becoming a necessary strategy to combat soil degradation under tidal flooding in coastal environments. The studies highlight the necessity of integrating modern drainage systems, including modular culverts [28], to manage runoff and prevent waterlogging across all regions.

TABLE I GEOTECHNICAL AND HYDROLOGICAL STUDIES ON INFRASTRUCTURE FAILURES

Author & Year	Objective of Study	Methodology	Study Area and Environmental Context	Soil and Geotechnical Characteristics	Flood and Erosion Dynamics	Infrastructure Type and Design Considerations	Failure Mechanisms	Sustainability and Resilience Strategies	Hydrological and Climate Considerations	Methodology Strengths and Limitations	Recommendations for Mitigation and Adaptation	Economic and Social Impacts	Key Findings and Conclusions
[1]	Examine subgrade hydraulic behavior, seepage-induced failures, and sustainable road design.	Field sampling, seepage analysis, and hydraulic testing.	Coastal Akwa Ibom; sandy soils, high water tables, prone to flooding.	Low-cohesion sandy soils with high permeability.	Persistent seepage and subgrade erosion from high water table.	Roads without robust drainage or reinforcement systems.	Pavement collapse from subgrade saturation.	Use geotextiles and impermeable barriers.	Frequent flooding exacerbated by poor drainage.	Strong field data but lacks regional modeling.	Improved drainage systems and subgrade stabilization techniques.	Costly repairs, restricted mobility, and accident risks.	Soil stabilization and drainage critical for coastal roads.
[8]	Explore adaptation strategies for climate-threatened urban transport.	Case studies, policy evaluation, and climate risk assessment.	Lagos City; urban and coastal, affected by sea-level rise and heavy rainfall.	Weak subgrade stability under flood-prone conditions.	Urban flooding disrupts infrastructure and mobility.	Aging and poorly designed urban transport systems.	Foundation destabilization from erosion and waterlogging.	Flood barriers, permeable pavements, and urban planning reforms.	Rising sea levels and erratic rainfall patterns.	Policy-driven insights but lacks detailed solutions.	Develop city-level resilience strategies.	Disruptions in transportation and economic activities.	Urgency of climate-resilient urban planning.
[16]	Analyze causes of erosion-induced road failure.	Geotechnical field study and erosion modeling.	Ifon-Benin Highway; steep embankments and heavy rain.	Silty and lateritic soils prone to erosion	Heavy rainfall causing concentrated runoff and embankment erosion.	Highways with inadequate embankment stabilization measures.	Slope instability and washouts.	Use bioengineering techniques and erosion control measures.	Seasonal heavy rains and concentrated surface runoff.	Robust geotechnical insights but lacks consideration of climate variability.	Strengthen embankments and implement runoff control systems.	Road closures disrupt connectivity and economic activities.	Erosion control is critical for maintaining embankment stability.
[33]	Assess geotechnical properties of coastal soils for infrastructure stability.	Laboratory-based geotechnical analysis.	Port Harcourt coastal areas; saline and waterlogged environments.	Saline, silty clay soils with low permeability and high compressibility.	Coastal erosion and tidal flooding exacerbate soil instability.	Coastal roads with minimal subsurface stabilization.	Differential settlement and pavement collapse.	Improved compaction and use of salinity-resistant materials.	Frequent tidal flooding and salinity-induced soil degradation.	Well-executed lab experiments but limited field validation.	Use of saline-resistant stabilizers and improved drainage systems.	High maintenance costs due to frequent infrastructure failures.	Highlights the importance of addressing salinity in coastal soil stabilization.

[36]	Evaluate road failure mechanisms along erosion-prone highways.	Integrated geophysical and geotechnical methods.	Ogun State; hilly terrain with seasonal rains and poor vegetation cover.	Lateritic soils prone to rapid erosion.	Sheet erosion and heavy runoff destabilising slopes.	Highways with poorly designed embankments.	Slope failure and cracking due to soil instability.	Use geotextiles and slope stabilisation techniques.	Seasonal rainfall exacerbates slope erosion.	Strong geophysical data but lacks implementation details.	Reinforce slopes with geotextiles and establish vegetation cover.	Erosion-induced failures cause economic losses and disruptions.	Demonstrates geophysical tools' effectiveness in diagnosing failures.
[2]	Investigate subsurface conditions contributing to road failure using electrical resistivity imaging.	Geophysical survey and subsurface analysis.	Lagos-Badagry Expressway; urban area with poor drainage.	Sandy and clayey soils with varied stability.	Subsurface water intrusion causing subgrade instability.	Urban roads with poor foundation planning.	Pavement cracking and material washout.	Reinforce subgrades with impermeable layers.	Seasonal rainfall intensifies subsurface water issues.	Accurate imaging but lacks hydrological data integration.	Integrate subsurface reinforcements and better drainage.	Frequent road closures affect regional transport and trade.	Highlights geophysics' role in identifying failure mechanisms.
[28]	Evaluate highway drainage systems for flood mitigation.	Field-based drainage assessment.	Benin-Auchi Expressway; flat terrain prone to flooding.	Poorly compacted soils with low drainage capacity.	Persistent waterlogging caused by inadequate drainage.	Highways with insufficient culverts and runoff channels.	Foundation weakening from prolonged waterlogging.	Install larger culverts and improve runoff channels.	Intense rainfall overwhelms drainage systems.	Practical drainage assessment but lacks modeling for extreme events.	Redesign drainage systems to handle higher volumes.	Road closures disrupt local mobility and commerce.	Highlights drainage design's importance in flood mitigation.
[27]	Investigate pavement failure causes on rural roads.	Case study and field sampling.	Edunabon-Sekona Road, rural area with clayey soils.	Expansive clay soils prone to swelling and shrinkage.	Seasonal moisture variations destabilize pavement foundations.	Rural roads with unpaved or poorly maintained surfaces.	Cracking and deformation from moisture-induced swelling.	Stabilize soils with lime treatment and improve drainage.	Seasonal rainfall exacerbates swelling and shrinking cycles.	Detailed soil analysis but lacks long-term monitoring.	Soil treatment and consistent maintenance strategies.	Frequent failures increase costs and reduce rural accessibility.	Emphasizes soil stabilization for longevity in rural roads.
[20]	Analyze rain-induced pavement collapse mechanisms.	Geotechnical analysis of rain impacts.	Obolo-eke, Southeast Nigeria; undulating terrain and heavy rains.	Clay-rich soils with low shear strength.	Intense rainfall leading to rapid soil weakening.	Rural highways with minimal reinforcement.	Soil shear failure and surface cracking.	Use reinforced materials to counteract soil weakening.	Heavy rainfall and infiltration accelerate soil degradation.	Robust soil failure analysis but lacks preventive focus.	Reinforce roads with stabilized layers and monitor infiltration.	Increased costs from frequent failures in rural areas.	Highlights rainfall's critical role in soil stability.
[32]	Develop drainage systems for flat terrain roads	Design and case study review.	New Owerri, flat terrain with poor natural drainage.	Poorly compacted sandy soils prone to saturation.	Waterlogging caused by ineffective drainage systems.	Urban roads with inadequate runoff management.	Foundation weakening and surface cracks.	Develop innovative drainage designs for flat terrain.	Frequent waterlogging during the rainy season.	Effective drainage design but lacks scalability.	Implement modular drainage solutions for scalability.	High repair costs and reduced urban mobility.	Highlights drainage solutions tailored to flat terrain challenges.

However, infrastructure failures have substantial socioeconomic consequences, such as restricted mobility, higher repair costs, and disruptions in economic activities. Transport disruptions during floods cause significant economic losses in urban areas like Lagos and Ibadan [8], [13]. Key road failures, as reported in [27] and [20], restrict access to essential services, exacerbating social inequalities in rural areas. Field sampling, geotechnical analysis, GIS-based risk modeling, and climate policy analysis form the methodologies used in these studies. These approaches offer considerable insight into the road failure mechanisms and potential solutions. Nevertheless, some studies, such as [16] and [2], lack long-term monitoring data and region-specific models, making their findings less generalizable. These gaps need to be addressed through multi-year studies and integrated modeling frameworks to facilitate more robust recommendations.

Like the global literature, analysis of African studies on road infrastructure resilience in flood-prone regions reveals shared challenges, transferable solutions, and distinctive needs. Geotechnical and soil properties are both identified as critical factors in infrastructure vulnerability in both African and global studies. For example, in African areas like Akwa Ibom and Lagos [1], [20], [27], sandy soils prone to subgrade erosion and expansive clays undergoing swelling cycles are significant issues. In Thailand's Chiang Mai flood-prone region, soil permeability and hydrological stress play important roles in infrastructure transportation and need to be well considered in terms of robust design [35]. Similarly, hydrological dynamics, such as waterlogging and drainage inadequacies, also interfere with transport systems in urban centers like Lagos and Edo State of Nigeria [8], [28], similar to how, elsewhere, such as in Newcastle upon Tyne, overloaded transport networks are mitigated by adapting drainage systems during extreme rainfall [34]. Furthermore, lacking sound design and maintenance, such as inadequate foundation reinforcement and drainage in Lagos [2] and Port Harcourt [33], and in urban areas like Freetown, Sierra Leone [25], with poor infrastructure management, further amplify flood impacts and underscore the importance of greater redundancy in the road network.

Technological innovation is crucial for addressing these challenges. According to African studies, geotextiles, impermeable barriers, and salinity-resistant materials are recommended to combat soil degradation and subgrade instability [1], [33]. These strategies echo some of the approaches in the Mekong flood plains, where materials and techniques are developed and employed to minimize disruption to hydraulics while conserving the ecological balance [12]. Nature-based solutions (NbS) are also critical in resilience planning. Global practices, including floodplain restoration and green infrastructure in Portland, Oregon [10], emphasize the integration of ecological systems with flood mitigation strategies, while African bioengineering techniques for slope stabilization [16] are similar. East African cities also emphasize public awareness and stakeholder engagement as key factors in the adoption of NbS [36]. As with global practice, advanced planning tools, including GIS-based risk modeling and climate-adaptive infrastructure planning, are increasingly used in African contexts. For example, travel demand analysis was used in conjunction with flood hazard maps to prioritize infrastructure upgrades in Senegal [34].

Region-specific applications reflect Africa's socioeconomic constraints and geographical needs. Global solutions often focus on high-cost infrastructure investments in urban centers like Tokyo and Portland, while resource limitations often favor low-cost, community-focused flood mitigation strategies like modular culverts and localized NbS. Like African rural areas, global urban solutions focus on technological advances in traffic modeling and predictive flood systems [34], while African rural areas suffer from unprotected embankments and lack of emergency route access [16].

IV. CONCLUSION

Overall, this review makes a compelling case for sustainable soil-structure interaction (SSI) principles to inform the design and maintenance of road infrastructure in Nigeria's flood-prone areas. Severe socio-economic risks exist due to frequent failures in road networks driven by extreme weather events and compounded by factors such as subgrade instability, relatively poor drainage, and climate change. Several key findings indicate that road durability and performance can be greatly improved through the use of innovative materials, such as recycled low-density polyethylene (LDPE), bioengineered additives, and salinity-resistant solutions. Nature-based solutions, such as vegetative embankments and permeable pavements, are also low-cost, environmentally sustainable solutions to reduce waterlogging and erosion. Finally, despite these advancements, challenges remain, namely the limited application of predictive modeling and the lack of adaptation to local hydrological and geotechnical conditions. Moreover, current strategies lack integration between engineering practices, policy considerations, and economic issues. Gaps in this area need to be addressed through a paradigm shift. The multidisciplinary approaches should therefore include technological innovation, environmental science, policy frameworks, and economic analyses. These holistic strategies are key elements not only for boosting the resilience of roads but also for protecting communities and leveraging a sustainable economy in Nigeria.

V. RECOMMENDATIONS OF THE STUDY

In addition, the use of advanced materials and innovative construction practices should be a top engineering priority. LDPE-modified asphalt materials can enhance tensile strength and moisture resistance, while bioengineered additives, geotextiles, and impermeable barriers can aid in soil stabilization and prevent subgrade erosion. These solutions can be integrated into design standards to address structural vulnerabilities and ensure long-term durability.

Additionally, traditional engineering methods should be supplemented with nature-based solutions. Permeable pavements, vegetative embankment systems, and ecological drainage systems can better minimize trapped water and prevent hazardous flooding, while simultaneously protecting the natural environment. These strategies are cost-effective, scalable, and particularly well-suited for resource-constrained regions.

Climate-resilient construction practices should be mandated by policy and regulatory frameworks, and stakeholder cooperation should be encouraged. Large-scale infrastructure projects should be promoted through public-private partnerships to mobilize resources. Furthermore, regional policies should incorporate site-specific hydrological and geotechnical data to appropriately address localized infrastructure needs. Decision-making should prioritize economic concerns. A comprehensive cost-benefit analysis will highlight the economic advantages of implementing sustainable infrastructure practices, leading to reduced maintenance costs and minimal economic disruptions caused by disasters. Financial constraints should be addressed through innovative funding mechanisms, such as green bonds and international climate funds.

Finally, improving resilience requires technological integration. GIS-based flood risk mapping and predictive modeling can be used to plan and maintain infrastructure. In addition to monitoring, applied strategies should be continuously evaluated and adapted to changing climatic conditions through long-term performance monitoring.

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