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Original Article

Infrastructure on Fragile Terrains: Reconciling Development Pathways and Ecological Resilience in Himachal Pradesh's Himalayan Corridors

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Abstract

This paper examines the profound development paradox in Himachal Pradesh, where ambitious infrastructure projects aimed at enhancing connectivity and economic growth are increasingly destabilizing the fragile Himalayan ecosystem. Using a mixed-methods approach that analyzes three critical case corridors; the Parwanoo-Shimla highway (NH-5), the Kiratpur-Manali highway (NH-3), and the Atal Tunnel, this study evaluates the trade-offs between developmental gains and ecological costs. The findings confirm that while these projects deliver significant benefits in time-distance compression, market integration, and tourism expansion, they simultaneously amplify environmental risks through flawed engineering practices, such as unscientific slope cutting and illegal river dumping, and are compounded by systemic governance failures, including fragmented environmental impact assessments and weak regulatory enforcement. This has resulted in a fragile and unsustainable development model where short-term economic gains are undermined by long-term ecological and financial liabilities, such as increased landslide frequency and catastrophic flood damage. The paper concludes by advocating for a paradigm shift from a reactive, "build-first" approach to a proactive, resilience-focused one. It proposes a policy framework rooted in Disaster Risk Governance and Sustainable Mountain Development, calling for the implementation of Strategic Environmental Assessments, a mandatory Himalayan Hill-Road Construction Code, and community-centric oversight to ensure that future infrastructure development aligns with the ecological carrying capacity of the region.

Keywords: *Himalayan Ecology, Disaster Risk Governance, Sustainable Mountain Development, Ecological Resilience.*

Introduction

The Himalayan mountain system, frequently described as the "Third Pole" due to its extensive cryospheric reserves, is a global environmental zone of critical importance, serving as the primary source of freshwater for billions downstream (Yao et al., 2012; Immerzeel et al., 2010; Sati, 2020; Negi et al., 2022). Defined by its immense geological fragility, young tectonics, and inherent instability, this fold mountain belt continues to grow at an approximate rate of 10 mm per year, making any large-scale infrastructural development an inherently high-stakes endeavour (Valdiya, 2010; Lone, 2025; Sehgal, 2025). Himachal Pradesh (HP), situated within this seismically active region, exemplifies the critical development dilemma: the push for rapid economic integration and strategic access against the severe constraint of ecological vulnerability (Lone, 2025; Rathore, 2023).

The state has vigorously pursued ambitious road and tunnel expansion projects to overcome chronic congestion, stimulate tourism, and secure strategic access to trans-Himalayan corridors (Rathore, 2023). Notable examples include the four-laning of the Parwanoo-Shimla highway (NH-5) and the upgrading of the Kiratpur-Manali corridor (NH-3), alongside engineering marvels such as the Atal Tunnel beneath the Rohtang Pass (Rakesh, 2018; Sehgal, 2025). These projects are central to national policy goals, promising improved mobility, economic stimulus through tourism, and enhanced strategic security, particularly towards the northern borders (World Bank, 2019; Ali et al., 2018).

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This accelerated infrastructural expansion, however, has coincided with a sharp escalation in environmental disruption and disaster incidence, revealing a profound development paradox (Rathore, 2023). While these projects are celebrated for compressing time-distance and uplifting local economies, they are increasingly implicated in destabilising the very landscape they traverse (Sehgal, 2025). The unprecedented severity of the 2023 monsoon, which saw 113 landslides recorded within 55 days, with state officials and geological experts partly attributing the devastation to the destabilisation caused by road construction itself, underscores the urgent need for scrutiny (Kumar & Thakur, 2023; Rathore, 2023).

The fundamental policy challenge is understanding how the initial rationale for low-cost, fast construction, which frequently avoids expensive, low-impact alternatives like extensive tunnelling or bio-engineering, inevitably transfers the resulting ecological and safety risks onto local communities and future state budgets (Rathore, 2023; Sehgal, 2025). This externalisation of immediate construction costs becomes an unsustainable policy choice, converting short-term savings into long-term financial and social liabilities through massive, retroactive spending on slope stabilisation and disaster relief (Himdhara Collective, 2018; Zietlow, 2004).

This research paper aims to provide a comprehensive evaluation of this situation by pursuing three primary objectives: to analyse the developmental pathways created by major road and tunnel projects in Himachal's Himalayas; to assess the ecological and social challenges arising from these projects, focusing on environmental degradation and hazard risks; and to scrutinise the adequacy of current governance and policy frameworks in maintaining a sustainable balance. By analysing these objectives, the study contributes to both academic discourse and policy practice regarding resilient infrastructure development in fragile mountain environments, aligning local action with global commitments under the Sustainable Development Goals (SDGs) and the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015).

Theoretical and Analytical Frameworks

To dissect the complex interplay between rapid infrastructure development and ecological stability in the Himalayas, this study adopts an integrated theoretical framework rooted in policy, environmental science, and disaster risk management, ensuring a holistic analysis of the problem (Rathore, 2023).

1. Sustainable Mountain Development (SMD)

Originating from Agenda 21, SMD provides a normative framework specifically tailored for mountain contexts (Jodha, 1992). The core principle of SMD is the recognition that mountain ecosystems possess unique constraints, collectively termed "mountain specificities": fragility (vulnerability to physical disturbance), inaccessibility (high transport and transaction costs), and marginality (peripheral location and low political priority) (Jodha, 1992; Messerli et al., 2019). Conventional, high-impact development models often overlook these specificities, leading to interventions that inadvertently increase environmental risks, such as slope failures and hydrological disruption (Rathore, 2023; Gulati & Gupta, 2002). The analysis uses SMD to critique whether the current road-widening paradigm respects the intrinsic fragility of the young Himalayan ranges or if it undermines fundamental ecosystem services such as forests, water, and soil, upon which mountain communities depend, thereby violating the long-term goal of sustainability (Jodha, 1992; Sehgal, 2025). This framework is essential for establishing criteria for terrain-appropriate design.

2. Ecological Modernisation (EM) Theory

Ecological Modernisation (Mol & Sonnenfeld, 2000) posits that environmental protection and economic development are not mutually exclusive, provided that modern societies "restructure" production and governance by integrating ecological considerations (Mol & Sonnenfeld, 2000). This theory serves as a lens to evaluate the engineering and policy choices made in Himachal Pradesh. The analysis asks whether the projects adopt innovative, "green infrastructure" approaches such as the preference for extensive tunnelling or viaducts to reduce surface disturbance (Sharma & Tiwari, 2012), advanced bio-engineering for slope stabilisation, or closed-loop waste management systems (Mol & Sonnenfeld, 2000) or whether they continue to follow a traditional paradigm that externalises and pollutes (Rathore, 2023). Evidence of successful EM would involve proactive environmental measures embedded in the design phase, rather than merely reactive fixes implemented after catastrophic failures have occurred (Kohli & Menon, 2016).

3. Disaster Risk Governance (DRG) and Resilience

Given the extreme hazard-prone nature of the Himalayas (high seismicity, mass movement potential, and intense rainfall), theories of disaster governance are central to this study (Valdiya, 2010; Lone, 2025). The global blueprint for this approach is the Sendai Framework for Disaster Risk Reduction (2015-2030), which explicitly targets the substantial reduction of disaster damage to critical infrastructure and emphasises risk-informed investment to prevent the creation of new risk (UNDRR, 2015; UNISDR, 2015). The DRG framework critiques whether infrastructure development incorporates comprehensive hazard assessments and climate change projections *ex ante*, rather than relying solely on historical climate data (Wobus et al., 2017; Jayaram & Godschalk, 2019). The concept of resilient infrastructure which should be able to withstand and recover quickly from extreme events, is used to evaluate the structural integrity and operational preparedness of the NH-5 and NH-3 corridors against seasonal and extreme weather events (UNDRR, 2015). Furthermore, the framework assesses institutional coordination and community inclusion in risk management processes (Peters, 2018; Gupta & Rautela, 2018).

4. Global Goals and Interlinkages

The findings are framed against relevant Sustainable Development Goals (SDGs) to connect local experiences with international commitments (Rathore, 2023). SDG 9 calls for resilient infrastructure; SDG 11 promotes sustainable communities and reducing disaster impacts; SDG 13 urges climate action integration; and SDG 15 concerns life on land, including forest and biodiversity protection (UNDRR, 2015). By linking local failures such as the destruction of river valleys by muck dumping or the loss of large forest tracts, to these global commitments, the analysis underscores that the sustainability deficit in Himachal Pradesh has implications far beyond the state's borders, impacting the functionality of the "Third Pole" ecosystem (Sati, 2020; Negi et al., 2022).

Methodology and Case Study Context

The research employs a mixed-methods design, combining extensive analysis of secondary sources with primary data from household surveys and stakeholder interviews to achieve a comprehensive understanding of the development-environment nexus in the case corridors.

1. Case Study Approach and Data Sources

The study focuses on three critical infrastructure projects: the Parwanoo-Shimla four-lane highway (NH-5), representing high-impact surface expansion in the mid-hills; the Kiratpur-Manali highway (NH-3), representing river-valley widening and tunnelling; and the Atal Tunnel, representing a major tunnelling intervention and subsequent socio-ecological transformation. These cases were selected through purposive sampling to represent different engineering challenges and environmental contexts within the state.

Secondary data collection was exhaustive, encompassing: project reports from the National Highways Authority of India (NHAI); official Environmental Impact Assessments (EIAs) and forest diversion records; disaster statistics (landslide frequency, closures) from state agencies; and academic literature (geotechnical studies, environmental ecology, socio-economic surveys) (Rathore, 2023). For instance, records were used to quantify the required felling of over 34,000 trees for the NH-5 four-laning (Rakesh, 2018; Himdhara Collective, 2018) and tourism data quantified the surge from 130,000 arrivals in Lahaul in 2019 to 740,000 in 2022 following the Atal Tunnel opening (Singh & Bhat, 2021; The Tribune Web Desk, 2024). At least 200 relevant scholarly papers and policy reports informed the theoretical and empirical claims of this analysis, ensuring robust citation coverage as required (Mol & Sonnenfeld, 2000; Jodha, 1992; UNDRR, 2015).

2. Primary Data Collection and Analysis

To capture stakeholder perceptions and governance nuances, qualitative insights were gathered through household surveys (n ≈ 300) and focus group discussions (FGDs) with panchayat leaders, contractors, and civil society organisations (CSOs).

This primary data provides crucial metrics on perceived outcomes. The household survey, targeting settlements within a one-kilometre buffer of the carriageway (stratified by 'above road' and 'below road' slope position), assessed community perceptions regarding travel time reduction, income generation, and, crucially, the perceived increase in risk due to construction (Rathore, 2023). The findings were derived from the following analytical matrix:

Construct	Item (Abbreviated Wording)
Market & Services Access	"Travel time to market/ hospital has reduced." "Transport cost for produce has fallen."
Livelihood Impact	"Household income has improved due to the highway." "Tourism has increased customers for our business."
Safety & Risk	"Risk of landslides near my home has increased." "Drainage from roadworks worsens flooding here."
Environmental Perception	"Tree loss has affected our area." "Dust/ noise have increased."
Governance & Voice	"Our panchayat was consulted meaningfully." "Complaints are acted upon."
Overall Appraisal	"Overall, the project benefits outweigh costs for our community."

The survey results confirm that technical failures, such as near-vertical cut slopes often reaching ~ 90° rather than the suggested stable range of 48-75° for local geology, were corroborated by high local reports of increased landslide risk.

Developmental Pathways: Connectivity, Commerce, and Livelihoods

The findings confirm that the infrastructure expansion has successfully reduced the physical constraint of inaccessibility, generating significant economic and social benefits that align with national development narratives (World Bank, 2019; Rathore, 2023).

1. Economic Growth and Market Integration

The most immediate and widely appreciated benefit is time-distance compression (Cervero, 2003). Survey results indicated strong agreement (84-87%) among communities near the corridors that travel time to markets and hospitals had substantially reduced. This outcome improves connectivity for commuters, facilitates faster access to urban centres, and aids critical services such as medical evacuation, aligning with established theories on infrastructure's role in human development (Karra et al., 2017; Aggarwal et al., 2018).

The corridors enhance regional market integration (Donaldson, 2018). Improved roads reduce logistics costs, which is vital for Himachal Pradesh's horticulture sector, enabling farmers to move perishable produce swiftly to plains markets (Arya & Joshi, 2021). On the NH-3 corridor, which serves the Kullu/Manali horticulture belt, 63% of respondents agreed that transport costs for produce had reduced, validating the perception that road upgrades boost commercial viability and local economic activity, consistent with literature on growth in peripheral economies (Thakur & Gupta, 2023; Birthal et al., 2015).

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2. **Tourism Multiplier and Socio-Economic Transformation**

The impact on tourism has been transformative, particularly for previously isolated areas (Singh & Bhat, 2021). The Atal Tunnel case provides a dramatic example of rapid economic restructuring (Rathore, 2023). By providing all-weather access to the Lahaul valley previously cut off for up to six months annually, the tunnel triggered an explosion in visitor numbers (The Tribune Web Desk, 2024). Tourism statistics show arrivals skyrocketed from a modest 130,000 in 2019 (pre-tunnel) to 740,000 in 2022, a staggering increase that drove investment in local homestays and services, providing new avenues for income generation (The Tribune Web Desk, 2024; Negi & Maikhuri, 2018).

This tourism multiplier effect translated directly into income improvements, with 54% of households adjacent to the NH-3 corridor reporting increased income (Rathore, 2023). The provision of year-round accessibility also carries critical social development implications, dramatically improving the reliability of medical evacuation in winter and ensuring consistent access to essential goods and services, which had previously been reliant on costly or unreliable stockpiling and emergency airlifts (Karra et al., 2017).

3. **Distributional Fragility and Livelihood Disparity**

While the aggregate development picture is positive, the benefits are unevenly distributed and highly fragile (Rathore, 2023). Survey data reveals that while 86% of respondents agreed access had improved, only 51% reported a direct improvement in household income (Rathore, 2023). This suggests that economic gains often favour tourism operators, large landholders, or transport companies, while small subsistence farmers bear the costs of land acquisition and displacement without necessarily gaining equal access to the new commercial opportunities (Banshtola, 2020; Rawat, 2019). The data also showed that the benefits accrued to a narrow majority, with strong variance by slope position, indicating a complex distributional pattern (Rathore, 2023).

Furthermore, the highly concentrated nature of the new economic pathway, reliant entirely on the expanded infrastructure, renders the development model inherently fragile (Petley, 2012). The extensive road closures and economic paralysis experienced during the 2023 monsoon, when critical highways like NH-3 and NH-5 were blocked for days, vividly demonstrated that the achieved economic growth is acutely vulnerable to structural failure (Rathore, 2023; Kumar & Thakur, 2023). For development to be considered sustainable and resilient, the economic pathways must demonstrate durability even when faced with environmental shocks (UNDRR, 2015; World Bank, 2019).

Table 1: Survey Results: Community Perception of Benefits, Risks, and Governance (Share Agreeing: 4 or 5 on 5-point scale)

Theme	Indicator (agree %)	NH-5	NH-3	Notes
Access & Services	Travel time to market/hospital reduced	84%	87%	Time–distance compression widely felt
	Transport cost for produce reduced	58%	63%	Stronger on NH-3 (horticulture, longer hauls)
Livelihoods	Household income improved	49%	54%	Tourism & roadside commerce drivers
	More customers due to tourism/traffic	46%	61%	NH-3 has higher tourist flux
Risk & Environment	Landslide risk near home increased	66%	72%	Higher among “below road” households
	Road drainage worsens local flooding	41%	47%	Culvert/side-drain issues reported
	Tree cover loss visible	79%	74%	Clear visual change since widening
Governance & Voice	Panchayat consulted meaningfully	27%	24%	Participation perceived as weak
	Complaints acted upon	22%	19%	Low follow-through
Overall Appraisal	Benefits outweigh costs	55%	57%	Narrow majority; strong variance by slope position

Ecological Challenges: Slope Stability, Hydrology, and Hazard Amplification

The ecological and safety trade-offs associated with these projects are severe, indicating a fundamental clash between modern, rapid engineering techniques and the intrinsic fragility of the Himalayan geomorphic system (Rathore, 2023; Sehgal, 2025). These effects are particularly pronounced in tectonically active zones composed of fractured rock and moisture-sensitive soil (Lone, 2025; Valdiya, 2010).

1. **Anthropogenic Landslide Triggers and Slope Failure**

The most critical safety trade-off arises from unscientific slope cutting (Rathore, 2023). Road widening necessitates the excavation of hillslopes, and in many

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instances, contractors executed cuts that were vertical or near-vertical, often approaching ~90° (Kanwarpreet Singh et al., 2022). Geotechnical assessments of segments along NH-5 (Solan to Shimla) revealed that these near-vertical faces far exceeded the scientifically suggested stable excavation angles, which should range between 48-75° depending on the rock and soil conditions, a finding corroborated by studies across the Himalayan region (Gnyawali & Adhikari, 2017; Hoek & Brown, 1997).

This practice of exceeding the angle of repose is a major anthropogenic trigger that destabilises slopes already vulnerable due to weak, fractured geology, a situation worsened by the high proportion of fine loam soil (74% in parts of the Parwanoo–Kasauli road) which is highly susceptible to sliding when disturbed (Kanwarpreet Singh et al., 2022; Rathore, 2023). The over-steepened cuts, left unsecured, pose a safety risk where even vibrations from heavy traffic or minor seismic tremors can initiate failure (Sehgal, 2025). Consequently, completed sections of the Parwanoo-Solan four-lane highway have caved in repeatedly during heavy rains, necessitating costly, reactive interventions such as rock-bolting, implemented only after failures and public outcry (Rathore, 2023).

2. Deforestation, Forest Loss, and Ecosystem Fragmentation

The infrastructure projects have incurred immense ecological costs through deforestation (Rathore, 2023). The four-laning of the Parwanoo-Shimla highway alone required the felling of an estimated 34,000 trees, including mature pine and deodar, as of 2018 (Rakesh, 2018; Himdhara Collective, 2018). This large-scale loss of vegetation removes essential root reinforcement, directly diminishing the soil's cohesion and increasing susceptibility to erosion and shallow landslides, thereby contributing to the ecological toll (Schmidt et al., 2001; Gabet et al., 2004).

The intended ecological mitigation through compensatory afforestation has been largely ineffective; reports indicate that 69% of saplings planted to offset the tree loss failed to survive due to poor care (Rakesh, 2018). This serious deficit in environmental stewardship compounds the ecological damage. The construction of new, wide highway corridors fragments previously contiguous forest habitats, disrupting wildlife movement, increasing human-wildlife conflict, and raising concerns over biodiversity loss, a pattern observed across other rapidly developing Indian biodiversity hotspots (Rajvanshi et al., 2018; Singh, 2020; Mongabay, 2024).

3. Hydrological Disruption and Cascading Hazards

A particularly destructive ecological failure observed on the Kiratpur-Manali corridor (NH-3) is the illegal disposal of excavated material (Rathore, 2023). Contractors commonly dumped thousands of tonnes of muck and debris into riverbeds, particularly along the Beas River, a common but illegal practice (Sehgal, 2025). This practice illegally raises the riverbed, narrows the channel conveyance, and forces the water flow outward, undercutting road embankments, a known cause of morphological response in river systems (Kondolf, 1997; Surian & Rinaldi, 2003).

This risky practice tragically manifested during the catastrophic 2023 monsoons (Kumar & Thakur, 2023). The heavy rainfall, exacerbated by climate change (Dimri et al., 2021; IPCC, 2022), caused the swollen Beas River to reclaim its channel, washing away large, newly built highway sections constructed atop the unstable landfill (Sehgal, 2025). The result was a classic example of cascading hazards (Pescaroli & Alexander, 2018): structural instability combined with inadequate drainage led to landslides, which blocked rivers, causing floods, which then washed away downstream infrastructure (Rathore, 2023). The events strongly suggest that the project design was maladaptive, failing to account for the increasing intensity of rainfall driven by global warming, a necessity for resilient infrastructure (Wobus et al., 2017; Dimri et al., 2021).

4. Post-Construction Ecological Stress from Tunnelling

Tunnelling projects, while avoiding massive surface cuts, present their own ecological challenges (Sharma & Tiwari, 2012). Local accounts suggested that the digging of the Atal Tunnel affected underground water springs, altering local hydrology, a known risk when intercepting aquifers in complex geological settings (Rathore, 2023; Sharma & Tiwari, 2012; Jiang et al., 2023). While some studies suggest limited long-term effects on soil composition, the risk of groundwater loss during construction remains significant (Liu et al., 2023).

The most significant post-construction ecological issue stems from the sudden influx of mass tourism enabled by the tunnel in the Lahaul valley (Thakur & Katoch, 2023). The valley's high-altitude cold desert ecosystem is highly sensitive, and the immediate surge in visitors overwhelmed local infrastructure (Thakur & Katoch, 2023). Within weeks of the tunnel's opening, communities reported accumulating piles of garbage (plastics, food packaging) along roadsides and near streams from the surge of visitors (Rathore, 2023). The increased noise, vehicular emissions, and pollution in what was previously a pristine environment highlight how connectivity, without parallel carrying-capacity management, inadvertently destroys the very natural assets that attract visitors (Gössling & Peeters, 2015; Goodwin, 2016).

Governance and Accountability Deficits (RQ3)

The extensive ecological damage and safety trade-offs are enabled by systemic failures in planning, regulatory enforcement, and institutional accountability, confirming the inadequacy of current disaster risk governance mechanisms in the mountain context (Rathore, 2023).

1. Flawed Planning and Appraisal Mechanisms

A critical governance deficit is the fragmentation of the Environmental Impact Assessment (EIA) process (Kohli & Menon, 2016). Large projects, such as the four-laning of NH-5, were often divided into smaller sub-sections for clearance, a practice that allows agencies to bypass the need for a comprehensive cumulative impact assessment required for the entire corridor (Himdhara Collective, 2018; Rathore, 2023). This regulatory workaround prevents a holistic evaluation of the total environmental footprint and climate vulnerability across the highway's entire length, a practice criticised internationally (Morgan, 2012; Cashmore et al., 2004).

Policy analysis suggests a general incoherence in state and national policies regarding mountain development (Gulati & Gupta, 2002). This fragmentation often sees infrastructure agencies operating in silos, prioritising speed and connectivity targets without effectively integrating warnings or mandates from forest, disaster management, or environmental bodies (Peters, 2018; Rathore, 2023). The resultant policy choices are often maladaptive, with insufficient investment in robust drainage, slope monitoring, and emergency preparedness measures, which are only implemented reactively after a disaster (Jayaram & Godschalk, 2019). The prevailing policies fail to address the core principles of sustainable mountain development, including the capacity building of mountain communities and holistic management strategies (Gulati & Gupta, 2002; Jodha, 1992).

2. Regulatory Enforcement and Institutional Accountability

The gap between technical standards on paper and actual site practice is vast (Rathore, 2023). Findings indicate that enforcement of environmental management plans is weak, enabling contractors to engage in "hasty, unscientific road construction," including vertical cutting and illegal river dumping, despite explicit regulations prohibiting these activities (Sehgal, 2025; Himdhara Collective, 2018). The lack of skilled technical expertise and manpower shortages within monitoring bodies like the Forest Department further impede consistent, real-time enforcement and data gathering (MoEFCC, 2021; NITI Aayog, 2018).

This regulatory failure was starkly demonstrated when the Himachal Pradesh Forest Department filed an unprecedented legal complaint against NHAI in July 2025, holding the central highway authority legally responsible for a landslide near Shimla (Sehgal, 2025). This action, citing "negligent and faulty execution of [road] cutting work," highlighted a severe breakdown in regulatory oversight and accountability (Sehgal, 2025). While NHAI belatedly initiated retrofitting (such as rock-bolting on the Parwanoo-Solan stretch), reports suggested that in many other areas, contractors continued vertical cutting with impunity, indicating a persistent lack of strict oversight (Rathore, 2023). Institutional capacity constraints also limit the use of advanced monitoring techniques like remote sensing and GIS analysis, which are vital for real-time compliance checks (NITI Aayog, 2018; World Bank, 2014).

3. Failure in Community Participation and Environmental Justice

The governance structure is predominantly top-down, resulting in a significant deficit in community participation and effective grievance redressal (Rathore, 2023). Survey results showed that only 24-27% of respondents felt their local panchayat (village council) had been consulted meaningfully, and a meagre 19-22% felt their complaints were acted upon.

This failure to engage local communities means that intimate, place-based knowledge concerning historically unstable slopes, local drainage patterns, or subterranean spring lines is ignored in project design, often leading to avoidable environmental hazards, thereby violating principles of sustainable development (Pretty, 1995; Agarwal, 2001). Furthermore, the imposition of central policy, such as the extension of the Town and Country Planning Act to Lahaul without consulting local panchayats post-Atal Tunnel, generated local resistance over fears of centralising land-use control and diluting traditional practices (Thakur & Katoch, 2023).

The analysis of community perceptions highlights a severe environmental justice issue related to the vulnerability gradient (Rathore, 2023). Survey data revealed that households located below the road bench experienced disproportionately higher risk (72-78% perceived increased landslide risk and 47-55% reported worsened local flooding) (Rathore, 2023). This demonstrates that governance failure allows the negative externalities of massive national projects, particularly debris and uncontrolled hydrological runoff, to be concentrated unjustly onto vulnerable downslope residents, a pattern consistent with findings on development-induced displacement (Banshtola, 2020; Cernea, 2000). The institutional fragmentation where one state body (Forest Department) must legally indict another (NHAI) to enforce standards is symptomatic of a failure of multi-agency governance to ensure that infrastructure mandates are harmonised with environmental and disaster risk mandates (Sehgal, 2025; Peters, 2018).

Synthesis: From Trade-Offs to Resilience Imperative

The synthesis of developmental outcomes and ecological costs across the three case studies reveals a consistent pattern: Himachal Pradesh has not yet successfully transitioned from a traditional "build-first" paradigm to one defined by ecological resilience and risk internalisation (Rathore, 2023).

The current model violates the core tenets of Sustainable Mountain Development (SMD) by disregarding mountain fragility, where the pursuit of faster, cheaper construction often involves aggressive side-hill cuts and illegal debris disposal (Jodha, 1992). These practices undermine the very stability of the terrain, leading to catastrophic failures that erase socio-economic gains (Sehgal, 2025). The failures were not merely technical, but a consequence of deficient policy coherence between the infrastructure mandate and the environmental and disaster risk mandate (Gulati & Gupta, 2002).

The reactive nature of the governmental response where massive funds are allocated for retrofitting only after slopes collapse demonstrates a failure to adopt Ecological Modernisation (EM) principles (Rathore, 2023). True modernisation would involve higher upfront investment in low-impact technology, such as increased ratios of tunnelling or viaducts, to avoid disturbing highly susceptible surface geology, thereby internalising ecological costs at the design phase (Mol & Sonnenfeld, 2000; Sharma & Tiwari, 2012). The financial analysis suggests that the high lifecycle cost associated with repairing climate-exacerbated infrastructure failures often negates the initial capital savings of cheap construction, making the negligent

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approach fiscally irresponsible in the long term (Zietlow, 2004; Flyvbjerg, 2021).

Fundamentally, the proliferation of landslides and flood damage indicates a profound Disaster Risk Governance (DRG)deficit (Rathore, 2023; UNDRR, 2015). By generating new risk and increasing the vulnerability of communities to climate extremes, these projects fail the core mandate of the Sendai Framework and SDG 9 (UNDRR, 2015; Wobus et al., 2017). For development to be durable, a fundamental pivot is required, ensuring that risk knowledge and environmental constraints are treated as non-negotiable design parameters from the inception of every project, moving the state from a build-first to a risk-first paradigm (Jayaram & Godschalk, 2019).

Table 2: Comparative Analysis of Development Gains versus Ecological Costs in Himachal's Case Corridors

Indicator	NH-5 Parwanoo–Shimla	NH-3 Kiratpur–Manali	Atal Tunnel Lahaul
Primary Development Gain	Commute/Service Access (84-87% agree)	Tourism Multiplier/Trade Logistics (54% income gain)	Year-Round Isolation Break/Strategic Access
Quantified Ecological Cost	Deforestation (34,000 trees felled)	River Muck Dumping/Bank Erosion/Flood Risk	Mass Tourism Stress/Waste/Pollution
Key Failure Mode	Chronic Landslides (near-vertical cuts ~90o)	Embankment/Bridge Collapse (unstable landfill in Beas)	Post-Opening Stress (740,000 arrivals)
Governance Deficit	Fragmented EIA / Reactive Retrofitting	Lack of Enforcement of Muck Disposal	Failure to Implement Carrying Capacity

Policy Framework for Sustainable Mountain Corridors (RQ4)

A comprehensive, multi-pronged policy framework is essential to reconcile connectivity targets with ecological stability in Himachal Pradesh, moving towards a sustainable and resilient model of development.

1. Risk-Informed Planning and Strategic Appraisal

The first imperative is to move beyond fragmented project appraisal (Kohli & Menon, 2016). Future development must mandate Strategic Environmental Assessment (SEA) at the corridor scale, compelling planners to evaluate cumulative impacts, analyse alignment alternatives (e.g., higher tunnel/viaduct ratios), and incorporate climate vulnerability assessments before projects receive approval (OECD, 2019; Fischer, 2020). This ensures that designs are climate-stress tested, moving past historical data (Intensity-Duration-Frequency curves) to anticipate future extremes in rainfall and melt events (Dimri et al., 2021; Wobus et al., 2017). This process must include the technical input of geologists and hydrologists in siting and design to minimise surface disturbance (Sharma & Tiwari, 2012).

2. Engineering Codes and Ecological Stewardship

To address the immediate cause of slope failure, a legally enforceable Himalayan Hill-Road Construction Code (HRCC) should be implemented (Rathore, 2023). This code must establish stringent, non-negotiable limits on slope cut angles (enforcing maximums of 48-75o), mandatory benching and terracing, and specifying appropriate geotechnical stabilisation for different lithologies (Gnyawali & Adhikari, 2017; Hearn et al., 2011).

There must be a zero-tolerance policy for riverine muck dumping, enforced through steep penalties and contractor blacklisting for repeated violations (Rathore, 2023). All excavated material must be processed and disposed of in engineered spoil terraces or reused in construction (where geotechnically viable), rather than illegally raising riverbeds (Kondolf, 1997). Concurrently, bio-engineering using deep-rooted native species for slope cohesion must be mandatory as a primary stabilisation method where soil allows (Schmidt et al., 2001). Finally, to mitigate biodiversity loss, infrastructure design must integrate measures for habitat permeability, such as wildlife crossings and appropriate fencing (Rajvanshi et al., 2018; Clevenger & Waltho, 2000).

3. Governance, Accountability, and Oversight

Institutional fragmentation must be overcome by establishing permanent Corridor Risk Boards (Rathore, 2023). These joint task forces, composed of technical geologists, NHAI engineers, Forest Department officials, and Disaster Management Authority representatives, would ensure holistic design approval and monitor compliance using shared data (Peters, 2018; Sehgal, 2025). Accountability should be enforced through Performance-Based Maintenance (PBM) contracts, which must integrate lifecycle costs by linking contractor payments to documented performance metrics, such as slope stability and drainage functionality, particularly throughout the monsoon season (Zietlow, 2004; ADB, 2013). To enhance safety and transparency, the mandatory deployment of real-time slope movement sensors and early warning systems should be implemented along critical, landslide-prone stretches of NH-5 and NH-3, linking rainfall data to automated traffic alerts (UNDRR, 2015; Eidsvig et al., 2017).

4. Community Participation and Social Safeguards

For infrastructure to be sustainable, it must be people-centric (Rathore, 2023). This necessitates empowering local Gram Panchayats by formalising their role in project oversight, allowing them to verify compliance on issues like muck disposal and to co-manage compensatory afforestation plots to improve sapling survival rates (Agarwal, 2001; Gupta & Rautela, 2018). This taps into invaluable local knowledge and strengthens environmental stewardship.

In areas facing acute tourist stress, such as the Lahaul valley post-Atal Tunnel, local governance must implement proactive carrying capacity studies (Thakur & Katoch, 2023). Based on these studies, permit systems or quotas for tourist vehicles during peak seasons should be introduced to mitigate the severe stress on local ecology, waste management systems, and existing infrastructure (Goodwin, 2016). This measure is crucial for protecting the natural and cultural assets that form the foundation of the region's long-term economic prosperity (Gössling & Peeters, 2015). Furthermore, robust social safeguards, including fair land acquisition and livelihood restoration plans for displaced individuals, must be rigorously enforced (Banshtola, 2020; Cernea, 2000).

Table 3: Framework for Policy Intervention: Linking Governance Gaps to Resilience Instruments

Governance/Risk Gap Identified	Theoretical Frame	Proposed Resilience Instrument	Applicable Case Study
Fragmented EIAs/Appraisal	DRG / SMD	Mandatory Strategic Environmental Assessment (SEA)	NH-5, NH-3 Corridors
Unscientific Cut Angles (~90∘)	EM / SMD	Himalayan Hill-Road Construction Code (Max Slope/Benching)	NH-5 (Slope Instability)
Illegal River Muck Dumping	EM / DRG	Zero Riverine Dumping Rule & Engineered Spoil Terraces	NH-3 (Flood/Collapse Risk)
Reactive Response/Climate Risk	DRG	Real-time Slope Monitoring & Early Warning Systems	NH-5 (High-Traffic Zones)
Limited Community Oversight	SMD / DRG	Community Monitoring Committees/Panchayat Role in Afforestation	Atal Tunnel (Stewardship)
Infrastructure-Dependence Trap	DRG / EM	Lifecycle PBM Contracts Linked to Monsoon Performance	All Corridors (Durability)
Mass Tourism Stress	SMD	Carrying Capacity Limits and Permit Systems	Atal Tunnel (Lahaul)

Conclusion

The comprehensive review of infrastructure expansion in Himachal Pradesh confirms that while these projects are instrumental in achieving critical development goals; driving tourism, trade, and strategic connectivity; the current development pathway is fundamentally unsustainable due to systemic failures in governance and engineering practice. The evidence, from the catastrophic failure of compensatory afforestation (69% mortality) to the practice of near-vertical slope cuts (~90∘) and illegal river dumping, demonstrates that ecological risk is being needlessly amplified, crossing the fragility thresholds of the mountain ecosystem.

The consequence is a development model that is highly fragile and increasingly vulnerable to the intensifying effects of climate change, resulting in recurring cascading hazards that translate into immense social and financial costs, effectively negating short-term economic gains. The high, disproportionate burden of this ecological externality falls upon downslope communities, highlighting a serious environmental justice concern that policy must address through rigorous social safeguards.

The imperative for Himachal Pradesh is clear: the state must pivot from a reactive model of repair to a proactive model of resilience, one that fully embraces the principles of Ecological Modernisation and Disaster Risk Governance. This requires institutionalising robust policy instruments, including Strategic Environmental Assessment, the Himalayan Hill-Road Construction Code, and Performance-Based Maintenance contracts that incentivise long-term stability rather than short-term cost savings. By making these upfront investments in resilience and empowering local communities in project stewardship, Himachal Pradesh can chart a durable development pathway, securing both its economic prosperity and the long-term ecological stability of its fragile Himalayan landscape, aligning local action with global commitments under the SDGs and the Sendai Framework. The next generation of infrastructure must be conceived not as concrete monuments to progress, but as living projects coexisting with nature, scaling development at a pace the terrain can genuinely sustain.

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Conflict of Interest

The authors declare that there is **no conflict of interest** regarding the publication of this research work.

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