

Landslides (2023) 20:97–109
 DOI 10.1007/s10346-022-01977-6
 Received: 1 July 2022
 Accepted: 13 October 2022
 Published online: 24 October 2022
 © Springer-Verlag GmbH Germany,
 part of Springer Nature 2022

Priyom Roy · Tapas R. Martha  · K. Vinod Kumar · Prakash Chauhan ·
 Vala Venkateshwar Rao



Cluster landslides and associated damage in the Dima Hasao district of Assam, India due to heavy rainfall in May 2022

Abstract During 11–18 May 2022, the Dima Hasao district of Assam state in India received heavy rainfall. The rainfall triggered floods and landslides across the district, resulting in the death of three people and damage to property (mainly road and rail network) worth few hundred crores of Indian rupees. Platforms of the New Haflong railway station were completely buried by multiple debris flows, and several coaches of a train were overtopped. We hereby investigate the cause of the landslide disaster by analyzing temporal rainfall data and also assess damages in the region using high-resolution optical satellite imagery from Resourcesat-2A (5.8 m), Sentinel-2 (10 m), and Cartosat-3 (1.1 m) satellites. It is seen from the satellite-based precipitation measurement that the region around Haflong town received maximum 24 h rainfall (156 mm) on 11 May 2022 and the heavy rainfall continued till 18 May 2022. This resulted in the occurrence of 5178 landslides, which are mapped using multi-temporal cloud free optical satellite data. Rainfall data analysis shows that 4 days antecedent rainfall of ~200 mm has mainly triggered landslides in this area. The initial heavy rainfall has saturated the soil and increased the pore pressure, which caused slope failure due to subsequent spell of rains. Small-sized landslides are seen to damage buildings in the Haflong town and neighboring villages. Various roads, including the Lumding-Silchar highway, were damaged at multiple places by landslides. Landslides were triggered mainly within Renji and Bokabil Rock Formations on moderate to high slopes. Results are further substantiated by debris flow simulations which showed that ~4 m height of debris may have been accumulated in the New Haflong railway station, thus burying the railway track and platforms.

Keywords Himalaya · Debris flow · Rail damage · Disaster · Satellite data

Introduction

Landslides are one of the common geological hazards in hilly areas throughout the world (Larsen and Simon 1993; Crosta 1998; Guzzetti et al. 2008; Zhang et al. 2018; Achu et al. 2021; Wooten et al. 2008; Martha et al. 2017; Martha et al. 2021a). In recent times, high intensity rainfall in short spell due to climate change is resulting in large debris flows, and “cluster” landslides (close occurrences) are being increasingly reported in several regions of the world (Jain et al. 2021; Wang et al. 2022; Feng et al. 2022). According to Froude and Petley (2018), South and East Asia are geographically the main regions affected by landslide disasters in the world and India ranks first among nations in terms of fatal landslides. A recent study by Martha et al. (2021a) has ranked 145 hilly districts of India, covered in the Himalayan and Western Ghat regions, for their landslide exposure.

The Dima Hasao district ranks first among all the districts of Assam state of India in terms of exposure to landslide disaster (Martha et al. 2021a). During 11–18 May 2022, heavy rainfall and consequent landslides ravaged roads and railway tracks in several parts of the Dima Hasao district. The worst hit was the district headquarter, Haflong, where debris flows buried the railway station (<https://www.sentinelassam.com/>).

ISRO programmed its high-resolution satellites to acquire imagery over this region and assess the damage as a part of the Disaster Management Support Program (DMSP). National Remote Sensing Centre (NRSC), India had carried out landslide damage assessment studies using post-landslide satellite images for several past major landslide events (Roy et al. 2014; Martha et al. 2017). For example, 1408 landslides were mapped in 2011 for the Sikkim earthquake, 473 landslides were mapped in 2012 for the Okhimath cloudburst, 6985 landslides were mapped in 2013 for the Kedarnath disaster (Martha et al. 2015), and 6324 landslides were mapped in 2018 during the Kerala landslide disaster (Jain et al. 2021). An assessment of the Rishiganga rock and glacier avalanche event in 2021 was also carried out using high-resolution satellite data (Martha et al. 2021b).

In addition to damage assessment and landslide inventory mapping, debris flow modeling has now become an important method for understanding the kinematic behavior of landslides (Jain et al. 2021; Roy et al. 2022). Such debris flow modeling mainly requires the characteristics of source area and runout path, type of triggering process, and lastly the type and volume of material deposited (Luna et al. 2013). Flow prediction models can be empirical, statistical, physical, or dynamic-based model depending on inputs available (Schraml et al. 2015). Empirical-statistical-based approaches were developed to model runout path using flow volume (Tang et al. 2012) and require additional ground information, while physically based dynamic model mostly depends upon fluid mechanic equations. The R.avaflow code represents an innovative open-source computational tool for simulating rapid mass flows (Mergili et al. 2017). It simulates the flow behavior from a defined release area to a deposition area and is suitable for modeling a complex landslide process chain. As a post-disaster analysis, mapping of event-based landslides and correlating their occurrence with major terrain factors and rainfall intensity are required to prevent future landslide-related damage in this part of the Himalaya.

In this paper, we investigate the cause of the landslide disaster in the Dima Hasao district and the damage caused to roads, railway tracks, and the New Haflong railway station due to the triggered landslides using high-resolution Resourcesat-2A, Sentinel-2, and

Cartosat-3 imageries. We have analyzed the rainfall pattern which led to this landslide disaster and the controlling parameters (e.g., slope and lithology) for the spatial occurrence of landslides. We have also carried out a rapid debris flow modeling using R.avaflow code to understand the pattern of inundation in and around the New Haflong railway station.

Study area

The Dima Hasao district is located in South Central Assam, bounded by North latitudes 24° 58' and 25° 47' and East longitudes 92° 32' and 93° 28' (Fig. 1). The district covers an area of ~ 4700 sq. km. The maximum and minimum elevations of the district are ~ 1909 m and ~ 25 m, respectively, and it is drained by rivers such as Mahur, Kopili, and Jatinga, which are tributaries to Barak and Brahmaputra rivers. It mainly receives rainfall during the monsoon season (June to September) and the average monthly rainfall in June is 393 mm with number of heavy rainfall days ranges between 0.5 and 1.06 (IMD Pune 2020).

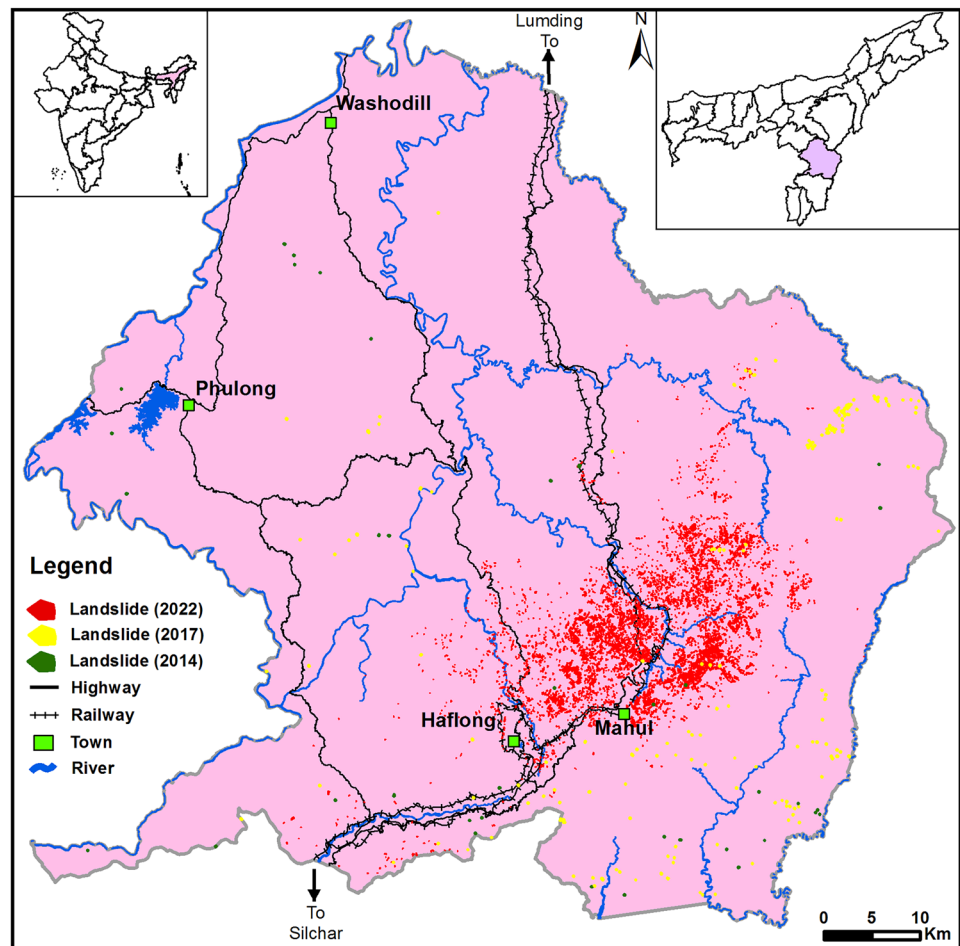
Geologically, rocks of Barail, Disang, and Surma Group from Lower Cretaceous to Eocene age mainly comprised of flaggy sandstones, siltstones, claystones, conglomerates, and semi-metamorphosed phyllites are exposed in this area (CGWB 2013). The Haflong thrust passes through the Dima Hasao district. This has created a schuppen structure and folded sequence south of

the Haflong town. The fold-thrust sequence caused reduction in rock strength and the fissile nature of the rock material, and heavy rainfall is the main triggering factor for slope failures in this area (CGWB 2013). Geotechnically, the rocks are soft to moderately hard sandstone, shales, and boulder-conglomerates with low to medium compressive strength (50 to 500 kpa/cm²) with fair foundation characteristics (GSI 2017). Land cover in the region is that of deciduous and evergreen forests, barren, and scrub lands and is seen to be more or less unchanged over the last two decades (source: www.bhuvan.nrsc.gov.in).

May 2022 heavy rainfall event

Satellite-based precipitation measurements show that the Dima Hasao district received 540 mm average rainfall in May 2022 before the onset of actual monsoon season, which is much higher than the maximum monthly (June) average rainfall (393 mm). Daily rainfall distribution in May 2022 was also uneven with 11–18 May 2022 period receiving majority of rainfall in and around the Haflong town. Maximum rainfall (156 mm) was received on 11 May 2022 and the heavy rainfall continued till 18 May 2022. This sudden and abrupt spell of high rainfall triggered large number of landslides in and around the Haflong town. Initial media reports suggest that the landslides have damaged roads and railway lines, killing at least three people and

Fig. 1 Location map of the Dima Hasao district in the Assam state of India. Distribution of landslides triggered due to heavy rainfall in May 2022 and previous landslide inventory for the years 2014 and 2017 are also shown



leaving thousands stranded. Important rail routes such as railway tracks at Jatinga-Harangajao and Mahur-Phaiding were disrupted due to landslides. The major arterial roads connecting the Lumding-Silchar highway were washed away at several locations. The new Haf-long station bore the brunt of the disaster, with several landslides completely inundating the station and covering it with debris (Fig. 2).

Datasets

We carried out a rapid analysis of damage to the roads and railway tracks using medium (5.8 m) and high-resolution (1.1 m) multispectral imagery from Resourcesat-2A and Cartosat-3 satellites, respectively. These datasets were also used in conjunction with Sentinel-2 data to map landslides that occurred in this region. Analysis of rainfall was carried out using Integrated Multi-satellite Retrievals for GPM (IMERG). This data, also known as GPM-IMERG, is made available by NASA on a daily basis for the entire globe with an approximate spatial resolution of 10 km (www.gpm.nasa.gov/data/imerg). In the absence of rainfall data from local gauge stations, GPM-IMERG data are very useful, particularly to correlate spatial occurrence of landslides with rainfall intensity. Further, the effect of controlling parameters such as lithology and slope on landslide occurrence was carried out using lithological map of India on 1:50,000 scale (GSI 2022) and slope map derived from Cartosat DEM (10 m), respectively. The DEM was also used for topographic information in flow modeling. A list of satellite data used in the study is provided in Table 1.

Methodology

Rainfall analysis

We used GPM-IMERG daily rainfall data (GPM-IMERG 2022) for analyzing the temporal and spatial distribution of landslides in the Dima Hasao district. We divided the landslide affected areas of Dima Hasao district into 6 major zones (i.e., A to F) based on square grids representing the pixel size (10 km × 10 km) of the GPM-IMERG data (Fig. 3). Daily and antecedent (2 to 5 days) rainfall data for these six grids were used to understand the rainfall intensity that caused landslides in this area. As per the news reports, landslides

Table 1 List of satellite data used in this study

Sl. no	Satellite (resolution)	Date of acquisition	Sources
<i>Pre-disaster</i>			
1	Resourcesat-2A LISS IV Mx (5.8 m)	13 February 2021	ISRO
2	Cartosat-2 (1.6 m)	08 October 2021	ISRO
<i>Post-disaster</i>			
3	Resourcesat-2A LISS IV (5.8 m)	20 May 2022	ISRO
4	Resourcesat-2 (5.8 m)	01 Jun 2022	ISRO
5	Cartosat-3 (1.1 m)	29 May 2022	ISRO
6	Sentinel-2 (10 m)	28 May 2022	ESA

have occurred in this area during 14–16 May 2022 period. Hence, we have calculated the antecedent rainfall for these 3 days.

Landslide inventory mapping

Use of manual method for mapping landslides by visual image interpretation is an arduous task. Therefore, the semi-automatic method developed by Martha et al. (2010a, b, 2011, 2012) for the detection of landslides from high-resolution satellite data and DEM was used for the creation of the event-based landslide inventory database. This method follows a knowledge-based generic spectral-spatial-morphometric approach for the detection of landslides from high-resolution satellite and DEM data (Martha et al. 2010a, b). It uses an object-based change detection approach which mainly identifies vegetation changes to extract landslide polygons from satellite images. Landslides mapped by this method were further checked for their quality, and false alarms were removed.



Fig. 2 a New Haf-long railway station covered with debris from landslides triggered around the adjacent slopes (source: www.downtoearth.org.in). b Railway locomotive buried till roof under debris (source: www.indianexpress.com)

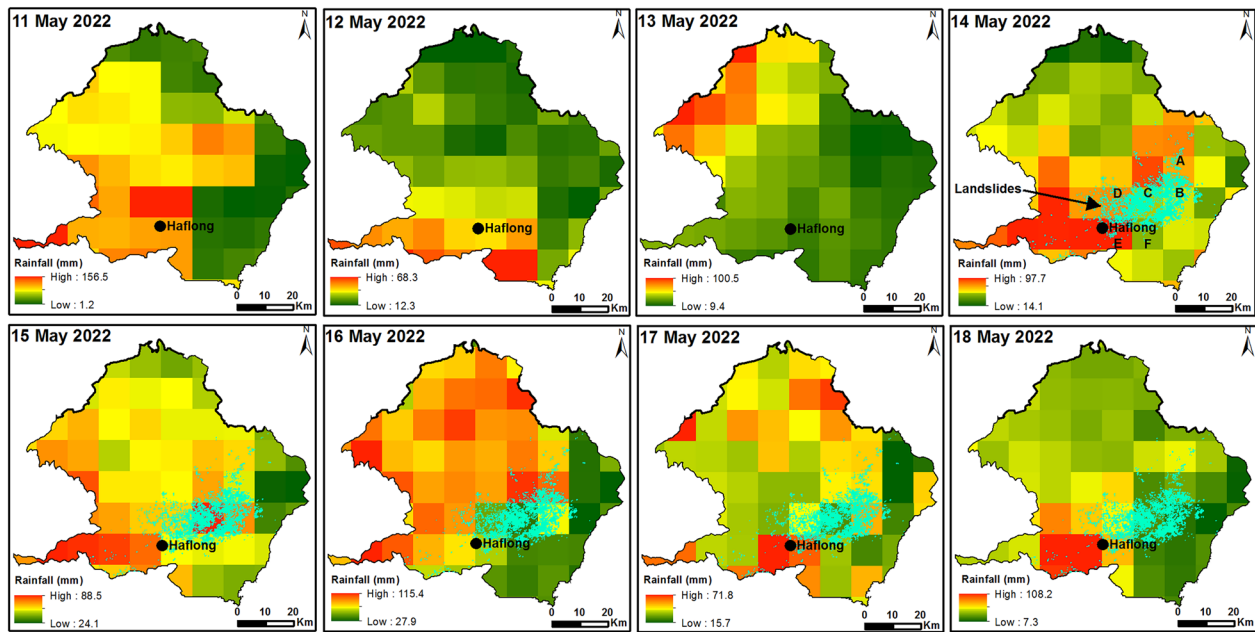


Fig. 3 Spatial occurrence of rainfall from GPM-IMERG data over the Dima Hasao district from 11 to 18 May 2022. Six zones (A to F) corresponding to 10 km × 10 km grid size covering the landslide distribution (cyan color dots) are shown on the 14 to 18 May 2022 rainfall grids

Damage assessment

Comparative assessment of pre- and post-event satellite data was carried out using image enhancement aided visual change detection method. High-resolution data from Resourcesat-2 and 2A and Cartosat-3 were analyzed to identify damage within the Haflong town, in and around the Haflong railway station and the connecting road and rail corridors. Further, Pan and multispectral data from Cartosat-3 were fused to generate high-resolution image product, thus enabling identification of damage on narrow hilly roads and neighborhood within the Haflong town.

Assessment of landslide controlling factors

To assess the control of lithology, structure, and slope (primary geofactors) on the occurrence of landslides in the Dima Hasao district, we have carried out a GIS-based analysis. The landslide polygons in geospatial format (.shp) were intersected with the lithology layer and the area in each class of the thematic layer was estimated and interpreted as the influence of particular geological formation. Further, orientations of structural discontinuities were also analyzed to identify any apparent correlation. Similarly, the slope derivative of DEM was estimated and classified into 5 classes, i.e., from very low to very high slope using natural breaks method. The landslide polygons were intersected with the slope classes to estimate the control of the class of slope on the spatial occurrence of landslides.

Debris flow simulation

We have carried out a rapid debris flow modeling using R.avaflow 2.4 code to understand the pattern of inundation in and around the New Haflong railway station (Mergili et al. 2017). Though landslide-induced damages were identified in many parts of the district, the new Haflong railway station, which is a major civil infrastructure of the Dima Hasao district, has bore the brunt of the damage. Hence, we focused our simulation in and around the railway station. The R.avaflow 2.4 represents a GIS-supported open-source software tool for the simulation of complex, cascading mass flows over arbitrary topography. It employs the NOC-TVD numerical scheme (Wang et al. 2004) along with a Voellmy-type model, with an enhanced version of the Pudasaini multi-phase flow model (Pudasaini and Mergili 2019). Additive functions include entrainment, deposition, stopping, and phase transformations. The starting mass has been defined through raster maps (Mergili and Pudasaini 2014–2020). The main input parameters to be ingested in the flow model are the topography and starting masses. To create the base layer topography, we have used the high-resolution CartoDEM (10 m) for flow modeling (Martha et al. 2010a, 2010b; Sharma and Kartikeyan 2014). To estimate the release volume of the starting masses, we have used a generalized landslide volume-area relationship applicable to this terrain and given by Larsen et al. (2010) as described in Eq. (1).

$$V = 0.186 * A^{1.35} \quad (1)$$

where V is the volume and A is the area of the landslide.

Once the volume is calculated, it is converted into respective block depths by dividing the volume with the area of starting masses. These block depths are used for the flow simulation in raster form. Further, we have used fluid phase as the flow mass (viscosity-dominated viscoplastic, non-frictional, viscous) and used simplified Pudasaini and Krautblatter (2021) entrainment and deposition model to simulate the entrainment behavior of the flow (Mergili and Pudasaini 2014–2020).

Results

Rainfall distribution in May 2022

Gridded rainfall data from IMERG for GPM for the entire Dima Hasao district was analyzed to understand the spatial variability of rainfall which triggered landslides in the region. Analysis of the daily rainfall data shows that there has been two distinct spells of heavy rainfall in the region (Fig. 4). The first spell of heavy rainfall occurred in A, D, and E zones on 11 May 2022 and was followed by second spell between 14 and 18 May 2022. Similarly, a milder spell of rain occurred in zones B, C, and F on 12 May 2022 and was followed by a heavier spell between 14 and 17 May 2022. Since there were no landslides recorded in the region on 11 May 2022, it can be stated that the landslides are triggered by variable antecedent rainfall patterns rather than daily rainfall.

We analyzed the 2, 3, 4, and 5 days antecedent rainfall along with the daily rainfall for the 14, 15, and 16 May 2022 (Fig. 4b to d). It is seen that on 14 May 2022, in zones A, D, and E, landslides were triggered due to the effect of 4 days antecedent rainfall over the region which amounted to ~200 mm. This zone includes the Haflong town and the surrounding regions as well as the hills towards the north-east of Mahul. Similarly, on 15 May 2022, zone C exhibited 4 days antecedent rainfall of ~200 mm, which resulted in landslides those were triggered towards the east of Haflong town and between Haflong and Mahul. Finally, on 16 May 2022, high 4 days antecedent rainfall was observed further towards the east of Haflong in zones B and F, resulting in landslides in this region.

Landslide inventory of Dima Hasao district

The heavy rainfall triggered a large number of landslides in the hilly regions of Haflong and Mahul towns (Figs. 1 and 5). A total of 5178 landslides were mapped in the Dima Hasao district using multi-temporal cloud free satellite data. Total area of landslides is 17.5 sq. km. Average size of landslides is 3386 sq. m (minimum: 101 sq. m and maximum: 3,78,800 sq. m). The landslides have occurred as a “cluster” and are mostly shallow translational slides (debris slides/flows), caused by erosion of the top soil over the slope (Fig. 5). A comparison of archived landslide inventory data (Martha et al. 2021a, b) with current event-based inventory data shows that

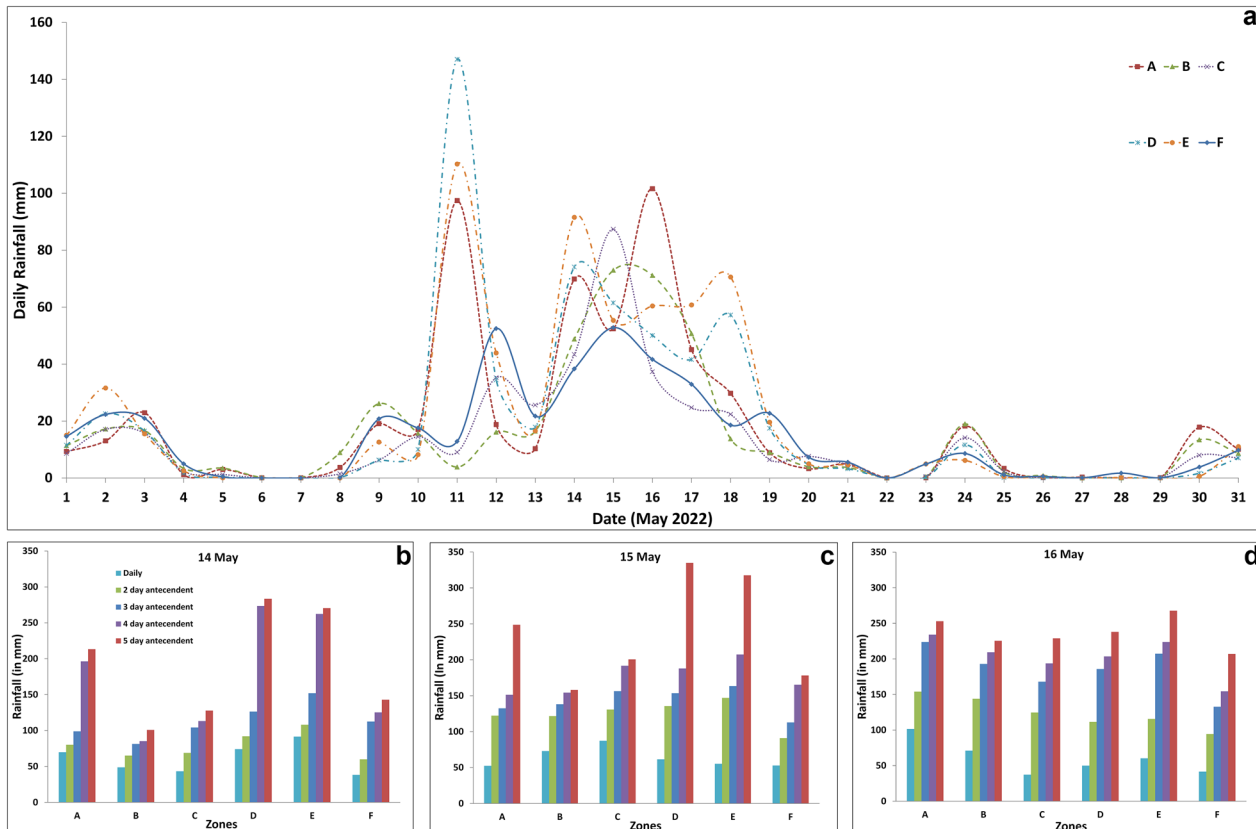


Fig. 4 a Daily rainfall data for the May (2022) month measured from the GPM-IMERG data for the six zones (shown in Fig. 3). Antecedent rainfall in zones A to F for b 14 May 2022, c 15 May 2022, and d 16 May 2022

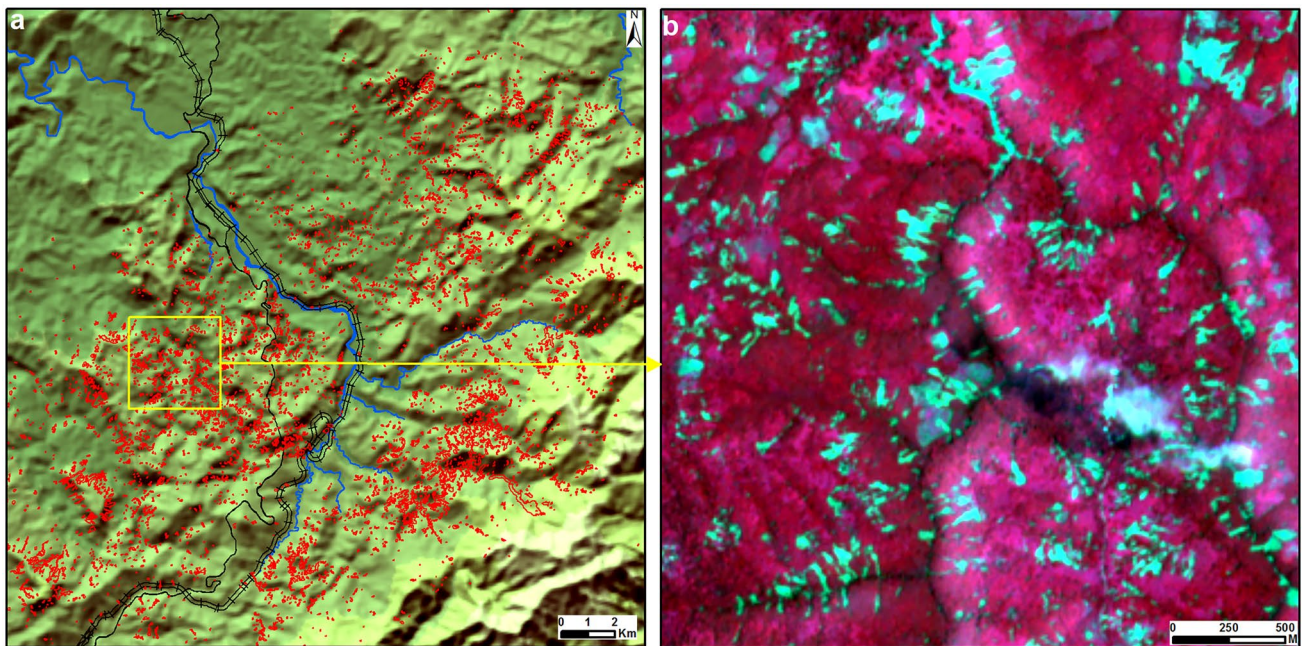


Fig. 5 Landslide inventory of the Dima Hasao district showing high density of landslides in the hilly regions around Haflong and Mahul. **a** Landslide distribution (red polygons) shown over the relief map

prepared from DEM. **b** Post-disaster Sentinel-2 satellite image shows cluster landslides

landslides in May 2022 clearly outnumbered those occurred in 2014 and 2017 (Fig. 1 and Table 2).

and 7a1). Further, debris have covered railway tracks and partially covered the station platform. Damage to nearby railway tracks was also mapped (Fig. 7b1 and c1).

Damage to buildings

The Haflong town is located on the foothills of the Barail range and the topography within the town is undulated with houses on moderate to low slopes ($\sim 20^\circ$). As a consequence of the rainfall, these slope materials have failed causing slumps and slides in few places within the town, thus damaging houses and other civil establishments (Fig. 6). Post-event Cartosat-3 data shows damaged houses in the Haflong town (Fig. 6a1) and near Suongpijang village (Fig. 6b1).

Damage to road infrastructure

The Lumding-Silchar road, which is one of the major highways connecting the southern districts of Assam to the state capital of Guwahati, was damaged by landslides at several places. Post-event satellite image from Resourcesat-2A (20 May 2022) was analyzed over the region. The road which mainly follows the course of the Jatinga River was seen to have been damaged near the Bandarkhal railway station and at several other places. Further various smaller and connecting roads in and around the villages in vicinity of the Haflong town have also been damaged due to landslides (Fig. 8).

Damage to rail infrastructure

Post-event satellite image from Cartosat-3 was analyzed over the New Haflong railway station. Results show occurrence of a number of landslides on the slopes on either side of the station (Fig. 7). A large debris flow in the NW part of the station has resulted in the overtopping and damage of a train parked in the station (Figs. 2

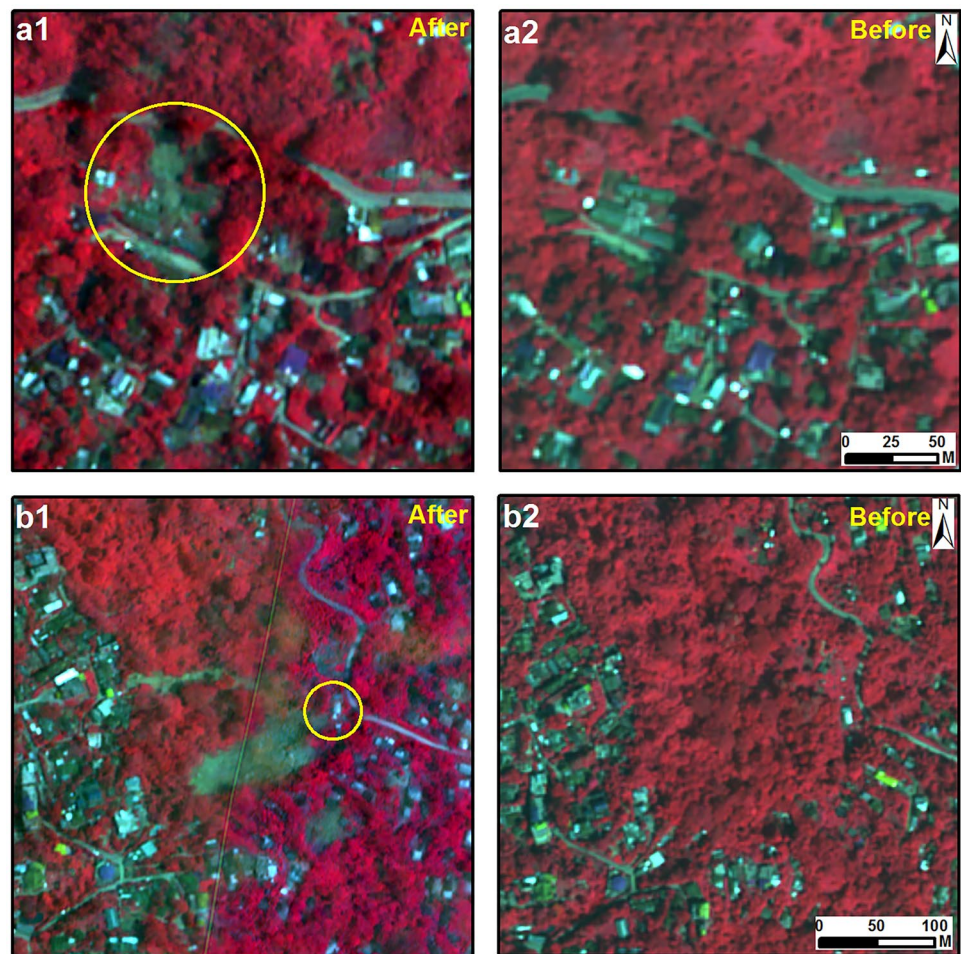
Factors controlling landslide occurrence

The landslide inventory database was used for terrain factor control analysis. Considering the lithological variations in the region, it is seen that the Renji Formation comprising of sandstone, carbonaceous shale with conglomerate/limestone and Bokabil Formation comprising of shale, siltstone, ferruginous sandstone, and mudstone are the main rock groups in which majority of the landslides have been triggered by heavy rainfall (Fig. 9). These rock formations are followed by Disang Formation (shale, flaggy sandstone, and calcareous rocks) and Tipam Sandstone (ferruginous sandstone with siltstone and clay) wherein landslides were found. The orientation of planar structures was analyzed and a rose diagram was created (Fig. 9b: inset). The control of structural discontinuities

Table 2 Comparative statistics of landslides in the Dima Hasao district triggered in the monsoon seasons of 2014, 2017, and by heavy rainfall in May 2022

	Monsoon 2014	Monsoon 2017	May 2022
Number of landslides	41	221	5178
Total area (sq. m)	65,302	2,31,054	1,75,34,380

Fig. 6 Post (a1, b1) and pre (a2, b2) satellite imagery of the Haflong town and Suong-pijang village, respectively, showing landslides triggered within the town damaging houses. Locations of landslides are denoted by “L”



is generally seen in deep-seated landslides (rock slides, rock falls, etc.). However in the present scenario, the landslides are shallow translational wherein the interface of soil and bedrock forms the plane of failure. Therefore, it can be inferred that there is no apparent control of structural discontinuities in the landslide occurrence and distribution of in this region. Topographically, it is seen that moderate to high slopes (between 17° and 42°) contributed to maximum occurrence of landslides (Fig. 9a). Shallow translational slides are seen to occur on moderate slopes where there are adequate possibility of soil accumulation and formation. Hence in the present case, $17\text{--}42^\circ$ slopes are seen to have the most number of landslides. The inset in Fig. 9a shows that landslides were initiated from the steep upslope areas.

Debris flow simulation around New Haflong station

The New Haflong station lies in a narrow valley with steep side slopes. We identified ~ 15 landslides (initiation points) with an estimated thickness range of 2.9 to 4.1 m on slopes on either side of the station. The simulation was executed for 400 s with a 10 s time step (Fig. 11a to f).

Observations from the simulation suggest that multiple regions of the slopes on either side of the railway station collapsed and coalesced to form channelized/nonchannelized mud/debris flows. These flows descended down on the station along the steep slopes entraining material and gathering velocity. The simulated peak velocity was 42 m/s. Once on the valley floor, the mud and debris engulfed the station from all sides and were further channelized downslope along the narrow valley to flow further in NNE direction meeting an existing channel. The maximum simulated flow height is ~ 8 m located in the station region (approximate location: 25.14°N , 93.03°E), with an average overall thickness of deposited sediments around ~ 3.5 to 4 m. This, when multiplied by the approximate inundated area of 21,105 sq. m, resulted in a debris volume of $\sim 84,420$ cubic meter. A saddle-like depression along the railway station resulted in accumulation of the mud and debris. Further, three small landslides (marked as 1, 2, and 3 in Fig. 11a) coalesced to form a larger mud flow which came down the slope along an existing channel with large momentum and resulted in overtopping of the parked railway carriages (as seen in Figs. 2 and 7). It has to be considered here that all the 15 landslides may not have occurred concurrently; however, result shown here is the cumulative impact on the railway station.

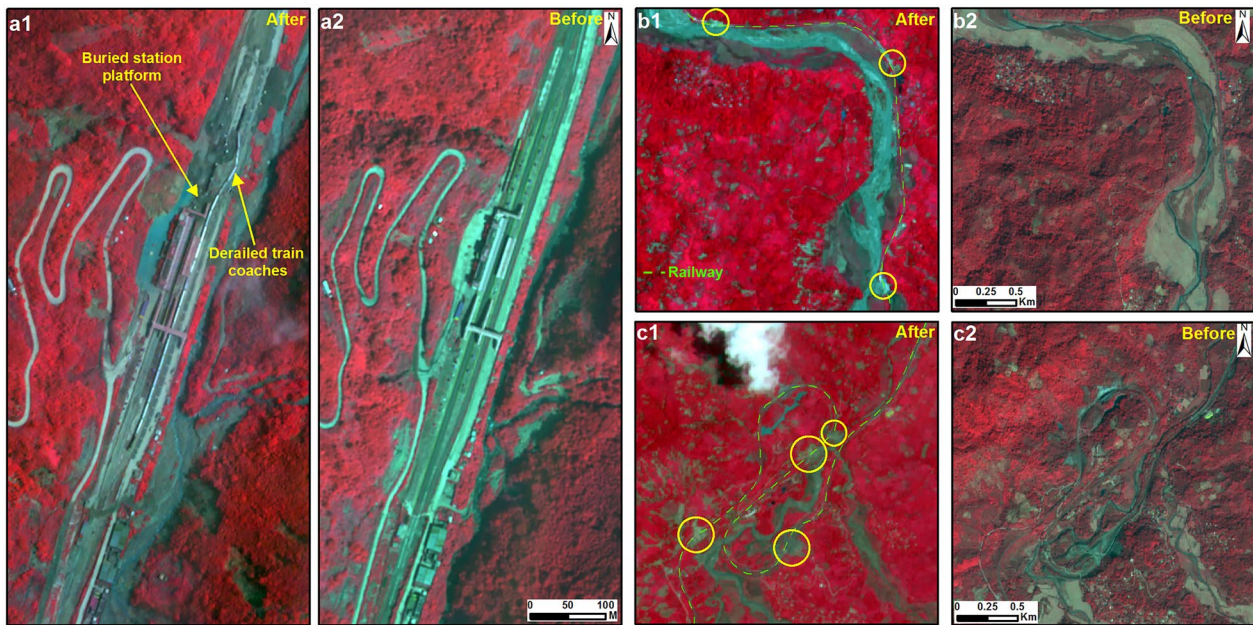


Fig. 7 Post (a1) and pre (a2) satellite imagery of the New Haflong railway station showing the landslides triggered on the adjacent slopes. The damaged train (Fig. 2) can be seen in the post-event satellite image. Post (b1) and pre (b2) imagery of damaged railway

tracks at three locations east of Haflong town. Similar damage is also seen on railway tracks at four locations northeast of Haflong town (c1 and c2). Locations of landslides are denoted by "L"

Discussion

The rainfall-induced landslides in the Dima Hasao district and the consequent damage to infrastructure may be termed as one of the major disasters in the North Eastern India in recent times. The high intensity

of rainfall in a relatively small area over a span of couple of days caused significant damage to the Haflong town, New Haflong railway station, and major connecting roads. This resulted in almost cut-off of all links between the southern districts of Assam with the rest of India.

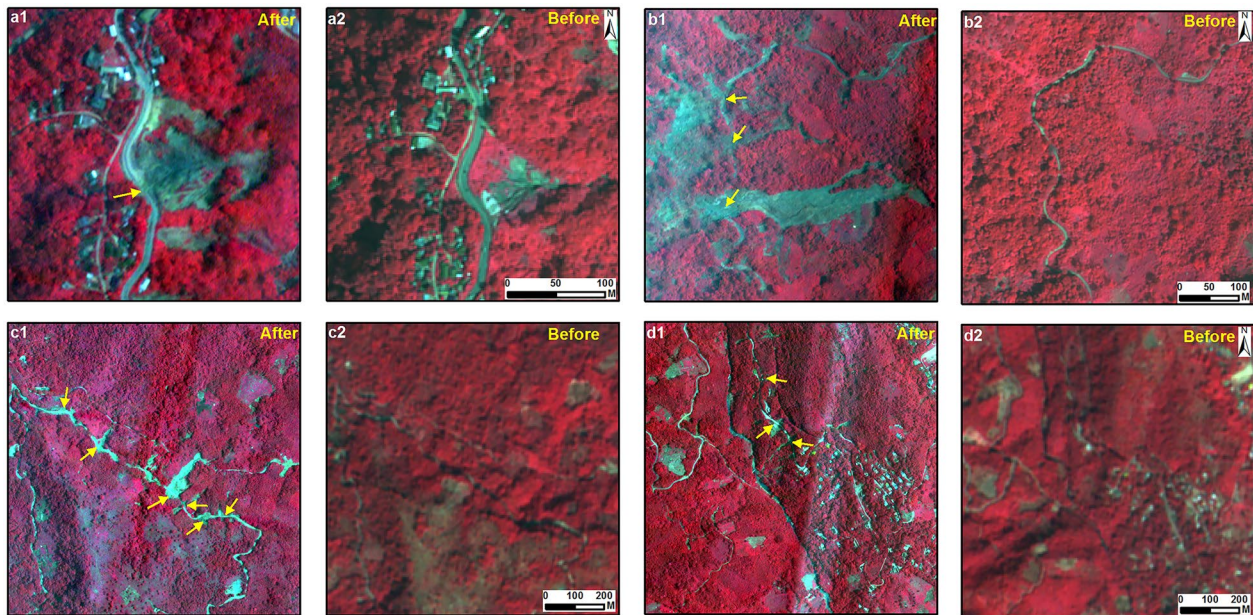


Fig. 8 Post (a1) and pre (a2) satellite imagery of slumping along the road connecting Haflong town to New Haflong railway station (Bara Haflong village). b1 and b2 Debris flow with long runout zones damaged roads at several locations near Daolung Purana village. Smaller

landslides obstructing roads are observed near Chottawapu village (c1 and c2) and west of Haflong town (d1 and d2). Locations of landslides are denoted by "L"

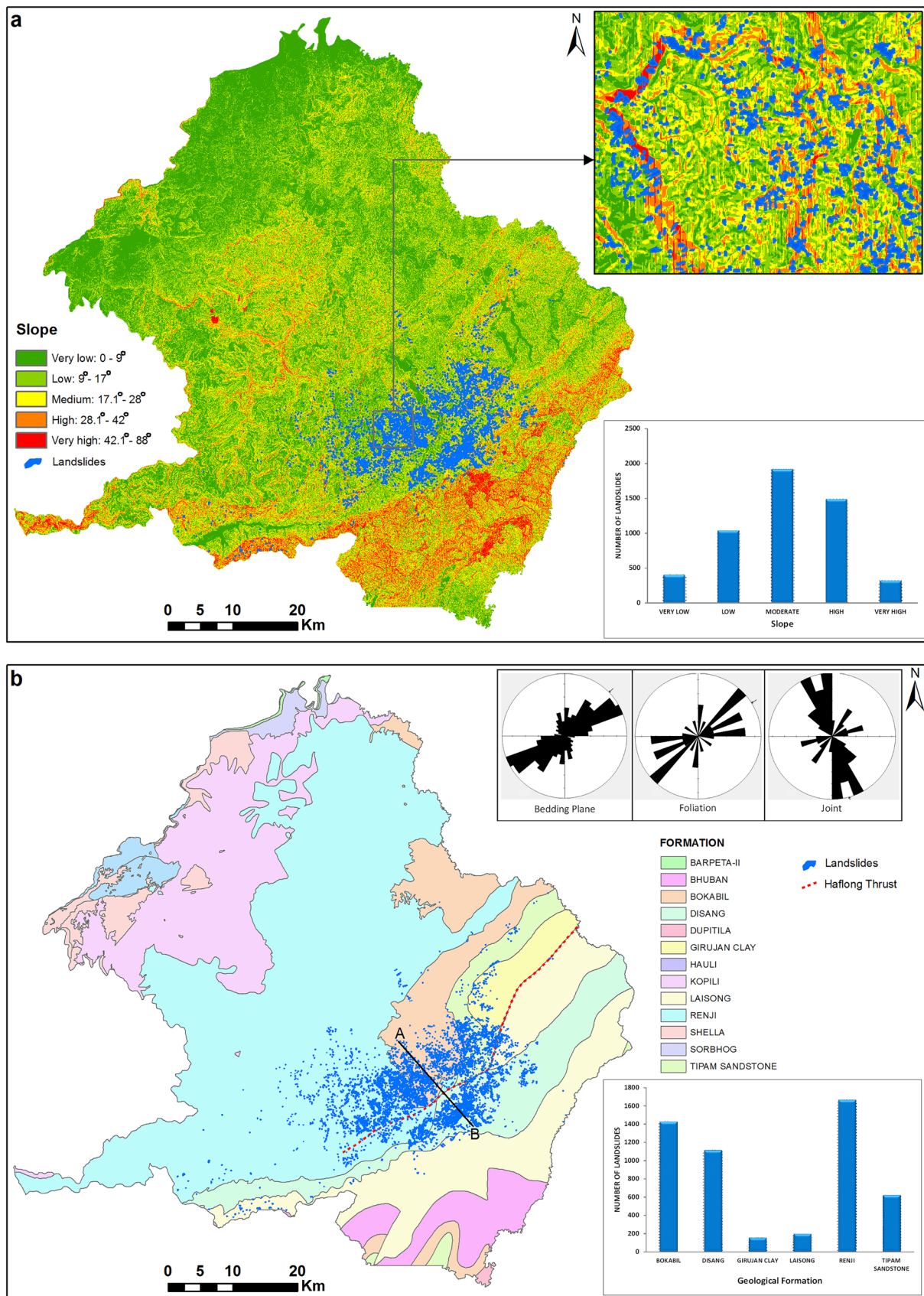


Fig. 9 Control of **a** slope and **b** geological formation on occurrence of landslides in May 2022. Inset shows general trend of bedding planes, foliations, and joints. Line A–B marks the geological cross section as shown in Fig. 10

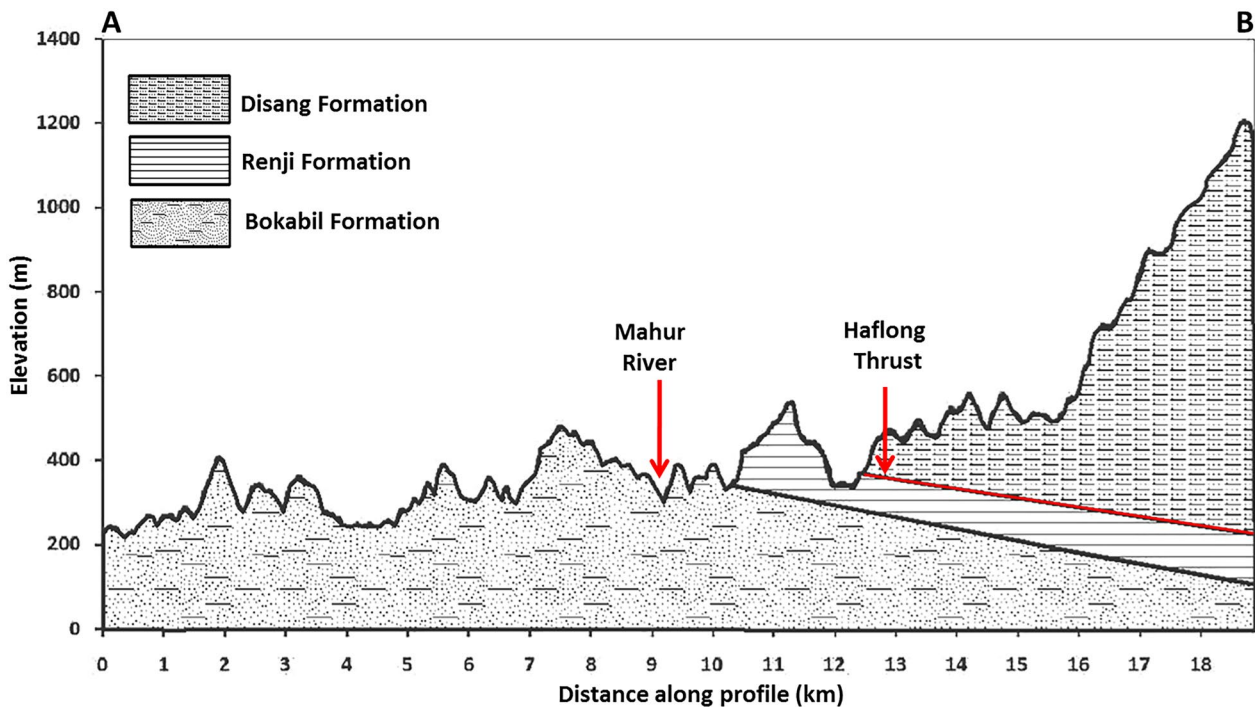


Fig. 10 Geological cross section along line (A–B) shown in Fig. 9b

The rainfall data analysis clearly demonstrates the spatial variation of rainfall over the region during 11 to 18 May 2022. Heavy rainfall on 11 May 2022 over Haflong town and surrounding region saturated the top soil and resulted in the increase of pore pressure. The subsequent spell of rainfall for 3 days till 14 May 2022 caused 4 days cumulative rainfall of ~ 200 mm, which caused the failure of the top soil layer resulting in shallow translational type landslides bringing debris and mud down slope, resulting in damage of infrastructures along the valley. It is also found that the spatial occurrence of landslides can be chronologically arranged based on the antecedent rainfall variations with respect to 14, 15, and 16 May 2022 in the region. The semi-deformed and fissile sandstone-shale bearing rock formations of Renji and Bokabil witnessed majority of landslides along moderate to high slopes of 17° to 42° . This is consistent with the observation on occurrence of landslides seen in the North Eastern Himalayas (Martha et al. 2021a). It is interesting to note that west of Haflong town did not witness much landslides despite heavy rainfall between 14 and 18 May 2022. A plausible reason could be due to the subtle variations in lithology. The Renji, Disang, and Bokabil formations, all contain very similar lithotypes (i.e., sandstone, siltstone, and shale). However, in the western side of Haflong, the sandstones are more massive and less dissected. Hence, degree of erosion is low. However, in the eastern region, around Maibang, the rocks consist of shale, siltstone intercalations with high dissection, thus more prone to erosion. This has led to occurrence of more landslides in this region as compared to western side of Haflong.

The Dima Hasao district was evaluated in terms of landslide occurrences and a comprehensive event-based inventory was prepared using object-oriented semi-automatic method. A total of 5178

landslides were mapped which were all triggered during 14 to 16 May 2022. The cluster of landslides related to a spell of rainfall event over a limited geographical extent demonstrates the high intensity of the rainfall event. Among the worst hit was the New Haflong railway station, which was buried by debris from the landslides originating from the adjacent slopes. At least 15 landslides have occurred from the slopes on either side of the valley which housed the station. Damages to houses and major connecting roads in the Haflong town and surrounding villages are also clearly seen in the high-resolution satellite imagery.

The simulation of the flow using R.avaflow code with empirically estimated starting mass thicknesses of mapped landslides around the New Haflong station demonstrates the pattern of mass flow and its consequence on the railway station. Several landslide masses collapsed into the valley where the station was located. The movements of the debris, which are simulated as viscous fluid, agree well with the observations seen in media reports and videos. The maximum attained flow velocity was ~ 42 m/s and the average thickness of deposited sediments is ~ 3.5 to 4 m (maximum thickness ~ 8 m), buried the station premises with debris. Though there is no direct evidence or ground truth available to verify this observation, however, we can have an approximate benchmark based on certain published photographs. In Fig. 2b, an electric locomotive is seen buried by debris up to the roof. The average heights of electric locomotives in India are ~ 4.3 m (source: https://indianrailways.gov.in/railwayboard/uploads/directorate/ele_engg/RE/Standard_Implantation/2_Heights.pdf). Since, as per Fig. 2b, the debris is covered almost to the roof level, it can be concluded that the debris height is around 4 m. This observation correlates well with the outcomes of the flow simulation at location 25.15° N and 93.03° E.

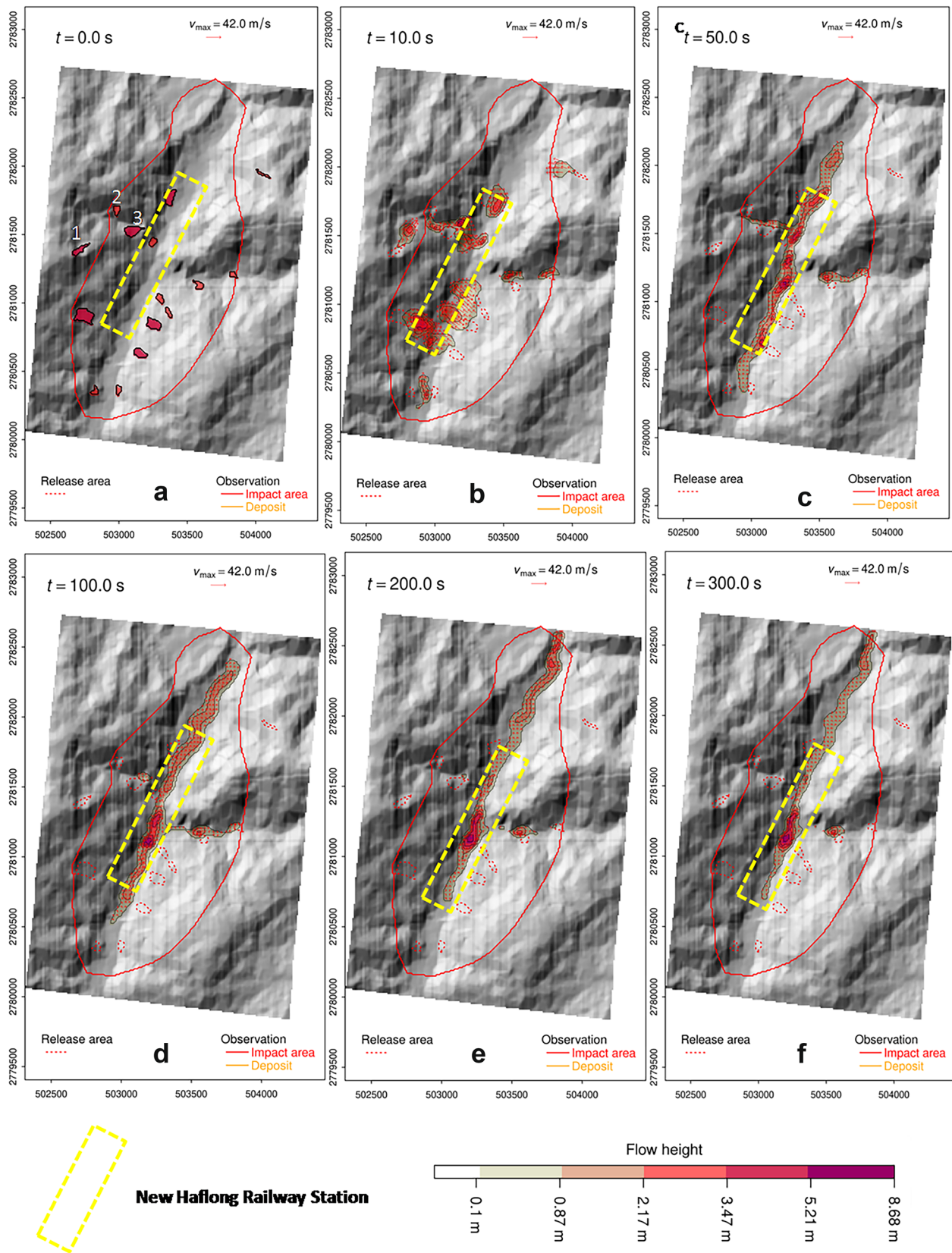


Fig. 11 Flow simulation time series. **a** Location of starting masses. **b** to **f** Movement of slope mass after failure

Conclusion

The Dima Hasao district of Assam received 540 mm of rainfall in May 2022, much higher than the monthly average rainfall in monsoon season. Daily maximum rainfall (156 mm) and heavy rainfall during 14 to 16 May 2022 have never happened before in this area. This along with the antecedent rainfall triggered a large number of landslides in the hilly regions of Haflong, Maibang, and Mahul. Friable rocks such as shale, flaggy sandstone, siltstone, and steep slope are also responsible for occurrence of landslides.

Analysis of high-resolution satellite imagery shows that major connecting roads have been damaged at several locations. Further, the New Haflong railway station has suffered massive damage due to landslide triggered on slopes on either side of the station. A total of 5178 landslides were mapped in the hills around Haflong, Maibang, and Mahul. Debris flow simulations suggest that the narrow valley, in which the New Haflong station is situated, received mud sliding from the slopes on either side, which was accumulated in and around the station thus burying it by debris. The observations reiterate the perils of important civil infrastructure within narrow valleys surrounded by weathered and friable rocks. Adequate slope stability measures are necessary to prevent such disasters in future. The event-based landslide inventory database created in this study will help to understand role of extreme rainfall events in changing climates.

Acknowledgements

This paper is the outcome of the work carried out under the Disaster Management Support (DMS) program of ISRO. We thank Dr. N Aparna, Group Director, NDC, NRSC, and her team for providing the IRS satellite data timely. We also thank Dr. Martin Mergilli for providing us the R.avaflow code. We also thank NASA and GSI for providing rainfall and geological data, respectively, for this study. We would also like to thank Dr. Shantanu Bhatawdekar, Director, EDPO and Scientific Secretary, ISRO; Dr. John Mathew, Associate Director, EDPO; and Dr. KHV DurgaRao, Group Head, DMSG, for their active support to this study.

Declarations

Conflict of interest The authors declare no competing interests.

References

- Achu AL, Joseph S, Aju CD, Mathai J (2021) Preliminary analysis of a catastrophic landslide event on 6 August 2020 at Pettimudi, Kerala State. *India Landslides* 18:7. <https://doi.org/10.1007/s10346-020-01598-CGWB> (2013) Ground water information booklet North Cachar Hills District, Assam. Central ground water board. North Eastern Region. Ministry of Water Resources, Guwahati. November 2013
- Crosta GB (1998) Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. *Environ Geol* 35(2–3):131–145. <https://doi.org/10.1007/s002540050300>
- Feng W, Bai H, Lan B, Wu Y, Wu Z, Yan L, Ma X (2022) Spatial-temporal distribution and failure mechanism of group-occurring landslides in Mibei village, Longchuan County, Guangdong. *China Landslides*. <https://doi.org/10.1007/s10346-022-01904-9>
- Froude MJ, Petley DN (2018) Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards Earth System Science* 18:2161–2181
- GPM IMERG (2022) Integrated multi-satellite retrievals for GPM. www.gpm.nasa.gov/data/imerg. Last accessed 26 Jun 2022

- GSI (2017) District Resource Map, North Cachar Hills District. Geological Survey of India, Government of India, Kolkata, India
- GSI (2022) Geology 50K. Geological Survey of India, Government of India, Kolkata, India
- Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity-duration control of shallow landslides and debris flows: an update. *Landslides* 5(1):3–17. <https://doi.org/10.1007/s10346-007-0112-1>
- IMD Pune (2020) Observed rainfall variability and changes over Assam state. Met Monograph No.: ESSO/IMD/HS/Rainfall Variability/03(2020)/27. www.imdpune.gov.in/hydrology/rainfall%20variability%20page/assam_final.pdf. Last accessed on 21 June 2022
- Jain N, Martha TR, Khanna K, Roy P, Kumar KV (2021) Major landslides in Kerala, India, during 2018–2020 period: an analysis using rainfall data and debris flow model. *Landslides* 18(11):3629–3645
- Larsen IJ, Montgomery DR and Korup O (2010) Landslide erosion controlled by hillslope material. *Nat Geosci* 3(4):247–251
- Larsen MC, Simon A (1993) A rainfall intensity-duration threshold for landslides in a humid-tropical environment Puerto Rico. *Geografiska Annaler Series A Physical Geography* 75(1/2):13–23. <https://doi.org/10.1080/04353676.1993.11880379>
- Luna BQ, Blahut J, Kappes M, Akbas SO, Malet JP, Remaitre A et al (2013) Methods for debris flow hazard and risk assessment. *Adv Nat Technol Hazards Res*. https://doi.org/10.1007/978-94-007-6769-0_5
- Martha TR, Kerle N, van Westen CJ, Jetten V, Vinod Kumar K (2011) Segment optimisation and data-driven thresholding for knowledge-based landslide detection by object-based image analysis. *IEEE Trans Geosci Remote Sens* 49:4928–4943. <https://doi.org/10.1109/TGRS.2011.2151866>
- Martha TR, Kerle N, van Westen CJ, Jetten V, Vinod KK (2012) Object-oriented analysis of multi-temporal panchromatic images for creation of historical landslide inventories. *ISPRS J Photogramm Remote Sens* 67:105–119. <https://doi.org/10.1016/j.isprsjprs.2011.11.004>
- Martha TR, Roy P, Govindharaj KB, Kumar KV, Diwakar PG, Dadhwal VK (2015) Landslides triggered by the June 2013 extreme rainfall event in parts of Uttarakhand state. *India Landslides* 12(1):135–146
- Martha TR, Roy P, Jain N, Khanna K, Kotteeswaran M, Vinod Kumar K, Rao PVN (2021a) Geospatial landslide inventory of India—an insight into occurrence and exposure on a national scale. *Landslides* 18:2125–2141. <https://doi.org/10.1007/s10346-021-01645-1>
- Martha TR, Roy P, Jain N, Vinod Kumar K, Reddy PS, Nalini J, Sharma SVSP, Shukla AK, Durga Rao KHV, Narender B, Rao PVN, Muralikrishnan S (2021b) Rock avalanche induced flash flood on 07 February 2021 in Uttarakhand, India—a photogeological reconstruction of the event. *Landslides*. <https://doi.org/10.1007/s10346-021-01691-9>
- Martha TR, Roy P, Vinod Kumar K (2017) Assessment of the valley-blocking ‘So Bhir’ landslide near Mantam village, North Sikkim, India, using satellite images. *Curr Sci* 113 (7):1228–1129. <https://www.currentscience.ac.in/Volumes/113/07/1228.pdf>
- Martha TR, Kerle N, van Westen CJ, Jetten V, Vinod Kumar K (2010a) Landslide volumetric analysis using Cartosat-1-derived DEMs. *IEEE Geosci Remote Sens Lett* 7:582–586. <https://doi.org/10.1109/LGRS.2010.2041895>
- Martha TR, Kerle N, van Westen CJ, Jetten V, Vinod Kumar K (2010b) Effect of sun elevation angle on DSMs derived from Cartosat-1 data. *Photogrammetry Eng Remote Sens* 76, 429–438. <https://doi.org/10.14358/PERS.76.4.429>
- Mergili M, Fischer JT, Krenn J, Pudasaini SP (2017) R. avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows. *Geosci Model Dev* 10(2):553–569. <https://doi.org/10.5194/gmd-10-553-2017>
- Mergili M, Pudasaini SP (2014–2021) R.avaflow — the mass flow simulation tool. <https://www.avaflow.org>
- Pudasaini SP, Krautblatter M (2021) The mechanics of landslide mobility with erosion. *Nat Commun* 12(1):1–15
- Pudasaini SP, Mergili M (2019) A multi-phase mass flow model. *J Geophys Res Earth Surf* 124(12):2920–2942
- Roy P, Martha TR, Kumar KV (2014) Assessment of the Sunkoshi (Nepal) landslide using multitemporal satellite images. *Curr Sci* 107(12):1961–1964

- Roy P, Martha TR, Khanna K, Jain N, Kumar KV (2022) Time and path prediction of landslides using InSAR and flow model. *Remote Sens Environ* 271:112899
- Schraml K, Thomschitz B, McArdell B, Graf C, Kaitna R (2015) Modeling debris-flow runout patterns on two alpine fans with different dynamic simulation models. *Nat Hazard*. <https://doi.org/10.5194/nhess-15-1483-2015>
- Sharma A, Kartikeyan D (2014) Potential of CartoDEM in disaster management. *Journal of Geomatics* 8:96–100
- Tang C, Zhu J, Chang M, Ding J, Qi X (2012) An empirical–statistical model for predicting debris-flow runout zones in the Wenchuan earthquake area. *Quatern Int* 250:63–73. <https://doi.org/10.1016/j.quaint.2010.11.020>
- Wang F, Yan K, Nam K, Zhu G, Peng X, Zhao Z (2022) The Wuxie debris flows triggered by a record-breaking rainstorm on 10 June 2021 in Zhuji City, Zhejiang Province. *China Landslides*. <https://doi.org/10.1007/s10346-022-01903-w>
- Wang FW, Zhang YM, Huo ZT, Matsumoto T, Huang BL (2004) The July 14, 2003 Qianjiangping landslide, three gorges reservoir, China. *Landslides* 1(2):157–162.
- Wooten RM, Gillon KA, Witt AC, Latham RS, Douglas TJ, Bauer JB, Fuemmeler SJ, Lee LG (2008) Geologic, geomorphic, and meteorological aspects of debris flows triggered by Hurricanes Frances and Ivan during September 2004 in the Southern Appalachian Mountains of Macon County, North Carolina (southeastern USA). *Landslides* 5:31–44. <https://doi.org/10.1007/s10346-007-0109-9>
- Zhang S, Zhao L, Delgado-Tellez R, Bao H (2018) A physics-based probabilistic forecasting model for rainfall-induced shallow landslides at regional scale. *Nat Hazards Earth Syst Sci* 18(3):969–982
-
- Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10346-022-01977-6>.
-
- Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.
-
- Priyom Roy · Tapas R. Martha** (✉) · **K. Vinod Kumar · Prakash Chauhan · Vala Venkateshwar Rao**
National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO), Hyderabad 500 037, India
Email: tapas_martha@nrcs.gov.in