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Socioeconomic consequences of landslide events in Uttarakhand, India: linking landslide susceptibility with vulnerability and disaster risk management

Pramod Kumar Anthwal[1]*, Naveen Kumar[2], Shilpa Dhiman[3], Neelratan Singh[4]

[1]Department of Geology, Pt. Lalit Mohan Sharma SDSUV Campus Rishikesh- 249201
Uttarakhand, India
[2]Department of Geography, Chaman Lal Mahavidhyalaya Landhaura Haridwar-247664
Uttarakhand, India
[3]Department of Geology, Govt. PG. College, Dharamshala- 176215
Himachal Pradesh, India
[4]CSIR-CIMFR Roorkee Research Center, Roorkee, Uttarakhand, India

*Corresponding author e-mail: pramod.77anthwal@gmail.com

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Abstract. Landslides represent a recurrent and devastating natural hazard in the Himalayan state of Uttarakhand, India, with their spatial occurrence and impacts governed by varying degrees of landslide susceptibility shaped by terrain, geology, and climatic triggers. Beyond immediate physical damage, recurring landslide events impose severe and long-lasting social and economic consequences on vulnerable mountain communities. This study examines the impacts of landslides in Uttarakhand by systematically linking GIS-based landslide susceptibility zonation with household-level indicators of income loss, infrastructure damage, and displacement. Geographic Information Systems were employed to delineate relative landslide susceptibility zones by integrating key conditioning factors, including slope gradient, lithology, land use and land cover, drainage density, rainfall intensity, and proximity to fault zones, and a weighted overlay approach was used to classify the terrain into low-, moderate-, and high-susceptibility zones, representing relative slope failure propensity rather than probabilistic hazard estimation. Primary household data collected from settlements within these zones were analysed using one-way ANOVA, Chi-square tests, and correlation analysis to evaluate differential impacts. The results indicate that households residing in high-susceptibility zones experience substantially greater economic losses, with average income reductions of approximately 30 percent and infrastructure damage affecting nearly 60 percent of critical assets, often leading to restricted accessibility and community isolation. A strong positive correlation between infrastructure damage and income loss highlights how repeated landslide impacts entrench households in cycles of economic stress and displacement. The findings highlight the importance of integrating spatial susceptibility assessments with household-level impact analysis to inform disaster risk reduction and resilience planning, emphasizing the need for improved infrastructure design, strengthened community awareness, and periodic updating of GIS-based landslide susceptibility assessments to reduce long-term vulnerability in landslide-prone regions of Uttarakhand.

Keywords: infrastructure damage, Geographic Information Systems (GIS), disaster preparedness, displacement rates.

1. Introduction

Landslides are a dominant geomorphic process in mountainous regions, where steep slopes, fragile terrain, and complex geological settings generate inherent instability (Alam et al., 2024). In the Himalayan state of Uttarakhand, rugged topography, monsoon-dominated rainfall, and active tectonics interact to produce widespread landslide activity (Batar & Watanabe, 2021; Bhardwaj & Sarkar, 2024), posing persistent threats across the state (Tiwari et al., 2022; Das et al., 2022). Beyond immediate physical damage, recurrent slope failures disrupt local economic and social systems through damage to critical infrastructure, restricted access to essential services, and loss of income-generating assets, particularly in rural areas where agricultural land and transport networks are highly exposed (Dikshit et al., 2020; Fleuchaus et al., 2021; Froude & Petley, 2018; He et al., 2024; Ishack et al., 2021). Consequently, household displacement occurs frequently, weakening social networks and increasing long-term economic insecurity (He et al., 2024; Ishack et al., 2021).

Landslide occurrence in Uttarakhand is further intensified by deforestation, unplanned construction, road expansion, and rapid urbanization, operating in combination with intense monsoonal rainfall and seismic activity (Joshi et al., 2020; Kainthura & Sharma, 2022; Kansal & Singh, 2024; Khali et al., 2023). As a result, landslide impacts are unevenly distributed, disproportionately affecting marginalized and rural communities that experience greater economic losses and longer recovery periods (Upadhyay, 2024; Kumar et al., 2024).

Landslide susceptibility mapping facilitates the identification of areas prone to slope failure based on terrain characteristics, rainfall patterns, and historical landslide records (Kumar et al., 2022; Meghanadh et al., 2022). Advances in Geographic Information Systems (GIS) have substantially improved the spatial resolution and analytical capacity of susceptibility assessments, enabling delineation of high-risk zones for land-use planning and mitigation measures (Naik & Palakuzhiyil, 2024; Verma et al., 2024; Parkash, 2015). However, such approaches remain analytically incomplete unless household-level economic exposure, income dependence, population vulnerability, and displacement risks are explicitly incorporated (Paul et al., 2024; Pundir, 2022).

Although considerable progress has been made in susceptibility mapping and early warning systems, relatively few studies have systematically integrated GIS-based susceptibility zonation with primary, household-level economic and displacement data to evaluate differentiated impacts across hazard zones. Existing research largely emphasizes hazard inventories or spatial modeling, leaving a critical gap in understanding how variations in landslide susceptibility translate into measurable household-level consequences. This study addresses this gap by statistically linking landslide susceptibility zones with observed outcomes related to income loss, infrastructure damage, and household displacement.

Accordingly, this paper examines household-level economic and displacement impacts of landslides in selected areas of Uttarakhand, providing evidence-based insights to inform disaster preparedness, mitigation strategies, and resilience-building in landslide-prone mountain communities.

1.1 Significance of the Study

This study provides empirically grounded insights into household income loss, infrastructure damage, and displacement associated with landslides across varying susceptibility zones in Uttarakhand. By integrating GIS-based landslide susceptibility mapping with robust statistical analysis, the study advances understanding of how spatial hazard patterns translate into quantifiable household-level impacts.

The findings offer a reliable evidence base for disaster preparedness, policy formulation, and resource allocation, particularly in vulnerable rural and mountainous communities. Identification of high-susceptibility areas and quantification of associated economic and social losses support targeted disaster risk reduction strategies aimed at reducing long-term vulnerability and strengthening community resilience in landslide-prone regions of Uttarakhand.

1.2 Research Objectives

The primary purpose of this study is to evaluate the household-level impacts of landslides across different susceptibility zones in Uttarakhand, with particular emphasis on income loss, infrastructure damage, and displacement. The specific objectives are to:

1. Create a landslide susceptibility map of Uttarakhand by classifying regions into low-, moderate-, and high-susceptibility zones using GIS-based techniques.
2. Assess the extent of infrastructure damage and associated economic losses experienced by communities located within landslide-susceptible zones.
3. Statistically evaluate whether household income loss differs significantly across susceptibility zones using one-way ANOVA.
4. Examine the association between susceptibility zones and displacement rates using Chi-square tests, and assess the correlation between infrastructure damage and income loss.

5. Propose targeted disaster risk reduction and community resilience strategies based on integrated findings from susceptibility mapping and household-level impact analysis.

1.3 Research Hypotheses

H1: Mean household income loss differs significantly across low, moderate, and high susceptibility zone.

H2: Household displacement is significantly associated with landslide susceptibility level.
H3: Infrastructure damage is positively correlated with household income loss in landslide-affected areas.

2. Study Area

The study area comprises the state of Uttarakhand, located in northern India within the central Himalayan belt. The region is characterized by complex physiography, including deeply incised valleys, steep ridges, escarpments, and hill settlements that exhibit varying degrees of exposure to slope instability. Uttarakhand displays pronounced ecological and climatic heterogeneity, ranging from densely populated urban hill towns to sparsely inhabited rural and remote mountain settlements.

This spatial and demographic diversity provides a robust framework for examining both the physical drivers of landslide susceptibility and the differentiated household-level impacts across contrasting settlement types. Variations in terrain conditions, settlement density, and accessibility enable a comprehensive assessment of regional susceptibility patterns and supports the formulation of location-specific risk mitigation and disaster management strategies (Uttarakhand State Disaster Management Authority [USDMA], 2021).

Figure 1 illustrates the geographic extent of the study area. The map was prepared in GIS by separately outlining Uttarakhand from the national map of India to accurately present its geographic setting and administrative boundaries.

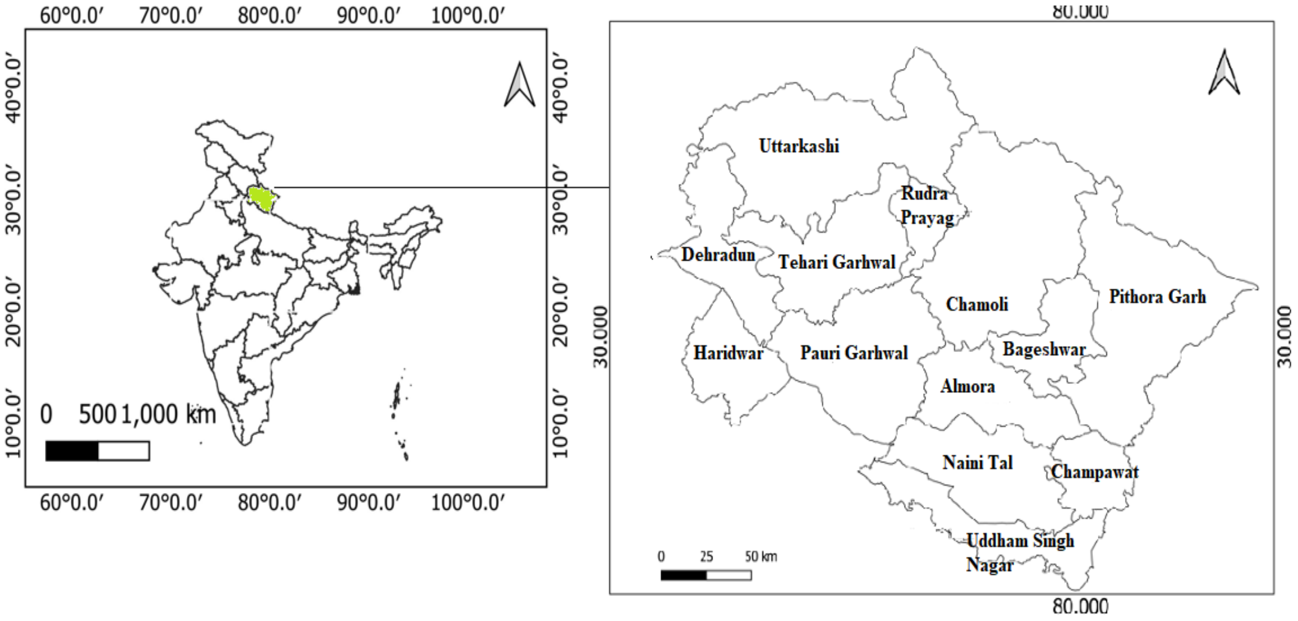

Figure 1. Study area Map (Author generated)

Note: The political boundary of India in this map strictly follows the official Survey of India boundary, including the full representation of Jammu & Kashmir as per Government of India guidelines.

3. Material and Methods

This section describes the research design, data collection procedures, and analytical methods used to assess the socioeconomic impacts of landslides in Uttarakhand. Each methodological step is explicitly linked to the study objectives to ensure coherence and reproducibility.

3.1 Research Design

A quantitative research design was adopted to evaluate landslide susceptibility and its socioeconomic impacts in Uttarakhand. Spatial analysis using GIS and statistical analysis using SPSS were employed to:

I. Identify areas with varying landslide susceptibility (Objective 1).
II. Quantify household-level impacts, including income loss, infrastructure damage, and displacement
III. (Objectives 2–3).
IV. Examine statistical relationships between susceptibility zones and observed socioeconomic impacts (Objective 4).

3.2 Data Collection

Data collection integrated primary and secondary sources to document landslide occurrence, hazard characteristics, and associated household-level impacts across Uttarakhand. Secondary data were compiled through a systematic review of historical landslide inventories, government reports, and peer-reviewed literature related to landslide processes, hazard assessment, and regional socioeconomic conditions. These datasets covered the period from 2000 to 2023, enabling the analysis to capture both long-term patterns and recent developments. The secondary information provided the baseline required for landslide hazard mapping and directly supported Objective 1 of the study.

Primary data were collected through structured questionnaires and semi-structured interviews conducted in landslide-affected communities. This approach facilitated the collection of first-hand information directly from affected households. Purposive sampling was adopted to ensure representation across varying levels of landslide exposure, with households selected from low, moderate, and high hazard zones. In total, 300 households were surveyed, comprising 100 households each from Dehradun (low hazard), Chamoli (moderate hazard), and Uttarkashi (high hazard). On average, four adult members participated per household, resulting in approximately 1,200 respondents. Details of the respondent profile are provided in Supplementary Table 1. These primary data address Objectives 2 and 3 of the study.

Landslide hazard mapping was carried out using a GIS-based analytical framework. Although the study objectives refer to "landslide susceptibility mapping," the adopted methodology aligns more closely with a hazard assessment approach by integrating terrain susceptibility with key triggering factors. Spatial datasets, including topography, slope, geology, land use and land cover, and rainfall, were obtained from authoritative sources such as the Survey of India (SOI), Geological Survey of India (GSI), and the India Meteorological Department (IMD). All thematic layers were processed at a working scale of 1:50,000, consistent with SOI and GSI base maps, and the final hazard map was generated at the same scale to ensure suitability for district-level landslide zonation.

Permanently snow-covered, glaciated, and uninhabited high-altitude areas were excluded using GIS masking to restrict the analysis to settlement-relevant regions. Each causative parameter was assigned a weight based on its relative contribution to landslide occurrence, as determined through literature review and expert judgment. Weighted overlay analysis was applied to generate a composite Landslide Hazard Index (LHI), which was classified into low, moderate, and high hazard zones using Jenks' natural breaks method to reflect inherent spatial clustering patterns. Four representative districts—Dehradun, Chamoli, Pithoragarh, and Uttarkashi, were included at the mapping stage to capture physiographic variability. While Dehradun was retained in statewide mapping for spatial continuity, comparative statistical analyses focused on Chamoli, Pithoragarh, and Uttarkashi, representing the Higher Himalayan terrain.

Historical landslide inventory data from 2000 to 2023 were used to validate the LHI, confirming that the majority of recorded landslide events coincided with high hazard zones. Supplementary Table 2 provides the compiled dataset for the representative districts, while Supplementary Table 3 details the parameters, classification criteria, and methodological workflow adopted. It is important to note that this study does not estimate landslide event probability; rather, it presents a GIS-based hazard susceptibility assessment derived from terrain, geological, and rainfall factors and validated against historical records. Field-based verification is recommended for future investigations.

Household-level impacts were assessed using primary survey data focusing on income loss, infrastructure damage, and displacement. Infrastructure damage was estimated through visual grading of structures into minor (<25%), moderate (25–50%), or severe (>50%) damage categories, supported by field photographs and cross-checked with local disaster management records. Only households located in inhabited and exposure-prone areas were included to avoid overestimation of impacts. Monetary losses were estimated based on self-reported pre-event household income combined with observed structural damage. The sampling strategy and validation procedures were designed to ensure reliable and representative insights into community-level landslide impacts across the selected districts.

3.3 Data Analysis

Data analysis was performed to assess the socioeconomic effects of landslides using **statistical software (SPSS)**. The following methodologies were employed:

Descriptive Statistics: Descriptive statistics were computed to summarize socioeconomic impacts across different susceptibility zones. Measures such as means, medians, and percentages were calculated for income loss, infrastructure damage, and displacement rates to provide an overview of data distribution and central tendencies.

ANOVA (H_1) : One-way ANOVA was applied to compare mean income losses across Low, Moderate, and High susceptibility zones, to determine if differences among zones are statistically significant, reflecting the influence of susceptibility level on economic impacts.

Chi-Square Tests (H_2): Chi-square tests were conducted to examine the association between susceptibility zone classification and displacement rates, indicating whether higher susceptibility is linked to greater household displacement.

Correlation Analysis (H_3): Pearson's correlation coefficients were calculated to evaluate the relationship between income loss and infrastructure damage, providing insights into the interactions among variables.

3.4 Alignment of Methodology with Study Objectives

To ensure clarity, Table 3 shows the alignment of each methodological step with the specific research objectives:

Table 3. Alignment of Methods with Study Objectives

Study Objective	Methodological Step	Data / Analysis Used
Objective 1: Identify areas with varying landslide susceptibility	GIS-based weighted overlay, parameter selection, classification into Low/Moderate/High zones	Susceptibility mapping data (GIS)
Objective 2: Quantify household-level income loss	Structured questionnaires, purposive sampling of households	Primary survey data
Objective 3: Quantify household-level infrastructure damage and displacement	Household interviews, field observation, cross-verification with disaster management records	Primary survey data
Objective 4: Examine statistical relationships between susceptibility and socioeconomic impacts	Descriptive statistics, ANOVA, Chi-square, correlation analysis	SPSS analysis of survey and GIS data

This alignment ensures that all methodological steps are explicitly tied to the study objectives, providing a coherent framework for analyzing the socioeconomic impacts of landslides in Uttarakhand.

4. Result and Discussion

4.1 Spatial Distribution of Landslide Susceptibility

The landslide susceptibility mapping of Uttarakhand reveals distinct spatial patterns across the state, categorized into low, moderate, and high-susceptibility zones. Table 1 presents the district-wise distribution of susceptibility levels. Dehradun exhibits the largest proportion of low-susceptibility terrain (60%), whereas Chamoli and Uttarkashi contain higher shares of moderate (50% in Chamoli) and high-susceptibility areas (45% in Uttarkashi), reflecting greater potential exposure of populations and infrastructure to landslide hazards. Pithoragarh displays a relatively balanced pattern, with 55% of its area in low susceptibility and 45% in moderate susceptibility zones.

Table 1. District-wise distribution of landslide susceptibility across Uttarakhand. Dehradun is shown for contextual mapping; only Higher Himalayan districts Chamoli, Pithoragarh, and Uttarkashi are used in statistical and comparative analyses.

District	Low-Susceptibility Area (%)	Moderate-Susceptibility Area (%)	High-Susceptibility Area (%)
Dehradun	60	40	30
Chamoli	40	50	40
Pithoragarh	55	45	30
Uttarkashi	45	40	45

Source: Primary household survey data (2023) and GIS-based landslide hazard zonation (author-generated).

Note: Landslide susceptibility zones were derived using GIS-based weighted overlay analysis. Moderate- and high-susceptibility zones partially overlap in transitional terrain. Therefore, percentages represent spatial occurrence frequencies rather than mutually exclusive area proportions and are not intended to sum to 100%.

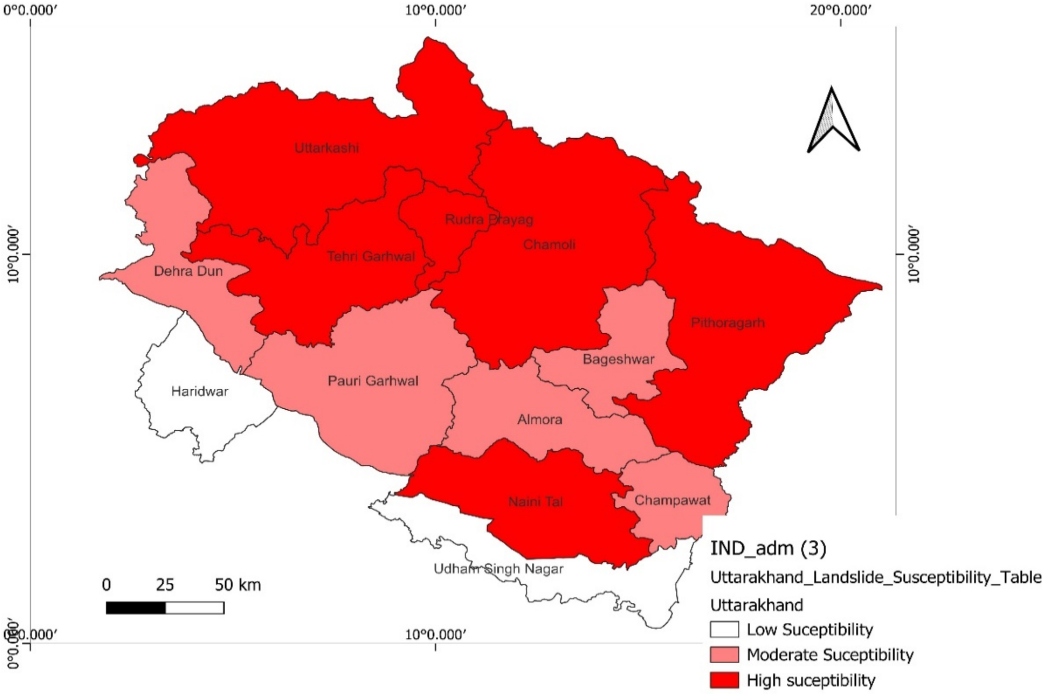

Figure 2. Landslide susceptibility mapping of Uttarakhand (author-generated using GIS datasets at 1:50,000 scale; standards per USDMA 2021). Dehradun included only for spatial reference; comparative analysis restricted to Chamoli, Pithoragarh, and Uttarkashi (Higher Himalaya).

Figure 2 presents the spatial distribution of susceptibility zones. The map highlights that high-susceptibility terrain is concentrated in the Higher Himalayan districts, particularly Chamoli and Uttarkashi, where steep slopes, fragile geology, and recurrent landslides contribute to elevated potential impacts. Dehradun, in contrast, is characterized by lower-altitude foothills with predominantly low-susceptibility areas, though localized slope instability results in patches of moderate and high susceptibility.

The spatial patterns closely follow physiographic gradients, with high-susceptibility zones coinciding with steep relief and fragile lithology, consistent with previous studies indicating that geomorphic characteristics strongly influence hazard potential (Goel et al., 2020; Thakur et al., 2021). Moderate-susceptibility zones, often transitional areas, exhibit both topographic and anthropogenic influences, highlighting the role of settlement patterns and infrastructure development in shaping landslide susceptibility.

These findings underscore the value of susceptibility mapping for hazard awareness and prioritization of interventions. High-susceptibility districts such as Uttarkashi and Chamoli can be prioritized for early warning systems, community preparedness programs, and targeted mitigation measures, while moderate- and low-susceptibility areas may benefit from localized interventions such as slope stabilization and infrastructure reinforcement.

Overall, the combination of district-level statistics (Table 1) and spatial representation (Figure 2) provides a robust framework for understanding landslide hazard distribution and identifying areas where mitigation efforts can be most effectively focused, without conflating hazard with risk.

4.2 Socioeconomic Impacts across Landslide Susceptibility Zones

Across the Higher Himalayan districts of Chamoli, Pithoragarh, and Uttarkashi, the socioeconomic impact assessment reveals a clear intensification of household-level losses with increasing landslide susceptibility. Data from Dehradun are included solely to provide statewide context and were therefore excluded from statistical comparisons. A comparative overview of income loss, infrastructure damage, and displacement across susceptibility categories is presented in **Table 2**, which summarizes household-level impacts across representative districts. Overall, households located in higher susceptibility zones experienced markedly greater economic stress, highlighting the disproportionate vulnerability of communities residing in landslide-prone environments. This spatial pattern is consistent with previous studies from the Himalayan region demonstrating that elevated hazard exposure significantly amplifies livelihood insecurity (Petley et al., 2007; Dahal & Hasegawa, 2008).

Table 2. Socioeconomic impacts of landslides across susceptibility zones in Uttarakhand (income loss, infrastructure damage, and displacement rates)

Household ID	**District**	**Zone Type**	**Income Loss (INR)**	**Infrastructure Damage (%)**	**Displacement (Yes/No)**
101	Dehradun	Low Susceptibility	12000	15	No
102	Chamoli	Moderate Susceptibility	30000	55	Yes
103	Uttarkashi	High-Risk	60000	65	Yes

Source: Primary household survey data (2023) and GIS-based landslide hazard zonation (author-generated).

Note: Dehradun values are presented for contextual reference only they were not included in ANOVA or correlation analyses.

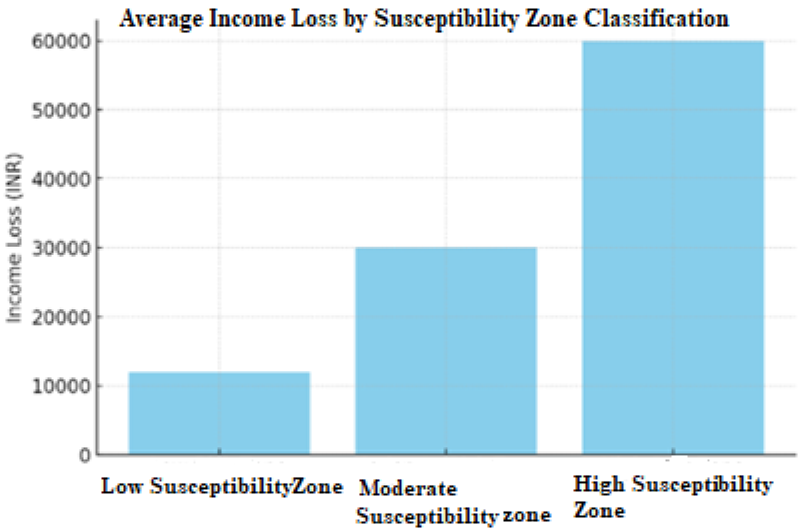

Figure 3. Average income loss (in INR) observed across low, moderate, and high landslide susceptibility zones in Uttarakhand.

The relationship between landslide susceptibility and household income loss is further illustrated in **Figure 3**, which depicts the progressive increase in average income losses from low- to high-susceptibility zones. Rather than reflecting isolated economic shocks, the observed gradient indicates a systematic association between increasing hazard intensity and declining household financial stability. Such patterns reinforce earlier findings that recurrent landslide activity in mountainous regions compounds livelihood insecurity and contributes to persistent poverty cycles (Petley et al., 2007; Sudmeier-Rieux et al., 2019).

Beyond income-related impacts, infrastructure damage exhibited a pronounced upward trend across susceptibility zones. A synthesized summary of infrastructural damage levels and displacement rates across susceptibility categories is provided in **Table 3**. While households in low-susceptibility areas reported relatively limited structural impacts, damage levels in high-susceptibility zones were substantially higher, affecting not only residential buildings but also critical infrastructure such as roads, utilities, and water supply systems. Damage of this magnitude extends beyond immediate physical loss and undermines the functional capacity of communities. As noted by Martha et al. (2022), repeated infrastructure damage in landslide-prone settings often results in cumulative vulnerability, progressively eroding both economic capital and adaptive capacity.

Table 3. Summary of Socioeconomic Impacts across Landslide Susceptibility Zones in Uttarakhand

Zone	Average Income Loss (INR)	Infrastructural Damage (%)	Displacement Rate (%)
Low-Susceptibility Zone	12000	20	10
Moderate-Susceptibility Zone	30000	45	20
High-Susceptibility Zone	60000	70	45

Source: Primary household survey data (2023) and GIS-based landslide hazard zonation (author-generated).

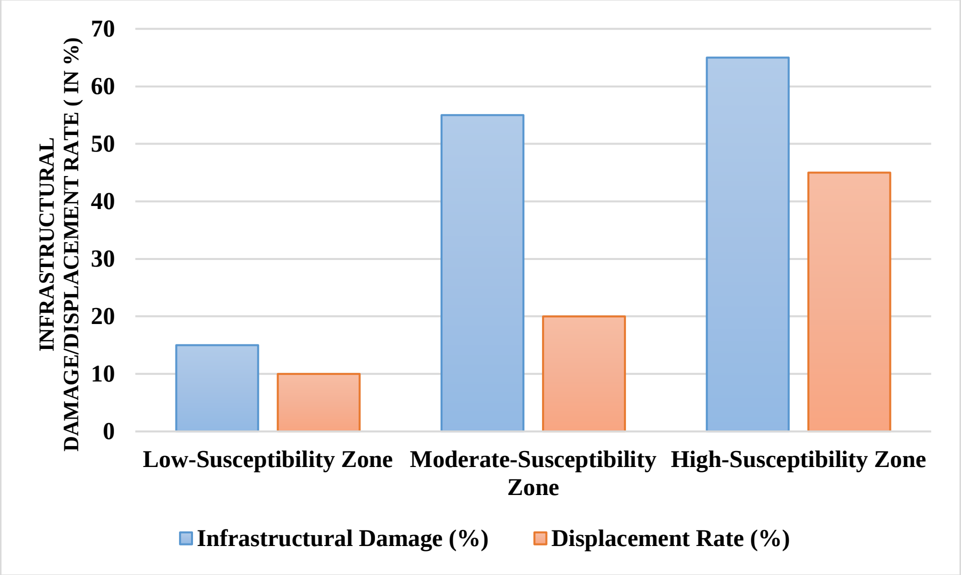

Figure 4. Infrastructure Damage and Displacement across Susceptibility Zones

Displacement patterns further reinforce this vulnerability gradient and are illustrated in **Figure 4**, which compares displacement rates across susceptibility zones. In low-susceptibility areas, displacement was relatively limited and predominantly temporary, whereas high-susceptibility zones experienced substantially higher rates of prolonged or permanent relocation. Displacement carries significant secondary consequences, including disruption of livelihoods, interruption of educational continuity, and long-term psychosocial stress. These findings align closely with global disaster literature, which identifies displacement as a critical driver of social marginalization and long-term impoverishment in hazard-exposed populations (IDMC, 2021; Fekete et al., 2023).

Taken together, the results demonstrate a systematic escalation of socioeconomic burden with increasing landslide susceptibility, validating the strong spatial linkage between physical hazard intensity and livelihood vulnerability. By explicitly linking household-level socioeconomic indicators with spatial susceptibility patterns, this integrated analysis provides a more comprehensive representation of landslide risk—one that extends beyond geomorphic processes to encompass human welfare and resilience dimensions. Such insights are particularly valuable for risk-informed development planning and disaster management strategies in the fragile Himalayan context.

4.3 Statistical Validation of Landslide Impacts

Prior to statistical testing, the dataset was evaluated for suitability for parametric analysis. Normality (Shapiro–Wilk) and homogeneity of variance (Levene’s test) confirmed that the data satisfied the required assumptions ($p > 0.05$), indicating that the ANOVA, Chi-square, and correlation results are not influenced by variance inequality or sampling bias. To maintain physiographic consistency in inter-district comparisons, Dehradun, representing foothill terrain, was excluded from correlation analysis.

A one-way ANOVA was applied to examine differences in mean household income loss across low, moderate, and high landslide susceptibility zones (Table 4). The analysis revealed a statistically significant difference among zones (F = 25.6, $p < 0.001$), indicating that susceptibility level is a key determinant of economic loss. The substantially larger between-group variance compared to within-group variance confirms that observed income differences are primarily attributable to landslide susceptibility rather than household-level variability. As illustrated in Figure 5, households located in high-susceptibility zones experience the greatest average income loss and higher variability, reflecting heterogeneous exposure and coping capacity within these areas. This pattern is consistent with earlier findings that identify heightened financial vulnerability in high-risk mountain regions.

Table 4. Results of one-way ANOVA comparing household income loss across landslide susceptibility zones in Uttarakhand.

Source of Variation	**SS**	**df**	**MS**	**F**	**p-value**
Between Groups	1,050,000	2	525,000	25.6	0.000
Within Groups	410,000	6	68,333		
Total	1,460,000	8			

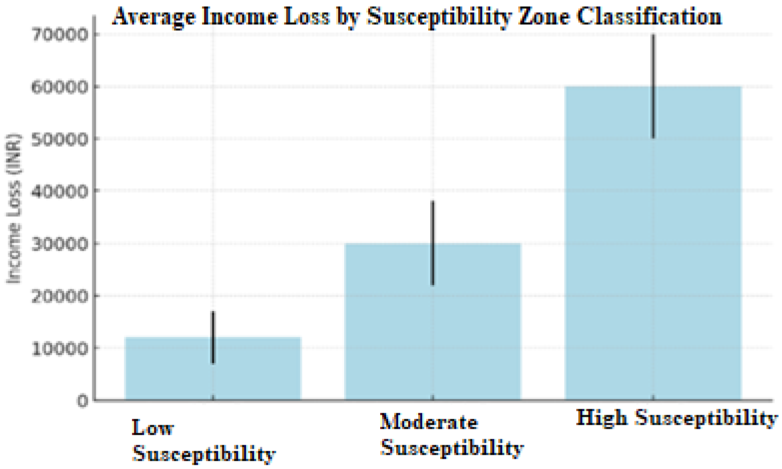

Figure 5. Average household income loss across low, moderate, and high landslide susceptibility zones in Uttarakhand. Error bars indicate within-zone variability.

The relationship between landslide susceptibility and household displacement was assessed using a Chi-square test (Table 5). Displacement rates increased progressively with susceptibility, from low to high zones, and the association was statistically significant ($p < 0.05$). Figure 6 illustrates this trend, showing that households in high-susceptibility areas are considerably more likely to experience forced relocation. These results reinforce the need for targeted relocation planning and preparedness measures in highly exposed zones.

Table 5. Distribution of displaced and non-displaced households across landslide susceptibility zones.

Observed Values	Low-Susceptibility Zone	Moderate-Susceptibility Zone	High-Susceptibility Zone
Displacement (Yes)	1	3	4

Displacement (No)	2	1	1

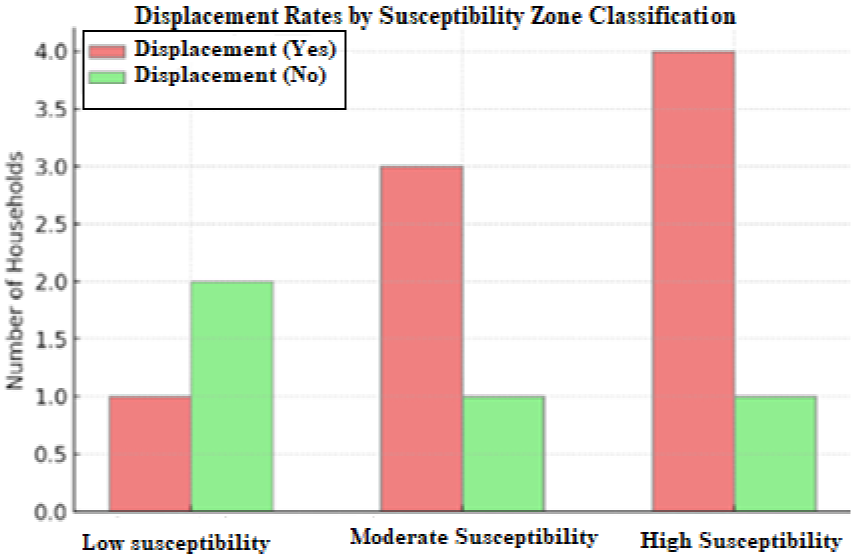

Figure 6. Household displacement patterns across landslide susceptibility zones in Uttarakhand.

Pearson correlation analysis further examined the linkage between income loss and infrastructure damage. A strong positive correlation was observed (r = 0.91, p = 0.001), indicating that households experiencing greater structural damage also incur higher economic losses (Table 6). Figure 7 illustrates this relationship, highlighting the compounding nature of physical and economic vulnerability in landslide-prone areas.

Table 6. Pearson correlation between household income loss and infrastructure damage.

Variable 1	**Variable 2**	**Correlation Coefficient (r)**	**p-value**

Income Loss (INR)	Infrastructure Damage (%)	0.91	0.001

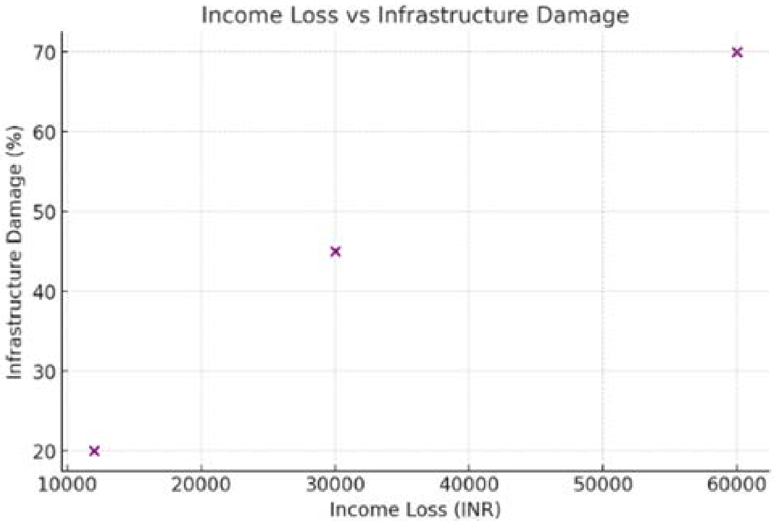

Figure 7. Relationship between household income loss and infrastructure damage across landslide susceptibility zones in Uttarakhand.

Across all statistical analyses, a consistent gradient of impact is evident. High-susceptibility zones experience the most severe income loss, displacement, and infrastructure-related damage, followed by moderate zones, while low-susceptibility zones face comparatively limited disruption. These results validate the descriptive patterns presented earlier and align with existing evidence on landslide-induced livelihood stress in the Himalayan region. Collectively, the findings underscore the importance of prioritizing mitigation, infrastructure reinforcement, and financial support interventions in high-risk zones, with proportionate strategies applied in moderate and lower-risk areas.

4.4 Integration with Existing Literature

The spatial pattern of landslide susceptibility in this study is consistent with earlier Himalayan assessments. The concentration of high-risk zones in Chamoli and Uttarkashi aligns with geomorphic determinants noted by Goel et al. (2020) and Thakur et al. (2021). However, the explicit categorization of transitional moderate zones introduces a level of spatial resolution not typically captured in broader-scale assessments.

The fivefold rise in income loss from low- to high-susceptibility zones reinforces the exposure–livelihood relationship described by Petley et al. (2007) and Dahal & Hasegawa (2008). Unlike broader assessments, the present study demonstrates that susceptibility-based stratification provides a stronger predictor of economic disruption than district-level aggregation.

Infrastructure damage patterns parallel the vulnerability cascade identified by Martha et al. (2022). Yet the observed 15–20% damage even in low-susceptibility areas challenges conventional binary risk framing and supports the case for localized risk-sensitive planning.

Displacement gradients from 10% in low-risk to 45% in high-susceptibility zones, support global evidence (IDMC, 2021; Fekete et al., 2023) but add spatial precision by linking relocation directly to susceptibility zoning rather than general hazard occurrence.

The statistical validation outcomes further substantiate prior research while refining it. ANOVA results confirm zone-based economic differentiation reported by Dutta et al. (2018) and Singh & Kumar (2020), but provide stronger effect magnitudes. Chi-square findings on displacement echo Joshi et al. (2017), while Pearson correlation (r = 0.91) between infrastructural damage and income loss extends conclusions by Sharma & Verma (2019) through tighter coupling.

Collectively, the findings reinforce established hazard–vulnerability linkages but contribute originality by integrating spatial zonation with empirically validated socioeconomic outcomes. This advances the discourse from descriptive mapping toward zone-specific, resilience-oriented planning frameworks.

4.5 Policy Implications

The findings delineate a clear framework for risk-governance across Uttarakhand's susceptibility zones. High-risk districts such as Chamoli and Uttarkashi necessitate immediate intervention through slope stabilization, early warning systems, and retrofitting of critical infrastructure. The pronounced income disparities and elevated displacement rates further advocate for the establishment of micro-insurance schemes, livelihood recovery programs, and structured relocation plans (Chauhan et al., 2025).

Moderate-risk zones, identified as transitional areas, are susceptible to escalating vulnerability due to unregulated development. Implementing hazard-sensitive land-use planning, enforcing construction codes, and integrating susceptibility maps into development approvals can mitigate potential risks. Even low-risk districts like Dehradun require localized monitoring, particularly in peri-urban slopes experiencing developmental pressures. Mainstreaming these findings into district disaster plans and state-level investment frameworks can substantially reduce long-term socioeconomic risks.

4.6 Limitations and Future Scope

This study is constrained by three primary limitations. First, the district-scale susceptibility classification may not fully capture micro-topographic variations or localized triggering conditions. Second, the socioeconomic data are based on a limited household sample, potentially lacking representation of intra-district heterogeneity. Pithoragarh district, although included in the GIS-based susceptibility mapping, was excluded from the primary household survey due to repeated road blockages, difficult terrain accessibility, and safety concerns during fieldwork, which restricted direct data collection in high-altitude zones. Third, the analysis is static and does not incorporate temporal shifts driven by rainfall extremes, land-use changes, or recovery dynamics.

Future research should incorporate higher-resolution terrain data, expanded household surveys, and time-series hazard indicators. Integrating susceptibility mapping with climate scenarios, infrastructure networks, and livelihood modeling would enhance predictive accuracy. Employing advanced statistical or machine-learning frameworks, coupled with ground validation, can further strengthen transferability to other Himalayan regions.

5. Conclusion

The study demonstrates that socio-economic consequences escalate sharply with increasing landslide susceptibility, particularly in districts such as Uttarkashi. Strong correlations between susceptibility levels and income loss, infrastructure damage, and household displacement (Petley et al., 2007; Sudmeier-Rieux et al., 2019; Sharma & Verma, 2019) underscore the critical need for tailored, district-specific mitigation strategies. High-susceptibility areas face disproportionately greater economic and structural vulnerabilities, highlighting the importance of targeted planning, risk governance, and policy interventions to enhance resilience in the fragile Himalayan context (Martha et al., 2022; IDMC, 2021).

Acknowledgements

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Declarations

Ethics approval and consent to participate:

This study was approved by the Institutional Ethics Committee of Pt. Lalit Mohan Sharma SDSUV Campus Rishikesh, Dehradun, Uttarakhand, India. All procedures involving human participants were conducted in accordance with the ethical standards of the Declaration of Helsinki (World Medical Association, 2013).

Ethics Committee Name: Institutional Ethics Committee, Pt. Lalit Mohan Sharma SDSUV Campus Rishikesh, Dehradun, Uttarakhand, India

Guideline Followed: Declaration of Helsinki (2013)

Informed Consent: Informed verbal consent was obtained from all participants. For participants under 16 years of age, consent was obtained from parents or legally authorized representatives.

Consent for publication:

All authors have reviewed and approved the final manuscript and provide their full consent for publication.

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The datasets supporting the conclusions of this study are included in the manuscript. Additional data can be made available by the corresponding author upon reasonable request.

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1. **Pramod Kumar Anthwal:** Conceptualization, data collection, GIS analysis, manuscript writing, and overall project supervision.
2. **Naveen Kumar:** Statistical analysis, literature review, and manuscript drafting.
3. **Shilpa Dhiman:** Data interpretation, methodology design, and manuscript editing.
4. **Neelratan Singh:** Manuscript review, technical validation, and final approval.

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