Assessment of the Sunkoshi (Nepal) landslide using multitemporal satellite images

Nepal occupies about one-third of the Himalayan mountain arc. As a consequence of rugged topography, complex rock types and high rainfall, landslides are a common phenomenon in Nepal. The sharp change of elevation from the southern plains (~60 m amsl) to the mountainous northern parts of the country (~8000 m amsl) has resulted in steep slopes that are highly prone to slope failures[1]. On 2 August 2014, a massive landslide occurred near the Jure village, close to Mankha, located in Sunkoshi River valley in the Central Region of Nepal. Sunkoshi River is one of the main tributaries of the Kosi River (as it enters India) and is perennially prone to floods. Reports suggest that the instantaneous down-slope movement of debris buried about 24 houses and accounted for the lives of at least 33 people. It is believed that there may be about 150 more people buried in the landslide, whose bodies may not be retrievable[2].

Monsoon rainfall in Nepal annually ranges from 160 mm in the northwestern region to 5500 mm in some isolated areas of Nepal with a mean annual rainfall[3] of 1500–2500 mm. Around 80% of the total annual precipitation occurs between June and September. Distribution of daily precipitation during the monsoon is also erratic. Extreme and uneven rainfall pattern plays an important role in triggering landslides in Nepal. During 1–2 August 2014, continuous heavy rainfall was recorded in the rainfall stations located in Pachuwarghat and Bahrabise in the Sunkoshi and Bhote Koshi valleys respectively. This heavy rainfall may be the primary cause that triggered the slope failure, in an already unstable slope close to the Mankha village[4].

We interpreted multi-temporal high-resolution satellite images and digital elevation model to analyse the Sunkoshi landslide (Table 1).

Using pre- and post-event IRS-P6 LISS-IV Mx images, we analysed the morphology of the landslide (Figure 1). The length of the landslide is approximately 1.3 km. The maximum width is around 0.65 km. The post-event satellite image of the landslide clearly shows that the slope failure initiated from the upper scarp region. A small accumulation zone is formed above the lower scarp followed by a major accumulation zone at the valley base below it.

This is further illustrated by a field photograph[5] which clearly shows the landslide profile and the zones of depletion and accumulation, with debris at the valley floor (Figure 2).

A cross-section profile of the slope was derived from ASTER digital elevation model (ASTER DEM). It clearly exhibits the culmination of the two scarps and the slopes below them, which has formed zones of depletion and accumulation respectively[6] (Figure 3).

Historic Google Earth © images from 2001 onwards were analysed to understand the landslide activity on this hill slope. These images clearly indicate that the slope section on which the landslide occurred was unstable with presence of smaller landslides. The slope of the affected area is between 40° and 45° with two smaller intermittent scarp sections. Over time, multiple smaller landslides have initiated from these two scarp sections. In the 2001 image, it is seen that a single small landslide has been initiated in the upper scarp region, whereas multiple smaller landslides were initiated from the lower scarp slope (Figure 4 *a*). In 2004, the number of landslides has decreased to one in each of the scarp regions (Figure 4 *b*). However, a small landslide was initiated in the lower part of the hill slope, which has affected the Araniko highway. Further in 2009, it was found that the entire hill slope has destabilized further (Figure 4 *c*). A number of landslides of much larger areal extent have been triggered from both the upper and lower scarp areas. These small

Table 1. Satellite images used in the study

Satellite	Date of acquisition	Sensor type (resolution; in m)	Source
Resourcesat-2 LISS-IV Mx (Post-event data)	17 September 2014, 9 August 2014, 5 August 2014	Multispectral (5.8)	ISRO
Resourcesat-2 LISS-IV Mx (Pre-event data)	27 February 2013	Multispectral (5.8)	ISRO
ASTER	–	Digital Elevation Model	ASTER GDEM
World View	19 October 2001, 8 March 2004, 25 November 2009, 6 October 2012	Multispectral (2.4)	Google Earth © Digital Globe

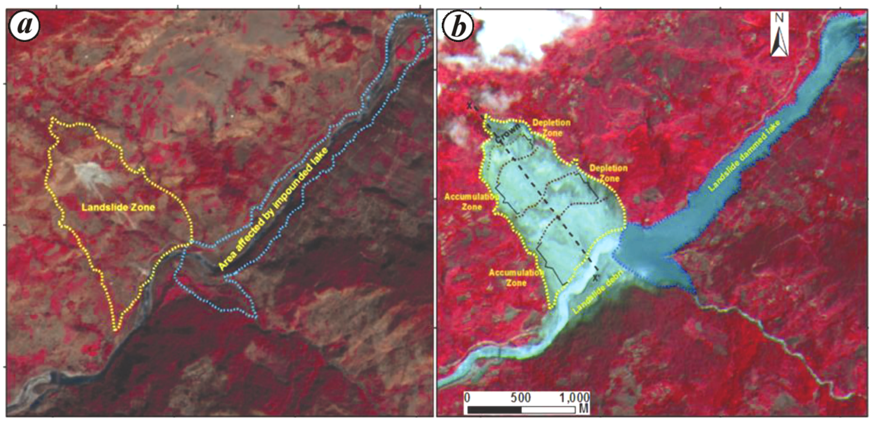

Figure 1. ***a***, Pre-event IRS-P6 LISS-IV FCC image showing location of the landslide and area of inundation due to lake formation. ***b***, Post-event IRS-P6 LISS-IV FCC image showing landslide and dammed lake.

landslides have coalesced together resulting in a significant crown formation. The occurrence of landslides in the lower part of the scarp has also increased in number and spatial extent. Finally, during 2012–14, it was found that a considerably large and permanent head scrap had formed in the upslope area with smaller slides originating from it (Figures 4 *d* and 1 *a*). These observations clearly indicated a gradual destabilization of the hill slope which eventually led to a complete slope failure on 2 August 2014.

Formation of lakes due to large landslides has already been reported from a number of places in the Himalayas[7,8]. In this case also the landslide debris completely blocked the Sunkoshi River, thus forming a debris-impounded lake close to the Sunkoshi Hydropower project intake site (Figure 1 *b*). The accumulated water rose quickly after the dam formation, to submerge around 2.4 km river valley with width ranging from 200 to 250 m. The water submerged a considerable length of the Araniko Highway and completely inundated the Sanima Small Hydroelectric project near Dhuskun[9]. A total of 19 houses built along the banks of the river were completely inundated by the lake[2].

Figure 2. Field photograph of the Sunkoshi landslide (source: www.ekantipur.com).

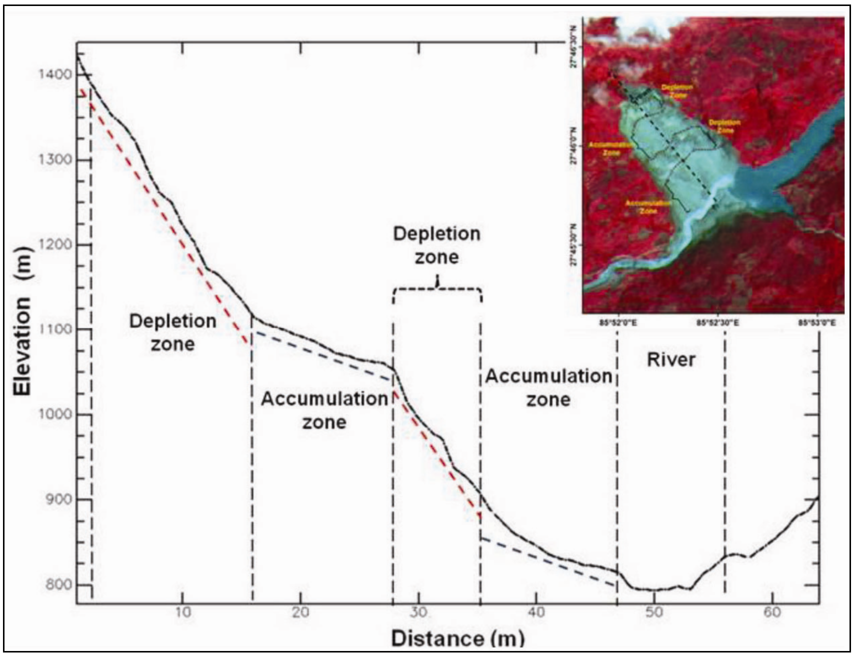

Figure 3. Section of the landslide area derived from ASTER DEM.

IRS P-6 LISS-IV images of 5 and 9 August and 17 September were used to monitor the temporal changes in landslide zone with reference to the pre-event image of 27 February 2013. Comparison of crown area of the landslide in these images clearly indicates that the crown has receded during the period of observation (Figure 5). Hence, it may be possible that due to this continuous recession of the crown of the landslide and consequent influx of debris, the impounded water spread of the lake has almost been at a constant level (Figure 5 *b* and *c*) despite attempts to drain it by the Nepalese Army[10]. However, on 7 September 2014, it was reported[9] that the debris dam had breached abruptly and the lake outflow had substantially increased. No damages were reported due to this, as the water flow was accommodated in the downstream channels adequately. From the 17 September 2014 image, it can be seen that inundated areas re-emerged within a short span of time, including the submerged hydroelectric power station (Figure 5 *d*).

The Sunkoshi landslide exemplifies the extended consequences of heavy rainfall on already destabilized slopes. As seen from historical imageries, the slope section was scarred with small multiple events of failure. Debris from the landslide blocked the course of the Sunkoshi River and formed an impounded lake. The outburst of this lake could have threatened a large area, downstream of the Sunkoshi valley and eventually of the Kosi River in India. Due to timely adequate remedial measures and possibly due to wide valley geometry downstream, any catastrophic outburst of the lake was averted. However, conditions like those of Sunkoshi are prevalent in many of the Himalayan valleys of Uttarakhand and Himachal Pradesh in India. In places, slopes are scarred with previous landslides with valleys that are narrow and deeply incised with large rivers like the Mandakini and Alaknanda flowing through them. A sudden massive 'valley blocking'

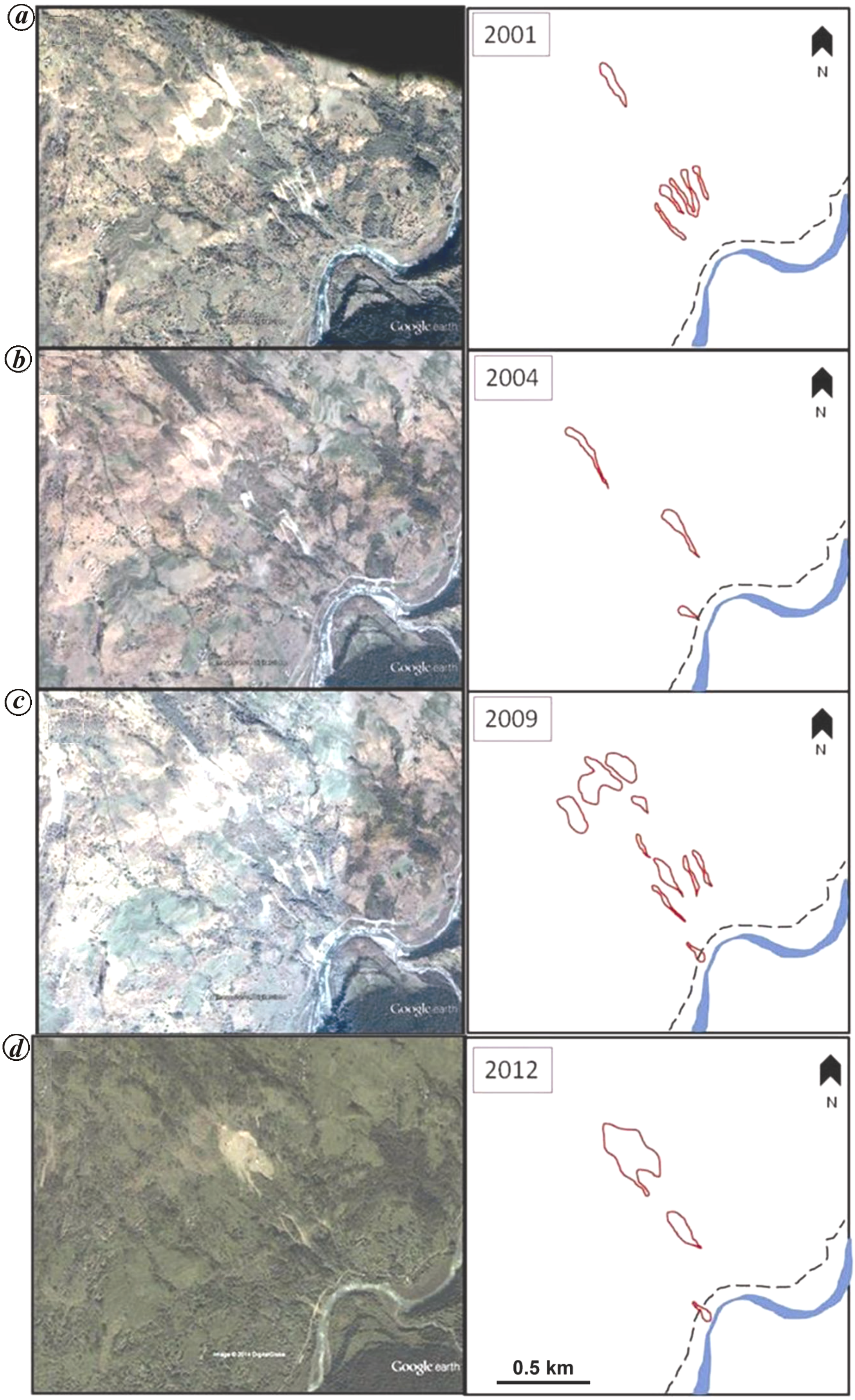

Figure 4 ***a–d***. Historical Google Earth Imagery showing gradual destabilization of the hill slope and occurrence of smaller landslides from 2001 to 2012.

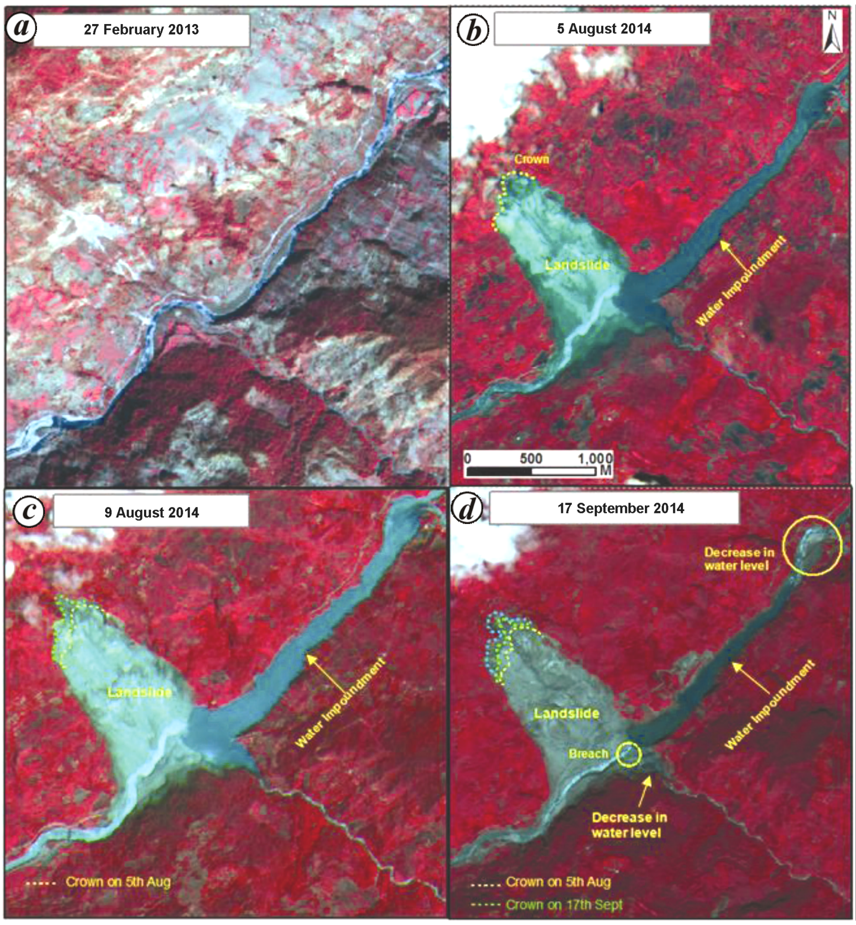

Figure 5 *a–d*. Temporal images of the landslide and lake formation from IRS P-6 LISS-IV.

landslide similar to Sunkoshi, can cause rapid water impoundment and lake formation. This can put the population of major cities downstream of the river at high risk, as most of these are thickly populated centres of pilgrimage. Therefore, monitoring of destabilized slopes, geo-technical preventive measures and remedial measures on standby are a necessity in these regions[11].

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PRIYOM ROY*
TAPAS R. MARTHA
K. VINOD KUMAR

Geosciences Group,
National Remote Sensing Centre,
Indian Space Research Organisation,
Hyderabad 500 037, India
**For correspondence.*
e-mail: roy.priyom@gmail.com