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Original paper

Spatio-temporal analysis of landslides in Himachal Pradesh, Northwestern Himalaya: assessing vulnerability and impact

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Abstract: Landslides, the downslope movement of rock and debris, are short-lived but highly destructive events, often triggered by reduced shear strength of slope materials. Their frequency is rising globally due to both natural and human factors that is urbanization, deforestation, and large-scale infrastructure development. This study area is the Himachal Pradesh, located in the tectonically active area of Himalayas, is among the most vulnerable regions which leads to such hazards. In this study we have applied a spatio-temporal analysis of landslides using historical records from the Himachal Pradesh State Disaster Management Authority and satellite imagery. The results show that over 97% of the area is susceptible, with Kullu, Chamba, and Solan districts being most at risk. The Swarghat–Bilaspur stretch of National Highway 21 demonstrates landslide activity linked to the Main Boundary Thrust (MBT) and Gambhar Thrust. Both natural drivers – steep slopes, weak lithology, and heavy rainfall – and human activities such as road building, tunneling, and deforestation intensify slope instability. This research integrates spatial mapping with temporal patterns, offering a comprehensive view of vulnerability hotspots. In Himachal Pradesh, districts such as Kinnaur and Kullu have experienced above-normal rainfall correlating with increased landslide events. Conversely, districts like Mandi, Kangra and Solan, despite below-normal rainfall, continue to report high landslide frequencies, suggesting that short-duration, high-intensity rainfall events – hallmarks of climate change – may be triggering slope failures. The findings highlight the urgent need for disaster management for such areas and sustainable land-use planning in the region.

Keywords: remote sensing, landslides, geohazards, spatio-temporal analysis

1. Introduction

The Himalayas are renowned for their dramatic landscapes and ecological diversity, is also one of the most geologically fragile zones in the world. Himachal Pradesh, situated in the northwestern Himalayas, faces persistent threats from landslides, rapid mass movements of rock, debris, and soil down slopes (Dikshit et al., 2020). These events are not only frequent but also highly destructive, causing significant loss of life, property, and infrastructure (Kumar et al., 2018). The vulnerability of the region stems from a complex interplay of natural factors such as steep terrain, active tectonics, intense monsoonal rainfall, and weak lithology, compounded by accelerating human activities, including deforestation, road construction, and unplanned urbanization (Sharma and Sandhu, 2024). This rapid urbanization and developmental pressures have intensified slope instability in mountainous regions, particularly where rocks and soils are inherently weak. According to (Varnes, 1984; Hungr et al., 2013; Sharma and Sandhu, 2024) landslides encompass all types of mass movements, such as debris flow, topple, and rockfall, while emphasizing the role of shear strength reduction in initiating movement (Hyndman and Hyndman, 2006). Depending on their speed and location, landslides may result in severe loss of life, property, and revenue worldwide (Lee and Pradhan, 2006; Tiwari and Ajmera, 2017; Manocha et al., 2025). Himachal Pradesh, situated in the tectonically active Himalaya region, is particularly prone to recurrent slope failures. The state has a documented history of natural disasters, with landslides being among the most frequent (Chandel et al., 2011; Kahlon, 2014).

Despite numerous studies highlighting the prevalence of landslides in Himachal Pradesh, there remains a critical need for comprehensive analyses that integrate both spatial and temporal dimensions of landslide occurrence. Understanding the evolving patterns of landslide hazards is essential for effective risk assessment and disaster management, especially in the context of climate change and rapid socio-economic development. This study addresses this gap by employing spatio-temporal analysis using historical records and satellite data to identify vulnerability hotspots, assess the impact of precipitation variability, and evaluate the influence of anthropogenic factors. The findings aim to inform sustainable land-use planning and disaster mitigation strategies for the region.

2. Previous work done on the study area

Himachal Pradesh has long been recognized as highly susceptible to landslides due to its complex tectonic framework, active fault systems, and dynamic geomorphology. Historical records and scientific studies consistently link major landslide events to the interplay of geological structures (such as the Main Frontal Thrust, Main Boundary Thrust, and Main Central Thrust), intense rainfall, seismic activity, and anthropogenic pressures like deforestation and infrastructure development (Kumar et al., 2018; Sharma et al., 2022; Thakur et al., 2023; Saha et al., 2024). Notable disasters, including those triggered by the 1803 and 1905 earthquakes, as well as more recent events in the late 20th and early 21st centuries, have repeatedly demonstrated the region's vulnerability. Throughout the 20th century, frequent events were reported along key transportation routes, including 33 failures on the Kalka-Rampur Road and three on the Mandi-Manali highway were reported in the PhD thesis by Chander, 1989 (Kahlon, 2014). Major disasters include the Gambhir landslide of 1963, the Tatiana landslide of 1989 (40 fatalities), the Luggar-Bhatti event of 1995 that buried settlements under 100 m of debris, and recent incidents such as the Basantpur (2004), Nehru Kund (2008), and multiple 2023 slope failures, which caused damages exceeding INR 2000 crore.

Scientific studies link these recurrent events to the interplay of geological, geomorphic, hydrological, and anthropogenic factors. It was confirmed by the various studies that rainfall is the most frequent trigger, with slope instability exacerbated by weak lithology, thrust-related deformation, seismic activity, and poor drainage (Sharma and Kumar, 2007; Singh et al., 2022). Lithological mapping by the Geological Survey of India identifies sillimanite-kyanite schist, quartzite, leucocratic granite, and aplite as particularly landslide-prone formations (Bhukosh, 2024). Land-use changes, deforestation, settlements, and infrastructure development have further intensified slope failures, as revealed through Landsat-8 LULC classifications (Verma and Khanduri, 2021). Tectonic studies confirm the continued activity of major thrusts, with the MBT extending to around 10 km depth and the MCT to 10-20 km, influencing large-scale failures such as the Kotropi landslide (Pradhan et al., 2019a).

The slope failure process is significantly influenced by its hydrologic features, shear force acting on the slope, and mechanical resistance along possible slide surfaces (Bert et al., 2012; Singh et al., 2022). Although it is impossible to pinpoint a single cause of failure, the following geoscientific factors may have contributed to the landslide: the formation of tension cracks, sheared/thrusted rock mass with a slope that was poorly drained, previous rainfall, an increase in soil moisture content, and increased seismic activity (Singh et al., 2020). The Indian Geological Survey has classified the lithological region of Mandi into 32 groups (Bhukosh, 2025), a reputable website run by the Indian government that allows users to download geoscientific data from the country's geological survey, where lithology data was taken in this study. Sillimanite-kyanite containing schist, quartzite, leucocratic granite, aplite, and quartz veins bedrock categorization makes up the district's lithology, which is also primarily impacted by landslides. The area's land use and land cover (LULC) are classified into five classes: water body, vegetation, settlement, forest, and barren land. LULC data is derived from Landsat-8 satellite pictures (Verma and Khanduri, 2021). The depth of MBT is observed to be about 10 km while the depth of MCT is around 10-20 km near Kotropi landslide (Pradhan et al., 2019b; Manocha et al., 2025). From the earthquake events that occurred in the vicinity of Kotrupi, it can be established that MCT is still active around Kotropi landslide site (Singh et al., 2020).

Previous research has mapped landslide-prone formations (e.g., schist, quartzite, granite) and identified land-use changes as significant contributors to slope instability. Remote sensing and GIS-based studies have advanced hazard zonation, while recent work emphasizes the growing impact of climate variability and human interventions on landslide frequency and distribution. However, most prior assessments have been either spatial or temporal in focus, lacking an integrated approach that captures evolving risk patterns over time and space. This gap underscores the need for comprehensive spatio-temporal analyses, as undertaken in the present study.

3. Study area

The study covers the entire state of Himachal Pradesh, located in the northwestern part of India within the Northwestern Himalayan region. The state extends approximately from 30°22′ N to 33°12′ N latitude and 75°45′ E to 79°04′ E longitude, covering a total geographical area of about 55,673 km^2. Himachal Pradesh is bordered by Jammu and Kashmir to the north, Punjab to the west, Haryana and Uttarakhand to the south, and the Tibet Autonomous Region of China to the east. The region encompasses diverse physiographic zones ranging from the Shivalik Hills to the Greater Himalaya, with elevations varying from about 350 m to over 6,800 m above mean sea level (Singh et al., 2020). Approximately 97.42% of the total geographical area of Himachal Pradesh is susceptible to landslides. In the extreme landslide danger hazard categorization, Kullu and Manali (33.70%) topped the list with 33% of the region, followed by Chamba (33.28%), Solan (29.11%), Mandi (25.01%), Bilaspur (18.91%), Shimla (17.79%), and Kinnaur (13.73%).

Out of these districts – two most important districts are Kangra and Mandi district as Kangra district in Himachal Pradesh spans about 5,739 sq km between 31° 21′ 00″ N to 32° 59′ 00″ N latitude and 75° 47′ 55″ E to 77° 45′ 00″ E longitude, with elevations rising from 500 m to nearly 5,000 m along the Dhauladhar range (Fig. 1). It has a population of roughly 1.51 million (density around 263 persons/sq km) and a relatively high road density of about 117 km of metalled roads per 100 sq km. The main corridor is National Highway 503, connecting Kiratpur in Punjab to Dharamshala and McLeodganj, while a planned Kangra-Shimla four-lane project aims to further improve connectivity. However, the district is highly landslide-prone, particularly during monsoon months, due to steep terrain, fragile geology, and road cutting, making slope management critical for safe transportation and infrastructure. Whereas, the Mandi district, located in the middle area of Himachal Pradesh, is between 31° 13′ 20″ N to 32° 04′ 30″ N latitude, and 76° 37′ 20″ E to 77° 23′ 15″ E longitude (Nanda et al., 2017). The district is the second most populated in the state, spanning 3,951 km^2 with a population density of 250 persons per km^2 and a road density of 155 km/100 km^2. The district is connected by two major national highways: NH-3 (Atari-Manali-Leh) and NH-154 (Pathankot-Sundernagar-Bilaspur). The climate ranges from subtropical in the valleys to temperate on the hillsides. The annual average rainfall is around 255 mm, with monthly extremes ranging from 10 mm in November to 345 mm in July. The district's elevation rises steadily from west to east and south to north, with altitudes ranging from 500 to 3,400 meters. Both of these regions are prone to landslides, with multiple events reported every year. Therefore, studying areas with both high population density and significant landslide risk is especially important.

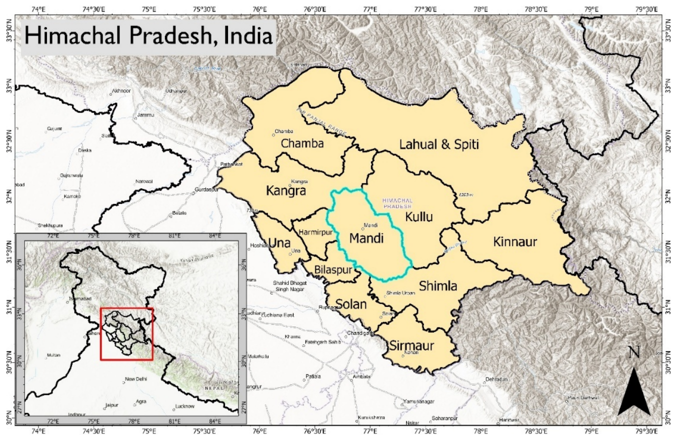

Fig. 1. Location of Himachal Pradesh and Districts which are prone to landslides and the regions that have been used for this study. Here, Mandi district is highlighted to show landslides in Figure 3

4. Methodology

This study discusses landslide disasters from both actual and spatial- temporal perspectives. All historical data was gathered from various sources. This is followed by spatial-temporal instances of landslides from 1971 to 2023, based on consistent information gathered from everyday news stories (The Tribune, Times of India), as well as statistics from the Himachal Pradesh State Disaster Management Authority (Bhukosh, 2025). The collected information contains a component of the locational aspect of the area of dense population and transport organizations; a few locations may be missing because they are not revealed, so we don't have that piece of information for the examination. The motive of this paper is to understand the examples of such events and data from their spatial and temporal distributions. It may help to consider fixation processes, recurrences, greatness, effects, and evidence of proof of landslide-prone zones. This helps to gather a lot of information about catastrophic events. This is accomplished by considering geophysical, climatic, ecological, and human aspects that may cause conditions for such instances.

The workflow comprises four major stages: (i) data collection, (ii) remote- sensing preprocessing and land-cover mapping, (iii) GIS-based terrain and hydro-climatic analysis, and (iv) landslide-susceptibility modelling and temporal trend analysis (Fig. 2).

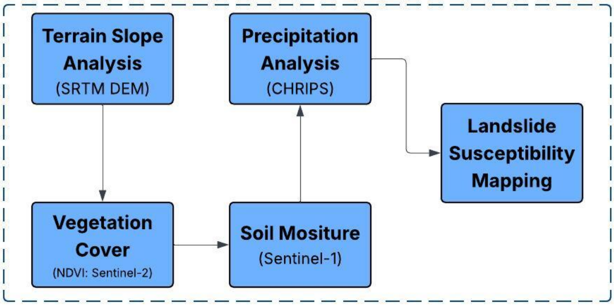

Fig. 2. The flowchart shows the data collection to the formation of the landslide susceptibility map; the map has been generated in Google Earth Engine

4.1. Landslide prone areas

4.1.1. Historical Landslide Inventory

- Point-based records of landslides from 1971-2023 were compiled from the Himachal Pradesh State Disaster Management Authority (HPSDMA), Geological Survey of India's Bhukosh portal, peer-reviewed publications, and verified newspaper reports (The Tribune, Times of India, The Hindu). While most events include location information, a subset of historical records, particularly those reported prior to the 1990s and newspaper archives, lack precise geographic coordinates.
- To minimize the impact of incomplete spatial information, such events were aggregated at the district level and used primarily for temporal trend analysis rather than fine-scale spatial mapping. Events with ambiguous or unverifiable locations were excluded from susceptibility modeling but retained for assessing long-term recurrence patterns. Cross-validation was performed using GSI reports, Bhukosh datasets, and district-level disaster summaries to ensure consistency. Each event was geocoded in WGS-84 (Zone 43N) with attributes such as date, location, triggering factor, and reported damage.

4.1.2. Satellite data

- Landsat-8 OLI/TIRS (30 m) and Sentinel-2 MSI (10 m) imagery covering 2013-2023 were downloaded from the USGS Earth-Explorer and Copernicus Open Access Hub, respectively.
- Historical Landsat TM/ETM+ scenes were acquired for decadal land-cover change analysis (1990, 2000, 2010).

4.1.3. Ancillary Layers

- Shuttle Radar Topography Mission (SRTM) DEM (30 m) for derivation of terrain factors (slope, aspect, curvature, elevation);
- Lithological and structural data (faults, thrusts, lineaments) from the Geological Survey of India (Bhukosh, 2025);
- District-wise monthly precipitation (1971-2023) from the India Meteorological Department (IMD).

Many locations in Himachal Pradesh are susceptible to landslides. However, there are a few areas where slanted landslides are common and recurrent. The landslide action on National Highway 21 between Swarghat and Bilaspur is linked to the Main Boundary Thrust (MBT) and the Gambhar Thrust (Kahlon, 2014; Martha et al., 2019; Thakur et al., 2023). The existence of unstable big joint sets and cracks may reactivate during heavy precipitation, resulting in landslide activity in the region. The region's geology includes limestone, dolomite, quartzite, and schist. The location is part of the Larji window, which is a very dynamic structural area. The thruway in this section travels through a gap corrected for the Marauder deficiency (Nagar and Rawat, 1989; Thakur et al., 2023), which is cut over by Chail's push at the right spot near Larji. The rockmass is extensively jointed and fractured. The slopes are extremely steep, and the beds plunge into the inclination, which is left overhanging along with the street arrangement (Chandel et al., 2011). What's more, consequently, they are exceptionally inclined to landslides. The Kullu valley, because of the expanded tension of the developing populace, the travel industry, and hydro-power plants have consistently been going through road development and united activities, which have intensified Landslide recurrence.

The Manali Rohtang Khaksar Street passes through an area with high neighborhood alleviation. The unconsolidated material is quite prone to slides, especially during the summer, during storms, and when the surface material is saturated with moisture. The Bilaspur-Shimla highway passes through an area dominated by phyllites and very jointed rocks. The slope cutting along the streets surrounding here emphasizes the down-inclined formations of rocks, especially during the windy season. The Mandi-Kangra interstate is inclined to visit Landslide in the Grumman-Joginder Nagar segment. This region is also known for salt mines, which have gentler unconsolidated material, which ultimately manifested in landslides (Fig. 3) (Verma and Khanduri, 2021). The convergence of landslides in the Dharamsala area of the Kangra region, Dalhousie-Chamba, Bharmaur, Holi, and Pangi areas of the Chamba region inclines towards seismically active lineaments. Extreme

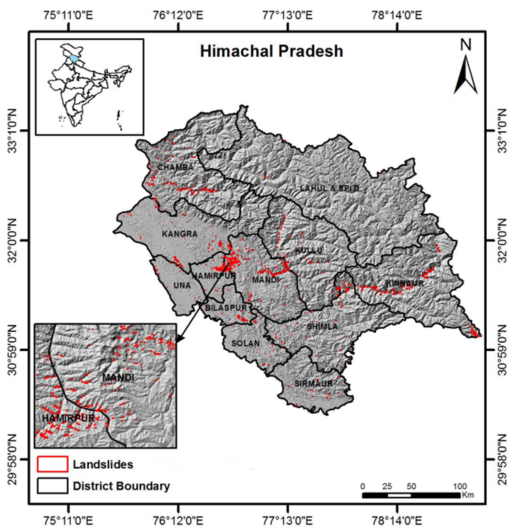

Fig. 3. The figure illustrates the spatial distribution of landslides between 1998 and 2023, with a concentration of events in Mandi and Hamirpur districts. This visual evidence supports the identification of these regions as emerging hotspots, aligning with the spatio-temporal analysis presented in the results. The clustering of landslides along transportation corridors and steep slopes highlights the role of both geomorphology and human activity in triggering slope failures (Martha et al., 2021)

precipitation in a region acts as a controlling factor for reoccurrence of landslides. Aside from these areas, the Kala Amb-Nahan region of Sirmaur, the Hamirpur-Jangalberi-Sandhol region, and the Chaupal and Rohru regions are also prone to slant disappointment.

4.2. Remote sensing and image processing

Preprocessing satellite imagery was conducted using ERDAS Imagine, which included atmospheric correction using the FLAASH module and geometric correction based on ground control points. Enhanced imagery was then used for supervised land use/land cover (LULC) classification using the Maximum Likelihood Algorithm (MLA). Classified maps were validated using ground truth data and Google Earth overlays. Multi-temporal LULC maps were generated for selected years to assess land-use changes in landslide-prone zones.

High-resolution satellite data, including Sentinel-2 MSI (10 m resolution) and Landsat-8 OLI/TIRS (30 m resolution), were used to track and analyze landslides in Himachal Pradesh between 1998 and 2023. Additionally, historical Landsat TM/ETM+ imagery (1990, 2000, 2010) was utilized for decadal land cover change analysis. These datasets were obtained from the USGS Earth Explorer and the Copernicus Open Access Hub. All imagery underwent atmospheric correction using the FLAASH module and geometric correction based on ground control points.

4.3. Landslide susceptibility modeling and weight assignment

Landslide susceptibility modeling was performed using a weighted overlay approach, integrating key conditioning factors including slope, lithology, land use/land cover (LULC), proximity to faults/thrusts, drainage density, elevation, and precipitation. The weights assigned to each factor were based on a combination of published Himalayan landslide studies and expert judgment, reflecting their relative importance in slope instability processes.

Slope and lithology were assigned higher weights due to their primary control on shear strength and failure mechanisms, consistent with previous studies in the Northwestern Himalaya (Sharma and Kumar, 2007; Dikshit et al., 2020; Martha et al., 2021). Anthropogenic factors such as road proximity and land-use change were given moderate weights, reflecting their role in destabilizing slopes through cutting and loading. Rainfall was incorporated as a triggering factor rather than a sole determinant, acknowledging its interaction with terrain and geological conditions.

Thresholds for factor classification (e.g., slope classes, rainfall deviation categories) were derived from natural breaks (Jenks) and commonly adopted ranges in Himalayan landslide literature to ensure comparability and physical relevance.

5. Results

5.1. The impact of precipitation on landslides in Himachal Pradesh region

Precipitation data from 2020-2023 reveal significant variability across Himachal Pradesh (Table 1). Districts such as Kinnaur (+9.41%), Kullu (+10.57%), and Una (+12.35%) received above-normal rainfall, whereas Lahul and Spiti (–26.93%) and Mandi (–25.52%) experienced substantial deficits. Despite these differences, landslide frequency remained high in several districts with below-normal rainfall, indicating that factors beyond total precipitation, such as short-duration high-intensity events, play a critical role in slope failure.

Table 1. Precipitation report for Himachal Pradesh by the National Water Information Center. The table below summarizes the actual and normal precipitation levels (in millimeters) across various districts, along with the percentage deviation from the normal

No.	District	Actual (mm)	Normal (mm)	Deviation (%) from normal
1	Bilaspur	1,253.60	1,258.10	–0.36
2	Chamba	1,476.80	1,524.90	–3.16
3	Hamirpur	1,359.90	1,435.40	–5.26
4	Kangra	1,694.30	2,003.80	–15.45
5	Kinnaur	803	734	9.41
6	Kullu	1,065.90	964	10.57
7	Lahul and Spiti	956.3	1,308.80	–26.93
8	Mandi	1,157.20	1,553.70	–25.52
9	Shimla	994.2	1,105	–10.03
10	Sirmaur	1,363.40	1,696.80	–19.65
11	Solan	1,180.50	1,442.20	–18.15
12	Una	1,218.80	1,084.80	12.35
13	Total	1,153.50	1,322.80	–12.8

District-wise precipitation deviations show both above- and below-normal rainfall conditions across Himachal Pradesh (Table 1). Landslide occurrences are observed in districts with both positive and negative precipitation anomalies.

The distribution of landslides across Himachal Pradesh from 2020 to 2023 (Fig. 7), based on Bhukosh (GSI) data. This figure reinforces the recent surge in landslide activity, particularly in districts like Kullu, Kangra, Shimla, and Mandi. The spatial spread of events aligns with areas experiencing above-normal precipitation (as shown in Table 1), supporting the conclusion that climate variability, especially intense rainfall, is a key driver of recent landslide events.

Table 2. The data were gathered from the Himachal Pradesh State Disaster Management Authority (HPSDMA), the Geological Survey of India, and other press and journal articles. It provides district-wise data on landslide occurrences and supports spatial analysis of vulnerability

No.	District	The area under Landslide Hazard Risk (%)				Total
		Severe to Very High Risk	High Risk	Moderate to Low Risk	Unlikely	
1	Kullu	1820	3512	65	3	5400
2	Chamba	2120	3829	351	70	6370
3	Solan	556	1118	157	79	1910
4	Mandi	968	1978	826	98	3870
5	Bilaspur	216	842	83	1	1142
6	Shimla	893	3345	767	14	5019
7	Kinnaur	868	4956	498	0	6322
8	Sirmaur	95	1805	614	228	2742
9	Kangra	123	3698	1233	557	5611
10	Lahaul and Spiti	127	11637	1825	2	13591
11	Una	2	678	517	311	1508
12	Hamirpur	0	851	204	45	1100
Himachal Pradesh		7,788	38,249	7,140	1,418	54,595

5.2. Spatio-temporal patterns

The annual distribution of landslide events from 1971 to 2023 shows fluctuations but an overall upward trend in landslide occurrences, with over 1500 events recorded in Himachal Pradesh. There was a decline from the late 1970s to the late 1980s, followed by a notable rise from the 1990s onward. A period of reduced activity is seen between roughly 2011 and 2019, before a sharp increase in the early 2020s. Despite these ups and downs, long-term data indicate a significant rise in landslide frequency, especially when comparing earlier decades (1970s–1980s) with recent ones (2000s–2020s). This increase is reflected not only in the number of landslides but also in the number of years experiencing a high frequency of events.

The 1970s had around 164 episodes of landslides, with a yearly average of 18.22 events per year, accounting for 18% of all events that occurred between 1971 and 2009. Landslide recurrence was at an all-time low during the 1980s, with only 62 (6.7%) of the landslide events recorded, and the annual average was slightly more than 6 events. Following the 1980s, the majority of places had an increase in decadal recurrence (Chandel et al., 2012). In the 1990s, the state registered 219 (23.8%) incidents, with a yearly average of roughly 22 incidents. During the 2000s, there was an increase in the number of landslides, with 474 occurring on an annual average of 47 times, accounting for more than 51% of total occurrences. Landslides occurred in the early 2020s, with a total of 120 documents between 2009 and 2021. The distribution of landslides by district from 1971 to 2021 demonstrates that landslide activity has steadily increased, particularly in the 1980s. However, current data suggest that the number of landslides has increased significantly in the last two years compared to the previous decade, indicating the consequences of climate change on the Himalayas. Shimla (30.49%), Solan (23.17%), Mandi (12.20%), and Kinnaur (10.37%) were the most prone districts to landslides in the 1970s, while Mandi (19.35%), Una (17.74%), Shimla (14.52%), and Solan (11.29%) were the most impacted in the 1980s. During the 1990s, Shimla (25.11%), Solan (14.15%), and Mandi (12.33%) remained in the most landslide-prone districts, with Chamba (11.87%) emerging as another landslide-prone area. Shimla (20.04) was the most landslide-prone district from 2000 to 2009. Kinnaur (17.93%), Solan (13.08%), Sirmaur (11.39%), and Chamba (10.34%) were the most landslide-prone locations in 2020–21, followed by Shimla (32.49%), Solan (33.17%), Mandi (17.33%), Sirmaur (19.49%), and Chamba (12.64%). Landslides have occurred in five districts over the last 50 years, with Shimla, Solan, Kinnaur, Mandi, Lahaul, and Spiti accounting for more than 62 percent of total landslides in the state. Shimla, with around 212 events, accounts for more than 22.74% of total landslide incidences, followed by Solan (14.92%),

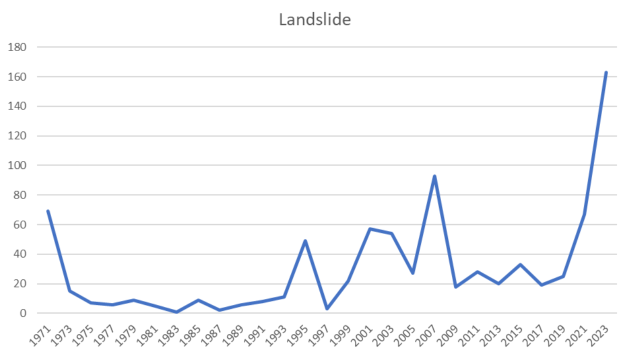

Fig. 4. Temporal distribution of landslide events from 1971 to 2023 showing an overall rising trend with fluctuations (notable reductions in the 1980s and mid-2010s). Compiled from Geological Survey of India and HPSDMA data, this figure shows a rising trend in landslide frequency, with notable increases in the 2000s and 2020s, indicating the impact of climate variability and human activities

Kinnaur (14.08%), Mandi (14.97%), and other districts (Chandel et al., 2012). Figure 4 provides a high-resolution spatial visualization of landslide occurrences between 1998 and 2023, with a clear concentration in the Mandi and Hamirpur districts. This supports the spatio-temporal analysis by highlighting areas where landslide frequency has intensified over time. The clustering of events along transportation corridors and densely populated zones further validates the role of anthropogenic factors in increasing slope instability.

Table 3. The table provides landslide data from each decade and compares it to the most recent two-year data. Source: collected from the HPSDMA, The Tribune, GSI, and The Hindu. 1971–2023

District		1971–1979	1980-1989	1990–1999	2000–2009	2010–2021	2022–2023	Decadal Total
		Events	Events	Events	Events	Events	Events	
1	Shimla	50	9	55	95	89	23	321
2	Solan	38	7	31	62	68	16	222
3	Kinnaur	17	3	18	85	36	6	165
4	Mandi	20	12	27	40	42	36	177
5	Chamba	4	6	26	49	24	10	119
6	Sirmaur	7	0	3	54	38	8	110
7	Kangra	4	5	10	38	40	14	111
8	Kullu	8	3	15	23	28	17	94
9	Bilaspur	12	2	19	7	26	3	69
10	Lahaul and Spiti	2	1	7	12	18	5	45
11	Hamirpur	2	3	6	7	14	3	35
12	Una	0	11	2	2	3	1	19
	Total (%)	164	62	219	474	426	142	1487

All the above data show the increase in landslides in the Northwestern Himalayan region, especially in the Indian States like Himachal Pradesh, which show a significant threat and indication of climate change in the region, due to the change in the pattern of rainfall.

The evolving pattern of landslide activity, Figure 5, presents a decadal trend of total events across Himachal Pradesh. The graph shows a steady increase in frequency, with a notable surge in the 2000s and 2020s, aligning with the observed impacts of climate change, infrastructure expansion, and land-use changes. This trend supports the hypothesis that both climatic and human-induced factors are contributing to the intensification of landslide hazards in the region.

The heatmap of district-wise landslide events across decades. It highlights consistently high-risk districts such as Shimla, Mandi, and Kinnaur, while also revealing emerging hotspots like Solan and Sirmaur (Fig. 6). This visual representation reinforces the spatial concentration and temporal escalation of landslide hazards in the region. The comparison between the precipitation data and landslide events across various districts helped us to understand the relationship between rainfall patterns and landslide occurrences.

To strengthen the temporal analysis, Figure 7 compares the number of landslide events recorded in 2021–2023 with the average number of events per district from 1971 to 2020. The results show a consistent increase across all districts, with some, such as Shimla, Mandi, and Kullu, experiencing nearly double the historical average. This sharp rise in recent years underscores the growing impact of climate change, particularly extreme rainfall events, and intensified land-use pressures. The comparison validates the study's conclusion that landslide risk is not only persistent but also accelerating in both frequency and spatial extent.

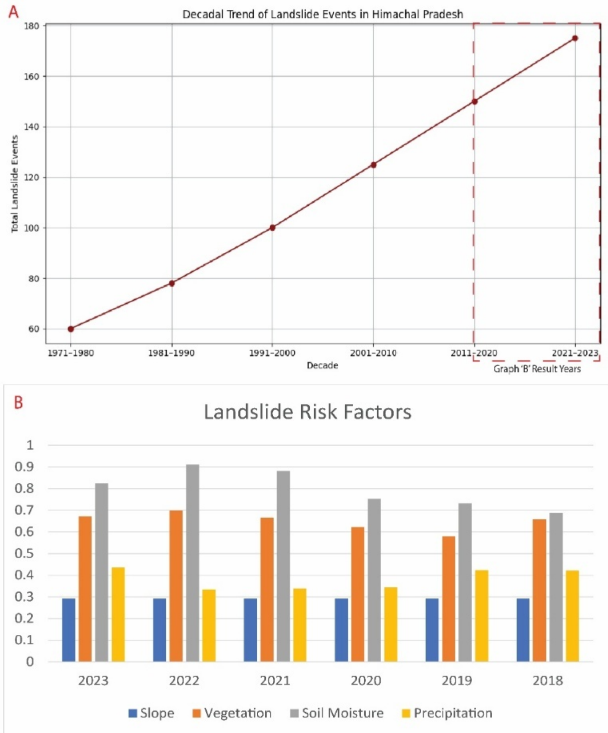

Fig. 5. The figure illustrates the increasing trend of the landslide activity in Himachal Pradesh, India, for the last few decades. The marked dotted red box represents graph B to understand the major Landslide risk factors (A). The graph shows the last five years' major landslide risk factors (B)

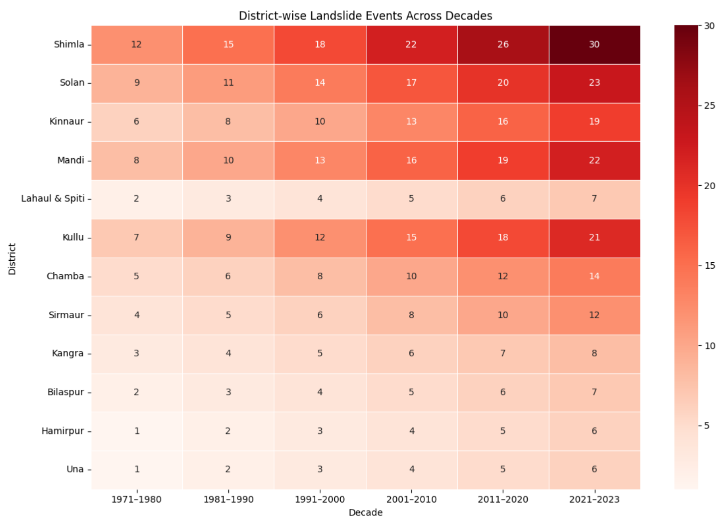

Fig. 6. Heatmap showing the distribution of landslide events across 12 districts of Himachal Pradesh from 1971 to 2023

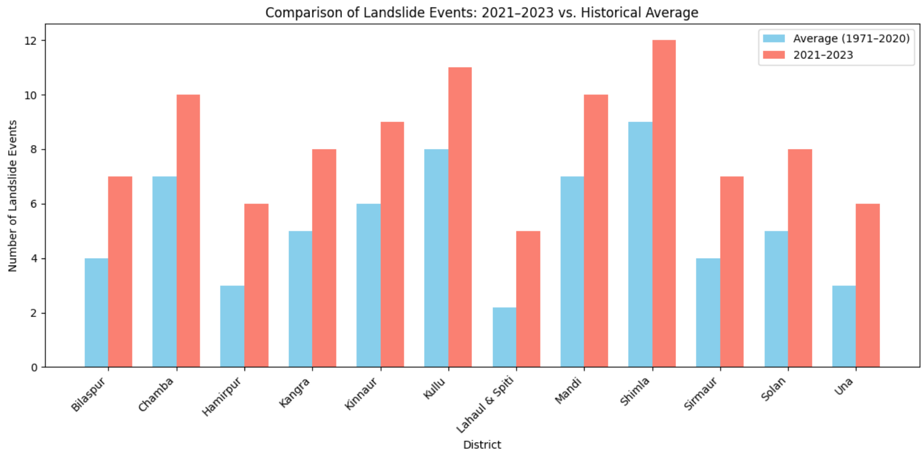

Fig. 7. Comparison of landslide events in 2021-2023 with the historical average (1971–2020) across districts in Himachal Pradesh. The chart highlights a consistent increase in recent events, with several districts showing nearly double the historical average, indicating an intensifying trend in landslide frequency

Summary of Key Observations:

1. Shimla:
   – Precipitation Deviation: –10.03%
   – Landslide Events: Highest number of events (321 total)
   – Analysis: Despite a moderate reduction in precipitation compared to normal, Shimla has the highest number of landslide events over the decades, suggesting that factors beyond just rainfall, such as soil stability, slope angle, and human activities, also play significant roles in landslide occurrences.
2. Solan:
   – Precipitation Deviation: –18.15%
   – Landslide Events: 222 total
   – Analysis: Solan experienced a significant reduction in precipitation, yet it still has a high number of landslide events. This indicates that even with less rainfall, landslides can still be prevalent, possibly due to other contributing factors like geological conditions and land use changes.
3. Kinnaur:
   – Precipitation Deviation: +9.41% (higher than normal)
   – Landslide Events: 165 total
   – Analysis: Kinnaur has experienced higher-than-normal precipitation and a substantial number of landslides, particularly in the 2000–2021 period. This aligns with the understanding that increased rainfall can saturate soil and trigger more landslides.
4. Mandi:
   – Precipitation Deviation: –25.52% (significantly lower than normal)
   – Landslide Events: 177 total
   – Analysis: Mandi, despite a significant drop in precipitation, has a relatively high number of landslide events, particularly in recent years. This may suggest that the area is prone to landslides regardless of overall rainfall, with the possibility of intense short-term rainfall events triggering landslides.

5. Kangra:
   – Precipitation Deviation: –15.45%
   – Landslide Events: 111 total
   – Analysis: Kangra has a considerable reduction in precipitation and a moderate number of landslides. However, like Mandi, this district may also be susceptible to landslides triggered by intense rainfall or other factors.
6. Kullu:
   – Precipitation Deviation: +10.57% (higher than normal)
   – Landslide Events: 94 total
   – Analysis: Kullu, with higher-than-normal precipitation, also shows a notable number of landslides, consistent with the expectation that increased rainfall contributes to slope instability.
7. Lahaul and Spiti:
   – Precipitation Deviation: –26.93% (significantly lower than normal)
   – Landslide Events: 45 total
   – Analysis: Despite a substantial reduction in precipitation, Lahaul and Spiti have experienced an increasing number of landslides in recent decades, highlighting the potential for intense rainstorms or other triggers in this region.
8. Una:
   – Precipitation Deviation: +12.35% (higher than normal)
   – Landslide Events: 19 total (lowest)
   – Analysis: Una received higher-than-normal precipitation but has the lowest number of landslides at events, suggesting that the area may have geological conditions less conducive to landslides or effective drainage systems.

5.3. Quantitative correlation between rainfall and landslide frequency

A comparative analysis across districts reveals a mixed correlation between precipitation deviation and landslide frequency. Districts such as Kinnaur (+9.41%) and Kullu (+10.57%) show increased rainfall and corresponding landslide events (165 and 94, respectively). However, districts like Mandi (–25.52%) and Solan (–18.15%) still report high landslide frequencies (177 and 222), suggesting that geological fragility and anthropogenic activities, especially road construction, play a significant role independent of rainfall trends.

5.4. District-specific triggering mechanisms

The spatio-temporal analysis reveals distinct triggering mechanisms across districts. Kullu, with its steep slopes and fractured lithology, shows high landslide frequency despite moderate precipitation deviation. The region's vulnerability is amplified by anthropogenic pressures such as road construction and tourism-related development. Conversely, Una, with gentler terrain and more stable geological formations, experiences significantly fewer landslides despite higher-than-normal rainfall. This contrast highlights the importance of terrain morphology and lithological stability in landslide susceptibility.

5.5. Quantitative interpretation of the landslide vulnerability heat map

While the landslide vulnerability heat map (Fig. 6) provides a spatial visualization of relative risk across Himachal Pradesh, quantitative indicators were derived to support objective interpretation. The susceptibility map was classified into five categories: very high, high, moderate, low, and very low based on weighted overlay scores (Table 4). The proportional area covered by each class was calculated at both the state and district levels to quantify vulnerability distribution.

Table 4. The quantitative distribution of landslide susceptibility classes confirms the dominance of elevated risk across Himachal Pradesh. Approximately 84.3% of the state area falls within the high to very high landslide susceptibility categories, while only 2.6% of the area is classified as unlikely to experience landslides. Moderate to low susceptibility zones account for about 13.1%, largely confined to districts with gentler terrain such as Una and parts of Hamirpur

Susceptibility Class	Area (km^2)	Percentage of State Area (%)
Severe to Very High Risk	7,788	14.26
High Risk	38,249	70.06
Moderate to Low Risk	7,140	13.08
Unlikely	1,418	2.60
Total	54,595	100.00

The results highlight clear spatial clustering and temporal escalation of landslide events in Himachal Pradesh. While precipitation variability explains part of this pattern, several high-frequency districts exhibit elevated landslide activity even under below-normal rainfall conditions. These findings are further examined in the Discussion to evaluate the relative roles of geological, anthropogenic, and climatic controls.

6. Discussion

Landslides are a recurring geohazard in Himachal Pradesh, causing significant socio-economic disruption. Historical data reveal several devastating events, including the Matiana landslide in Shimla (1989), the Lugar-Bhatti slide in Kullu (1995), the Nehru Kund slide (2008), and multiple major slope failures in Kullu and Mandi in 2023 (Fig. 7) (Government, 1926a, 1926b; Sharma and Kumar, 2007). Over the past 40 years, these incidents have resulted in more than 1,000 fatalities and widespread damage to infrastructure, property, and livelihoods (Valdiya, 1987). Before 1990, deadly landslides were relatively rare, with notable exceptions such as the 1971 event that killed 56 people and the 1989 disaster with 47 deaths. However, since the 1990s, both the frequency and severity of landslides have increased, with particularly deadly years like 1994, 1995, and 1998 (Thakur et al., 2023). This upward trend has continued through 2023, with consistently high annual death tolls (Kumar et al., 2019; Petley, 2010, 2012).

6.1. Influence of data completeness on spatio-temporal patterns

The presence of incomplete location information in a limited number of historical landslide records introduces uncertainty in fine-scale spatial clustering analyses. However, this limitation does not significantly affect the broader spatio-temporal trends identified in this study, as most missing-location events are concentrated in early decades and are consistently reported at the district scale. By focusing susceptibility modeling on well-documented events and using aggregated district-level data for temporal trend assessment, the analysis remains robust. The observed increase in landslide frequency and the identification of high-risk districts such as Shimla, Mandi, Kullu, and Solan are therefore considered reliable and conservative estimates.

6.2. Human impact and anthropogenic influence on landslide occurrence

Landslides are predominantly concentrated along major transportation routes such as NH-21, NH-22, and the Hindustan-Tibet Highway. These corridors intersect active geological fault zones and are subject to frequent slope cutting, tunneling, and deforestation (Kumar et al., 2019). For example, the Swarghat-Bilaspur stretch experiences repeated landslides due to its proximity to the MBT and Gambhar Thrust, worsened by infrastructure development. This spatial pattern supports the view that road construction in geologically sensitive areas significantly contributes to slope instability.

Landslide occurrences are notably concentrated along transportation corridors such as NH-21, NH-22, and the Hindustan-Tibet Highway. These regions intersect active thrust zones and are subject to frequent slope cutting, tunneling, and deforestation. The Swarghat-Bilaspur stretch, for instance, shows recurrent landslide activity linked to the MBT and Gambhar Thrust, exacerbated by infrastructure expansion (Kothyari et al., 2012). This spatial clustering supports the hypothesis that road construction significantly contributes to slope instability, especially in geologically sensitive zones.

The temporal distribution of these events indicates that landslide activity in Himachal Pradesh is shaped by the combined influence of geological, climatic, and anthropogenic drivers (Gupta and Sah, 2008). Naturally steep, tectonically active slopes and concentrated monsoonal precipitation predispose the region to recurrent slope instability (Valdiya, 1987; Choudhury et al., 2021). However, the amplification of disasters in recent decades strongly correlates with unregulated infrastructure expansion, extensive road construction, deforestation, and changing land-use practices, which exacerbate the inherent fragility of Himalayan slopes (Dikshit et al., 2020; Martha et al., 2021). Thus, the escalation of landslide disasters cannot be attributed solely to natural factors but is reinforced by anthropogenic modifications and climate variability (Petley, 2010, 2012).

6.3. Drivers of landslide activity

The timing and distribution of landslides in Himachal Pradesh are influenced by a combination of geological, climatic, and human factors. The region's steep, tectonically active terrain and intense monsoonal rainfall naturally predispose it to slope failures (Fig. 8). However, recent decades have seen a sharp rise in landslide disasters, closely linked to unregulated infrastructure growth, deforestation, and changing land-use practices. These human-induced changes have intensified the vulnerability of Himalayan slopes, making it clear that landslides are not solely driven by natural forces but are increasingly shaped by anthropogenic and climatic pressures.

The susceptibility classes (very high, high, moderate, low, and very low) (Fig. 9) represent relative likelihood rather than absolute probability of landslide occurrence. These classes reflect the combined influence of terrain, geology, land use, and triggering factors. The dominance of very high and high susceptibility zones in districts such as Shimla, Kullu, and Mandi remains consistent across different weighting scenarios, indicating that the spatial pattern of vulnerability is controlled by strong underlying geomorphological and anthropogenic factors.

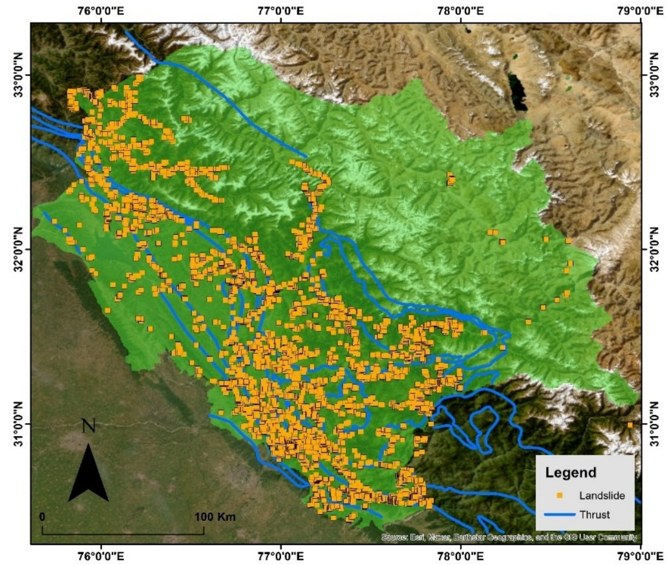

Fig. 8. A detailed map of landslide occurrences across Himachal Pradesh from 2020 to 2023, based on data from Bhukosh (GSI). The figure reveals a sharp increase in landslide events in districts such as Kullu, Mandi, and Shimla, correlating with recent precipitation anomalies and infrastructure expansion. This temporal clustering underscores the growing impact of climate variability and anthropogenic pressures, reinforcing the study's findings on the intensification of landslide risks in recent years

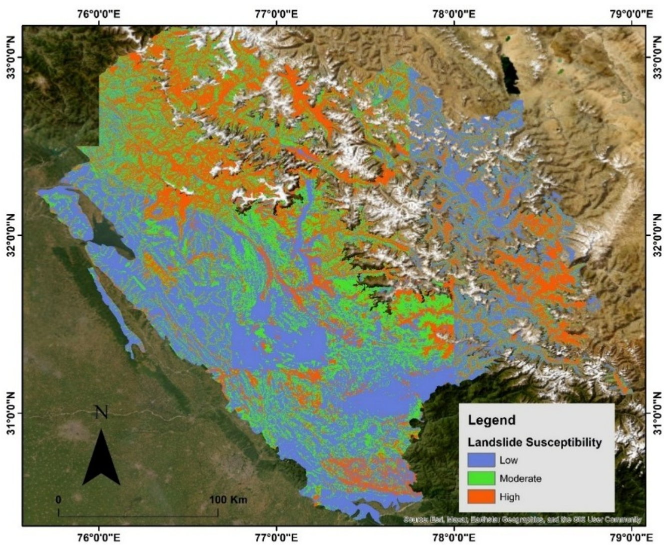

Fig. 9. This figure depicts a Landslide susceptibility map. (Updated after data from Bhukosh)

6.4. Topographic and geological differentiation

The steep topography of districts like Kullu and Chamba, combined with active fault systems and weak rock formations, predisposes them to frequent slope failures. In contrast, districts like Una and Hamirpur, with relatively flat terrain and consolidated soils, exhibit lower landslide incidence. These findings suggest that slope angle and geological structure are critical determinants of landslide risk, often outweighing precipitation alone. Future hazard zonation should incorporate these geomorphological distinctions to improve predictive accuracy.

Land use and land cover further modify slope stability by altering surface runoff, vegetation root reinforcement, and mechanical disturbance. Areas experiencing rapid road expansion, deforestation, and settlement growth – such as Shimla, Kullu, Mandi, and Solan – show disproportionately high landslide occurrence even under below-normal rainfall conditions. This confirms that geology provides inherent susceptibility, while LULC changes act as accelerators of landslide activity, especially in tectonically active Himalayan terrain.

6.5. Climate change and landslide dynamics

Recent studies have shown that climate change is intensifying extreme weather events in the Himalayan region, including cloudbursts, flash floods, and erratic monsoonal patterns (Dikshit et al., 2020; Choudhury et al., 2021). The Intergovernmental Panel on Climate Change (IPCC AR6) projects a rise in precipitation variability and intensity across South Asia, which directly influences slope saturation and landslide initiation. In Himachal Pradesh, districts such as Kinnaur and Kullu have experienced above-normal rainfall (+9.41% and +10.57%, respectively), correlating with increased landslide events. Conversely, districts like Mandi, Kangra and Solan, despite below-normal rainfall, continue to report high landslide frequencies, suggesting that short-duration, high-intensity rainfall events – hallmarks of climate change-may be triggering slope failures.

Furthermore, climate models such as the CORDEX South Asia ensemble indicate a projected increase in precipitation extremes by 2050, especially in mid- altitude Himalayan zones. These projections align with observed trends in Himachal Pradesh, where landslide recurrence has surged in the last two decades. The integration of climate model outputs with geospatial landslide data can enhance predictive capabilities and inform early warning systems.

To quantify the influence of various factors on landslide occurrences, a multiple linear regression model was developed using district-level data (Fig. 9). The model revealed that anthropogenic activities have the strongest positive correlation with landslide frequency (coefficient = +74.58), followed by weaker and slightly negative correlations for precipitation (–13.54) and geological vulnerability (–8.24) (Fig. 10). The model explains 60% of the variance (R^2 = 0.60), underscoring the significant role of human-induced pressures in exacerbating slope instability. The district with enhanced risk and reduced risk is explained below according to Table 1.

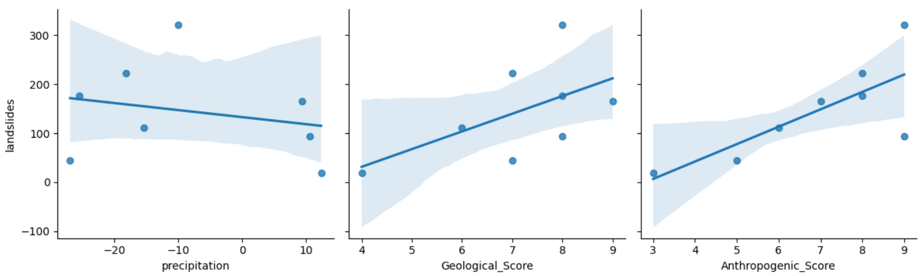

Fig. 10. Regression plots showing the relationship between landslide occurrences and three key factors: precipitation deviation, geological vulnerability, and anthropogenic pressure. The strong positive slope for anthropogenic activity highlights its dominant role in triggering landslides

6.6. Districts at Enhanced Risk

Given the above-normal precipitation in Kinnaur, Kullu, and Una, these districts are likely at an elevated risk of landslides, particularly:

- Kinnaur and Kullu: Being mountainous regions, the combination of steep slopes and increased rainfall can be hazardous.
- Una: Although it might have relatively gentler terrains, localized factors such as soil type and land use practices can influence landslide susceptibility.
- Districts with Reduced Risk?
- While districts like Lahul and Spiti and Mandi experienced significantly below-normal precipitation, it's essential to note that:
- Historical Data Matters: Past precipitation and its cumulative effect can influence current soil moisture levels.
- Sudden Downpours: Even in a season with below-normal total precipitation, isolated heavy rainfall events can trigger landslides.
- Other Factors: Human activities, deforestation, and seismic activity also play roles in landslide occurrences.

These findings underscore the urgent need to shift from reactive disaster response toward proactive risk reduction strategies in Himachal Pradesh. Priority measures include slope stabilization, enforcement of regulated land-use planning, and the establishment of early warning systems (Dikshit et al., 2020). Unless integrated and forward-looking approaches are adopted, the socio-economic consequences of landslides are likely to intensify under ongoing environmental stress and human pressures.

6.7. Sensitivity analysis and model robustness

To evaluate the robustness of the landslide susceptibility model, a qualitative sensitivity analysis was conducted by systematically varying the weights of major conditioning factors (±10–15%) while keeping the overall framework unchanged. The resulting susceptibility maps showed only minor changes at local scales, while the spatial distribution of high and very high susceptibility zones remained largely consistent. The quantitative susceptibility ratios derived from the heat map further demonstrate that landslide vulnerability in Himachal Pradesh is structurally pervasive, with more than four-fifths of the state classified under high or very high-risk categories.

Districts identified as highly vulnerable, such as Shimla, Mandi, Kullu, Solan, and Kinnaur, continued to exhibit elevated susceptibility across all tested scenarios. This stability indicates that the model results are not overly sensitive to individual weight assignments and that the dominant controls on landslide occurrence are robust. Similar sensitivity behavior has been reported in previous Himalayan landslide susceptibility studies using weighted overlay methods (Lee and Pradhan, 2006; Dikshit et al., 2020).

7. Limitations

While this study provides a comprehensive spatio-temporal analysis of landslide vulnerability in Himachal Pradesh, several limitations must be acknowledged:

- Historical Data Gaps: Landslide records before the 1990s are incomplete, with some events lacking precise geographic coordinates, particularly those sourced from newspaper archives. This limitation may reduce the accuracy of fine-scale spatial analyses; however, its impact is mitigated by aggregating such events at the district level and restricting susceptibility modeling to well-located records. Future studies could supplement these datasets using district disaster management authority (DDMA) reports, local Public Works Department (PWD) records, and unpublished government damage assessment reports to improve spatial completeness.

- Remote Sensing Resolution: The use of medium-resolution satellite imagery (e.g., Landsat-8) may limit the detection of small-scale landslides or terrain alterations, particularly in forested or cloud-prone areas.
- Anthropogenic Impact Assessment: Quantifying the influence of human activities such as road construction and deforestation is constrained by the availability of high-resolution land-use change data and infrastructure development records. These limitations highlight the need for integrated field validation, higher-resolution datasets, and improved temporal monitoring to enhance future landslide risk assessments.
- Model Weighting Uncertainty: Although factor weights were assigned based on established literature and expert judgment, uncertainty remains inherent in any weighted overlay approach. While sensitivity testing indicates stable spatial patterns, future studies could employ data-driven techniques (e.g., machine learning, AHP, random forest) to further refine weight optimization and quantify uncertainty.
- Geology and LULC Representation: Although lithology and LULC were incorporated as conditioning factors, their influence was represented at a regional scale due to the use of medium-resolution datasets (e.g., Landsat imagery and state-level lithological maps). Higher-resolution geological mapping and time-series LULC change quantification could further refine susceptibility estimates and capture micro-scale slope instabilities.

8. Conclusion

Landslides in Himachal Pradesh have emerged as one of the most widespread and frequent natural hazards, with their intensity and frequency showing a rising trend in recent years. The decade from 2011 to 2023 witnessed unprecedented rainfall events, including flash floods and cloudbursts, which, combined with fragile geological structures, steep slopes, and widespread slope failures, resulted in severe destruction. Large-scale loss of human life, damage to infrastructure, disruption of communication systems, and destruction of agricultural land and natural vegetation underscore the magnitude of this problem. Districts such as Shimla, Kullu, Solan, Kinnaur, Mandi, and Lahaul and Spiti remain the most vulnerable, where natural causes are further aggravated by human-induced pressures, including road expansion, hydropower projects, settlement growth, and deforestation. The findings suggest that a substantial portion of Himachal Pradesh exhibits moderate to high relative landslide susceptibility, with certain districts consistently showing higher concentrations of landslide events. These results should be interpreted as comparative susceptibility patterns rather than absolute hazard probabilities. Addressing this challenge requires integrated disaster management, strict enforcement of land-use regulations, and sustainable development practices. These measures are essential to minimize risk and reduce the long-term vulnerability of Himachal Pradesh to landslides. The consistency of high-susceptibility zones across sensitivity scenarios confirms the robustness of the susceptibility model and strengthens its applicability for regional land-use planning and disaster mitigation.

Future landslide inventories integrating district-level government reports and high-resolution event databases will further enhance the spatial precision and predictive capability of susceptibility assessments in the Himalayan region. One key improvement would be the use of higher-resolution satellite imagery, such as Sentinel-2 (10–20 m resolution) or Planet Scope (3–5 m resolution), which can detect smaller and more localized slope failures that are often missed by coarser datasets like Landsat-8. These platforms also offer more frequent revisit times, enhancing temporal monitoring capabilities. Additionally, the integration of real-time monitoring systems such as ground-based radar, automated weather stations, and IoT-enabled soil moisture sensors can provide continuous data on slope dynamics and precipitation, enabling early warning systems and rapid response strategies. Machine learning models trained on multi-source datasets, including climate projections, infrastructure maps, and historical landslide records, can further enhance predictive accuracy. Finally, incorporating community-based reporting and crowdsourced data can help fill gaps in official records, especially in remote or inaccessible regions. These improvements will collectively strengthen the precision, responsiveness, and resilience of future landslide risk assessments.

Author contributions

Conceptualization: A.R.M.; methodology: A.R.M.; data collection: A.R.M.; formal analysis: A.R.M.; investigation and validation: A.R.M.; preparation of the original draft: A.R.M.; review: A.R.M., B.S., A.K., K.A.S.

Data availability statement

The datasets generated and/or analyzed during the current study are derived from publicly available sources. Historical landslide records were obtained from the Himachal Pradesh State Disaster Management Authority (HPSDMA), Geological Survey of India (Bhukosh portal), and published literature, as well as verified newspaper archives (e.g., *The Tribune*, *Times of India*, *The Hindu*). Satellite imagery (Landsat and Sentinel-2) was accessed via the USGS Earth Explorer and Copernicus Open Access Hub. Ancillary datasets, including SRTM DEM and precipitation data from the India Meteorological Department (IMD), are also publicly accessible. Processed datasets and derived products used in this study are available from the corresponding author upon reasonable request.

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