Spatial distribution of landslides vis-à-vis epicentral distribution of earthquakes in the vicinity of the Main Central Thrust zone, Uttarakhand Himalaya, India

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Landslides and related mass movement activities along with earthquakes are common in the Himalayan terrain. The distribution of seismic activities in the vicinity of the Main Central Thrust (MCT) is well known. However, in order to assess the relationship between these seismic events and landslides, the spatial distribution of landslides and earthquake events (magnitude >1.5) on either side of the MCT zone was evaluated. It has been observed that seismic events of magnitude <2.1 are clustered around the 1991 Uttarkashi earthquake rupture, 1999 Chamoli earthquake rupture and around Munsiyari. The zone surrounding 1999 Chamoli earthquake rupture indicates the highest earthquake and landslide density of ~75% and 53% respectively.

Keywords: Earthquakes, landslides, rainfall, spatial and epicentral distribution.

LANDSLIDES and related mass movement activities are common geomorphic processes in the mountainous terrains. These are caused by both external and internal factors. Internal factors are mainly the geological and geomorphological configuration of the terrain, whereas the external factors include anthropogenic pressure on the terrain. However, it is generally rainfall or earthquakes that trigger these activities.

The Himalayan terrain experiences landslides and earthquakes. Both rainfall- and earthquake-induced landslides are observed. The former occur mostly during or immediately after rainfall[1–4], whereas the latter are contemporaneous with earthquakes[5–7]. Many a times, it is difficult to differentiate between these two types of landslides. Nevertheless, in general, rainfall-induced landslides are deeper, arcuate shaped and of debris slide and debris flow types, whereas earthquake-induced landslides are shallow, elongated and of debris fall and rock fall types[6]. Besides, the type and geometry, earthquake-induced landslides are controlled by various factors, such as the magnitude of the earthquake, distance of landslide from the epicentre, maximum ground acceleration and various geological factors[8].

During the recent past, the Uttarakhand Himalaya has witnessed two major earthquakes, viz. the 1991 Uttarkashi and the 1999 Chamoli earthquakes that were triggered in the vicinity of the Main Central Thrust (MCT)[9–11]. Besides, numerous small earthquakes, ranging in magnitude from 1.5 to 4.0 occur almost every day. Majority of these events are shallow having <25 km depth and are concentrated in certain regions of the MCT[12,13]. The causes of spatial distribution of these earthquakes along the strike length of the MCT are well known[14,15]. On the contrary, there are several causes for the occurrence of landslides in the region. Though most of the landslides are reported during the rainy season and are distributed throughout the Himalayan terrain, there are certain 'hotspots' in the region where the concentration of these landslides is high and these may be related to the climate, lithology and tectonics of the area[3,4]. Though microearthquake activities in the region do not indicate the presence of instantaneous landslides, it is hypothesized that the continuous ground shaking due to earthquakes destabilizes the slopes that may be triggered by various other factors such as rainfall or fractured rock mass. Therefore, in the present study, we try to understand whether there exists any relation between the spatial distribution of landslides and the epicentral distribution of earthquakes of varying magnitude in the MCT zone of the Uttarakhand Himalaya.

The study area is located between 29°33′30″–31°18′47″N lat. and 77°44′04″–80°24′13″E long. (Figure 1). It extends 10 km to the north of the Vaikrita Thrust and 10 km to the south of the Berinag Thrust within the boundary of the Uttarakhand Himalaya, thus covering a linear stretch of ~278 km along the strike length of MCT, and an area of ~19,000 km^2.

Geologically, the area encompasses rocks of the Lesser Himalaya and the Higher Himalaya. The rocks of the Lesser Himalaya are further differentiated into the Lesser Himalaya metasedimentary sequence and the Lesser Himalayan Crystallines, and the rocks of the Higher Himalaya as the Higher Himalayan Crystallines. The rock types constituting the Lesser Himalayan metasedimentary sequence are mainly quartzite, limestone, phyllite, shale and slate, whereas the Lesser Himalayan Crystallines are mainly low-grade schist and gneisses. The Higher Himalayan Crystallines mainly constitute schist, augen gneisses, and mylonites with bands of quartzites and metabasics. In general, the rocks of the Higher Himalaya are stronger; nevertheless, the strength of the rocks mainly depends on their deformational history[16].

There are numerous faults and thrusts in the area. The MCT, one of the major north-dipping intercontinental thrust resulting from continent–continent collision runs all along the study area and in the direction of the strike length of the Himalaya. It is ~10–15 km wide and separates the rocks of the Lesser Himalaya and the Higher Himalaya. The upper contact of the zone is designated as Vaikrita Thrust and the lower as Munsiyari Thrust. To the

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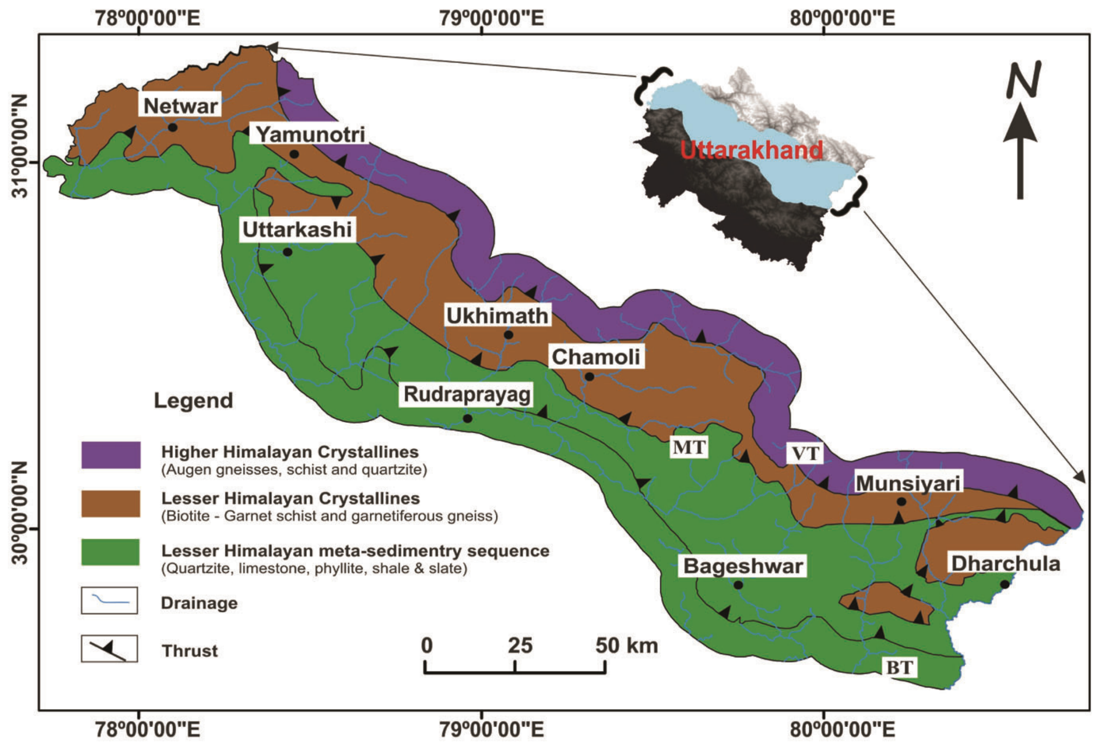

Figure 1. Location map of the study area depicting the regional geological setting. BT, Berinag Thrust; MT, Munsiyari Thrust; VT, Vaikrita Thrust.

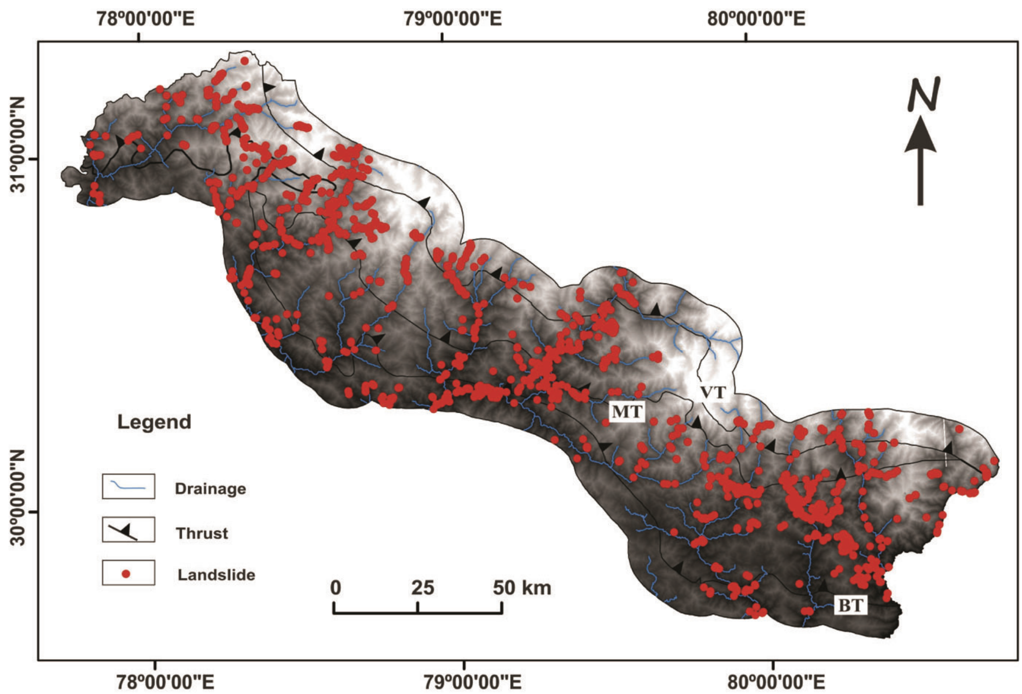

Figure 2. Inventory of landslides in the study area.

south of the Munsiyari Thrust lies the Lesser Himalayan metasedimentary sequence. This sequence is invariably referred to as the Garhwal Group comprising Berinag and Deoban formations. The Deoban Formation comprises dolomite with bands of phyllite, slate and occasionally quartzite, whereas the Berinag Formation comprises quartzite and metabasics. The Berinag Thrust separates the two. There are also numerous small-scale thrusts, faults,

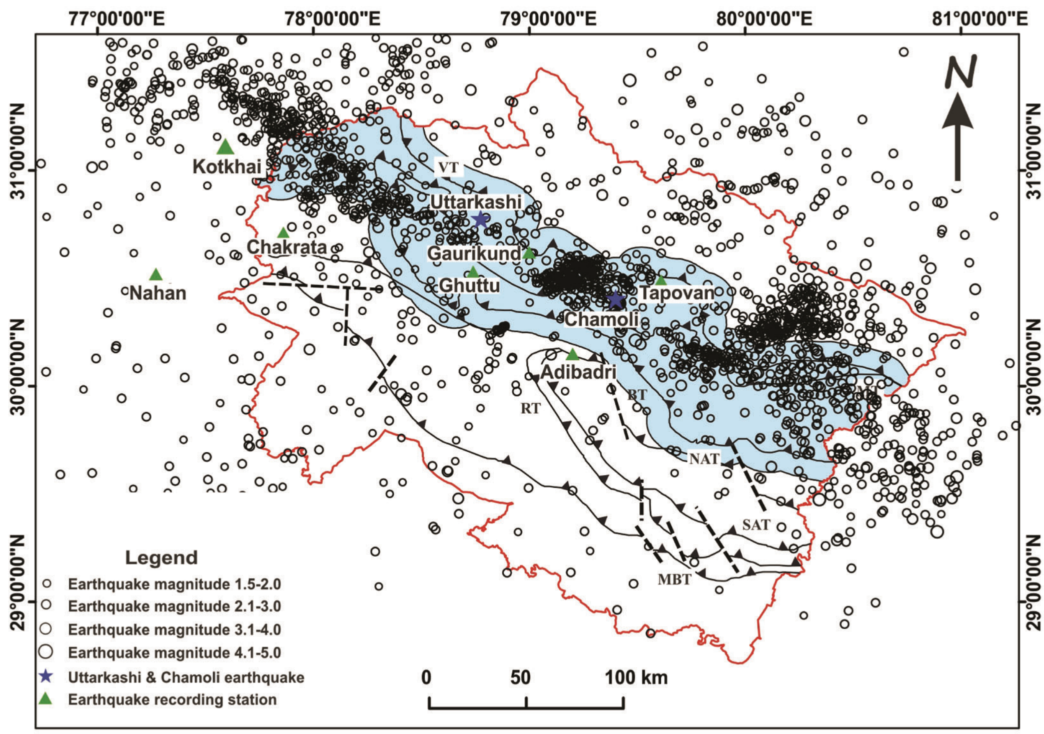

Figure 3. Inventory of earthquakes of magnitude ranging between 1.5 and 5.1 recorded during July 2007–October 2015 on the seismic network of 10 broadband seismographs. (The location of seismographs for recording earthquake data is also shown.)

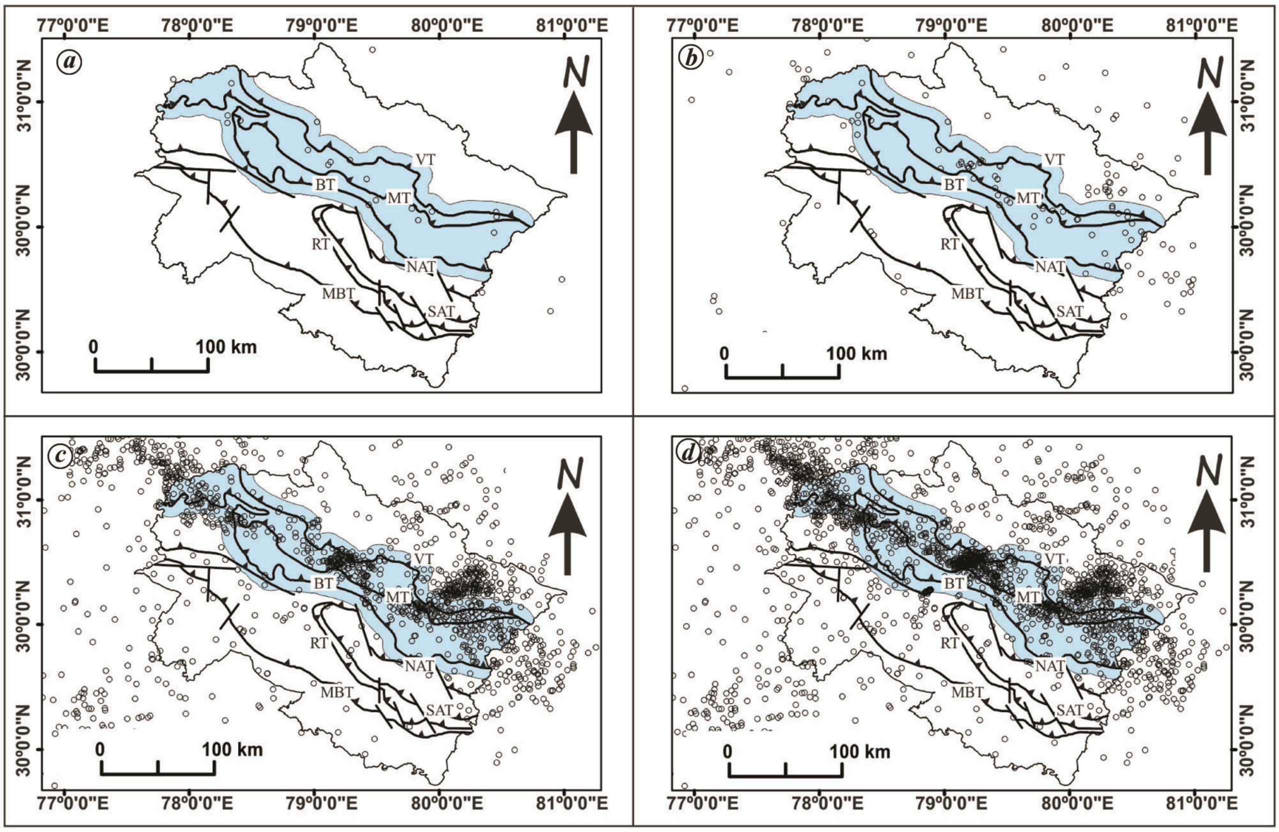

Figure 4. Data plot of the spatial distribution of earthquakes recorded in the study area and its environs of magnitude: ***a***, ≥4.1; ***b***, ≥3.1; ***c***, ≥2.1; ***d***, ≥1.5.

Table 1. Earthquake and landslide counts, and density of landslides and earthquakes of different magnitude in each of the three clusters

Cluster	Area (km^2)	Number of landslides	Number of earthquakes	Number of landslides/km^2	Landslide density	Number of earthquakes/km^2	Earthquake density
1	3179	300	145	0.09	36.30	0.05	24.01
2	2291	313	328	0.14	52.55	0.14	75.35
3	4220	401	269	0.10	36.55	0.06	33.55

nappe, klippen and tectonic windows in the area. Details about the geological and structural set-up of the area and its environs have been studied[17]. Figure 1 depicts the geological map of the area.

The preparation of an inventory depicting the spatial distribution of landslides and epicentral distribution of earthquakes is a prerequisite for studies that involve the spatial distribution of these events. For the present study, an inventory of landslides has been prepared using high-resolution satellite images as well as images on the Google Earth platform and LISS IV images having a resolution of ~1 m and 5.8 m respectively. In addition, data from extensive fieldwork have been incorporated. A total of 1342 landslides of different sizes have been mapped in the area (Figure 2).

The inventory of earthquakes has been acquired from the seismic network of 10 broadband seismographs installed in July 2007. Seven of these stations are located in Uttarakhand, two in the adjoining Himachal Pradesh and one to the south of the study area in the Gangetic plains (Figure 3). Each station is equipped with a Trillium-240 seismometer of high dynamic range (>138 dB) and a Taurus data acquisition system (DAS) that gives high accuracy of global positioning system. The catalogue compiled for the present study consists of 2260 earthquake events of magnitude (M_L) ≥1.5 acquired between July 2007 and October 2015.

A number of earthquakes have been recorded outside the study area, and these might have affected the occurrence of landslides and slope instability in the region. It is, however, reported that small magnitude earthquakes, probably <5.0, are not sufficient for triggering landslides. It is generally observed that landslides are triggered by earthquakes having magnitude >5.0, as has been widely reported as in case of the 1991 Uttarkashi, 1999 Chamoli, 2005 Kashmir, 2011 Sikkim and 2015 Gorkha earthquakes. Nevertheless, it is hypothesized that the concentration of small magnitude earthquakes affects the slope instability in a region, leading to subsequent failure possibly by other triggering agents like rainfall[18].

There were 2260 earthquakes of magnitude ranging between 1.5 and 5.1 in the study area during July 2007–October 2015. Among these, 769 were of magnitude ranging between 1.5 and 2.0, 1335 between 2.1 and 3.0, 129 between 3.1 and 4.0, and 27 between 4.1 and 5.0. Data plots indicate that there is no preferential distribution of earthquakes of magnitude >3.1; however smaller earthquakes of magnitude <3.0 are clustered (Figure 4 *a*–*d*). Three clusters are clearly visible, and their boundaries are visually drawn for statistical analysis (Figure 5 and Table 1).

Cluster-1 is located in the western part of the study area and its aerial coverage is ~3179 km^2. It covers the 1991 Uttarkashi earthquake rupture zone and the area to the west of it. The spatial distribution of earthquakes in this cluster is scattered; they are mainly located between the Berinag Thrust and the Munsiyari Thrust. The landslides in this cluster are also scattered and mainly located along the drainage. With earthquake and landslide counts of 145 and 300 respectively, this zone exhibits earthquake and landslide density of ~24% and 36% respectively (Table 1). The 1991 Uttarkashi earthquake generated 183 landslides immediately after the earthquake and 360 landslides during the succeeding rainy season of 1992 (ref. 19).

Cluster-2 is located in the central part of the study area and its aerial coverage is ~2291 km^2. It covers the 1999 Chamoli earthquake rupture zone and the area to the west of it. This is the most pronounced of all three clusters. It includes the highest number (328 earthquakes) of seismic events located between the Munsiyari Thrust and the Vaikrita Thrust. Majority of the earthquakes in this cluster are of magnitude <3.1 (Figure 5). With earthquake and landslide counts of 328 and 313 respectively, this cluster exhibits earthquake and landslide density of ~75% and 53% respectively (Table 1).

Various researchers[13,15,20] have observed low *b*-value, low frictional coefficient, and high peak ground acceleration (PGA) near this cluster, as well as the presence of fluids near the detachment below this cluster[21]. All these indicate that there is higher probability of occurrence of earthquake-induced landslides in this zone. This has been further substantiated by the fact that 338 landslides have been mapped in the vicinity of Chamoli after the 1999 earthquake[22].

Cluster-3 is located in the eastern part of the study area near Munsiyari and its aerial coverage is ~4220 km^2. This cluster is scattered in the Uttarakhand Himalaya, though all the earthquakes of magnitude >2.1 are clustered oblique to the strike of the Himalaya (Figure 4 *d*) between the Munsiari Thrust and the Vaikrita Thrust, and further north in the Tibetan part. Most of the landslides in this

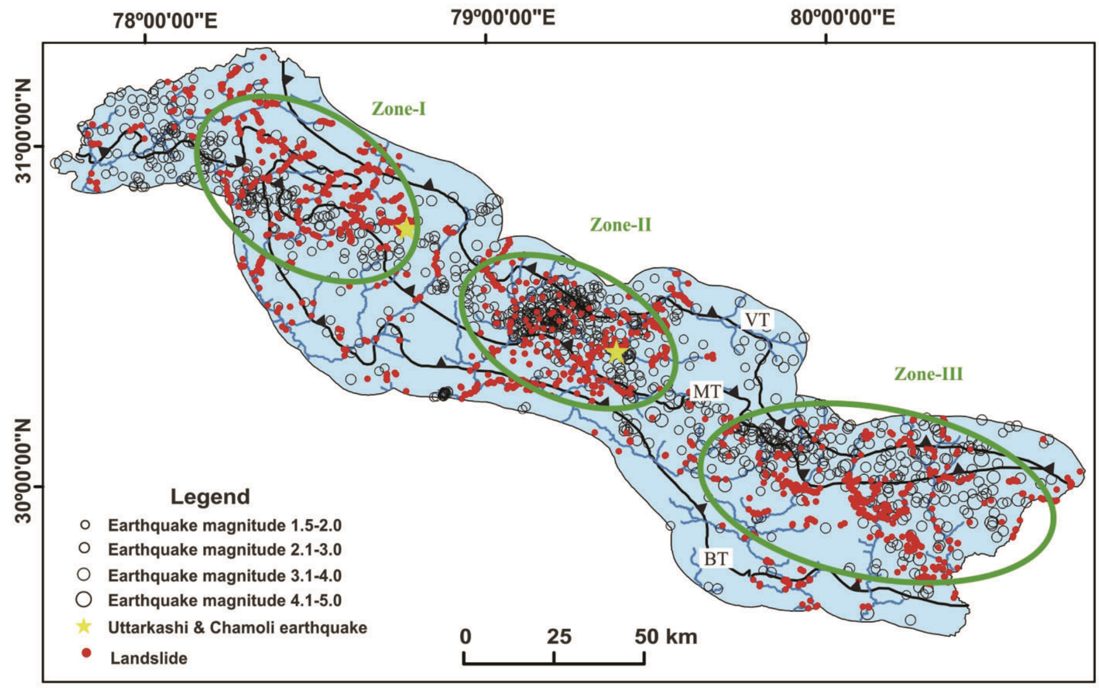

Figure 5. Data plot of the spatial distribution of landslides and earthquakes of different magnitude. Three prominent clusters of earthquakes and landslides are clearly marked.

cluster, particularly in the Kali valley and its adjoining region are due to the active nature of the area[23]. With earthquake and landslide counts of 269 and 401 respectively, this cluster exhibits earthquake and landslide density of ~34% and 37% respectively (Table 1). Though there are few isolated earthquakes of magnitudes 3.1–4.0 in the areas between the demarcated clusters, clustering of the small magnitudes earthquakes is notably missing.

The Uttarakhand Himalaya is seismically active, particularly along the strike length of the MCT. Three clusters of earthquakes with magnitude >1.5 located in the western, central and eastern parts of the Uttarakhand Himalaya have been identified (Figure 5). The occurrence of landslides in the area is widely distributed; however, there are certain landslide 'hotspots' and their spatial distribution may well be correlated with the clustering of the earthquakes. The visual correlation between the spatial distribution of earthquakes and landslides in these three clusters indicates the following:

- Cluster 2 comprising the Chamoli region located in the central part of the Uttarakhand Himalaya exhibits the highest earthquake and landslide density of 75% and 53% respectively.
- Clusters 1 and 3 located in the western and eastern ends of the Uttarakhand Himalaya exhibit earthquake and landslide density of 24% and 36%, 34% and 37% respectively.
- The inter-cluster areas between clusters 1 and 2 and clusters 2 and 3 do not exhibit any concentration of earthquakes and the landslides, though there is isolated presence of both events in these areas.

Finally, with the limitation and non-availability of the time-series history of landslide events, it is difficult to correlate the occurrence of landslides with particular seismic events. It is generally considered that the concentration of small magnitude earthquakes in a particular area affects slope instability in the region either by the appearance of tension cracks or by weakening of rock-mass strength, leading to subsequent failure of slope possibly by other triggering agents like rainfall. Lastly, as several construction activities are ongoing in the area, and all of them require prior knowledge of the hazard potential, the results of this study can be utilized for assessing the hazard potential of the study region, and thus have societal implications.

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