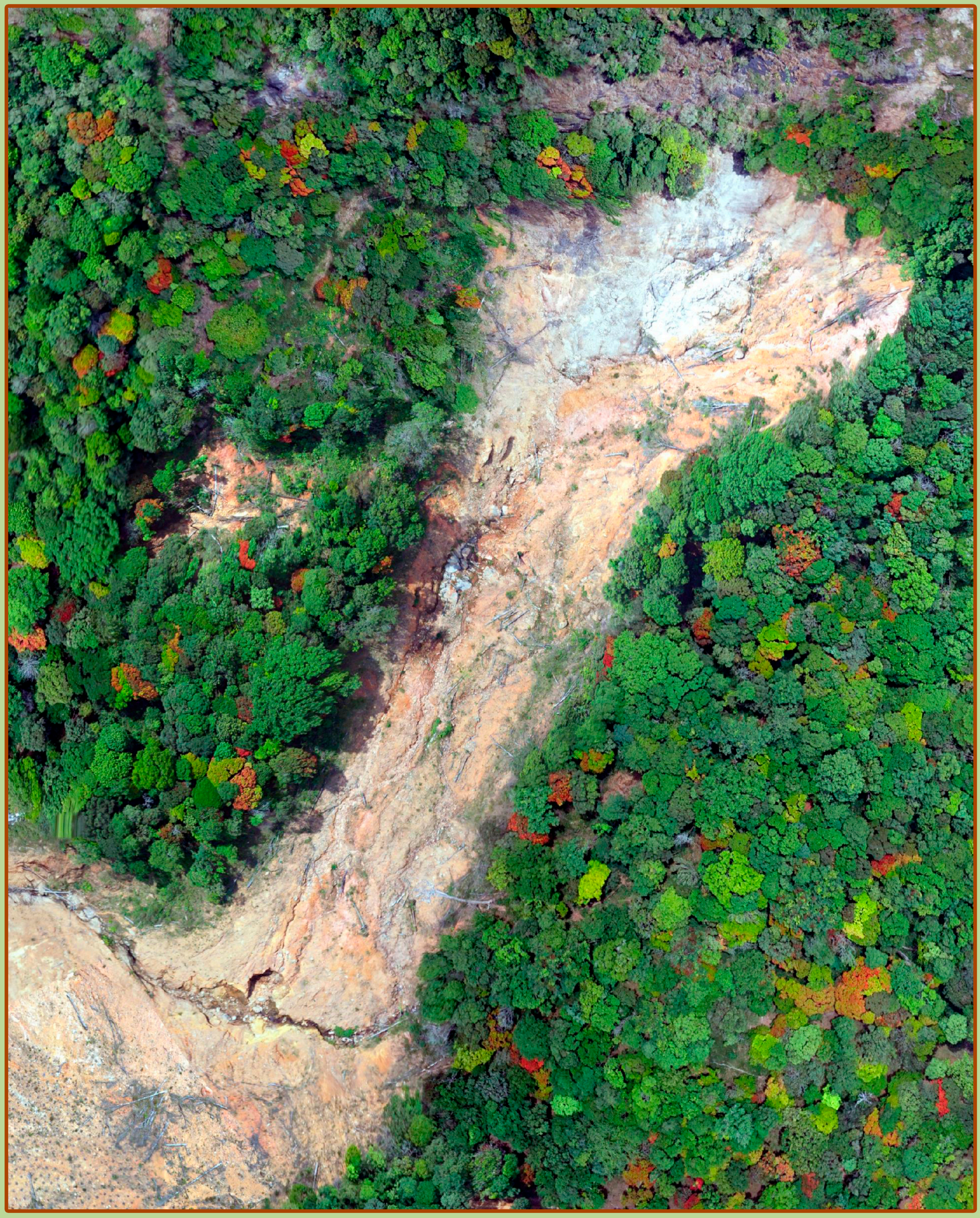
Landslide Atlas of India
भारत के भूस्खलन एटलस

(Mapping, Monitoring and R&D studies using Remote Sensing data)

(सुदूर संवेदन आधारित मानचित्रण, निगरानी और अनुसंधान एंव विकास)



राष्ट्रीय सुदूर संवेदन केन्द्र
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National Remote Sensing Centre
Indian Space Research Organisation
Dept. of Space, Govt. of India
Balanagar, Hyderabad - 500037

February 2023

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राष्ट्रीय सुदूर संवेदन केंद्र / National Remote Sensing Centre

भारतीय अंतरिक्ष अनुसंधान संगठन / Indian Space Research Organisation

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Photos
Front Cover page: High-resolution Image of landslide crown area of the Puthumala landslide taken from UAV.

Back Cover Page: Field photographs of landslides from different parts of Uttarakhand.

Production
NRSC has played a key role in the DMS programme of ISRO in providing space-based support to various landslide disasters since 2005 in a programmatic manner. NRSC has prepared landslide hazard zonation (LHZ) map and Atlas for the first time in India on 1:25000 scale in the year 2001. Damage assessment for major landslide disasters was carried out using satellite data and aerial images and value-added products are provided to stake holders. NRSC has completed Seasonal Landslide Inventory Mapping Project (SLIM) for India for the post-monsoon of 2014 and 2017.

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<tr><td>15</td><td colspan="5">Abstract: This Atlas provides the details of landslide present in Landslide provinces of India including damage assessment of specific landslide locations. Geospatial landslide inventory database consisting of ~80,000 landslides in India mapped by NRSC/ISRO under its DMS programme during the 1998-2022 period is reported here. The database covers landslide vulnerable regions in 17 states and 02 UTs of India in the Himalayas and Western Ghats. The database includes three types of landslide inventory – seasonal, event-based and route-wise for the 1998-2022 period. Seasonal inventory contains pan-India landslide database corresponding to the 2014 and 2017 rainy season in India. Event-based inventory contains details of some of the major triggering events such as Kedarnath and Kerala disasters, and Sikkim earthquake as well as few large valley blocking landslides. Route-wise inventory contains details of landslides along selected routes of tourist and pilgrimage importance. Satellite data of high to very high resolution such as IRS-1D PAN+LISS-III, Resourcesat-1, 2 and 2A LISS-IV Mx, Cartosat-1 and 2S, data from International satellites (Sentinel-1&2, Pleiades and WorldView) and Aerial images were used in the mapping of landslides. Some of the mapped landslides were validated in the field using mobile App and news reports. The database were used to rank 147 districts in 17 states and 02 UTs of India for their exposure to landslides in terms of key socio-economic parameters. Lastly advanced techniques in landslide detection, modeling and prediction are also explained.

Keywords: Landslides, Remote Sensing, Landslide Provinces in India, Landslide Inventory</td></tr>
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एस. सोमनाथ
S. Somanath

सत्यमेव जयते

अध्यक्ष, अन्तरिक्ष आयोग
व
सचिव, अन्तरिक्ष विभाग
Chairman, Space Commission
&
Secretary, Department of Space

MESSAGE

India is prone to many natural disasters like flood, landslide, cyclone, forest fire, earthquake, drought etc. Remote sensing, satellite communication and satellite navigation play important role in disaster management. Disaster Management Support (DMS) Programme of ISRO comprehensively addresses various aspects of natural disasters in the country, using space-based inputs. Relevant information is disseminated to the stakeholders, and is also published through the Geoportals like Bhuvan, National Database for Emergency Management and MOSDAC, facilitating effective disaster management by the nodal agencies.

Under the DMS programme, ISRO has been actively working on landslide disaster response and mitigation. Satellite data and derived information have been provided for major landslide disasters such as those occurred in Kedarnath, Kerala, Chamoli, Assam, etc.

The "Landslide Atlas of India" generated by National Remote Sensing Centre (NRSC), Hyderabad, illustrates the overall landslide scenario in India and presents key research outcomes in the field of landslide hazard.

I am sure that the atlas will be beneficial to everyone involved in disaster management endeavours, including the researchers. I congratulate team NRSC for bringing out the atlas.

Bengaluru
Feb 22, 2023

(सोमनाथ एस / **Somanath S)**

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डॉ. प्रकाश चौहान / **Dr. Prakash Chauhan**
निदेशक / **Director**

FOREWORD

NRSC has played a pivotal role in the DMS programme of ISRO in providing space-based support to various natural disasters since 2005 in a programmatic manner. Many projects, both operational and R&D nature, are executed by NRSC as a part of the ISRO's DMS programme.

In the field of landslide studies, NRSC has prepared a landslide hazard zonation (LHZ) map on 1:25,000 scale in the year 2001 for the first time in India using GIS and AHP techniques. Damage assessment for major landslide disasters was carried out using satellite data and aerial images and value-added products are provided to stakeholders. NRSC has completed Seasonal Landslide Inventory Mapping Project (SLIM) for India for the post-monsoon season of 2014 and 2017. Pan-India rainfall-triggered landslide databases are available for the first time in the country as a result of this project. NDMA has assigned the responsibility of rapid landslide mapping using satellite data to NRSC through office memorandum no. 6-66/2013-Mit-II/4531, dated 18 Jan 2017. New research activities were taken up by NRSC, particularly, understanding the kinematics of landslides using PSInSAR technique that will be a new paradigm for landslide early warning in near future.

The "Landslide Atlas of India" created by NRSC showcases the recent responses and developments in the landslide disaster in the country using space data and geospatial models. The state-wise landslide maps show the geospatial distribution of landslides. Few representative large landslides from the Himalaya and Western ghats have been showcased using high-resolution satellite imagery. I congratulate the team for compiling this atlas and hope it will prove to be beneficial to researchers and experts of landslides.

(Prakash Chauhan)

Hyderabad
Feb 27, 2023

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PREFACE

Landslides are controlled and triggered by geological, topographical and hydrological factors. Studying landslide hazard using satellite data has an inherent advantage since it occurs mostly in remote and inaccessible mountains. NRSC has developed expertise in addressing various aspects of landslide hazard using both optical and SAR satellite images.

NRSC has created a pan India database of ~80,000 landslides those occurred during last two decades using satellite data. This database contains both seasonal landslides and event-based landslides. These data were created as polygons in GIS, and contains several attribute information relevant for management of landslide disaster. This pan India database of landslides helped to understand the critical lithology, geological structure and rainfall responsible for occurrence of landslides. This database also helped to understand the district-wise landslide exposure in India. Other than the landslide database, various technological advancements such as debris flow modeling using UAV, landslide volume estimation, landslide mobile app and landslide kinematics using InSAR were also developed by NRSC.

The "Landslide Atlas of India" prepared by NRSC is a rich collection of landslide inventory which will help user departments in prioritisation of developmental activities in tectonically and ecologically sensitive mountainous areas in India. I congratulate the team for preparing this atlas.

Hyderabad
Feb 27, 2023

(K Vinod Kumar)
Deputy Director, RSAA

ACKNOWLEDGEMENTS

The "Landslide Atlas of India" is a consolidation of work carried out by NRSC related to landslide disasters under the Disaster Management Support (DMS) programme of ISRO. We sincerely thank Shri S Somanath, Secretary DOS and Chairman ISRO, Dr. Prakash Chauhan, Director NRSC for their encouragement and support to this work. We thank Dr. Shantanu Bhatawdekar, Scientific Secretary ISRO and Director EDPO, Dr. K Vinod Kumar, DD, RSA, NRSC, Dr. John Mathew, Associate Director EDPO and Dr. K H V Durga Rao, Group Director, DMSG, NRSC for their active support to this study.

Satellite data are the main requirement for this work carried out by NRSC. Hence, we thank Dr. N Aparna, Group Head NDC, NRSC and her team for providing the IRS satellite data. We also thank Copernicus, USGS, International Charter Space and Major Disasters for providing satellite data for emergency response to landslide disaster events in India. We also thank Shri M. Arulraj and Bhuvan team for their support in the web-based cataloguing of landslides. We thank our colleagues in Geosciences Group, NRSC and knowledge partner institutions (GSI, NDMA, SDMAs, NIDM, CBRI, WIHG, NRSC-RRSCs, NRSC-ASDMA, IIRS, SAC, NESAC, CRRI, DGRE, IITs, ITC-Netherlands, State remote sensing centres etc.) in India who have contributed to this work.

Dr. Iswar Chandra Das
Group Head, Geosciences Group

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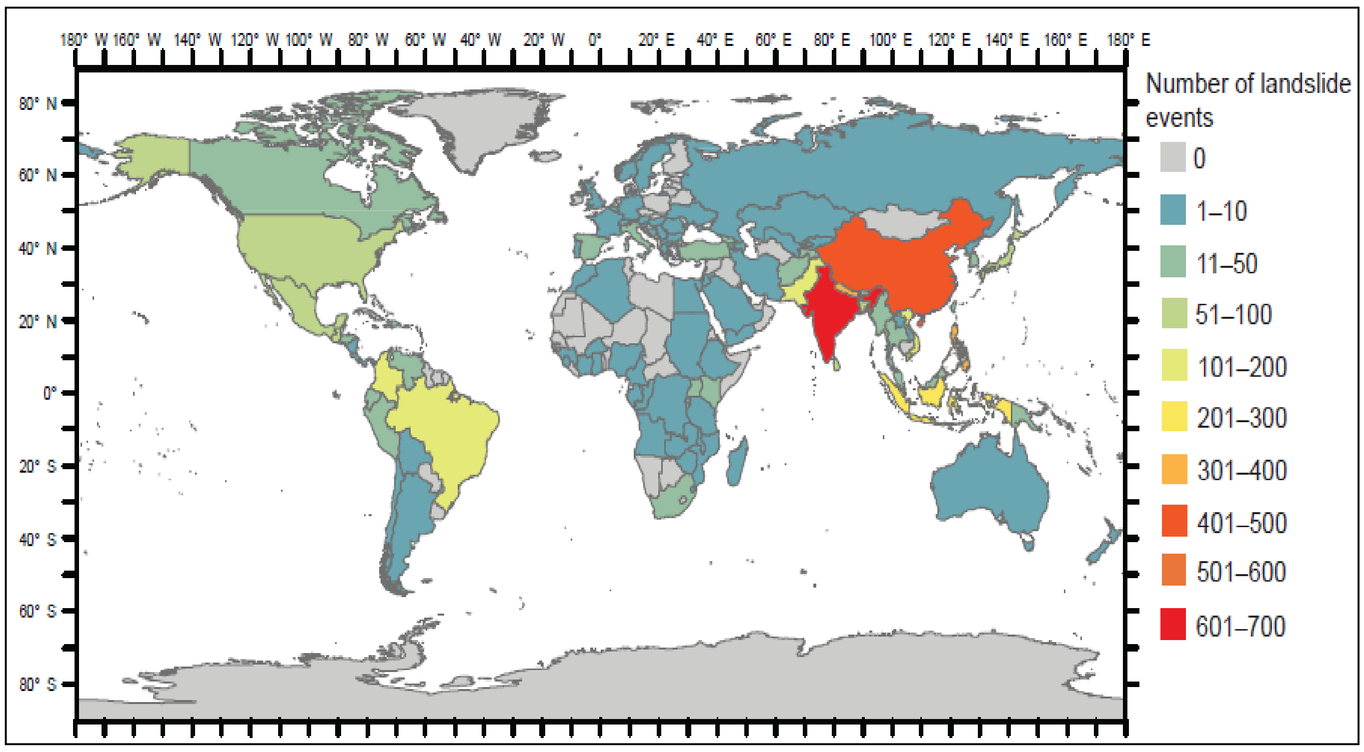
Introduction and background

The frequently used definition of landslide is "a movement of mass of rock, earth or debris down a slope" (Cruden, 1991). Different types of landslides such as Debris slide, debris flows, Rock slide, rock fall etc. can be triggered by rainfall, undercutting of slopes due to flooding or excavation, earthquakes, snowmelt and other natural causes, as well as anthropogenic causes such as over grazing by cattle, terrain cutting and filling, excessive development, etc. They can occur on many types of terrain given the right conditions of soil, rock, geological structure and slope.

Landslides are among the main natural catastrophes, which cause major problems in mountainous terrain by killing hundreds of people every year besides damaging property, disrupting transportation and blocking communication links. In some areas, such as the western coastal parts of North and South America, Central America, Alpine regions of Italy, France, Switzerland and Austria in Europe, Himalayan regions of India, Nepal in Asia and parts Central Asia, the effects of landslides are more pronounced mainly due to the spurred developmental activities to meet the ever growing demand of people. As per the official figures of United Nations International Strategy for Disaster Reduction (UN/ISDR) and the Centre for Research on the Epidemiology of Disasters (CRED) for the year 2006, landslide ranked 3rd in terms of number of deaths among the top ten natural disasters. Approximately 4 million people were affected by landslides in 2006 (OFDA/CRED, 2006). Regions with the highest landslide risk can be found in Colombia, Tajikistan, India, and Nepal where the estimated number of people killed per year per 100 km^2 was found to be greater than one (Nadim et al., 2006)



India is among the top four countries with highest landslide risk, where for every year the estimated loss of life per 100 km² is greater than one

Figure 1. Country-wise non-seismically triggered fatal landslides from 2004 to 2016 (Source: Froude and Petley, 2018).

Landslide disaster in India

Landslides are one of the common geological hazards in hilly areas throughout the world. Other than geological and anthropogenic causes, rainfall is the natural triggering factor for occurrence of landslides. Rainfall-induced landslides are the result of the combined action of water on topography, geology, soil and vegetation. Landslides have led to massive environmental damages such as increase in sediment discharge due to soil erosion and loss of human lives every year. India, a country with varied physiographic and climatic conditions, frequently faces the vagaries of landslide disaster. Approximately 0.42 million sq. km or 12.6% of land area, excluding snow covered area, is prone to landslide hazard. Out of this, 0.18 million sq. km falls in North East Himalaya, including Darjeeling and Sikkim Himalaya; 0.14 million sq. km falls in North West Himalaya (Uttarakhand, Himachal Pradesh and Jammu & Kashmir); 0.09 million sq. km in Western Ghats and Konkan hills (Tamil Nadu, Kerala, Karnataka, Goa and Maharashtra) and 0.01 million sq. km in Eastern Ghats of Aruku area in Andhra Pradesh (www.gsi.gov.in). In India, landslides mostly occur in the monsoon season. Himalayas and Western Ghats are highly susceptible to mass movements due to hilly topography and heavy rainfall

The majority of landslides are triggered by variability in rainfall patterns, while sporadic events such as very heavy rainfall outside the monsoon period (Kedarnath event of 2013) and earthquakes (Sikkim earthquake) cause significant disruption to livelihood and infrastructure. The Northernmost Indian states, J&K, Himachal Pradesh, and Uttarakhand, are the worst affected states by the landslides disasters as the majority of the territory falls within the Himalayas. Many districts of these states have high population densities, and major pilgrimage routes or major tourism spots are exposed and affected by landslides. Although the North Eastern states have many landslides yearly, they are not particularly vulnerable to them in terms of socioeconomic factors due to their lower population density and wide unoccupied mountain areas.

The vulnerability of the inhabitants and households is more significant in the Western Ghats due to the very high population and household density, especially in Kerala, even when fewer landslides exist than in the Himalayan regions. The Himalayan range has a significant influence on the geographic distribution of landslides. The spatial distribution of landslides is controlled by the shale-sandstone-metasediments generating dissected hills and valleys over the Himalayan range with slopes 30° to 45°. This, together with rainfall between 750-1000 mm is the cause of landslides. Also, the Chenab subbasin, whose geographic expanse primarily comprises steeply sloping mountains, records the highest number of landslides. The steep escarpments of the Western Ghats record occurrences of landslides, but however, these are primarily controlled by the soil cover on the slopes.

Landslide Classification

Table 1. The classification of landslides.

Abbreviated Classification of Slope Movements				
Type of movement		TYPE OF MATERIAL		
		Bed Rock	Engineering Soils	
			Predominantly Course	Predominantly Fine
Fall		Rock Fall	Debris Fall	Earth Fall
Topple		Rock Topple	Debris Topple	Earth Topple
Slide	Rotational (Slump)		Rotational Debris Slide	Rotational Earth Slide
	Translational	Translational Rock Slide	Translational Debris Slide	TranslationalEarth Slide
Lateral Spread		Rock Spread	Debris Spread	Earth Spread
Flow		Rock Flow (Deep creep)	Debris Flow (Soil Creep)	Earth Flow (Soil Creep)
Complex	Combination of two or more principal types of movement			

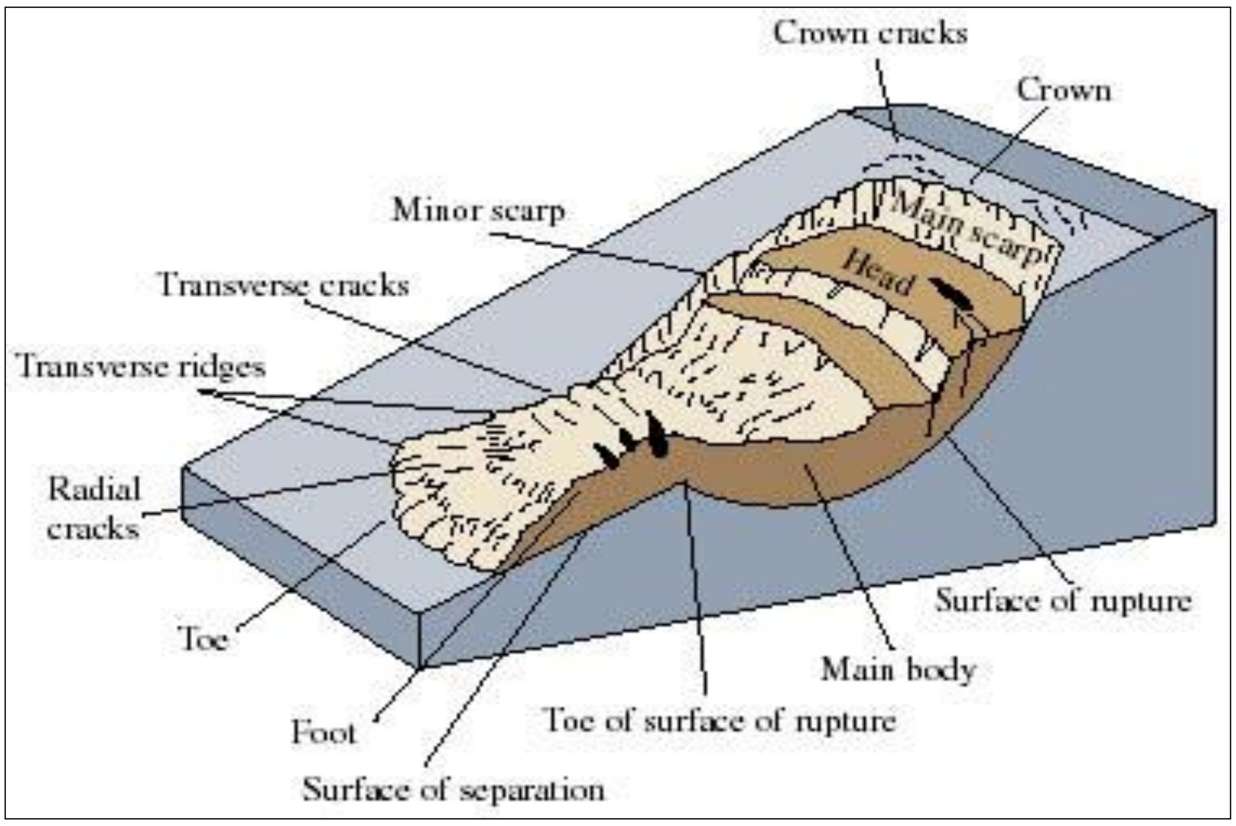


Figure 2. Block diagram of features of landslide: Earth flow type (pubs.usgs.gov).

Landslide Classification

Types of Movement

Falls: Falls are rapid movements of rocks and boulders detached from steep slopes or cliffs along fractures, joints, and bedding planes.

Topple: It is the forward rotation of a mass of debris or rock out of a slope. The slope failure generally occurs at point near the base of the block of rock.

Slides: A slide is a downslope movement of material that occurs along a slip surface.

Rotational slide: In this slide the slide movement is roughly rotational about an axis which is parallel to the ground surface and transverse across the slide.

Translational slide: In this slide the landslide mass moves along a planar surface with rotation or backward tilting

Types of Materials

Rock: hard or firm mass.

Debris: 20% to 80% of the particles are larger than 2mm, and the remainder is less than 2mm".

Earth: material in which 80% or more of the particles are smaller than 2mm.

Soil: an aggregate of solid particles, generally of minerals and rocks.

Mud: material in which 80% or more of the particles are smaller than 0.06mm.

Types of flows

Debris flow: It is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, slurry that flows downslope. They are commonly caused by intense precipitation or rapid snow melt.

Earth flow: It is down slope viscous flow of fine grained material saturated with water.

Mudflow: A mudflow is wet or viscous fluid mass of fine and coarse grained material flows rapidly along drainage channels.

Creep: Creep is the slow, steady, downward movement of material under gravity occurs in large area.

Lateral Spreads: It is the lateral movement usually occur on very gentle slopes or flat terrain. The failure is caused by liquefaction due to earthquake.


Debris flow landslide, Mahad, Maharashtra


Debris flow landslide, Maaniyankunnu, Kerala


Rock slide, Rudraprayag, Uttarakhand

RAPID RESPONSE TO LANDSLIDE DISASTER USING EO DATA

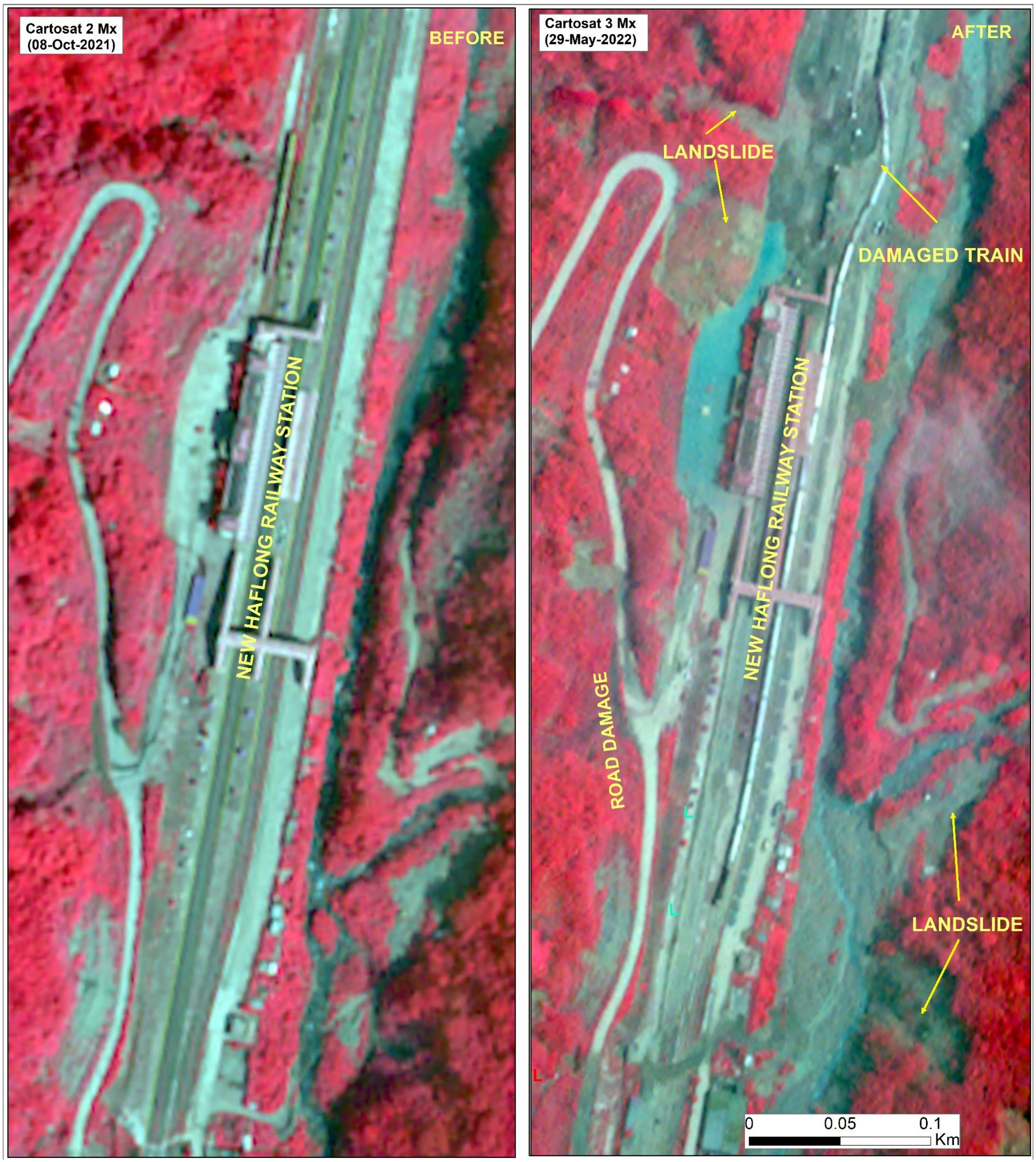


Figure 3. Landslide damage to New Haflong Railway Station Dima Hasao District of Assam (15-16 May 2022). Preliminary observation shows the occurrence of a number of landslides on the slopes on either side of the station. A large debris flow on the NW of the station has resulted in the overtoppling and damage of a parked train in the station.

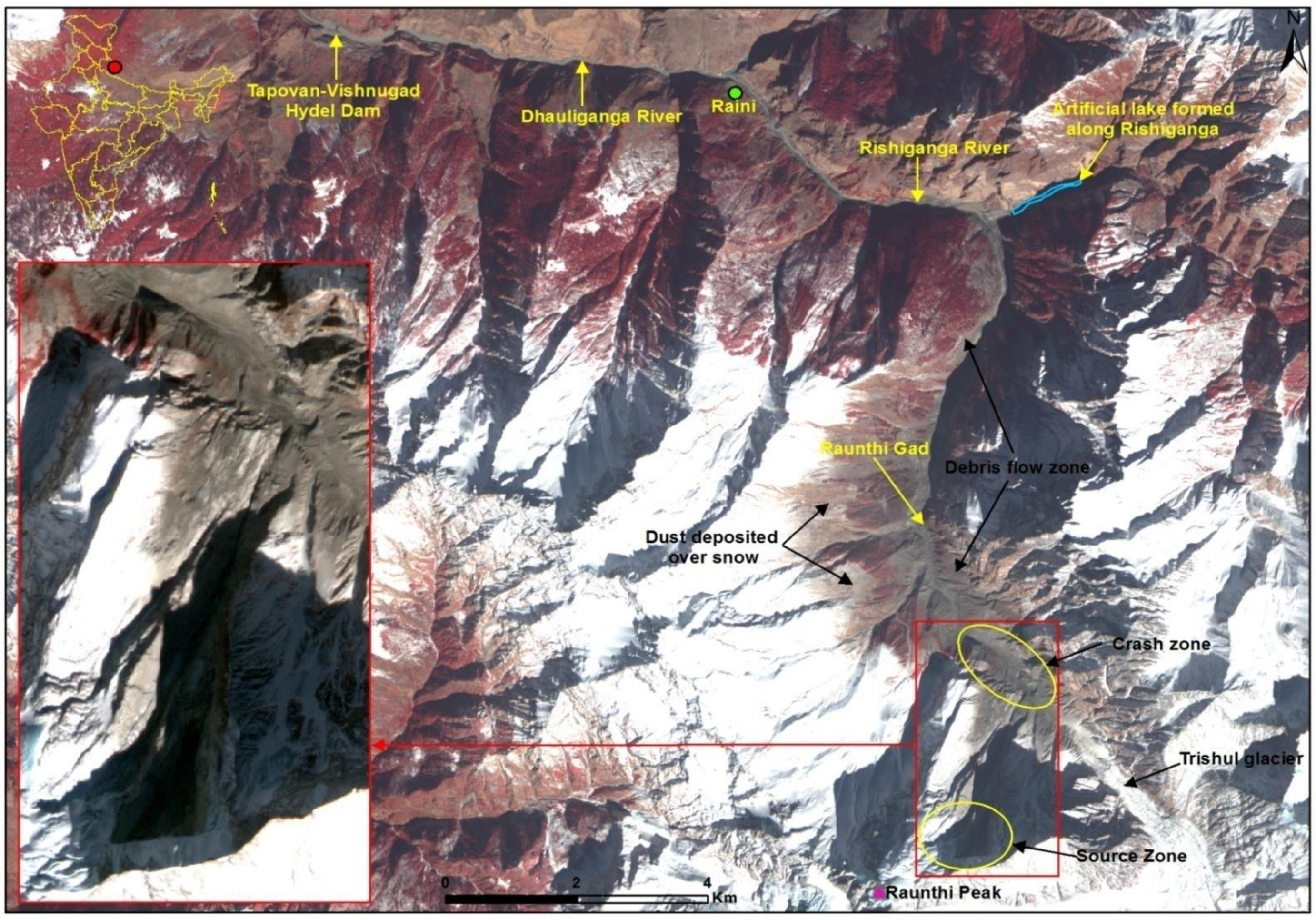


Figure 4. Damage caused by the Raunthi Gad landslide. Synoptic view of the affected region by Raunthi Gad rock fall and Debris flow (7 Feb 2021) as seen from Resourcesat-2A LISS IV image (08 February 2021) shown in FCC. Inset: shows enlarged view of the rock avalanche zone with joints and foliation.

Figure 5. Damage caused by the Raunthi Gad landslide a. Photograph taken from the helicopter showing the triangle shaped release area of the rock avalanche b. Foliation and joint-1 exposed on the joint-2 section, c. Ground photograph showing boulders of various sizes over the dam and on the valley floor, d. Tunnel filled with debris and water e. Ground photograph showing debris flow mark above the valley floor.

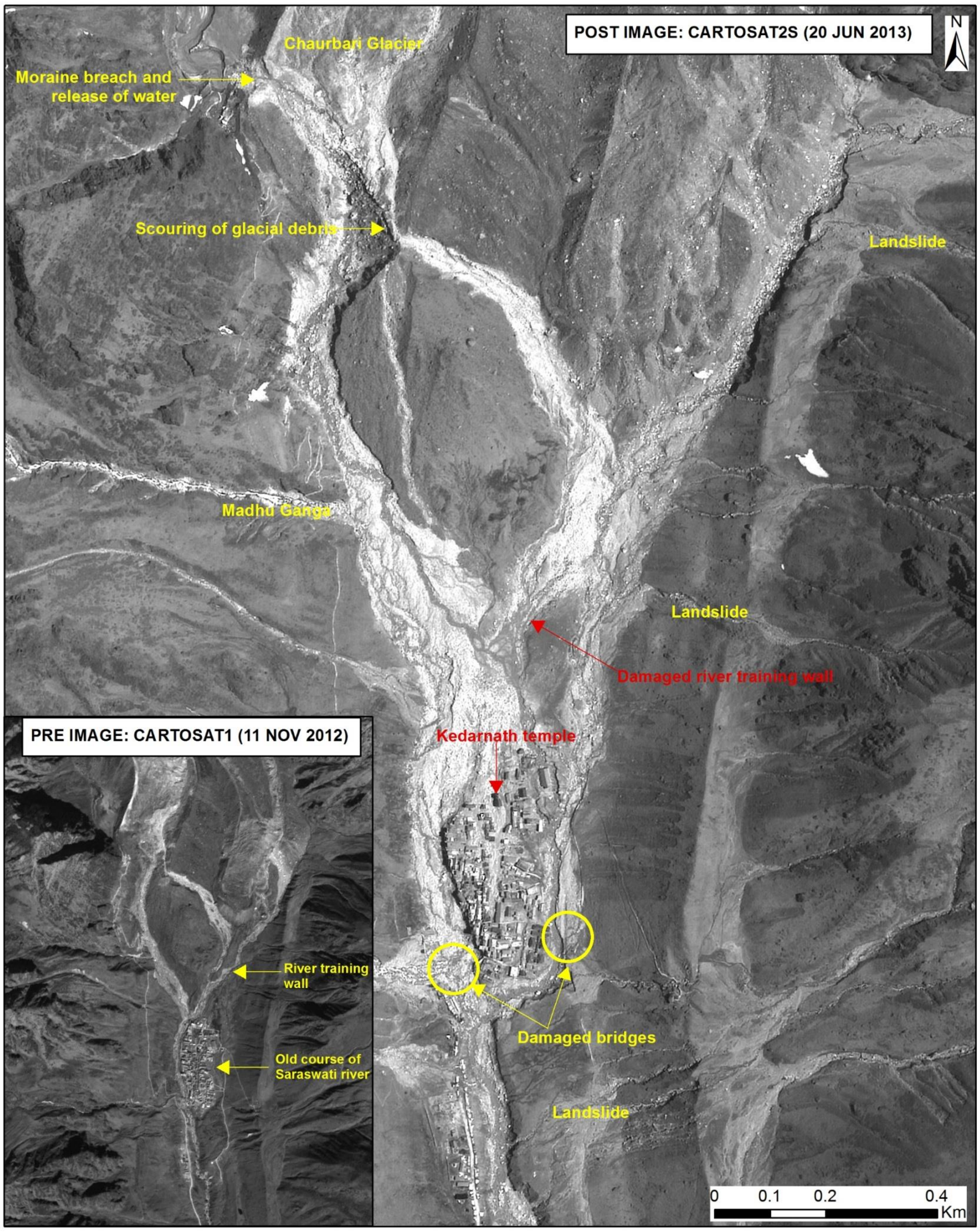


Figure 6. Geomorphological changes leading to the disaster around Kedarnath, Uttarakhand (2013). Satellite data reconstructed the chain of events around Kedarnath during 16-17 June 2013. It was found that reactivation of a large old landslide damaged a river training wall that resulted in the flooding of Kedarnath town on 16 June 2013. The twin events not only buried Kedarnath town with debris brought down from terminal and lateral moraines of Chorabari and Companion glaciers but also changed the course of Mandakini river from west of Kedarnath town to east of it. Pre-disaster Cartosat 1 image and post-disaster Cartosat-2S image of Kedarnath town showing structural damage to buildings and other facilities due to debris flow and flash flood.

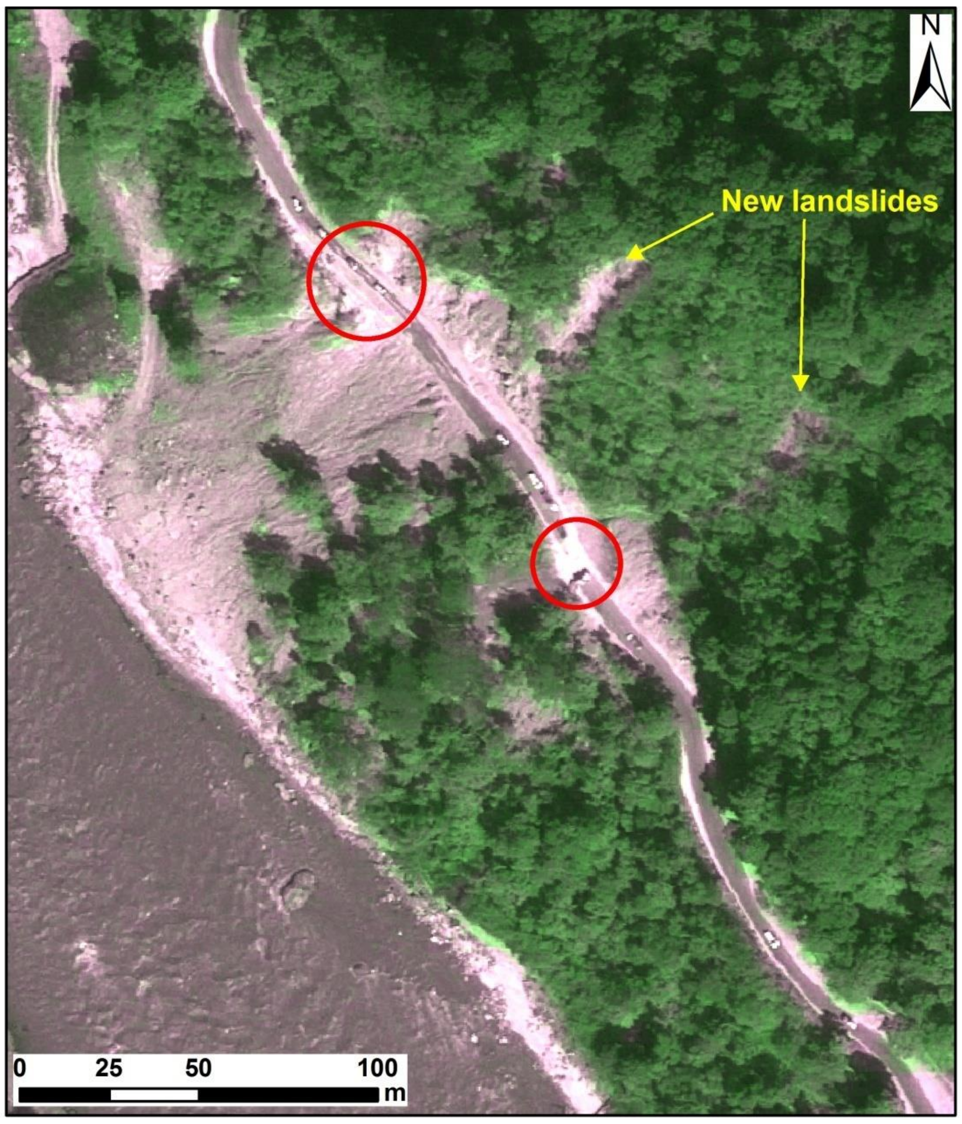
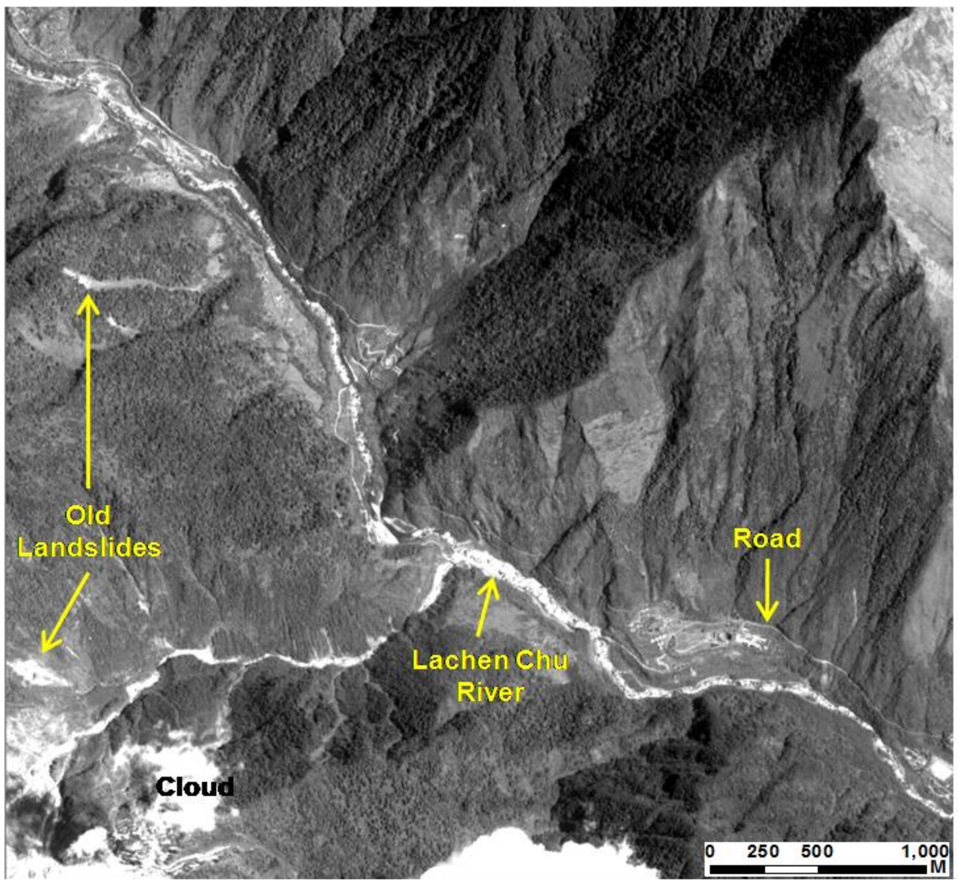


Figure 7. Blockage of road (highlighted with circles) adjacent to the Tista river due to landslides triggered by Sikkim Earthquake, 2011 . Left - pre-earthquake WorldView-2 image, and right - post-earthquake pansharpened GeoEye-1 image shown with natural colour composite.



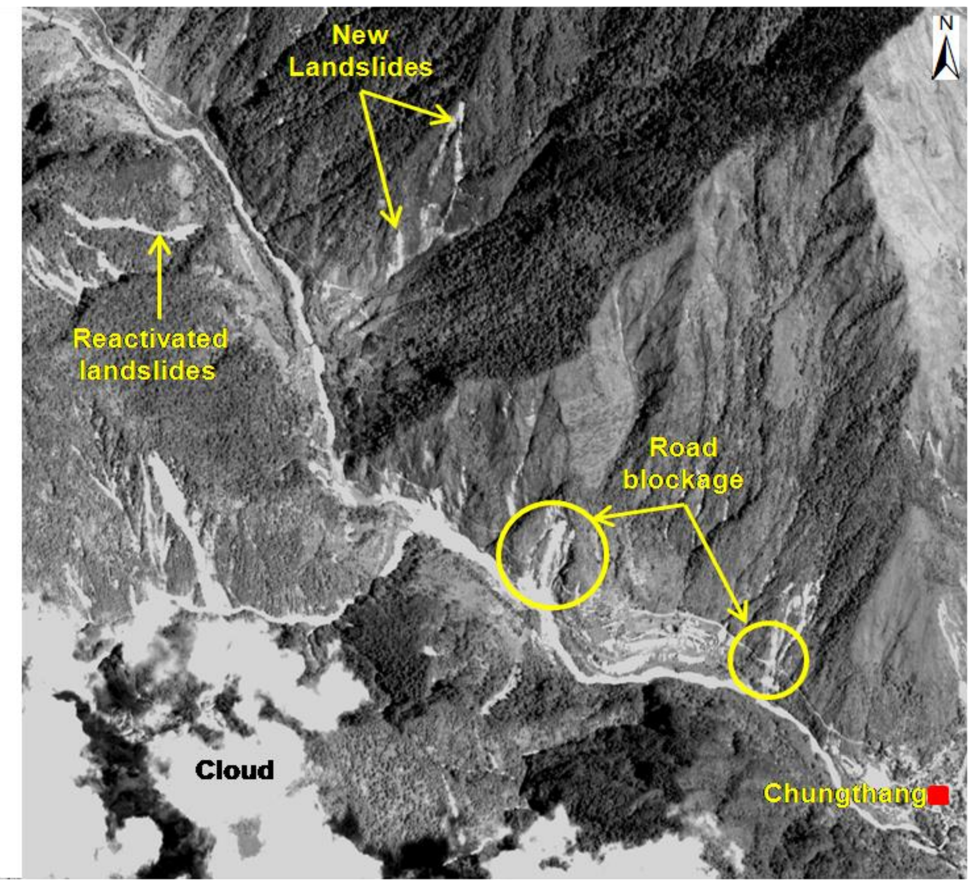


Figure 8. Parts of the road destroyed by landslides triggered due to the earthquake near Chungthang area in north Sikkim. Pre- and post-earthquake Cartosat-1 images are shown in left and right, respectively.

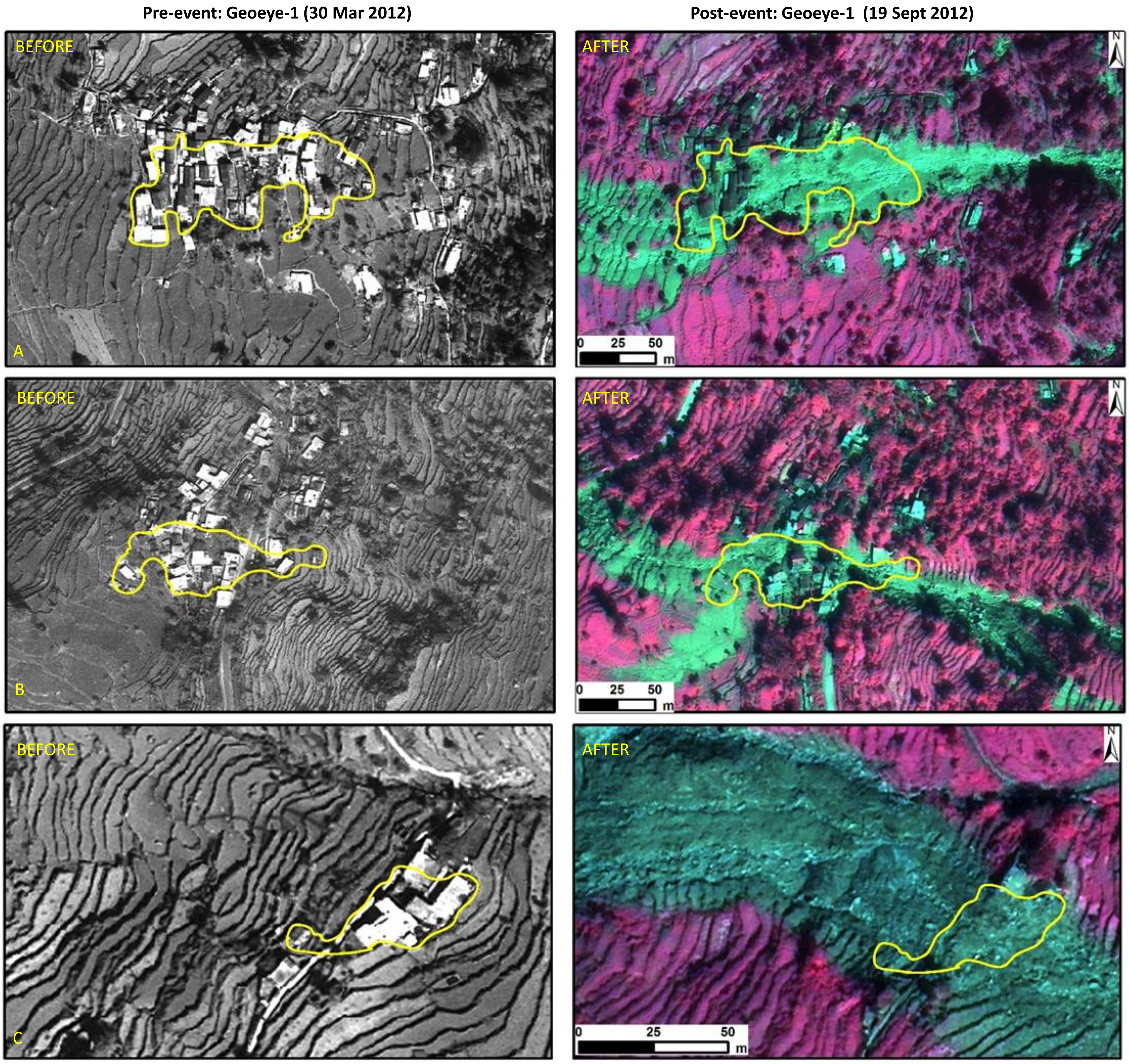


Figure 9. Landslide damage in Okhimath town. Pre- (left) and post- (right) landslide GeoEye-1 images showing buildings that were damaged (yellow outlines) by landslides. A. Mangali village - debris flow buried majority of houses, B. Chunni village - The debris flow that has buried Mangali village has also buried the majority of houses in Chunni village located in the downslope. C. Buildings in the debris flow path were levelled to the ground.

LANDSLIDE INVENTORY OF INDIA

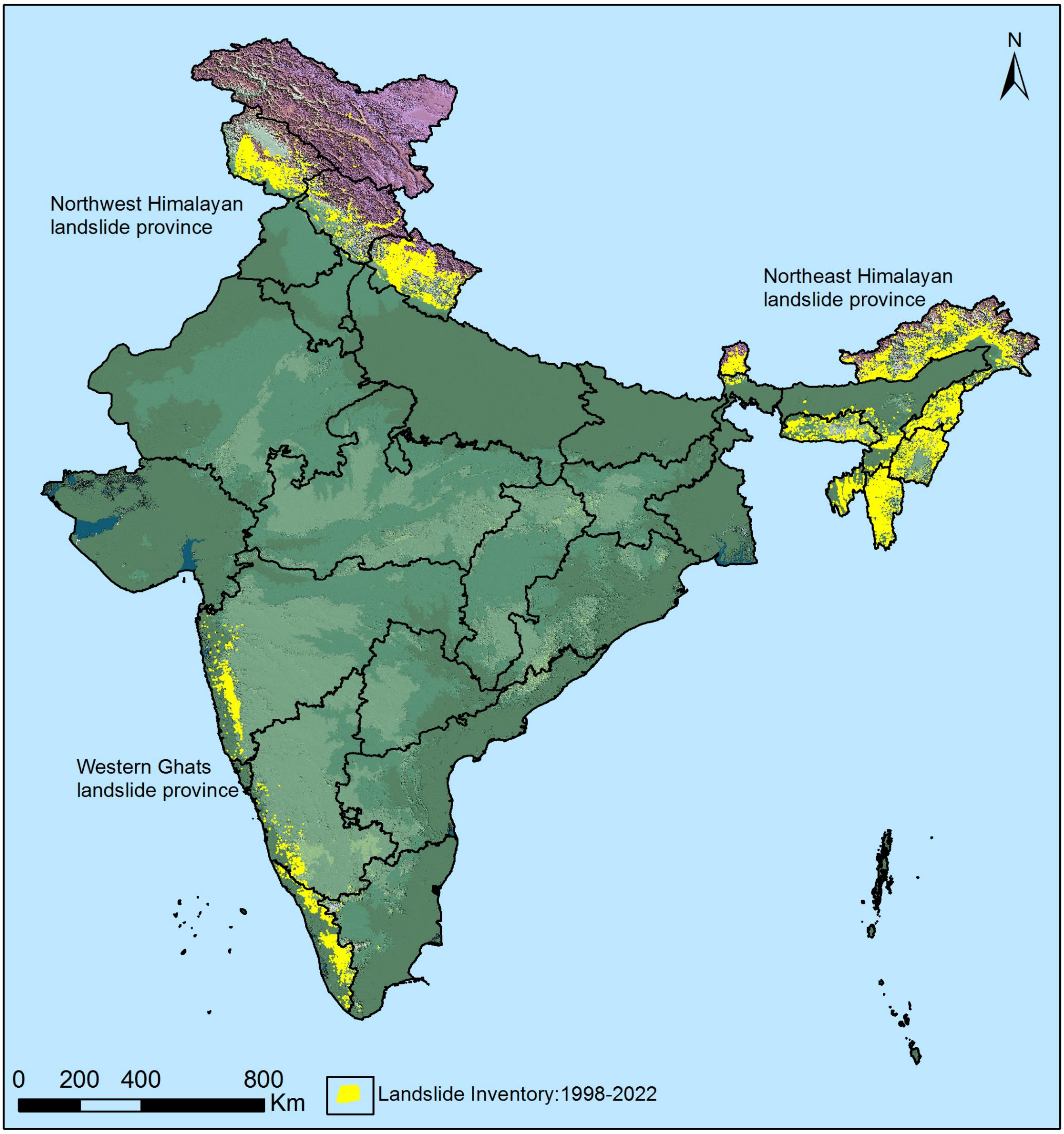


Figure 10. Landslide inventory of India.

The database covers landslide-vulnerable regions of India in the Himalayas and Western Ghats. Satellite data of high to very high resolution nature such as IRS-1D PAN+LISS-III, Resourcesat-1, 2 and 2A LISS-IV Mx, Cartosat-1 and 2S, Aerial images were used in the mapping of landslides. Change detection using visual (manual) and digital (automatic) techniques were used to prepare the landslide inventory database. Some mapped landslides were validated in the field using mobile App and from the news report. The database mainly contains three types of inventory – seasonal, event-based and route-wise for the 2000-2017 period. Seasonal inventory contains pan-India landslide database corresponding to the 2014 and 2017 rainy season in India. The inventory database is available in a web GIS platform in the Bhuvan portal. The landslide inventory database shows the hotspot areas.

Table 2. Landslides inventory database of India.

Sl. No.	State/UTs	Monsoon season 2014	Monsoon season 2017	Field-based/year	Event-based / year	Total
1	**Jammu and Kashmir**	6826	19	434 / 2011	1 / 2015	**7280**
2	**Ladakh**	23		-	-	**23**
3	**Himachal Pradesh**	922	172	413 / 1998	1/ 2017 51/2013 2/2021	**1561**
4	**Uttarakhand**	1593	455	1419 / 1998	32/2003 307/2010 473 / 2012 6610 / 2013 1 / 2017 329/2021 1/2022	**11219**
5	**Sikkim**	73	79	-	1408 / 2011 8 / 2012 1/ 2016	**1569**
6	**West Bengal**	24	82	-	66 / 2011	**172**
7	**Arunachal Pradesh**	2904	4709	-	75 / 2016 1/2021	**7689**
8	**Nagaland**	54	2071	-	7/2017	**2132**
9	**Manipur**	379	4559	-	556/2017 1/2022	**5494**
10	**Mizoram**	1205	2254	-	8926/2017	**12385**
11	**Tripura**	56	8014	-	-	**8070**
12	**Assam**	1243	793	-	533/2017 5091/2022	**2569**
13	**Meghalaya**	2127	512	-	-	**2639**
14	**Maharashtra**	97	3	-	5012/2021	**5112**
15	**Goa**	2	1	-	-	**3**
16	**Karnataka**	82	19	-	993/2018	**1094**
17	**Kerala**	9	45	-	5191/2018 756/2019 09/2020 29/2021	**6039**
18	**Tamil Nadu**	79	8	-	603/2018	**690**
19	**Haryana**	-	100	-	-	**100**
Total		**17,698**	**23,895**	**2,266**	**37,074**	**80933**

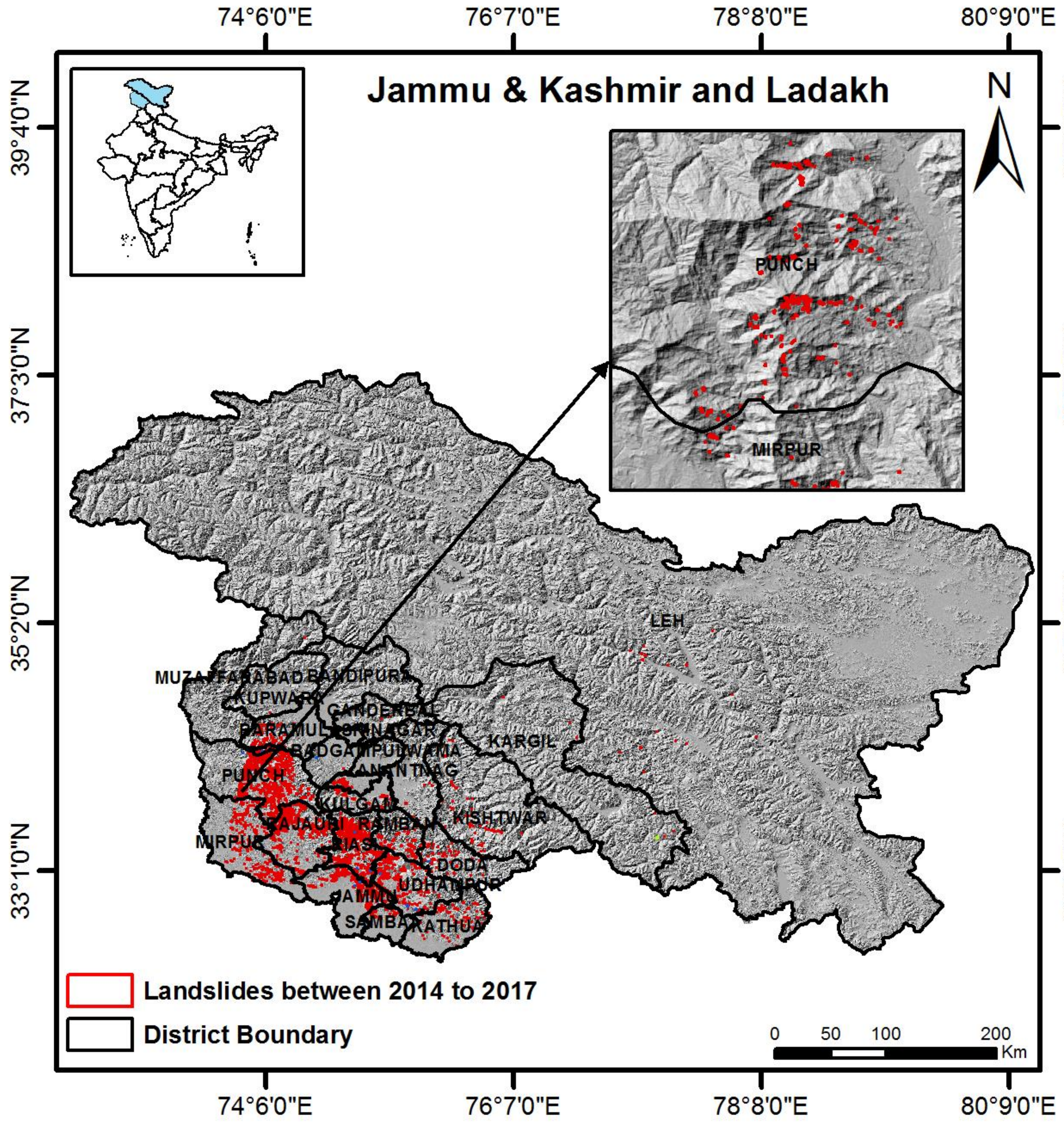


Figure 11. Landslides mapped using high-resolution satellite data in Jammu & Kashmir and Ladakh, which occurred between 2014 to 2017.

Figure 12. Paryote landslides near Paryote village in Doda district, Jammu and Kashmir. The continuous reactivation of Paryote Landslide near Paryote village in Doda district of Jammu and Kashmir. Translational-type failure with rock fall has occurred near the crown of the landslide, followed by a partially channelized debris flow along the main body of the landslide.

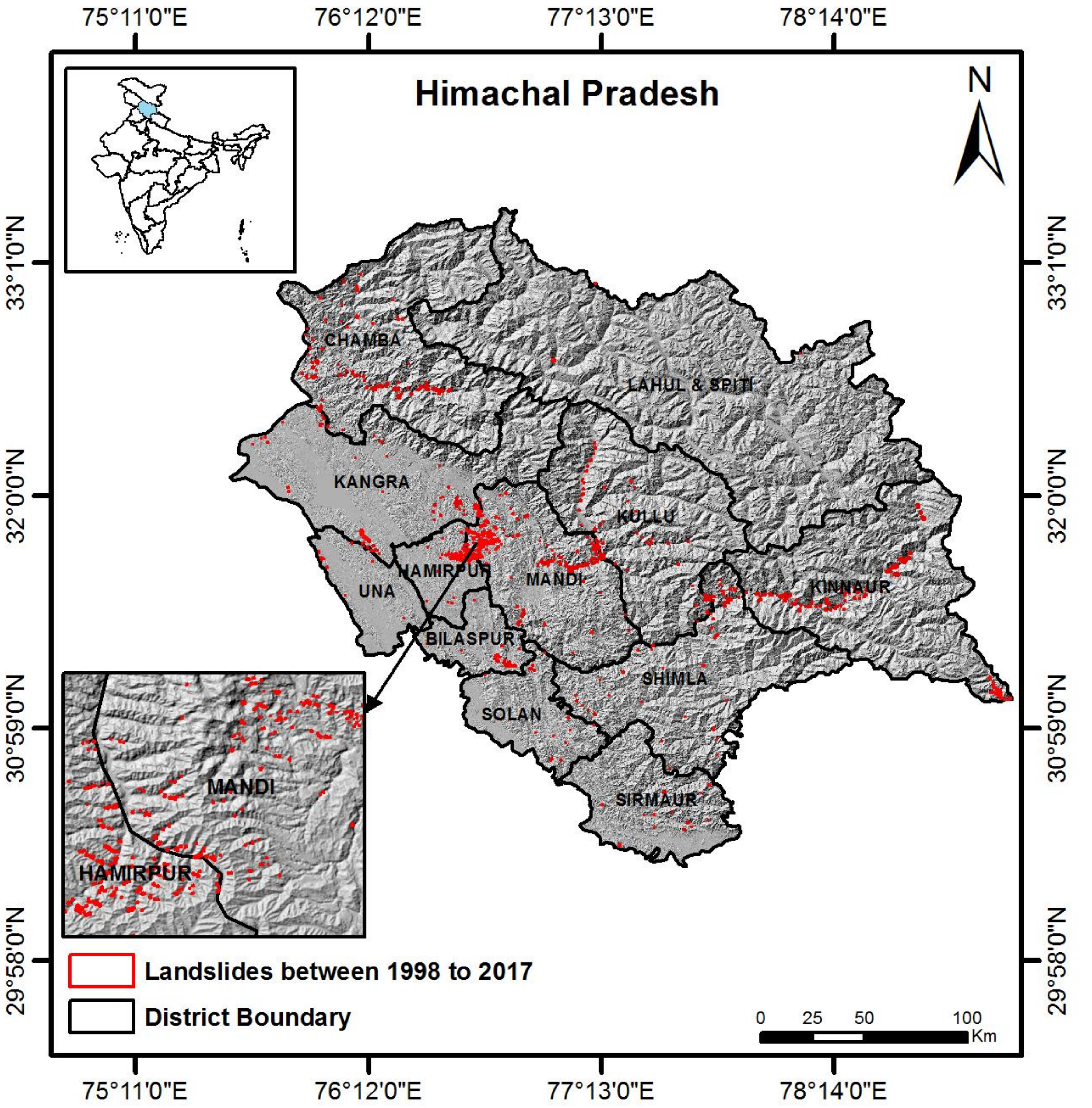


Figure 13. Landslides mapped using high-resolution satellite data in Himachal Pradesh, which occurred between 1998 to 2017.

Figure 14. Kotropi landslides, Mandi district, Himachal Pradesh. A massive landslide occurred near the village of Kotropi in Mandi district of Himachal Pradesh, on Sunday, 13th of August, 2017. The landslide occurred on National highway 154, the road between Mandi and Pathankot. The landslide resulted from rotation failure near the crown region followed by deep translational mechanism along the landslide body and channelised debris flow along the toe.

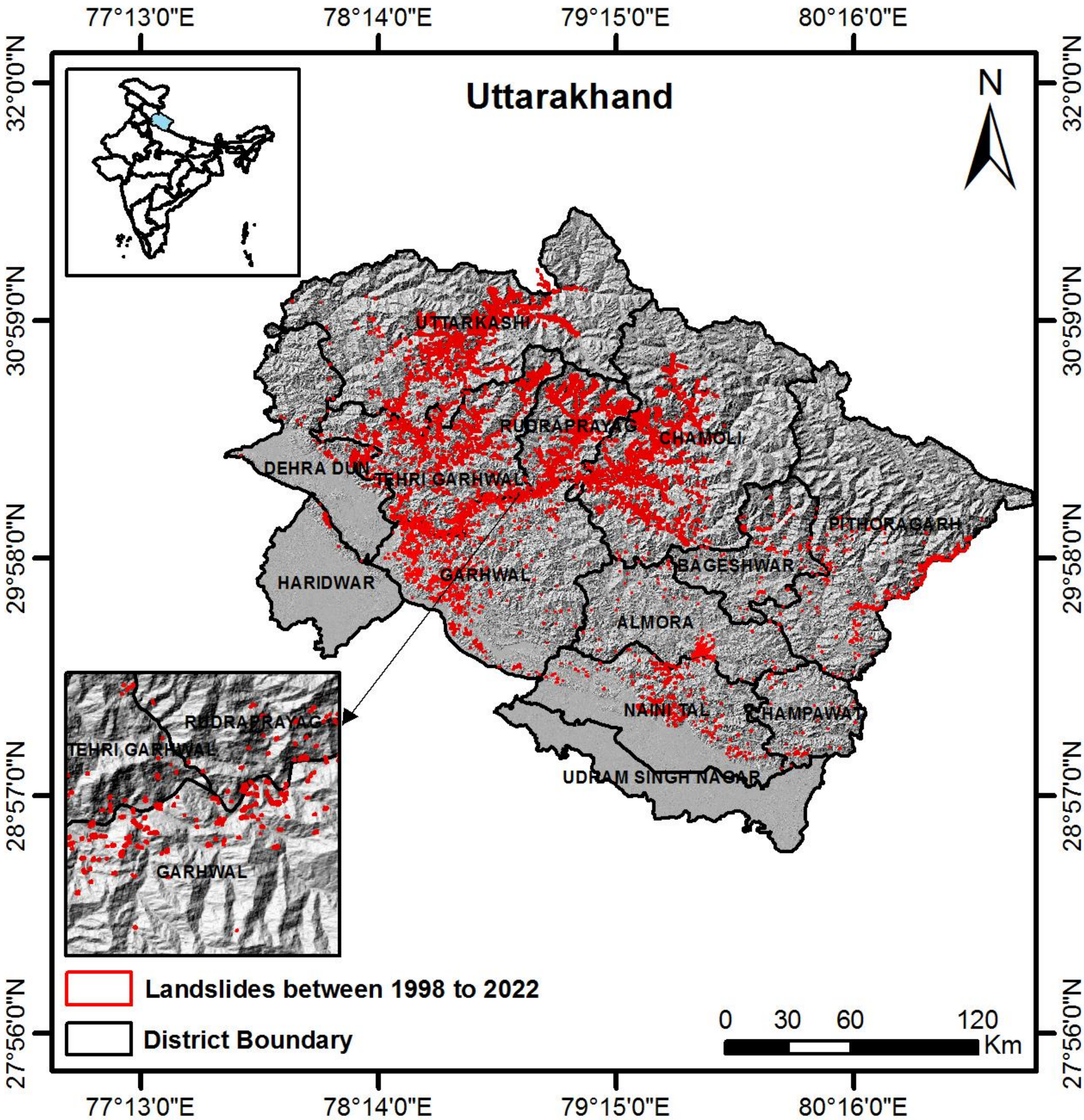


Figure 15. Landslides mapped using high-resolution satellite data in Uttarakhand, which occurred between 1998 to 2022.

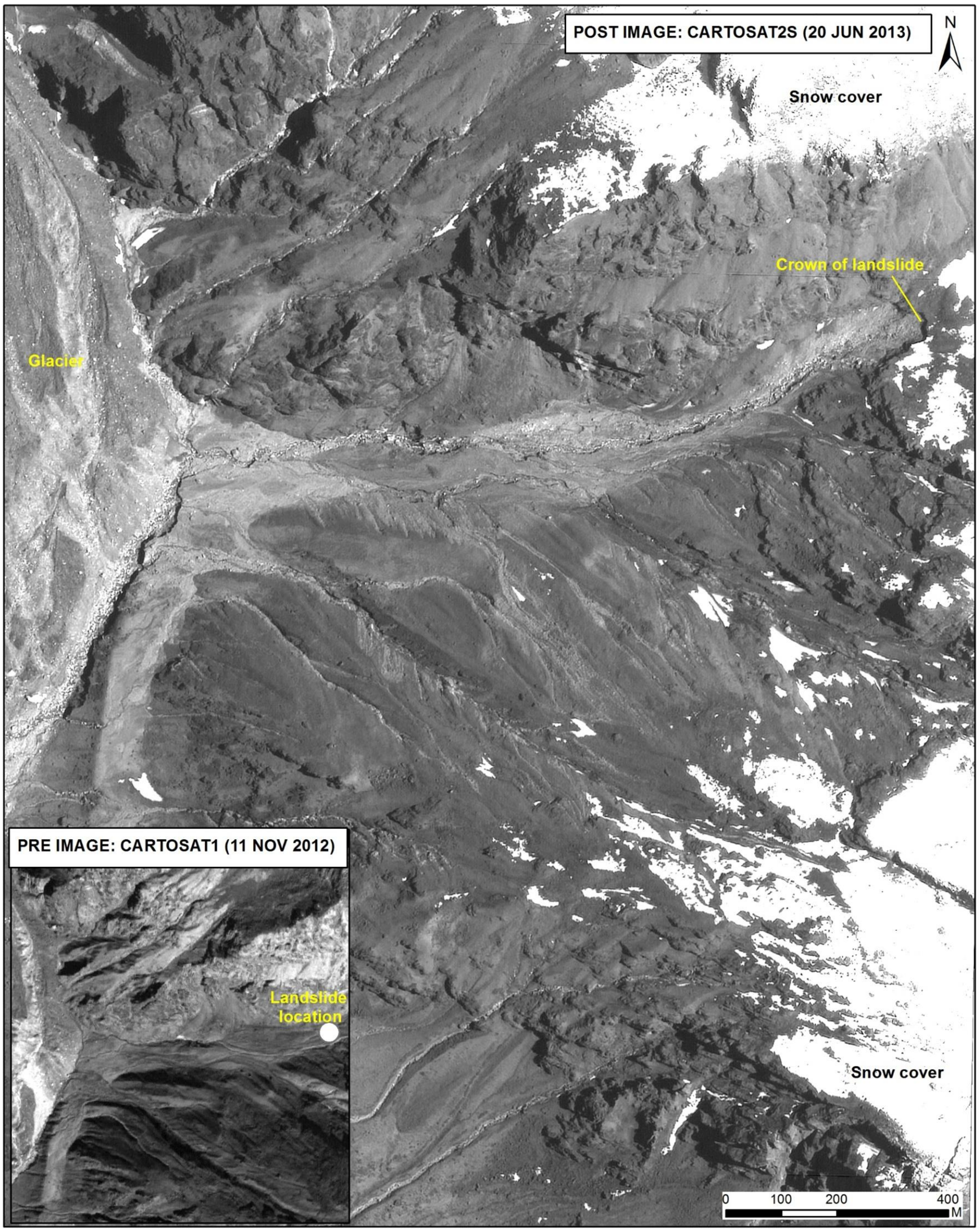


Figure 16. Landslides around Kedarnath, Uttarakhand. During 16-17 June 2013, heavy rainfall (approximately 325 mm) caused widespread flash floods in the upstream areas of Mandakini, Alaknanda and Bhagirathi rivers resulting in massive damage to properties and infrastructures in the Kedarnath valley and areas in the downstream of Badrinath and Gangotri. A large reactivated landslide breached an artificial embankment north of the Kedarnath town.

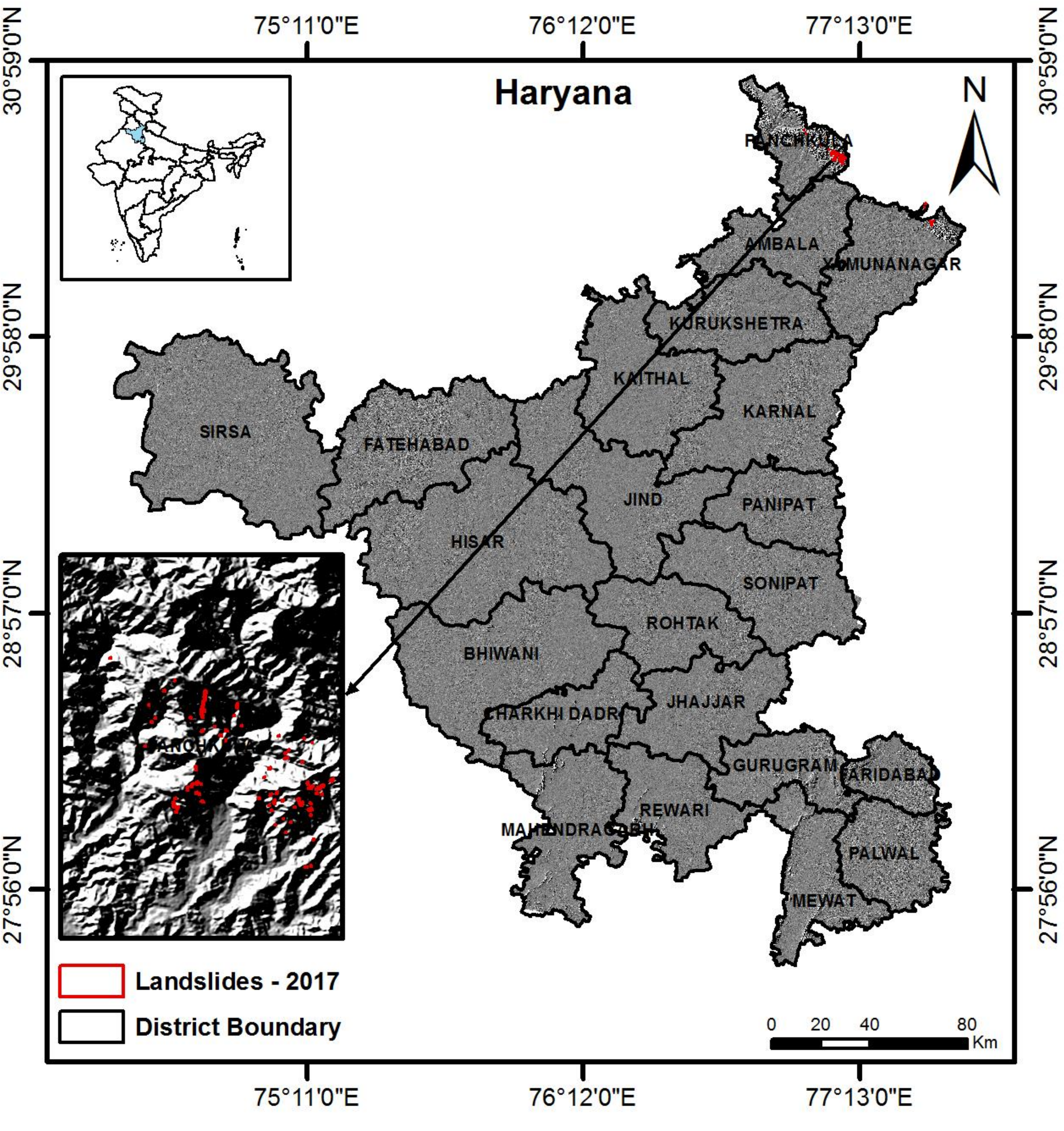


Figure 17. Landslides mapped using high-resolution satellite data in Haryana, which occurred in 2017.

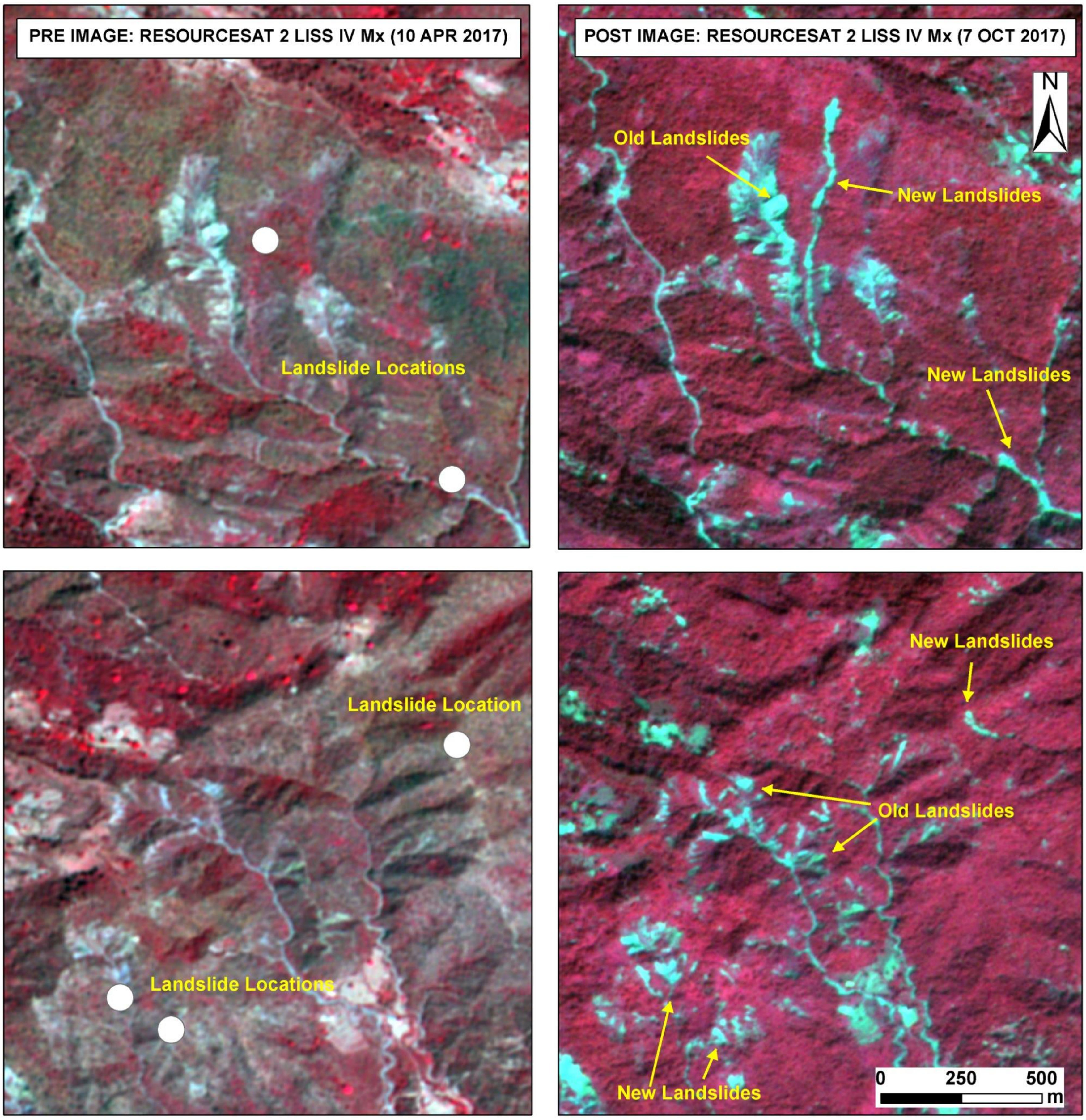


Figure 18. Panchkula landslides, Haryana. Landslide was triggered in the Panchkula of Haryana to heavy monsoonal rain in 2017. The landslide is shallow translational failure followed by channelized debris flow.

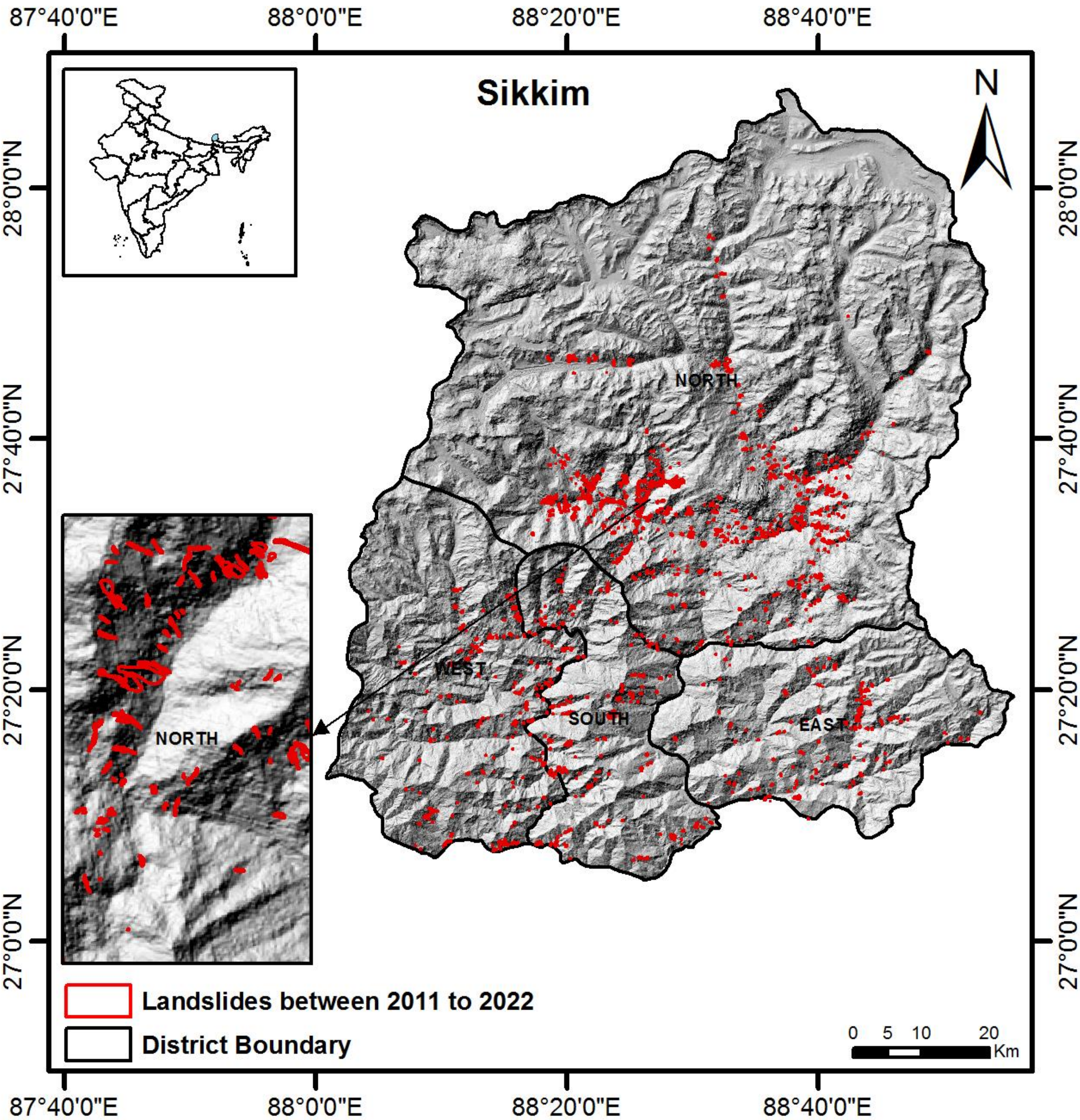


Figure 19. Landslides mapped using high-resolution satellite data in Sikkim, which occurred between 2011 to 2022.

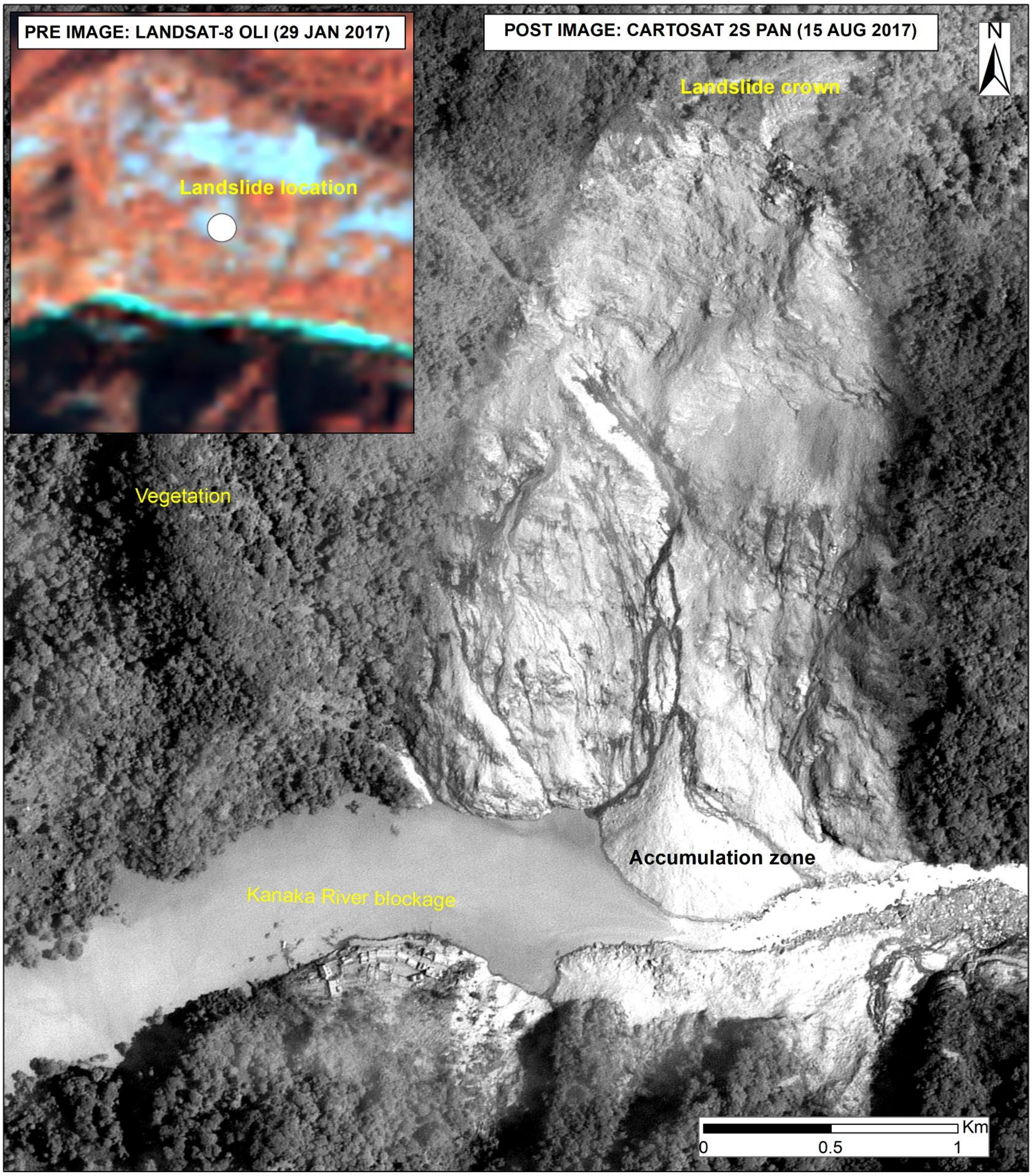


Figure 20. Mantam landslide, Sikkim. A massive landslide occurred near the village of Mantam (opposite the Passingdang-Mantam road) in Sikkim on 13th of August, 2016. Wedge type failure has occurred near the crown of the landslide followed by a translational type of failure in the main body of the landslide.

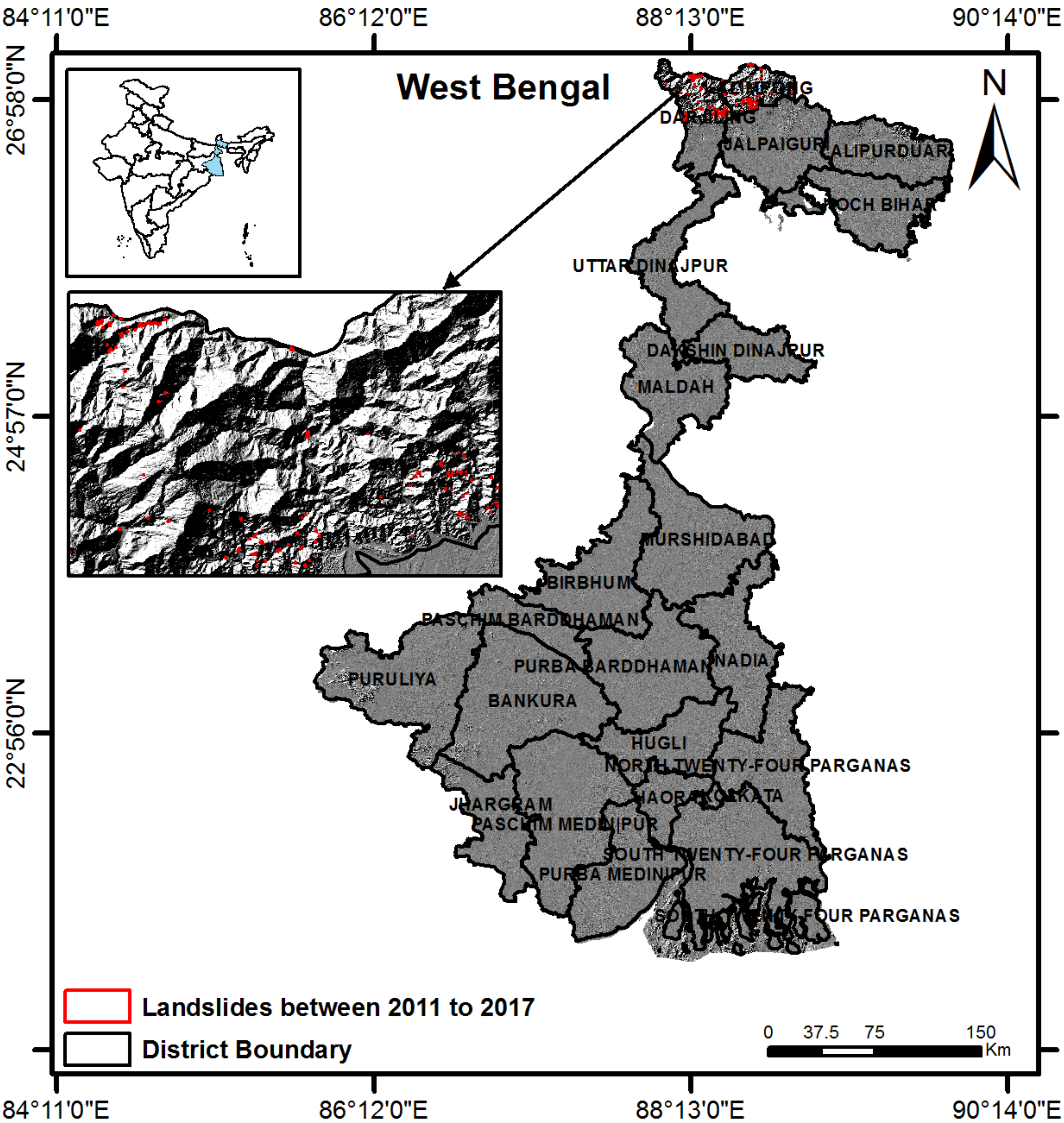


Figure 21. Landslides mapped using high-resolution satellite data in West Bengal, which occurred between 2011 to 2017.

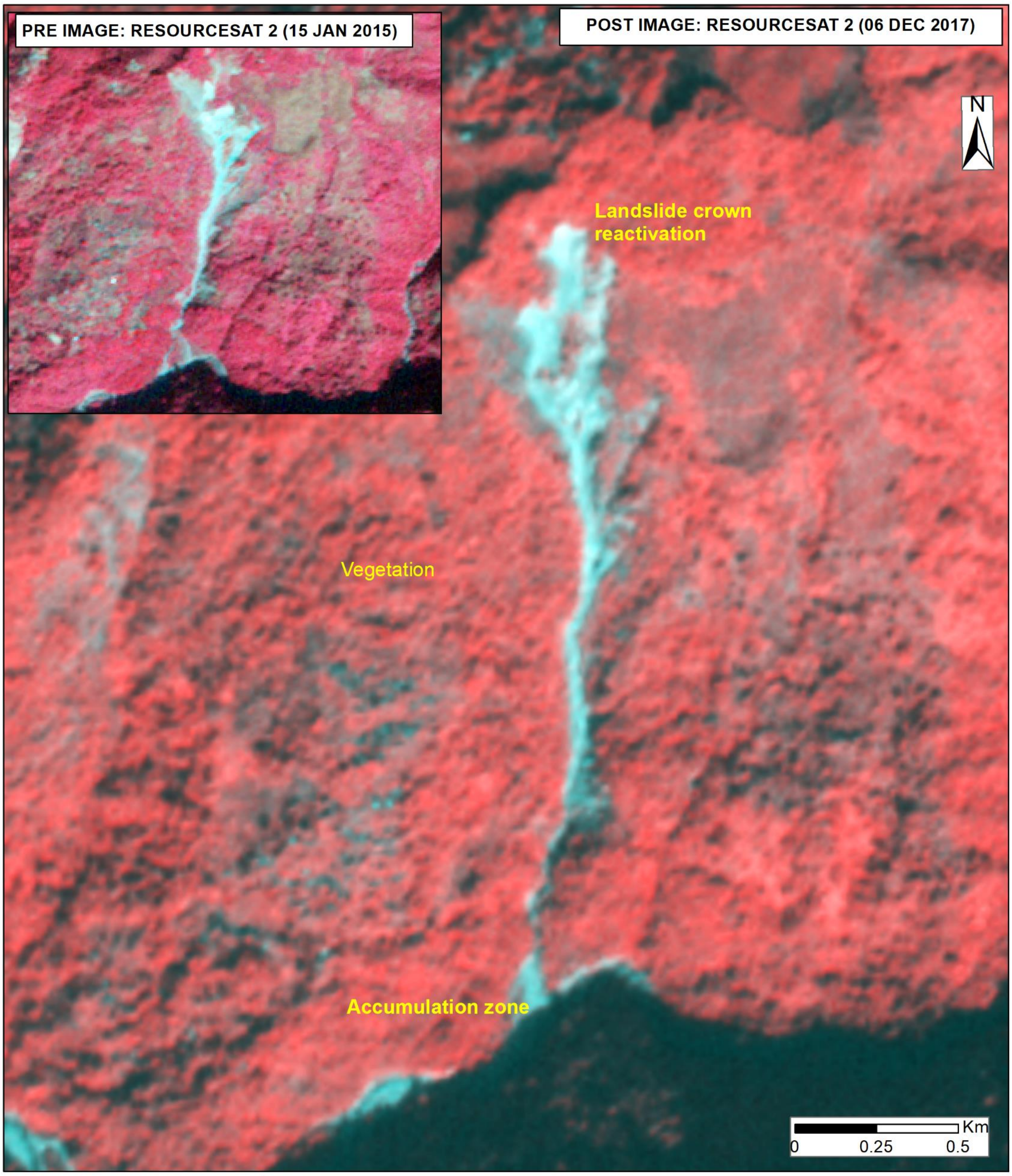


Figure 22. Landslide near Kurseong village, West Bengal. Reactivation of a large landslide near Kurseong town in Darjeeling district of West Bengal. Translational-type failure has occurred near the crown of the landslide, followed by a channelized debris flow along the main body of the landslide.

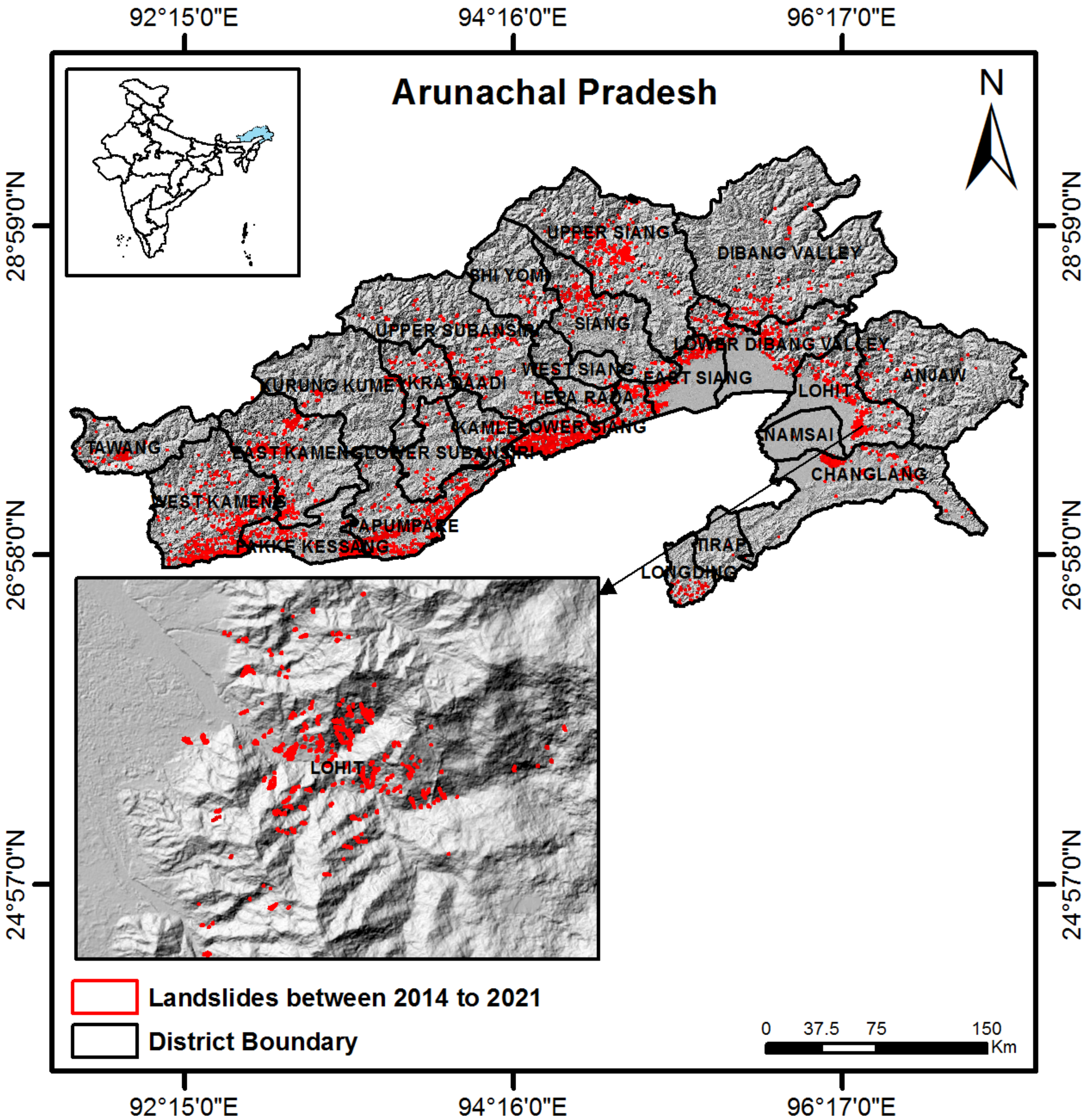


Figure 23. Landslides mapped using high-resolution satellite data in Arunachal Pradesh, which occurred between 2014 to 2021.

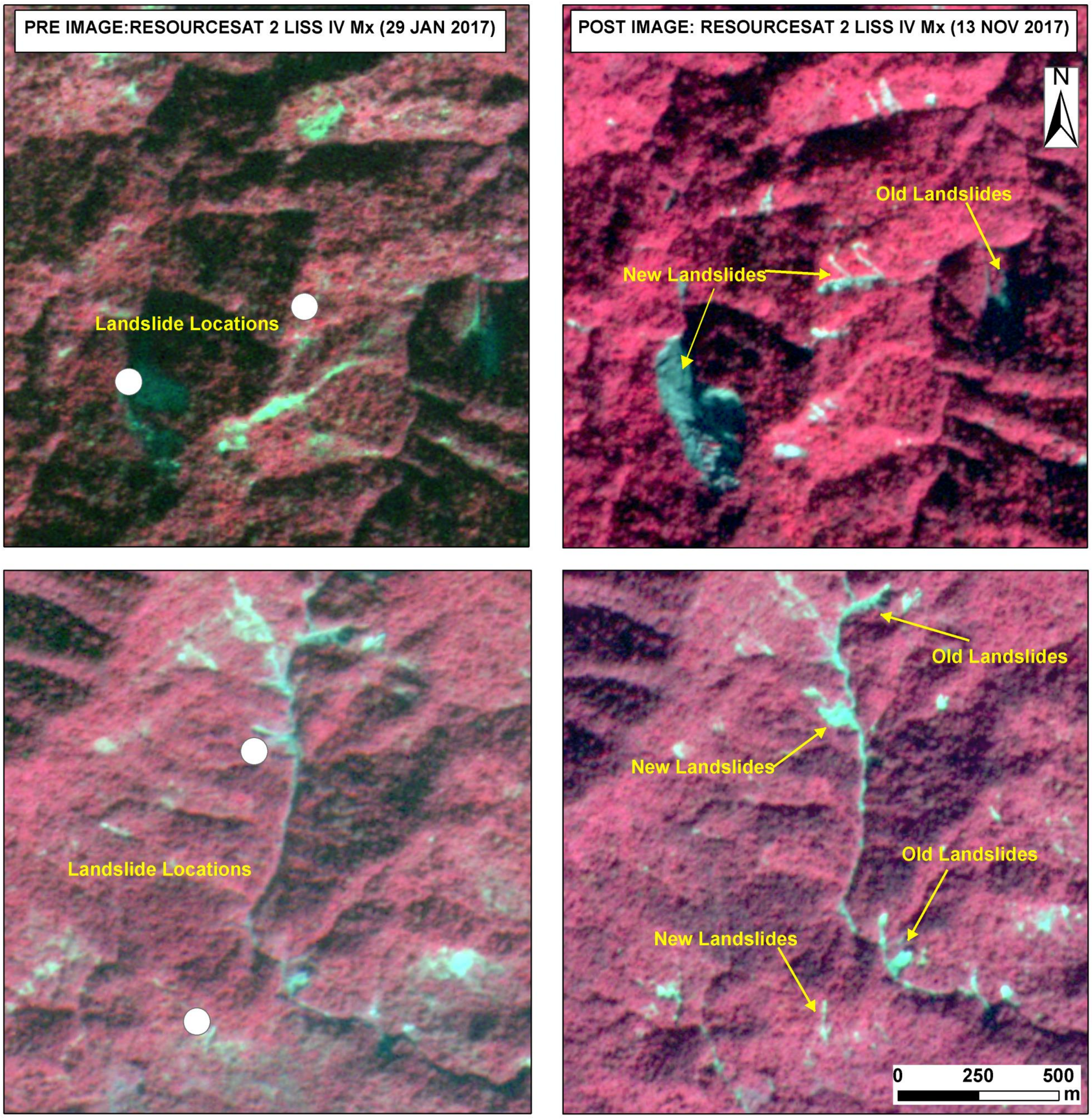


Figure 24. Landslide from West Siang, Arunachal Pradesh. Landslide was triggered in the West Siang of Arunachal Pradesh to heavy monsoonal rain in 2017. The landslide is shallow translational failure.

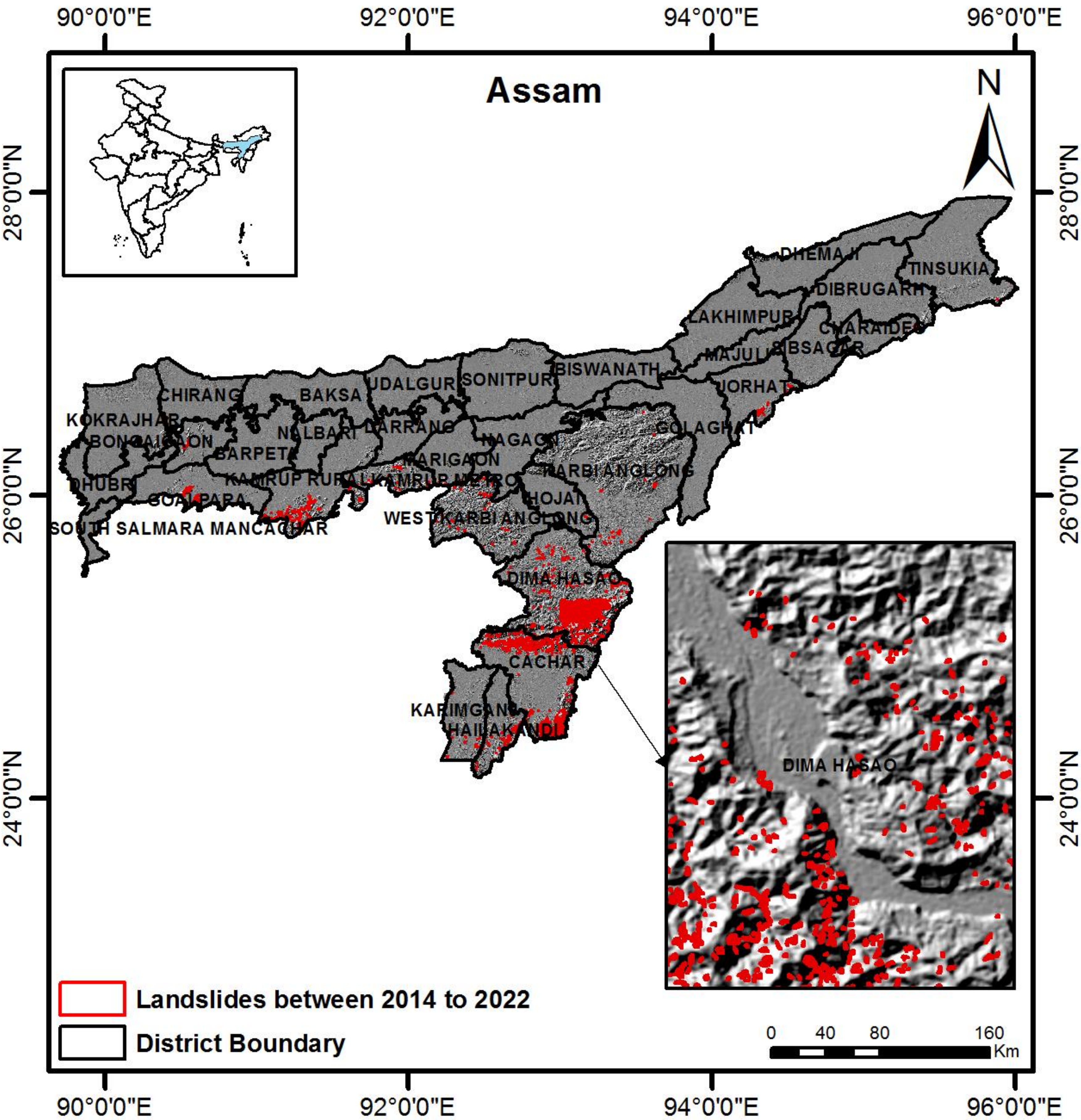


Figure 25. Landslides mapped using high-resolution satellite data in Assam, which occurred between 2014 to 2022.

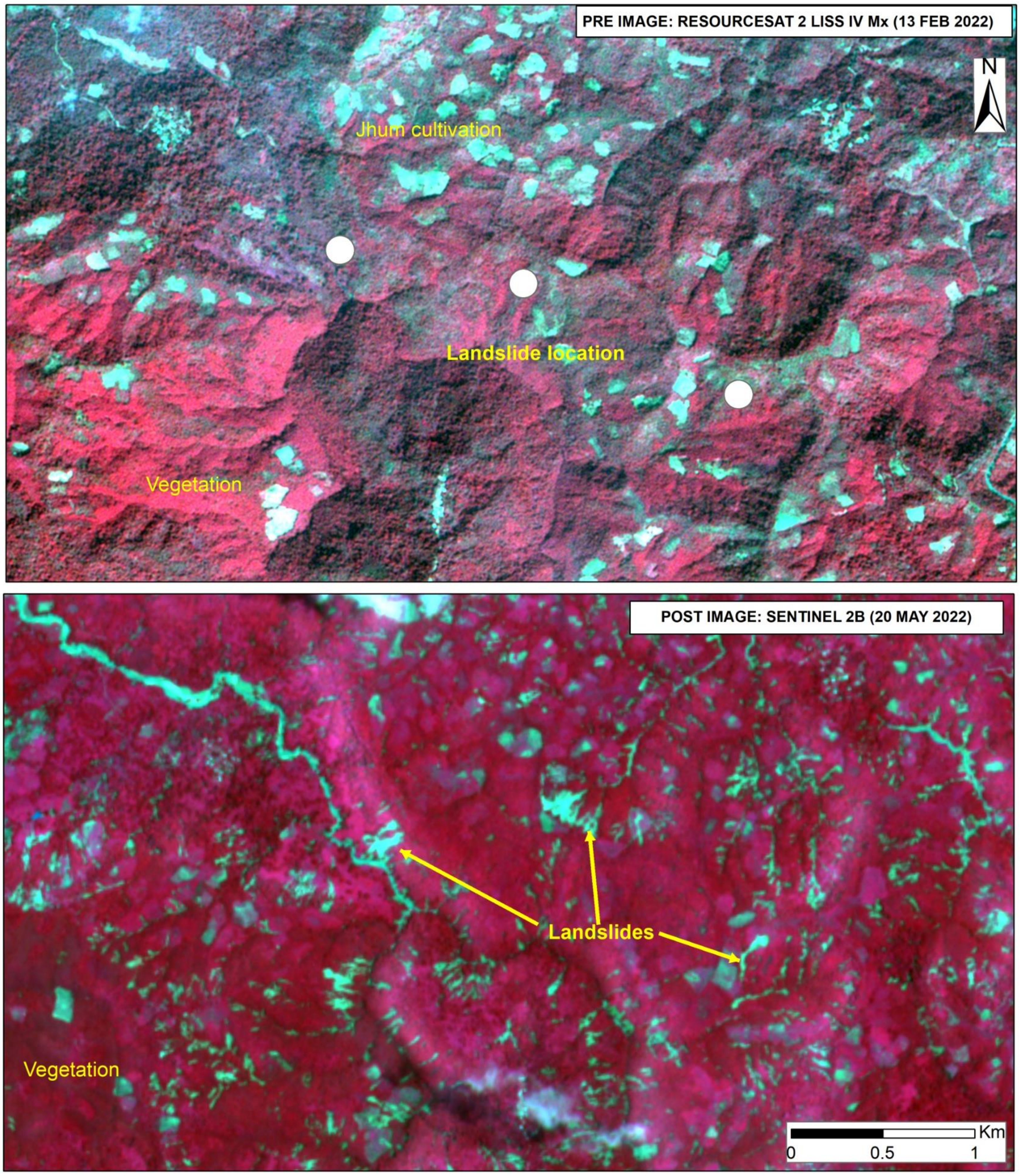


Figure 26. Landslide from Dima Hasao District, Assam. Cluster landslides in Dima Hasao District of Assam caused by heavy rainfall in the month of April, 2023. Most of the landslides are shallow translational failures.

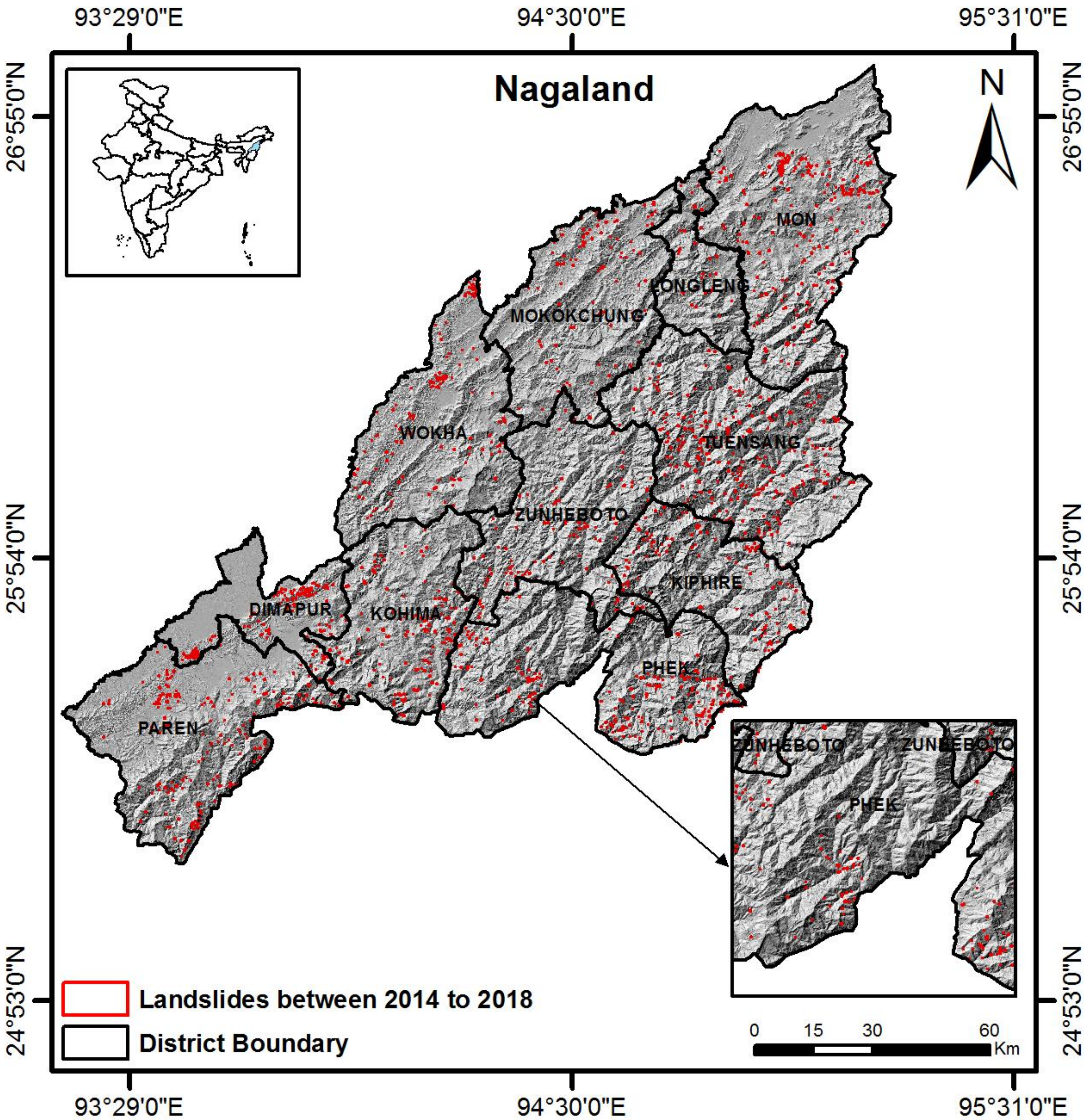


Figure 27. Landslides mapped using high-resolution satellite data in Nagaland, which occurred between 2014 to 2018.

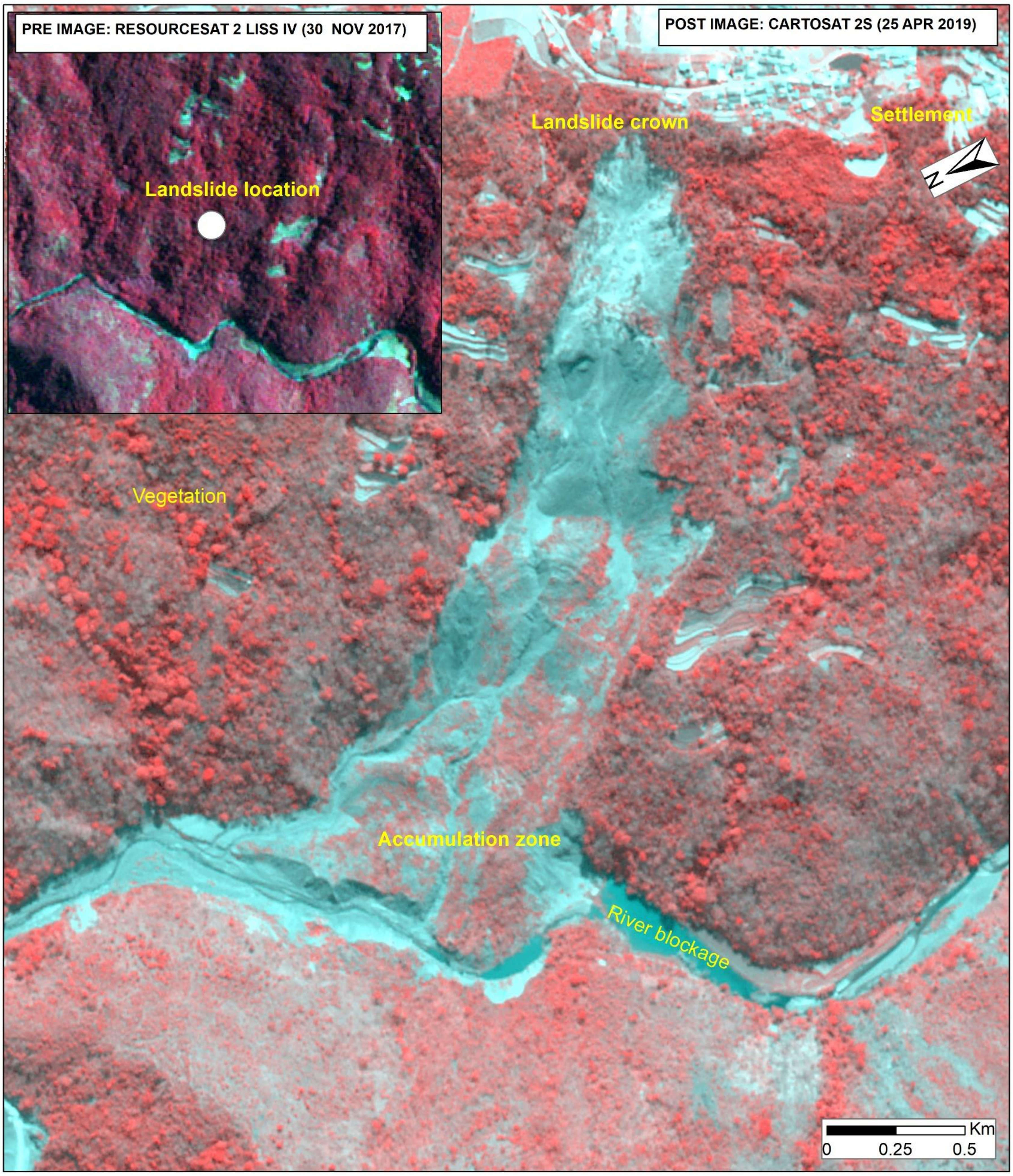


Figure 28. Landslide from Kikruma from Phek district, Nagaland. A large landslide was triggered on 29 July 2018 near Kikruma village in Phek district of Nagaland resulting in the formation of an artificial dam on the Sidzu. The failure mechanism of the landslide is deep translational (planar) .

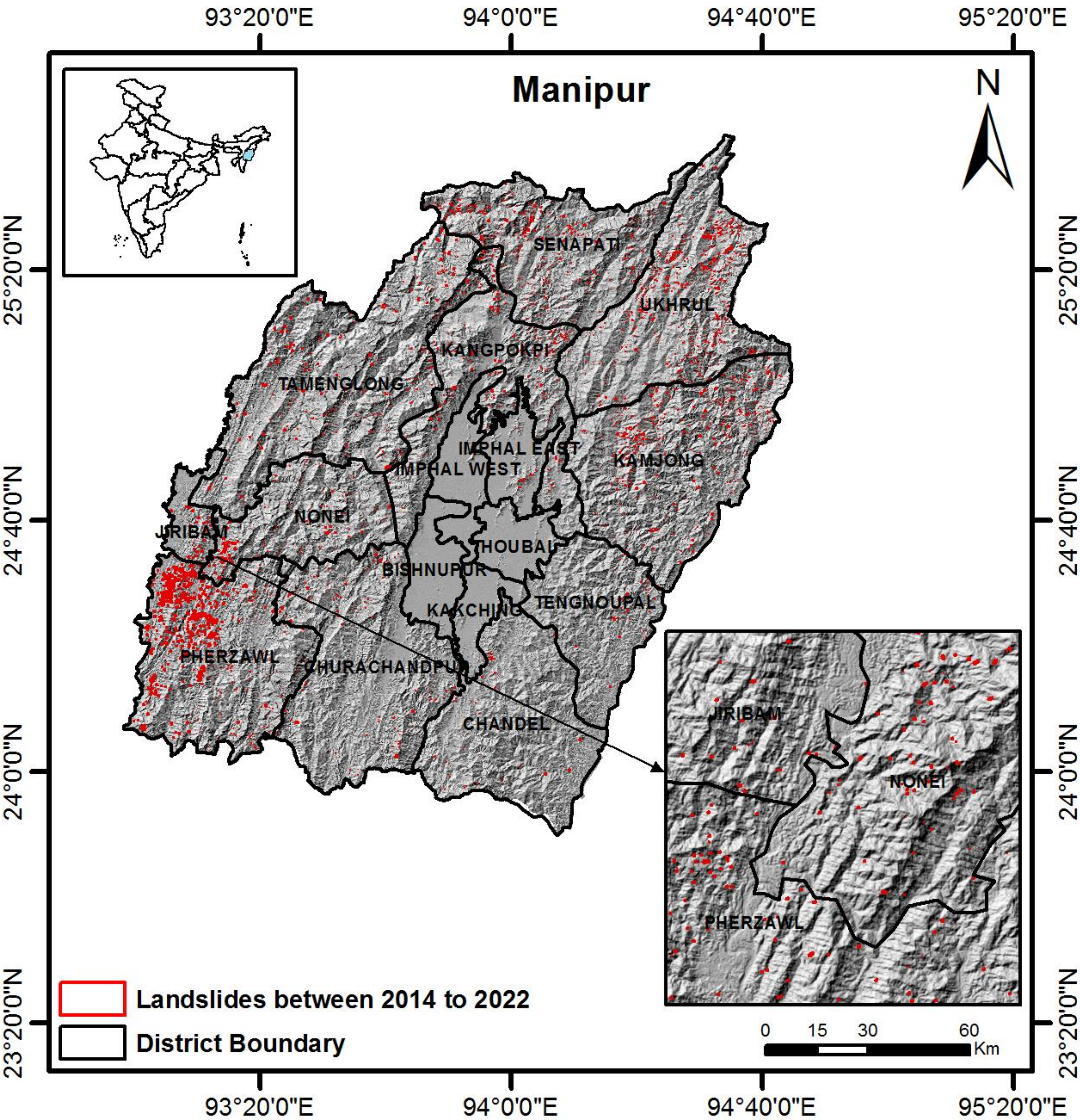


Figure 29. Landslides mapped using high resolution satellite data in Manipur which were occurred between 2014 to 2022.

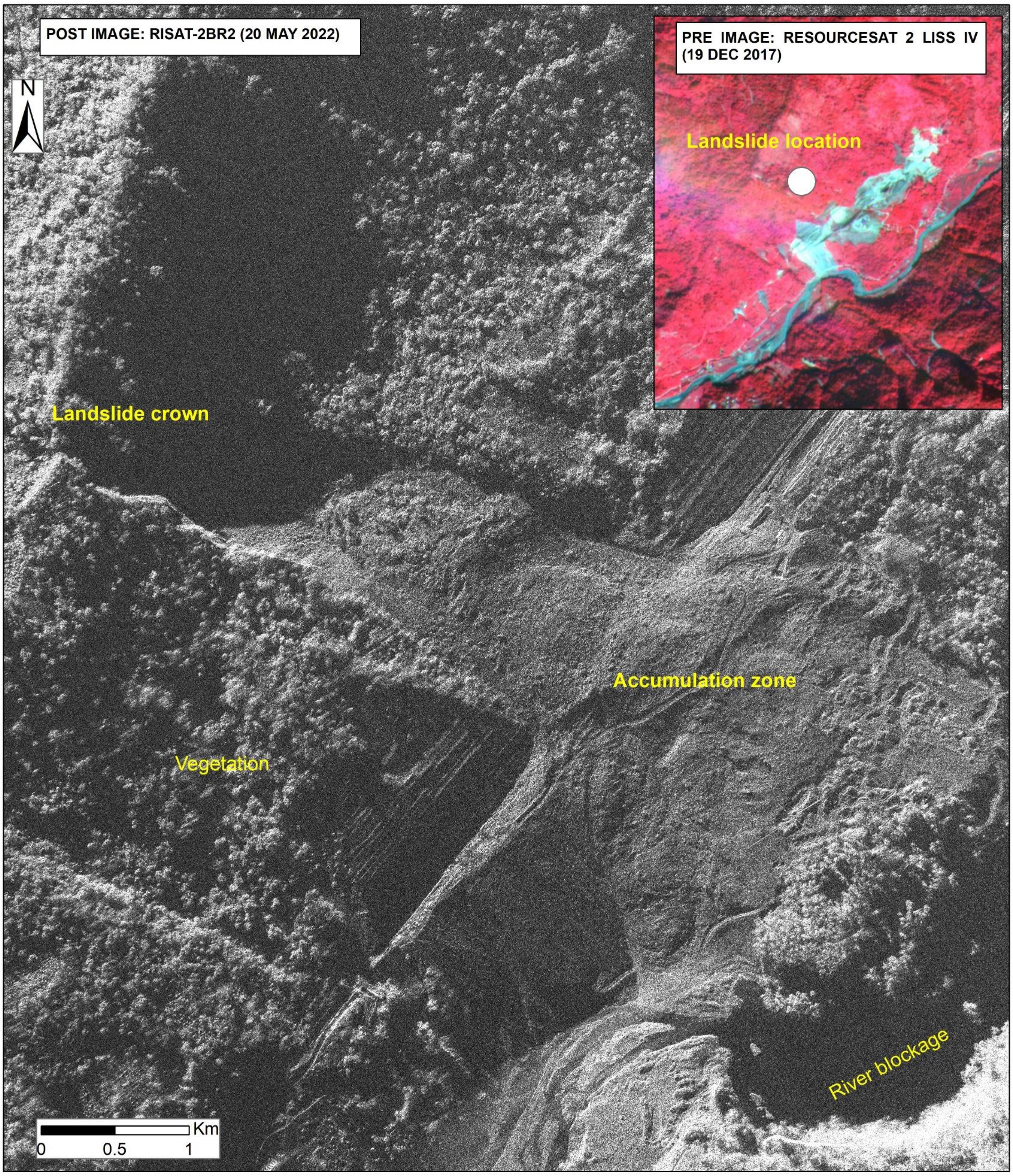


Figure 30. Landslide Occurred near Tupul Railway Station, Noney, Manipur . A large landslide occurred near Tupul railway station in the Noney district of Manipur on 30 June 2022. From the geometry of the landslide, it can be inferred that the failure is a rotational type, and the crown is located on an unstable slope.

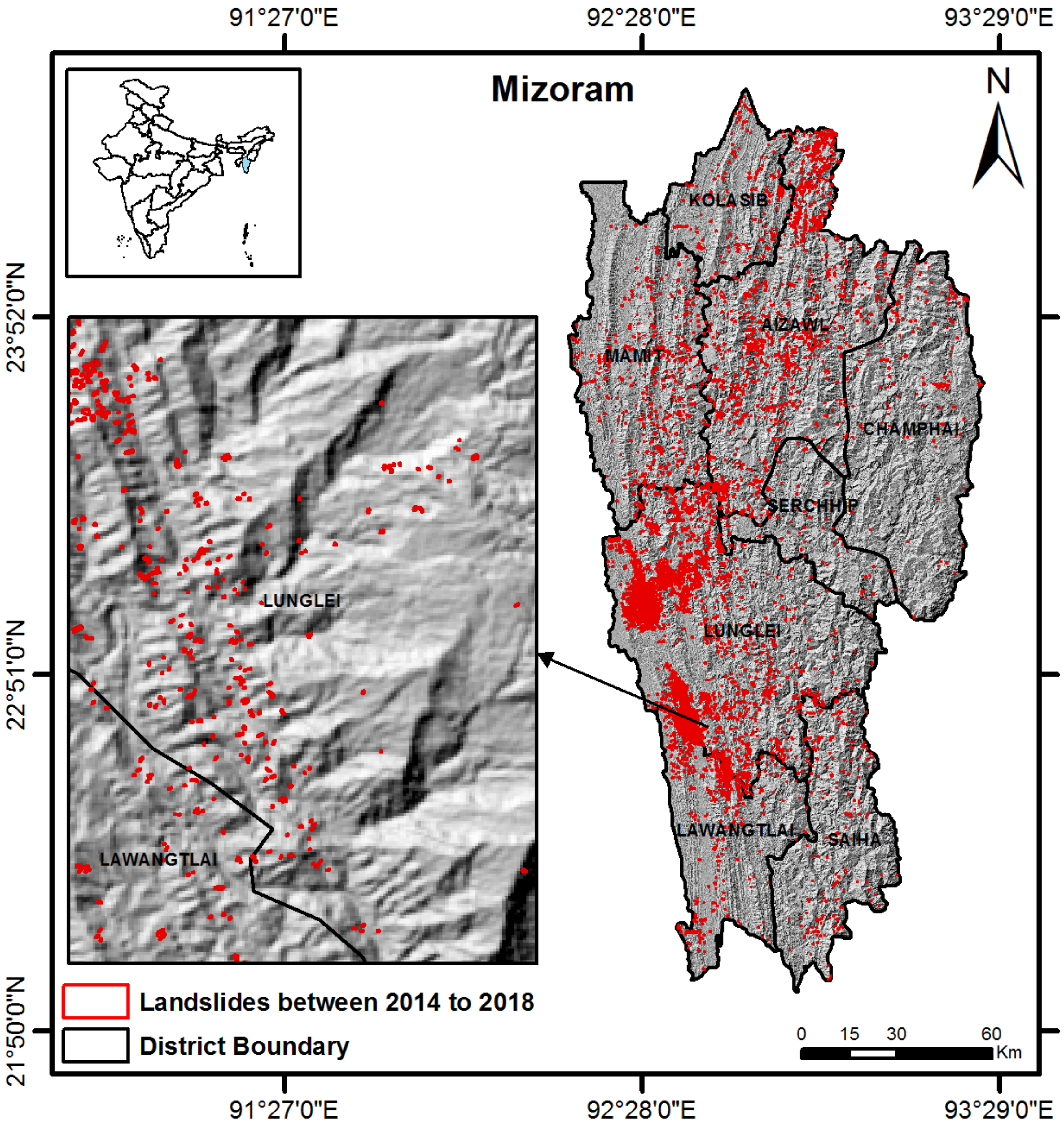


Figure 31. Landslides mapped using high-resolution satellite data in Mizoram, which occurred between 2014 to 2018.

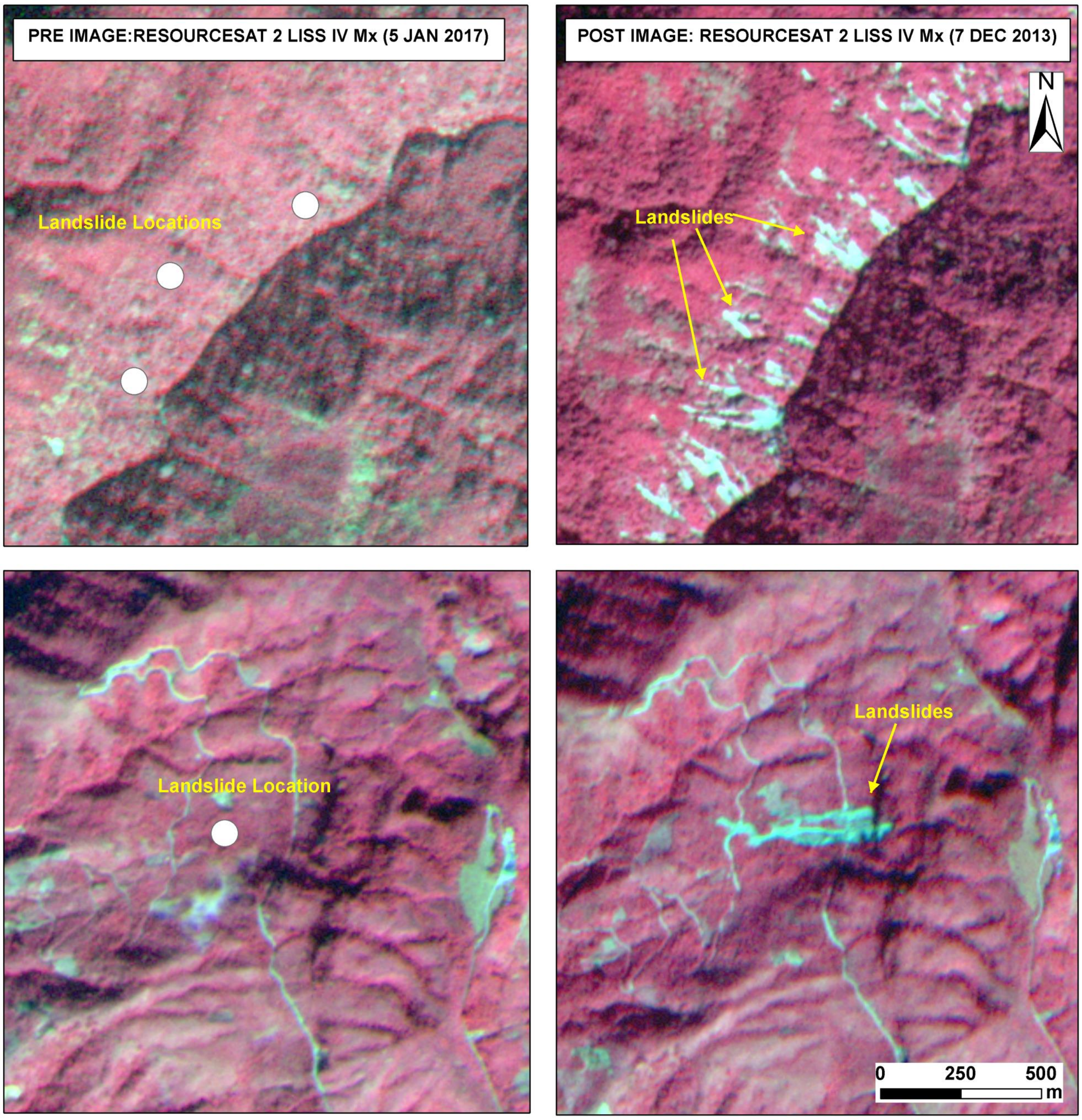


Figure 32. Landslide from Aizwal, Mizoram. Landslide was triggered in the Aizawl of Mizoram to heavy monsoonal rain in 2017. The landslide is shallow translational failure.

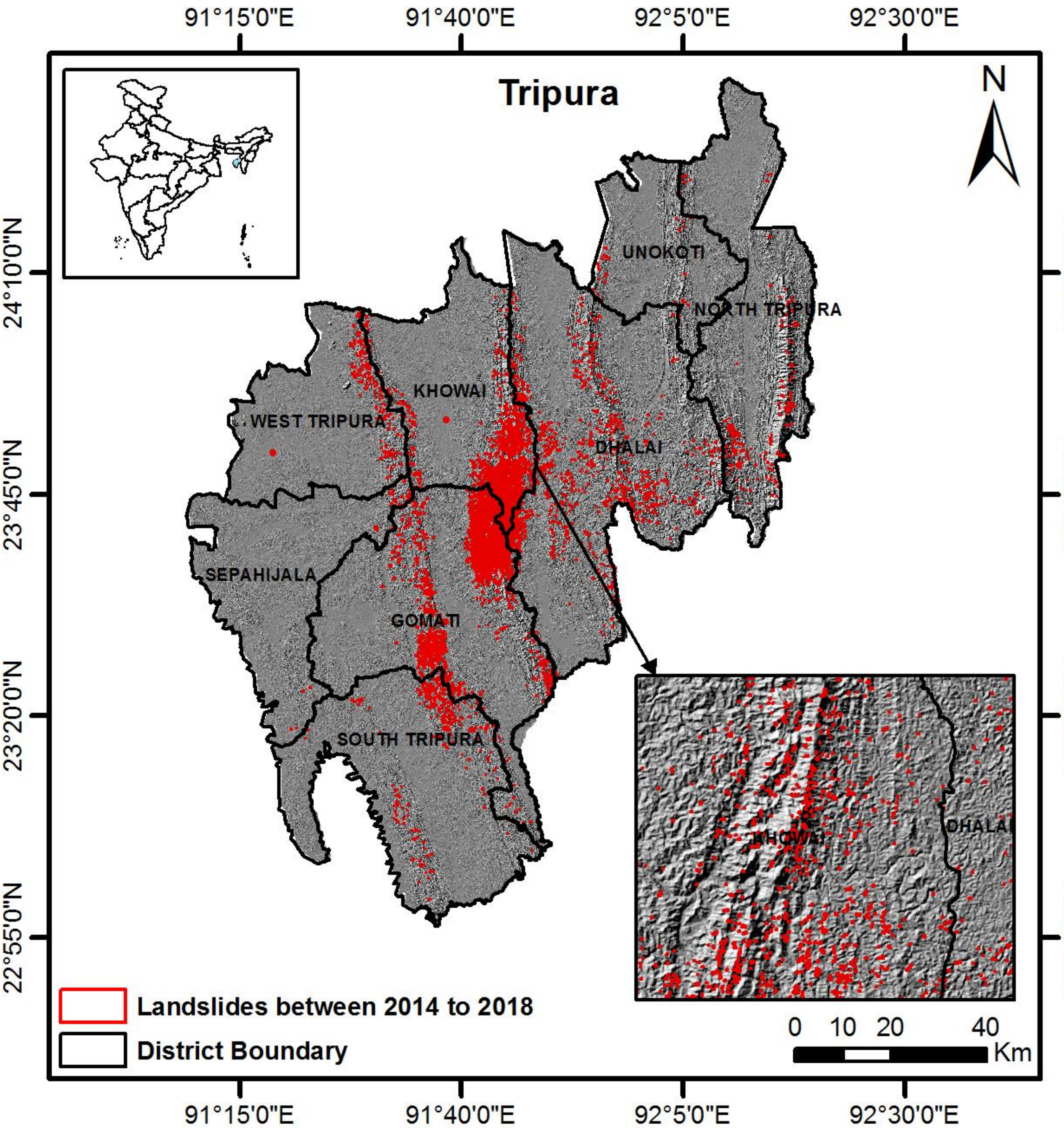


Figure 33. Landslides mapped using high-resolution satellite data in Tripura which, occurred between 2014 to 2018.

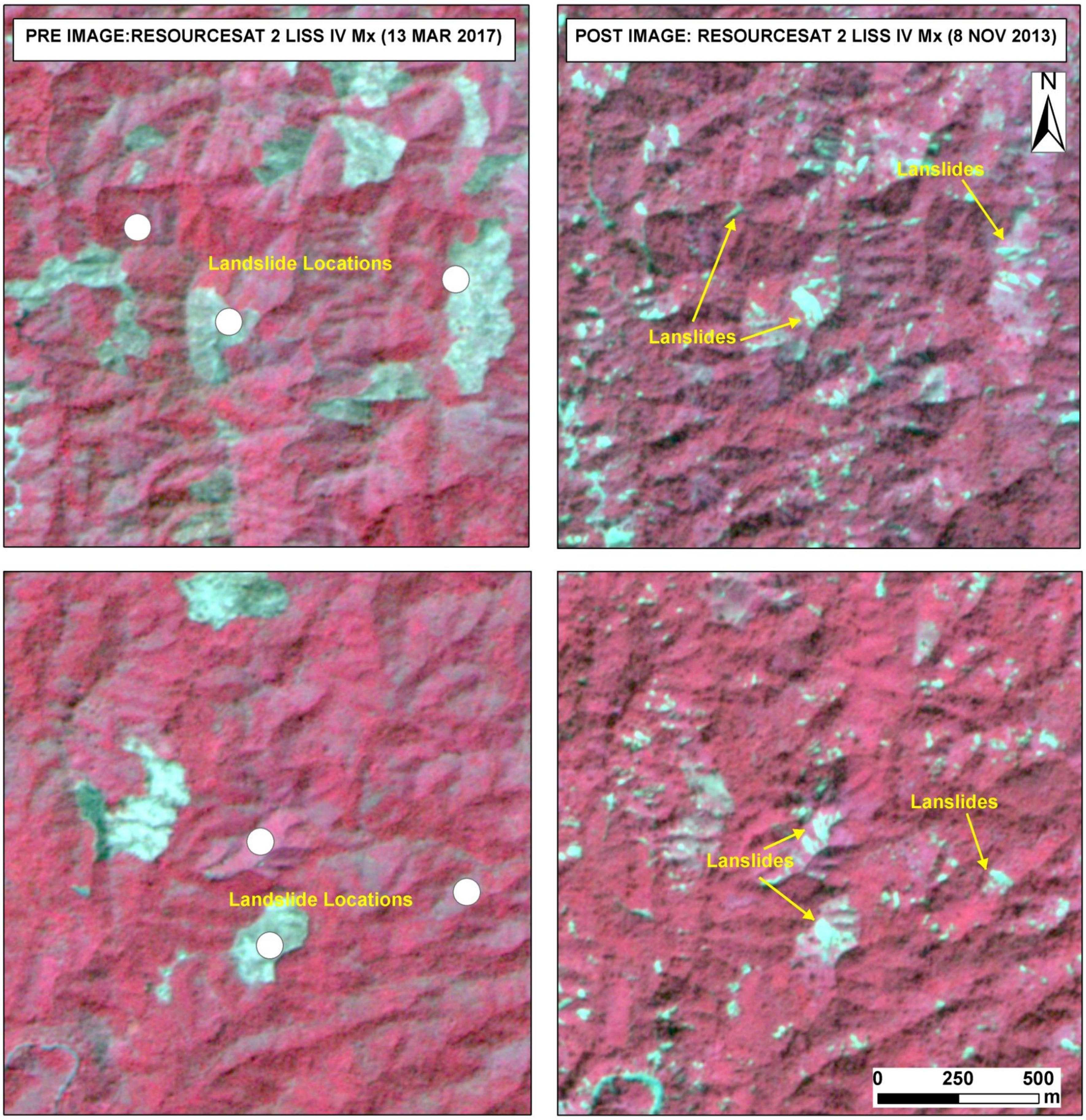


Figure 34. Landslide from Dhalai, Tripura . Landslides were triggered in the Dhalai of Tripura to heavy monsoonal rain in 2017. The landslide is shallow translational failure.

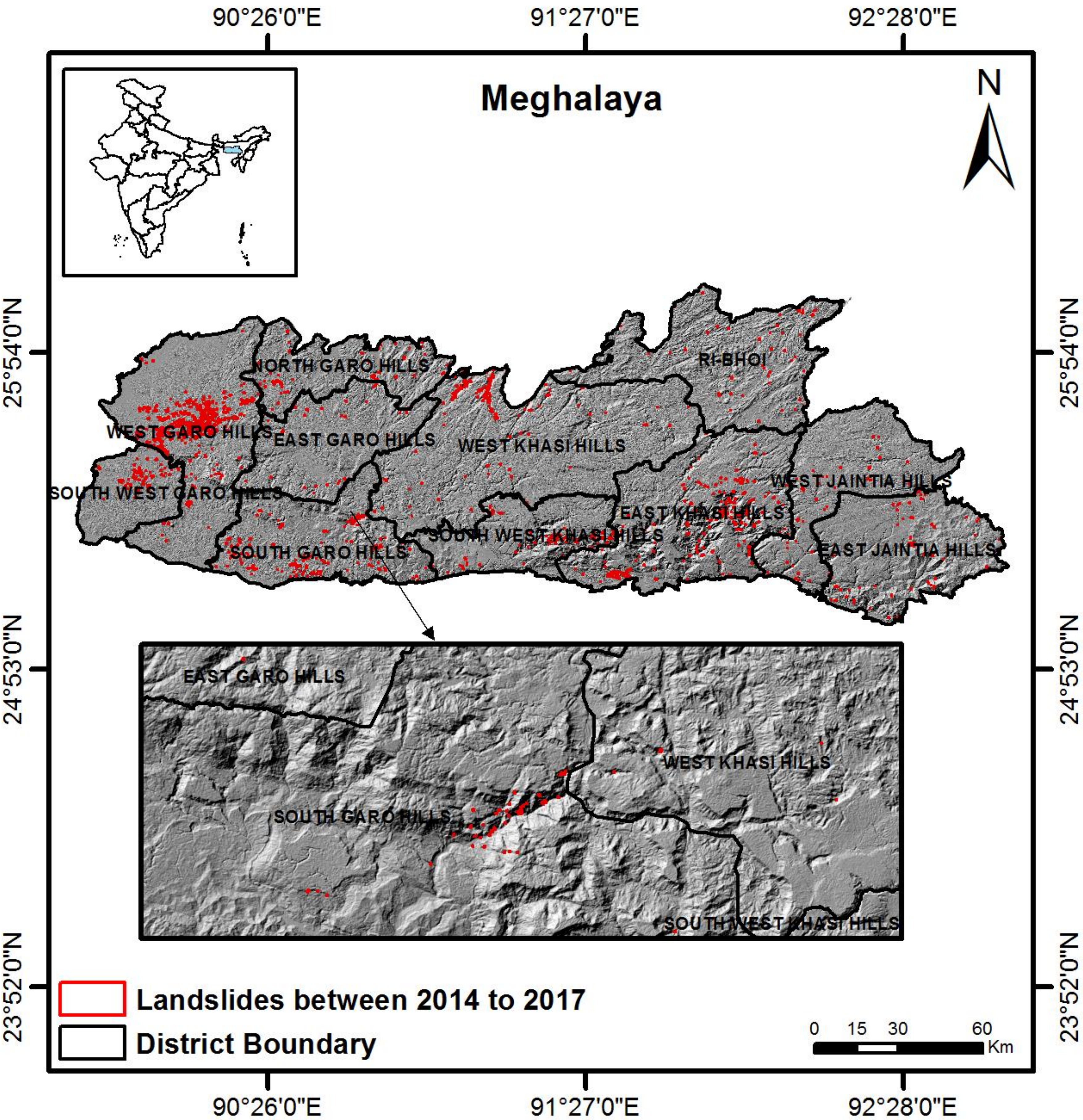


Figure 35. Landslides mapped using high-resolution satellite data in Meghalaya, which occurred between 2014 to 2017.

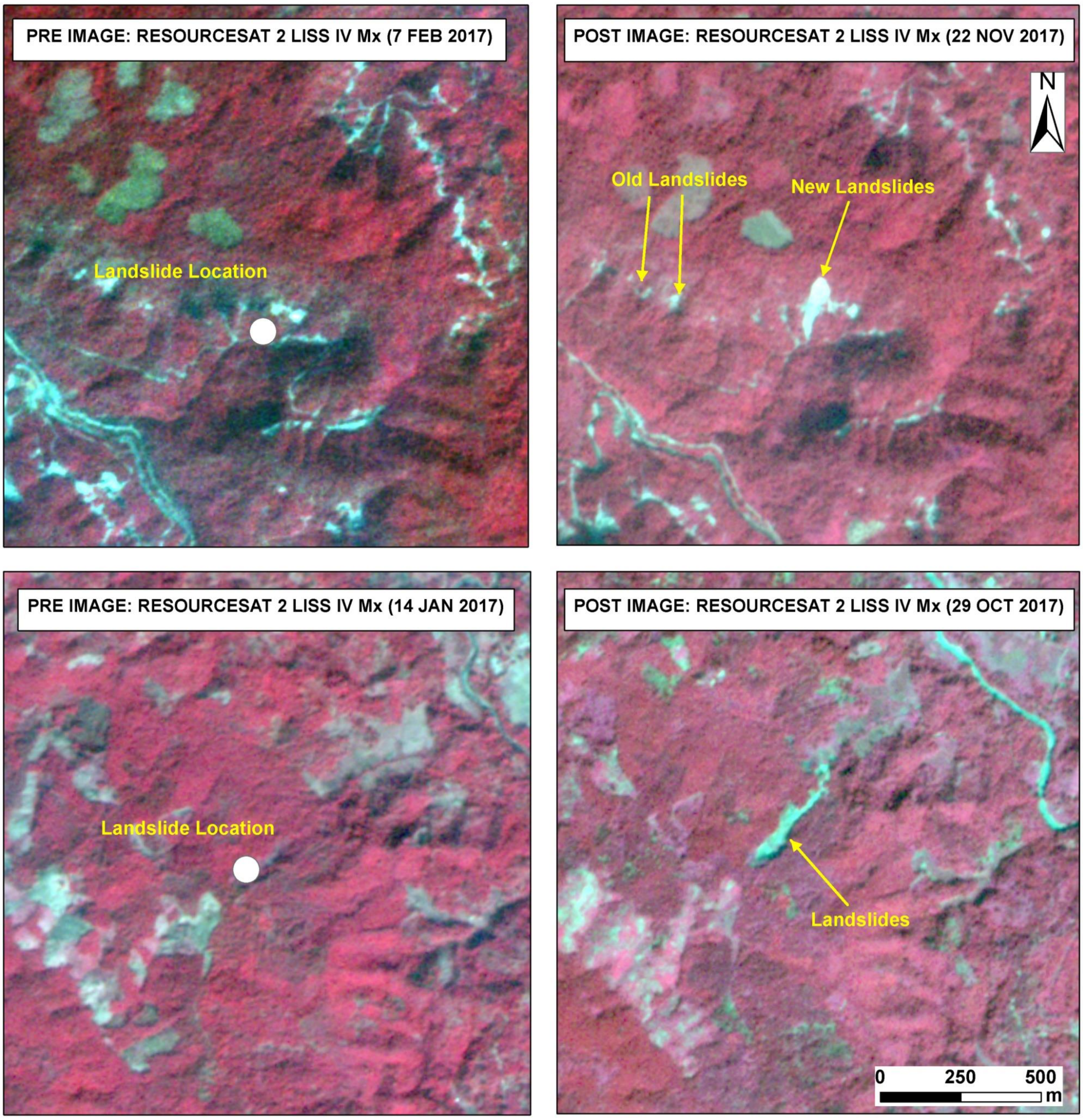


Figure 36. Landslide from East Khasi Hills, Meghalaya. Landslides were triggered in the East Khasi Hills of Meghalaya due to heavy monsoonal rain in 2017. The landslides are shallow translational failures.

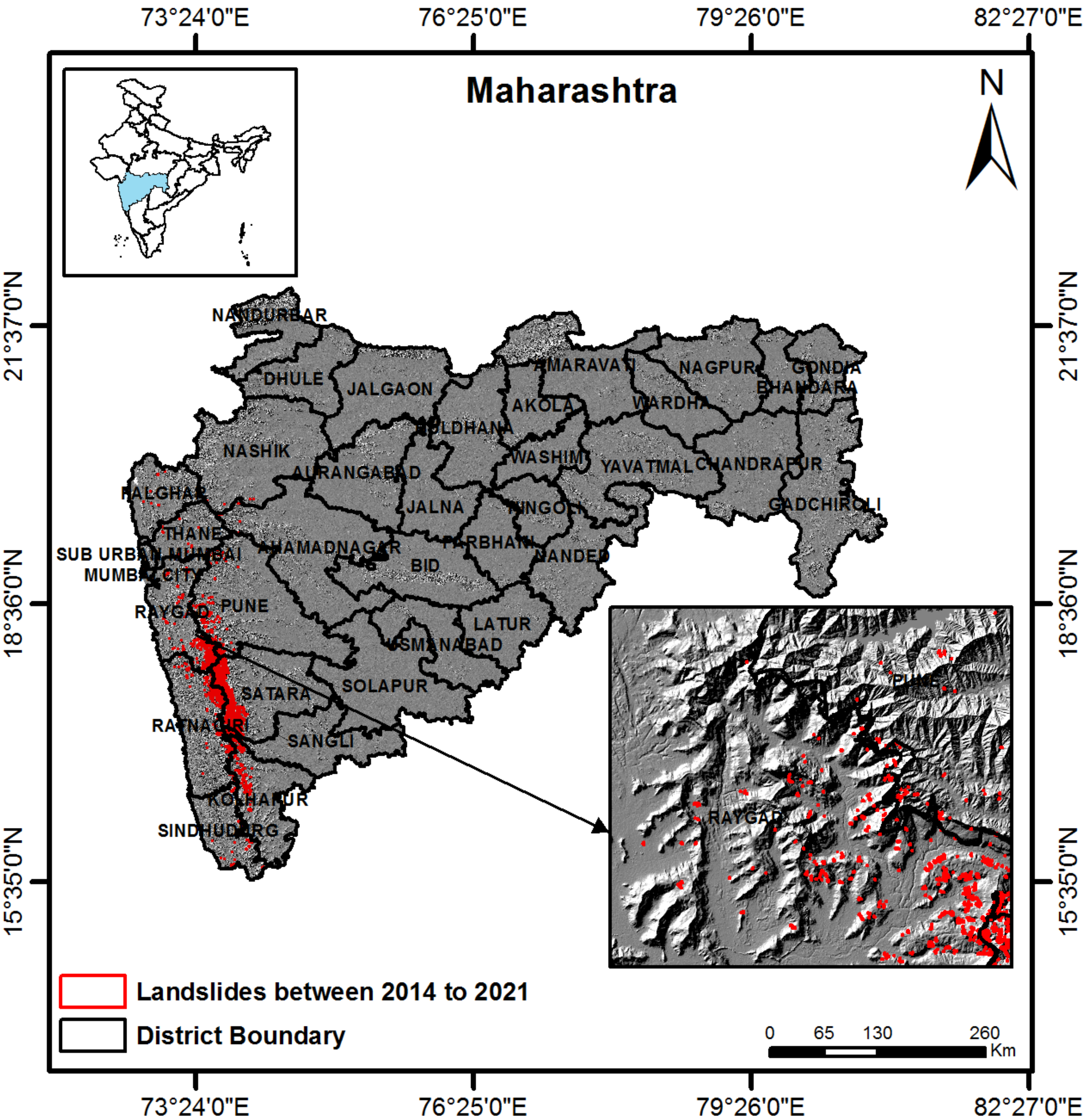


Figure 37. Landslides mapped using high-resolution satellite data in Maharashtra, which occurred between 2014 to 2021.

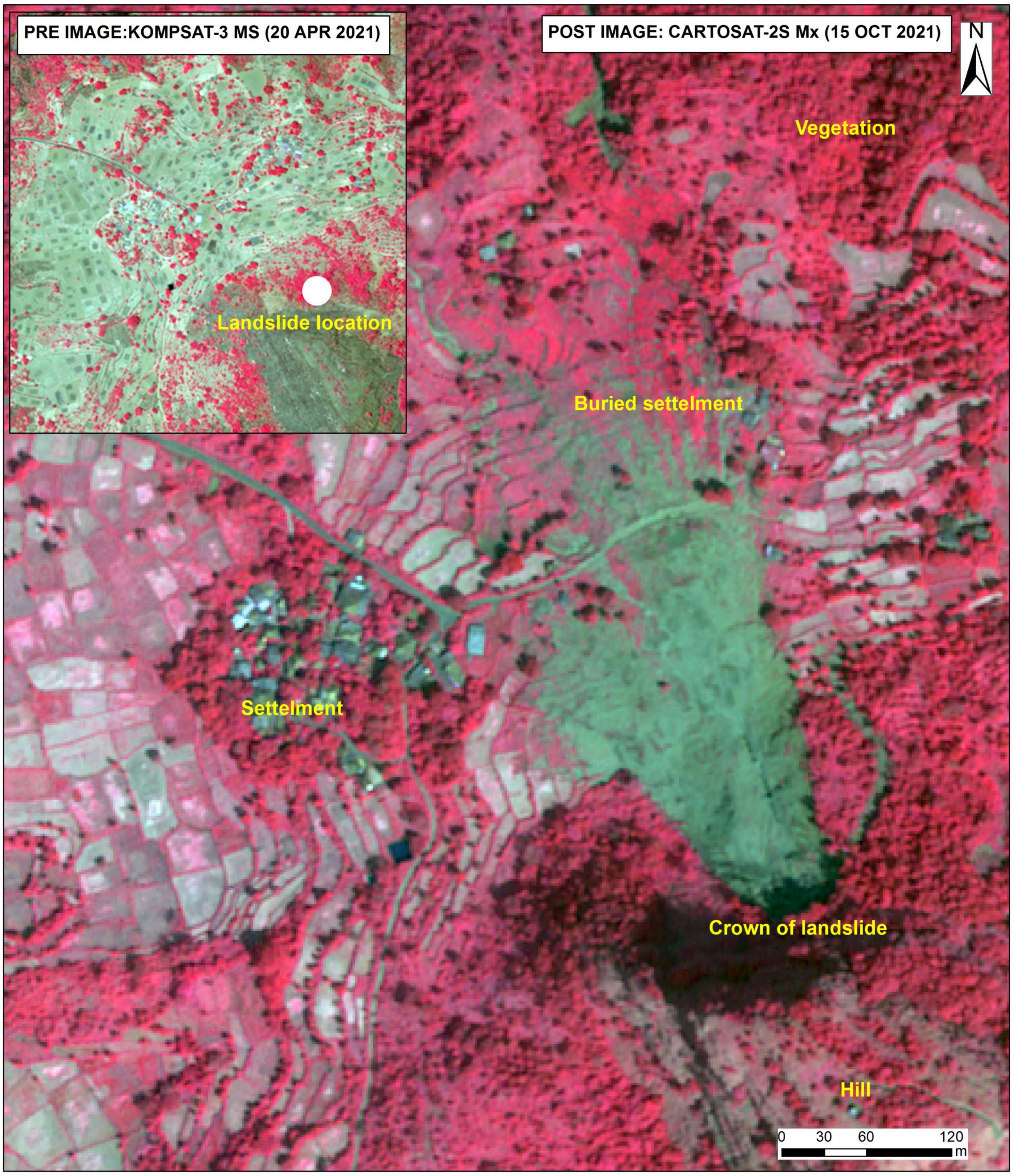


Figure 38. Landslide from Taliye Village ,Mahad district, Maharashtra. A catastrophic landslide occurred at the village of Taliye in Mahad taluk of Raigad on 22 July 2021. The landslide crown shows a rotational failure followed by deep translational failure along the main body.

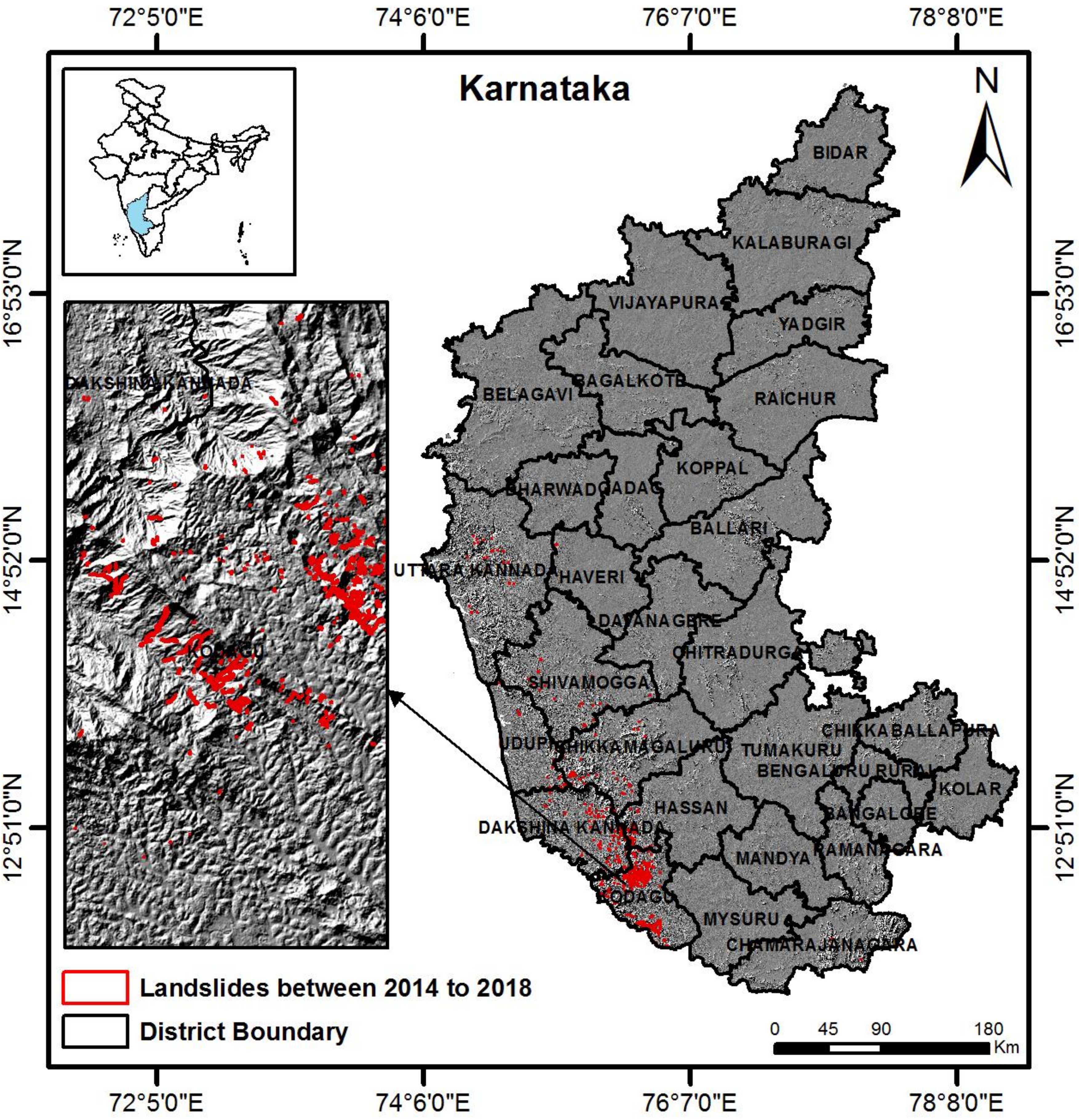


Figure 39. Landslides mapped using high-resolution satellite data in Karnataka, which occurred between 2014 to 2018.

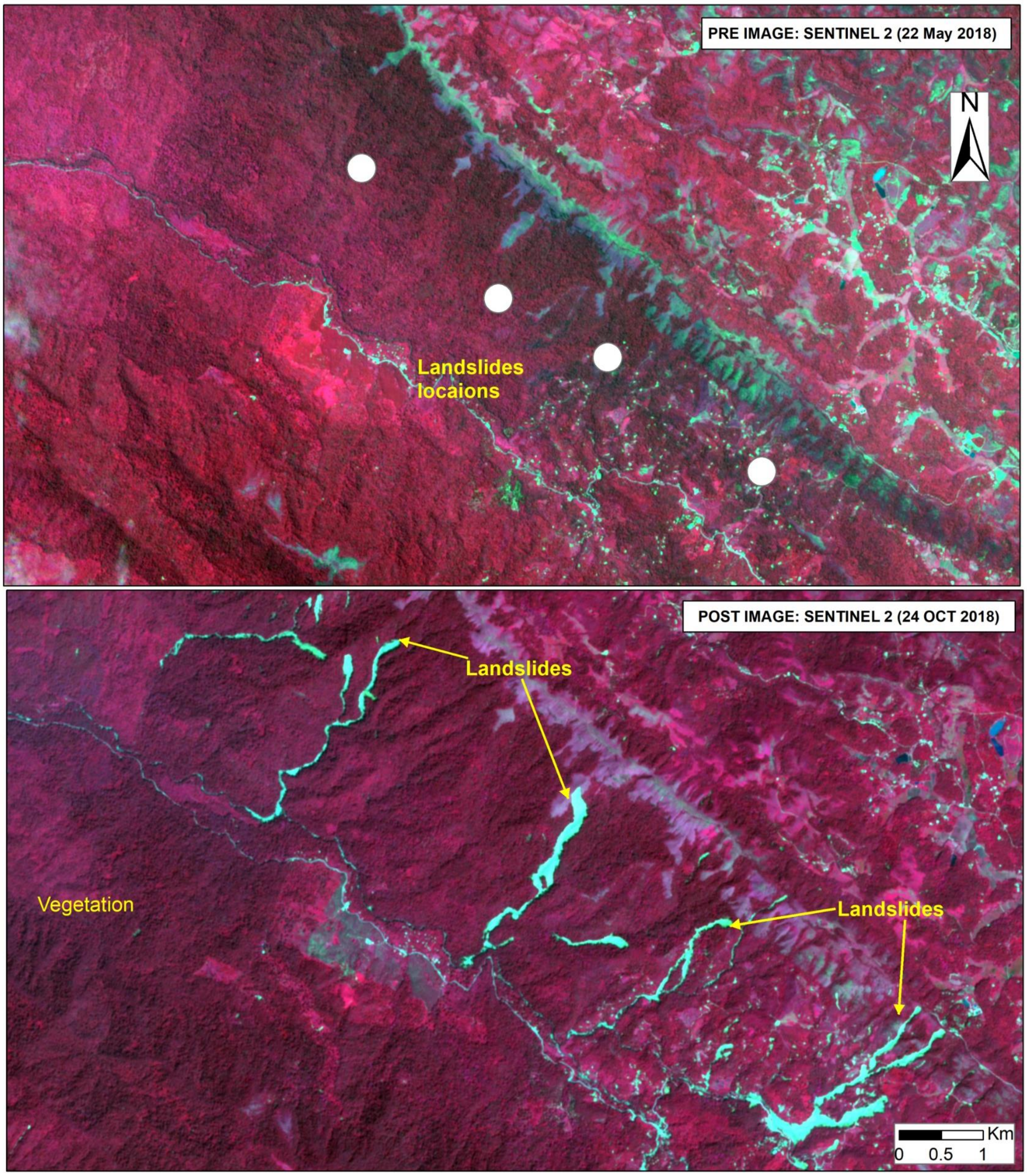


Figure 40. Landslide from Kodagu and Dakshina Kannada districts, Karnataka. Landslides were triggered in the Kodagu and Dakshina Kannada districts of Karnataka due to heavy rain in the 3rd week of August, 2018. Majority of the landslides were shallow translational failures.

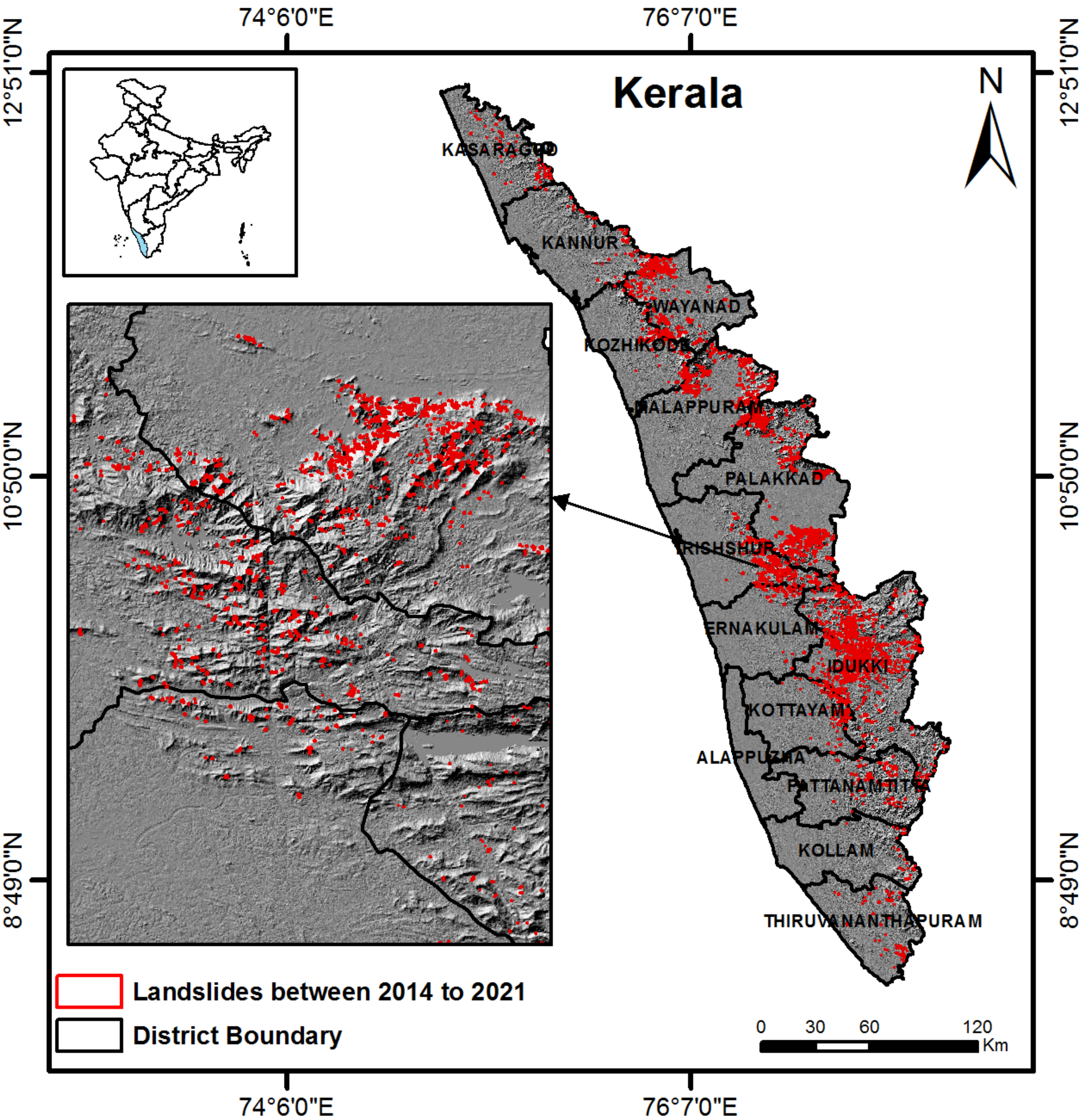


Figure 41. Landslides mapped using high-resolution satellite data in Kerala which, occurred between 2014 to 2021.

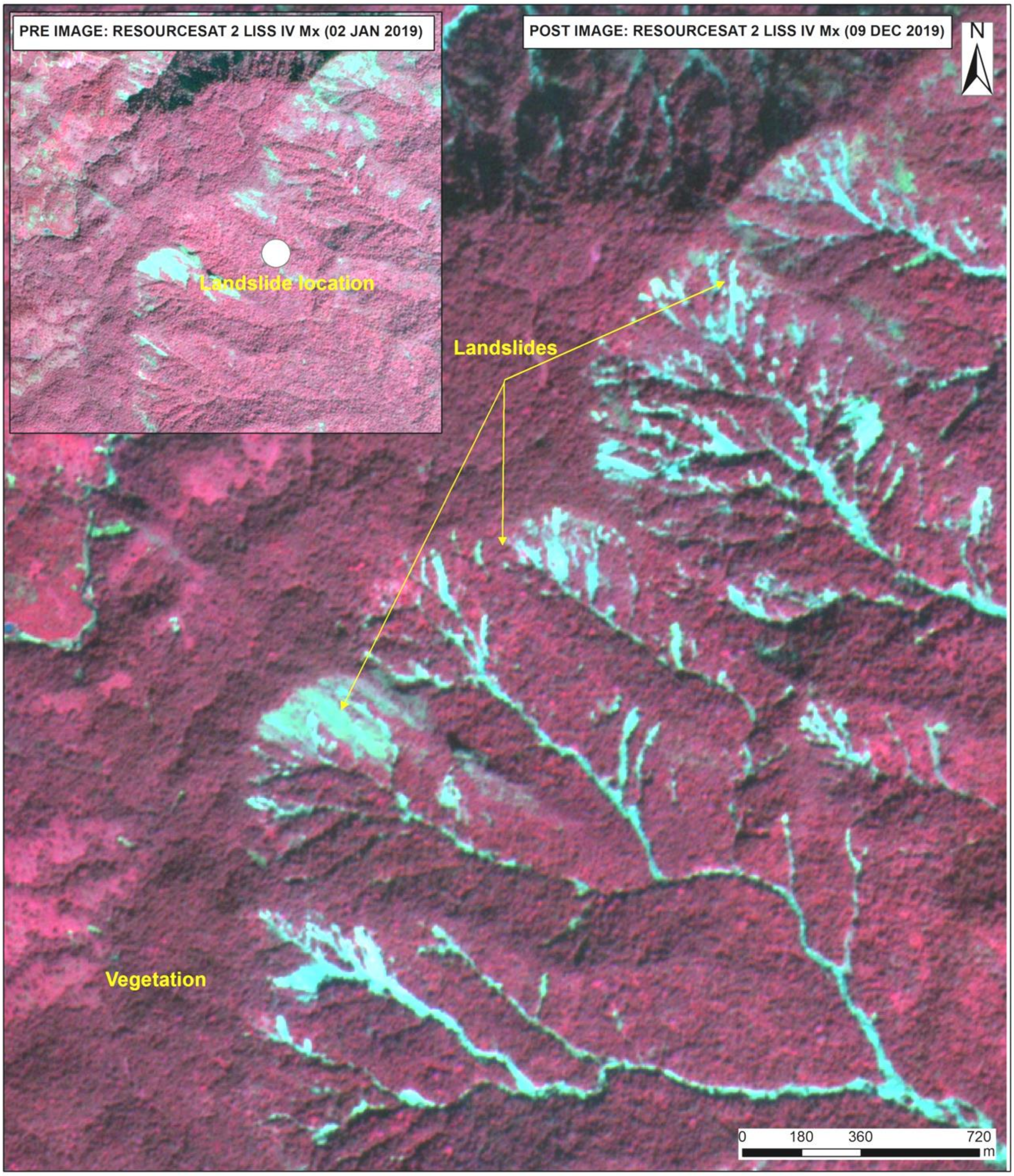


Figure 42. Landslide from Puthumala region, Wayanad district, Kerala. Most of these landslides are channelised debris flows

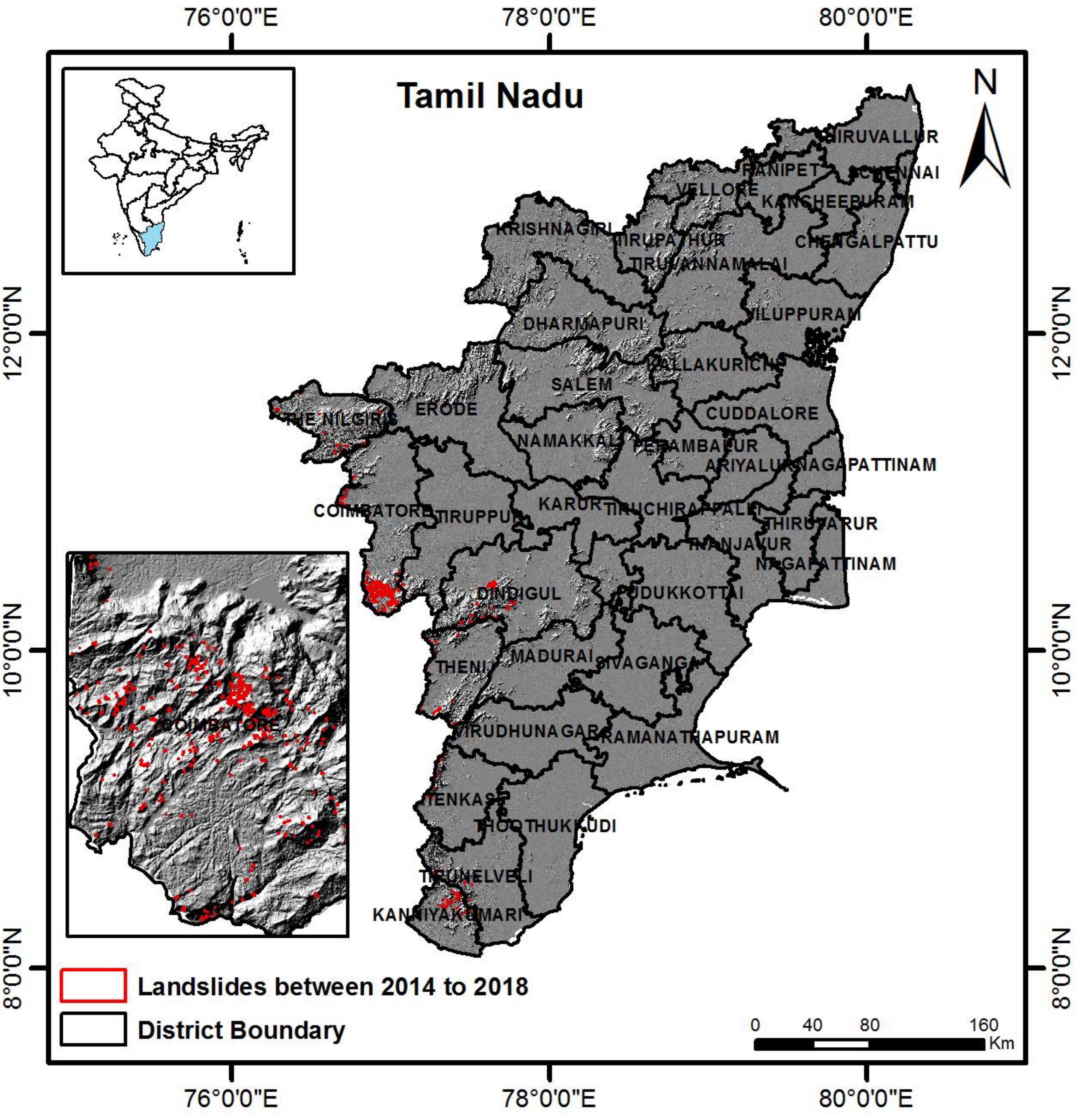
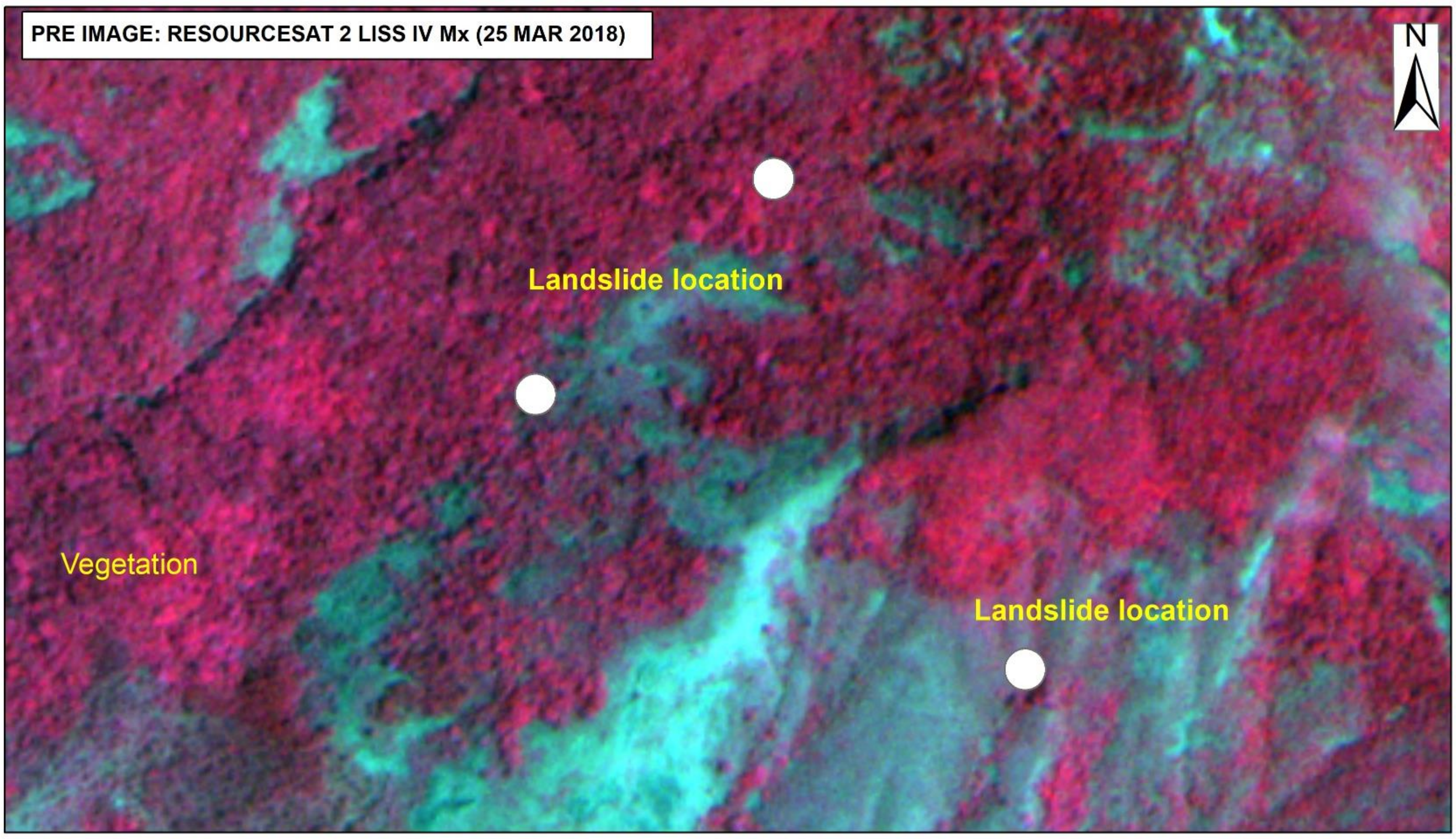


Figure 43. Landslides mapped using high-resolution satellite data in Tamil Nadu, which occurred between 2014 to 2018.



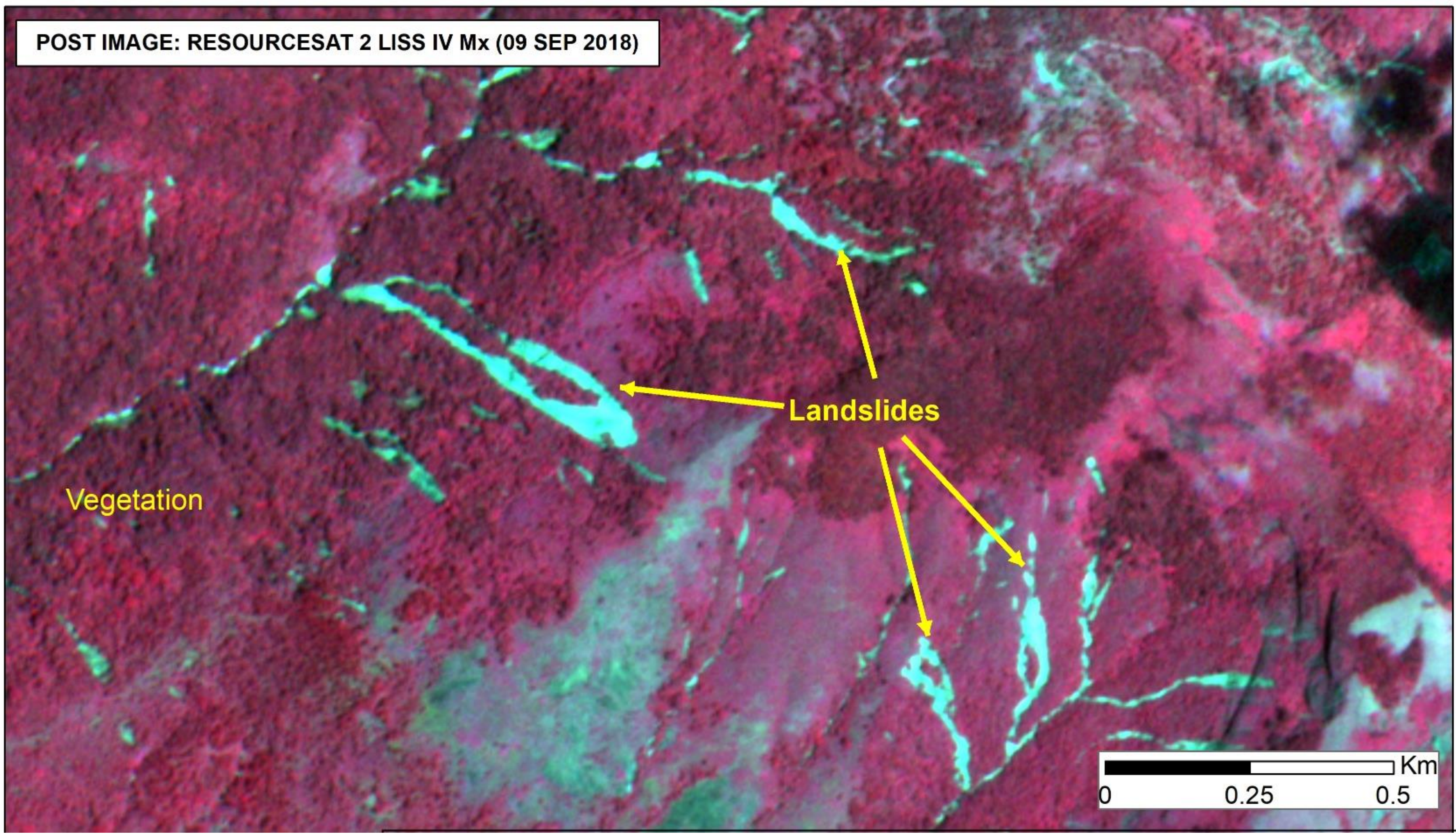


Figure 44. Landslide in Coimbatore district, Tamil Nadu. Most of the landslides are shallow translational failures or channelised debris flows

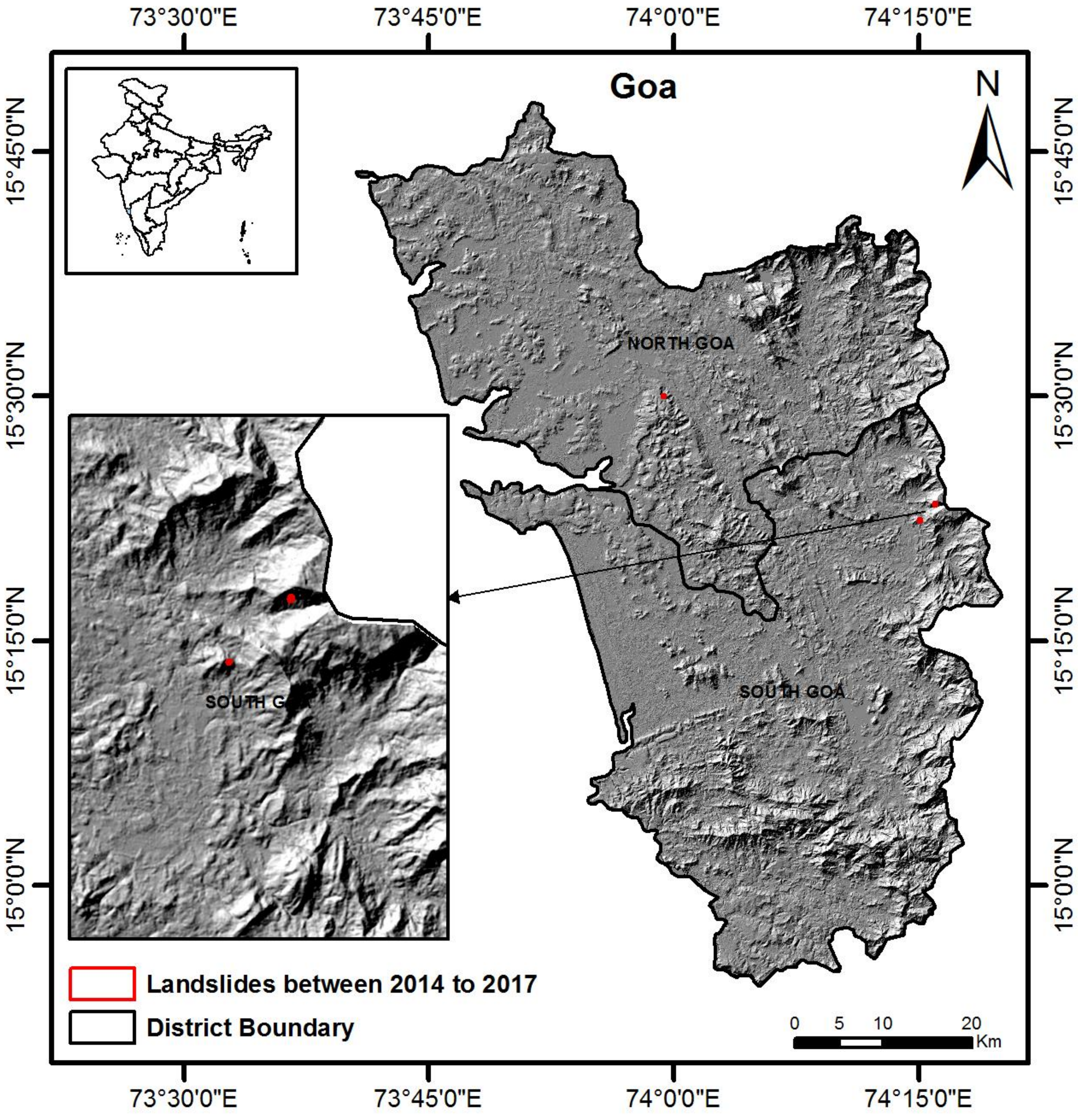


Figure 45. Landslides mapped using high-resolution satellite data in Goa, which occurred between 2014 to 2017.

LANDSLIDE SUSCEPTIBILITY MAPPING AND DISTRICTS-WISE LANDSLIDE RISK EXPOSURE

Landslide Susceptibility Zonation

In view of the recurrence of landslides and resultant death toll in recent years in the Himalayas, and also appreciating the importance of remote sensing techniques in landslide related studies, at the instance of Cabinet Secretary, Government of India, Department of Space had undertaken a specific project for preparation of Landslide Susceptibility Zonation (LSZ) and Management maps on 1:25,000 scale in the Himalayas of Uttarakhand and Himachal Pradesh states.

The whole process of landslide phenomena is dependent on two groups of causative factors as below:

Geological / Topographic factors

* Lithology
* Geological structures (fault, trust, lineament etc)
* Slope-dip (bedding, joint) relation
* Geomorphology
* Drainage
* Slope angle, slope aspect and slope morphology
* Land use / land cover
* Soil texture and depth
* Rock weathering

Triggering Factors

* Anthropogeny
* Rainfall
* Earthquake

The geological factors are often considered for the Landslide Susceptibility Zonation, as they play a dominant role in the prognosis of landslide.

Keeping in view the various techniques of model, it has been felt that a model addressing the expert knowledge combined with a statistical technique suffices the need.

In this method, how each parameter of the terrain and categories within the parameters respond to landslide susceptibility are considered and ranked as per domain expert opinions. Finally, ranks are translated to weightages using the Decision space software and LSZ modeler for generation of the hazard maps. The basic principle used for developing this model is the Analytical Hierarchical Process (AHP) and Saaty's Principle of pair wise comparison.

Landslide Susceptibility Zonation

About 2000 km stretch of routes was taken up for LSZ study. For convenience in handling the huge database, the routes were divided into different sectors

Uttarakhand

1. Rishikesh – Rudraprayag – Chamoli – Badrinath
2. Rudraprayag – Okhimath – Kedarnath
3. Chamoli – Okhimath
4. Rishikesh – Uttarkashi – Gangotri – Gaumukh
5. Pithoragarh – Khela - Malpa

Himachal Pradesh

1. Shimla – Rampur – Sarahan – Sumdo
2. Shimla – Bilaspur – Kulu – Manali
3. Dalhousie – Chamba – Brahmaur

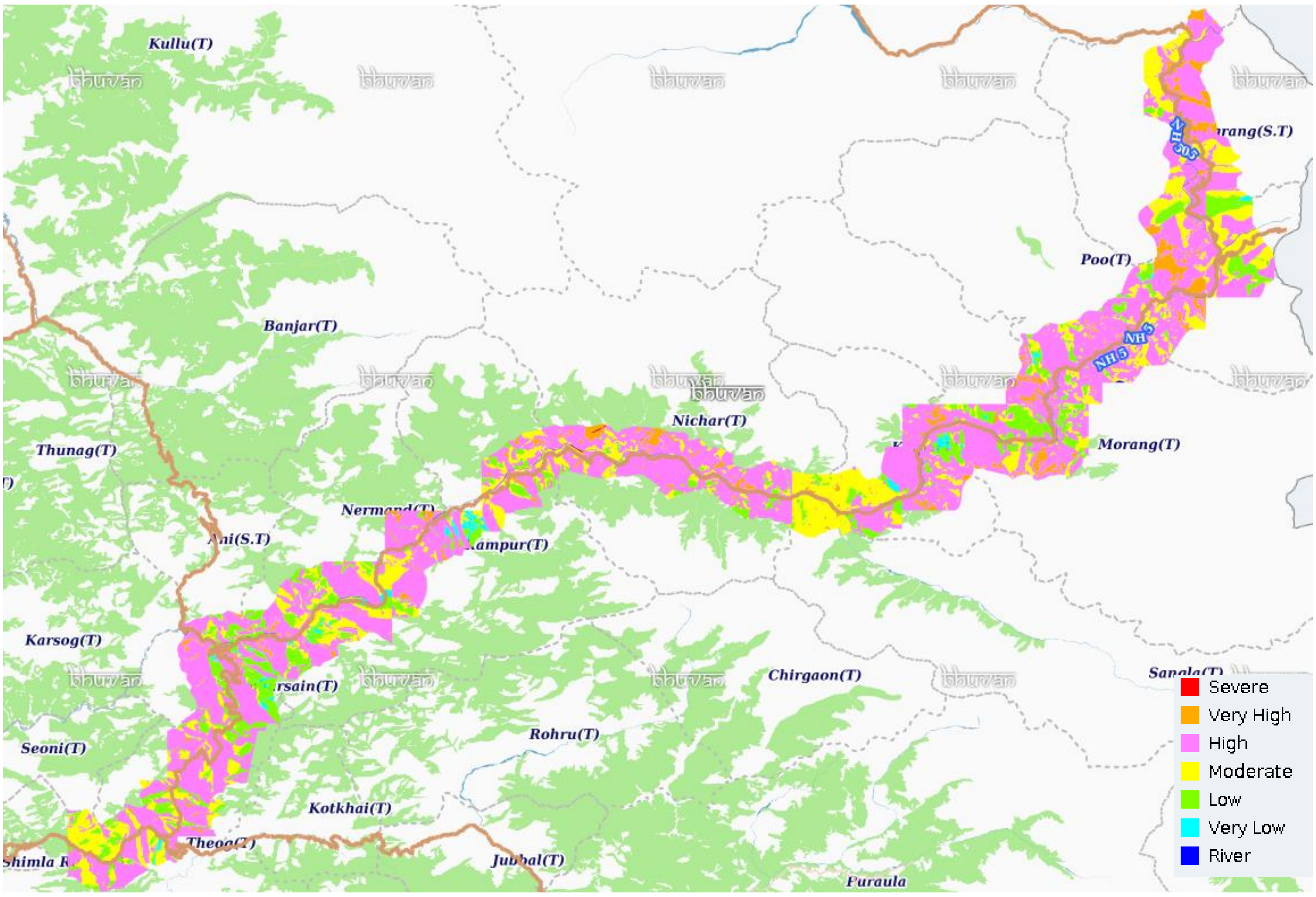


Figure 46. LSZ map for Shimla – Rampur – Sarahan – Sumdo Route.

Landslide risk exposure

The occurrence of landslides in an area is due to the interplay of favorable terrain parameters such as slope, lithology, topography and land use which trigger landslides in response to rainfall or earthquake events.

Preparation of landslide inventory, hazard, and risk mapping is done in India using satellite data to analyze the cause of landslides which is mostly found to be :

•Litho-tectonic control- earthquake

•Precipitation (rainfall) control.

In India, the major areas which are affected by landslides are :

•The Northwest Himalayas contribute- 66.5% of landslides in India, followed by the Northeast Himalayas -18.8% and the Western Ghats - 14.7%.

Methods of mapping landslide inventory

Data collected: pre-monsoon season (Mar–May, 2014) and post-monsoon season (Oct–Dec, 2014).
Satellites used: Resourcesat-2 LISS-IV Mx (5.8 m)- for seasonal landslide mapping - trigger by monsoon rainfall.

As manual method of landslide mapping is a tedious job, so 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.

Event-based landslide (caused by earthquakes or short-duration rainfall event) inventory mapping:
An event-based landslide inventory map was prepared using the same method as adopted for the SLIM.

Field-based landslide inventory:
This landslide inventory tallies to 1998, which was prepared by NRSC by means of merged IRS-1D PAN+LISS III data (5.8 m) by visual image interpretation and verified on the ground (NRSA 2001).

Assessment of Socio-economic Parameter exposure

Socio-economic parameters (SEP) include total population, number of households, road and livestock. The unit of exposure analysis is taken as district and two indices were created so that they normalize with the area of the same district. These Indices are :

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

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

These indices were calculated using excel table operation.
Later district exposure index (DEI) was calculated to rank the districts.

$$\text{District Exposure Index} = \text{DLD}^* \left(\text{DSEPD}_\text{p} + \text{DSEPD}_\text{h} + \text{DSEPD}_\text{l} + \text{DSEPD}_\text{r}\right)$$

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

Landslide risk exposure

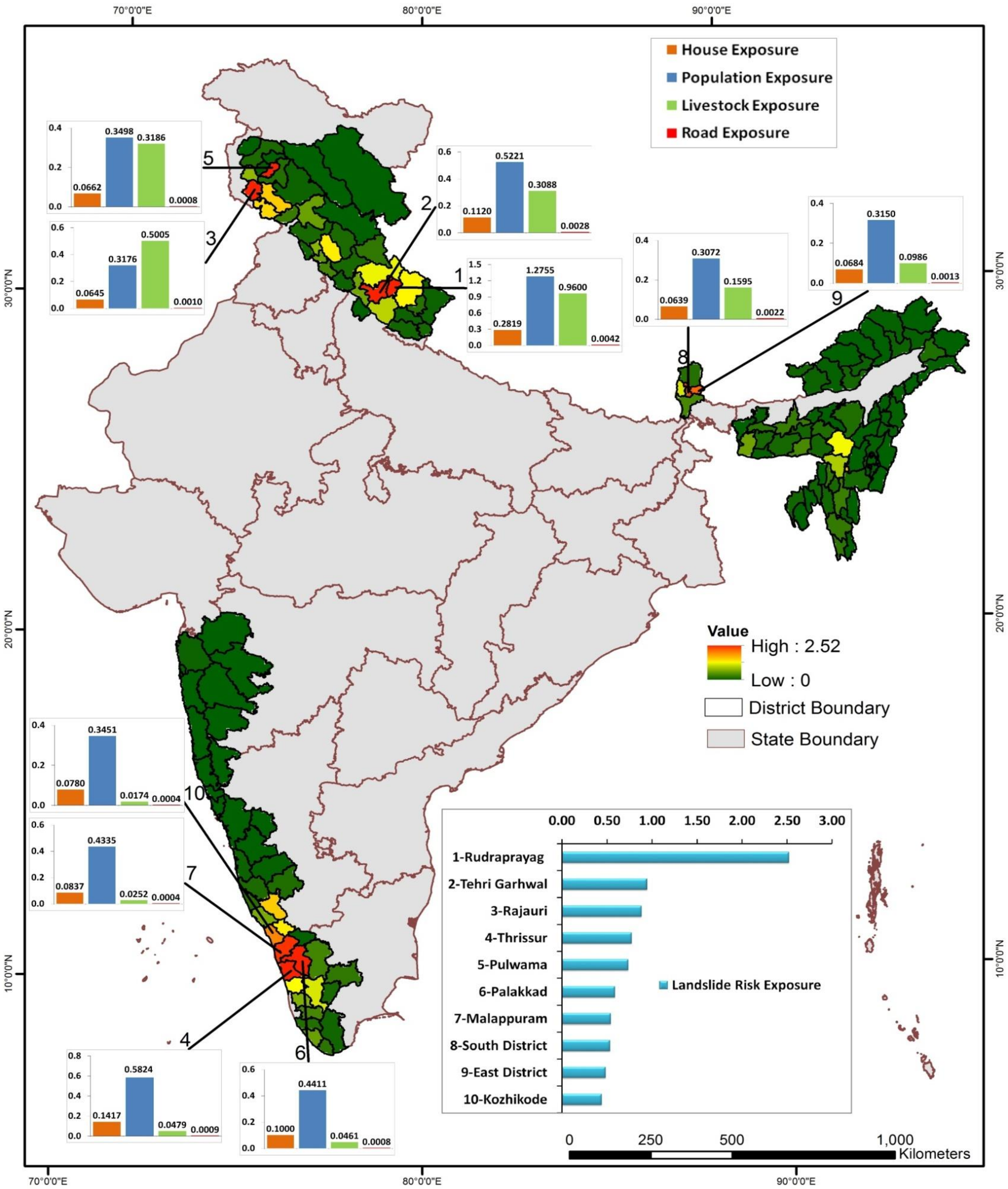


Figure 47. Socio-economic parameter risk exposure map, The contribution of each exposure element for the top ten landslide exposed districts is shown in bar diagram.

Socio-economic parameter exposure

Landslide exposure analysis were carried out in the mountainous areas. Rudraprayag district in Uttarakhand state which has highest landslide density in India is also having highest exposure to total population, working population, literacy and no. of houses. Below is the rank of all 147 districts in 17 states and 02 UTs of India for their exposure to landslides in terms of key socio economic parameters.

Table 3. Table shows the rank of districts of India for their exposure to landslides.

District Rank	District	State
1	Rudraprayag	Uttaranchal
2	Tehri Garhwal	Uttaranchal
3	Thrissur	Kerala
4	Rajauri	J&K
5	Palakkad	Kerala
6	Poonch	J&K
7	Malappuram	Kerala
8	South District	Sikkim
9	East District	Sikkim
10	Kozhikode	Kerala
11	Imphal West	Manipur
12	Kodagu	Karnataka
13	Wayanad	Kerala
14	Jammu	J&K
15	Ernakulam	Kerala
16	Mandi	Himachal Pradesh
17	Udhampur	J&K
18	Idukki	Kerala
19	Chamoli	Uttaranchal
20	West District	Sikkim
21	Uttarkashi	Uttaranchal
22	Cachar	Assam
23	Garhwal	Uttaranchal
24	Kottayam	Kerala
25	Hamirpur	Himachal Pradesh
26	Kannur	Kerala
27	Pulwama	J&K
28	Thiruvananthapuram	Kerala
29	Dehra Dun	Uttaranchal
30	Bilaspur	Himachal Pradesh
31	West Garo Hills	Meghalaya
32	Chamba	Himachal Pradesh
33	Pathanamthitta	Kerala
34	East Khasi Hills	Meghalaya
35	Darjiling	West Bengal
36	Coimbatore	Tamil Nadu
37	Solan	Himachal Pradesh
38	Aizawl	Mizoram
39	Lunglei	Mizoram
40	Kamrup	Assam
41	Dindigul	Tamil Nadu
42	Kathua	J&K
43	Kanniyakumari	Tamil Nadu
44	Kasaragod	Kerala
45	Lawngtlai	Mizoram
46	Kinnaur	Himachal Pradesh
47	Hailakandi	Assam
48	Kollam	Kerala
49	Goalpara	Assam
50	Bageshwar	Uttaranchal
51	North District	Sikkim
52	Anantanag	J&K
53	Hassan	Karnataka
54	Dakshina Kannada	Karnataka
55	Karbi Anglong	Assam
56	Lohit	Arunachal Pradesh
57	Kullu	Himachal Pradesh
58	Baramulla	J&K
59	Theni	Tamil Nadu
60	Kolasib	Mizoram
61	Shimla	Himachal Pradesh
62	Kangra	Himachal Pradesh
63	Churachandpur	Manipur
64	East Garo Hills	Meghalaya
65	Champawat	Uttaranchal
66	West Khasi Hills	Meghalaya
67	Ribhoi	Meghalaya
68	Naini Tal	Uttaranchal
69	Jaintia Hills	Meghalaya
70	Una	Himachal Pradesh

Table 3. Table shows the rank of districts of India for their exposure to landslides continues……

District Rank	District	State
71	Mamit	Mizoram
72	Tirunelveli	Tamil Nadu
73	Papum Pare	Arunachal Pradesh
74	Tawang	Arunachal Pradesh
75	West Tripura	Tripura
76	North Tripura	Tripura
77	Udupi	Karnataka
78	East Siang	Arunachal Pradesh
79	Doda	J&K
80	Thane	Maharashtra
81	Almora	Uttaranchal
82	Serchhip	Mizoram
83	North Cachar Hills	Assam
84	Lower Subansiri	Arunachal Pradesh
85	The Nilgiris	Tamil Nadu
86	Pithoragarh	Uttaranchal
87	West Kameng	Arunachal Pradesh
88	Sirmaur	Himachal Pradesh
89	Phek	Nagaland
90	South Garo Hills	Meghalaya
91	Changlang	Arunachal Pradesh
92	Chikmagalur	Karnataka
93	Mon	Nagaland
94	Tuensang	Nagaland
95	Bongaigaon	Assam
96	Lower Dibang Valley	Arunachal Pradesh
97	Senapati	Manipur
98	Srinagar	J&k
99	Morigaon	Assam
100	Tamenglong	Manipur
101	East Kameng	Arunachal Pradesh
102	Saiha	Mizoram
103	Shimoga	Karnataka
104	Upper Siang	Arunachal Pradesh
105	Mokokchung	Nagaland
106	Kohima	Nagaland
107	Pune	Maharashtra
108	West Siang	Arunachal Pradesh
109	Raygarh	Maharashtra

District Rank	District	State
110	Dhalai	Tripura
111	North Goa	Goa
112	Ukhrul	Manipur
113	Kurung Kumey	Arunachal Pradesh
114	Sindhudurg	Maharashtra
115	Tirap	Arunachal Pradesh
116	Uttara Kannada	Karnatka
117	Nagaon	Assam
118	Champhai	Mizoram
119	Budgam	J&K
120	Upper Subansiri	Arunachal Pradesh
121	South Goa	Goa
122	Chandel	Manipur
123	Kargil	J&K
124	Haveri	Karnataka
125	Anjaw	Arunachal Pradesh
126	Lahul & Spiti	Himachal Pradesh
127	Dhubri	Assam
128	Nashik	Maharashtra
129	Ratnagiri	Maharashtra
130	South Tripura	Tripura
131	Ahmadnagar	Maharashtra
132	Kupwara	J&k
133	Kolhapur	Maharashtra
134	Satara	Maharashtra
135	Dibang Valley	Arunachal Pradesh
136	Leh-ladakh	J&K
137	Karimganj	Assam
138	Alappuzha	Kerala
139	Mumbai Suburban	Maharashtra
140	Mumbai	Maharashtra
141	Thoubal	Manipur
142	Imphal East	Manipur
143	Bishnupur	Manipur
144	Zunheboto	Nagaland
145	Wokha	Nagaland
146	Haridwar	Uttaranchal
147	Udham Singh Nagar	Uttaranchal

RESEARCH & DEVELOPMENT IN LANDSLIDES STUDIES

Multitemporal SAR interferometry for Landslide prediction

Landslides from remote steep slopes render people living downhill vulnerable, unaware of the impending danger. Identifications of slow-moving mountain slopes are possible now due to time series measurements from space using microwave satellite data and the InSAR technique, which can detect displacement at the millimetre level. The availability of open-source Sentinel-1 data has revolutionised the study involving landslide kinematics and predicting the time of failure. However, identifying accelerating trends, demarcation of the release area, and predicting flow path after failure initiation is still challenging.

Time of failure prediction of the Kikruma landslides in the NE Himalaya is carried out using Persistent Scatter Interferometry (PSI) interferometric technique on Sentinel-1 SAR data to analyse the trend of ground deformation leading to slope failures. The displacement time series of the measurement points (MPs), analysed using inverse velocity and modified inverse velocity methods, show that the instability had commenced almost a year or more with the final onset of acceleration (OOA) triggered by heavy rainfall, couple of weeks prior to the actual failure (Roy et al. 2022).

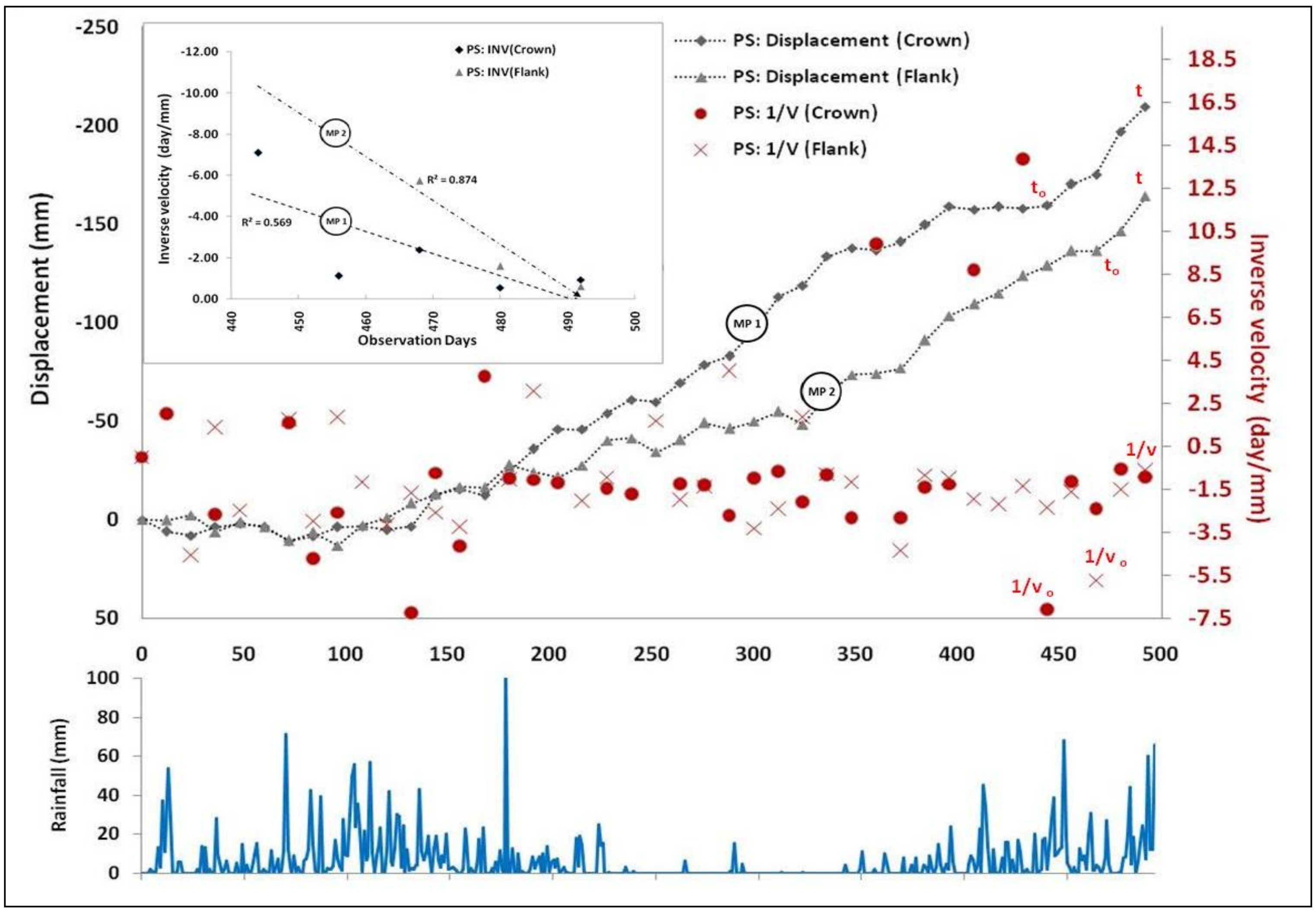


Figure 48. Landslide prediction using MT InSAR. Top panel: Representative displacement time series and inverse velocities for the Kikruma landslide showing the OOA (t_0) and last observation point (t). Inset: Failure day estimation using INV. Bottom panel: Rainfall variation in the region during the observation period. Predicted day of failure: 26 July 2018; Actual day of failure: 29 July 2018.

Debris Flow Modelling

Dynamic modelling of debris flow landslides has become an increasingly important practice for simulating the characteristics and behaviour of debris flow relying on the physical laws of conservation of mass, momentum and energy (Melo et al., 2018). This model approach can be broadly classified as the lumped mass moment where motion of slide is considered as a single point which is not always the case or based on continuum mechanics associated with a distinct rheology (Hungr, 1995). To simulate the deformation of the moving mass along the flow path, choosing appropriate friction parameters and material rheologies is taxing (Rickenmann, 2005).

Numerical debris flow modelling was carried out for several major landslides in Kerala to characterize the landslide geometry and assess their impact.

For modeling debris flow paths, Rapid Mass Movement Simulation (RAMMS) software developed by WSL Institute for Snow and Avalanche Research SLF and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL, was used. The model gives flow height, velocity and pressure of debris flow. The main input parameters to be ingested in the model are high resolution Digital Elevation Model (DEM) for deriving topographic parameters, release area and friction information. CartoDEM (2.5 m) was used for flow modeling (Jain et al. 2021).

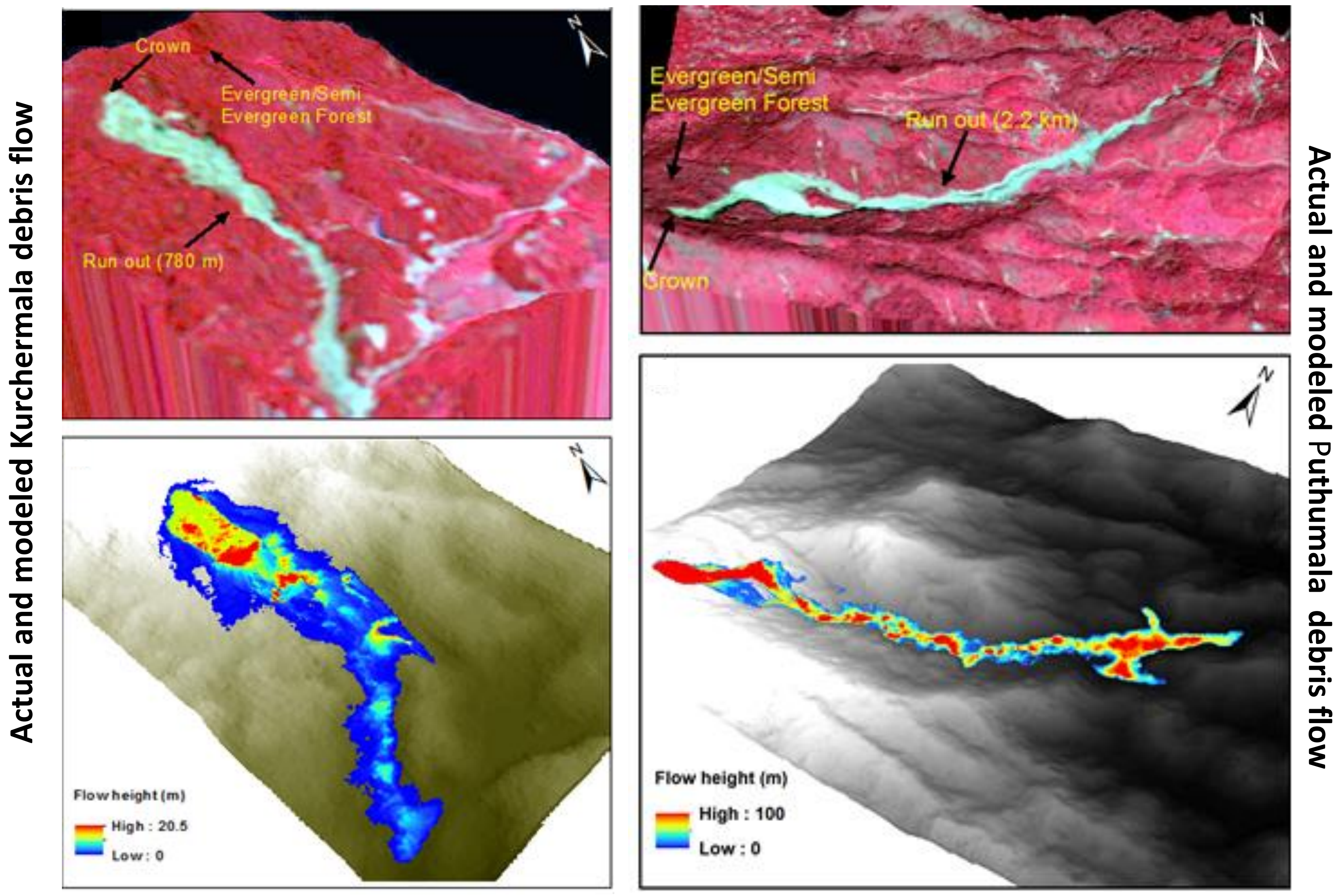


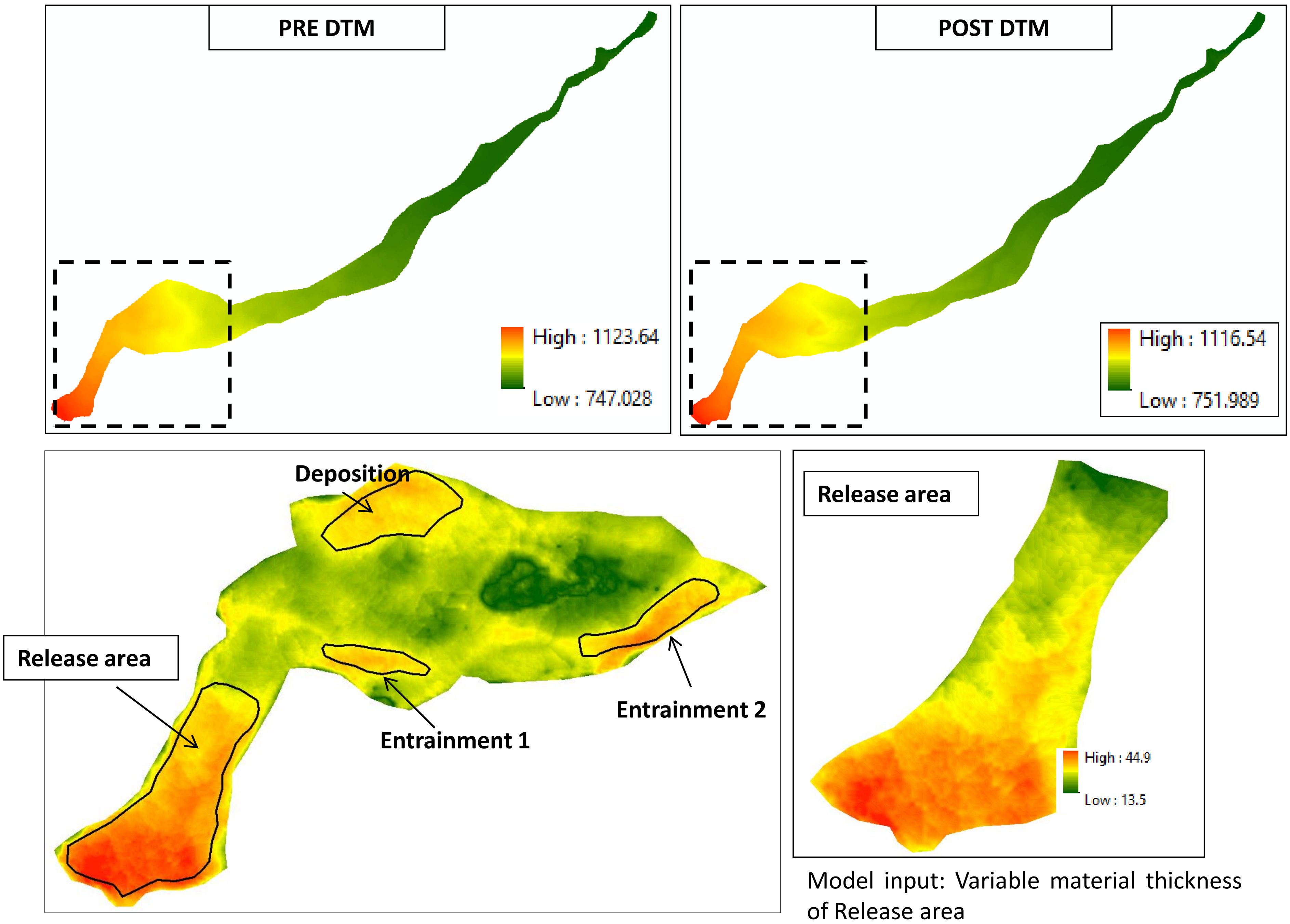
Figure 49. Flow modeling for Puthumala Landslide, Wayanad District, Kerala.

UAV data in landslide modeling

Photogrammetric techniques have been increasingly used because of their capability to rapidly reconstruct the 3-D topography from aerial photographs and provided such data exist for different time periods, allow objective change detection (Martha et al, 2010). Knowledge of failure volumes is also critical for a more accurate understanding of the landslide process and its flow, which shows the affected areas.

The increasing availability of high-resolution UAV data, quantitative studies on landform changes using DEMs have become a viable option.

UAV data were acquired over the Puthumala landslide in Kerala area on 22 March 2021. The resolution of orthoimage of UAV is 2 cm and the grid size of DTM is 8 cm. The positional accuracy of the image is 1-2 m. . Pre and post-DEM were utilized for volumetric estimation and release area mapping.



Model input: Variable material thickness of Release area

Figure 50. Landslide modeling using UAV data, Puthumala Landslide, Wayanad District, Kerala.

Landslide Susceptibility Zonation: New Approach

A large area covering 21,087 km^2 of the Mizoram state, India has been investigated, using five statistical methods of susceptibility models viz. Multi Criterion Weighted Overlay (MCWO), Information Value (IV), Weights of Evidence (WoE), Logistic Regression (LR) and Artificial Neural Network (ANN) to prepare macro-scale landslide susceptibility maps

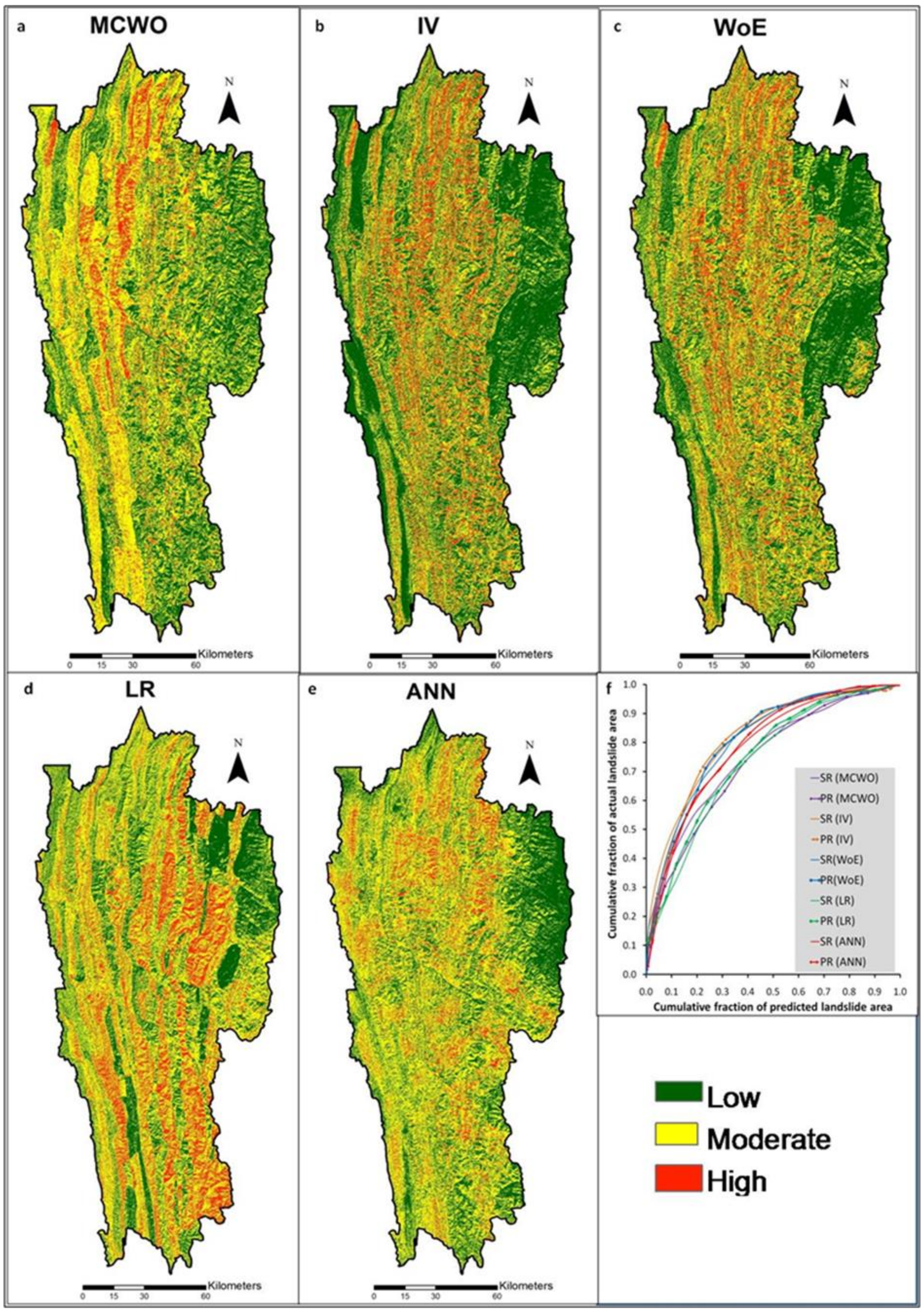


Figure 51. Landslide susceptibility maps generated using spatial sampling strategy by a) MCWO, b) IV, c) WoE, d) LR and e) ANN. f - prediction and success rate curves for of all five models.

Rainfall-Threshold based landslide early warning

A regional landslide early warning system for selective routes of HP, Uttarakhand and NER is operational on an experimental basis for monsoon season. It uses rainfall forecast data from MOSADAC, IMD and Climate Prediction Center (CPC). Below is the landslide early warning was given along the Dalhousie-Chamba route.

Rainfall threshold for landslides is the value which when reached or exceeded is likely to trigger landslides. Rainfall thresholding for slope failure can be established using process based, empirical or statistical approach. Historical data on landslide causing rainfall events and the corresponding landslide records can be used to establish rainfall thresholds for various geographical extents based on consideration of specific rainfall events or using antecedent conditions. The I-D based thresholding is the most widely used empirical thresholding method. The thresholding is done by drawing lower-bound lines on plots of points representing landslide triggering rainfall events. The daily, 3-day cumulative and 15-day & 30-day antecedent rainfall values associated with landslides had been subjected to binary logistic regression using landslide as dichotomous dependent variable. significant predictors influencing slope failure. By using binary logistic regression model the slope failure triggering probability is estimated.

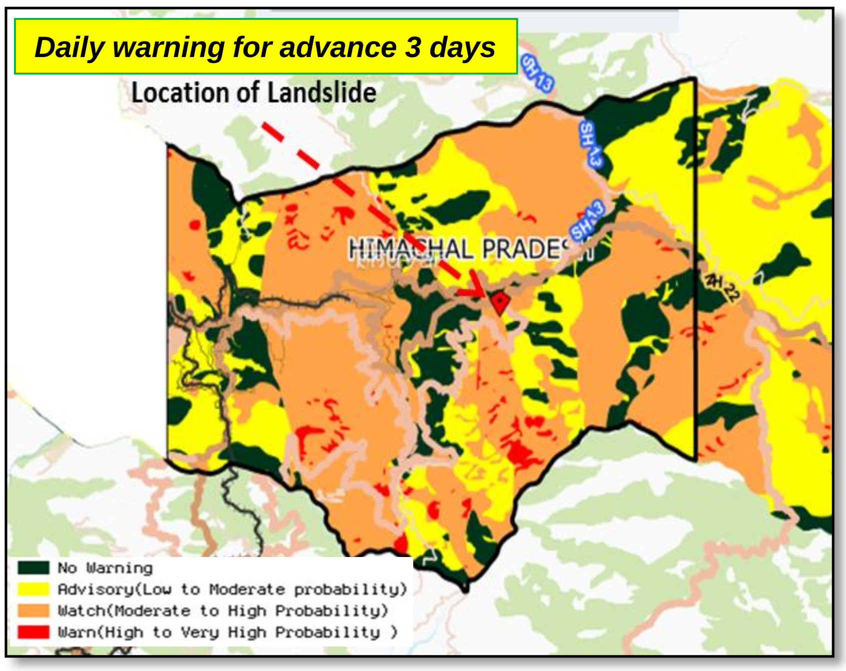


Figure 52. Landslide early warning for advance 3 days given in parts of Himachal Pradesh.

Landslide in Shimla

The logistic regression retained the daily (DR), 3-day cumulative (3DCR) and 30-day antecedent rainfall (30DAR) as significant predictors influencing slope failure.

$$z = -3.817 + DR * 0.077 + 3DCR * 0.058 + 30DAR * 0.009$$

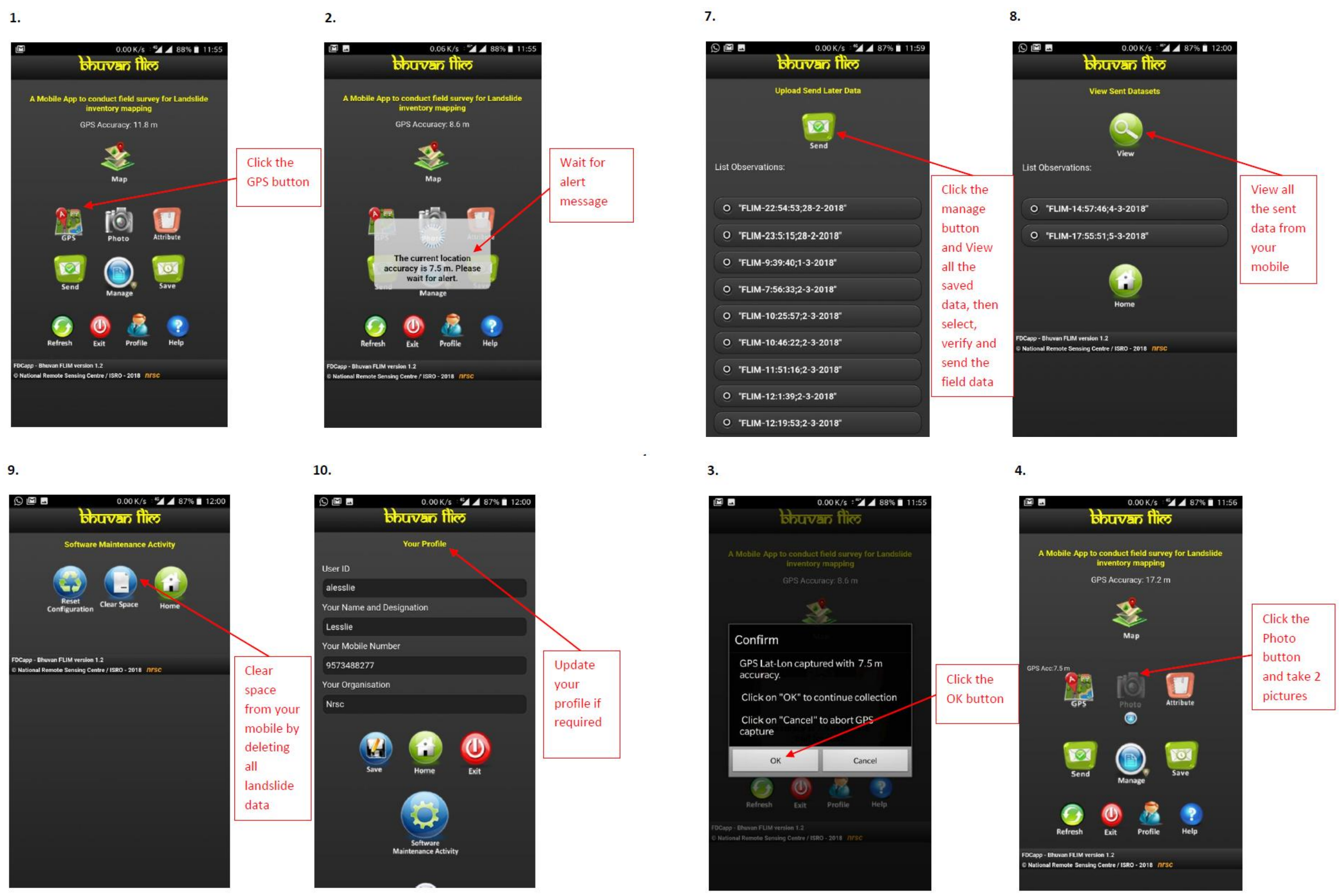
$$f(z) = \frac{1}{1+e^{-z}}, \quad z: -\infty \text{ to } +\infty, \text{P}: 0 \text{ to } 1$$

Different combinations of triggering probability and the Landslide Susceptibility classes used in this approach are described below:

Landslide Susceptibility	Triggering Probability	
	0.75 to 0.85	> 0.85
Severe	Warn	Warn
Very High	Watch	Warn
High	Watch	Watch
Moderate	Advisory	Advisory

Table 4. Table showing triggering probability for landslide trigger.

Mobile Application for Landslide data collection



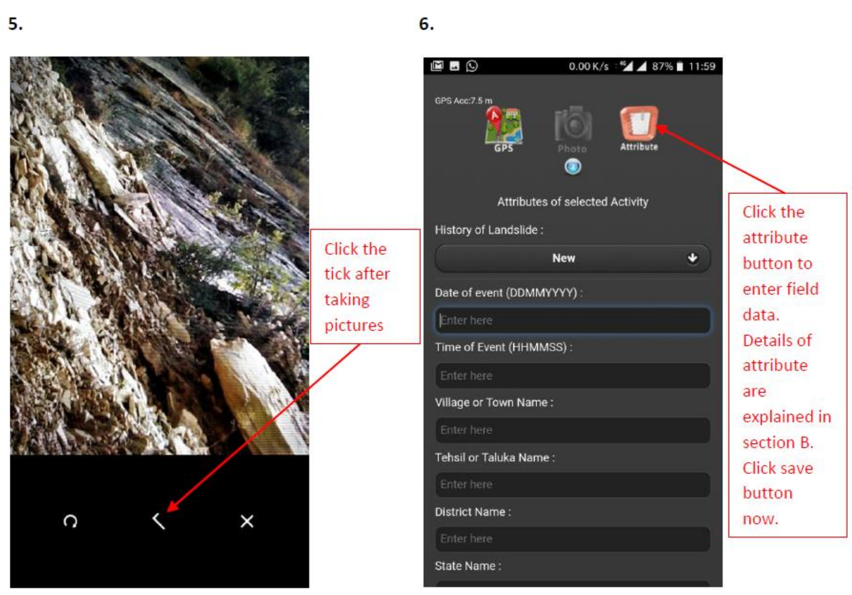


Figure 53. Step-by-step procedure for landslide data collection using FLIM mobile app.

The FLIM mobile app is developed by NRSC/ISRO. It aimed to be used by SDMAs/DDMAs/Govt. organizations/researchers with reasonable knowledge on landslides. The main purposes of this app are to collect data of landslides from the field and to develop a landslide warning system for the region using the collected field landslide data.

Mobile Application for Landslide data collection

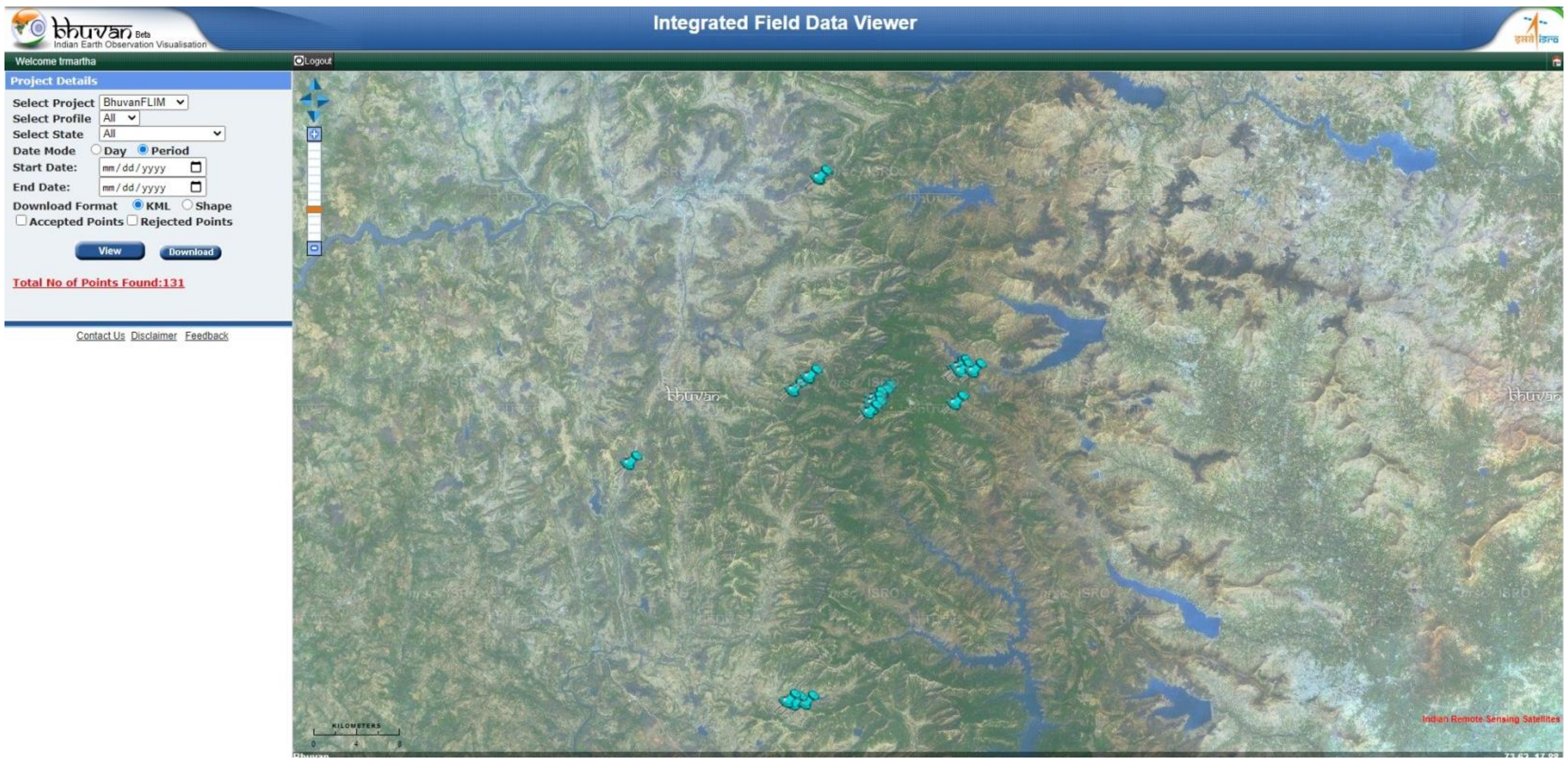


Figure 54. Landslide data from western Maharashtra collected in Bhuvan FLIM database.

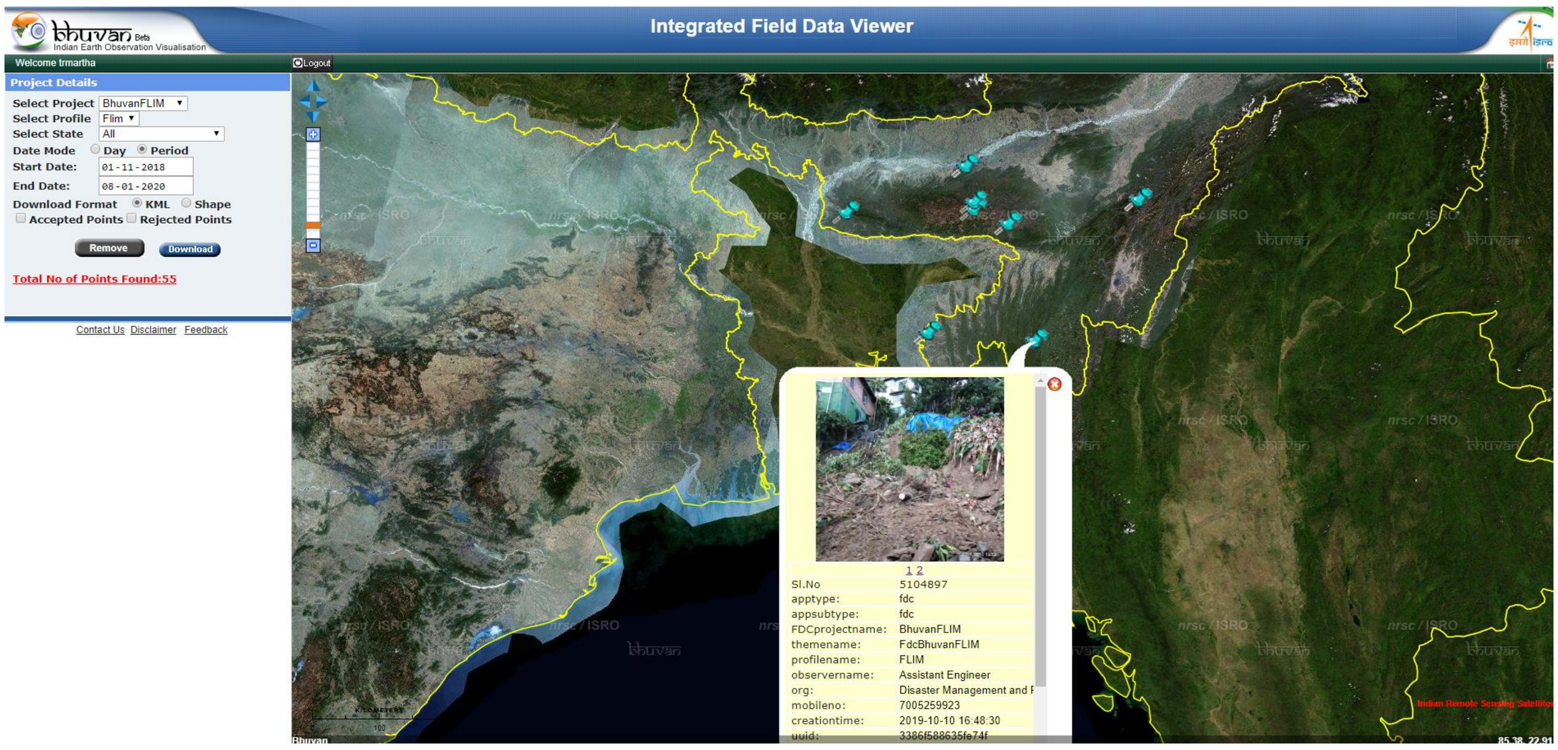


Figure 55 . Ground landslide data collected in NER using FLIM mobile App.

The FLIM mobile app is developed by NRSC/ISRO. It aimed to be used by SDMAs/DDMAs/Govt. organizations/researchers with reasonable knowledge on landslides. The main purposes of this app are to collect data of landslides from the field and to develop a landslide warning system for the region using the collected field landslide data. The collected data sent from the field using this app will be uploaded in the BHUVAN and NDEM servers for analysis and visualization. Hence, the app will help the state agencies as incident reporting system for landslide disasters and for development of a landslide early warning system in the region.

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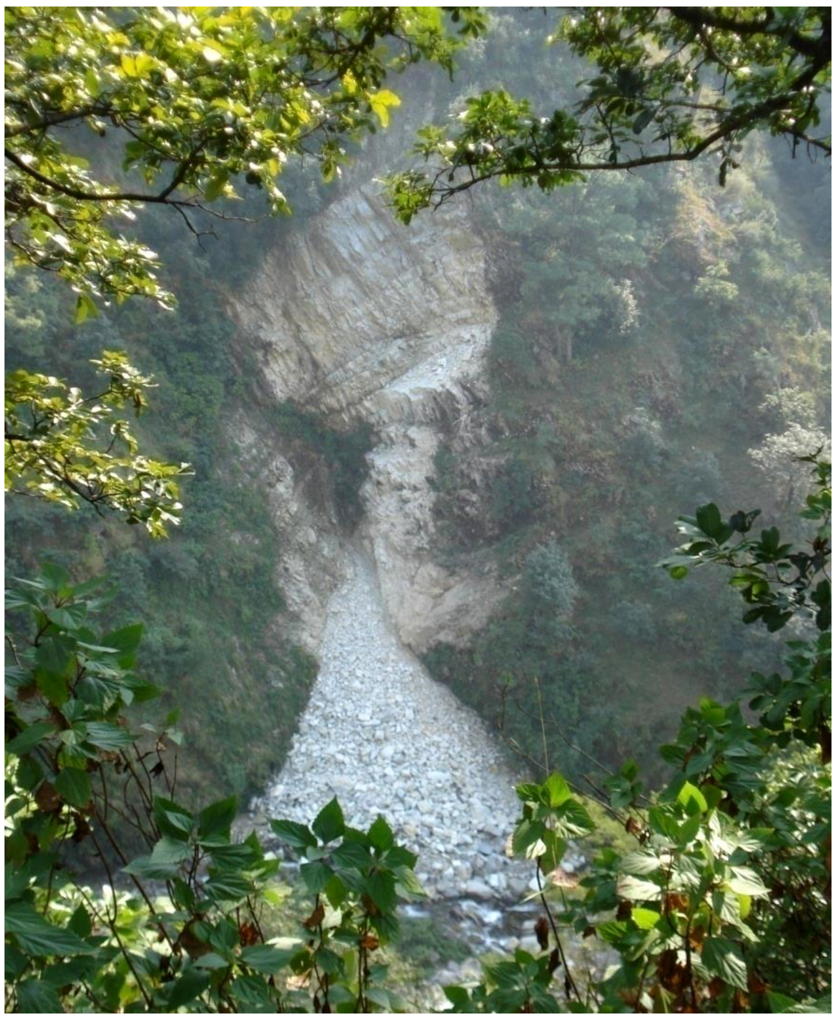
Landslide near Jakholi village, near Agastyamuni town, Rudraprayag district, Uttarakhand

Landslide from Bhiri village, near Guptakashi, Mandakini Valley, Uttarakhand



Landslide is located in Mohand ridge in Sivallik hills near Deharadun, Uttarakhand

Landslide from Chamoli district, Uttarakhand