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Multi-Hazard Resilience of Desert Roads in Southern Libya: A Geo-Engineering Decision Framework

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ABSTRACT

Background: Desert roads in southern Libya connect dispersed settlements but face interacting sand encroachment, episodic flash floods, extreme heat, and geotechnical deterioration. Objective: This article develops a transparent geo-engineering decision framework for multi-hazard resilience screening and selection of feasible interventions without claiming new field measurements. Methods: A critical, thematic synthesis of recent peer-reviewed research and publicly accessible Libyan hazard reports was organized around exposure, asset fragility, network criticality, intervention performance, and evidence confidence. A staged appraisal procedure integrates multi-hazard screening, engineering suitability checks, multicriteria comparison, and uncertainty testing. Results: The synthesis identifies distinct failure pathways: sand impedes carriageway operation, floods threaten drainage crossings and embankments, while heat and weak subgrades accelerate pavement distress. The proposed framework produces a hazard–asset matrix, a tiered portfolio of avoidance, protection, maintenance, and monitoring responses, and explicit gates for local verification. It distinguishes transferable international methods from location-specific evidence that remains incomplete. Discussion: Network redundancy and access to emergency services can change priorities even where physical damage is modest. Uncertain baseline conditions preclude numerical claims about local risk reduction or investment returns. Conclusion: A low-data screening framework can structure early decisions in southern Libya, provided that priority rankings are treated as provisional and validated using road inventories, drainage surveys, and local stakeholder review before design or procurement.

INTRODUCTION

Roads in arid regions are not simply pavements placed upon dry terrain. They are long linear systems exposed to mobile aeolian sediment, discontinuous drainage, thermal loading, and variable ground conditions. These processes can occur sequentially or in combination. Windborne sand may narrow a carriageway, reduce sight distance, cover markings and drainage inlets, and impose recurrent removal costs. At wadi crossings, short-duration runoff may overtop the road, erode approach embankments, undermine culverts, or interrupt access after comparatively infrequent rainfall. Thermal aging and rutting, meanwhile, can weaken operational reliability between extreme events (Gössling et al., 2023; Sias et al., 2025).

Southern Libya offers a particularly relevant setting because road links are important for access across geographically separated communities. The local evidence base is growing. Alsbhawy and Inweer (2025) examine strategies for protecting the Sebha–Brak road from sand encroachment, while Nasser (2023) analyzes flash-flood pathways and protective options in the Ghat area. A more recent investigation of the Tanezzuft Valley addresses the use of spatial technologies to characterize flood exposure near Ghat (Alkasih et al., 2026). Separately, satellite interpretation by the United Nations Satellite Centre (2024) reported flood-related exposure of approximately 13 km of roads in an analyzed part of Ghat during August 2024; its mapping was explicitly preliminary and not field validated. Such accounts establish plausible local hazards, but they do not amount to a corridor-wide engineering asset register or a calibrated probability model.

International transport research clarifies why a road cannot be prioritized solely by the intensity of the surrounding hazard. The functional loss caused by one damaged segment depends upon detour availability, corridor centrality, vehicle

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accessibility, restoration time, and the services that the link supports. He et al. (2024) combine flood-related roadworthiness with network topology; Boeing and Ha (2024) demonstrate the wider importance of connectivity and chokepoints; and Zeleke et al. (2026) identify continued weaknesses in integrating multi-hazard interactions and dynamic functions within road resilience assessments. These contributions support a systems perspective but require cautious transfer to sparsely connected Saharan corridors.

The research gap is therefore integrative rather than a claim that sand, floods, or road resilience have not been studied. Existing local studies often address particular places or hazards, while general resilience tools are commonly developed in relatively data-rich, dense networks. The present paper asks how their insights can be assembled into an auditable decision sequence usable before expensive surveys are commissioned, how differences between hazard mechanisms should determine engineering responses, and how uncertainty should change recommendations. Its contribution is an original, non-calibrated screening framework and an explicit evidence-to-design pathway for southern Libya. This paper is a critical review and conceptual methods contribution; it does not report field inspections, new remote-sensing classifications, instrument readings, or numerical performance improvements.

LITERATURE REVIEW

The physical processes must be separated before they can be integrated. Aeolian mobility is governed by sediment supply, surface condition, wind direction and speed, and local dune geometry. Remote-sensing analyses can identify migrating landforms and changing exposure, but detection accuracy and forecast skill depend upon the terrain, imagery and validation data. Abd El Aal et al. (2024) demonstrate machine-learning-based encroachment mapping in an arid setting, while Mokarram and Pham (2025) combine remote sensing with computational methods for dune-migration risk. For roads, the engineering endpoints are operational obstruction and maintenance frequency, not merely dune displacement. The Sebha–Brak study translates this distinction into proposed physical protection choices, although its evidence cannot automatically be extended to other Fezzan routes (Alsbhawy & Inweer, 2025).

Flash flooding has a different temporal structure. Dry channels can convey episodic concentrated flows, and an apparently small crossing may become a service bottleneck when a culvert lacks sufficient capacity or an approach embankment is eroded. For Ghat, geomorphological analysis, drainage delineation and satellite-based flood mapping provide local context (Nasser, 2023; Alkasih et al., 2026). Normand and Heggy (2024), examining the impacts of Storm Daniel in northeastern Libya rather than Fezzan, reinforce the importance of flood-driven sediment transport and erosion. Their findings should inform mechanism awareness but cannot be treated as a direct design discharge estimate for southwestern watersheds.

Slow deterioration adds a third risk dimension. Sias et al. (2025) review roadway vulnerability to temperature and moisture stresses, while Peduto et al. (2025) show how geotechnical movement evidence can support prioritization of road risk mitigation in a different geological environment. These studies illustrate a basic distinction: screening indicators can flag potentially weak subgrades or distress-prone pavements, yet selection of pavement layers, stabilizers, flood structures and foundations requires site-specific material and hydraulic verification. The article consequently avoids assigning unmeasured bearing capacity, asphalt failure rates or runoff coefficients to Libyan corridors.

Resilience comprises both resistance to disturbance and the capacity to sustain or restore useful service. Bergantino et al. (2024) synthesize empirical transport-network studies and emphasize redundancy, infrastructure condition and institutional preparedness. He et al. (2024) distinguish segment accessibility from whole-network function during flooding. A global simulation by Boeing and Ha (2024) suggests that network connectivity and the presence of chokepoints shape vulnerability, but a national-scale or urban indicator cannot simply substitute for travel times and access needs in a sparse desert network. Under prolonged disruption, a link's importance may derive from its role as the only practical connection to health services, fuel supply, or emergency response rather than its average traffic volume.

Recent models increasingly combine topology with environmental exposure and operational data. Ashja-Ardalan et al. (2025) employ spatial-topological assessment under climate scenarios; M. Li et al. (2025) investigate resilience with observed rainstorm-related traffic data; and Zeleke et al. (2026) call for stronger integration of link-level, time-varying and interacting hazards. The asset-management synthesis by Allen et al. (2025) calls for stronger integration of hazard risk and resilience into maintenance decisions, while S. Li et al. (2025) examine system interdependencies; both perspectives help explain why one road segment may matter beyond its immediate repair bill. Ren et al. (2026) additionally synthesize cascading failure and recovery methods, and Arango et al. (2025) develop recovery assessment based on dynamic thresholds in a non-desert context. Their techniques depend upon input quality. Transferring numerical weights or threshold values from European or East Asian networks to Fezzan would risk false precision. Accordingly, this work uses published evidence to identify candidate criteria and intervention families, not to estimate quantitative local benefits.

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METHOD

The method is a structured critical evidence synthesis followed by the design of a conceptual decision-support workflow. It is not a statistical meta-analysis, a systematic review claiming exhaustive database coverage, or an empirical case study. Relevant literature was identified through focused searches for the combined themes of desert road exposure, sand migration, arid-region flooding, pavement climate stress, road-network vulnerability, and hazard-informed infrastructure decisions. Priority was given to accessible peer-reviewed works published in 2023–2026, complemented by a clearly labelled institutional satellite report. Each source was examined for setting, hazard mechanism, input data, output metric, engineering relevance, and transferability. Inclusion required direct relevance to at least one stage of hazard identification, link susceptibility, network criticality or option selection; studies of unrelated transport modes were not used to infer road performance. No claim is made that all published articles were captured.

Extraction deliberately separates three evidence levels: directly reported observations or findings from the cited source; cautious mechanism-based interpretation across settings; and original proposed decision rules in this paper. No unpublished Libyan traffic volumes, flood depths, sand deposition rates, financial costs or geotechnical measurements are assumed. This separation matters because evidence sufficient to motivate monitoring is not necessarily adequate for structural or hydraulic design.

Framework construction and decision sequence

The unit of analysis is the road segment, bounded where hazard setting, geomorphology, drainage interaction, asset type, or available alternative routes change meaningfully. Each segment is linked to potential failure pathways. Screening first records aeolian exposure, proximity to mapped channels and crossings, indicative thermal or ground-condition concerns, and the type of road asset at risk. A second pass evaluates functional criticality through detour availability, essential-service access and the consequences of closure. The third pass compares feasible intervention families subject to constructability, maintenance burden, environmental impacts, lifecycle implications and institutional capacity. Candidate measures failing a minimum engineering or safety requirement are excluded before ranking. Figure 1 outlines the proposed sequence.

For an eventual data-supported application, normalized criterion scores $x(i,j)$, criterion weights $w(j)$ and an intervention feasibility indicator $F(i)$ may be used to calculate an indicative preference $P(i) = F(i) \times \Sigma[w(j) \times x(i,j)]$, where $\Sigma w(j) = 1$. This is a general proposed form, not a computation undertaken here. To prevent benefit–cost compensation from concealing a critical defect, an option with demonstrably inadequate hydraulic capacity, safety clearance or material performance must be rejected regardless of its composite preference. Stakeholders should determine admissible weights after a documented elicitation exercise. Rankings should be tested against alternative weight sets and plausible uncertainty ranges; an option that changes rank readily is provisionally classified rather than presented as robust.

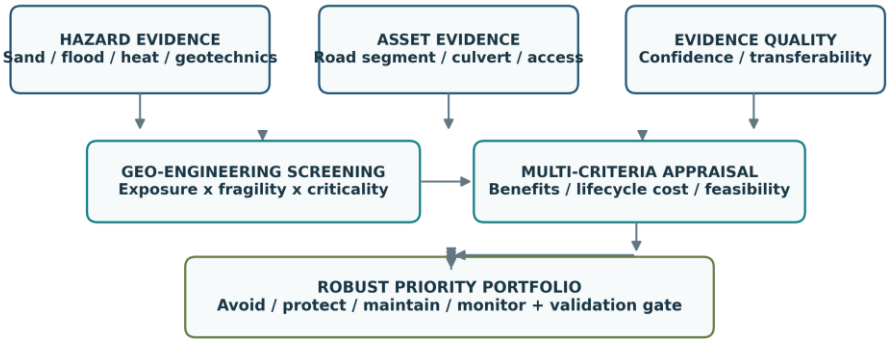


Figure 1. Proposed evidence-to-decision workflow for desert road resilience

Information layers and validation gates

Potential future inputs include road centerlines and crossing inventories, publicly available topography and imagery, rainfall or flood records, wind and dune observations, pavement-condition surveys and local accessibility information. Remote-sensing products may suggest spatial exposure, but they require positional checks and validation of change detection before road-specific statements are made. Drainage interventions require cross-section surveys and design-storm calculations; sand-control installations require site exposure and maintenance assessment; pavement adaptations require material characterization and temperature considerations. Each segment receives an evidence-confidence category (documented local measurement, local spatial indication, transferable analogue, or unverified assumption). Where inputs are uncertain, the framework recommends inspection or temporary monitoring before committing to high-cost capital works.

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The operational decision sequence therefore proceeds from screening to targeted validation, then to detailed feasibility, design and adaptive monitoring. Evaluation in later empirical work would test whether priority rankings are stable, whether predicted failures match observed closures and maintenance logs, and whether chosen interventions reduce closure duration and lifecycle burden relative to counterfactual practice. These are future test criteria and not outcomes established by the present manuscript.

An important distinction in the proposed appraisal is between exposure, fragility and consequence. Exposure describes how strongly a road location intersects a potential process, such as a mobile-dune corridor or wadi floodplain. Fragility concerns whether its specific formation, protection or drainage arrangement is likely to experience functional degradation at that intensity. Consequence describes the effects on access and recovery if degradation occurs. Treating these terms independently avoids double-counting geomorphic proximity as both hazard likelihood and structural vulnerability. A segment close to a drainage line is not necessarily unsafe when crossing elevation and drainage capacity are adequate; conversely, a low-lying structure can be vulnerable even when published regional hazard maps are coarse (He et al., 2024; Miano et al., 2024).

The framework specifies data provenance at the same level as performance criteria. Every screening layer should include source institution, year, spatial resolution, observation period, geometry and its stated validation status. For a crossing assessment, a remotely mapped flow pathway can trigger a survey, but the design gate requires catchment delineation, hydraulic boundary assumptions, measured opening geometry and a safety analysis. For sand encroachment, the preferred sequence is to verify the dominant wind and active transport direction, map repeated deposition, check sight-distance impacts, and compare options for maintenance accessibility. Road criticality is not assigned from annual-average traffic alone: service dependence, available detours and emergency travel times are also examined (Boeing & Ha, 2024; Bergantino et al., 2024).

Decisions should be evaluated under at least three logically different evidence scenarios: a conservative upper-bound exposure interpretation, a central interpretation supported by available records, and a data-gap case in which decisive information is absent. In the first two, practitioners can test whether candidate interventions remain preferred across admissible criterion weights. In the third, the principal output is a prioritized investigation rather than an engineered intervention. Where uncertainty intervals overlap substantially, the decision register records tied or conditional options instead of presenting a false ordinal precision. Such transparency is especially important when observations are sparse, as the sophisticated modelling approaches reported for data-rich networks should not be mistaken for reliable performance without locally appropriate inputs (Ashja-Ardalan et al., 2025; Zeleke et al., 2026).

Table 1. Information and evaluation indicators for a future pilot application

Decision dimension	**Indicative indicator**	**Minimum evidence / caution**
Aeolian exposure	Repeated sand cover, sight-distance restriction, dune proximity	Dated field logs + checked satellite imagery; no inferred annual rate
Flood susceptibility	Overtopping evidence, drainage intersection, scour condition	Surveyed crossing + mapped catchment; hydraulic design separately
Pavement / subgrade fragility	Distress category, material susceptibility, drainage condition	Condition survey and material evidence; no assumed California Bearing Ratio
Network consequence	Closure duration, detour length, emergency-service access	Verified route network and local access requirements
Implementation feasibility	Equipment availability, maintainability, lifecycle cost range	Local quotations and operations capacity, not imported unit costs
Evidence confidence	Source age, validation, spatial precision, uncertainty span	Mark unsupported criteria provisional and commission validation

A pilot should be designed as a prospective test rather than a retrospective narrative. Before reviewing future failure records, analysts would define segment boundaries, candidate predictors, response indicators and the handling of missing observations. One evaluation outcome could be road-days unavailable to all vehicles; another could be emergency travel-time increase under closure. Asset damage costs and clearance hours should remain separate from network accessibility losses to avoid conflating outcomes. Reported performance would require defined observation intervals and

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appropriate controls or comparable historical periods. Where only anecdotal reports exist, a systematic incident register is a more credible first investment than a complex predictive algorithm.

Reproducibility further requires publication of the criteria dictionary, source metadata, exclusion rules, candidate intervention list and a sensitivity record. An audit should identify whether the priority ordering depends on one poorly observed criterion, whether a proposed option is dominated by a cheaper and equally feasible option, and whether any construction recommendation violates a non-negotiable safety threshold. These safeguards transform the conceptual process from a collection of recommendations into an inspectable engineering decision protocol.

RESULT

In this section, the researcher will explain the results of the research obtained. Researchers can also use images, tables, and curves to explain the results of the study. These results should present the raw data or the results after applying the techniques outlined in the methods section. The results are simply results; they do not conclude.

The critical synthesis produced four linked outputs: an evidence-to-hazard summary, a failure-pathway diagram, an intervention matching matrix, and a confidence-aware priority logic. Table 1 separates place-specific information from general models; it is a qualitative research synthesis, not a field inventory or an assessment of measured road-condition frequencies.

Table 2. Evidence domains informing the southern Libya screening framework

Evidence domain	Supported insight	Boundary for use
Sebha–Brak road	Sand obstruction requires coordinated protective and maintenance responses (Alsbhawy & Inweer, 2025).	Local strategy; no extrapolated corridor-wide rates.
Ghat / Tanezzuft Valley	Wadi routing, satellite mapping and flash-flood pathways merit crossing-level assessment (Nasser, 2023; Alkasih et al., 2026).	Flood maps are not surveyed design discharges.
Ghat 2024 satellite report	Road exposure to floodwater was identified in a preliminary satellite assessment (UNOSAT, 2024).	No independent field validation of reported extents.
Dunes / geotechnics	Image analysis and geomorphic variables can screen changing exposure (Abd El Aal et al., 2024; Mokarram & Pham, 2025).	Transfer of trained models requires local checks.
Networks / pavements	Topology and climate stresses affect functionality beyond asset damage (He et al., 2024; Sias et al., 2025).	No local calibrated vulnerability functions.

Fig.2 distinguishes mechanisms that can affect the same road in different ways. Sand accumulation typically first impairs operations, whereas flood-induced overtopping or scour may rapidly compromise both the asset and access. Heat-related pavement or weak-ground deterioration more commonly changes performance progressively, although combined stressors may accelerate deterioration. These directional relationships are conceptual interpretations of the cited evidence, not measured causal coefficients.

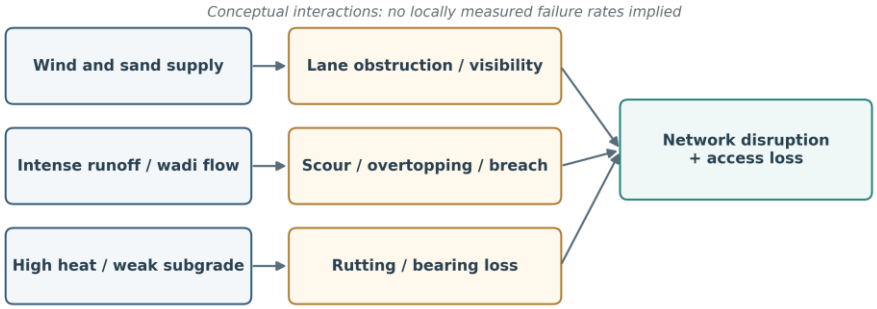


Figure 2. Conceptual hazard-to-failure pathways and common network-service endpoint

The proposed intervention screen uses hazard mechanism, exposure certainty, engineering prerequisites and anticipated maintenance capability before option ranking. The matrix in Table 2 intentionally describes candidate measures without asserting their tested performance in southern Libya.

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Table 3. Conceptual matching of hazard pathways to engineering and management responses

Exposure / failure pathway	Candidate intervention family	Mandatory verification
Sand drift; lane blockage	Targeted removal, trapping fences, graded setbacks, or context-suitable stabilization	Wind/dune survey, location, clearance, ecological feasibility
Flood at crossing; overtopping or scour	Culvert resizing, protected approaches, scour countermeasures, diversion where lawful	Catchment hydrology, site elevations, flow paths, scour check
Thermal rutting or cracking	Climate-aware binder or pavement design, preventive maintenance	Materials, temperatures, traffic, pavement condition
Weak ground / embankment instability	Drainage improvement, compaction, geotechnical reinforcement	Ground investigation, moisture regime, settlement and stability
Single-link network dependency	Emergency access plan, detour maintenance, staged recovery resources	Connectivity audit, accessibility needs, response capacity

A high-hazard segment with a reliable alternative route may justifiably receive a different response from a moderately exposed crossing that is the only access to an essential service. Priority must therefore recognize functional criticality and repair lead time alongside hazard exposure. Table 3 operationalizes that distinction by mapping screening conclusions to action classes. It is not a ranked list of real routes: the study lacks a verified segment inventory and stakeholder-defined weights.

A further result is the identification of a sequencing principle. Reversible and low-regret actions—inspection, debris removal, maintaining drainage openings, incident logging and clarifying emergency detours—can precede irreversible capital works when the evidence is weak. Conversely, demonstrated structural deficiency at a high-consequence crossing cannot be addressed by monitoring alone. This principle controls the decision process while leaving the final design and expenditure choice to verified local evidence.

Table 4. Proposed interpretation of screened risk and confidence

Finding	Recommended next step	Decision status
High consequence; hazard and defect evidenced	Commission detailed design and urgent safety management.	Design gate; prioritize verification.
High consequence; hazard plausible but location data weak	Rapid survey, stakeholder access audit, interim protection.	Provisional high attention.
Repeated service loss; manageable asset condition	Evaluate planned maintenance and operational controls.	Maintenance candidate.
Uncertain exposure; low immediate consequence	Targeted monitoring and scheduled reassessment.	Monitor; do not infer low risk.
Proposed intervention fails safety or hydraulic criteria	Reject or redesign before multi-criteria comparison.	Ineligible option.

DISCUSSION

The primary scientific contribution is the combination of a physical failure-pathway model with a network-function and confidence-aware intervention process. Studies dedicated to the Sebha–Brak road and the Ghat drainage environment provide local anchors, but neither alone supplies the cross-hazard, asset-level decision sequence developed here (Alsbhawy & Inweer, 2025; Nasser, 2023). The international literature supplies approaches to network criticality, link functionality and climate stress, yet its data requirements and spatial scale differ substantially from those of long desert corridors (Boeing & Ha, 2024; He et al., 2024; Ashja-Ardalan et al., 2025). The appropriate innovation is thus disciplined integration with explicit evidence boundaries, rather than a claim that a numerical risk model has already been validated in Fezzan.

A key practical implication is that geometric exposure maps are not engineering adequacy maps. Flood extent from satellite images, for example, can reveal where waters affected roads but cannot on its own establish the peak design flow, conveyance of a culvert, foundation scour depth, or recurrence interval. The United Nations Satellite Centre (2024) labelled its Ghat interpretation preliminary. Similarly, a dune-movement layer cannot specify optimal fence geometry or guarantee sediment capture at an individual road section. Validation gates link geoscience evidence to civil engineering

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design, and prevent screening artifacts from being misused as construction specifications (Mokarram & Pham, 2025; Normand & Heggy, 2024).

Multi-hazard treatment changes priorities because stressors interact through shared assets and maintenance systems. Blocked drainage inlets may aggravate flood interruption, while flood-generated erosion can make subsequent surface repairs ineffective; hot-weather pavement distress may intensify where moisture or ground conditions change. The relations in Figure 2 are mechanistically plausible, yet no combined-hazard frequency or synergistic damage function was estimated. Sias et al. (2025) discuss combined roadway climate stresses; Zeleke et al. (2026) similarly identify hazard interaction as a continuing gap. A future feasibility study should therefore compare single-hazard rankings against combined scenarios rather than simply add independent hazard scores without justification.

A sparse road network also demands a social-function perspective. Conventional traffic-volume or centrality indicators may undervalue links critical to medical referral, food and fuel provision, education, or emergency response. Bergantino et al. (2024) emphasize diverse empirical resilience determinants, and M. Li et al. (2025) show that road-network performance under rainstorms varies with demand and disturbance dynamics. In southern Libya, a road with modest daily traffic could have very high criticality if an alternative detour is exceptionally long or becomes impassable during floods. Such considerations should be established through public-service inventories and community consultation, not assumed from an external urban model.

The approach also has governance consequences. Road agencies may collect pavement-condition data while local government, meteorological units and water institutions hold other parts of the risk picture. A practical decision register should therefore specify who owns each evidence layer, when it was last checked, what uncertainty remains, the condition triggering field inspection, and which authority can authorize temporary closure or permanent construction. Without shared records, repeated clearing of sand may mask recurring risk, and emergency reconstruction can restore the same vulnerable geometry. The present framework offers a structure for coordinated appraisal but cannot establish that the institutional arrangements already exist.

Despite these constraints, the paper offers a more defensible starting point than treating the mere presence of a mapped hazard as an instruction to build a specific protective structure. It makes evidence confidence and constructability part of the decision. It also distinguishes immediate maintenance, interim risk reduction and capital investment. This separation aligns the analytical outputs with realistic staged infrastructure planning where resources and observational records are limited.

CONCLUSION

This research addresses how desert-road decisions in southern Libya can integrate sand encroachment, episodic flooding, pavement-climate stress and geotechnical susceptibility without inventing local measurements. Its contribution is an auditable geo-engineering screening pathway that couples hazard mechanisms to asset failure modes, network criticality, intervention eligibility and evidence confidence. The evidence synthesis demonstrates why single-hazard maps or traffic-centered rankings are insufficient foundations for design decisions. It does not demonstrate quantified resilience gains, because no local intervention trials or calibrations were conducted.

A practical first implementation should compile a segment-level road and drainage register, compare it with verified remote-sensing exposure, log historical closures and sand-removal activities, and determine detour and essential-service dependencies. Each shortlist should undergo hydraulic and geotechnical verification where relevant, lifecycle maintenance appraisal, and sensitivity testing before procurement. Further research should calibrate hazard thresholds against observed failures, test weights with Libyan road agencies and communities, and assess whether multi-hazard prioritization reduces closures and total ownership costs. These steps would move the proposed decision framework from defensible conceptual design toward tested infrastructure resilience practice.

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