A bird's-eye view of landslide dammed lakes in Zanskar Himalaya, India

The landslide lakes or dams are temporary lakes in the river valleys formed by landslide debris. Landslide dammed lakes and their outburst floods (LLOFs) are not uncommon in the Indian Himalaya. Breaching of such temporary lakes with huge amount of accumulated water and sediments can create devastating floods in the downstream areas. Landslide dams commonly form in mountains of high relief with mass movement activity[1] (rock and debris avalanches, rock and soil slides, mud–debris–earth flows). Schuster *et al.*[2] suggested four factors, namely seismicity, steep slope, lithology, and weathering and soil moisture content for the initiation of landslides. In most of the cases, earthquake and excessive precipitation are the triggering mechanisms of landslides. Most of the landslide lakes are formed by earthquake-triggered landslides. Geomorphology of the terrain such as high mountainous terrain with steep slope and narrow river valleys/gorges play an important role in the formation of such lakes[1–3].

In recent years, Wenchuan earthquake of 12 May 2008 in China generated 257 landslide lakes along the fault rupture zone and river channels[4]. Such natural disasters are unpredictable and may have impacts across political boundaries. The landslide dam formed across Yigong Zangbo River, a major tributary of the River Brahmaputra in Tibet during 2000 and its subsequent failure caused damage even in the North East States of India[5]. Such disasters are not rare in the Hindu Kush Himalaya mountains. The lake Gojal formed in the Hunza River in Pakistan by a major landslide in 2010 is still extant as a natural lake with a small outlet created for discharge[6]. Landslide dam formation and LLOFs are common in countries such as New Zealand, Nepal, Tibet, China and Canada. In August 2014, heavy precipitation induced a huge devastating landslide in Nepal that created a landslide lake across the River Sunkoshi. The size of the lake increased in due course. After 45 days the lake was emptied using geo-engineering methods[7].

The longevity of landslide-generated lakes and their failure mechanisms are quite different and the dynamics is not fully understood. In general, most of the lakes fail by overtopping. Failure by erosion and piping is rare[8,9]. The world's worst landslide-dam disaster occurred in China in 1786, due to the failure of earthquake-triggered landslide lake on River Dadu. After 10 days of its formation, the dam breached and released the flood waters that reached up to 1400 km downstream and destroyed several properties and lives[10]. In contrast, a dam formed by the rock and debris fall over the Tagermarch River, Kirghizstan, formed the lake Yashingul in 1835 which failed in 1966, after 131 years[10]. The failure mechanisms are poorly known due to the lack of direct observations of dam failures[10,11].

In the Indian Himalaya, formation of landslide lakes and LLOFs has been reported in the past. One of the oldest recorded landslide lakes is the Gohna Tal formed in 1893 in the Kumaon Himalaya[12]. In September 1893, pronounced rainfall triggered a massive landslide and the debris blocked the Birahi Ganga River and formed a lake which was named as Gohna Tal. In due course, the lake increased its extent – 4000 m length, 340 m average width and 300 m total depth. On 26 August 1894, the lake created a devastating flood downstream of Birahi Ganga. Due to precautionary measures taken, there was not much damage to property and life.

Satellite remote sensing is considered to be a vital tool for the identification of landslides in inaccessible areas of the Himalaya[13,14]. Satellite data can be also used for monitoring landslide lakes and their impacts. Figure 1 shows the recent Tsarap Chu lake generated by landslide and also the historical landslide lakes in the surrounding area. A massive landslide in December 2014 (?)/January 2015 created a blockage across the Tsarap Chu River and a lake was formed. Subsequently, the extent of the water increased in the lake which breached in May 2015. Interpretation of satellite data indicates that Lake-1 (Tsho Tok Phu)[15], and Lake-2 exist near to the recent Tsarap Chu landslide lake (Figure 1). Interpretation of the geology indicates that the region lies in Zanskar synclinorium which is tectonically active and comprises nappes and many imbricate thrusts. The lithology of the area is dominated by the Tibetan/Tethys sedimentary sequence which is in tectonic contact with the Zansakr unit (top) and High Himalayan Crystallines (bottom). Baud *et al.*[17] classified the Tethys sedimentary sequence into Pughtal and Zangla units, which are basically nappes separated by thrusts.

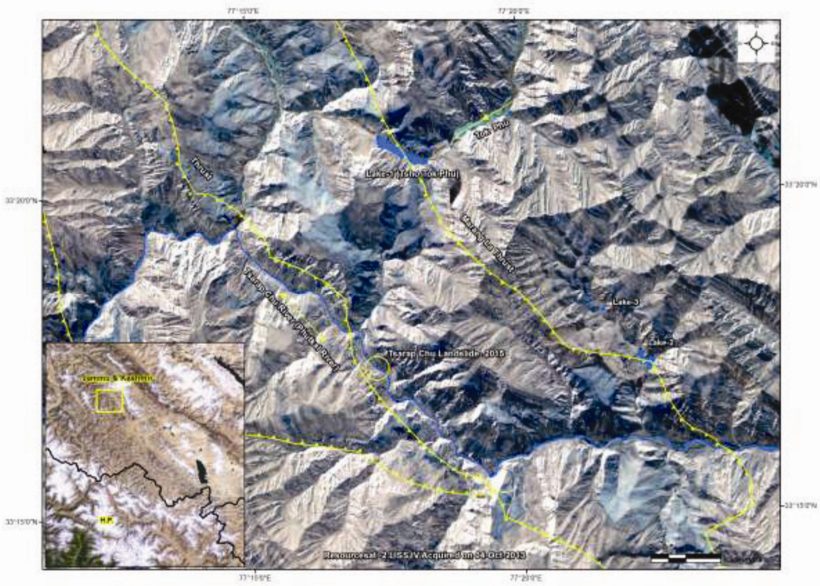

Figure 1. Location of the landslide dammed lakes in the Zanskar Himalaya, India.

The Phugtal unit is characterized by low-grade to anchimetamorphic overprinting and large recumbent folds. The Zangla unit had deformed by anchimetamorphic conditions with the development of disharmonic decollement folds in the Lilang Group and Chevron folds in the Kioto limestone. Mainly overturned thick calcareous/dolomitic Kioto limestone formed steep hills in and around the Tsarap Chu area. The lineament map of the area extracted from the National Geomorphology and Lineament map database (source: National Remote Sensing Centre) shows a major lineament, 'Marang La Thrust' passing through the Nimaling–Tsarap nappe of Zanskar synclonorium.

To evaluate the history of the existing lakes, the oldest available Corona satellite data were analysed. These are the world's oldest declassified high-resolution satellite data acquired by the United States of America. The Corona KH4B image acquired in 1971 shows the existence of the Tsho Tok Phu lake (lake-1) (Figure 2). This indicates that the lake might have formed prior to 1971. Interpretation of the satellite data shows clear-cut evidences of landslide signatures for the formation of the lake. Moreover, field surveys carried out in Tsho Tok Phu reported this lake as dammed by landslide[15,16]. The lake morphology has remained unchanged from 1971 to 2013 as observed in space imagery data.

Lake 2 is also a landslide-blocked lake that lies downstream of the Tso Tok Phu and might have formed along with the Tsho Tok Phu. The 1971 Corona image also shows the existence of this lake (Figure 3). The stability of the lakes since 1971 indicates that the landslide debris might have got cemented by carbonate solution derived from the Kioto limestone. The dominant calcium carbonate in the limestone acts as a good binding material, and the landslide debris might have been cemented and stabilized by the carbonate precipitated from solution derived from limestone. Although landslide lakes seem to be stable, their formation and failure are unpredictable. Multi-temporal satellite data observations can reveal the stability and prevailing conditions of such lakes in the inaccessible difficult terrains of the Himalaya.

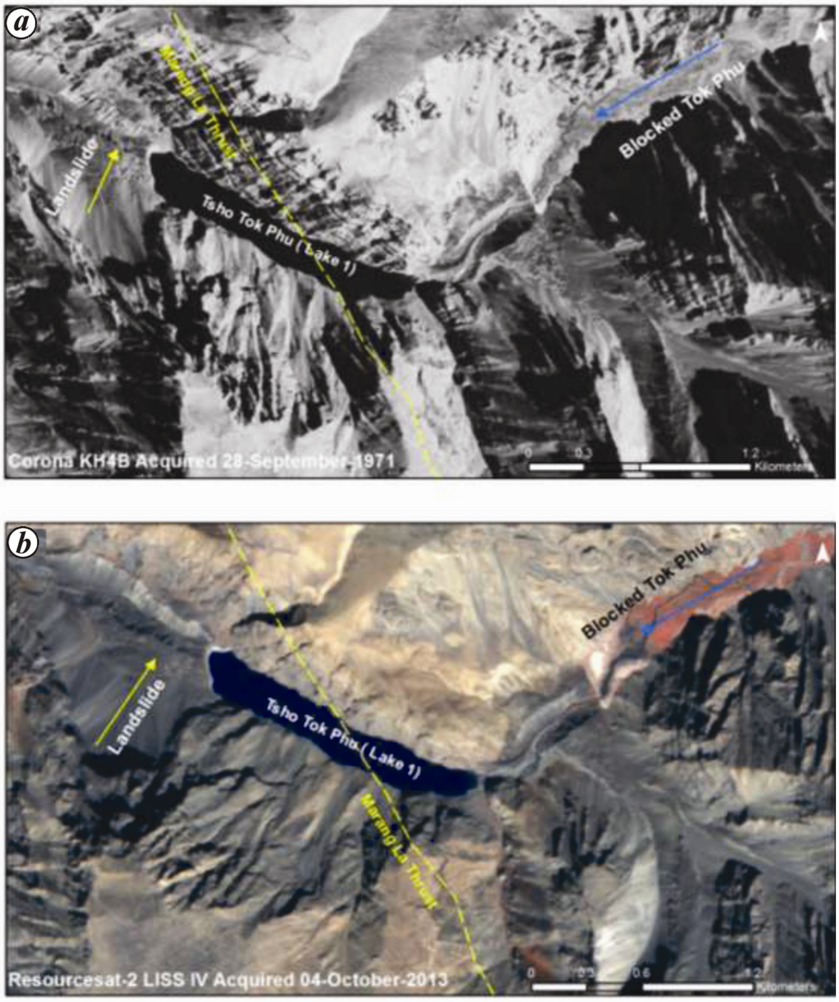

Figure 2. Tsho Tok Phu landslide lake in Zanskar Himalaya from (***a***) Corona and (***b***) LISS IV data.

The dams formed by landslides are classified mainly into six types based on the dimensions of the lakes, morphology of the landslide and the terrain[1,18].

Type-I dams are small in size and the debris does not reach the other side of the valley.

Type-II dams generate large-dimension lakes and the debris spreads across the valley.

Type-III dams are large in size and the debris extends both upstream and downstream of the dam along the river channel and involves enormous volume of landslide debris.

Type-IV dams form when landslide occurs from both sides of the valley and the lobes join or juxtapose each other.

Type-V dams form when a single landslide has multiple lobes extending into the valley and form more than one lakes.

Type-VI dams involve one or more failure surfaces that extend under the stream or river valley and emerge on the opposite valley side from the landslide.

Figure 4 shows a schematic representation of these six different types of landslide dams. Among these, type-III dams form large lakes behind the landslide and also can block the main valley and create a hazardous situation.

The satellite image analysis of the recent Tsarap Chu landslide lake classifies itself as type-3 landslide dam with the landslide debris extending upstream and downstream along the narrow river valley and forming a long landslide lake (www.nrsc.gov.in/Phuktal).

The landslide dams can fail due to mainly piping or overtopping and subsequent breach. Most of the landslide dam failures occurred due to overtopping and breaching. The impounded lake water can create more landslides in the upstream and the waves generated by such landslides can breach the dam. The

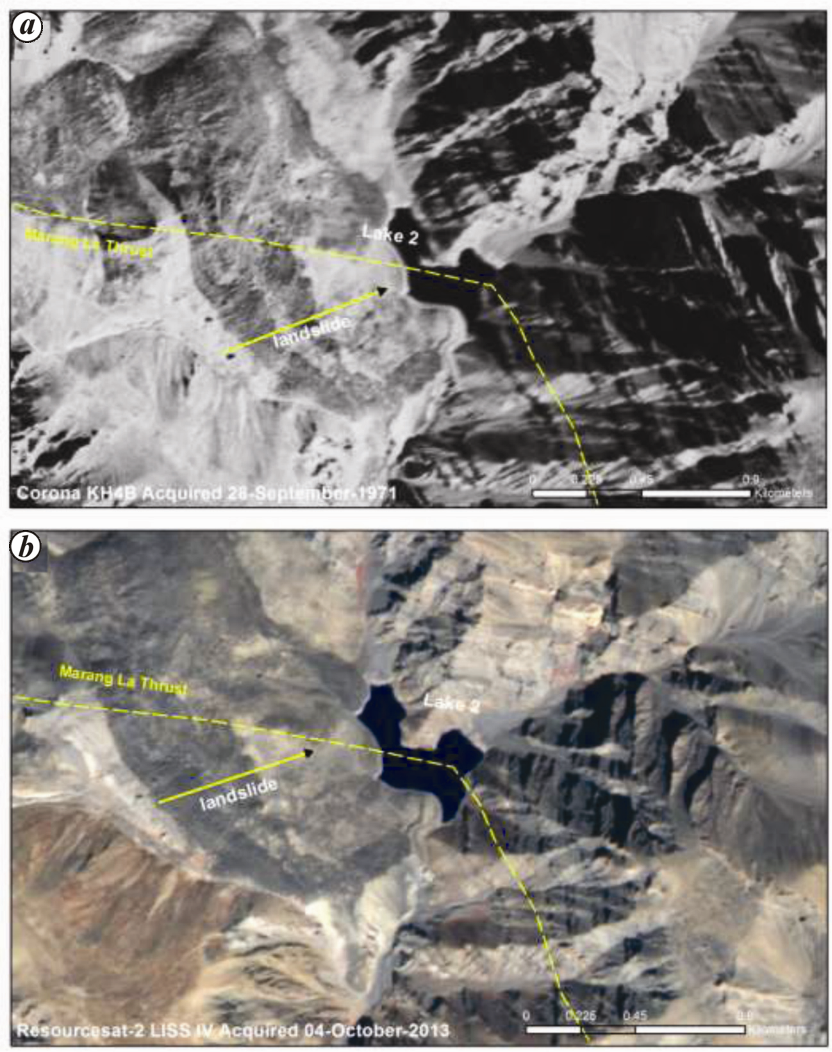

Figure 3. Landslide lake 2 in Zanskar Himalaya from (***a***) Corona and (***b***) LISS IV data.

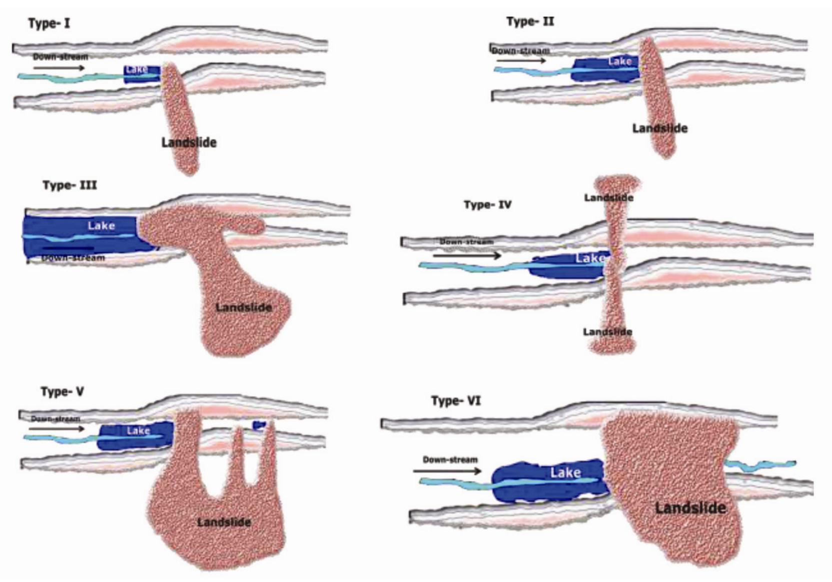

Figure 4. Schematic diagrams of different types of landslide dammed lakes (after Costa and Schuster[1]).

downstream flood also can create secondary landslides during the course of high discharge. The composition of the dam material also controls the stability of the dam and its failure mechanism. Some of the methods of preventing floods following a landslide dam burst are: constructing an erosion-resistant spill way, drainage conduit and drainage tunnel through the dam.

Initial analysis of Zanskar Himalaya shows that the area is vulnerable for formation of such landslide-generated lakes. The steep, narrow river valley with fragile Tethyan rocks and the active tectonic segment of the Himalaya and already existing landslide lakes indicate that the area is a plausible site for the formation of landslide dams. Remote sensing is one of the best tools available to identify, analyse and monitor such dams and lakes in the tectonically active Himalaya.

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Received 11 August 2016; revised accepted 19 January 2017

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Coordinates and chronology of the ancient port city of Poompuhar, South India

As the southern part of the Indian Peninsula including the state of Tamil Nadu (TN) (Figure 1 *a* and *b*) is a low easterly gradient plain, the rivers that originate from the Western Ghats and the uplands in the west seem to have flowed towards the east with stable dynamics as evidenced from their well-evolved life histories with youthful, mature and old stages. So, the mouths of these river systems provided favourable avenues for ports and the related flourishing maritime activities since historical times[1]. The port city of Poompuhar located at the mouth of River Cauvery in TN was one such a city of glory and had a prominent maritime history attracting traders from several countries (Figure 1).

Poompuhar was established by the Chola Empire during the Sangam period (300 BC–AD 300) of the Tamils and its glory was maintained even after the Chola dynasty during the Kalabras' rule (AD 300–600) and its legacy continued further during the rule of the Pallavas as well (AD 600–850). When the Chola dynasty re-emerged during AD 850, the later Chola kings added further fortification to Poompuhar, which seems to have later submerged in the Bay of Bengal[2]. Several mentions have been made about Poompuhar in the Sangam and post-Sangam literature, *Silapathikaram*, *Manimekalai*, *Purananuru*, *Agananuru*, *Natrinai* and *Pattinappalai*[1–4]. Owing to its maritime importance, researchers from archaeology, epigraphy, history, Tamil literature, geology and other related fields have attempted to unravel the history of the submerged port city.

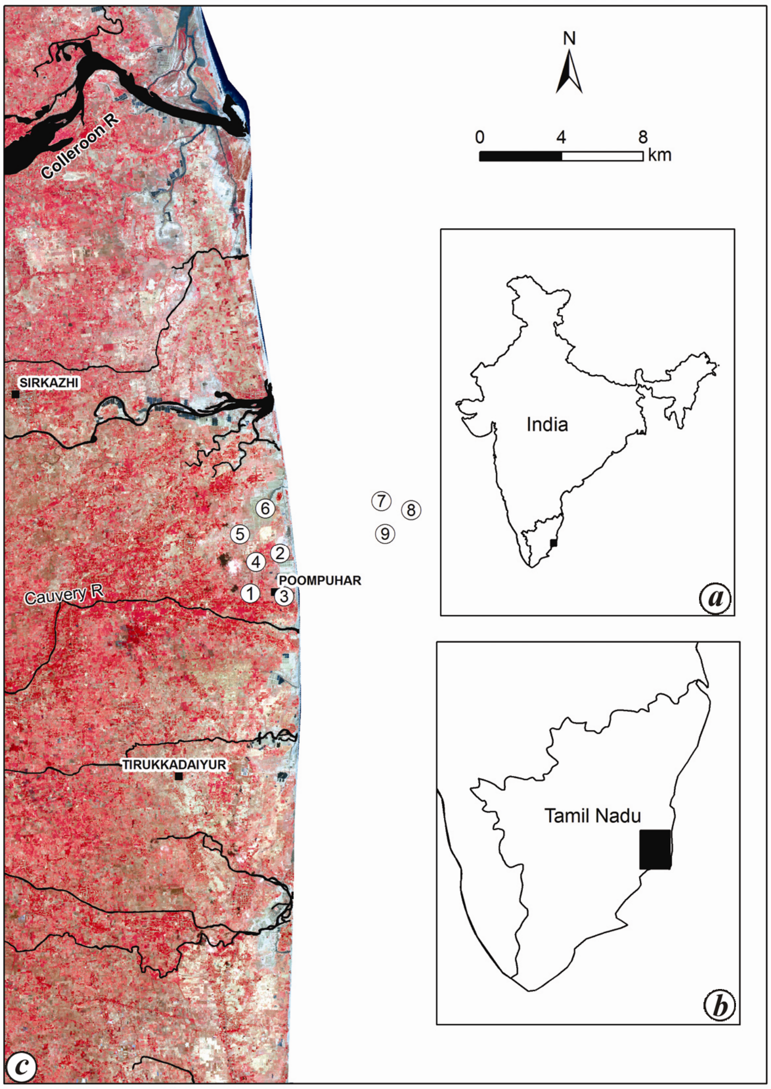

Figure 1. ***a***, ***b***, Key maps. ***c***, IRS satellite false colour composite image showing archaeological remains (1–9) of Poompuhar.