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Research Article

Assessment of Ecotourism Suitability and Hazard Risk Management in the Chamoli District, Uttarakhand: An Integrated AHP-GIS Approach (1990–2026)

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Abstract

The Chamoli district of Uttarakhand, India, situated in the ecologically sensitive western Himalaya, is simultaneously a zone of exceptional ecotourism potential and acute multi-hazard exposure. This study applies an Analytical Hierarchy Process (AHP) integrated with Multi-Criteria Evaluation (MCE) within a Geographic Information System (GIS) framework to assess ecotourism suitability and identify hazard risk across the district. Seven thematic criteria Tourist Hotspots, Protected Area Proximity, Village Proximity, River Proximity, Road Proximity, Slope, and Elevation — were evaluated using CARTOSAT-1 DEM and OpenStreetMap data. AHP weight assignment yielded Tourist Hotspots (0.376) and Protected Area Proximity (0.271) as dominant determinants. Results indicate that approximately 35.4% of the district falls within High or Very High suitability zones, concentrated around the Nanda Devi range and major pilgrimage nodes including Badrinath and Joshimath. A critical spatial paradox was identified: zones of highest ecotourism potential coincide with areas of elevated natural hazard risk, including flash floods, landslides, and seismic activity. The study underscores the urgent need for hazard-integrated ecotourism planning and provides a spatially explicit framework for sustainable tourism governance in this climate-sensitive Himalayan landscape.

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1. INTRODUCTION

The Chamoli district of Uttarakhand, India, occupies a strategically significant position in the western Himalaya — a region of outstanding ecological, cultural, and geomorphological importance. Characterised by high-altitude terrain ranging from 651 m to 7,816 m above sea level, the district encompasses the Nanda Devi Biosphere Reserve (a UNESCO World Heritage Site), major pilgrimage destinations of the Char Dham circuit, glaciated alpine landscapes, and a dense network of rivers including the Alaknanda and Dhauliganga. These attributes make Chamoli one of Uttarakhand's most significant tourism destinations, while simultaneously rendering it one of its most hazard-prone.

The global emphasis on sustainable development — defined as the optimal use of resources to meet current needs without compromising the needs of future generations — has generated growing interest in ecotourism as a framework for reconciling conservation imperatives with economic development in mountain regions (International Ecotourism Society, n.d.; Scheyvens, 1999). Ecotourism, as a branch of sustainable tourism, emphasises the unification of conservation, local community development, and responsible travel. India's tourism sector has expanded substantially, with the World Travel and Tourism Council reporting a 4.9% growth in India's Travel and Tourism GDP contribution in 2021 — the third highest globally after China and the Philippines (WTTC, 2021). However, unregulated tourism development in ecologically and geologically sensitive landscapes such as the Himalayas carries significant risks. Infrastructure expansion without geological and ecological assessment has been shown to intensify natural hazards including landslides, flash floods, and debris flows (Cohen, 1978; Khanduri, 2017; Ramya et al., 2023; Rautela et al., 2015). The 2013 Kedarnath disaster and the 2021 Chamoli disaster — involving a rock–ice avalanche and glacial lake outburst flood (GLOF) on the Rishiganga and Dhauliganga rivers — starkly demonstrated the catastrophic potential of the intersection between natural hazard processes and inadequately planned infrastructure (Shugar et al., 2021).

Despite a growing body of literature on Himalayan hazard mapping, climate change, and land use/land cover (LULC) change in Uttarakhand, integrated district-scale studies that jointly assess ecotourism suitability, long-term climate trends, and multi-hazard exposure remain scarce for Chamoli specifically (Naithani, 2025; Singh et al., 2025; Aves et al., 2026). This study addresses that gap by applying an Analytical Hierarchy Process (AHP) integrated with Multi-Criteria Evaluation (MCE) within a GIS environment to produce a spatially explicit ecotourism suitability assessment for Chamoli district, while contextualising findings within the district's documented hazard and climate change trajectory from 1990 to 2026.

2. LITERATURE REVIEW

2.1 1990–2010 Baseline: Early Uttarakhand studies established the foundational geospatial workflow for Himalayan landscape change detection using multi-temporal Landsat imagery, supervised classification, and GIS. In Hawalbagh, Landsat TM imagery from 1990 and 2010 was classified into vegetation, agriculture, barren land, built-up land, and water, revealing increases in vegetation and built-up area alongside declines in agriculture, barren land, and water bodies (Rawat & Kumar, 2015). In the Kail watershed, Landsat TM scenes from 1990, 1999, and 2010 — classified using maximum-likelihood methods — showed increased vegetation and barren land but reduced snow cover and agriculture (Rawal et al., 2014). This phase was stronger on mapping change than on climate attribution, though later syntheses identify 1990-era imagery as the baseline for long-run comparisons in Uttarakhand (Rawat & Kumar, 2015).

2.2 2011–2020 Expansion: From 2011, the literature broadened into parallel strands: climate trend detection, hazard analysis, and district- or watershed-scale LULC studies. Dehradun Valley mapping using Landsat, LISS-III, SRTM, and Survey of India maps detected a 112.4% increase in built-up area, 3.75% forest decline, and 9.5% seasonal water decline for 2000–2009 (Tiwari & Khanduri, 2011). Bhilangana basin rainfall analysis combining IMD station data with CHIRPS and PERSIANN-CDR in Google Earth Engine showed an annual rainfall decline of 15.75 mm per decade for 1983–2008 (Banerjee et al., 2020).

The 2013 Kedarnath disaster shifted the literature toward climate-extreme and hazard coupling. Long climate series for Uttarakhand showed a significant rise in pre-monsoon air temperature after 1997, increasing June–July rainfall, covariance between monsoon rainfall and March Eurasian snow cover, and a greater likelihood of anomalous high rainfall during negative Arctic Oscillation phases (Agnihotri et al., 2017). State-scale analyses over 1955–2016 identified significant post-1986 increases in annual precipitation and temperature in Uttarakhand, rising hot extremes, declining cold extremes, and increasing precipitation indices, using modified Mann–Kendall, Sen's slope, and change-point methods (Manzoor & Ahanger, 2022).

2.3 2021–2026 Integration: Recent work is more integrated. Uttarakhand-wide studies report declining total precipitation, runoff, soil water content, and leaf area index over 1981–2020, alongside more consecutive dry days in central-western Uttarakhand, more very wet days at high elevations, warming-driven forest-fire risk, and elevation-dependent warming (Kumar et al., 2023). Future projection studies using NEX-GDDP and CORDEX-SA suggest stronger monsoon precipitation extremes and substantial warming through mid- and late-century, though projected mean precipitation direction differs by scenario and time slice (Vinodhkumar et al., 2022; Tyagi et al., 2022).

Chamoli-specific studies in this period emphasise hazard cascades and geospatial vulnerability. The 2021 Chamoli disaster was traced to the collapse of approximately 27 million m^3 of rock and glacier ice from Ronti Peak, which transformed into a highly mobile debris flow and became catastrophic when it intersected downstream hydropower infrastructure (Shugar et al., 2021). Glacial-lake mapping in Chamoli identified approximately 500 lakes, with 40.92% concentrated between 5,000 and 6,000 m elevation, reported minimum temperature increase of 0.68°C per decade, and documented built-up expansion with losses in dense forest and fallow land from 2000 to 2020 (Nautiyal et al., 2022).

2.4 Himalayan Cryosphere and Hazards: Warming in the Himalaya is strongly associated with glacier shrinkage, glacial lake growth, and higher compound hazard potential, with glacier retreat widely documented across regional syntheses (Shrestha & Aryal, 2011). Himalayan glaciers have retreated rapidly — often 10–60 m per year — increasing glacial lake number and size (Bajracharya et al., 2007). Glacial lakes and supraglacial ponds expand under glacier recession and raise GLOF risk to downstream communities and infrastructure (Bajracharya et al., 2008; Srivastava et al., 2022). The 2021 Chamoli disaster is not attributable to climate change alone, but regional warming, glacier loss, and destabilised high-mountain slopes likely increased geomorphic sensitivity (Shugar et al., 2021).

2.5 Geographic Significance: Climatic trends alter water availability, slope stability, ecosystems, and exposure of settlements and infrastructure. Temperature rise and changing rainfall rhythm are associated with adverse effects on hydrology and agriculture in Chamoli-type watersheds (Deepak, 2023). Precipitation trends are less uniform than temperature trends, so hazard derives not only from totals but from timing, intensity, and sequence of events (Shrestha & Shrestha, 2004; Khadka et al., 2023). Glacier melt can temporarily increase runoff, but long-term ice loss tends to reduce future water security (Chaulagain, 2009). High-altitude monitoring remains limited, and long-term station maintenance is needed for reliable trend detection (Khadka et al., 2023).

2.6 Hazard, Tourism, and LULC: Chamoli District

2.6.1 1990–2010 Baseline: Early literature for the 1990s and 2000s is dominated by the regional hazard setting, particularly the 1991 Uttarkashi and 1999 Chamoli earthquakes and the recognition of Uttarakhand as a seismically and geomorphologically fragile mountain state (Chauhan et al., 2025; Rautela et al., 2025). Tourism was already visible as a pressure on mountain landscapes, especially pilgrimage-based mobility and ecotourism in protected or sacred landscapes, but systematic Chamoli-specific tourism-risk studies were largely absent in this period (Shugar et al., 2021; Rawat & Semwal, 2022).

2.6.2 2011–2021 Turning Point: After the 2013 Kedarnath disaster, hazard research in Uttarakhand shifted toward rainfall-triggered cascades, infrastructure vulnerability, and the interaction between development and fragile terrain (Chauhan et al., 2025). The 2021 Chamoli disaster was analysed using satellite imagery, seismic records, numerical modelling, eyewitness videos, precipitation data, snow cover, land surface temperature, and permafrost processes (Shugar et al., 2021; Thayyen et al., 2021). These studies tied the event to a rock–ice avalanche and debris-flow cascade, while emphasising that infrastructure placement transformed a natural hazard into a major disaster (Shugar et al., 2021).

2.6.3 2022–2026 Consolidation: Recent work emphasises higher-resolution and more predictive geospatial methods. Landslide studies now use frequency ratio, Shannon entropy, MCDA, fuzzy AHP, logistic regression, Random Forest, XGBoost, geomorphons, and hybrid GIS–ML frameworks (Bhardwaj & Sarkar, 2023; Chauhan et al., 2025). Review studies argue that knowledge is increasingly available but not well translated into land-use regulation, no-build zoning, early warning, or tourism safety governance (Nautiyal et al., 2025; Aves et al., 2026).

2.7 Research Gaps and Study Positioning: The literature supports the core claim that Chamoli research is unevenly developed: hazard-specific studies are common, but integrated, site-specific, and longitudinal analyses are much thinner (Chauhan et al., 2025; Naithani, 2025). Key gaps include:

- **Tourism-site vulnerability:** Tourism risk is discussed at Himalayan scale, but comparable named-site assessments for Chamoli are absent (Ziegler et al., 2021; Sapkota et al., 2026).
- **LULC–hazard coupling:** Reviews show agricultural abandonment, forest fragmentation, and built-up growth across Uttarakhand, yet Chamoli-specific studies rarely isolate how tourism infrastructure changes land cover and alters hazard susceptibility (Aves et al., 2026; Chughtai et al., 2021).
- **Integrated climate–hazard–LULC framework:** A district-scale analysis combining long-term climate trend detection, ETCCDI/RClimDex extreme indices, hazard-activity pairing, and multi-date LULC change detection using modern machine-learning or cloud platforms is absent for Chamoli (Singh et al., 2025; Bohat et al., 2025; Aves et al., 2026).

3. Study Area: The Chamoli district is located in the Garhwal division of Uttarakhand, India, within the western Himalaya. Elevation ranges from 651 m to 7,816 m above sea level, encompassing subtropical foothills, mid-mountain forests, alpine meadows, and glaciated terrain. The district is drained by the Alaknanda and Dhauliganga rivers and encompasses the Nanda Devi National Park and Biosphere Reserve — a UNESCO World Heritage Site.

Ecotourism and Sustainable Development: Ecotourism, as defined by the International Ecotourism Society, emphasises uniting conservation, communities, and sustainable travel (International Ecotourism Society, n.d.). Scheyvens (1999) defines ecotourism as a tourism form that contributes to local community development by creating economic linkages and respecting cultural heritage while providing ecological benefits. Effective promotion of ecotourism requires integration with local agricultural practices, community participation, infrastructure development, and public education (Sharpley, 2006; Batta, 2006).

Unregulated tourism can generate negative externalities including air and noise pollution, traffic congestion, water scarcity, and infrastructure strain (Sundriyal et al., 2018). Unplanned construction that increases built-up areas and road networks without considering ecological and geological sensitivities intensifies natural hazards such as landslides (Cohen, 1978; Khanduri, 2017). Climate change and unregulated infrastructure development in seismically sensitive zones have heightened these risks (Ramya et al., 2023; Rautela et al., 2015).

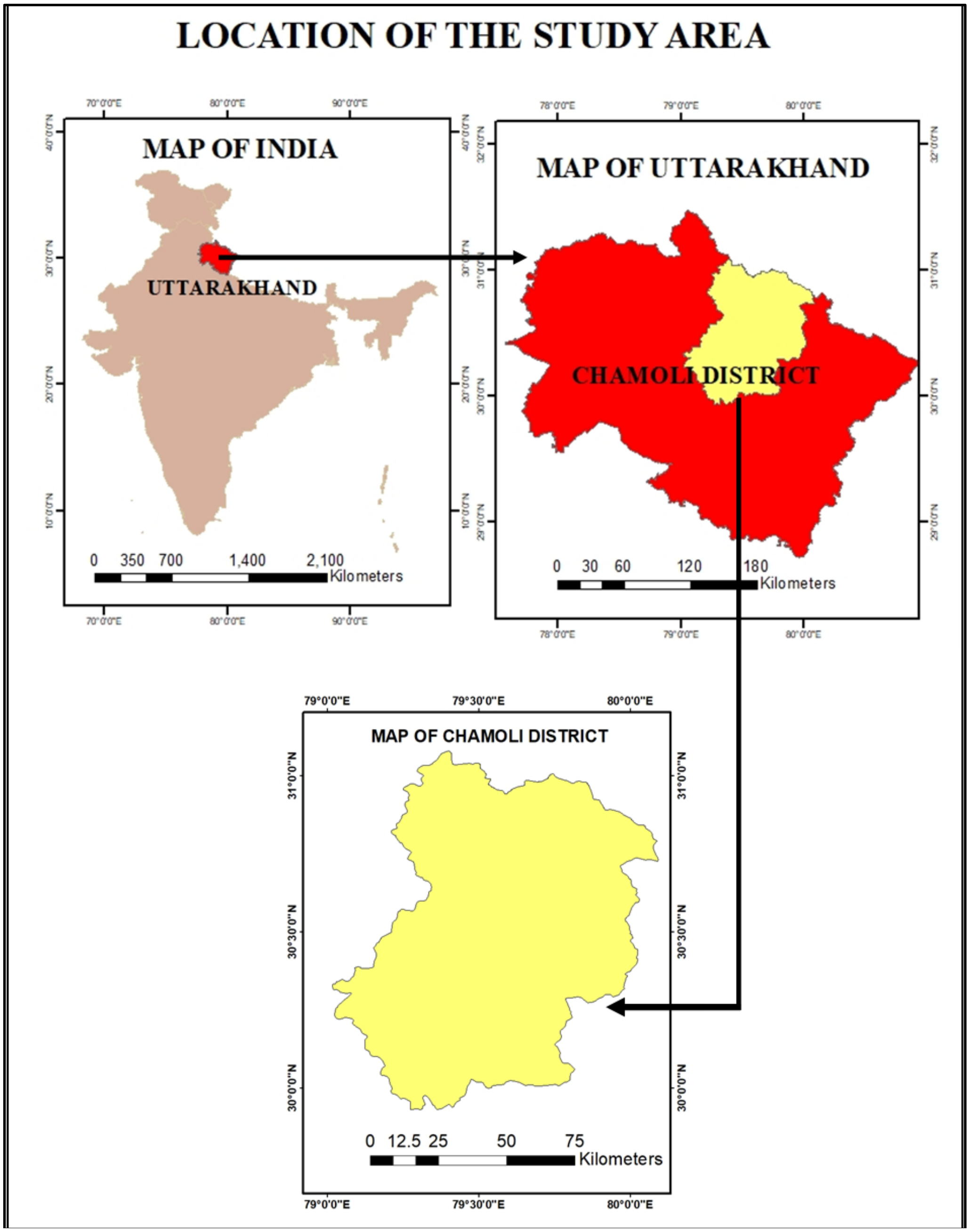

Figure 1: Location of the Study Area, Chamoli District, Uttarakhand

4. MATERIALS AND METHODS

This study utilised two main categories of data: satellite remote sensing imagery and open-source digital maps.

Table 2: Data sources and spatial resolutions

Element	Data Source	Scale/Resolution
Slope	CARTOSAT-1 DEM (ISRO Bhuvan)	30 m spatial resolution
Elevation	CARTOSAT-1 DEM (ISRO Bhuvan)	30 m spatial resolution
Touristic Hotspots	Airbus and Maxar via Google Earth Pro	Digitised vector data
River Proximity	OpenStreetMap	Digitised vector data
Road Proximity	OpenStreetMap	Digitised vector data
Village Proximity	OpenStreetMap	Digitised vector data
Protected Area Proximity	OpenStreetMap	Digitised vector data

Slope and elevation data were derived from the CARTOSAT-1 Digital Elevation Model (DEM) Version 3 R1, accessed via the Bhuvan Geo-Portal (https://bhuvan.nrsc.gov.in/). Geospatial features including road networks, village locations, surface water bodies, and protected areas were obtained from OpenStreetMap (https://www.openstreetmap.org/). Tourist hotspot locations were manually digitised using high-resolution satellite imagery from Airbus and Maxar Technologies, accessible through Google Earth Pro.

4.1 Thematic Layer Selection and Processing: Based on existing literature (Kumari et al., 2010), seven thematic layers were identified as essential for ecotourism site suitability analysis: slope, touristic hotspots, elevation, river proximity, road proximity, village proximity, and protected area proximity. Each proximity layer was reclassified to suit the requirements of ecotourism suitability modelling, transforming raw proximity values into categorised raster layers for overlay analysis.

4.2 Geospatial Database Generation

- **Slope:** Derived from the DEM using the degree method and classified into five categories (Very High, High, Moderate, Low, Very Low). Areas with steeper slopes were considered less suitable (Kumari et al., 2010).
- **Elevation:** Reclassified to reflect lower suitability at higher altitudes due to hypoxia risk (Ahmadi et al., 2015). Elevation in Chamoli ranges from 651 m to 7,816 m.
- **Touristic Hotspots:** Identified through digitisation using high-resolution imagery. Euclidean distance analysis was used to create proximity maps.
- **River, Road, Village, and Protected Area Proximity:** Extracted from OpenStreetMap, converted to raster using ArcGIS, and proximity maps were created using Euclidean distance analysis.

4.3 Analytical Hierarchy Process (AHP) for Weight Assignment: To evaluate the relative importance of each criterion, a pairwise comparison matrix was constructed following Saaty's (1980) AHP methodology. The study employed the AHP integrated with Multi-Criteria Evaluation (MCE) as proposed by Ullah and Hafiz (2014). Each of the seven criteria was compared against the others, and weights were assigned based on expert judgment and literature. The matrix was normalised and the Consistency Ratio (CR) was calculated to validate logical coherence.

The final weights were:

- Tourist Hotspot: 0.376
- Protected Area Proximity: 0.271
- Village Proximity: 0.124
- River Proximity: 0.113
- Road Proximity: 0.061
- Slope: 0.033
- Elevation: 0.019

Overlay Analysis and Suitability Classification

A weighted linear combination overlay was conducted in GIS using

E = F (S, TH, E, RP, R*d*P, VP, PAP)

Where:

- E = Ecotourism Potential
- SL = Slope
- TH = Touristic Hotspots
- RP = River Proximity
- E = Elevation
- PA = Protected Area Proximity
- RdP = Road Proximity
- VP = Village Proximity

The resulting composite map was categorized into five suitability classes: Very Low, Low, Moderate, High, and Very High. Table 3 presents the weightage assignments.

Table 3: Overlay Weightage Table

Factor	Class	Assigned Weight	Normalized Weight
Village Proximity	0–1000 m to 4000–5000 m	5 to 1	0.124
Protected Area Prox.	0–1000 m to 4000–5000 m	3 to 1 (mid-high best)	0.271
River Proximity	0–1000 m to 4000–5000 m	5 to 1	0.113
Road Proximity	0–1000 m to 4000–5000 m	5 to 1	0.061
Slope	Very Low to Very High	5 to 1	0.033

Tourist Hotspot	Very Low to Very High	5 to 1	0.376
Elevation	Very Low to Very High	2 to 1	0.019

Using the weighted overlay approach, an ecotourism suitability map was generated. The Chamoli district was categorized into five suitability zones:

- Very Low Suitability: 4.15%
- Low Suitability: 28.42%
- Moderate Suitability: 32.02%
- High Suitability: 25.75%
- Very High Suitability: 9.66%

Very High suitability areas are concentrated around the Nanda Devi range, including peaks like Hathi Parvat, Trishul Parvat, and Dronagiri Parvat. High suitability zones are mostly around the Alaknanda and Dhauliganga rivers, especially near Nanda Devi National Park. Moderate suitability zones are widely distributed across the region, while Very Low and Low suitability areas are located in inaccessible higher Himalayan regions and the southern part of the district. Seasonal variations in stream flow, such as flash floods, limit the ecotourism potential in valley regions. Notably, high to very high suitability areas are generally located around major tourist zones like Badrinath, Joshimath, Auli, and Nanda Devi National Park, recognized for their ecological and cultural significance.

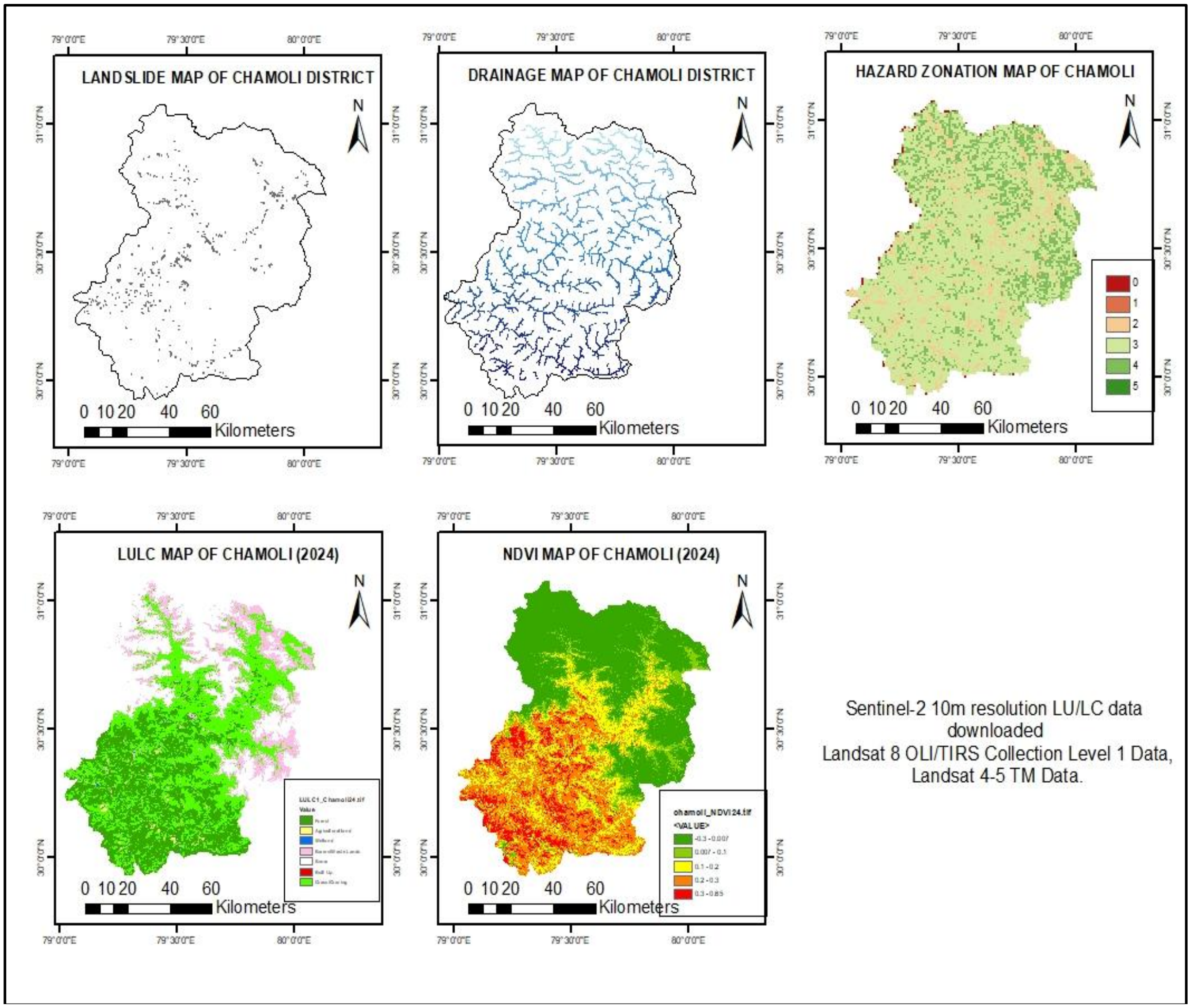

Figure 2: Landslide, Drainage, Hazard Zonation, LULC, and NDVI map of Chamoli district

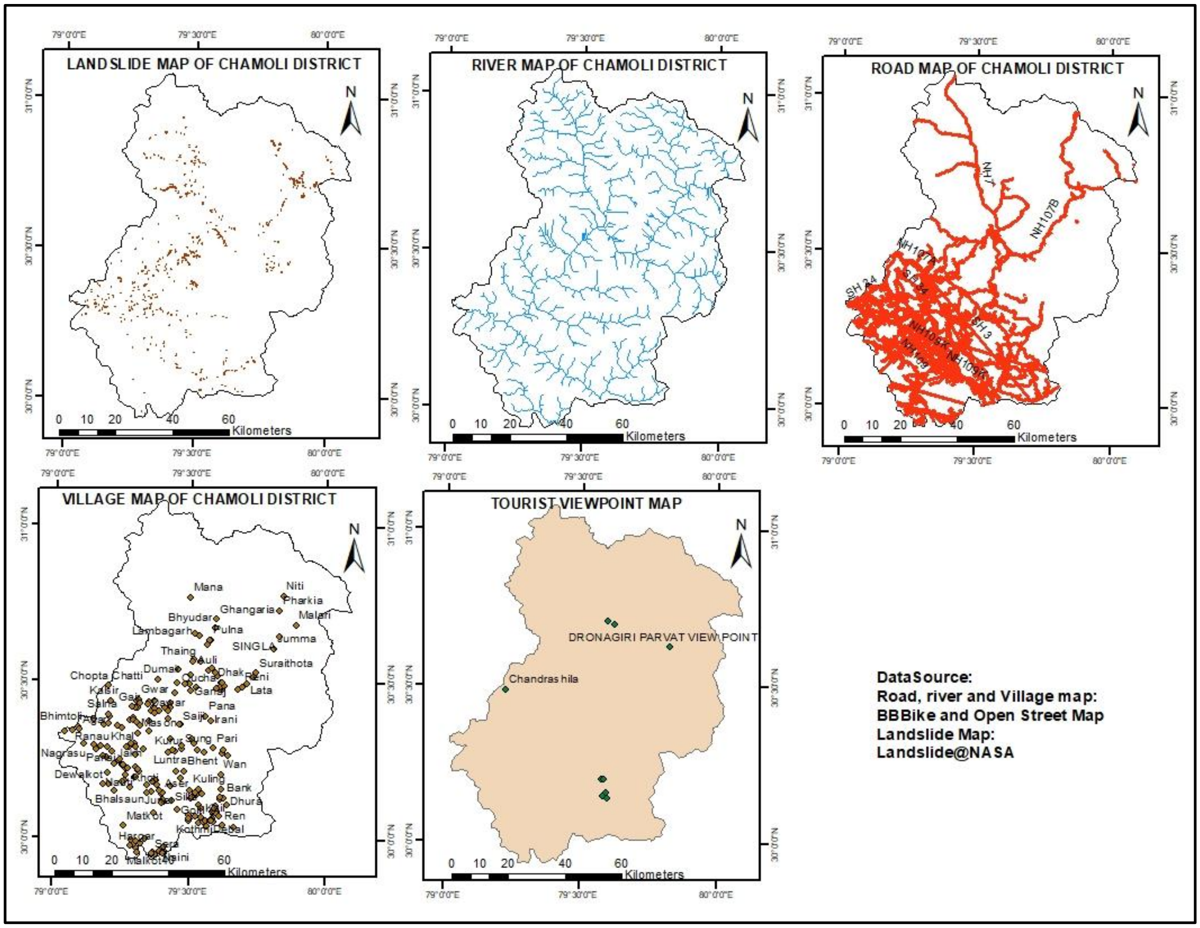

Figure 3: Landslide, Drainage, Road, Village, and Tourist Viewpoint map of Chamoli district

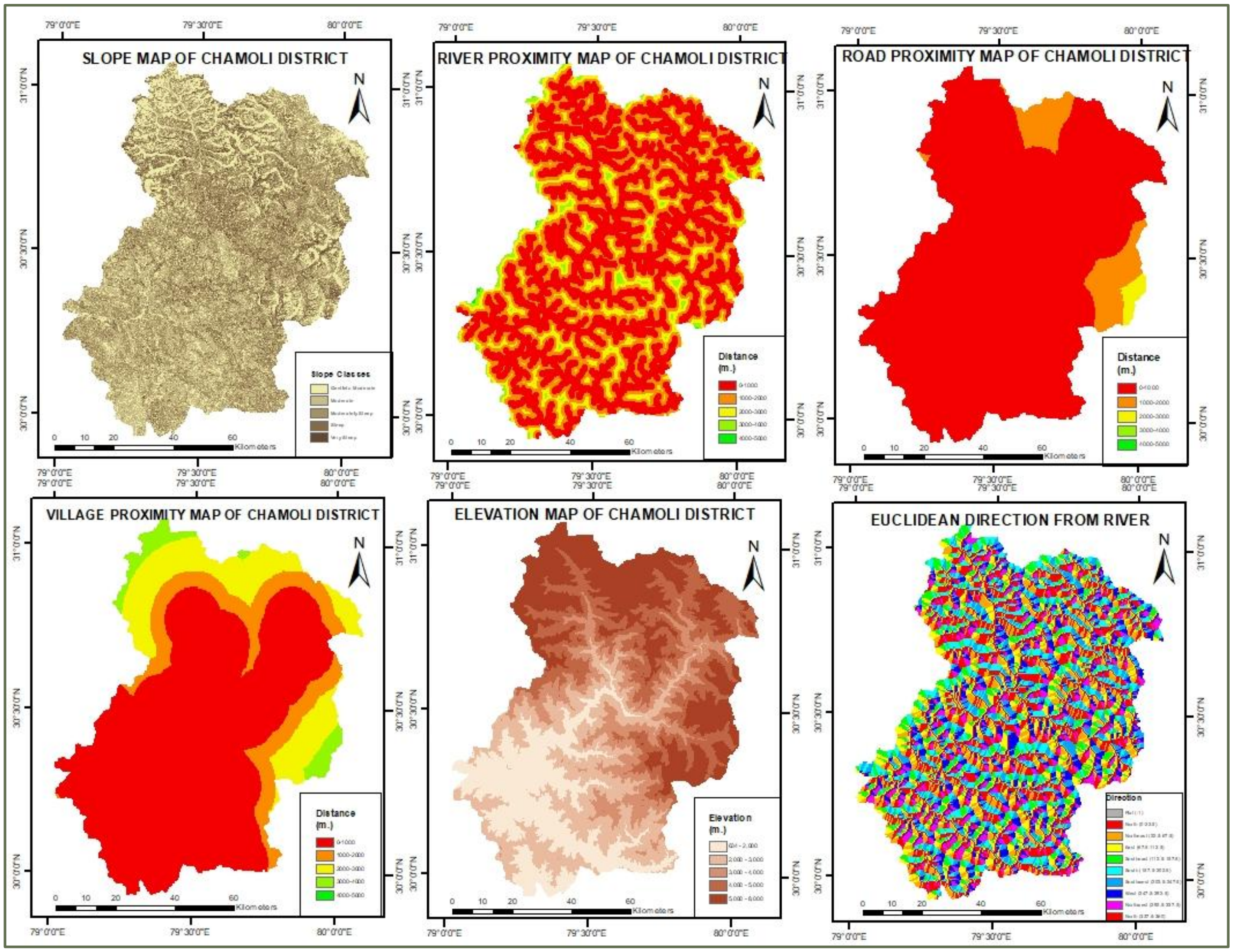

Figure 4: Slope, River Proximity, Road and Village Proximity, Elevation, and Euclidean Direction from River map of Chamoli district

5. RESULTS AND DISCUSSION

5.1 AHP Weight Assignment and Consistency Validation: The AHP pairwise comparison yielded a Consistency Ratio of CR = 0.096/1.35 ≈ 0.07, well below the acceptable threshold of 0.10, confirming the logical coherence and reliability of the expert judgments (Saaty, 1980).

Table 4. AHP Normalised weights by criterion

Criterion	Normalised Weight	Rank
Tourist Hotspot	0.376	1st
Protected Area Proximity	0.271	2nd
Village Proximity	0.124	3rd
River Proximity	0.113	4th
Road Proximity	0.061	5th
Slope	0.033	6th
Elevation	0.019	7th

Tourist Hotspots emerged as the dominant factor (37.6%), reflecting the fundamental role of existing visitation patterns in defining ecotourism potential. Protected Area Proximity ranked second (27.1%), underscoring the ecological value of conservation zones as anchor attractions for ecotourism. Together, these two criteria account for 64.7% of the composite suitability score, indicating that ecological significance and established tourism infrastructure are the primary drivers of ecotourism viability in Chamoli district. Physical terrain parameters — Slope (0.033) and Elevation (0.019) — contributed the least to the composite index, though their role as hard constraints at extreme values remains operationally significant.

5.2 Overlay Analysis and Ecotourism Suitability Zonation
A weighted linear combination overlay was conducted in GIS using the formula:

E = F (SL, TH, E, RP, RdP, VP, PAP)

The resulting composite map was categorised into five suitability classes.

Table 5: Ecotourism suitability zonation results

Suitability Class	Area Coverage (%)	Spatial Characteristics
Very High	9.66%	Nanda Devi range — Hathi Parvat, Trishul Parvat, Dronagiri Parvat
High	25.75%	Alaknanda & Dhauliganga river corridors; Nanda Devi National Park buffer
Moderate	32.02%	Widely distributed across mid-elevation zones
Low	28.42%	Southern district; partially accessible mid-Himalayan zones
Very Low	4.15%	Inaccessible high-altitude Himalayan terrain

Approximately 67.4% of the district falls within Moderate to Very High suitability classes, indicating substantial ecotourism potential across the region. Very Low suitability accounts for only 4.15% of the area, confined to extreme high-altitude zones where physical inaccessibility and hypoxia risk preclude sustainable tourism activity.

5.3 Spatial Correlation with Major Tourism Nodes
A strong spatial correspondence was observed between High and Very High suitability zones and the district's principal tourism destinations:

- **Badrinath** — One of the Char Dham pilgrimage sites; high cultural and religious tourism significance.
- **Joshimath** — Gateway to Auli ski resort and Valley of Flowers National Park.
- **Auli** — Premier winter sports and alpine meadow ecotourism destination.
- **Nanda Devi National Park** — UNESCO World Heritage Site and biodiversity hotspot.

This spatial alignment validates the model's performance and confirms that the AHP-weighted overlay captures the multi-dimensional nature of ecotourism suitability effectively.

5.4 Hazard Risk Considerations: Seasonal hydrological variability — particularly flash floods in valley regions — was identified as a significant constraint on ecotourism potential in river-proximate zones. Despite high scenic and ecological values, these areas face periodic inaccessibility and safety risks that limit year-round ecotourism viability. This finding is consistent with the documented vulnerability of Chamoli district to hydro-meteorological hazards, including the 2021 GLOF on the Rishiganga and Dhauliganga rivers (Shugar et al., 2021).

5.5 Ecotourism Potential vs. Hazard Risk: A Spatial Paradox: A critical finding of this study is the spatial overlap between high ecotourism suitability and elevated natural hazard risk. The river corridors of the Alaknanda and Dhauliganga — classified as High suitability zones — are simultaneously among the most hazard-prone areas of the district. Unregulated tourism development along these corridors' risks amplifying existing vulnerabilities through:

- **Infrastructure strain:** Road construction on unstable slopes increases landslide susceptibility (Cohen, 1978; Khanduri, 2017).
- **Hydrological disruption:** Impervious surface expansion in catchment areas accelerates runoff and flash flood risk.
- **Seismic sensitivity:** Construction in seismically sensitive zones without geological assessment heightens disaster risk (Ramya et al., 2023; Rautela et al., 2015).

This paradox underscores the imperative of hazard-integrated ecotourism planning — where suitability maps are overlaid with hazard zonation maps (landslide susceptibility, flood inundation zones, seismic microzonation) to identify areas where development should be restricted, regulated, or designed to hazard-resilient standards.

5.6 The Role of Community Proximity in Sustainable Ecotourism: Village Proximity ranked third in the AHP weighting (0.124), reflecting the importance of local communities as both beneficiaries and stewards of ecotourism development. Sustainable ecotourism frameworks emphasise that tourism benefits must flow to local communities to ensure long-term conservation incentives and cultural authenticity (International Ecotourism Society, n.d.; Scheyvens, 1999). Villages proximate to High and Very High suitability zones — particularly those near Badrinath, Joshimath, and Nanda Devi National Park — represent strategic nodes for community-based ecotourism initiatives. Integration with local agricultural practices and traditional knowledge systems can enhance both the ecological and cultural dimensions of the ecotourism product (Sharpley, 2006; Batta, 2006).

5.7 Physical Terrain as a Constraint: The relatively low weights assigned to Slope (0.033) and Elevation (0.019) do not diminish their operational significance as hard constraints. At extreme values — slopes exceeding 45° and elevations above approximately 4,000–5,000 m — these factors effectively exclude areas from ecotourism suitability regardless of other criteria scores. The reclassification of elevation to reflect hypoxia risk (Ahmadi et al., 2015) is particularly relevant given Chamoli's elevation range of 651 m to 7,816 m. The 4.15% Very Low suitability area corresponds precisely to these extreme terrain zones.

5.8 Methodological Strengths and Limitations: The AHP-GIS integrated approach offers transparency, reproducibility, and the capacity to integrate heterogeneous spatial data at a consistent 30-metre resolution. The CR value of 0.07 confirms internal consistency.

However, several limitations warrant acknowledgement:

- **Static snapshot:** The model reflects current conditions and does not account for dynamic changes in land use, climate, or tourism demand.
- **Data resolution constraints:** The 30-metre CARTOSAT-1 DEM may underrepresent micro-topographic features relevant to local-scale hazard assessment.
- **Absence of socioeconomic layers:** Factors such as land tenure, community willingness, and economic infrastructure capacity were not incorporated.
- **Seasonal variability:** A single composite map cannot capture the seasonal fluctuation in suitability driven by monsoon hydrology and winter snowpack.

5.9 Implications for Tourism Management and Policy: The suitability zonation has direct policy implications for the Chamoli district administration and the Uttarakhand Tourism Development Board:

- **Zoning regulations:** Very High and High suitability zones should be designated as priority ecotourism development areas, subject to carrying capacity assessments and environmental impact evaluations.
- **Hazard-sensitive infrastructure planning:** Road and accommodation development in river valley zones should be governed by geological and hydrological risk assessments.
- **Seasonal management:** Flash flood seasonality (June–September monsoon period) necessitates temporal zoning of ecotourism activities in river-proximate areas.
- **Conservation finance:** Revenue from ecotourism in Very High suitability zones should be channelled into protected area management and community livelihood programmes.
- **Climate adaptation:** Given the documented acceleration of glacial retreat and GLOF risk in the Chamoli-Nanda Devi region, long-term ecotourism planning must incorporate climate change projections into hazard risk assessments.

6. CONCLUSION

This study applied an AHP-integrated Multi-Criteria Evaluation (MCE) approach within a GIS environment to assess ecotourism suitability across Chamoli district, Uttarakhand — a high-altitude Himalayan region of exceptional ecological and cultural significance. Seven thematic criteria were evaluated: Tourist Hotspots, Protected Area Proximity, Village Proximity, River Proximity, Road Proximity, Slope, and Elevation. The AHP weight assignment confirmed Tourist Hotspots (0.376) and Protected Area Proximity (0.271) as the dominant determinants of ecotourism suitability, together accounting for nearly 65% of the composite index. A Consistency Ratio of 0.07 validated the logical coherence of the pairwise comparison matrix.

The resulting suitability map revealed that approximately 35.4% of Chamoli district falls within High or Very High ecotourism suitability zones, concentrated around the Nanda Devi range, the Alaknanda and Dhauliganga river corridors, and major tourism nodes including Badrinath, Joshimath, Auli, and Nanda Devi National Park. Moderate suitability covers the largest share (32.02%) of the district, while Very Low suitability is restricted to 4.15% of the area in extreme high-altitude terrain. Critically, the study identified a spatial paradox between high ecotourism potential and elevated natural hazard risk — particularly in river valley zones susceptible to flash floods, landslides, and seismic activity. This overlap underscores the urgent need for hazard-integrated ecotourism planning that balances development opportunity with disaster risk reduction.

The findings provide a scientifically grounded spatial framework for sustainable ecotourism planning in Chamoli district, with direct implications for zoning regulations, infrastructure siting, community engagement strategies, and seasonal tourism management. Future work should incorporate dynamic hazard layers, socioeconomic variables, and climate change projections to refine the suitability model and strengthen its applicability to long-term landscape management and tourism governance in this ecologically sensitive Himalayan region.

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