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Climate Change Impacts on Road Infrastructure Resilience in Bireuen Regency, Aceh: An Environment-Based Adaptation Approach

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ABSTRACT

The escalating frequency and intensity of climate-induced extreme weather events present a critical challenge to the durability and functionality of road infrastructure, particularly in vulnerable tropical regions. This study provides a comprehensive analysis of the impacts of climate change on road infrastructure resilience in Bireuen Regency, Aceh, Indonesia. Employing a mixed-methods approach, the research integrates historical climate data (2015-2023) from the Meteorology, Climatology, and Geophysics Agency (BMKG), field survey data on road damage, and questionnaire responses from key stakeholders, including road users and local government officials. The findings reveal a statistically significant upward trend in extreme rainfall events, which correlates strongly with the prevalence of specific road damage modalities, predominantly potholes (45%) and crocodile cracking (30%). A thorough assessment of the road network condition indicates that only 51.19% is classified as being in good condition, with a substantial 42.46% suffering from light to severe damage, underscoring a high degree of climate vulnerability. The study concludes that a multifaceted adaptation strategy is imperative. Key recommendations include the urgent enhancement of drainage systems, the adoption of climate-resilient construction materials, the implementation of GIS-based hazard zoning, and the strict application of sustainable road management standards as outlined in national regulations. This research offers valuable evidence-based insights for policymakers and engineers aiming to bolster the climate resilience of critical infrastructure in disaster-prone areas.

1. INTRODUCTION

Climate change has unequivocally emerged as one of the most pressing global challenges of the 21st century, with far-reaching implications for socio-economic development and infrastructure integrity. The Intergovernmental Panel on Climate Change (IPCC, 2021) has consistently highlighted the increased variability and intensity of hydrological cycles, leading to more frequent and severe extreme weather events such as torrential rainfall, floods, and landslides. Transport infrastructure, particularly road networks, is highly susceptible to these changes due to its extensive spatial exposure and direct interface with environmental elements (Sharma & Ghosh, 2020). The vulnerability is especially pronounced in tropical developing countries like Indonesia, where infrastructure development often struggles to keep pace with rapidly evolving climate risks (World Bank, 2019).

Roads are the lifelines of economic activity, facilitating the movement of goods, services, and people. Their failure or degradation disrupts supply chains, impedes access to essential services, and escalates maintenance costs, thereby undermining regional development goals (Ng et al., 2022). The degradation mechanisms are complex and multifactorial. Extreme precipitation leads to water saturation of subgrade materials, reducing soil bearing capacity and causing structural failures like potholes and stripping. Conversely, prolonged dry spells and high temperatures can induce thermal cracking and rutting in asphalt pavements (Amin & Abbas, 2021). These processes are exacerbated by non-climatic factors such as inadequate drainage design, suboptimal construction quality, and heavy traffic loads.

Bireuen Regency, situated in the northern part of Sumatra, Indonesia, exemplifies a region facing acute climate risks. Its geographical disposition, characterized by steep topography in some areas and inadequate urban drainage systems, makes it recurrently susceptible to flooding and landslides during the monsoon season (BPBD Bireuen, 2023). Historical data from the local Disaster Management Agency (BPBD) indicates a rising trend in hydro-meteorological disasters, which have directly impacted the regency's road infrastructure, valued as a critical asset for local connectivity and economic vitality. While the Indonesian government has introduced forward-looking policies such as the Minister of Public Works and Housing Regulation (Permen PUPR) No. 21/PRT/M/2021 concerning Sustainable Road Management, the translation of these national guidelines into effective local action remains a significant challenge. There is a discernible gap in localized, empirical studies that quantitatively and qualitatively link observed climate trends with specific infrastructure performance metrics at the regional level.

This research seeks to address this gap by conducting a detailed investigation in Bireuen Regency. The study is guided by three primary objectives: first, to analyze the decadal pattern of climate change, with a specific focus on extreme rainfall; second, to assess the resultant impacts on the types and extent of road damage; and third, to formulate a set of context-specific, evidence-based adaptation strategies to enhance the resilience of road infrastructure. The findings aim to bridge the science-policy divide, providing actionable intelligence for local governments, planners, and engineers to integrate climate adaptation into mainstream infrastructure development and maintenance practices.

2. METHOD

Study Area

Bireuen Regency is a strategic administrative region within Aceh Province, Indonesia, located on the northern coast of Sumatra. It encompasses an area of approximately 1,899 square kilometers, featuring a diverse topography that includes coastal lowlands and hilly interiors. This geographical diversity, coupled with its location in a high-rainfall zone, renders it particularly vulnerable to climate-induced hazards such as flash floods and landslides, especially along its road corridors that connect vital economic hubs.

Data Collection

The study adopted a convergent parallel mixed-methods design, wherein both quantitative and qualitative data were collected concurrently to provide a comprehensive understanding of the problem.

1) Secondary Data: Extensive secondary data were collected from various official sources. Decadal historical rainfall data (2015–2023) were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG). Detailed records on road conditions, including type, location, and severity of damage, were sourced from the Public Works and Spatial Planning Office (Dinas PUPR) of Bireuen Regency. Furthermore, data on the frequency and spatial distribution of flood and landslide events were acquired from the Regional Disaster Management Agency (BPBD) for the same period.
2) Primary Data: Primary data were gathered through two main instruments:

a) Field Surveys: Detailed field observations were conducted on selected road segments identified as highly vulnerable based on secondary data. These surveys documented visual manifestations of road damage (e.g., potholes, cracking, rutting) and assessed the condition of accompanying drainage infrastructure.
b) Structured Questionnaires: A survey was administered to a purposively selected sample of 85 respondents. This cohort included regular road users, residents living adjacent to vulnerable road sections, and technical officials from relevant local government agencies (Dinas PUPR and BPBD). The questionnaire was designed to capture perceptions regarding the perceived increase in climate extremes, the observed impacts on road conditions, and the prioritization of potential adaptation measures.

Data Analysis

The analysis involved a multi-pronged approach:

1) Trend Analysis: Historical rainfall data were analyzed using descriptive statistics and graphical plots (e.g., time-series graphs) to identify patterns and trends in annual and monthly precipitation, with a specific focus on detecting increases in extreme rainfall events (defined as >100 mm/day).
2) Damage Correlation Analysis: The frequency and distribution of different road damage types were cross-tabulated with climate data (e.g., rainfall intensity) to establish correlational relationships and identify dominant climate triggers for specific failure modes.

Descriptive and Likert Scale Analysis: Questionnaire responses were coded and analyzed using statistical software. Descriptive statistics (frequencies, percentages) summarized the respondent demographics and general perceptions. A five-point Likert scale (1=Strongly Disagree to 5=Strongly Agree) was used to analyze attitudes towards climate risks and the acceptability of proposed adaptation strategies, with results presented as mean scores and percentages of agreement.

3. RESULTS AND DISCUSSION

Result

Climatic Trends: Intensification of Rainfall Extremes

The analysis of BMKG data from 2015 to 2023 reveals a clear and concerning trend of increasing rainfall intensity in Bireuen Regency. The average annual rainfall demonstrated a steady rise from 1,740 mm in 2015 to 2,145 mm in 2023. More critically, the frequency of extreme rainfall events (exceeding 100 mm within 24 hours) showed a marked increase, particularly during the peak monsoon months from October to February. This trend is visually summarized in Table 1, which displays the monthly rainfall averages, showing consistent increases across virtually all months over the nine-year period. This finding aligns with broader regional climate projections for Southeast Asia, which predict an increase in the intensity and variability of precipitation due to global warming (IPCC, 2021).

Manifestation of Climate Impacts on Road Infrastructure

The synthesis of field survey data and official records from Dinas PUPR provides compelling evidence of the direct impact of these changing climate patterns on road infrastructure. The damage is not random but follows predictable patterns linked to specific hydrological and thermal stresses. As detailed in Table 2, potholes are the most prevalent form of damage (45%), directly triggered by the combined effect of water stagnation from heavy rains and the abrasive action of traffic on weakened pavement. Crocodile cracking (30%), indicative of fatigue failure, is strongly associated with repeated cycles of saturation and drying of the road base and subgrade. Stripping or raveling (15%), the loss of surface aggregates, is a direct consequence of water infiltration into the asphalt layer. A significant 65% of survey respondents confirmed that road deterioration accelerates noticeably following major flood events, reinforcing the causal link.

Table 1: Typology of Road Damage and Associated Dominant Climate Triggers

Type of Damage	Frequency (%)	Dominant Climate Trigger	Underlying Mechanism
Potholes	45	High-intensity rainfall + Traffic	Water seepage weakens subgrade; traffic dislodges saturated pavement material.
Crocodile Cracking (Fatigue)	30	Wet-Dry Cycles	Repeated expansion and contraction of subgrade and base layers lead to fatigue failure.
Stripping/Ravelling	15	Water Infiltration	Water penetrates the asphalt-aggregate bond, causing aggregate loss.
Rutting	7	High Temperature + Axle Loads	Asphalt binder softens under heat, leading to permanent deformation under heavy loads.

Assessment of Road Network Resilience

A critical assessment of the entire road network's condition in Bireuen Regency, as cataloged by Dinas PUPR in 2025, reveals a state of significant vulnerability. Out of a total network length of 1,207.67 km, only 618.26 km (51.19%) are classified as being in 'good' condition. A combined 42.46% (231.83 km 'lightly damaged' + 280.90 km 'severely damaged') of the network requires urgent attention. This statistic translates to nearly half of the regency's road infrastructure being susceptible to accelerated degradation under current and projected climate stresses, posing a substantial threat to mobility, safety, and economic efficiency.

Prioritized Adaptation Strategies

The questionnaire responses from stakeholders, including technical experts from Dinas PUPR and BPBD, provided clear directives for adaptive action. The strategies were ranked based on the percentage of respondents who agreed or strongly agreed on their importance:

1. Enhancement of Road Drainage Systems (85% agreement): This was identified as the most critical intervention. Improving the capacity and maintenance of drainage infrastructure is fundamental to diverting surface water and preventing saturation of the road structure.
2. Use of Climate-Resilient Materials (80% agreement): Specifying materials such as polymer-modified asphalt, which offers greater resistance to water damage and temperature variations, was highly recommended.
3. GIS-Based Disaster Risk Mapping (75% agreement): Developing detailed spatial maps that overlay climate hazard data (flood/landslide susceptibility) with road network layers can guide targeted investments and preventive maintenance.
4. Strict Implementation of Sustainable Construction Standards (70% agreement): Enforcing regulations like Permen PUPR No. 21/2021 ensures that climate resilience is embedded in the design, construction, and maintenance phases of road projects from the outset.

The discussion underscores that a siloed approach is insufficient. An integrated strategy that combines engineering solutions (drainage, materials), spatial planning (GIS mapping), and robust governance (implementation of standards) is essential for building long-term resilience.

Discussion

The findings of this study demonstrate that climate change has become a significant driver of road infrastructure degradation in Bireuen Regency. The increasing trend in annual rainfall and the growing frequency of extreme precipitation events observed between 2015 and 2023 indicate that local road networks are experiencing escalating climatic pressures. These findings are consistent with the projections of the IPCC (2021), which emphasize that global warming intensifies the hydrological cycle, resulting in more frequent heavy rainfall events, particularly in tropical regions. Similar observations have been reported by Sharma and Ghosh (2020), who identified transport infrastructure as one of the sectors most vulnerable to climate variability due to its continuous exposure to environmental stressors.

The predominance of potholes (45%) and crocodile cracking (30%) found in this study confirms that excessive moisture infiltration remains the primary mechanism responsible for pavement deterioration in humid tropical environments. Water penetration weakens the subgrade and reduces its bearing capacity, accelerating pavement fatigue under repeated traffic loading. This mechanism corresponds with the findings of Amin and Abbas (2021), who highlighted moisture-induced weakening as a major factor affecting road service life under changing climate conditions. Likewise, Arsic et al. (2020) reported that intensified precipitation significantly increases maintenance costs and shortens pavement design life, particularly in developing countries where drainage systems are often inadequate.

The substantial proportion of damaged roads in Bireuen Regency, reaching 42.46% of the total network, indicates a relatively low level of infrastructure resilience against current and future climate hazards. Road resilience is increasingly understood not merely as the capacity to withstand disturbances but also as the ability to adapt, recover, and maintain functionality under changing environmental conditions (Moeinaddini & Asadi-Shekari, 2022). The present findings suggest that existing road management practices in Bireuen remain largely reactive, focusing on post-disaster repairs rather than preventive adaptation measures. Similar challenges have been documented in many Southeast Asian regions, where infrastructure development has not yet fully integrated climate risk considerations into planning and maintenance frameworks (Ng et al., 2022).

Stakeholder perceptions further reinforce the importance of proactive adaptation strategies. The prioritization of drainage system improvement by 85% of respondents reflects a widespread recognition that effective stormwater management is essential to reducing pavement saturation and preventing structural failure. Jumar and Hadisantono (2020) emphasized that drainage optimization is among the most cost-effective approaches for increasing the durability of roads in flood-prone areas. Furthermore, the recommendation to utilize climate-resilient materials, such as polymer-modified asphalt, aligns with the findings of Ginting and Sari (2022), who demonstrated that advanced pavement materials exhibit greater resistance to moisture damage, temperature fluctuations, and permanent deformation.

The strong support for GIS-based hazard mapping also indicates growing awareness of the importance of spatial planning in climate adaptation. Spatially explicit assessments can assist decision-makers in identifying highly vulnerable road segments, prioritizing investments, and designing targeted interventions. Dewan and Corner (2021) argued that integrating flood susceptibility analysis with transportation networks substantially enhances infrastructure planning and emergency response capabilities. In the context of Bireuen Regency, such an approach could contribute to more efficient allocation of limited financial resources while reducing long-term maintenance expenditures.

The implementation of sustainable road management standards, including the provisions outlined in Permen PUPR No. 21/PRT/M/2021, represents another important pathway toward strengthening climate resilience. Sustainable infrastructure governance requires not only technical innovations but also institutional commitment, adequate funding mechanisms, and effective coordination among stakeholders. Kumar et al. (2021) emphasized that developing countries can significantly enhance infrastructure resilience by mainstreaming climate adaptation principles throughout the entire infrastructure life cycle, from planning and design to operation and maintenance.

Overall, the findings of this study indicate that climate adaptation for road infrastructure in Bireuen Regency should not rely solely on engineering interventions. Instead, a comprehensive resilience framework combining technological innovation, risk-informed spatial planning, sustainable governance, and community participation is needed to address the increasingly complex impacts of climate change. Such an integrated approach is essential to ensuring the long-term functionality, safety, and socio-economic benefits of transportation infrastructure in climate-vulnerable regions.

4. CONCLUSION AND RECOMMENDATION

Conclusion

This study demonstrates that climate change has significantly affected the resilience of road infrastructure in Bireuen Regency, Aceh. The analysis of rainfall data from 2015–2023 reveals an increasing trend in the intensity and frequency of extreme precipitation events, which are strongly associated with accelerated road deterioration. Potholes and crocodile cracking were identified as the dominant damage types, primarily resulting from water infiltration, repeated wet-dry cycles, and inadequate drainage performance. The assessment of road conditions further indicates that nearly half of the regency's road network is currently in lightly to severely damaged condition, highlighting a considerable level of vulnerability to climate-related hazards. To enhance infrastructure resilience, this study emphasizes the importance of adopting integrated adaptation measures, including improving drainage systems, utilizing climate-resilient construction materials, implementing GIS-based disaster risk mapping, and strengthening compliance with sustainable road management standards. These measures are expected to support more adaptive, durable, and sustainable road infrastructure development, thereby ensuring long-term connectivity, mobility, and socio-economic stability in climate-vulnerable regions such as Bireuen Regency.

Recomendation

Based on the findings of this study, it is recommended that the local government of Bireuen Regency prioritize climate adaptation within road infrastructure planning and management. Efforts should focus on upgrading and maintaining drainage systems in flood-prone areas, incorporating climate-resilient materials into road construction projects, and developing GIS-based hazard maps to support risk-informed decision-making. Furthermore, the implementation of sustainable road management practices in accordance with Permen PUPR No. 21/PRT/M/2021 should be strengthened through adequate funding, regular monitoring, and inter-agency coordination. Future studies are also encouraged to employ predictive climate modeling and cost-benefit analyses of adaptation measures to provide more comprehensive guidance for long-term infrastructure resilience planning in vulnerable tropical regions.

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