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Geospatial landslide inventory of India—an insight into occurrence and exposure on a national scale

Abstract India ranks first in the world in terms of fatal landslides. Large vulnerable area (0.42 million km²), high population density and monsoon rainfall make India's landslide management and mitigation task difficult. Therefore, an understanding of landslide occurrences and exposure of socio-economic parameters on a national scale is essential to prioritise landslide mitigation efforts. In this paper, a database of 45,334 landslides (polygons) in India mapped by the National Remote Sensing Centre (NRSC) during the 1998–2018 period was compiled and catalogued in a WebGIS platform. High-resolution satellite data such as IRS PAN+LISS-III, Resourcesat LISS-IV Mx, Cartosat, WorldView, Pleiades and GeoEye were used to map landslides as small as 12 m² to as big as 1,390,350 m². GIS analysis using the landslide inventory revealed interesting results about control, exposure and pattern of landslide occurrences in India. The Northwest Himalayas contribute 66.5% of landslides in India, followed by the Northeast Himalayas (18.8%) and the Western Ghats (14.7%). The Greater Himalayan sequence consisting of high-grade metamorphic rocks has a considerable control (32%), and the Main Central Thrust is the major regional structure controlling (12%) landslides in India. In the Northeast Himalayas, the size of landslides and the slope gradient controlling landslide occurrence are less in comparison to the Northwest Himalayas and the Western Ghats. Landslides in the Western Ghats are triggered with a lesser amount of rainfall than the Himalayan regions. Exposure analysis using four key socio-economic parameters in the 145 hilly districts shows that Rudraprayag district is most affected by landslides in India. The understanding derived using the landslide database on a national scale will help to prioritise and strengthen landslide disaster risk reduction strategies in India.

Keywords Satellite data · Landslide catalogue · Disaster risk reduction · District rank · Himalayas

Introduction

Landslide is a global problem and its incidences and impacts are increasing steadily due to unpredictable extreme events and exposure of the human population to climatic vagaries in the mountains (Gariano and Guzzetti 2016). According to a new database released by EM-DAT, landslides accounted for an economic loss of 0.9 billion US\$ in 2018 (EMDAT 2019). A study on fatal global landslides by Froude and Petley (2018) shows that spatial distribution of landslides is heterogeneous, globally, with Asia (mainly south and east) representing the dominant geographical region affected by landslide disaster. India ranks first among nations in terms of fatal landslides (Froude and Petley 2018). The Himalayas and the Western Ghats in India are ordained with high mountains and steep slopes, and the frequent presence of escarpments covered with friable rocks are hotbeds for the occurrence of landslides (Anbalagan 1992; Shroder and Bishop 1998; Nagarajan et al. 1998;

Rautela and Lakhera 2000). India is home to 1.38 billion people (1/6th of the world population) spread unequally across the Himalayan arc in the north and the Western Ghats in Peninsular India in the south. Given the vast geographic extent of India and exposure to different climatic conditions, it is essential to develop an understanding of controlling parameters and exposure of landslides in India as a vital ingredient to disaster risk reduction plans.

Landslide inventory is the key requirement for evaluating the exposure of socio-economic parameters and understanding the controlling parameters in the mountains and, hence, considered crucial to develop landslide mitigation strategies (Cruden and Varnes 1996; van Westen et al. 2008). Therefore, globally, there have been several attempts to prepare a landslide catalogue. Kirschbaum et al. (2010, 2015) made a global landslide inventory, mainly compiled from crowdsourcing and online reports, to understand the distribution and control of landslide disasters in the world. Herrera et al. (2017) prepared a European landslide inventory and analysed the landslide density map at the municipality level. Rosser et al. (2017) created a national landslide database of New Zealand that helped to understand the triggering parameters and impact of landslides. Lin and Wang (2018) created a database of fatal landslides in China and showed the temporal trend in landslide fatalities and the influence of terrain parameters for the occurrence of landslides. Lin et al. (2017) analysed the landslides triggered by the typhoon in Taiwan and found the hotspots to manage landslide disasters. Mirus et al. (2020) compiled a new landslide database of the USA and found out the areas where a further improved understanding of landslide disaster is necessary. Sepúlveda and Petley (2015) compiled the fatal landslide database in Latin America and the Caribbean and found the controlling factors of their occurrence. Pennington et al. (2015) and Taylor et al. (2015) prepared the landslide database of Great Britain and used them in landslide hazard mapping. Guzzetti (2000) prepared the landslide database of Italy and showed that the northern part of Italy is more prone to landslide disasters in comparison to the middle and southern regions. These studies carried out on a national scale showed the importance of landslide inventory database and provided guidelines to landslide disaster management and mitigation in respective countries.

In India, although several studies have been carried out on landslide inventory, hazard and risk mapping, they are mostly confined to local scale. For example, Martha et al. (2015) and Ghosh et al. (2020) prepared landslide inventory and analysed the cause of the occurrence of landslides in the Mandakini valley in parts of the Northwest Himalayas in India. Jaiswal et al. (2011) and Mathew et al. (2009) carried out landslide inventory, susceptibility and risk mapping along mountainous road corridors in the south and north India, respectively. Sarkar and Kanungo (2017) used GIS techniques for landslide susceptibility mapping in several parts of the Indian Himalayas with data

prepared from remote sensing and field investigation. Jamir et al. (2019) studied litho-tectonic and precipitation control on landslides in the Yamuna valley in the Uttarakhand state. The National Remote Sensing Centre (NRSC) has prepared a landslide hazard zonation Atlas for important tourist and pilgrimage routes in Uttarakhand and Himachal Pradesh states using the AHP technique (NRSA 2001). Sajinkumar and Oommen (2020) compiled the database of landslides in Kerala and prepared a landslide atlas. Similarly, Ghosh et al. (2016) prepared a compendium of landslides in Sikkim and Darjeeling Himalayas. The Department of Science and Technology (DST) in India sponsored many landslide-related research projects to academic institutions for site-specific mitigation and investigations (Singh 2014). A detailed bibliographic list of studies carried out on landslides in India was prepared by Parkash and Kathait (2014). These studies helped to understand the landslide problem in a localised manner across India. However, holistic research on a national scale with an in-depth analysis in various states and districts of India for understanding the exposure of socio-economic parameters to landslides and controlling terrain parameters has not been attempted so far to the best of our knowledge. Lack of a national scale landslide inventory catalogue can be attributed as one of the major causes.

In this paper, we present a catalogue of a pan-India geospatial inventory of landslides for the 1998–2018 period prepared from time to time by the National Remote Sensing Centre (NRSC) under the disaster management support programme (DMSP) of the Indian Space Research Organisation (ISRO). These landslides are triggered either by rainfall or earthquake. Landslide, being a geomorphic process, leaves a distinct signature on the surface of the Earth, thereby enabling itself to be viewed or captured directly and repeatedly by Earth Observation (EO) systems such as satellite or airborne remote sensing technology (Brardinoni et al. 2003; Vinod Kumar et al. 2008; Martha and Vinod Kumar 2013). The study of landslides using remote sensing is further strengthened by the availability of data from a large number of EO satellites in a post-disaster situation. This resolves the accessibility issue faced in conventional ground-based investigations (van Westen and Lulie Getahun 2003; Galli et al. 2008). We have evaluated the tectonostratigraphic, topographic, land use and rainfall control of landslides in the three landslide provinces of India, i.e. Northwest and Northeast Himalayas and the Western Ghats using the geospatial landslide inventory. We have performed an exposure analysis, wherein the hilly districts of India are ranked in terms of their exposure of socio-economic parameters to landslides.

Materials and methods

Landslides in India

India, a country with varied physiographic and climatic conditions, frequently faces the vagaries of landslide disasters. Approximately 0.42 million km², i.e. 12.6% of India's land area, is vulnerable to landslides (www.gsi.gov.in). The geological survey of India (GSI) has identified 1106 topographic sheets on a 1:50,000 scale covering hilly areas as prone to landslides in India (www.gsi.gov.in). These topographic sheets mainly fall within 145 districts in the Himalayan and Western Ghats regions of India, and our exposure analysis is focussed on these districts where landslide disaster risk reduction is a priority.

Historically, catastrophic landslides in the Himalayas have caused large-scale deaths, blocked river valleys and damaged buildings and roads. For example, the Malpa landslide in 1998 caused the death of 221 people in the Uttarakhand state of India (Paul et al. 2000). Similarly, extreme rainfall in 2013 caused floods and landslides with large-scale human casualties in Uttarakhand Himalayas (Martha et al. 2015). The Western Ghats is the second most prone region to landslide occurrences in India after the Himalayas and has always been a prime concern for damage due to landslide disaster (Thampi et al. 1995). Steep slopes and thick soil cover make this area susceptible to landslides (Sajinkumar et al. 2011). Some of the infamous landslides that had caused large-scale deaths and damage to property in this region are the Amboori landslides in Kerala and the Marappalam landslide in the Nilgiris of Tamil Nadu (Jaiswal et al. 2011). In 2018, 500 people died in Kerala and the adjoining states of Karnataka and Tamil Nadu due to incessant rain and landslides (Martha et al. 2019). A database compiled by us from news reports and statistics published by disaster management agencies shows that 10,305 people have died in India due to landslides and associated causes during the 1998–2018 period (Fig. 1). This figure includes death due to landslide associated disasters such as earthquake and flood that is difficult to differentiate (Devoli et al. 2007; Kirschbaum et al. 2010).

Geology and topography

The Indian subcontinent exhibits one of the grandest displays of geological and topographic diversity seen on the Earth. Influenced by two major tectonic events, namely the breakup of the Gondwanaland and the formation of the Himalayas with intermittent Deccan volcanism, and upliftment of the Peninsular region with reactivation of faults leading to the creation of the Western and Eastern Ghats, have resulted in a diverse array of geomorphic features and landscapes (Valdiya 2016).

The collision of the Indian and Eurasian tectonic plates is the cause of the formation of the Himalayan Orogen extending 2400 km arcuately from east to west and bounded by Sulaiman-Kirthar mountains in the west and Arakan-Yoma mountains in the east. The significant faults/thrusts system that resulted from the collision covering the Himalayas from south to north are the Himalayan Frontal Thrust (HFT), the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). Further north of the MCT, a shallow angle normal fault called the South Tibetan Detachment (STD) is located. The tectonostratigraphic units that are situated between the STD and the Indus Tsangpo suture zone (ITSZ) are mainly that of the Tethyan Himalayas which includes rocks from Lower Proterozoic to Cambrian (Haimantas Group) in the western Himalayas (Frank et al. 1995) and the rocks of Paleozoic to Eocene Tethyan sedimentary sequence (Gansser 1964; Gaetani and Garzanti 1991; Steck 2003). Towards the south of the STD, the underthrusting of the Greater Himalayan Crystalline (GHC) was accommodated in the South Tibetan Detachment System (STDS) (Herren 1987; Wiesmayr and Grasemann 2002). MCT separates GHC in the north and Lesser Himalayas in the south. The Lesser Himalayas rock units are mostly characterized by a series of anticlines and synclines. To the south of the Lesser Himalaya, the tectonic subdivision of the Himalayas termed as Siwalik Himalayas or sub-Himalayas is bounded by the MBT at its northern side and HFT on the southern side and is comprised of

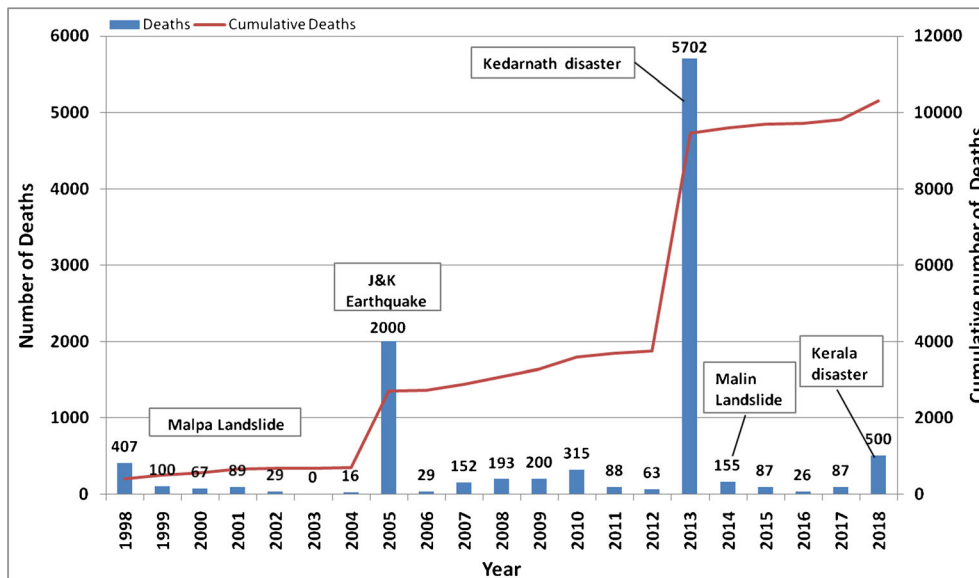


Fig. 1 Deaths due to landslides in India during the 1998–2018 period

rocks that are characterized by a series of folded and faulted molasses of Miocene and younger ages. The deformational regime spanning over the last ~ 50 Ma (and continuing) yielded inherent fissile nature to the rocks, making them highly prone to landslides.

The Western Ghats extending ~ 1600 km north-south is a part of the faulted south Indian Precambrian terrain (Valdiya 2016). Charnockites, charnockitic gneisses and pyroxene-bearing granulites occupy significant parts of the Western Ghats. Khondalites with garnet-sillimanite bearing gneisses are other major rock types in this region. Lateritization due to weathering by heavy rainfall develops a thick regolith, which is the leading cause of slope failures. West coast fault, Chiplun fault, Periyar fault and Achankovil shear zone are some of the significant structural breaks in the Western Ghats (Ramasamy 2006).

The topography of the Himalayas mainly consists of a ridge and valley system controlled by major thrusts/faults and reshaped by large rivers originating from the glaciers. Hence, along with fluvial action, glacial action is also responsible for shaping the landforms in the Himalayas. The Western Ghats are relatively less steep, but the high escarpment of ~ 1000 m height has resulted in a ridge and valley topography that are ideal for landsliding (Thampi et al. 1995).

Physiography and rainfall

The physiography of the Indian subcontinent is controlled by its evolutionary and geological history that encompasses the majestic mountains of the Himalayas, which form the northernmost borders. This is followed by the flat expanse of the Indo-Gangetic and Brahmaputra plains. Further south is the plateau of the Peninsular India, which is flanked by the uplands of Eastern and the Western Ghats encompassing the narrow coastal plains along the eastern and western seaboard. The Western Ghats is a faulted escarpment that runs parallel to the west coast of India and physiographically can be divided from east to west into four main domains such as the Western Ghats, foothills, midland and coastal low-land (Soman 2002).

The rainfall pattern in India is mainly controlled by the physiographic disposition of the landmass. Precipitation in India is irregular over the year, with a well-defined monsoon season over most of the country starting in June and ending in September. The average annual rainfall in India is 118 cm (Guhathakurta and Rajeevan 2006). The distribution of rainfall can be categorized into the following:

- i. Extreme precipitation regions: regions with more than 400 cm of rainfall, primarily those towards the windward side of the Western Ghats, and the northeastern segment of the Himalayas comprising of the Indian states of Assam, Meghalaya and Arunachal Pradesh
- ii. Heavy Precipitation regions: regions with 200 to 300 cm of rainfall comprising of a more substantial part of eastern India and sub-Himalayas
- iii. Moderate rainfall regions: regions with less than 200 cm of rainfall comprising mainly the leeward side of Western Ghats>

Data sources

Satellite data

High-resolution satellite data and 10 m CartoDEM were used for the landslide mapping (Table 1). Most of the satellite data used in this study are from the LISS-IV Mx sensor in the Resourcesat satellite of the Indian Space Research Organisation (ISRO). Since the method of landslide inventory mapping mainly relies on the change in image characteristics, bi-temporal data (pre- and post-disaster) were used. The datasets were selected optimally to minimize the effect of topographic shadow, the extent of snow and cloud in the Himalayan region. Although the majority of datasets are from Indian remote sensing satellites, other datasets procured through International Charter Space and Major Disasters (ICSMD) by emergency satellite payload programming immediately after

catastrophic landslide disasters were also used. Image derivatives such as NDVI, GNDVI, PCA and DEM derivatives such as slope angle and flow direction were incorporated in the semi-automatic detection of landslides (Martha et al. 2010).

Thematic data

The occurrence of landslides in an area is due to the interplay of favourable terrain parameters such as slope, lithology, topography and land use. Suitable combinations of these favourable terrain parameters trigger landslides in response to rainfall or earthquake events. Although it is difficult to quantify the exact contribution of each parameter to landsliding, an understanding of their relative contribution is significant for landslide disaster management and mitigation. Thematic information regarding lithology and structure was incorporated using maps of GSI (www.bhukosh.gsi.gov.in) and seismotectonic atlas of India. The land use information was included from the LULC 2nd Cycle Project carried out by the National Remote Sensing Centre (NRSC) on a 1:50,000 scale (NRSC 2014). Topographic thematic data such as slope angle and slope position were derived from the 10-m CartoDEM. Slope angle map was prepared in GIS, and the Topographic Position Index (TPI) tool was used to identify slope positions such as ridges, valleys, flat slope and mid-slope (Jenness 2006).

Rainfall data

Over 75% of the rainfall in India is received in the four monsoon months from June to September. Analysis of landsliding due to rainfall in India requires a large spatial extent of data. Although the Indian Meteorological Department (IMD) monitors the rainfall in India using a large number of rain gauge stations, the spacing of such data points is such that it cannot be interpolated to create maps which is essential for a meaningful spatial correlation with landslides. Therefore, we have used rainfall data from the Climate Prediction Centre (National Oceanic and Atmospheric Administration, USA). This data, also known as CPC Merged Analysis of Precipitation (CMAP), is available (<ftp.cpc.ncep.noaa.gov/fews/S.Asia/data>) for the entire globe with an approximate grid size of 10 km × 10 km over the Indian region. Daily rainfall data products from CMAP were used to prepare monsoon rainfall maps (June–September) to understand the rainfall distribution pattern vis-a-vis the landslide occurrences.

Socio-economic data

Four major socio-economic parameters, i.e. population, house, livestock and road, bear the brunt of landslide disasters. They are also critical to the social and economic development of the region, and hence the exposure of a given area is high if these parameters are highly open to landslides. We extracted total population and household at the district level from the 2011 census report of India (Census 2011). Livestock data at the district level was extracted from the 2012 livestock Census report of India (Census 2012). The road database available in the National Emergency Database Management portal of India (www.ndem.nrsc.gov.in) was used in the exposure analysis.

Method

Landslide inventory mapping

Landslide inventory mapping was carried out to map landslides triggered by rainfall and earthquake using satellite data. Land-

slides triggered due to rainfall in the monsoon season (June–September) are labelled as seasonal landslides. Those triggered by extreme rainfall events of short duration or earthquake are labelled as event-based landslides. Additionally, archived landslide inventory data prepared using satellite data and field verification by the NRSC were used in the landslide catalogue.

Seasonal landslide inventory mapping (SLIM): Mainly pre-monsoon season (Mar–May, 2014) and post-monsoon season (Oct–Dec, 2014) Resourcesat-2 LISS-IV Mx (5.8 m) satellite data were used in the seasonal landslide mapping. Hence, the mapped landslides correspond to the new landslides triggered by rainfall during the monsoon season (June–September) of 2014. Given the vast geographical area of India to be covered for SLIM, the use of the manual method by visual satellite image interpretation is an arduous task. Therefore, the semi-automatic method developed by Martha et al. (2010, 2011, 2012) for the detection of landslides from high-resolution satellite data and DEM was used for the creation of the seasonal landslide inventory database. This method follows a knowledge-based generic spectral-spatial-morphometric approach to detect landslides from high-resolution satellite and DEM data. It uses an object-based change detection approach to extract landslide polygons from satellite images. The SLIM methodology adopted in this study is explained in detail by Martha et al. (2016). The objects or polygons classified as landslides were exported as GIS data for quality checking, which was done by visual inspection of images. Landslide polygons missed by the semi-automatic procedure were added, and erroneously detected landslides were deleted during the quality checking process.

Event-based landslide inventory mapping: An event-based landslide inventory map was prepared using the same method as adopted for the SLIM. However, the post-disaster satellite data covering the affected region acquired immediately after the event by emergency satellite payload programming was used with archived pre-disaster satellite data for event-based mapping purposes.

Field-based landslide inventory: This landslide inventory corresponds to 1998, which was prepared by NRSC using merged IRS-1D PAN+LISS III data (5.8 m) by visual image interpretation and verified on the ground (NRSA 2001). Here, the landslide mapping was carried along the road corridors.

Landslide control assessment

Control of tectonostratigraphy, topography, land use and rainfall on the occurrence of landslides was estimated through GIS analysis. The polygon landslide data were intersected with thematic layers and the area in each class of thematic data was calculated and interpreted as the influence of the terrain. To find the impact of major geological structures (line layer), the centroid of landslide polygons was estimated, and the shortest distance of the centroid to the line layer was calculated. A raster model was used to analyse the control of slope, topographic position and rainfall on the occurrence of landslides. For example, in case of slope, presence of landslides in each 10 m slope grid was calculated. The result was summarised for all the slope classes and then multiplied with 100 (grid area) to estimate the area of landslides.

Socio-economic parameter exposure assessment

Socio-economic parameters (SEP) (e.g. total population, no. of households, livestock and road) for 145 districts in the hilly region used in the study are non-spatial data. Since district is the unit of

Table 1 Satellite data used in landslide inventory mapping

Sl. No.	Data	Sensor	Resolution (m)
1	Resourcesat-1, 2, 2A	LISS-IV Mx	5.8
2	Cartosat-2 and 2S	PAN and Mx	0.6-1.6
3	Cartosat-1	PAN	2.5
4	WorldView-2	PAN and Mx	0.46-1.84
5	Komsat-2, 3	PAN and Mx	1-4
6	GeoEye-1	PAN and Mx	0.38-1.5
7	Pleiades-1A, 1B	Mx	2
8	SPOT-6, 7	Mx	6
9	GF-2	Mx	3.24
10	PlanetScope	Mx	3
11	RapidEye	Mx	5
12	Sentinel-2A, 2B	Mx	10
13	IRS-1C/1D	PAN+LISS-III	5.8

exposure analysis, we have created two indices that are normalised with the area of the district. Two indices, i.e. district landslide density (Eq. 1) and district SEP density (Eq. 2) were calculated using excel table operation. Subsequently, district landslide density was multiplied with each of the four district SEP densities separately for the 145 districts to estimate the exposure of each SEP and then combined to determine the district exposure index (Eq. 3) that was used to rank districts.

$$\text{District landslide density (DLD)} = \frac{\text{Area of landslide in district}}{\text{Area of district}} \tag{1}$$

$$\text{District SEP density (DSEPD)} = \frac{\text{SEP count}}{\text{Area of the district}} \tag{2}$$

$$\text{District Exposure Index} = \text{DLD} * (\text{DSEPD}_p + \text{DSEPD}_h + \text{DSEPD}_l + \text{DSEPD}_r) \tag{3}$$

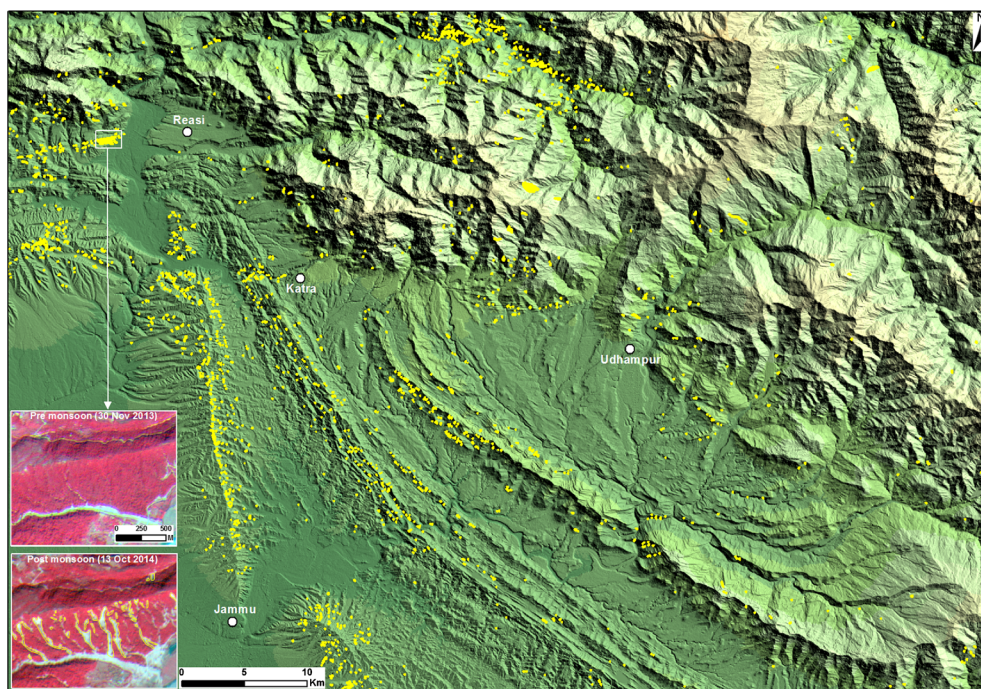


Fig. 2 Painted relief map showing Seasonal landslide inventory map (2014) in parts of the northwest Himalayas in India. Inset shows pre- and post-monsoon LISS-IV Mx images used in landslide (yellow polygons) mapping. The location of this figure is shown in Fig. 5

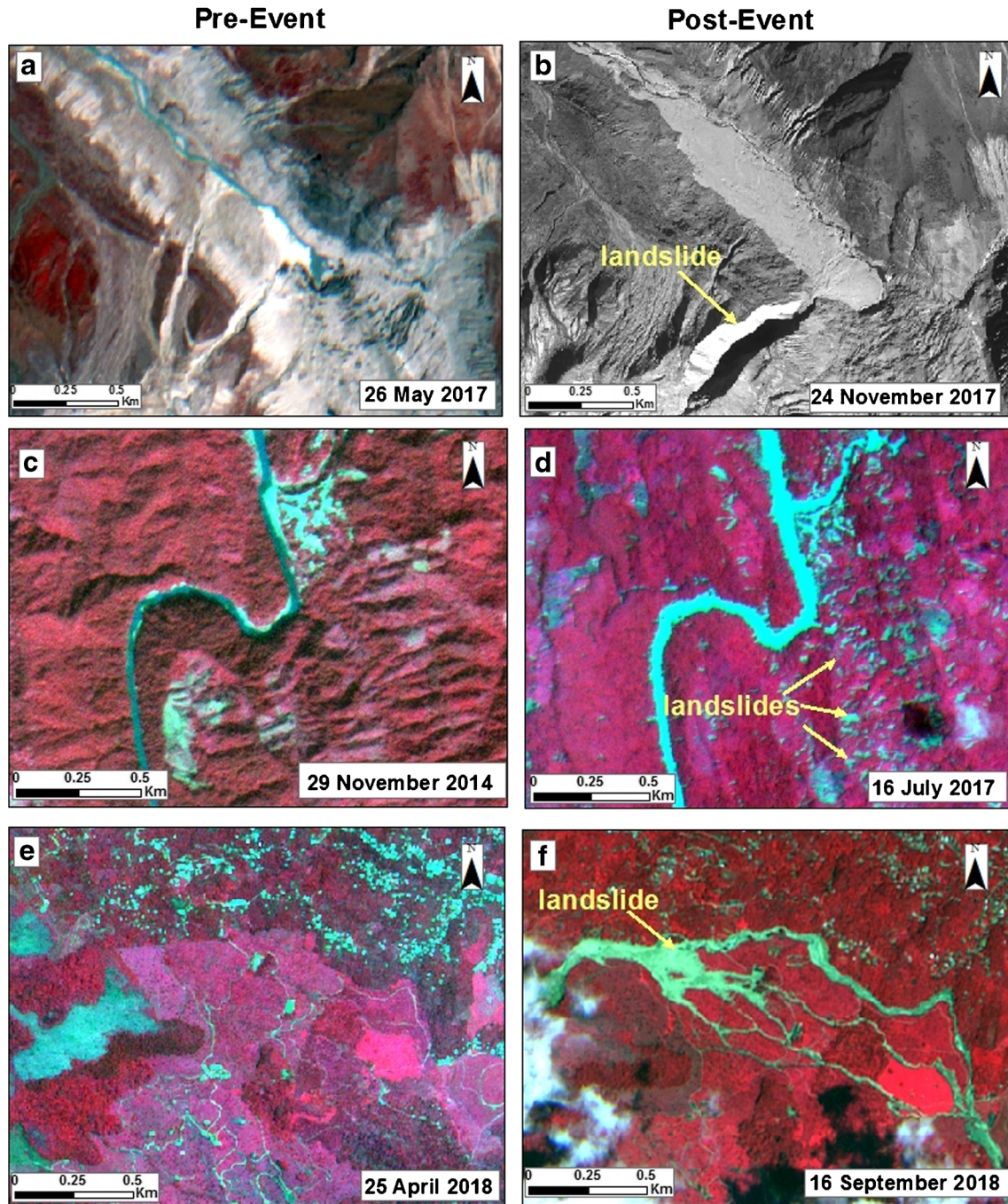


Fig. 3 Event-based landslide inventory of some of the significant landslides mapped using high-resolution satellite data. **a,b** Gaumukh, Uttarakhand. **c,d** Lunglei, Mizoram. **e,f** Kurchemala, Kerala. The left and right panel shows pre- and post-event satellite images, respectively

where subscripts p , h , l and r in $DSEPD$ refer to population, house, livestock and road, respectively.

Results

Landslide inventory

The landslide inventory database was created for India for the 1998–2018 period which consists of landslides triggered by 2014

monsoon season rainfall, extreme event rainfall and earthquake and archived field-based inventory along road corridors.

Monsoon season landslide inventory

The seasonal landslide inventory database corresponds to the 2014 monsoon rainfall period (Fig. 2). This inventory is the most comprehensive inventory mapping carried out, and the database is prepared for entire India, covering 16 states and two union

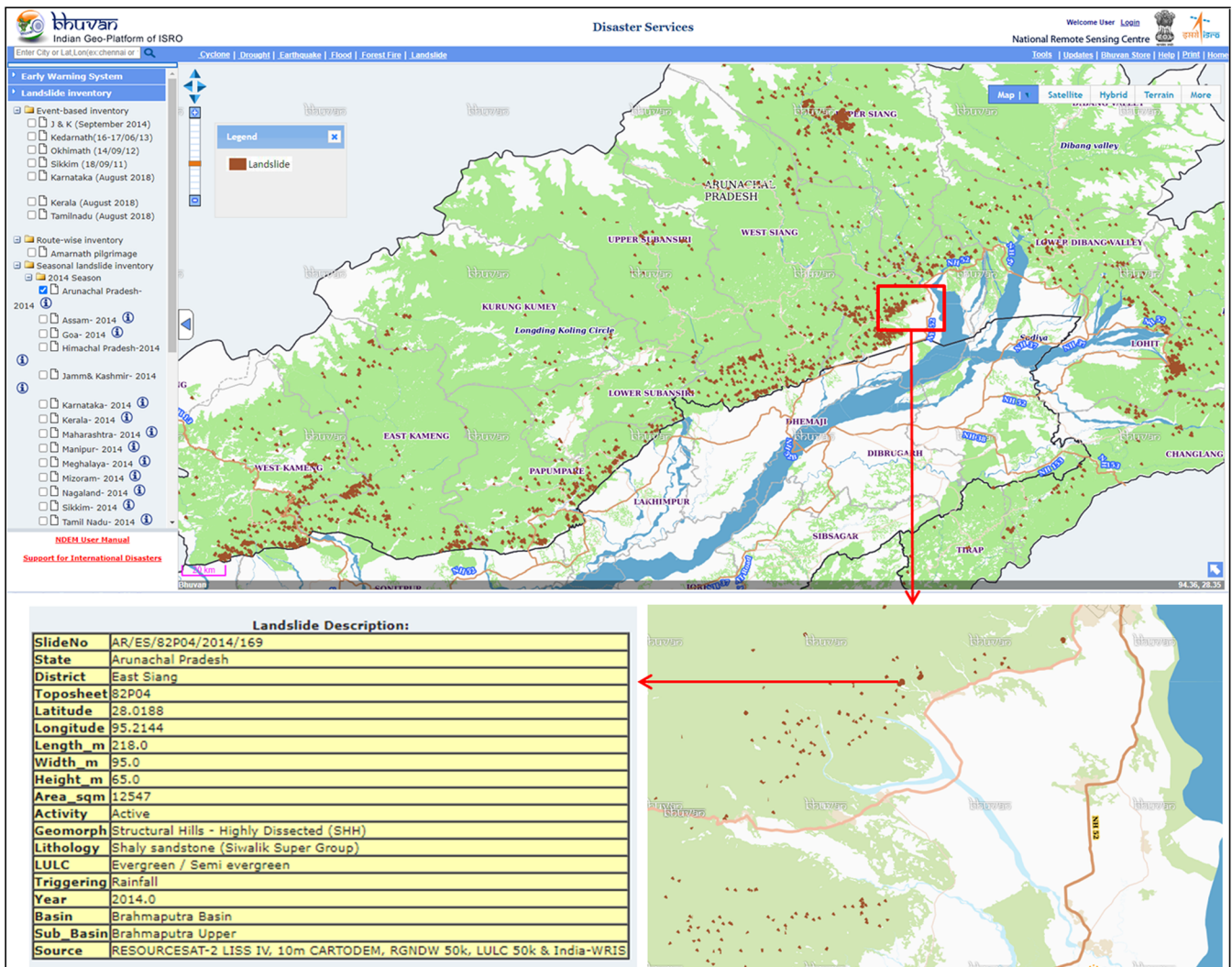


Fig. 4 The seasonal landslide inventory database in the Bhuvan portal (www.bhuvan.nrsc.gov.in) is shown with attribute information displayed for parts of Arunachal Pradesh state, India

territories. A total of 17,688 landslides were mapped for the 2014 monsoon period.

Extreme rainfall event-based landslide inventory

The event-based landslide inventory data captured those landslides, which have severely impacted river valleys due to damming, damaged houses and caused the death of people or blocked key road or railway routes (Roy et al. 2014; Martha et al. 2017, 2019). For example, large-scale occurrences of landslides on 14 September 2012 due to cloud burst resulted in the death of 51 people near Okhimath, Uttarakhand. An event-based inventory of 473 landslides covering a 2.25 km² area was created for the 14 September 2012 event using an object-based image analysis technique (Martha and Vinod Kumar 2013). Similarly, during 16–17 June 2013, unprecedented cloud burst and rainfall occurred in the Kedarnath, and surrounding valleys of Uttarakhand resulted in 6610 landslides in the valleys (Martha et al. 2015). A cyclonic event, Mora in May 2017, resulted in 10,022 landslides in the Northeastern states. In

August 2018, uncharacteristically heavy monsoon rains triggered 6324 landslides in hilly regions of Kerala, Karnataka and Tamil Nadu states in south India (Martha et al. 2019). Figure 3 shows some of the significant landslide events mapped using high-resolution satellite data.

Catalogue of geospatial landslide inventory of India

A catalogue of geospatial landslide inventory of India was created. The catalogue contains 45,334 landslides in India mapped by NRSC during the period from 1998 to 2018 and is available in the Bhuvan geoportal of NRSC (Fig. 4). The state-wise list of landslides in India is shown in Table 2. Figure 5 shows the distribution of landslides in India as available in the catalogue.

Landslide control analysis

The landslide inventory database was used for terrain control analysis. Given the vast geographic extent and local terrain variation of landslide affected areas in India, the results of the control analysis were mainly presented with reference to the three

Table 2 State-wise breakup of the number of landslides under the categories of monsoon season (2014), field-based and event-based

Sl. No.	State/UTs	Monsoon season (2014)	Field-based/year	Event-based/year	Total
1	Jammu and Kashmir	6826	*434/2011	1/2015	7261
2	Ladakh	23	-	-	23
3	Himachal Pradesh	922	413/1998	1/2017 51/2013	1387
4	Uttarakhand	1593	1419/1998	32/2003 307/2010 473/2012 6610/2013 1/2017	10,435
5	Sikkim	73	-	**1408/2011 8/2012 1/2016	1490
6	West Bengal	24	-	66/2011	90
7	Arunachal Pradesh	2904	-	75/2016	2979
8	Nagaland	54	-	7/2017	61
9	Manipur	379	-	556/2017	935
10	Mizoram	1205	-	8926/2017	10,131
11	Tripura	56	-	-	56
12	Assam	1243	-	533/2017	1776
13	Meghalaya	2127	-	-	2127
14	Maharashtra	97	-	-	97
15	Goa	2	-	-	2
16	Karnataka	82	-	993/2018	1075
17	Kerala	9	-	4728/2018	4737
18	Tamil Nadu	79	-	603/2018	682
	Total	17,688	2266	25,380	45,334

*Along a road corridor, but not field checked. **Landslides triggered by the 18 September 2011 Sikkim earthquake

landslide provinces of India, i.e. Northwest Himalayas, Northeast Himalayas and the Western Ghats, for a meaningful conclusion.

Tectonostratigraphy

Lithology and geological structures play a crucial role in conditioning the terrain for the occurrence of landslides during a triggering event. Analysis of landslide occurrences in the Indian Himalayas was performed with reference to the four major lithostratigraphic units (Tethyan Himalayan sequence, Greater Himalayan sequence, Lesser Himalayan sequence and sub-Himalayan sequence). Results reveal that the Greater Himalayan sequence has the highest (32%) control on the occurrence of landslides in India. The control of the other three lithostratigraphic units in the Himalayas is shown in Fig. 6a. Intrusive granites and quaternary deposits have limited control of landslide occurrences in the Himalayas. Gneisses, charnockites and khondalites mainly control landslides in the Western Ghats (Fig. 6a). In the Northeast Himalayas, the shale and sandstone of Disang, Surma and Tipam group mainly control landslides in Manipur, Mizoram and Tripura.

The influence of major geological thrusts/faults and lineaments on the occurrence of landslides is shown in Fig. 6b. Results show

that MCT has the maximum impact (12%) as a single regional structure on the occurrence of landslides compared to other thrusts/faults. HFT has the minimum impact (3%) on the occurrence of landslide. The number of landslides decreases with an increase in the distance, which shows the diminishing influence of structures with an increase in range for the occurrence of landslides (Fig. 6).

Topography

The disposition of landslides with respect to topographic positions, i.e. ridge, valley and mid-slope, has a clear distinction in the three landslide provinces of India. Landslides near ridges (9%) are much less in comparison to valleys (39%). Maximum landslide (52%) occurred in the mid-slope region. However, in the Western Ghats, landslides in the valleys are more than the mid-slope region (Fig. 7).

The topographic slope is the primary reason why landslides occur in mountainous areas. The slope angle derived from the 10-m CartoDEM was classified into 10 classes (Fig. 8). Generally, steep slopes are the main areas where landslides occur frequently and this trend is observed in all the three landslide provinces of India. However, in terms of the contribution of other slope categories for

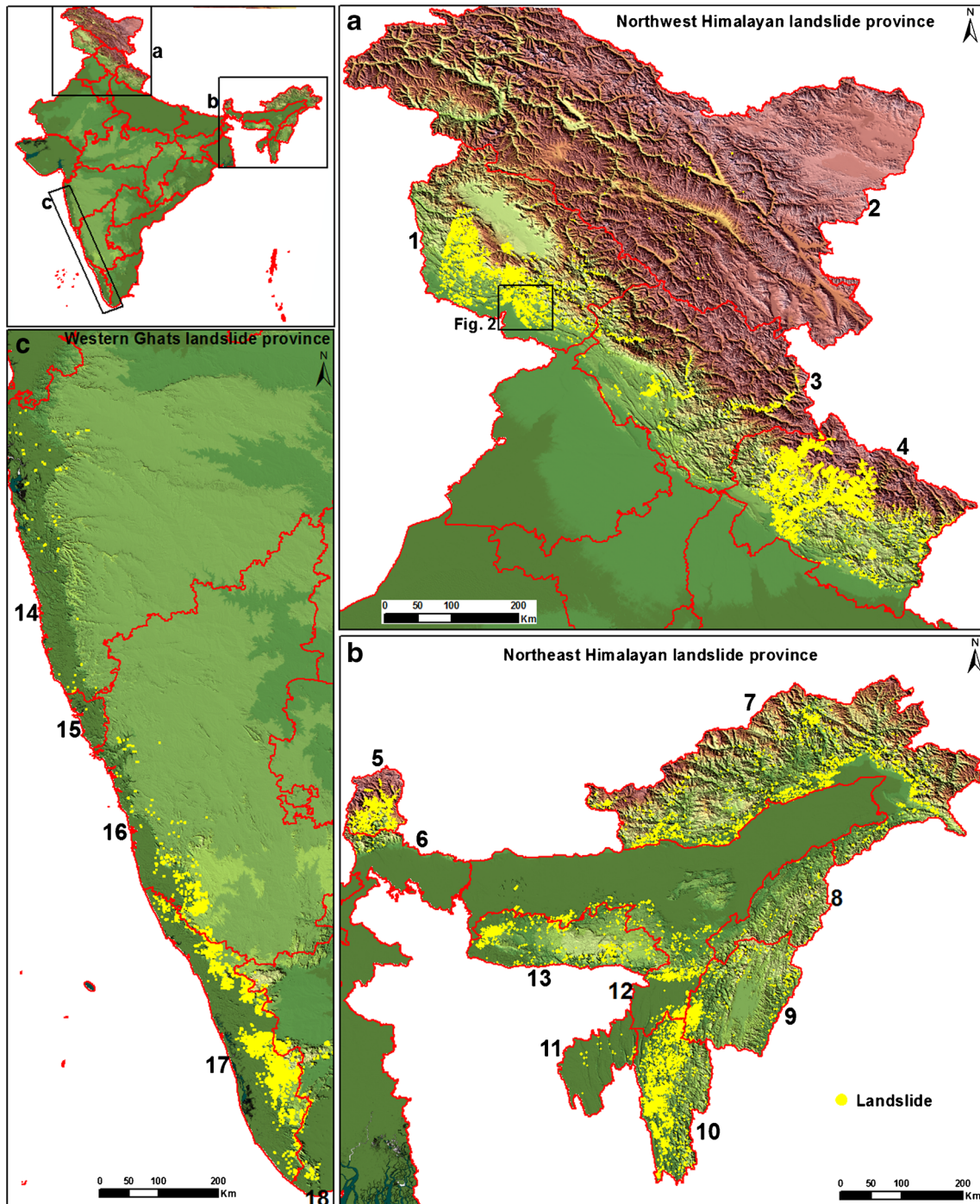


Fig. 5 Painted relief map showing a geospatial inventory of landslides in India mapped from 1998 to 2018 period using satellite data. **a** Northwest Himalayan landslide province, **b** Northeast Himalayan landslide province and **c** Western Ghats landslide province. States and UTs are numbered as per the sequence in Table 2

landsliding, the Northeast Himalayas witnessed a reasonable number of landslides in lower slopes (Fig. 8).

Rainfall

The pan-India seasonal landslide inventory database prepared using satellite data for 2014 was used for rainfall control analysis. It corresponds to whole monsoon rainfall for all the three

landslide provinces of India. The result shows a variation in rainfall intensity for the occurrence of landslides in India. In the Northwest Himalayas, maximum landslides are triggered with 1000–1250-mm rainfall, though 750–1000-mm rainfall is also responsible for the occurrence of significant landslides (Fig. 8). However, in the Northeast Himalayas, the occurrence of landslides does not show any clear dominance of any particular range of

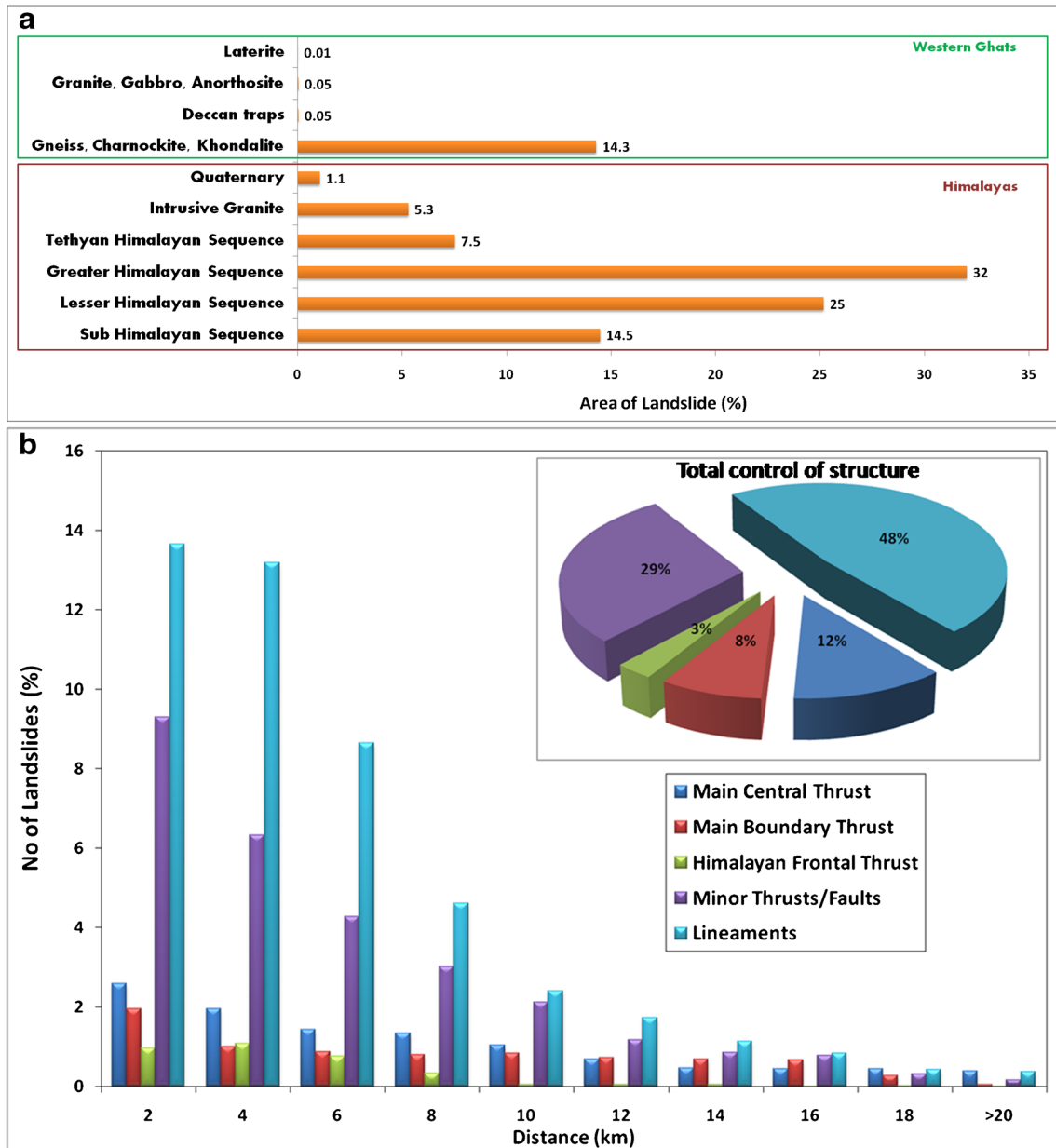


Fig. 6 Tectonostratigraphic control on the occurrence of landslides in India. **a** Lithostratigraphy and **b** geological structure

rainfall intensity, though 500–750 mm of rainfall has maximum control on landslide occurrences. Contrastingly, the Western Ghats have a single dominant category, though low-intensity range (250–500 mm) for the occurrence of maximum (70%) landslides (Fig. 8).

Land use/land cover

A total of 16 land use/land cover classes control the occurrence of landslides in the three landslide provinces of India. Evergreen/semi-evergreen and deciduous forests show apparent domination to control landslides in the Northeast Himalayas and the Western Ghats. However, in the Northwest Himalayas, though evergreen/semi-evergreen and deciduous forests have significant control over the occurrence of landslides, croplands show maximum

control in comparison to other categories (Fig. 8). Scrubland and scrub forests are the other land use/land cover category that controls the occurrence of landslides to a great extent. However, their control is more in the Northwest Himalayas than the other two landslide provinces (Fig. 8).

Socio-economic parameter exposure analysis

District-wise landslide exposure analysis of four socio-economic parameters was carried out, and the estimated landslide exposure index was used to rank each district. The result for the top ten rank districts is shown in Table 3. Rudraprayag district in the Uttarakhand state is the most exposed district in India to socio-economic parameters. Tehri-Garhwal is the second most exposed

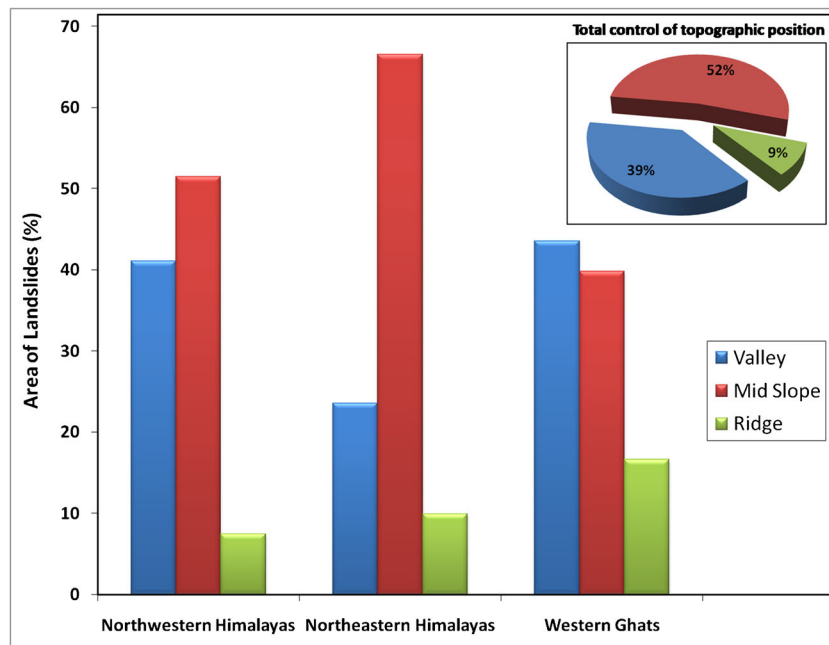


Fig. 7 The occurrence of landslides in different topographic positions within the three landslide provinces of India

district, but the exposure index of Rudraprayag is significantly high in comparison to Tehri-Garhwal, which shows its higher level of exposure to landslides (Table 3). Kerala has four districts in the top ten categories, which indicates the severity of the landslide disaster compared to other states of India. This is mainly due to the high density of the population, even though the density of landslides is less than Uttarakhand (Table 3).

The spatial distribution of the top ten exposed districts to landslide is shown in Fig. 9. The relative exposure of each of the four socio-economic parameters to landslides in the top ten ranked districts is shown in Fig. 9. Livestock contributes more to the ranking of the top ten districts within J&K. Ranking of all 145 districts based on the exposure index is given in the supplementary table.

Discussion

A geospatial (polygon) catalogue of 45,334 landslides covering 145 districts in 16 states and two union territories of India was prepared for the 1998–2018 period. The total area of landslides mapped in India during this period is 160 km², and Uttarakhand state has the highest area (75 km²) under landslides. Garhwal region of Uttarakhand has more landslides in comparison to the Kumaon region. The Northwest Himalayas covering Uttarakhand, Himachal Pradesh, Ladakh and Jammu and Kashmir contributes 66.5% of landslide area in India, followed by the Northeast Himalayas (18.8%) and the Western Ghats (14.7%) (Table 4). Although the number of landslides in the Northwest Himalayas is less than the Northeast Himalayas, contrastingly, the area of the former is significantly larger than the later. This is mainly due to the presence of small-sized landslides in the Northeast Himalayas controlled by rocks such as shale, sandstone and phyllite.

Frequency analysis of landslide dimensions was done using the 2014 seasonal landslide inventory since it is a complete data of

landslides corresponding to monsoon rainfall, and results were obtained uniformly in terms of satellite data type and method. Results of the analysis of landslide lengths estimated from the respective histogram distribution indicate that the modal length of landslides in the Northeastern Himalayas is approximately 35 m. In contrast, those in the Northwest Himalayas and the Western Ghats are approximately 46 m and 43 m, respectively (Fig. 10a). Further, as seen worldwide (Malamud et al. 2004), the area distribution of the landslides exhibits a power-law correlation with a peak at low values and tailing off towards higher values (Fig. 10b). This also substantiates the comprehensive and inclusive mapping of the landslides in this study.

In the Northeast Himalayas, Sikkim has the highest area (9.8 km²) under landslides (majority of them are triggered by the 18 September 2011 earthquake), although Mizoram has the highest number of landslides (10,131). In the Western Ghats region, which covers five states, Kerala has the maximum number of landslides (4737). The majority of landslides mapped in Kerala, Karnataka and Tamil Nadu correspond to the August 2018 rainfall event.

In the Western Ghats, the intensity of rainfall to trigger landslides is less than in the Himalayas. This is mainly due to lateritic soil with high soil depth that allows water to be retained in the pores quickly, leading to an increase in pore water pressure and subsequent landsliding. In the Himalayas, mostly hard rocks are exposed; thus, the rainwater quantity required to increase the pore water pressure is high. Similarly, in the Western Ghats, the majority (65%) of landslides are associated with a steep slope (> 40°). However, in Northeast Himalayas, the critical slope is 20° and above where 70% of the landslide is located. This is mainly because hills in the Northeast Himalayas part of compressed fold and fault sequence wherein rocks have reduced shear strength suitable for slope failures. Rudraprayag district in Uttarakhand state has the highest landslide density in India. The top four districts in India,

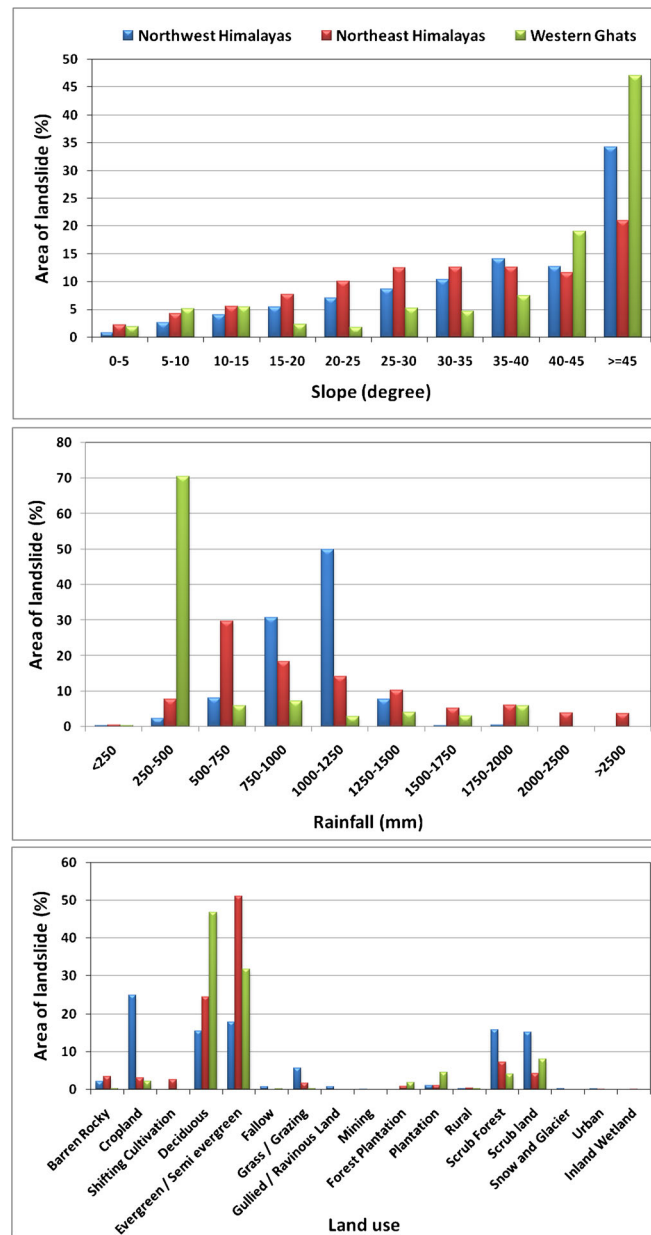


Fig. 8 Control of slope, rainfall and land use on occurrence of landslides in the Northwest Himalayas, the Northeast Himalayas and the Western Ghats

in terms of landslide density, are located in the Uttarakhand state. In the Northeastern states, North Sikkim district in the Sikkim state and in the Western Ghats and Idukki district in Kerala state have the highest landslide density.

Socio-economic parameter exposure analysis of total population, no. of house, livestock and road were carried out in the mountainous areas. Rudraprayag district in Uttarakhand state, which has the highest landslide density in India, is also having the highest exposure to all four socio-economic parameters among all 145 districts in India.

Conclusions

Landslides are one of the most common and repetitive natural disasters in India. Economic development and growing population

rate put more demand on limited land resources in mountainous regions, thus leading to unscientific planning and an increased number of landslide disasters. The factors responsible for the occurrence of landslides are interdependent. It is seen that the rainfall pattern and its variability is the dominant trigger of landslides and the monsoon rainfall in India generally controls their spatial distribution. However, it is also seen that sporadic events of heavy rainfall (e.g. Kedarnath event in 2013) and earthquake (e.g. Sikkim earthquake in 2011) may also trigger a large number of landslides. The northern states and UTs of India, mainly J&K, Himachal Pradesh and Uttarakhand, with their significant areal extent falling within the Himalayas, are the worst affected by landslide disaster. The extent of the Himalayas actively controls the geographic distribution of landslides. The shale-sandstone-

Table 3 Summary of the exposure analysis, categorising the top ten exposed districts under each socio-economic subfactor. The individual contribution of each subfactor in the overall ranking is also shown

District	Rudraprayag	Tehri-Garhwal	Rajauri	Thrisur	Pulwama	Palakkad	Malappuram	South District	East District	Kozhikode
State	Uttarakhand	Uttarakhand	J&K	Kerala	J&K	Kerala	Kerala	Sikkim	Sikkim	Kerala
House	53,542	132,714	130,401	759,210	86,241	637,220	793,999	30,543	61,567	697710
Population	242,285	618,931	642,415	3,121,200	560,440	2,809,934	4,112,920	146,850	283,583	3,086,293
Livestock	182,351	365,997	1,012,372	256,826	224,726	293,467	239,112	76,235	88,808	155,899
Road length (km)	800.87	3320.31	2072.91	4599.44	1156.40	4794.66	4097.78	1048.90	1185.02	3472.92
No. of landslides	1812	1861	1329	387	1206	1300	514	226	165	152
Landslide area (sq.km)	16.86	11.98	3.41	1.76	2.81	3.24	1.36	1.04	0.92	0.62
Area of district (sq.km)	1789.77	3768.12	2627.32	3070.97	1956.00	4542.03	3598.41	705.01	909.09	2349.17
Landslide density	0.0094	0.0032	0.0013	0.0006	0.0014	0.0007	0.0004	0.0015	0.0010	0.0003
House density	29.9156	35.2202	49.6327	247.2218	46.1457	140.2942	220.6526	43.3229	67.7235	297.0033
Population density	135.3721	164.2546	244.5134	1016.3573	243.7807	618.6521	1142.9819	208.2956	311.9404	1313.7823
Livestock density	101.8852	97.1299	385.3250	83.6303	222.0414	64.6115	66.4493	108.1336	97.6885	66.3635
Road density	0.4475	0.8812	0.7890	1.4977	0.5912	1.0556	1.1388	1.4878	1.3035	1.4784
House exposure	0.2819	0.1120	0.0645	0.1417	0.0662	0.1000	0.0837	0.0639	0.0684	0.0780
Population exposure	1.2755	0.5221	0.3176	0.5824	0.3498	0.4411	0.4335	0.3072	0.3150	0.3451
Livestock exposure	0.9600	0.3088	0.5005	0.0479	0.3186	0.0461	0.0252	0.1595	0.0986	0.0174
Road exposure	0.0042	0.0028	0.0010	0.0009	0.0008	0.0008	0.0004	0.0022	0.0013	0.0004
Total exposure	2.5215	0.9456	0.8836	0.7728	0.7355	0.5879	0.5428	0.5328	0.4834	0.4410
District rank	1	2	3	4	5	6	7	8	9	10

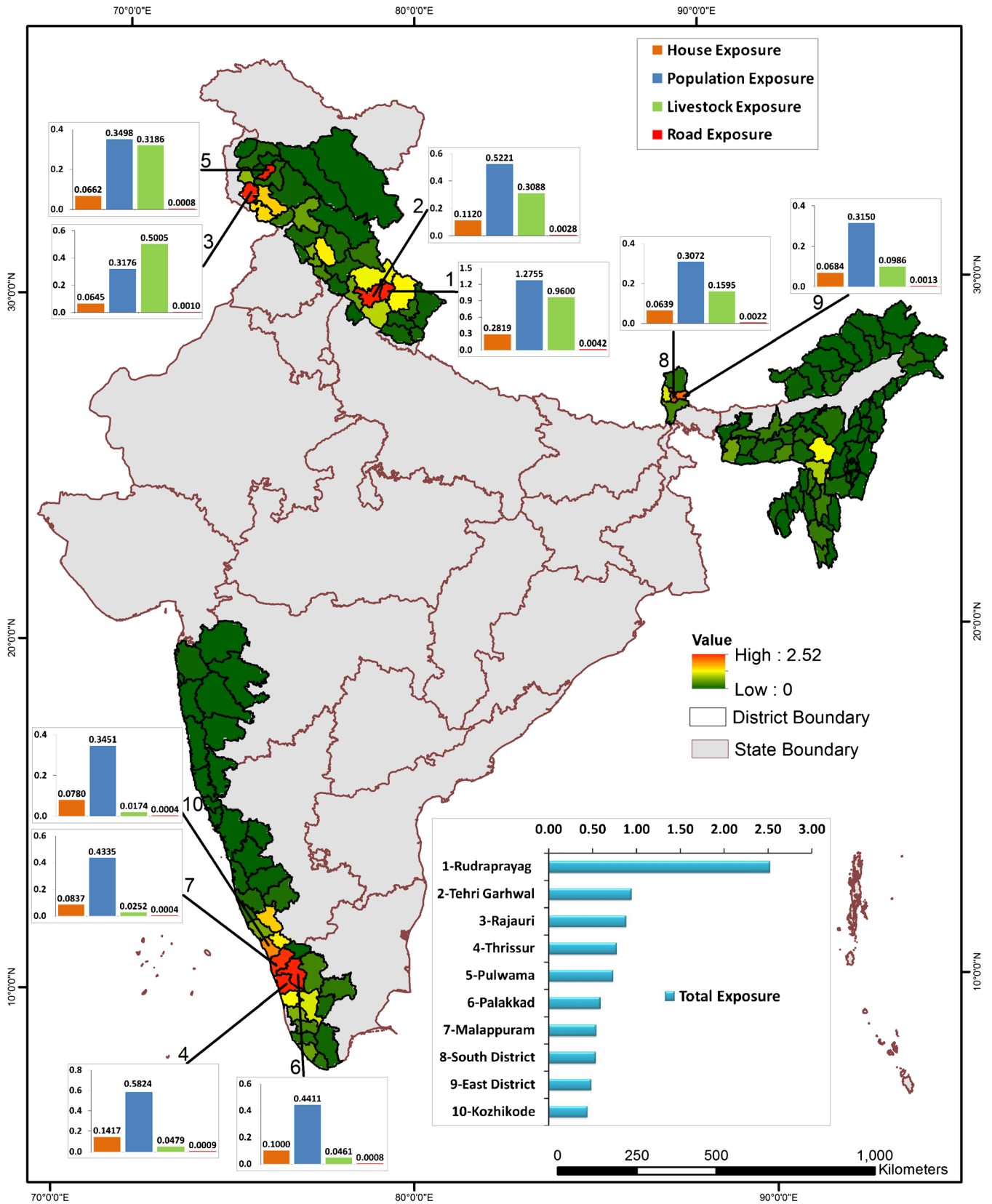


Fig. 9 Socio-economic parameter exposure map. The contribution of each exposure element for the top ten exposed districts is shown in vertical bars. Total exposure is shown in horizontal bars

Table 4 Landslide statistics in three landslide provinces of India

Sl. No.	Landslide province	No. of landslides	Minimum area (m ²)	Maximum area (m ²)	Mean area (m ²)	Total area (km ²)
1	Northwest Himalayas	19,096	25	1,390,350	5884	106.39
2	Northeast Himalayas	19,645	12	348,608	1559	30.14
3	Western Ghats	6593	20	603,747	3372	23.49

metasediments forming dissected hills along the slopes of 30° to 45° control the spatial distribution of landslides. This, coupled with rainfall of 750 - 1000 mm, is seen to trigger landslides.

The district of Rudraprayag in Uttarakhand ranks one in all major socio-economic parameters. Also, owing to the major pilgrimage routes, the state of Uttarakhand stands out to be the most vulnerable to landslide disaster. The Northeastern states record a large number of landslides annually, but due to less population density and the uninhabited significant areal extent of the mountain are not exposed to landslides to a large extent in terms of socio-economic parameters. The exposure of population and household is high in the Western Ghats, particularly in the Kerala state, though the landslide density is less in comparison to Himalayan areas. This can be attributed to the very high population and household density in some districts of Kerala such as Thrissur, Malappuram and Palakkad. The escarpments and slopes of the Western Ghats record occurrences of landslides, but these are primarily controlled by the soil cover on the slopes with rainfall as the critical trigger.

The main advantage of the landslide database created in this study is that they are prepared by a uniform change detection method using high-resolution pre- and post-disaster satellite data ranging in spatial resolution from 0.3 m to 5.8 m. So it captured the majority of landslide occurrences in remote areas that are difficult to map in the field-based method. Further, landslides in the database were mapped as polygons (not points as in many other studies) with high positional accuracy. Landslides were mapped in all landslide prone areas of India. However, we agree that many more landslides might have been missed to be mapped during the 1998–2018 period since it is difficult to map all of them on a national scale. The terrain parameter analysis, although carried out on a national scale, uses land use/land cover, lithology and structure maps on a 1:50,000 scale prepared using a uniform classification scheme and, thus, helped to draw results in a detailed manner. Further, this study ranks districts on a national scale using socio-economic parameters. A detailed study needs to be taken up at the local level to implement future developmental activities.

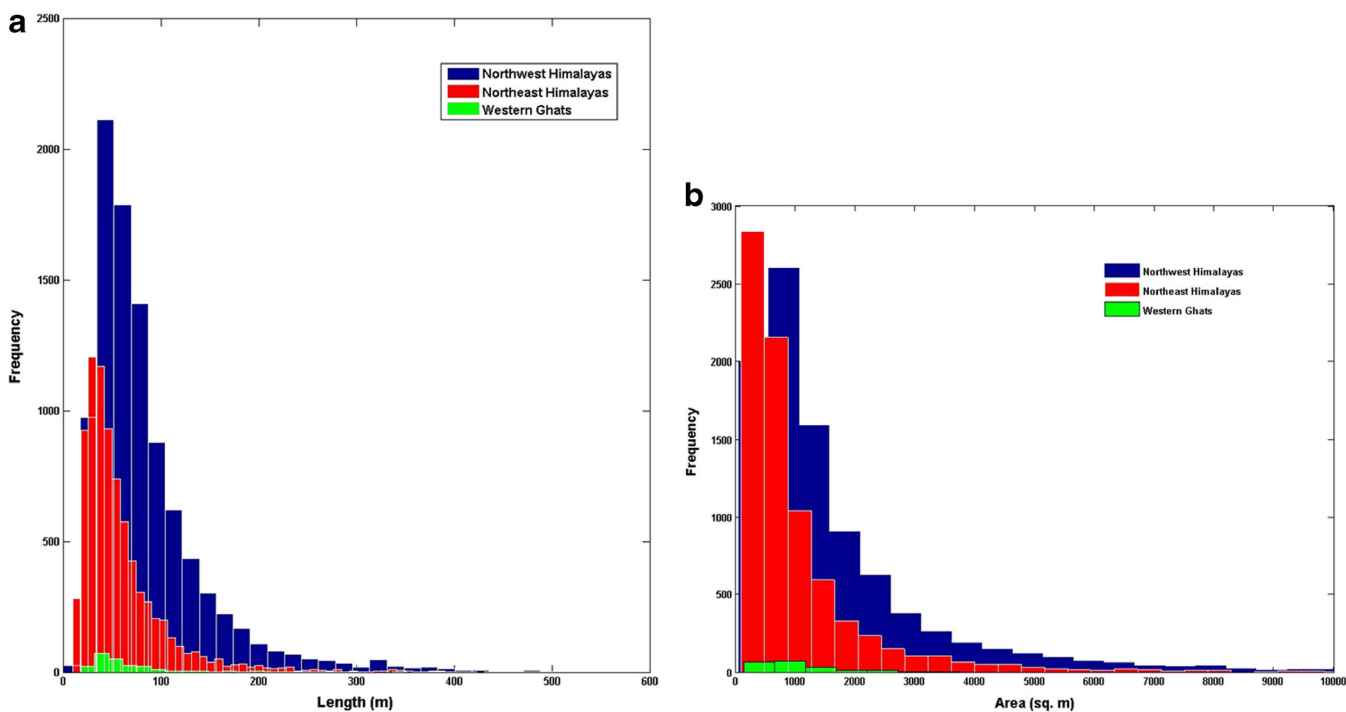


Fig. 10 Histogram of landslide length and area in **a** Northwest Himalayas, **b** Northeast Himalayas and **c** Western Ghats. For representation purposes, the length is shown up to 600 m, and the area is shown up to 10,000 m²

The geospatial landslide inventory catalogue of India will be useful for future studies. Since landslide is a crucial contributor to sediments in the mountains, the understanding pattern of its occurrence will help in the prioritisation of watershed management. The study of the relationship between rainfall and landslide incidences will help in the development of an early warning system for landslides.

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