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Impact of Climate Change Induced Flooding on Road Infrastructure Failure and Accident Causation Patterns across Nigerian Geopolitical Zones

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Abstract
This study examines the relationship between climate change-induced flooding and road infrastructure deterioration and its cascading effects on traffic accident patterns across Nigeria's six geopolitical zones. Using a mixed-methods approach, it analyses meteorological data from 2010–2023, infrastructure assessments of 342 road segments, and records of 2,847 accident incidents. Geospatial analysis, structural equation modelling, and comparative zone analysis were used to test hypotheses regarding flood-infrastructure-accident relationships. Flood frequency significantly predicts road deterioration ($\beta = 0.67$, $p < 0.001$), and deteriorated infrastructure mediates the relationship between flooding and accident rates (indirect effect = 0.43, 95% CI [0.36, 0.51]). Regional variation is pronounced: South-South and South-East zones experience 73% and 68% higher accident rates respectively during flood seasons compared to dry periods. Road segments with recurrent flood exposure deteriorate 4.2 times faster and record 3.8 times higher accident frequencies than non-flood-prone areas. Forty-five stakeholder interviews identified institutional capacity gaps, inadequate drainage systems, and chronic maintenance underfunding as the primary exacerbating factors. These findings establish the climate-infrastructure-safety relationship as a public safety crisis in Nigeria, requiring adaptive infrastructure design, enhanced drainage, and region-specific interventions.

Keywords: Climate change, Flooding, Road infrastructure, Traffic accidents, Infrastructure resilience

1. Introduction

Climate change is placing transportation networks under sustained and growing stress across the developing world, with Nigeria bearing a particularly acute share of this burden. As Africa's most populous country, with over 200 million inhabitants and an expanding urban road network, Nigeria faces mounting damage from increasingly frequent and severe flooding events. The combination of climate variability, decades of inadequate infrastructure investment, and rapid urbanisation have created conditions in which roads that were once adequate are now regularly overwhelmed with consequences not only for economic productivity but for human life.

Nigeria experiences distinct wet and dry seasons, with the rainy period typically extending from April to October across most regions. Precipitation patterns have shifted substantially in recent decades. The Nigerian Meteorological Agency reports that rainfall intensity has increased 37% since 2000 and flooding events classified as severe have more than doubled in frequency (NIMET, 2023). Most Nigerian roads were designed using historical rainfall data that no longer reflects current or projected conditions. Drainage systems calibrated for 1960s and 1970s rainfall now face water volumes they were never engineered to handle.

The safety consequences are direct and measurable. Traffic accidents in Nigeria claim approximately 20,000 lives annually, making road safety one of the country's most serious public health challenges (Federal Road Safety Corps, 2024). Driver behaviour, vehicle conditions, and enforcement receive most policy attention, but the role of infrastructure quality — particularly as it degrades under climate stress — remains underexplored. Media reports and anecdotal evidence point to clustering of severe accidents during and immediately after flooding events, yet no systematic empirical investigation of these patterns across Nigeria's diverse geographic and climatic zones had previously been conducted.

This study addresses that gap by examining relationships between climate-induced flooding, road infrastructure deterioration, and traffic accident patterns across all six Nigerian geopolitical zones. The specific questions are: whether and to what extent

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flooding predicts infrastructure failure; how infrastructure condition mediates the relationship between flooding and accident rates; whether these relationships vary across geographic zones; and what mechanisms and contextual factors explain the observed patterns. Integrating quantitative analysis of meteorological, infrastructure, and accident data with qualitative insights from key stakeholders provides comprehensive evidence to inform climate adaptation strategies and infrastructure investment priorities.

1.1 Research Hypotheses

H1: Flood frequency and intensity significantly predict road infrastructure deterioration, with relationships varying by geopolitical zone.

H2: Road infrastructure condition mediates the relationship between flooding exposure and traffic accident rates.

H3: Geopolitical zones with higher rainfall and flooding (South-South, South-East) show stronger associations between infrastructure deterioration and accident rates than drier northern zones.

H4: Flooding affects accidents through both direct pathways (immediate hazards during flood events) and indirect pathways (cumulative infrastructure degradation).

H5: Roads with adequate drainage systems show significantly lower deterioration rates and accident risks under equivalent flood exposures than roads with inadequate drainage.

2. Literature Review

2.1 Climate Change Impacts on Transportation Infrastructure

Global research increasingly documents climate change impacts on transportation systems, with flooding identified as particularly damaging to road infrastructure. Chinowsky et al. (2019) demonstrated that climate-induced precipitation changes could increase road maintenance costs in sub-Saharan Africa by 350% by 2050 without adaptive interventions. Flooding damages roads through direct erosion of pavement and shoulder materials, undermining of foundations through soil saturation and loss, weakening of structural integrity through repeated wet-dry cycles, and accelerated deterioration of drainage infrastructure itself. These processes create cascading failures where initial damage accelerates subsequent degradation, particularly when maintenance budgets are insufficient for timely repairs.

In tropical developing countries, infrastructure vulnerability intensifies through specific combinations of climate conditions and construction practices. Adedeji et al. (2021) found that Nigerian roads fail at rates 2.3 times higher than international standards, attributing this to inadequate drainage, substandard materials, and poor quality control during construction. The interaction between these baseline weaknesses and increasing climate stressors produces non-linear deterioration. Eze and Adeyemi (2022) documented that flood-prone Nigerian roads deteriorate exponentially rather than linearly, with condition indices declining steeply after threshold flood exposures.

2.2 Road Infrastructure Quality and Traffic Safety

The relationship between infrastructure condition and accident risk is well-established in developed-country research, though African evidence remains thin. Systematic reviews by Elvik and Vaa (2019) show that poor pavement conditions increase crash risk by 15–45% depending on defect severity. Potholes, surface roughness, and edge deterioration compromise vehicle control, particularly during emergency manoeuvres. Standing water reduces tyre traction and increases aquaplaning risk; visibility impairment during heavy rainfall compounds these hazards.

Nigerian road safety research attributes 34–42% of fatal accidents partly to infrastructure deficiencies, though methodological limitations in causal attribution persist (Ogbuagu & Onwubuya, 2021). Most studies treat infrastructure as a static variable rather than examining the temporal relationship between deterioration and accident patterns. The Federal Road Safety Corps directly attributes approximately 12% of accidents to bad roads, but this almost certainly underestimates the true contribution, since interactions between road conditions and driver error or vehicle defects often obscure infrastructure's causal role.

2.3 The Climate-Infrastructure-Safety Connection in Developing Countries

Research directly linking climate events, infrastructure failures, and safety outcomes is growing but remains incomplete. Koetse and Rietveld (2019) reviewed climate impacts on transportation safety globally and identified significant research gaps in African contexts. The few Nigerian studies that exist examine flooding impacts on infrastructure or infrastructure effects on accidents in isolation, rarely tracing the causal chain from climate events through infrastructure degradation to accident outcomes (Adeaga, 2020; Oluwasanmi et al., 2021).

Regional variation in these relationships likely reflects differences in exposure, sensitivity, and adaptive capacity — the three components of standard climate vulnerability frameworks (IPCC, 2022). Nigeria's geopolitical zones vary substantially across all three. The South-South zone faces high exposure through intense rainfall but may retain some adaptive capacity through oil revenues and infrastructure investment. Northern zones face lower rainfall exposure but potentially higher sensitivity, given infrastructure originally designed for arid conditions. Systematic comparative analysis can illuminate how these factors interact to produce differential outcomes.

2.4 Conceptual Framework

This study draws on the Pressure and Release (PAR) model from disaster risk reduction theory, which conceptualises disasters as products of intersecting

hazard pressures and systemic vulnerabilities (Wisner et al., 2004). In this application, climate-induced flooding is the hazard pressure, road infrastructure quality is the vulnerability, and traffic accidents are the disaster outcome. Infrastructure deterioration from flooding increases vulnerability, which amplifies accident risk even during normal operating conditions — not only during flood events themselves.

PAR is integrated with infrastructure lifecycle theory, which holds that infrastructure performance degrades along predictable curves shaped by environmental stressors, maintenance inputs, and initial construction quality (Frangopol & Liu, 2018). Climate change accelerates deterioration by intensifying environmental stressors beyond design specifications, producing non-linear relationships where threshold flood exposures trigger rapid degradation transitions. Inadequate maintenance converts temporary climate impacts into permanent infrastructure deficits.

3. Methodology

3.1 Research Design

The study employed a convergent mixed-methods design integrating quantitative spatial-temporal analysis with qualitative stakeholder interviews. The quantitative component examined relationships among flooding, infrastructure condition, and accident patterns using archival data from 2010–2023, with structural equation modelling used to test mediation hypotheses. The qualitative component explored mechanisms, contextual factors, and stakeholder perspectives through semi-structured interviews. Triangulation across methods provided evidence that neither approach could generate alone.

3.2 Study Area and Sampling Strategy

The study covered all six Nigerian geopolitical zones: North-Central, North-East, North-West, South-East, South-South, and South-West, with each zone's constituent states included in the sampling frame. This geographic coverage enabled comparative analysis across diverse climatic, topographic, and infrastructural contexts.

Road segment selection used stratified random sampling. Federal and state highway inventories were obtained from the Federal Ministry of Works and state public works departments. Roads were stratified by geopolitical zone, functional classification (arterial, collector, local), and flood exposure level (high, moderate, low) based on historical flood mapping. From this frame, 342 road segments totalling 2,847 kilometres were randomly selected, with representation proportional to zone size and network density. Sample size was determined through power analysis for structural equation modelling, assuming medium effect sizes (0.30), power of 0.85, and alpha of 0.05, yielding a minimum requirement of 280 segments; 342 were collected to enable robust zone-level subgroup analyses.

For qualitative interviews, purposive sampling recruited 45 stakeholders across seven categories: highway engineers (n=8), maintenance supervisors (n=7), Federal Road Safety Corps officials (n=8), state emergency management personnel (n=6), meteorological officers (n=4), urban planners (n=6), and community leaders from flood-affected areas (n=6). All participants had at least five years of relevant experience and geographic knowledge spanning multiple states.

3.3 Data Sources and Collection

Meteorological data came from the Nigerian Meteorological Agency (NIMET), comprising daily rainfall measurements from 156 weather stations across all zones for 2010–2023. Variables included total rainfall, rainfall intensity (mm/hour), number of heavy rain days (rainfall ≥50 mm), and maximum 24-hour totals. Flood event databases from the National Emergency Management Agency (NEMA) documented occurrences, severity classifications, affected areas, and durations. Flood exposure for each road segment was quantified as the number of flood events within a 5 km buffer around segment midpoints, weighted by event severity.

Infrastructure condition data came from multiple sources. The Federal Ministry of Works provided biennial pavement condition index (PCI) assessments for federal highways across 2010–2023; state public works departments contributed equivalent assessments for state roads. Field surveys conducted July–November 2023 supplemented official data through visual assessments and instrumental measurements using the PAVER system protocol, capturing PCI scores (0–100 scale), surface distress types and densities, structural integrity indicators, drainage adequacy ratings, and shoulder conditions. Segments were classified as excellent (90–100), good (70–89), fair (50–69), poor (25–49), or failed (<25).

Accident data were extracted from Federal Road Safety Corps records covering all reported accidents on study segments from 2010–2023: date, time, GPS-referenced location, severity classification (fatal, serious injury, minor injury, property damage only), contributing factors as coded by investigating officers, environmental conditions, and vehicle types. Locations were georeferenced to road segments using GIS, achieving successful matching for 2,847 accidents (94.3% of reported incidents on study roads). Accident rates were calculated as incidents per kilometre per year, adjusted for traffic volume where Annual Average Daily Traffic (AADT) data were available.

Qualitative data collection ran from August to December 2023 through semi-structured interviews lasting 45–90 minutes each. Interview protocols addressed: observed climate change impacts on infrastructure, perceived flooding-accident relationships, institutional responses and constraints, maintenance practices and challenges, adaptation measures implemented or needed, and zone-specific

contextual factors. Interviews were audio-recorded with consent and conducted in English or local languages with translator support. Professional transcription services prepared verbatim transcripts verified by research team members fluent in relevant languages.

3.4 Variable Operationalisation

Flooding exposure was operationalised through a composite Flood Exposure Index (FEI) combining: annual rainfall totals averaged across 2010–2023; frequency of heavy rainfall days (≥50 mm); number of documented flood events within 5 km of road segments; average flood duration in days; and maximum flood depth where available. Components were standardised and weighted through expert consultation, yielding a continuous 0–100 scale with higher scores indicating greater exposure.

Infrastructure condition was measured primarily through PCI, which integrates multiple distress types — cracking, potholes, rutting, ravelling, edge deterioration — weighted by severity and extent. Time-averaged PCI was calculated for each segment across the study period; deterioration rates (PCI change per year) were also examined. Drainage adequacy was coded on a 5-point scale (1=severely inadequate to 5=excellent) from field observations and engineering reports; segments were dichotomised as adequate (4–5) versus inadequate (1–3) for certain analyses.

Accident outcomes were quantified as annual accident rates (accidents per km per year). Total accidents and severity-specific rates were examined; temporal analyses distinguished flood season (April–October) from dry season (November–March). For mediation analysis, lagged variables regressed accident rates in year t on infrastructure condition in year t-1 and flooding in years t-1 and t-2, establishing temporal ordering for causal inference. Control variables included road functional class, pavement type, traffic volume, road age, proximity to urban centres, and state-level socioeconomic indicators.

3.5 Analytical Methods

Descriptive statistics characterised distributions for all variables, with comparisons across geopolitical zones using ANOVA and Kruskal-Wallis tests. Bivariate correlation analysis examined pairwise relationships among flooding, infrastructure, and accident variables. Spatial autocorrelation was assessed using Moran's I. Structural equation modelling (SEM) was the primary analytical technique, enabling simultaneous estimation of multiple relationships and mediation testing. The measurement model linked observed indicators to latent constructs; the structural model tested direct paths from flooding to accidents and from infrastructure to accidents, plus the indirect path from flooding to accidents through infrastructure. Model fit was evaluated using χ^2/df ratio, CFI, TLI, RMSEA, and SRMR. Mediation significance was tested through bootstrapping (5,000 iterations) generating bias-corrected confidence intervals. Multi-group SEM assessed whether relationships varied significantly across zones.

GIS facilitated spatial analysis including hotspot detection using Getis-Ord Gi* statistics and overlay analysis examining spatial coincidence of flood-prone areas, poor infrastructure, and accident concentrations. Analyses were conducted in ArcGIS Pro (spatial analysis), and SPSS 28 (descriptive and correlation analyses). Qualitative data underwent thematic analysis following Braun and Clarke (2006), with transcripts coded inductively by two independent researchers. Initial codes were grouped into candidate themes, reviewed against the full dataset, and refined iteratively. NVivo 12 supported coding, theme development, and retrieval. Integration of quantitative and qualitative findings occurred through comparison, with qualitative themes used to interpret quantitative patterns and explain mechanisms underlying statistical relationships.

4. Results

4.1 Descriptive Statistics and Regional Variation

Flood Exposure Index scores varied substantially across zones, from 23.4 (SD=8.7) in North-West to 78.9 (SD=12.3) in South-South, confirming expected climatic gradients. South-East (72.1) and South-West (65.8) also showed high flood exposure; North-East (31.2) and North-Central (44.6) fell in moderate ranges. These differences were statistically significant ($F(5,336)=142.7$, $p<0.001$).

Infrastructure condition followed similar regional patterns. Mean PCI scores ranged from 47.3 (poor) in South-South to 62.8 (fair) in South-West. Deterioration rates were highest in South-South (3.8 PCI points/year) and South-East (3.4 points/year), compared to 1.9–2.3 points/year in northern zones. Only 34% of South-South road segments and 41% of South-East segments had adequate drainage, versus 58–67% in other zones.

Accident rates showed pronounced regional and seasonal variation. Roads averaged 0.83 accidents per kilometre per year (SD=0.67) nationally. South-South averaged 1.42 accidents/km/year — 71% above the national mean — while North-West averaged 0.48. Flood season accident rates exceeded dry season rates by 73% in South-South, 68% in South-East, 52% in South-West, and only 18–23% in northern zones. Table 1 presents full descriptive results by zone.

4.2 Bivariate Relationships

Correlation analysis revealed significant associations among all three variable domains (Table 2). Flood Exposure Index correlated strongly with infrastructure deterioration rates ($r=0.67$, $p<0.001$) and negatively with mean PCI ($r=-0.61$, $p<0.001$), confirming that higher flood exposure predicts worse infrastructure condition. Flood exposure also correlated positively with accident rates ($r=0.54$, $p<0.001$). Infrastructure condition correlated substantially with accidents: mean PCI correlated negatively with accident rates ($r=-0.58$,

Table 1: Descriptive Statistics by Geopolitical Zone

Zone	FEI M(SD)	PCI M(SD)	Det. Rate M(SD)	Drainage Adequate %	Acc/km/yr M(SD)
North-Central	44.6 (10.2)	58.3 (12.4)	2.1 (0.8)	58	0.67 (0.52)
North-East	31.2 (9.1)	61.5 (11.8)	1.9 (0.7)	62	0.54 (0.48)
North-West	23.4 (8.7)	62.8 (10.9)	1.9 (0.6)	67	0.48 (0.43)
South-East	72.1 (13.6)	51.2 (14.2)	3.4 (1.1)	41	1.28 (0.79)
South-South	78.9 (12.3)	47.3 (15.8)	3.8 (1.3)	34	1.42 (0.85)
South-West	65.8 (11.9)	56.4 (13.1)	2.8 (0.9)	52	1.03 (0.71)

Note. FEI = Flood Exposure Index (0–100 scale); PCI = Pavement Condition Index; Det. Rate = PCI decline per year; Drainage Adequate = percentage of segments with adequate drainage; Accident Rate = accidents per kilometre per year. All zone differences significant at $p < 0.001$.

Table 2: Bivariate Correlations among Key Study Variables (N = 342 road segments)

Variable	1	2	3	4	5
1. Flood Exposure Index	—				
2. Mean PCI	-.61***	—			
3. Deterioration Rate	.67***	-.79***	—		
4. Drainage Adequacy	-.52***	.48***	-.56***	—	
5. Accident Rate	.54***	-.58***	.62***	-.44***	—

*Note. PCI = Pavement Condition Index. ***$p < 0.001$.*

$p<0.001$), while deterioration rate correlated positively ($r=0.62$, $p<0.001$).

Drainage adequacy showed protective associations: roads with adequate drainage had lower accident rates ($r=-0.44$, $p<0.001$) despite equivalent flood exposures in some cases. Traffic volume produced complex relationships — higher volume correlated with more total accidents but lower rates per vehicle-kilometre. Road age correlated positively with deterioration rates ($r=0.39$, $p<0.001$) and accidents ($r=0.31$, $p<0.001$), though age effects attenuated substantially after controlling for flood exposure, suggesting that climate impacts may be misattributed to ageing in standard infrastructure lifecycle models.

4.3 Structural Equation Modelling Results

The structural equation model showed excellent fit: $\chi^2(87)=143.2$, $p<0.001$; $\chi^2/df=1.65$; CFI=0.96; TLI=0.95; RMSEA=0.045 (90% CI: 0.034–0.056); SRMR=0.038. All fit indices exceeded recommended thresholds.

Consistent with H1, flood exposure significantly predicted infrastructure deterioration ($\beta=0.67$, SE=0.04, $p<0.001$). Every standard deviation increase in flood exposure corresponded to a 0.67 standard deviation increase in deterioration rates, controlling for road age, functional class, and traffic volume. The magnitude of this effect indicates that flooding is the dominant driver of infrastructure degradation in the Nigerian context, outweighing other factors typically emphasised in lifecycle models.

Supporting H2, infrastructure condition significantly mediated the flood-accident relationship. The direct path from flooding to accidents remained significant ($\beta=0.24$, SE=0.05, $p<0.001$) after including the mediator, indicating that flooding affects accidents through both immediate event hazards and cumulative infrastructure degradation. The indirect path through infrastructure was substantially larger ($\beta=0.43$, SE=0.04, 95% CI [0.36, 0.51]), showing that flooding's accident impact operates predominantly through infrastructure deterioration. The mediation accounted for 64% of the total flood-accident effect. Infrastructure condition showed strong direct effects on accidents ($\beta=-0.64$, SE=0.04, $p<0.001$): each standard deviation decrease in PCI corresponded to a 0.64 standard deviation increase in accident rates. Table 3 presents full path coefficient results.

4.4 Regional Variation in Flood-Infrastructure-Accident Relationships

Multi-group SEM confirmed that relationships vary significantly across geopolitical zones. Constraining path coefficients to equality across zones significantly worsened model fit ($\Delta\chi^2(25)=87.4$, $p<0.001$), supporting H3.

Table 3: Structural Equation Model Standardised Path Coefficients and Mediation Results

Path	**β**	**SE**	**p**
Direct Effects			
Flood → Infrastructure	0.67	0.04	<0.001
Flood → Accidents	0.24	0.05	<0.001
Infrastructure → Accidents	-0.64	0.04	<0.001
Traffic Volume → Accidents	0.18	0.06	0.002
Indirect Effect			
Flood → Infrastructure → Accidents	0.43	0.04	<0.001
95% CI: [0.36, 0.51]			

Note. Standardised coefficients. Model fit: $\chi^2(87)=143.2$, $p<0.001$; CFI=0.96; TLI=0.95; RMSEA=0.045; SRMR=0.038. Controls included: road age, functional class, pavement type, state GDP.

Table 4: Zone-Specific Path Coefficients from Multi-Group SEM

Zone	**Flood→Infra**	**Infra→Acc**	**Flood→Acc (direct)**	**Indirect Effect**	**Total Effect**
North-Central	0.56***	-0.45***	0.26*	0.25**	0.51***
North-East	0.48***	-0.38**	0.29*	0.18*	0.47***
North-West	0.38**	-0.42**	0.32**	0.16*	0.48***
South-East	0.74***	-0.68***	0.16	0.50***	0.66***
South-South	0.79***	-0.78***	0.18*	0.62***	0.80***
South-West	0.68***	-0.52***	0.21*	0.35***	0.56***

*Note. Standardised coefficients from multi-group SEM. Infra = Infrastructure condition; Acc = Accident rate. *p<0.05, **p<0.01, ***p<0.001. Cross-zone equality constraints rejected: $\Delta\chi^2(25)=87.4$, $p<0.001$.*

The flood-infrastructure relationship was strongest in South-South (β=0.79) and South-East (β=0.74), where high rainfall intensity and poor drainage combine to accelerate degradation. North-West showed the weakest relationship (β=0.38), consistent with lower baseline flood exposure keeping most roads below threshold stress levels. North-Central presented a moderate coefficient (β=0.56) despite only moderate flood exposure, potentially reflecting expansive clay soils that swell under saturation, producing differential settlement and pavement cracking — a finding that cautions against treating rainfall totals as a sufficient proxy for flood impact.

The infrastructure-accident relationship also varied by zone. South-South showed the strongest association (β=-0.78), where poor infrastructure interacts with high traffic volumes and limited emergency response capacity to maximise accident consequences. South-West, despite high flood exposure, showed a more moderate coefficient (β=-0.52), possibly because its more developed healthcare and emergency response systems reduce accident severity even when infrastructure-related crashes occur. Northern zones produced weaker relationships (β=-0.38 to -0.45), where lower traffic volumes and different vehicle mixes may attenuate the infrastructure effect. Mediation patterns differ correspondingly: in South-South and South-East, indirect effects through infrastructure (0.61 and 0.58) substantially exceed direct effects (0.18 and 0.16), while in North-East and North-West, direct and indirect effects are more balanced. Table 4 presents zone-specific coefficients.

4.5 Drainage Infrastructure as a Protective Factor

Among high-flood-exposure roads (FEI>70), those with adequate drainage showed 58% lower deterioration rates (2.3 vs 5.5 PCI points/year; $t(94)=7.8$, $p<0.001$) and 61% lower accident rates (0.94 vs 2.41 accidents/km/year; $t(94)=6.2$, $p<0.001$) compared to roads with inadequate drainage facing equivalent exposure. Cohen's d values of 1.13 for deterioration and 0.98 for accidents indicate large, practically meaningful effects, supporting H5.

Moderation analysis within the SEM framework confirmed these patterns. The interaction term between flood exposure and drainage adequacy was significant for both infrastructure condition (β=-0.34, $p<0.001$) and accident rates (β=-0.28, $p<0.01$). Simple slopes analysis showed that flood exposure predicted sharp infrastructure deterioration and accident increases on roads with inadequate drainage, with effects substantially attenuated on adequately drained roads. Spatial analysis found drainage inadequacy concentrated in southern zones: 73% of South-South roads, 64% of South-East roads, and 58% of South-West roads lacked adequate drainage, against 32–42% in northern zones. Cost-benefit analysis indicates drainage upgrades deliver benefit-cost ratios of 3.2–4.7 when accounting for avoided accidents, maintenance savings, and extended infrastructure lifespan.

4.6 Qualitative Findings: Mechanisms and Contextual Factors

Thematic analysis of stakeholder interviews identified six major themes. The first Overwhelmed by Nature — captured widespread recognition that infrastructure design assumptions no longer match climatic conditions. One highway engineer stated:

> *"We designed these roads 30, 40 years ago using rainfall data from the 1960s and 70s. The weather now is completely different. Drainage channels that were adequate then cannot handle what we get now."*

Respondents consistently described rainfall intensities and flood volumes exceeding design specifications, creating systematic infrastructure vulnerability that no amount of conventional maintenance can fully address.

Cascading Failures described how initial flood damage accelerates degradation. A maintenance supervisor explained:

> *"Once water gets under the pavement and weakens the foundation, everything deteriorates rapidly. A small edge crack from flooding becomes a pothole, then a section failure, then the whole road collapses. And we cannot afford to fix it quickly, so it just gets worse."*

This mechanism aligns with theoretical predictions of non-linear deterioration and explains why flood-infrastructure relationships exceed simple linear models.

Maintenance Deficit emerged as a critical exacerbating factor. A public works director noted:

> *"Our maintenance budget has not increased in ten years despite inflation and increased damage from flooding. We can only do emergency repairs on the worst sections. Preventive maintenance is impossible."*

Nigeria reportedly spends 0.8% of GDP on road maintenance against an estimated requirement of 2.5–3% (World Bank, 2023), meaning climate stressors operate against a pre-existing maintenance backlog that accelerates the transition from serviceable to failed conditions.

Institutional Fragmentation described coordination failures across agencies responsible for meteorology, infrastructure, and safety. A road safety official stated:

> *"We respond to accidents after they happen, but we do not get advance warning about which roads are deteriorating or where flooding makes conditions dangerous. If we knew, we could deploy patrols or close roads proactively."*

Regional Inequity captured perceptions that southern zones bear disproportionate climate burdens while receiving inadequate institutional support. Community leaders from Delta and Rivers states described years-long waits for repairs to flood-damaged roads during which accident risks remained elevated. Whether attributable to political factors, technical challenges, or resource constraints, perceived inequity affects community trust and willingness to engage with interventions. Adaptation Potential, the sixth theme, identified practical opportunities stakeholders saw for improvement: redesigning drainage for projected rather than historical rainfall, using flood-resistant materials, improving weather forecasting and early warning systems, coordinating maintenance scheduling with seasonal patterns, and developing rapid post-flood response capacity.

5. Discussion

5.1 Flood-Infrastructure Relationships and Regional Variation

The strong relationship between flood exposure and infrastructure deterioration (β=0.67) confirms H1 and aligns with international research on climate stress effects on transportation systems (Chinowsky et al., 2019). The magnitude exceeds what lifecycle theory alone predicts, suggesting that Nigerian roads face compound vulnerability: baseline construction quality problems, chronic maintenance underfunding, and climate stressors interact multiplicatively rather than additively. Qualitative findings reinforce this, with stakeholders describing cascading failure processes where initial flood damage triggers accelerating degradation that constrained budgets cannot arrest.

The stronger flood-infrastructure relationship in South-South (β=0.79) and South-East (β=0.74) reflects the intersection of high hazard exposure with high sensitivity and low adaptive capacity — conditions that disaster risk reduction frameworks associate with the most acute vulnerability profiles. The weaker relationship in North-West (β=0.38) likely reflects lower baseline flood exposure keeping most roads below the threshold stress level at which substantial degradation initiates. North-Central's moderate coefficient (β=0.56), which is stronger than its moderate flood exposure alone would predict, points to the role of soil conditions — specifically expansive clays — in amplifying water damage. These findings indicate that infrastructure design standards should account for local geotechnical conditions, not just rainfall projections.

5.2 Infrastructure as Mediator of Climate-Accident Relationships

The mediation finding is the study's most policy-relevant result: infrastructure condition mediates 64%

of flooding's total effect on accidents, with the indirect pathway (β=0.43) substantially exceeding the direct pathway (β=0.24). Flooding's accident impact operates predominantly through infrastructure degradation, not primarily through immediate flood-event hazards. This has a direct practical implication: investments in climate-resilient infrastructure and maintenance could substantially reduce accident burdens even if flood frequencies continue rising.

The infrastructure-accident relationship (β=-0.64) extends international road safety findings to a tropical developing-country context. Each standard deviation decline in PCI — approximately 15 points, representing movement from good to poor condition — corresponds to a 0.64 standard deviation increase in accident rates. In practical terms, deterioration from good to poor condition roughly doubles accident risk after controlling for other factors. Infrastructure quality is a first-order safety determinant, not background context.

The persistence of significant direct flood-accident effects (β=0.24) after accounting for infrastructure mediation confirms H4: flooding affects accidents through both mechanisms. Standing water, reduced visibility, and driver uncertainty create acute risks during events themselves. Effective interventions must therefore address both infrastructure resilience — to reduce long-term accident burdens — and emergency management during flood events to mitigate immediate risks.

5.3 Geographic Heterogeneity in Infrastructure-Accident Relationships

The variation in infrastructure-accident relationships across zones demonstrates that infrastructure quality affects safety differently depending on regional context — confirming H3 and complicating uniform national policy responses. South-South shows the strongest association (β=-0.78), where poor infrastructure combines with high traffic volumes, limited emergency medical services, and challenging terrain to maximise accident consequences. South-West shows a more moderate coefficient (β=-0.52) despite high flood exposure and moderate infrastructure conditions, which qualitative data suggest reflects better-developed healthcare infrastructure and emergency response systems that reduce fatality rates even when infrastructure-related crashes occur. That pattern points to emergency medical services and trauma care as meaningful components of comprehensive transport safety strategies, not only infrastructure and enforcement.

A road with a PCI of 50 presents meaningfully different safety profiles in Lagos and Yobe State due to differences in traffic composition, emergency response capacity, enforcement, and driver behaviour. Effective policy requires addressing these contextual factors alongside infrastructure improvements rather than applying uniform national standards that ignore them.

5.4 The Protective Role of Drainage

The large protective effects of adequate drainage — 58% lower deterioration rates and 61% lower accident rates under equivalent flood exposures — identify drainage improvement as the highest-priority near-term intervention. Benefit-cost ratios of 3.2–4.7 for drainage upgrades, accounting for avoided accidents, maintenance savings, and extended asset lifespan, provide a strong economic case. The geographic concentration of drainage inadequacy in southern zones (73% of South-South roads, 64% of South-East) means targeted investment there could yield disproportionate national safety benefits.

Drainage improvement in low-lying southern areas faces real technical constraints: minimal natural gradients and high water tables limit conventional gravity-based systems. Pumped systems, low-impact development approaches emphasising infiltration and retention, and innovations such as those piloted under the Netherlands' Room for the River programme or Singapore's Active, Beautiful, Clean Waters approach offer relevant precedents, though local adaptation to maintenance capacity and community conditions is essential.

5.5 Institutional and Governance Dimensions

Institutional fragmentation is a critical barrier to effective climate adaptation. Meteorological services, public works departments, and road safety agencies operate independently, missing opportunities for coordinated preventive action. Systematic sharing of NIMET flood forecasts with public works departments would allow pre-positioning of maintenance crews and materials for rapid post-flood repairs. Road condition data informing FRSC patrol deployment could concentrate enforcement on deteriorated segments where accident risk is highest. These are low-cost institutional adjustments with potentially significant safety returns.

The maintenance deficit is structural. Nigeria spends an estimated 0.8% of GDP on road maintenance against a requirement of 2.5–3% (World Bank, 2023). Climate adaptation investments will not hold against this backdrop of chronic underinvestment; even climate-resilient designs eventually require upkeep. Addressing the maintenance financing gap is a prerequisite for meaningful climate adaptation in the transport sector, not a parallel concern.

5.6 Practical Recommendations

Infrastructure design standards should shift from historical to projected climate baselines. Drainage systems should be sized for expected 2050 rainfall intensities, not 1960s–1970s data. Pavement specifications should account for increased wet-dry cycling and soil saturation. This requires structured collaboration between NIMET and engineering standards bodies to translate climate projections into design parameters.

Maintenance prioritisation should incorporate climate vulnerability and safety consequences explicitly. A vulnerability-weighted approach considering flood exposure, infrastructure condition, and accident history could direct resources where they deliver the greatest safety returns — a departure from current approaches that typically prioritise by traffic volume or political consideration. GIS-integrated decision support tools combining infrastructure databases with climate projections could operationalise this approach.

Drainage investment deserves the highest priority within transport infrastructure budgets, given the strong protective effects demonstrated. A phased national programme targeting high-flood, high-accident corridors first would rapidly reduce accident burdens while building the political case for broader implementation. Innovative financing — road user fees linked to drainage investment, green bonds for climate-resilient infrastructure, development finance institution support — could supplement constrained government budgets. Formalising inter-agency coordination through a national committee on climate-resilient transportation would create the institutional foundation for the information sharing and joint planning that currently does not exist.

6. Conclusion

This study provides systematic empirical evidence that climate change-induced flooding significantly accelerates road infrastructure deterioration in Nigeria, which in turn substantially increases traffic accident risk across the country's diverse geographic regions. The core finding — that infrastructure condition mediates 64% of flooding's total effect on accidents — means that climate change's road safety consequences operate primarily through cumulative infrastructure degradation, not only through immediate flood-event hazards. South-South and South-East zones face the most severe impacts, experiencing 73% and 68% higher accident rates during flood seasons and dramatically faster infrastructure deterioration.

The human cost of inaction is concrete. Nigeria's roads already claim approximately 20,000 lives annually. Without adaptive intervention, projected intensification of rainfall and flooding will accelerate infrastructure degradation and raise accident frequencies further, against maintenance budgets that are already inadequate for current conditions. The evidence does not support optimism about current trajectories.

It does, however, support optimism about intervention. Drainage improvements reduce both deterioration rates and accident frequencies by approximately 60% under equivalent flood exposure — a large, replicable effect with benefit-cost ratios of 3.2–4.7. Climate-informed design standards, vulnerability-weighted maintenance prioritisation, formalised inter-agency coordination, and genuine community participation in adaptation planning all have strong empirical or logical justification. These are not aspirational targets; they are achievable operational changes if political will and financing align.

Addressing climate-infrastructure-safety linkages requires no single-domain solution. Meteorological services must communicate flood forecasts to infrastructure managers. Public works departments must adopt climate-informed design and maintenance. Road safety agencies must treat infrastructure condition as a primary safety determinant rather than background context. Urban planners must integrate transportation resilience into broader climate adaptation frameworks. The coordination failures documented in this study are not inevitable — they reflect institutional arrangements that can be reformed.

Nigeria's experience is relevant to other developing nations confronting similar climate-infrastructure-safety challenges across sub-Saharan Africa, South Asia, and Southeast Asia. Adaptive infrastructure principles, vulnerability-weighted maintenance systems, and inter-agency coordination mechanisms developed in this context may transfer, with appropriate local adaptation. Climate change multiplies existing infrastructure challenges in all of these settings. The question is whether governments will act before deteriorating roads and rising flood frequencies make the cost of inaction impossible to ignore.

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