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Landslides triggered by the June 2013 extreme rainfall event in parts of Uttarakhand state, India

Abstract Extreme rainfall during 15–17 of June 2013 triggered numerous landslides and caused widespread damage and loss of life in the Bhagirathi and Alaknanda river valleys, with Kedarnath town bearing the brunt of the disaster. In this paper, we present a corroboration of observations gathered from very high resolution satellite data which indicated that two events in close succession caused damage to the Kedarnath town. While the flooding on June 16, 2013 was due to the reactivation of an old landslide that resulted in breaching of the river training wall, breaching of the moraine dammed Chorabari lake on June 17, 2013 caused further flooding and damage to the Kedarnath town. We also prepared a detailed landslide inventory using multi-temporal Resourcesat-2 images (5.8m) acquired before and after the event in order to avoid issues related to cloud and shadow. A total of 6,013 landslides were mapped, out of which 3,472 landslides with 30.4km² area were classified as new ones, 1,137 landslides with 9.1km² area were classified as old ones and 1,401 landslides with 11.7km² area were classified as reactivated ones. The frequency-area statistics of the mapped landslides shows near completeness of this event-based landslide inventory. The debris brought down by rivers from these landslides, particularly from the glaciated deposits in upstream areas, caused severe river bank erosion in downstream areas.

Keywords Kedarnath · Satellite data · Disaster · OBIA · Flood · River bank erosion · GLOF

Introduction

Extreme events such as high-magnitude earthquake and high-intensity rainfall are rare events that trigger landslides and induce significant morphological changes to a large area, particularly in a mountainous terrain (Gorum et al. 2011; Huang et al. 2012; Lin et al. 2011; Pánek et al. 2011; Xu et al. 2013). During June 15–17, 2013, Uttarakhand state in India and adjoining areas in the Himalayas received heavy rainfall, which was about 375% more than the benchmark rainfall during a normal monsoon (Dobhal et al. 2013). The unusual high rainfall in the upstream areas of Bhagirathi, Alaknanda and Mandakini rivers triggered large number of landslides. Kedarnath, Badrinath and Gangotri, the famous pilgrimage sites situated in those upstream areas and visited by millions of people every year, witnessed massive devastation as a result of landslides and floods. According to the Uttarakhand state government, an estimated 6,074 people have died due to landslides and floods, with maximum deaths reported at the Kedarnath town (www.euttaranchal.com/news/general/uttarakhand-missing-declared-dead.html). Destruction of bridges and roads left about 100,000 pilgrims and tourists stranded in the valleys who were later rescued by Indian army and air force with the help of other civic authorities. This event is considered as India's worst natural disaster since December 2004 Indian Ocean tsunami (Dubey et al. 2013).

According to Dimri (2013), extreme events have occurred in Uttarakhand previously. But, large number of human deaths and massive damage due to the June 2013 extreme event can be broadly attributed to two reasons: (1) coincidence of the annual pilgrimage with the event leading to large congregation of people at Kedarnath and (2) heavy rainfall on June 10 and 11, 2013 that saturated the soil moisture and made the ground vulnerable to landsliding during June 15–17, 2013 rainfall. Apart from landslides, channel shift and sediment transport are the other immediate effects of the extreme rainfall event. The sudden discharge of water loaded with debris derived from new landslides and unconsolidated glacial material has resulted in extensive side bank erosion and toe cutting of hill slopes at several places along the river valleys.

Landslide, being a geomorphic process, leaves a distinct signature on the surface of the Earth, thereby, enabling itself to be viewed or captured directly and repeatedly by earth observation systems such as satellite or airborne remote sensing technology. In recent times, disaster support activities are becoming dependent on results derived from satellite data (Martha and Vinod Kumar 2013; Voigt et al. 2007). Study of landslides using satellite image or aerial photograph is further strengthened by the availability of data from the large number of Earth Observation satellites in a post-disaster situation where accessibility is an issue by conventional ground-based investigations (Galli et al. 2008; van Westen and Lulie Getahun 2003). Previously, the National Remote Sensing Centre (NRSC) has carried out damage assessment studies using high-resolution satellite data and aerial photographs for landslides such as the Varunawat landslide in Uttarkashi in the year 2003 (Vinod Kumar et al. 2008), landslides in Sikkim in the year 2011 (Martha et al. 2014) and Okhimath in year 2012 (Martha and Vinod Kumar 2013). NRSC as a part of its disaster management support activities has programmed its satellites to acquire data over the affected area immediately after the June 2013 event. Initial results of the Uttarakhand disaster were subsequently hosted in the NRSC web portal (www.bhuvan.nrsc.gov.in). Since the occurrence of the Kedarnath disaster, several attempts were made by researchers to identify the causative mechanism of sudden flash floods and its subsequent effects such as landsliding and river bank erosion in the downstream areas (Dobhal et al. 2013; Dubey et al. 2013; Sati and Gahalaut 2013; Sati 2013; Uniyal 2013). However, to our knowledge, a comprehensive assessment of the entire affected area with respect to occurrence of landslides has not been done.

In this study, we mainly focussed our investigation on the (1) identification of the cause of the Kedarnath disaster and (2) preparation of an event-based landslide inventory map in the Bhagirathi and Alaknanda river valleys. The study was carried out using high-resolution satellite data acquired before and after the event. Spatial association of landslides with rocktypes, slope and rainfall distribution pattern was also studied.

Materials and methods

Study area

The study mainly focussed along the valleys of the Bhagirathi and Alaknanda rivers from their origin to the confluence near Devprayag from where it is known as river Ganges (Fig. 1). The important tributary rivers in the study area are Mandakini, Madhyamaheshwar, Kaliganga, Pindar, Birahi, Dhauri, Bhilangana and Asiganga (Fig. 1). Important towns in the region are Kedarnath, Sonprayag, Okhimath, Rudraprayag, Srinagar, Badrinath, Joshimath, Karnaprayag, Gangotri and Uttarkashi (Fig. 1). The spatial extent of the study area is approximately 15,410 km² covering parts of Chamoli, Rudraprayag, Uttarkashi and Tehri districts of Uttarakhand state, India.

Owing to the fragile mountainous ecosystem, landslides are not uncommon in this area. In August 1998, a total of 466 landslides

were triggered by a major rainfall event, which killed 103 people and damaged 47 villages in the entire Mandakini valley (Naithani 2001). Similarly, in July 2001, 27 people were killed in Phata (near Okhimath) due to landslides resulting from a cloudburst (Naithani et al. 2002; Vinod Kumar et al. 2003). Recently in September 2012, a total of 470 landslides were triggered by a heavy rainfall event in the Okhimath area resulting in severe loss of life and property (Martha and Vinod Kumar 2013). These events provide sufficient evidences about the proneness of the area to landslides due to rainfall.

June 2013 rainfall event

The Uttarakhand disaster was primarily triggered by unprecedented rainfall that occurred during June 10–18, 2013 (Durga Rao et al. 2014). The month of June, which is a summer season in northern India, generally sees moderate to low rainfall with occasional

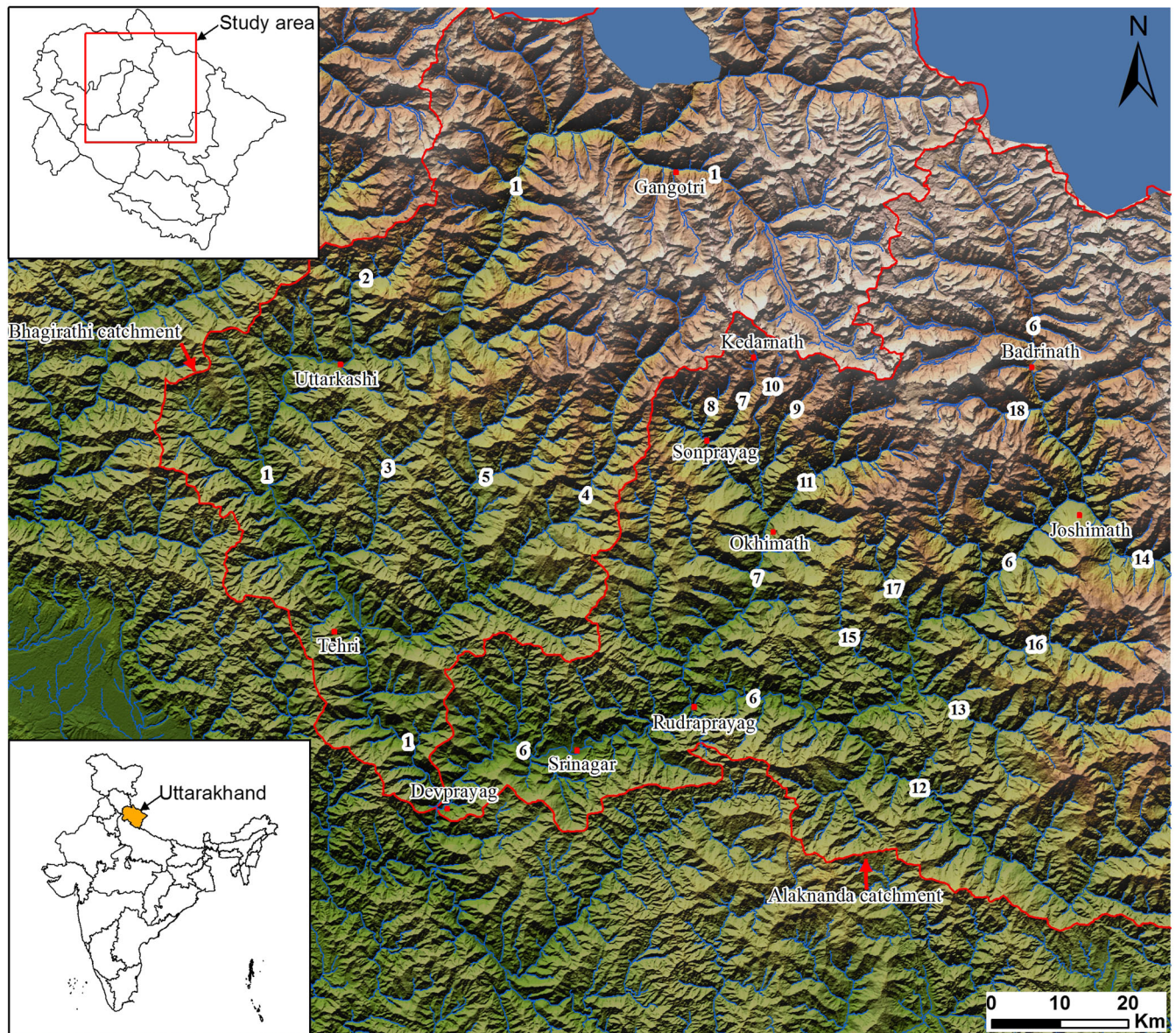


Fig. 1 A painted relief map showing Bhagirathi and Alaknanda catchments in the Uttarakhand state of India. Numbers show some of the important rivers in the study area. Refer “Event-based landslide inventory” for name of the rivers

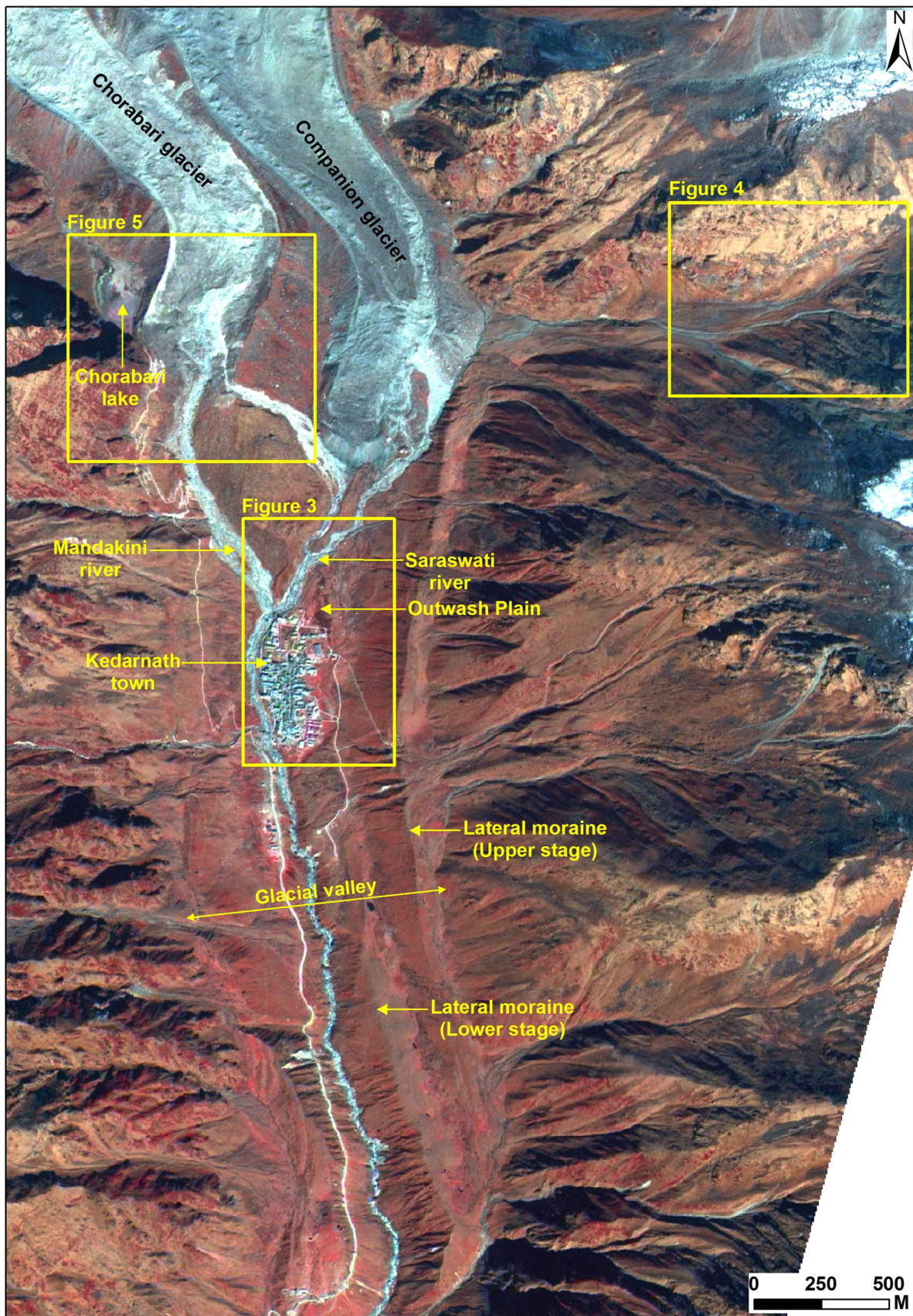


Fig. 2 A pre-disaster 2.5-m resolution satellite image showing some important geomorphic features in the Mandakini valley around Kedarnath town. Boxes outlined in yellow show areas analysed in detail to find out cause of the Kedarnath disaster

Table 1 Satellite data used in the study

Satellite	Date of acquisition	Sensor type (resolution)	Source
Pre-disaster			
Resurcesat-2 LISS-IV Mx	18 November 2011	Multispectral (5.8 m)	ISRO
	12 November 2012		
	23 January 2013		
	23 May 2013		
GeoEye-1	27 November 2011	Panchromatic (1 m)	USGS
Post-disaster			
Resurcesat-2 LISS-IV Mx	21 June 2013	Multispectral (5.8 m)	ISRO
	10 July 2013		
	03 August 2013		
	30 September 2013		
	01 December 2013		
Cartosat-2a	20 June 2013	Panchromatic (1 m)	

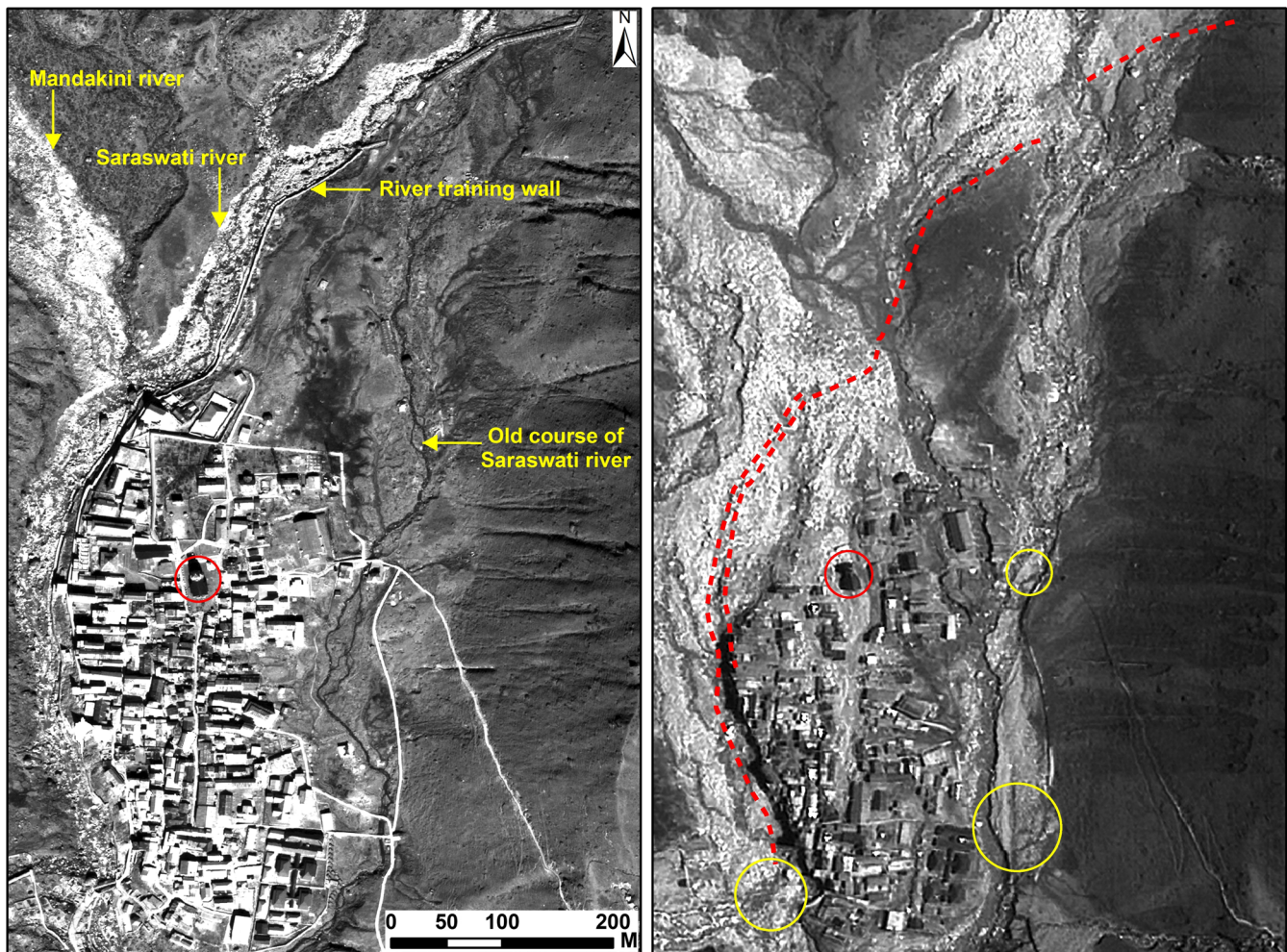


Fig. 3 Pre-disaster GeoEye image (*left*) and post-disaster Cartosat-2a image (*right*) of Kedarnath town showing structural damage to buildings and other facilities due to debris flow and flash flood. The river training wall (red dashed line) along the Saraswati river was completely washed out. Kedarnath temple (red circle) was partially damaged and the three bridges (yellow circle) connecting Kedarnath town to surrounding areas were also washed away. Location of this figure is shown in Fig. 2

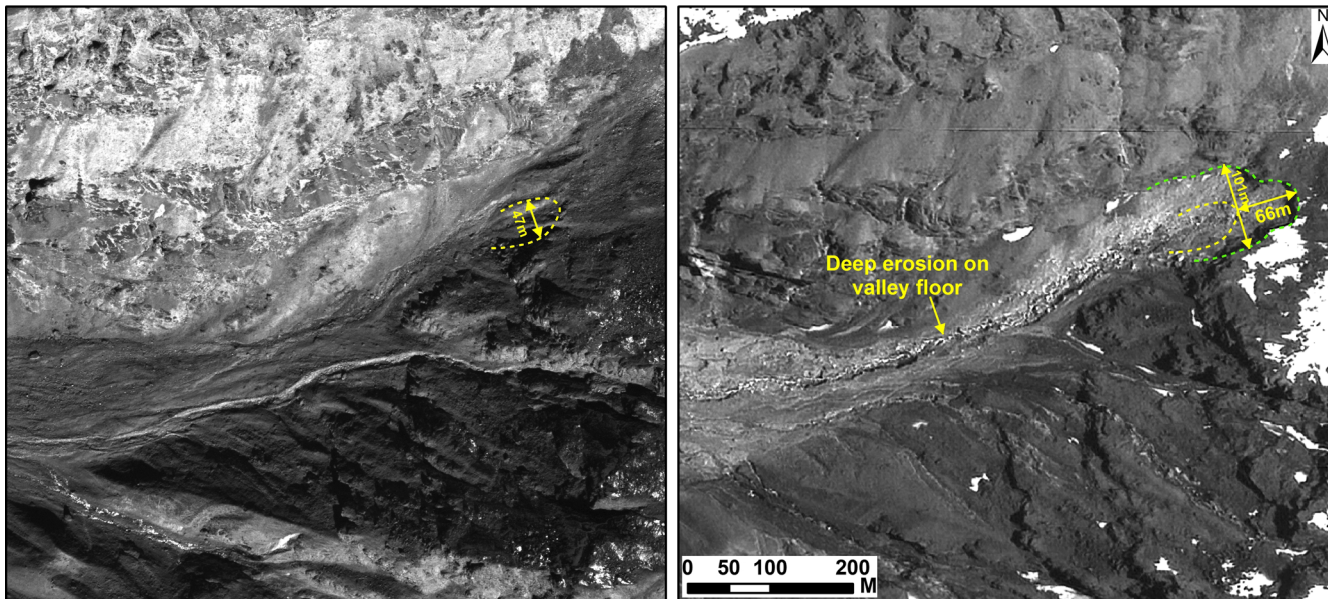


Fig. 4 Pre-disaster GeoEye-1 image (*left*) and post-disaster Cartosat-2a image (*right*) show an upstream area in a valley that joins with Companion glacier valley was subjected to severe landsliding due to high rainfall. Position of the landslide crown before and after the event is shown with *yellow* and *green dashed lines*, respectively. Location of this figure is shown in Fig. 2

localised heavy rainfall in the mountainous regions of the Himalayas. The average rainfall recorded at Kedarnath town over a period of 5 years from 2007 to 2012 was less than 200 mm (Dobhal et al. 2013). However, as per Indian Meteorological Department data, the average cumulative rainfall over the regions Tehri, Uttarkashi Tharali and Jakoli districts (which represents a major portion of the studied catchments) was more than 350 mm, within a period of 5 days, between 14 and 18 of June 2013 (IMD 2013). This very high rainfall resulted from the interaction between an on-coming trough of westerlies and the strong south easterly monsoon wind flow, associated with a low pressure system developed over North India. This resulted in lower tropospheric wind convergence over Uttarakhand, thus leading to sudden precipitation (IMD 2013). High-intensity rainfall also aided snowmelt in the

Alaknanda and Mandakini catchments that already witnessed approximately 30 % increase in snow cover prior to the main rainfall event (Durga Rao et al. 2014). In this study, we used rainfall data from Tropical Rainfall Measuring Mission (TRMM) due to the absence of sufficient ground rainfall observation in order to understand the spatial association of landslides with rainfall.

Geological and geomorphological setup

The entire area falls within the Himalayan tectonic zone and is very rugged with moderate to high relative relief. Towards the northern part, the areas around Kedarnath and Badrinath falls within Greater Himalayas and bounded by the active Main Central Thrust and Tethyan Detachment Fault (Valdiya 1980). The rocks in this area are categorised as the Higher Himalayan Crystallines with

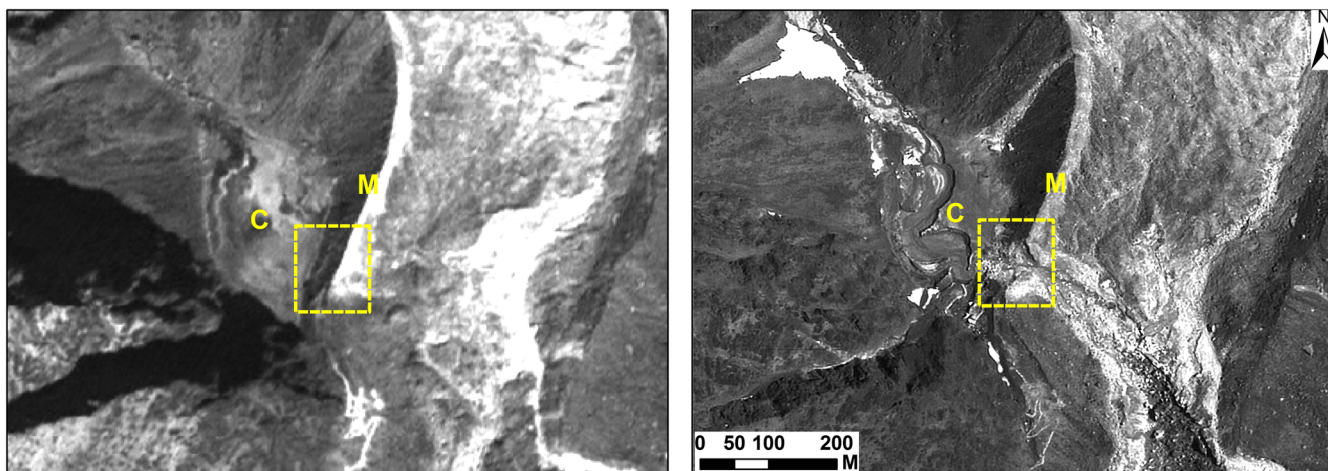


Fig. 5 Pre-disaster GeoEye-1 image (*left*) and post-disaster Cartosat-2a image (*right*) show breaching of the lateral moraine dammed Chorabari Lake (yellow square). The water released from the lake hit the pile of loose debris and then descended downslope, thereby burying the Kedarnath town. Location of this figure is shown in Fig. 2

associated granitic intrusions. The sequence shows progressive regional metamorphism ranging from amphibolites schists to granulite gneisses. Younger granitic bodies frequently intrude the metasedimentary rocks. Areas south of Kedarnath, till Rudraprayag (and further south till parts of Rishikesh), falls within the Lesser Himalayas and are bounded by the Main Central thrust towards the north and the main boundary thrust towards the south (Valdiya 1980). The predominant rock types in this area are quartzites, siltstones, shales with zones of low-grade metamorphosed phyllites, schists and impure marbles. The foliations of the schistose rocks mainly dip in N-NE direction and mostly have undergone high-intensity deformation. This makes the rock brittle, enabling easier to erosion and hence more prone to mass wasting processes.

Geomorphically, the upper reaches of Bhagirathi and Alaknanda rivers are dominated by different types of glacial landforms such as valley glaciers, lateral moraines, terminal moraines, outwash plains, hanging valleys and U shaped valleys. Kedarnath town is situated over an outwash plain at the confluence of Mandakini and Saraswati rivers originating from Chorabari and Companion glaciers, respectively (Fig. 2). The Chorabari and companion glaciers north of the Kedarnath town, gives rise to the Mandakini river which flows south to merge with the Alaknanda river at Rudraprayag along with other tributaries such as Mandani, Kali and Madhyamaheshwar (Fig. 1). Unlike U-shaped valleys in the upstream areas, V-shaped valleys with steeply dipping side slopes dominate the downstream areas. Both paired and unpaired fluvial terraces of different sizes are found on either side of the river valley at several places but are prominent at Uttarkashi and

Srinagar due to wide valley. Being a tectonically active zone, steep escarpments are also found in the area. The presence of steep side slopes and escarpments further increase the chances of slope failure.

Data sources

Pre- and post-disaster high-resolution satellite images used in this study are listed in Table 1. Post-disaster Cartosat-2a images were compared with pre-disaster GeoEye-1 images to find out the cause of severe destruction in the Kedarnath town. Similarly, Resourcesat-2 LISS-IV Mx images were used for creation of an event-based landslide inventory. A 10 m digital elevation model (DEM) was also used for detection of landslides.

Assessment of Kedarnath disaster

The chain of events, especially geomorphic processes that led to massive damage to the Kedarnath town, was reconstructed by correlating the literature published so far on the Uttarakhand disaster (e.g. Dobhal et al. 2013; Dubey et al. 2013; Uniyal 2013) and reports available based on the interviews given by eyewitnesses and survivors (www.discoverychannel.co.in/tv-shows/himalayan-tsunami) with the geomorphic evidences derived from very high resolution satellite data interpretation.

Detection of landslides

Landslides were detected from post-landslide Resourcesat-2 LISS-IV Mx images using a semi-automatic object-based image analysis (OBIA) technique developed by NRSC (Martha et al. 2010; Martha et al. 2011, 2012). OBIA was carried out using the eCognition s/w.

Table 2 Catchment wise distribution of landslides. Rivers are indexed with numbers and shown in Fig. 1

Catchment	Sub-catchment	Watershed	No. of Landslides
1 - Bhagirathi			1,608
	2 - Asi Ganga		382
	3 - Jalkor Nadi		155
	4 - Bhillangana		466
		5 - Balganga	181
6 - Alaknanda			1,007
	7 - Mandakini		524
		8 - Vasuki Ganga	136
		9 - Kali Ganga	98
		10 - Mandani	88
		11 - Madhyamaheshwar	186
		12 - Pindar	421
		13 - Nandakini	225
		14 - Dhauliganga	64
		15 - Nagol gad	53
		16 - Birahi Ganga	59
	17 - Kalapani gad	299	
	18 - Khirao ganga	61	
Total			6,013

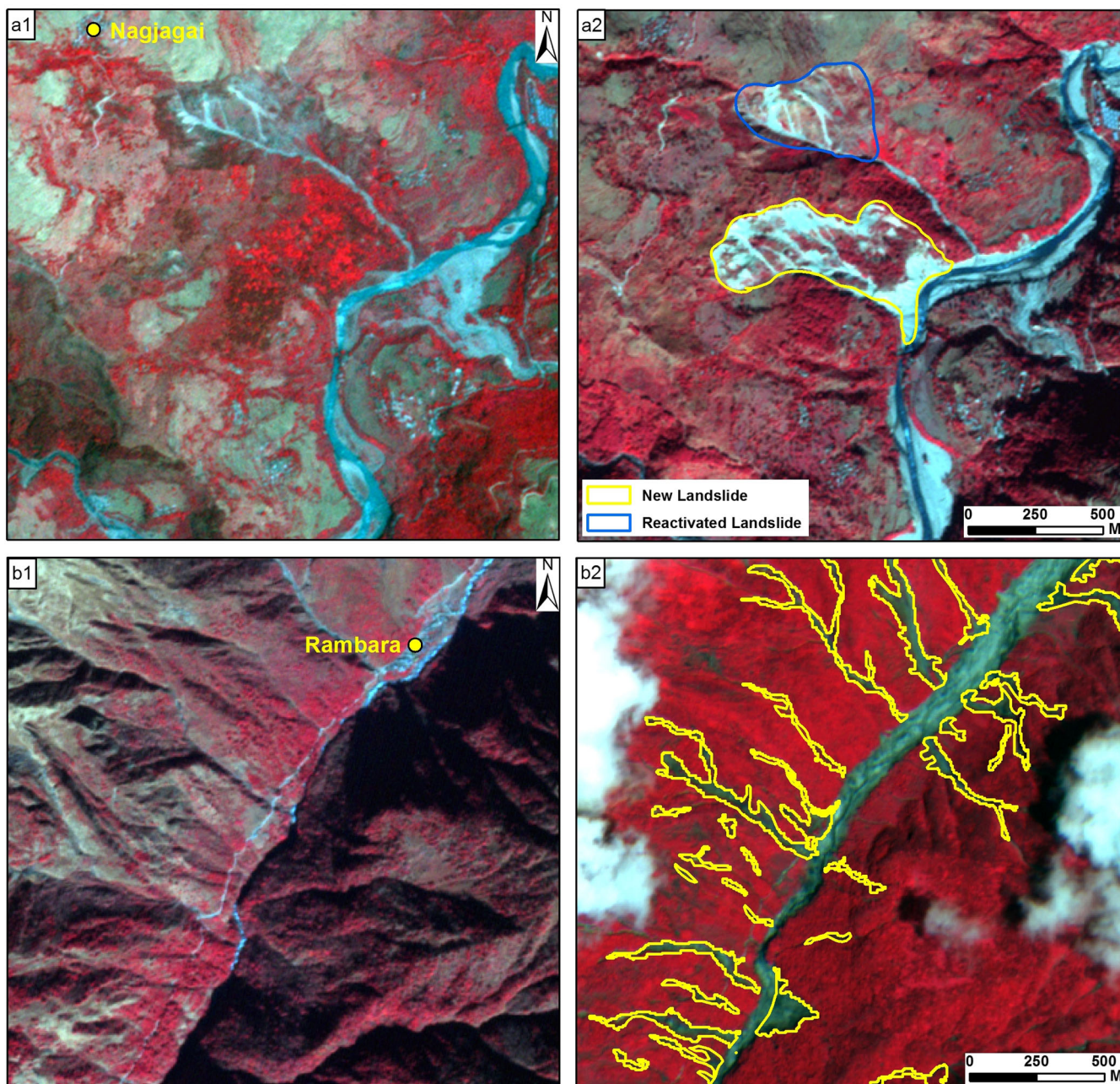


Fig. 6 *a1* and *a2*, pre- and post-event images, respectively, show reactivated and new landslides near Nagjagai village (field photograph is shown in Fig. 7d) in the Mandakini valley. Similarly, *b1* and *b2*, pre- and post-event images, respectively, show new landslides and bank erosion around Ramabara village (field photograph is shown in Fig. 7a) in the Mandakini valley

Multi resolution image segmentation was used to create meaningful objects. Initially landslide candidates were identified through a

NDVI threshold, and subsequently the false-positives such as river sand, barren land and build up area were sequentially eliminated

Table 3 Size distribution of landslide types mapped in Bhagirathi and Alaknanda catchments

Landslide type	Number	Total area (km ²)	Min area (m ²)	Max area (m ²)	Avg. area (m ²)
New Landslide	3,472	30.4	75	547,500	8,772
Old Landslide	1,137	9.1	157	672,631	7,993
Reactivated Landslide	1,404	11.7	207	705,372	8,326
Total	6,013	51.2			

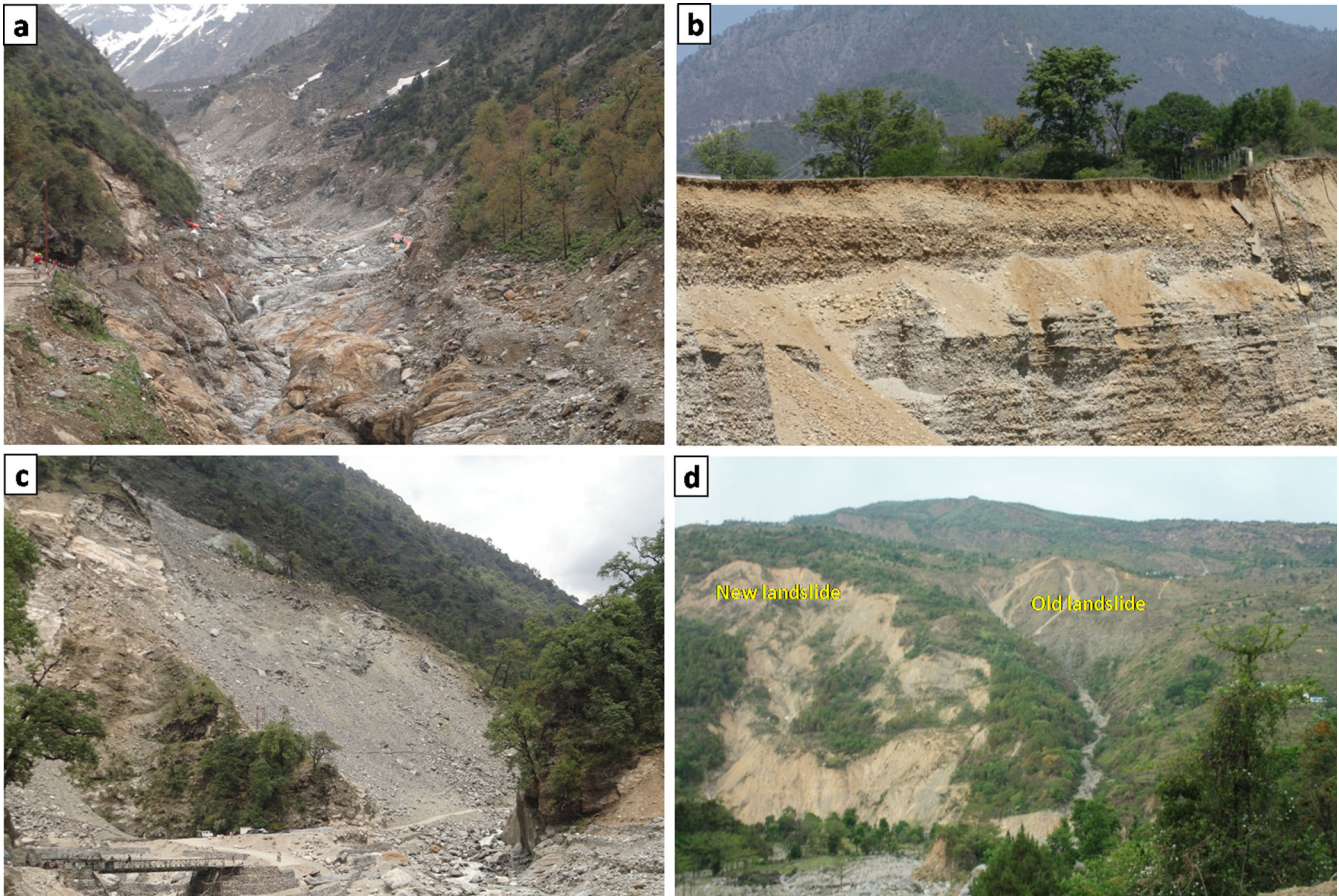


Fig. 7 Landslide field photographs. **a.** bank erosion along the Mandakini river around Rambara village, **b.** section of a river terrace collapsed due to undercutting by the Alakanada river at Srinagar town showing fluvial deposits in a layered sequence, **c.** Rock slide near Sonprayag and **d.** new debris slide triggered by the rainfall near Nagjagai village

using a generic approach. Some of the landslides were verified on the ground during the fieldwork after the disaster. The landslides

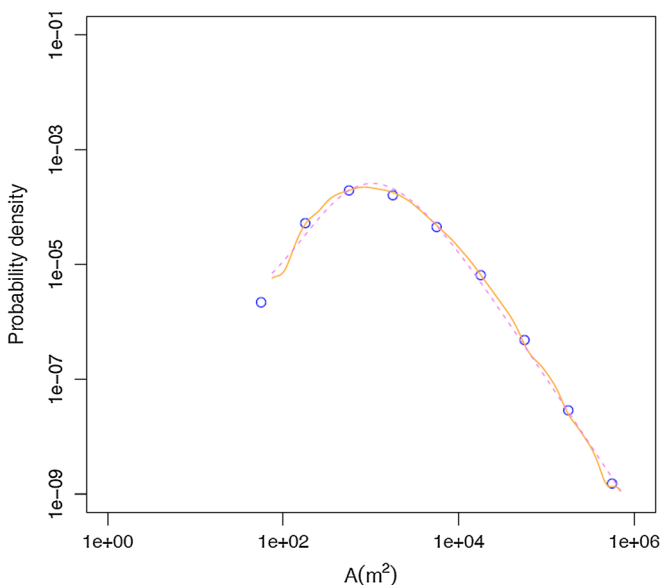


Fig. 8 Probability density of landslide area obtained through kernel density estimation

were further classified into three types (new, old and reactivated) depending upon their activity and disposition, and by comparing pre- and post-disaster satellite images as described below.

New landslide: Those landslides that occurred newly after the rainfall event and therefore will be absent in the pre-disaster satellite image.

Old landslide: Those landslides that existed prior to the rainfall event. They will be present in both pre- and post-disaster satellite images.

Reactivated landslide: The existing landslides which show activity after the rainfall event either in the crown or in the flanks and active parts are clearly seen in the post-event landslide image in comparison to the pre event image. The historical landslide inventory data were also consulted to find out those landslides where the activity was suspended for certain period, thus appeared as stable area in the image, but is reactivated after the recent rainfall event.

The landslide frequency-area statistics was generated using inverse gamma distribution model with a kernel density estimation probability distribution function (Guzzetti et al. 2009; Malamud et al. 2004; Rossi et al. 2012). The calculation was carried

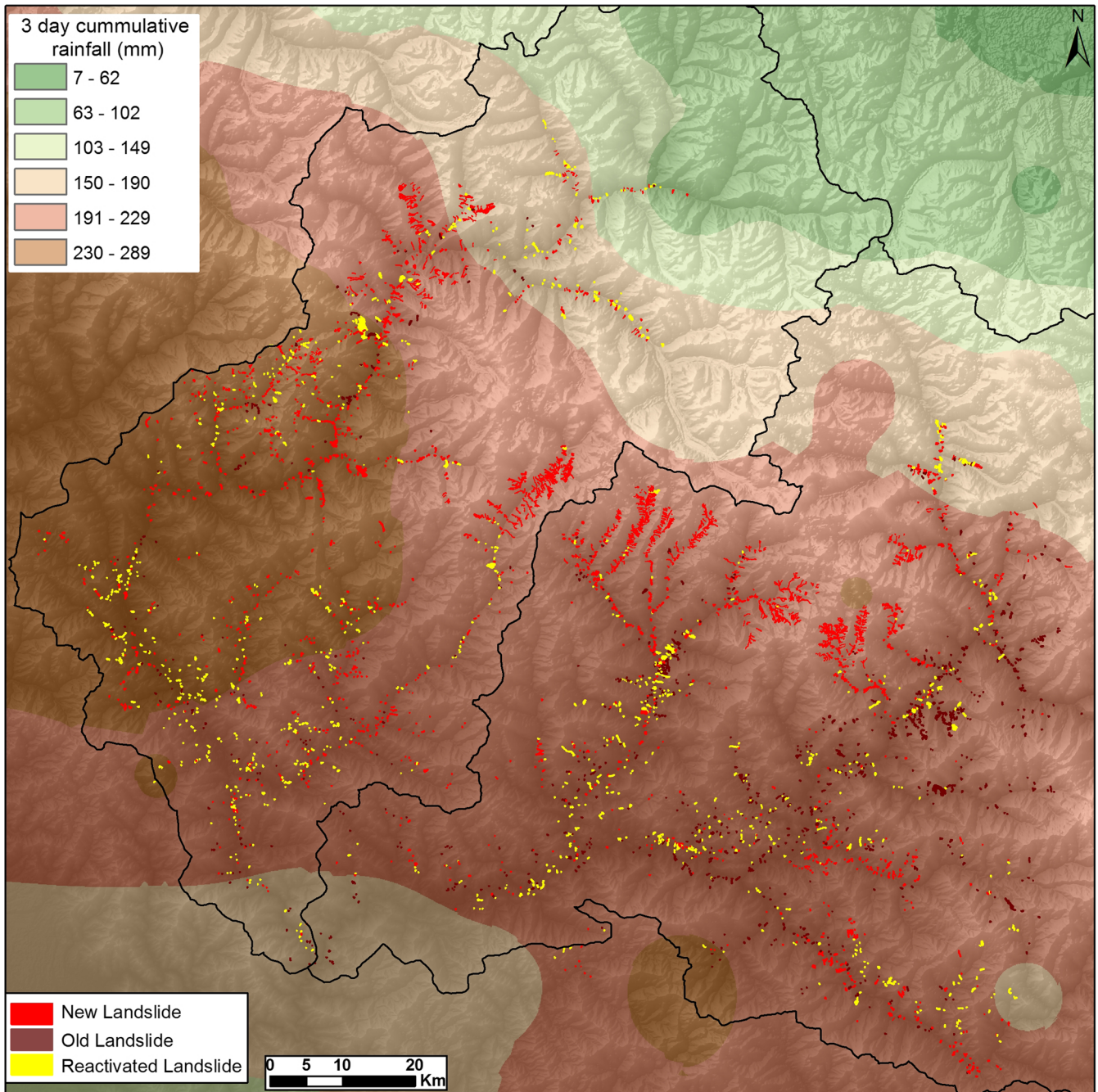


Fig. 9 Spatial association of landslides with rainfall distribution pattern

out using the “Areastat” WPS tool developed by CNR-IRPI (<http://giida.irpi.cnr.it/index.php/en>).

Results and discussion

Causes of Kedarnath disaster

As per the reports, two events that happened in close interval were responsible for severe damage to the Kedarnath town. The first event happened in the Saraswati river valley to the northeast of Kedarnath town late in the evening of June 16, 2013 and the second event happened in the Mandakini river valley to the northwest of Kedarnath town in the early morning of June 17 2013. These two

events are discussed in the following sections based on evidences derived from the satellite data interpretation.

Event in the Saraswati river valley

As per eyewitnesses, heavy rain commenced again on the Kedarnath town in the evening of June 16, 2013 (www.discoverychannel.co.in/tv-shows/himalayan-tsunami). During the evening prayer at the Kedarnath temple, sounds of huge rolling boulders and gushing water were heard. This may be correlated to the breaching of the river training wall of Saraswati river that was completely eroded and clearly seen in the post-disaster Cartosat-2a image (Fig. 3). This would have allowed

gushing of excessive water inside the Kedarnath town. The breaching of the river training wall also allowed Saraswati river to flow along its old course (Fig. 3). This event has also damaged bridges that connect the Kedarnath town to surrounding areas, thereby obstructing people inside from going to safer areas. The structural damage to buildings and other infrastructural facilities are clearly seen in the post-disaster image in comparison to the pre-disaster image (Fig. 3). Kedarnath temple, the place where millions of pilgrims visit every year, is partially damaged by the flash flood.

Further analysis of the satellite image in upstream areas clearly showed reactivation of a large old landslide (Fig. 4). The crown of the old landslide has retreated by 66 m and the width near the crown has increased from 47 to 101 m. The debris from the collapsed landslide crown moved downslope and caused deep erosion in the valley floor. Due to high gradient, this debris-laden flow could have hit the river training wall resulting in its collapse and subsequent flooding in the evening of June 16, 2013.

Event in the Mandakini river valley

As per the news report, Kedarnath town was again flooded in the early morning of June 17, 2013 (www.discoverychannel.co.in/tv-shows/himalayan-tsunami). The eyewitness report says that the water had obnoxious odour which can be correlated to a stagnant source of water. The analysis of pre- and post-disaster images clearly show breaching of the Chorabari lake situated in the north-west direction of the Kedarnath town (Fig. 5). Chorabari is a blocked lake formed in the valley due to the truncation of the lateral moraine of Chorabari glacier against the valley wall. The depth of the lake is ~18 m and area is ~0.032 km². It is a seasonal lake and holds water coming from the glacial melt. However, due

to heavy rainfall, a large amount of water would have accumulated behind the moraine. Since the lateral moraine is a non-lithified body, it failed to withhold the pressure of the water column and subsequently breached resulting in a glacial lake outburst flood (GLOF). The sinuous depression seen in the lake bed can be attributed to the release of water in a quick time from a flat valley floor. The momentum of water filled with debris was so huge that it scoured the loose material lying in the outwash plain and buried the Kedarnath town that had already been inundated on the previous day.

Event-based landslide inventory

Landslide inventory was prepared for the Bhagirathi and Alaknanda river valleys using a semi-automatic detection technique. A total of 6,013 landslides were detected in the Mandakini, Mandani, Kali, Madhyamaheshwar, Khirao river valleys in the Alaknanda catchment and Bhilangana and Asiganga river valleys in the Bhagirathi catchment. Catchment and watershed wise distribution of landslides is given in Table 2.

The landslides were further classified into three types (new, old and reactivated) depending upon their activity by comparing pre- and post-event high-resolution satellite images (Fig. 6). Table 3 shows size distribution of different types of landslides mapped in the study area. Majority of new landslides near glaciated areas are soil slips which occur due to removal of thin soil lying in the lower order channel. High-gradient rivers carrying debris from landslide caused bank erosion at several places resulting in occurrence of new landslides. Rambara village situated approximately 5 km from the Kedarnath town in the downstream direction was completely washed away due to river bank erosion caused by the flash flood (Figs. 6b, 7a). River terraces were damaged at several places due to

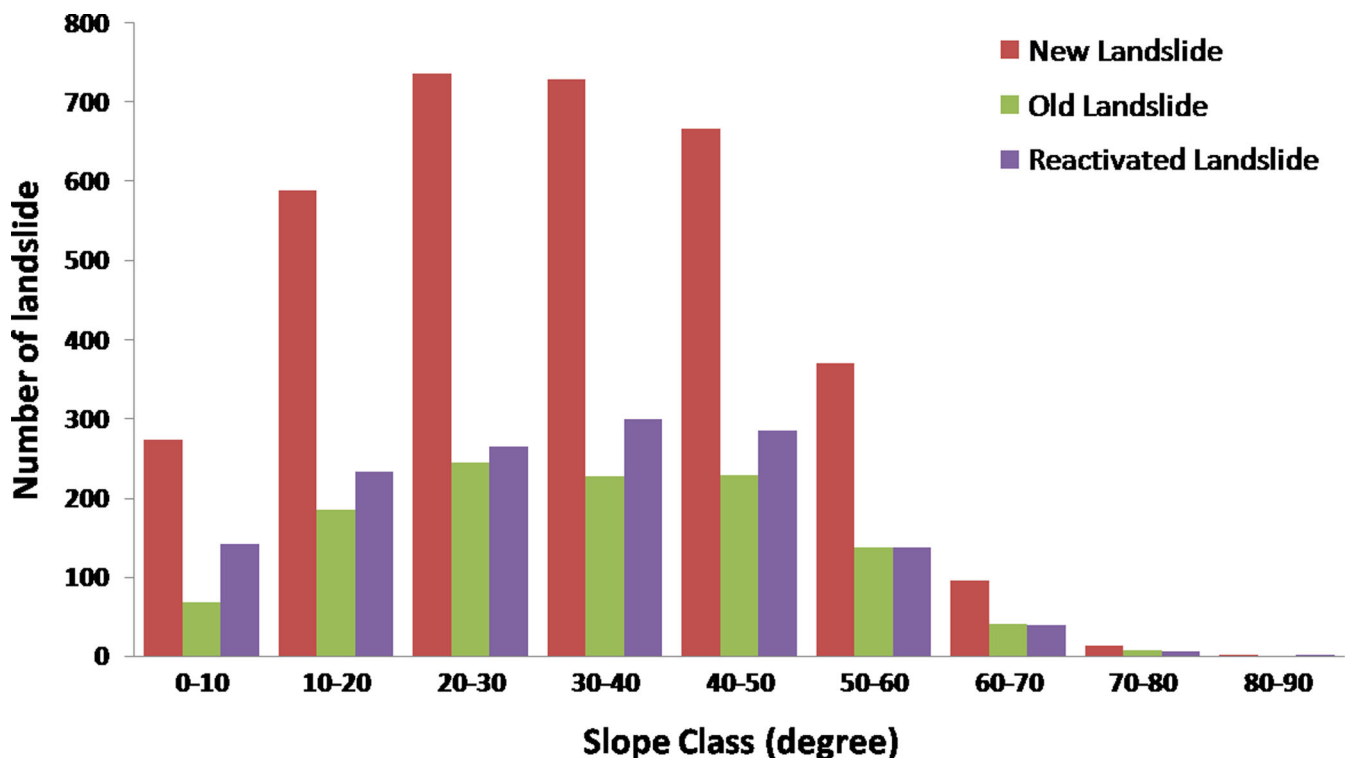


Fig. 10 Distribution of landslides in the study area with respect to slope

undercutting of the river (Fig. 7b). Figure 7c shows rock slide at Sonprayag in the confluence of Songanga and Mandakini rivers that damaged the bridge on the only approachable road to Kedarnath. Deep seated debris slides were also triggered by the rainfall (Fig. 7d).

The frequency-area relationship of the landslide inventory was generated using inverse gamma function (Fig. 8). The probability density graph shows characteristic “roll over” towards lower landslide areas and “tailing off” at landslides with larger areal extent. The roll over is seen at landslide area of 2,945 m² with a power-law decay exponent of 1.33. This agrees well with general frequency-area statistics

suggesting a near complete landslide inventory (Guzzetti et al. 2009; Malamud et al. 2004).

To understand the relationship of landslide occurrences with rainfall, the landslide inventory map was superimposed over the 3-day cumulative rainfall derived from TRMM data. Figure 9 shows cumulative rainfall distribution over the study area matched well with landslide locations indicating rainfall as the dominant factor in triggering landslides. Analysis of landslide inventory data with slope shows that new landslides occurred even in low slope classes in comparison to high-slope classes (Fig. 10). This shows that terrain slope has not significantly controlled the occurrence of new landslides for the June 2013 event. Further, superimposition

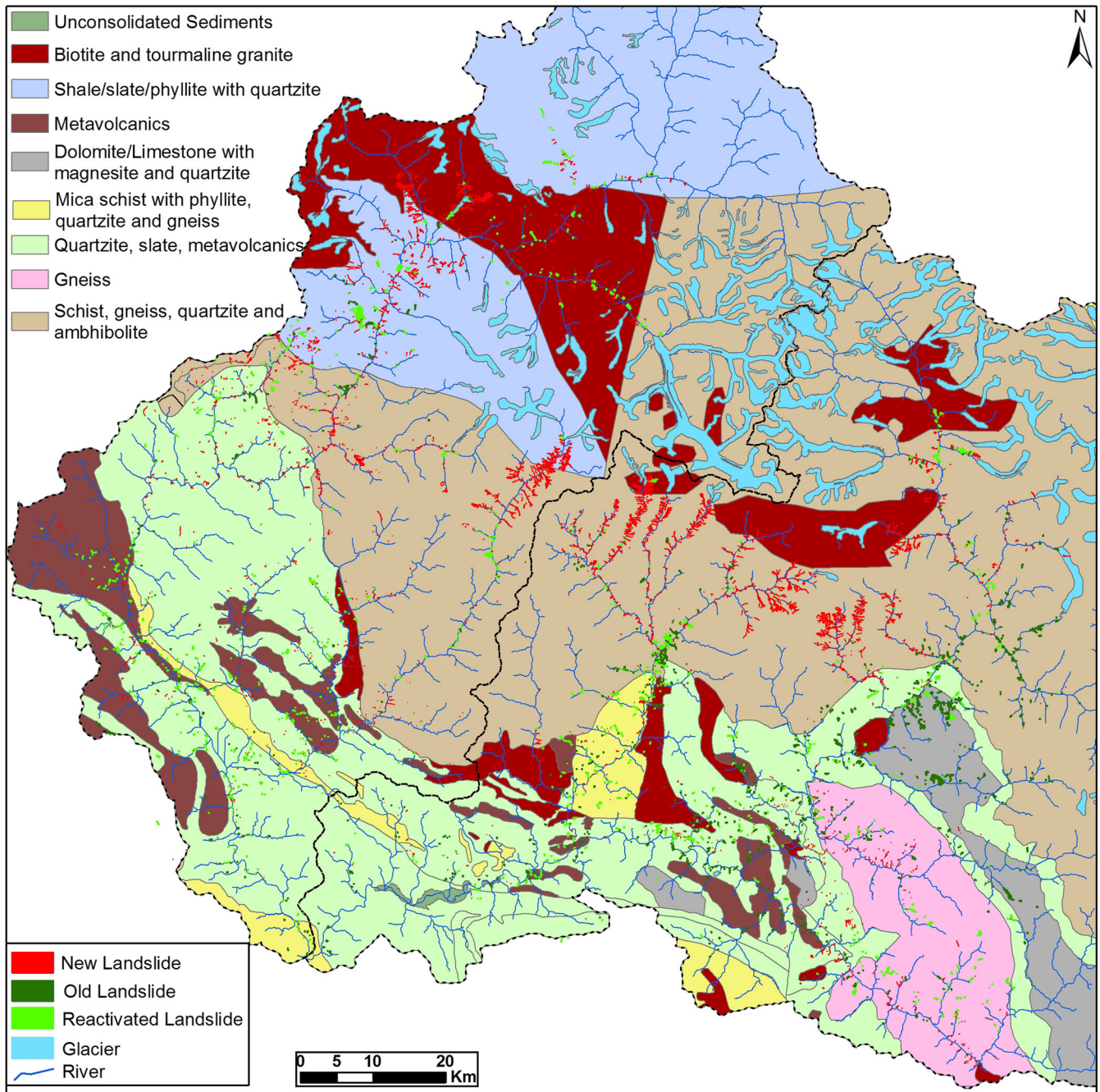


Fig. 11 Spatial association of landslides in the study area with rock types and glaciers

of landslide inventory over the lithology map could not also bring out any specific spatial association. However, majority of new landslides occurred in schist, gneiss, quartzite and amphibolite which have undergone deformation rendering them prone to slope failures (Fig. 11). From Fig. 11, it is also clear that most of the new landslides occurred near to glaciated areas i.e. in the glaciated valleys where loose debris were available in abundance.

Conclusions

The fragile geological and geomorphological setting of the Himalayas renders it vulnerable to landslides due to extreme weather events. Very high resolution data such as Cartosat-2a and GeoEye-1 were used in this study to investigate Kedarnath area that witnessed maximum death and damage due to the June 15–17 2013 rainfall event. Geomorphic evidences collected from the satellite data were corroborated with videos and news reports to reconstruct the chain of events around Kedarnath during June 16–17, 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 June 16, 2013. Kedarnath town witnessed a GLOF phenomenon on June, 17 2013 due to the breaching of the moraine dammed Chorabari lake. The twin events not only buried the 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 to east of Kedarnath. Further, intense rainfall during this period triggered numerous landslides across the entire catchment of Bhagirathi and Alaknanda. We identified a total of 6,013 landslides using high-resolution Resourcesat-2 LISS-IV Mx images in these two catchments. Out of the 6,013 landslides, 3,472 landslides covering an 30.4 km² area were classified as new ones triggered due to the June 2013 extreme event. The landslide frequency-area relationship shows near completeness of the event-based landslide inventory. Since majority of landslides occurred near to the glaciated areas, where debris and loose soil were available in abundance, prominent river bank erosion at several places in downstream areas were observed. Slope and rock type did not show any significant relationship with identified landslides, which indicates that occurrence of landslides was mainly controlled by rainfall. The event-based landslide inventory map prepared in this study will help catchment-wise sediment budget analysis that will indicate about the siltation-related issues to many existing hydro-electric dams in the Bhagirathi and Alaknanda river valleys.

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