

From Hazard to Heritage: Landslides Risks, Geoheritage Potential, and Geotourism Opportunities along NH-44 corridor, Jammu and Kashmir, India

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Abstract

The Ramban-Banihal section of National Highway-44 (NH-44), the only all-weather road linking the Kashmir Valley with mainland India, is among the most landslide-prone corridors in the Himalaya. Frequent slope instabilities, triggered by monsoon rainfall, seismic activity, fragile lithology, and anthropogenic modifications, lead to recurrent traffic disruptions, loss of life, and socio-economic challenges. This study presents a detailed landslide susceptibility mapping (LSM) of the corridor at a 1:10,000 scale, integrating thematic layers such as lithology, slope, structure, land cover, and drainage. A landslide inventory of 117 failures indicates that over 80% are structurally controlled, closely associated with thrust zones (Panjal, Digdole, and Murree Thrusts), sheared granites, and over-steepened slopes. Susceptibility analysis delineates approximately 39.8% of the corridor as high hazard, 40% as moderate hazard, and 20.1% as low hazard. Beyond its engineering challenges, the Ramban-Banihal corridor represents a remarkable geoheritage site, providing a continuous transect of Himalayan geology. It exposes Proterozoic–Permian stratigraphic successions, fossiliferous Paleozoic horizons, intrusive granites, and major thrust zones, making it a valuable natural archive for scientific study, education, and tourism. Drawing parallels with international geodisaster heritage sites, the corridor can be reframed as both a hazard hotspot and a geoheritage destination. A SWOC analysis highlights strengths (geodiversity, educational value), weaknesses (high instability, fragile infrastructure), opportunities (geotourism, disaster education, resilience building), and challenges (climate change, continued hazard exposure). Integrating hazard mitigation with geoheritage conservation could transform this corridor from a “zone of disruption” into a living laboratory for Himalayan geoscience, disaster awareness, and sustainable mountain development. Key infrastructure projects, including tunnels, flyovers, and roads, ensure year-round connectivity while traversing landscapes of scientific, cultural, and aesthetic significance. This study underscores the potential of combining engineering, conservation, and tourism strategies to promote education, community resilience, and socio-economic development in tectonically active Himalayan regions.

1. Introduction

The Himalaya, often described as the “youngest and most fragile mountain chain in the world,” is globally recognized as one of the most landslide-prone mountain belts. This vulnerability arises from the unique interplay of its active tectonics, high seismicity, steep relief, complex lithology, and intense monsoon precipitation (Petley, 2010; Gupta & Joshi, 1990; Thakur, 1992). Landslides occur across the Himalayan arc in response to both natural and anthropogenic drivers, ranging from earthquakes and prolonged rainfall to road construction, deforestation, and unplanned urban expansion. In the Indian context, landslides constitute a significant share of natural disasters, accounting for nearly 12% of all hazard-related fatalities annually (NDMA, 2019). In addition to human losses, they cause widespread socio-economic disruptions, including road blockages, damage to agricultural land, destruction of settlements, and interruption of essential supplies. A stark example of this hazard-prone environment is the Ramban–Banihal stretch of National Highway-44 (NH-44), located in the western Himalaya. This corridor serves as the sole all-weather arterial link to the Kashmir Valley, making it indispensable for the movement of

people, goods, and strategic supplies. However, it is also one of the most unstable segments of the entire Himalayan highway network. Frequent slope instabilities ranging from debris slides and rockfalls to massive rockslides and topple failures repeatedly disrupt traffic for hours to days, with severe consequences for the regional economy and security logistics (Sharma & Akram, 2020). Despite decades of stabilization efforts that include retaining structures, shotcreting, and tunneling projects, landslides continue to sever the route, underscoring the limits of engineering interventions in tectonically predisposed terrain (Bhat et al., 2019; Mir et al., 2024).

Traditionally, research along this corridor has focused primarily on engineering geology and slope stability assessments. Numerous studies have documented the distribution of landslides, identified causative factors such as thrust planes, shear zones, and cut slopes, and proposed mitigation measures to safeguard the highway (Bhat et al., 2019; Ahmad et al., 2021; Mir et al., 2024). While these contributions are essential for hazard reduction and infrastructure planning, they tend to emphasize the “problematic” dimension of the corridor while overlooking its scientific, educational, and cultural value. In fact, the Ramban–Banihal corridor traverses an extraordinary range of lithostratigraphic units from the Proterozoic Salkhala Formation (schists, phyllites, and quartzites) to the fossiliferous Fenestella Shale and Syringothyris Limestone (Devonian-Carboniferous), and the volcanic successions of the Permian Panjal Traps (Wadia, 1931, 1936; Bhat et al., 2017). These successions are intricately juxtaposed along major tectonic boundaries such as the Panjal Thrust, Digdole Thrust, and Murree Thrust, offering a unique window into the tectonic and stratigraphic evolution of the western Himalaya. In addition, granitic intrusions and sheared fault zones exposed along the road cuttings provide valuable insights into mountain-building processes. Taken together, this geodiversity transforms the corridor into a natural geoscience museum, where every road cut and landslide scar tells a story of orogeny, deformation, and geomorphic adjustment.

Coupled with its hazard-prone character, the Ramban–Banihal stretch offers a rare opportunity to reframe a “corridor of risk” into a “corridor of knowledge.” The juxtaposition of high geological diversity with recurrent landslide activity makes it a living laboratory for studying mountain hazards, resilience, and geoscientific processes. In this context, recent global scholarship has emphasized the importance of integrating geoheritage conservation, disaster memorialization, and geotourism into hazard-prone landscapes (Reynard & Brilha, 2018; Mandal & Sarkar, 2021; Ochoa-Tocachi et al., 2020). Such integration not only enhances scientific understanding but also promotes public awareness, disaster preparedness, and sustainable local development. Accordingly, the objectives of this study are manifold.

The primary objectives of this study are to comprehensively assess and manage landslide hazards while promoting geoheritage and geotourism along the Ramban–Banihal corridor. The study aims to map landslide susceptibility zones at a 1:10,000 scale, integrating thematic layers such as lithology, slope, structure, drainage, and land cover, to identify areas of high, moderate, and low hazard. It seeks to analyze structural and lithological controls on slope failures, highlighting the influence of thrust zones, sheared granites, and anthropogenic modifications in this tectonically active terrain. Simultaneously, the research emphasizes the geoheritage significance of the corridor, documenting stratigraphic

successions, fossiliferous horizons, volcanic formations, and thrust planes that collectively serve as a natural repository of Himalayan geological history. Further, the study explores the potential for geotourism and disaster education, examining opportunities for educational, cultural, and eco-tourism initiatives at key sites such as tunnels, rivers, and scenic viewpoints. An integrated approach is proposed to combine hazard mitigation with heritage conservation, ensuring sustainable slope stabilization while promoting scientific awareness and tourism. Finally, the study aims to enhance community engagement and resilience by developing frameworks for local participation, disaster preparedness, and capacity building through guided geotourism and educational outreach.

2. Study Area

2.1 Location

The Ramban–Banihal corridor, a ~ 50 km stretch of the Jammu–Srinagar National Highway-44 (NH-44), lies in the Lesser Himalaya of the Jammu and Kashmir Himalaya. Geographically, the corridor extends along the Chenab River valley, between latitudes 33°14'–33°28'N and longitudes 75°07'–75°22'E (Fig. 1). The alignment traverses rugged terrain, beginning at Ramban (~ 1200 m above sea level) and gradually ascending northward through Ramsu, Digdole, Makarkote, and Nachlana, before reaching the Banihal Pass (~ 4000 m asl) and the Jawahar Tunnel. This corridor represents the sole all-weather road connection between the Kashmir Valley and the rest of India, rendering it strategically and socio-economically vital. However, the terrain is among the most unstable in the entire Himalayan region, where a combination of steep slopes, fragile lithology, and active tectonic structures makes the highway highly vulnerable to landslides, debris flows, and rockfalls.

2.2 Geological Setting

Geologically, the Ramban–Banihal corridor is a window into the Lesser Himalayan lithotectonic domain, comprising a complex mosaic of stratigraphic units ranging from Proterozoic metasediments to Permian volcanic successions. This geodiversity, coupled with its accessibility through road cuttings, makes the corridor both a geological archive and a living natural laboratory. Figure 2 shows the major lithostratigraphic units exposed along the alignment which include:

Salkhala Formation (Proterozoic)

Consists predominantly of mica schists, phyllites, and quartzites, representing medium- to high-grade metamorphic rocks of the Lesser Himalayan Crystalline (Wadia, 1931; Thakur, 1992). These rocks are highly jointed and foliated, and are often intersected by shear zones, making them prone to planar and wedge failures.

Ramban Formation (Ediacaran–Cambrian)

Characterized by slates, thinly bedded quartzites, and gypsum-bearing horizons. The presence of gypsum and other evaporitic minerals introduces weak planes that contribute to slope instability, particularly along Nachlana and Digdole.

Sincha Formation (Cambrian–Ordovician)

Composed of dolomites, quartzites, and thin shale intercalations, this formation exhibits karst features in some sectors. The differential weathering of carbonate and siliceous units creates localized overhangs and steep scarps.

Ramsu Formation (Ordovician–Devonian)

Includes phyllites, quartzites, and limestones, frequently sheared and fractured due to tectonic activity. These weakly metamorphosed sedimentary rocks are prone to disintegration under heavy rainfall.

Machhal Formation (Carboniferous)

Dominated by arenites (sandstones) and phyllites, this unit is typically massive but locally affected by shearing.

Fenestella Shale and Syringothyris Limestone (Devonian–Carboniferous)

These fossiliferous units are critical for Himalayan stratigraphy, preserving marine invertebrate fossils (Wadia, 1936). Their shale members, however, are highly susceptible to weathering, making them critical zones for small-scale slides and soil creep.

Agglomeratic Slate & Panjal Volcanics (Permian)

The Agglomeratic Slate comprises dark slates interbedded with volcanic detritus, while the overlying Panjal Volcanics are made up of basalts, andesites, and pyroclastics (Bhat et al., 2017). The contact between volcanics and sediments is often tectonized, forming shear planes that host large failures such as those near Digdole.

In addition to these successions, the region is intruded by granitic bodies such as the Pipran and Lohar Granites, which are highly jointed and fractured. These intrusions create abrupt lithological contrasts and form zones of mechanical weakness, further predisposing slopes to instability.

Structurally, the corridor is dissected by a series of major thrusts and shear zones:

Panjal Thrust (PT)

Brings the Panjal Volcanics in contact with older sedimentary units.

Digdole Thrust (DT)

A subsidiary tectonic plane associated with intense shearing and slope failures.

Murree Thrust (MBT)

A regional-scale tectonic feature marking the boundary between Lesser Himalayan and Sub-Himalayan rocks.

The intersection of these thrusts with steep road cuttings explains the clustering of catastrophic landslides in sectors like Digdole, Battery Cheshma, and Nachlana.

2.3 Geomorphology and Climate

The corridor lies in a zone of rugged ridge–ravine topography, shaped by fluvial incision and tectonic uplift. Figure 3 illustrates the key geomorphic attributes including:

Slope Morphology

More than 60% of slopes exceed 35°, with several sectors displaying near-vertical scarps due to undercutting by roads or rivers. Relative relief often exceeds 100 m within short horizontal distances, enhancing gravitational stress.

Drainage

The corridor is deeply incised by the Chenab River, a major Indus tributary, and its right-bank tributaries such as the Bichlari Nala. Continuous lateral erosion and undercutting by these rivers contribute to slope oversteepening and toe removal, a key landslide trigger mechanism.

Geomorphic Processes

The terrain shows evidence of rockfalls, debris flows, gullies, and solifluction lobes. Landslide scars and old deposits are widespread, reflecting the long-term instability of the corridor.

Climate

The Ramban–Banihal region experiences a temperate to alpine climate, strongly influenced by both the Indian Summer Monsoon and Western Disturbances. Annual precipitation ranges between 1200 and 1400 mm, with the monsoon contributing ~ 60–70% of the total. Short-duration, high-intensity rainstorms saturate slope materials and initiate shallow slides, while prolonged rainfall episodes lead to deeper-seated failures. Winter snowfall followed by rapid spring snowmelt adds to seasonal slope instability (BIS, 2017; Bhat et al., 2019).

Together, the interplay of fragile lithology, active tectonics, steep topography, and intense precipitation renders the Ramban–Banihal corridor a highly unstable geomorphic system. It is simultaneously a hazard hotspot and a geoheritage site, where geological diversity and slope instability converge.

3. Methods

The methodological framework adopted in this study combines two complementary strands. Engineering geological and geospatial analysis for landslide susceptibility mapping. Geoheritage and geotourism evaluation to assess the educational and heritage value of the Ramban–Banihal corridor. Together, these approaches allow for both hazard reduction and heritage valorization, aligning with recent international practices (Brilha, 2016; Reynard & Brilha, 2018).

3.1 Landslide Inventory Mapping

A comprehensive landslide inventory was prepared by *integrating field-based mapping, remote sensing interpretation, and Google Earth imagery.*

Field Surveys

Extensive ground truthing was conducted along the NH-44 alignment and adjoining slopes between Ramban and Banihal as presented in Fig. 4. Each landslide was mapped, measured, and classified according to type, activity, and material involved (Mir et al., 2024).

Remote Sensing & Google Earth

High-resolution satellite imagery and multi-temporal Google Earth datasets were used to identify older landslide scars, debris deposits, and slope deformations that are not always visible on the ground.

Landslide Inventory

A total of 117 landslides were catalogued, comprising Debris slides – 50 cases, Rockfalls – 34 cases, Rock slides – 20 cases, Rock topples – 5 cases, Debris flows – 2 cases and old relict slides – 6 cases. This inventory formed the baseline dataset for susceptibility analysis and also highlighted clusters of failures in structurally controlled sectors such as Digdole, Battery Cheshma, Seri, and Nachlana.

The mapping carried was out in accordance with BIS (2017) guidelines, involved classifying the area into two categories as rocky (65.7%) and overburden-covered (34.3%), based on lithology, field observations, and geomorphic expression. Area was further characterized using multiple attributes, including slope angle, slope aspect, relative relief, lithology, structural controls (joints, thrusts, shear zones), proximity to drainage, and land cover (Ghosh et al., 2012; Bhat et al., 2019). GIS was used to integrate multiple thematic layers to analyze landslide factors. Slope gradient (< 15° to > 45°) and aspect (eight directions) influenced stability, with south- and southwest-facing slopes being more prone to failure. Relative relief reflected local elevation differences, while weak lithologies (phyllites, shales, gypsum) and structural features (thrusts, shear zones) increased susceptibility. Drainage proximity, land use/cover (barren, forest, agriculture, built-up), and geomorphology (ridges, escarpments, terraces, valleys) were also considered, highlighting areas more prone to landslides. These weighted layers were integrated in GIS

using a multi-criteria decision analysis (MCDA) to produce the landslide susceptibility (LSZ) map, which was classified into very high, moderate, and low susceptibility zones.

3.2 Geoheritage and Geotourism Assessment

To complement hazard mapping, a geoheritage and geotourism evaluation framework was applied, following international standards (Brilha, 2016; Reynard & Brilha, 2018).

Geoheritage Inventory

Key geological features (stratigraphic contacts, fossiliferous units, volcanic successions, thrust exposures, landslide scars) were documented during field surveys. Each feature was classified as a geosite with potential scientific, educational, cultural, or aesthetic value.

Scientific Value Assessment

Criteria such as representativeness, rarity, integrity, and scientific knowledge were evaluated (Brilha, 2016). For example, the Fenestella Shale and Syringothyris Limestone were rated high due to fossil content, while the Panjal Volcanics were noted for regional tectonic significance.

Educational and Tourism Potential

Accessibility, safety, visibility, and interpretability were assessed. Roadside exposures such as thrust planes and landslide scars near Digdole were considered suitable for interpretive panels and geotourism stops.

SWOC Analysis

Conducted to evaluate strengths, weaknesses, opportunities, and challenges of promoting geotourism in the corridor.

Stakeholder Input

Informal consultations with local communities, highway authorities, and academic institutions were conducted to gauge perceptions about geotourism feasibility and disaster education initiatives.

Proposed Geotourism Model

Based on results, a Geoheritage Interpretation Trail and a Geo-disaster Museum were conceptualized for Ramban and Banihal towns, emphasizing low-impact, educational geotourism rather than mass tourism.

4. Results

4.1 Landslide susceptibility zonation and failure controls along the corridor

The landslide susceptibility assessment along the corridor shown in Fig. 5 revealed a clear spatial distribution of risk zones, identifying areas that require prioritized attention for hazard mitigation and planning. High susceptibility zones cover approximately 39.8% of the corridor and are concentrated at Digdole, Seri, Battery Cheshma, Nachlana, and Painthyal. These locations are characterized by steep slopes, weak lithologies, pronounced structural deformation, and proximity to active drainage channels, making them highly prone to frequent landslide occurrences. Moderate–high susceptibility zones, comprising roughly 40% of the corridor, include Ramsu, Makarkote, and the Banihal vicinity. These areas, while less critical than the high-risk zones, still exhibit significant instability due to moderate slope gradients, fractured rock masses, and anthropogenic activities such as road cuttings and embankments. Low susceptibility zones account for about 20.1% of the corridor and are generally located on terraces, gentle valley bottoms, and areas with stable geomorphology, minimal structural disruptions, and protective vegetation cover. Analysis of landslide controls indicated that over 80% of observed failures were strongly associated with geological and geomorphological factors, particularly thrust contacts, sheared granite bodies, and over-steepened cut slopes resulting from road construction. This highlights the dominant influence of structural weaknesses and human-induced slope modifications in governing slope instability and emphasizes the need for site-specific stabilization measures and strategic land-use planning. A comprehensive landslide inventory was prepared using field surveys, historical records, and remote sensing data to document the location, type, and characteristics of slope failures along the corridor. Key observations from the inventory include:

High Susceptibility Zones (39.8%)

Digdole, Seri, Battery Cheshma, Nachlana, and Painthyal experienced frequent and active landslides, predominantly debris flows, rockfalls, and shallow translational slides, associated with steep slopes, weak lithologies, and structural discontinuities.

Moderate–High Susceptibility Zones (~ 40%): Ramsu, Makarkote, and the Banihal vicinity exhibited intermittent landslide activity, mainly rotational and translational slides, often triggered by heavy rainfall or minor anthropogenic disturbances.

Low Susceptibility Zones (20.1%)

Terraces, valley bottoms, and gentle slopes showed minimal landslide activity, typically limited to minor soil slips or localized erosion.

Failure Controls

Over 80% of landslides were aligned with thrust contacts, sheared granite bodies, or over-steepened cut slopes, highlighting the strong influence of geological structures and human interventions on slope

instability.

This inventory provides a baseline for validating the landslide susceptibility zonation and supports planning of targeted mitigation and management strategies along the corridor.

5. Discussion

5.1 Engineering geology implications

The Ramban Banihal corridor is recognized as one of India's most geologically and geo-technically challenging infrastructure alignments, exhibiting frequent landslide occurrences despite extensive engineering interventions, including slope stabilization, retaining structures, and drainage measures (Mir et al., 2024). The corridor traverses a highly complex litho-tectonic zone of the Lesser and Greater Himalaya, where steep slopes, structurally weak formations, and intensive anthropogenic modifications converge to create persistent instability. The recurrence of landslides along this corridor highlights the limitations of conventional engineering approaches in areas dominated by strong structural controls. Geological structures, particularly the prominent thrusts Panjal Thrust (PT), Deol Thrust (DT), and Main Boundary Thrust (MBT) act as primary failure planes, predisposing slopes to translational and rotational sliding. These tectonic discontinuities, often associated with sheared and fractured rock masses, provide zones of weakness along which gravitational stresses are concentrated. Furthermore, lithological variability, including phyllites, schists, and sheared granites, exacerbates susceptibility, as these units exhibit differential weathering and reduced shear strength under both natural and anthropogenic triggers.

Engineering activities such as road cuttings, slope over-steepening, and inadequate drainage exacerbate instability by removing natural support, increasing slope angles, and concentrating water infiltration along structural planes. Over 80% of observed landslides correlate with these geological and engineered features, emphasizing that slope failures are not purely stochastic but are strongly influenced by structural predisposition and human modification. From an engineering geology perspective, these findings underscore the critical need for integrated hazard management strategies that combine geotechnical solutions with structural and geomorphological considerations. Approaches such as detailed site-specific structural mapping, rock mass characterization, slope reinforcement using anchors and geogrids, bioengineering, and systematic drainage management are essential. Moreover, hazard mitigation must account for the corridor's tectonic setting, emphasizing proactive monitoring, early warning systems, and adaptive maintenance to address recurrent instability. The analysis demonstrates that sustainable infrastructure development in tectonically active and structurally complex Himalayan terrain requires a nuanced understanding of geological controls in conjunction with engineering interventions to minimize risk and ensure operational safety.

5.2 Geoheritage significance

The Ramban-Banihal corridor constitutes a remarkable and continuous litho-stratigraphic transect of the Lesser Himalaya, offering unparalleled exposure to the region's complex geological framework. Along this corridor, rare fossiliferous horizons, including the Fenestella Shale and Syringothyris Limestone, document significant paleontological records that are critical for understanding the evolutionary history of the Tethyan Himalaya. Volcanic successions, such as the Panjal Volcanics, along with intrusive bodies and granitoid formations, reveal the magmatic and tectonic evolution of the region (Wadia, 1936; Thakur, 1992). The juxtaposition of stratigraphic, structural, and geomorphological features within a relatively accessible terrain enhances its scientific, educational, and aesthetic value. This geodiversity ranging from fossiliferous layers and thrust exposures to landslide scars and fluvial terraces makes the corridor a prime candidate for formal geoheritage recognition under international frameworks (Brilha, 2016). Beyond its scientific importance, the corridor offers opportunities for hands-on education, geotourism, and public awareness on both geological processes and natural hazards.

5.3 Global parallels and lessons for geo-disaster interpretation

Globally, several hazard-prone sites have been successfully integrated into heritage and educational frameworks, demonstrating the potential for combining geohazard awareness with geotourism. The Vaiont landslide in Italy, which caused catastrophic damage in 1963, is now memorialized with a geo-disaster museum and interpretive trails, providing visitors with insights into landslide mechanics, hydrology, and mitigation (Genevois & Ghirotti, 2005). Similarly, landslide sites in Gansu Province, China, have been transformed into educational venues featuring guided trails and museums that document historical failures and engineering responses (Tang et al., 2011). In India, the 2014 Malin landslide has been proposed as a disaster learning site to promote community awareness and resilience (Mandal & Sarkar, 2021). The Ramban–Banihal corridor, given its combination of high landslide susceptibility, complex structural geology, and unique litho-stratigraphic exposures, could emulate these international models. Proposed initiatives could include the establishment of geoheritage trails along roadside exposures, interpretive panels at thrust planes and fossiliferous sites, and a geo-disaster museum highlighting Himalayan landslide processes. Such initiatives would not only conserve the region's geodiversity but also promote educational geotourism, disaster awareness, and community engagement, creating a model that integrates hazard mitigation with heritage conservation.

5.4 Geotourism and Disaster Education

The Ramban–Banihal corridor offers significant potential for geotourism and disaster education due to its unique combination of geoheritage, high landslide susceptibility, and accessibility along a major transportation route. A Geoheritage Interpretation Trail could be developed along strategically selected roadside pull-over zones, allowing visitors to safely observe key geological features, such as thrust planes, fossiliferous horizons, volcanic successions, and landslide scars. Informative panels could provide explanations of geological processes, tectonic evolution, and the mechanics of landslides, thereby creating an interactive learning experience that integrates hazard awareness with geoscientific education.

Complementing the trail, a Geo-disaster Museum in Ramban or Banihal could serve as a central hub for understanding Himalayan tectonics, landslide mechanisms, and regional geomorphology. Exhibits could include rock and fossil collections, scale models of landslides, multimedia presentations on slope instability, and demonstrations of mitigation techniques. This museum would not only enhance visitor engagement but also provide a scientific resource for students, researchers, and policymakers.

Community engagement forms a critical component of this initiative. Local youth could be trained as geo-guides, blending tourism promotion with resilience-building education. By actively participating in interpretation and outreach, communities would gain both employment opportunities and a stronger understanding of natural hazards, fostering local stewardship and preparedness. In addition, digital outreach strategies can expand the reach of geotourism and disaster education. Real-time hazard dashboards, interactive 3D geological models, virtual tours of key sites, and mobile applications could allow remote visitors to experience and learn from the corridor's geoheritage. Such initiatives would enhance hazard awareness, promote scientific literacy, and encourage responsible tourism, even during periods when field visits may be restricted due to seasonal instability or extreme weather.

5.5 SWOC analysis

A SWOC (Strengths, Weaknesses, Opportunities, Challenges) analysis was conducted to assess the feasibility and sustainability of geotourism and disaster education initiatives along the corridor:

Strengths

The corridor possesses exceptional scientific richness, visible and accessible geological features, and diverse geomorphology, offering excellent potential for education and tourism. Its location along a major highway increases visitor accessibility and outreach potential.

Weaknesses

Persistent slope instability, frequent landslides, and limited safety infrastructure pose significant risks to both tourists and local communities, requiring careful planning and mitigation measures.

Opportunities

Geotourism can promote sustainable livelihoods, enhance community resilience, and serve as a platform for disaster education. Educational programs, guided tours, and interpretive infrastructure can foster awareness about Himalayan hazards and geoconservation.

Challenges

Climate change and increasing extreme weather events may exacerbate hazard frequency and intensity, disrupting tourism and infrastructure. Institutional inertia, limited funding, and maintenance challenges could hinder the implementation and long-term sustainability of geotourism and educational initiatives.

This integrated approach emphasizes the dual objectives of preserving geoheritage and enhancing hazard awareness, while promoting sustainable tourism and community involvement in a region of high geohazard risk.

5.6 Infrastructure developments on NH44: Roads, Flyovers, and Tunnels

National Highway 44 (NH44), formerly known as NH1A, is the lifeline connecting Jammu to Srinagar, traversing the challenging terrains of the Pir Panjal and outer Himalayan ranges. To ensure year-round connectivity, several advanced engineering projects have been implemented along this corridor. One of the most significant developments is the Dr. Syama Prasad Mookerjee Tunnel (Chenani-Nashri Tunnel), located between Chenani and Nashri in Ramban district. This 9.28 km twin-tube tunnel, with two lanes per tube, was inaugurated in April 2017. It bypasses the avalanche-prone Patnitop region, drastically improving travel safety and reliability during winter months.

Another major project is the Banihal-Qazigund Road Tunnel, spanning 8.45 km and connecting Banihal to Qazigund. This twin-tube, four-lane tunnel, opened in August 2021, significantly reduces travel time by bypassing the steep and winding Banihal Pass. Similarly, the T5 Tunnel between Panthyal and Magerkote, 870 meters long, was inaugurated in March 2023 to bypass landslide-prone stretches, ensuring safer and faster transit. The Nandni Tunnels, a series of four tunnels totaling 1.4 km between Jammu and Udhampur, bypass approximately 6.8 km of rugged mountainous terrain, further reducing travel distance and enhancing highway safety. Collectively, these tunnels and related infrastructure have transformed NH44 into a modern, all-weather corridor.

Geoheritage and Geotourism significance

The NH44 corridor not only serves as a strategic transport route but also passes through a region of exceptional geological and cultural value, making it significant for geotourism. The highway traverses the Outer and Greater Himalayas, showcasing diverse geological formations, varying slope gradients, and striking mountain landscapes. These features make the corridor an ideal site for educational tourism, allowing students, researchers, and enthusiasts to study Himalayan geology in situ. The route is also dotted with historical and cultural landmarks, including Mughal-era roads, ancient temples, and hill forts, which enrich its heritage value. Scenic spots such as Patnitop and Banihal Pass provide panoramic vistas that attract nature lovers and eco-tourists alike, making the corridor a blend of natural beauty, scientific interest, and historical importance.

Strategic and Economic Importance

From a strategic perspective, NH44 ensures uninterrupted connectivity between Jammu and Srinagar, which is vital for both civilian travel and military logistics. The highway also has substantial economic significance as it facilitates trade, tourism, and regional development in Jammu & Kashmir. By improving safety through bypassing landslide-prone areas and reducing travel time with tunnels and flyovers, the

highway enhances accessibility to remote regions, boosting local economies. Furthermore, the corridor's integration of modern engineering within a geologically sensitive landscape provides a model for sustainable infrastructure development, balancing transportation needs with environmental and heritage conservation.

5.7 Geotourism potential of Jawahar Tunnel on the corridor

The Jawahar Tunnel, also known as the Banihal Tunnel, is a 2.85 km long road tunnel situated at an elevation of 2,194 meters in the Pir Panjal mountain range of Jammu and Kashmir. Constructed between 1954 and 1956 by German engineers Alfred Kunz and C. Barsel under the supervision of the Border Roads Organisation (BRO), it was inaugurated on December 22, 1956. The tunnel was designed to ensure year-round connectivity between Jammu and Srinagar by bypassing the snow-prone Banihal Pass (Fig. 6). Due to the challenging geological conditions of the region, the construction employed the New Austrian Tunneling Method (NATM), which adapts to surrounding rock conditions and minimizes ground disturbance, making it ideal for the complex geological strata encountered during excavation. The tunnel passes through the Panjal Volcanics and the Zewan Formation, part of the Tethyan Himalayan belt. These formations mainly consist of Upper Carboniferous to Lower Permian rocks, including basaltic lavas, agglomerates, slates, and limestones. The varied rock types posed significant construction challenges, such as unexpected rock bursts and water seepage. Some sections of the tunnel passed through soft ground, while others encountered very hard rock, requiring careful planning, excavation, and stabilization measures to ensure safety and structural integrity. The construction alignment traversed eight distinct geological strata, necessitating a combination of excavation techniques. Drill and blast methods, road headers, and tunnel excavators were employed to manage the differing rock conditions. These methods were essential not only for excavation but also to maintain the stability of the tunnel through soft ground and hard rock sections. The engineering solutions applied during construction exemplify adaptive techniques in complex mountainous terrains.

Beyond its engineering importance, the Jawahar Tunnel is a site of significant geoheritage value. The surrounding geological formations provide insights into the tectonic and sedimentary processes that shaped the Kashmir Valley. Adjacent landscapes showcase sedimentary rock layers and fossilized remains from the Permian-Triassic periods, making the area valuable for paleontological and geological studies. These unique features highlight the tunnel's importance as a geotourism site and as a living classroom for Earth science enthusiasts. While primarily functional, the Jawahar Tunnel holds substantial tourism potential due to its historical and geological significance. The Jammu-Srinagar National Highway, which the tunnel is part of, offers scenic vistas including the Banihal Pass and surrounding mountainous landscapes, attracting travelers interested in nature, photography, and cultural heritage. Recognizing this, authorities have planned renovations to transform the tunnel into a tourist destination, preserving its historical essence while enhancing visitor experience. Such initiatives are expected to boost the local economy, generate employment opportunities, and promote sustainable tourism in the region.

5.8 Geoheritage and geotourism potential of physiographic features

Bichalrai Nala

The Bichalrai Nala, also known as the Bichalri River, is a key watercourse in Ramban district, flowing through rugged mountainous terrains and shaping the local hydrology and geomorphology. Its geoheritage significance is highlighted by events such as the August 2023 landslide at Khuni Nallah, which blocked the river and formed a natural dam, providing insights into landslide dynamics, river morphology, and disaster management in the Himalayas. The river also offers considerable tourism potential, with scenic gorges and ravines that attracts nature enthusiasts and photographers as highlighted in Fig. 7, while eco-friendly trails and viewpoints could further promote sustainable tourism for local communities.

Pir Panjal Range

The Pir Panjal Range, forming part of the western Himalayas, acts as a natural divide between the Jammu region and the Kashmir Valley and is traversed by NH44. Its geoheritage value lies in its tectonic complexity and preserved glacial features such as moraines and U-shaped valleys, reflecting the region's glacial history. For tourism, the rugged terrains provide opportunities for trekking, mountaineering, and camping, while traditional villages along the range offer cultural experiences. Travelers along NH44 also enjoy breathtaking scenic drives with views of snow-capped peaks and alpine meadows presented in figure (8).

Chenab River

The Chenab River, originating from the confluence of Chandra and Bhaga rivers in Himachal Pradesh, flows through Ramban before entering Pakistan. It holds significant geoheritage importance due to its hydrological role in supporting agriculture and ecosystems, as well as its cultural and spiritual significance in local traditions. The river also presents tourism opportunities through fishing, boating, and rafting, along with visits to archaeological and heritage sites. Some of the major sites are shown in Fig. 9. Its scenic journey through valleys and plains makes it an attractive destination for nature and landscape enthusiasts.

5.9 Geotourism potential of Banihal Town and Ramban District

Banihal Town

Banihal, situated at the gateway to the Kashmir Valley, is a town of strategic and natural significance along NH44. Geologically, it lies in the Pir Panjal range, offering views of steep slopes, deep gorges, and snow-clad peaks during winter. The Jawahar Tunnel near Banihal adds historical and engineering

interest, making the area appealing to tourists interested in geological engineering heritage. Banihal's natural features, including streams, meadows, and surrounding forests, provide scenic landscapes ideal for photography, nature walks, and eco-tourism. Additionally, its location as a hill pass makes it a hub for adventure tourism, with trekking and hiking routes connecting to nearby villages and mountain trails.

Ramban District

Ramban District is characterized by rugged terrains, river valleys, and high mountain ridges of the Pir Panjal range. Its major rivers, such as the Chenab and Bichalrai Nala, along with tributaries and waterfalls, provide opportunities for river-based tourism, including boating, fishing, and nature-based excursions. The district's landslide-prone slopes and gorges also serve as a live example of Himalayan geomorphology, appealing to geology enthusiasts and educational tourism. Moreover, Ramban is home to traditional villages and cultural sites, which combined with the natural scenery, make it suitable for cultural and eco-tourism. Scenic drives along NH44, with viewpoints overlooking deep valleys and the Chenab River, further enhance the district's attractiveness for travelers.

Some of the major tourist sites are shown in Fig. 10.

5.10 Integrating hazard mitigation with geoheritage and geotourism

The Ramban–Banihal section of NH-44 presents a unique intersection of geohazard risk and geoheritage significance, reflecting the dual identity of the Himalaya as both a corridor of hazards and a corridor of heritage. Landslide susceptibility mapping along this route underscores the corridor's extreme vulnerability, with high and moderate–high risk zones concentrated at locations such as Digdole, Seri, Battery Cheshma, Nachlana, and Painthyal, where steep slopes, weak lithologies, and structural discontinuities dominate. At the same time, these same exposures reveal remarkable geoheritage features, including fossiliferous horizons, volcanic successions, thrust planes, and fluvial terraces, which provide insight into the tectonic evolution and geomorphological dynamics of the Lesser Himalaya. Integrating hazard mitigation with heritage conservation offers an innovative approach to transform this unstable corridor into a living classroom of Himalayan geology and resilience. Key recommendations included are as

Geoheritage Interpretation and Trail Development

Establish safe roadside pull-over zones with well-designed interpretive panels explaining geological structures, fossiliferous units, landslide mechanics, and tectonic evolution. Include marked trails for short excursions where feasible, allowing visitors, students, and researchers to engage directly with geological features while maintaining safety protocols.

Geo-disaster Museum and Educational Centers

Develop a geo-disaster museum in Ramban or Banihal, featuring interactive displays on landslide processes, Himalayan tectonics, slope stabilization methods, and the history of significant regional landslides. Incorporate educational modules for school and university groups, emphasizing both scientific understanding and practical disaster preparedness.

Community Engagement and Capacity Building

Train local youth as geo-guides and disaster educators to foster community participation in geotourism and resilience education. Promote local employment opportunities linked to tourism services, hospitality, and interpretive programs, thereby linking hazard awareness with sustainable livelihoods.

Digital Outreach and Technological Integration

Develop digital platforms such as real-time hazard dashboards, 3D geological models, virtual site tours, and mobile applications to extend access to remote audiences and enhance geoscience literacy. Utilize these platforms for early warning and disaster awareness initiatives, integrating geohazard monitoring with tourism and educational activities.

Safety, Infrastructure, and Risk Mitigation Measures

Implement targeted slope stabilization measures at high-risk zones, including retaining walls, rock anchors, bioengineering, and improved drainage systems, informed by detailed structural and geotechnical mapping. Establish early-warning systems and hazard signage along the corridor to safeguard both travelers and geotourists.

Policy, Institutional Coordination, and Sustainable Planning

Encourage collaboration between geological surveys, highway authorities, tourism departments, and local governance to integrate hazard mitigation, heritage conservation, and tourism development. Incorporate geotourism and disaster education into regional planning frameworks, ensuring that *infrastructure development aligns with both safety and conservation priorities*.

Monitoring and Research Recommendations

Conduct continuous monitoring of slope stability, geological exposures, and visitor impact to inform adaptive management strategies. Promote long-term research on Himalayan tectonics, landslide triggers, and climate change impacts, leveraging the corridor as a research and training platform for geoscientists and disaster managers.

6. Conclusion

The Ramban–Banihal corridor along NH44 exemplifies the dual identity of the Himalaya as both a high-risk geohazard zone and a region of exceptional geoheritage significance. Landslide susceptibility mapping identifies extensive high and moderate–high risk zones, primarily at Digdole, Seri, Battery

Cheshma, Nachlana, and Painthyal, where steep slopes, weak lithologies, and structural discontinuities dominate. These geohazards are strongly influenced by geological structures, lithological variability, and anthropogenic interventions such as road cuttings and slope over-steepening. At the same time, the corridor exposes a remarkable range of geological, geomorphological, and paleontological features, including fossiliferous horizons, volcanic formations, thrust planes, and fluvial terraces, making it a valuable site for geoheritage conservation and educational geotourism. Key infrastructure, including the Jawahar Tunnel, Banihal-Qazigund Tunnel, Chenani-Nashri Tunnel, and associated roads and flyovers, not only ensure year-round connectivity but also traverse landscapes of significant scientific and aesthetic interest. Integrating hazard mitigation with geoheritage promotion offers an innovative framework to transform the corridor into a living classroom of Himalayan geology and disaster resilience. Initiatives such as geoheritage trails, geo-disaster museums, community-based geotourism, digital outreach, and site-specific slope stabilization can simultaneously enhance safety, education, and sustainable livelihoods. In essence, the Ramban–Banihal NH44 corridor demonstrates how geoscientific understanding, infrastructure development, and tourism potential can be harmonized to conserve heritage, mitigate risks, and promote socio-economic growth in a geologically sensitive Himalayan region.

Declarations

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Authors Contribution

RAM: Initial conceptualization, writing of original draft, Supervision during field visit, Overall Supervision
HB: Mapping, editing, revision SK: proof reading, data compilation, review MSA: Editing, data analysis and revision.

Data Availability Statement

Data used in this study will be made available upon reasonable request.

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Conflict of Interest/ Competing Interests

The authors declare that there is no conflict of interest associated with this submission.

Ethics and Consent to Participate declarations: not applicable

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Figures

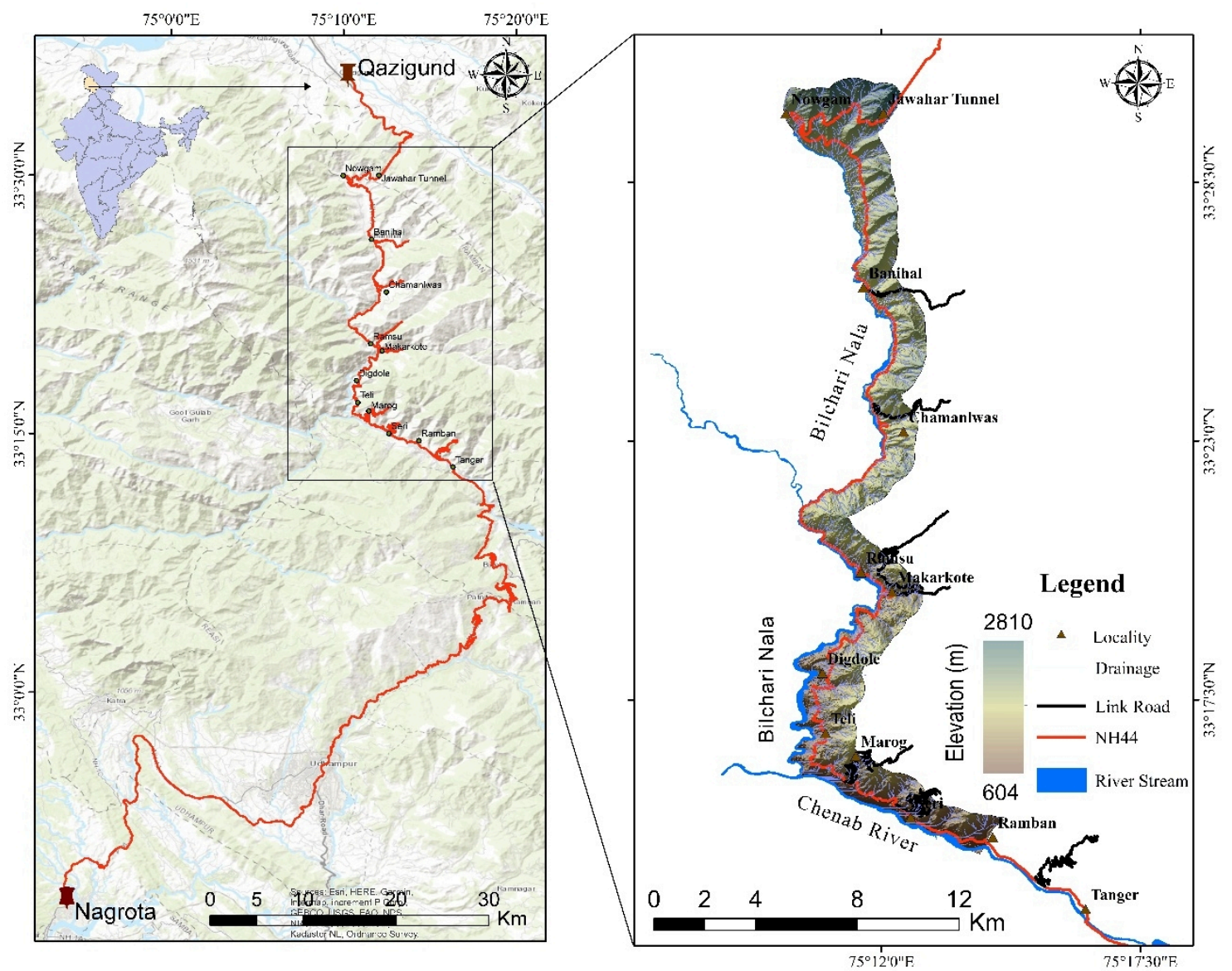


Figure 1

Location and geological map of the study area

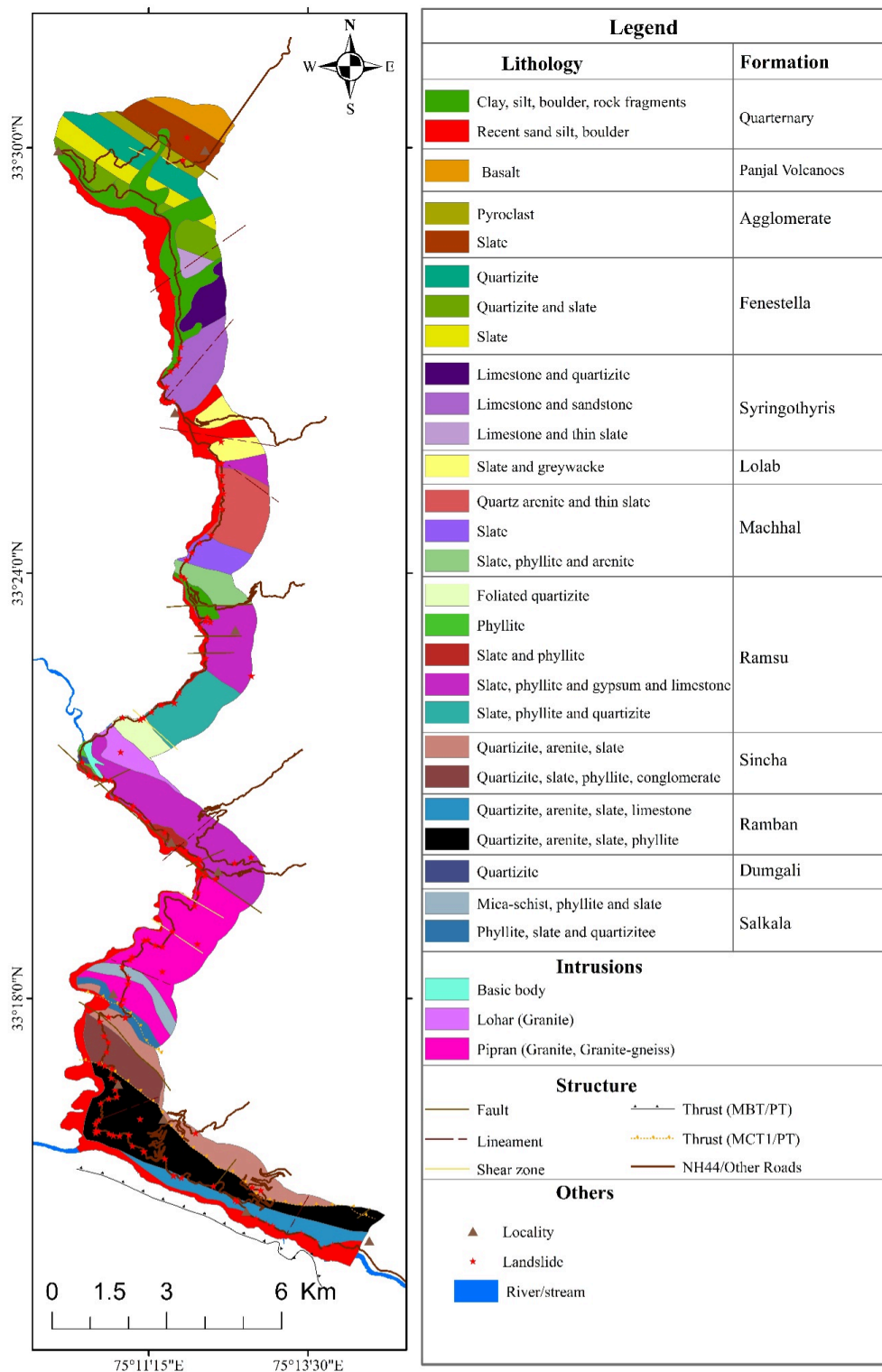


Figure 2

Geology of the study area.

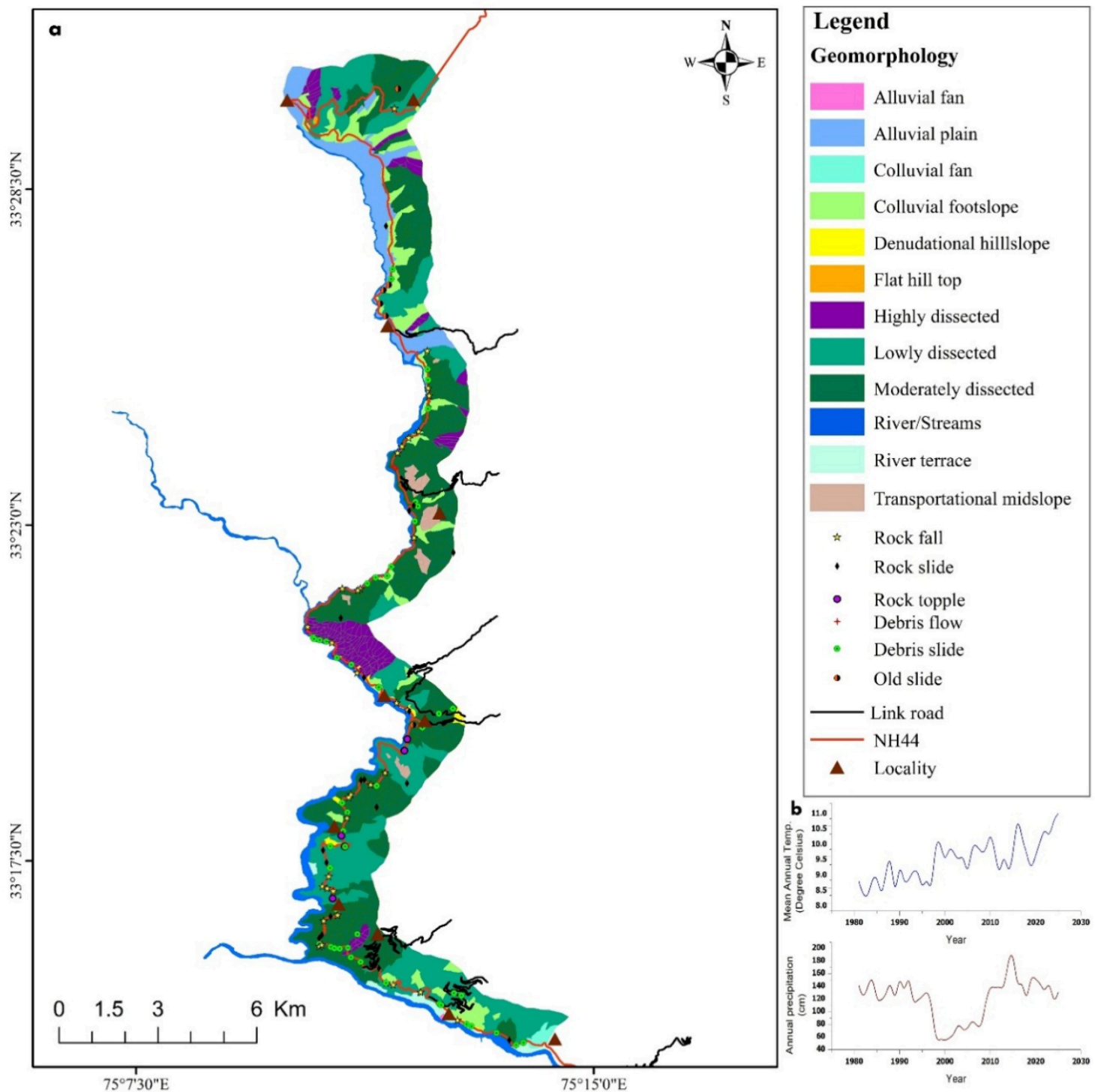


Figure 3

(a) Geomorphology and 3(b) Annual Mean Temperature & total annual precipitation of the study area.

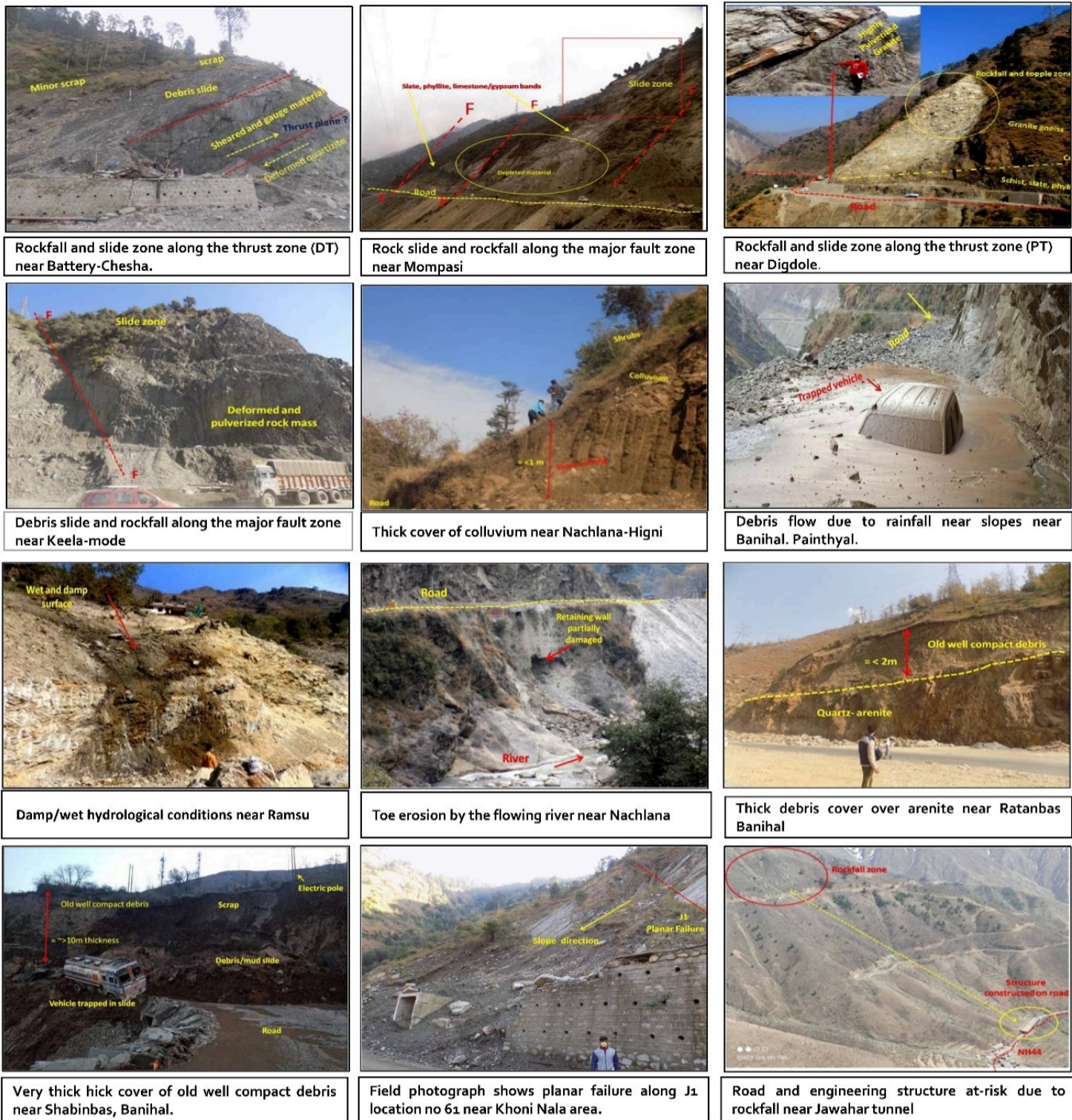


Figure 4

Field sites of landslide inventorying along the Ramban-Banihal corridor.

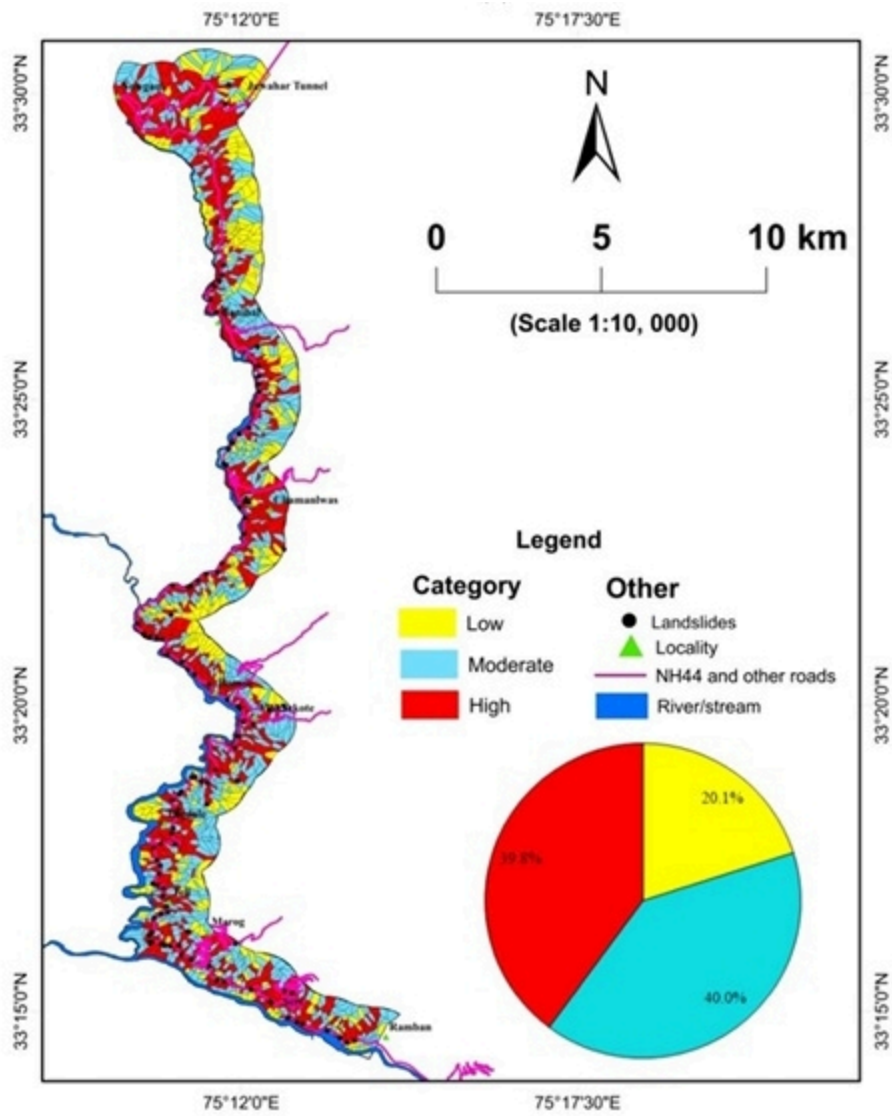


Figure 5

Landslide zonation map of the study area.



Figure 6

(a) Front view of Jawahar Tunnel (b)pyroclastic rock of Agglomerate & (c) Arenite/ sandstone with burrows at the contact Formation exposed on road near Jawahar Tunnel area between Agglomerate Formation and Panjal Volcanics along NH-44 exposed above Jawahar Tunnel along old Road area.

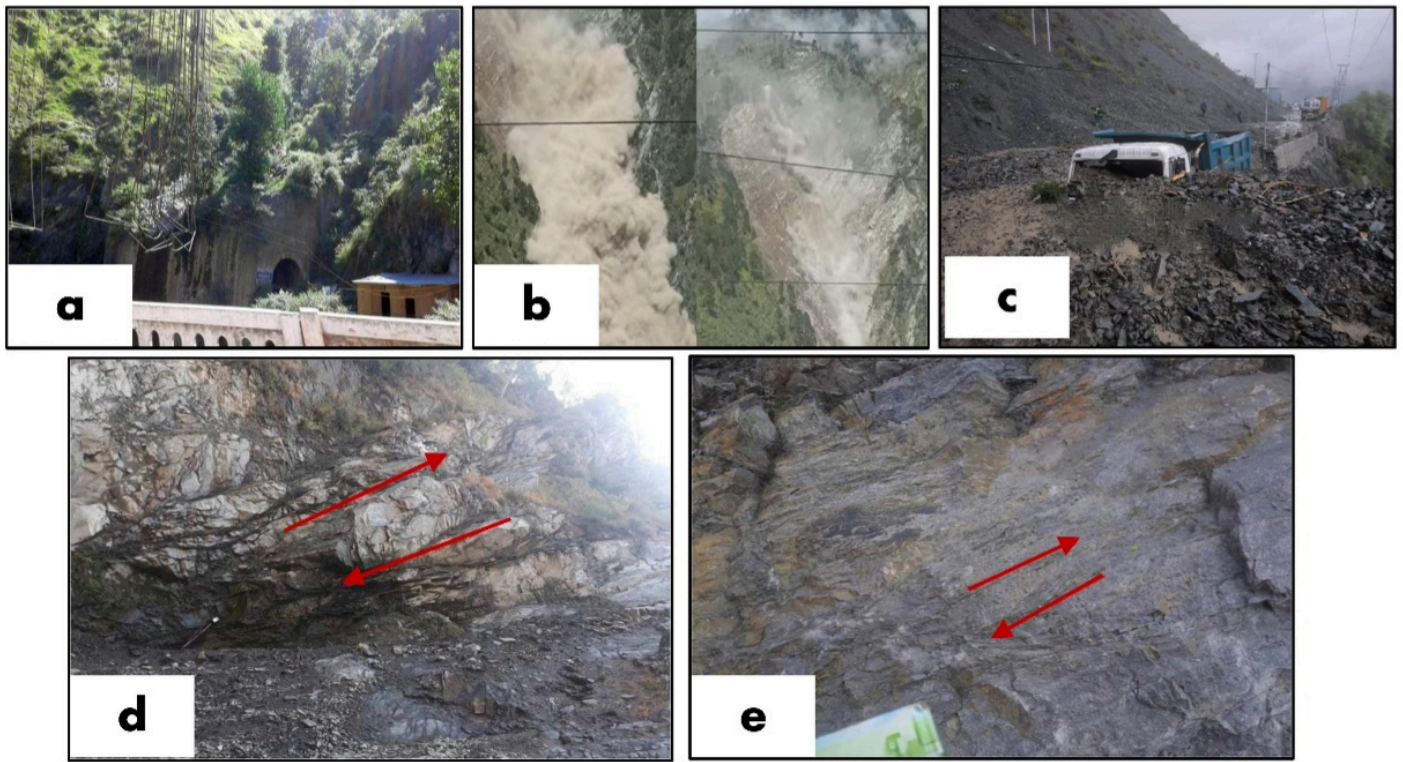


Figure 7

(a) side view of Bichalrai Nala from the main road (NH44), 7(b) view of 2013 flash flood from Bichalrai Nala 7(c) Flash flood induced blockage of NH-44 by Bichalrai Nala debris, 7(d) & 7(e) Field photograph shows dextral sense of shearing within Pipran Granites at Khoni Nala bridge. shearing within sheared Granites of Pipran near Khoni Nala.



Figure 8

Visual scene of the Pir Panjal Range near Banihal.



Figure 9

(a), 9(b) showing Chenab River view near Ramban along NH-44 & 9(c) Worlds' tallest Rail bridge over Chenab River, near NH44.



Figure 10

Famous Tourist sites in the study area near NH-44 corridor.

