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ORIGINAL PAPER

Remote sensing and in situ-based assessment of rapidly growing South Lhonak glacial lake in eastern Himalaya, India

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Abstract Melting glaciers are mostly associated with formation of proglacial lakes and the expansion of existing glacial lakes in Himalayan region. These expanding glacial lakes can induce the risk of glacial outburst floods that pose a great potential threat to natural resources and human lives. In Sikkim Himalaya, South Lhonak lake (SLL) (5200 masl) is rapidly expanding over the few decades due to the ongoing glacier melting. We recorded that the lake size increased from 0.20 ± 0.020 to 1.31 ± 0.001 km^2 with the length change of 1.6 km during the period from 1976 to 2016. The average rate of expansion was recorded of 0.027 km^2 per year; however, it increased drastically since 2000. The in situ-based bathymetric study of SLL showed that the storage volume was 65.81 ± 2.5 million m^3 and maximum and average depths were 131 ± 2.5 and 67.05 ± 2.5 m, respectively. We observed that the substantial calving of ice bodies during the melting seasons and partly from the melting of North Lhonak glacier and flow of the Lhonak lake have contributed in expansion of SLL. We have also proposed an empirical equation of volume–area relationship to calculate the storage capacity of similar moraine-dammed glacial lakes in the Himalaya. In addition, we have suggested effective precautionary and mitigation measures to minimize the risk of GLOFs in future. The present study provides vital inputs for hydrodynamic modelling for flood simulation of potentially vulnerable lakes and to formulate the effective strategies in disaster risk reduction and mitigation plan in minimizing the threat of GLOFs.

Keywords South Lhonak lake · GLOFs · Remote sensing · Bathymetric volume · Volume–area relationship · Mitigation measures · Sikkim Himalaya

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1 Introduction

According to IPCC (2014), glaciers are continuously shrinking globally due to the ongoing phenomenon of climate change and the global glacier volume is projected to decrease by 15–55% considering the lowest emission projection (RCP2.6). In the Himalaya, glacier melting is associated with the formation of proglacial lakes (Costa and Schuster 1988; Richardson and Reynolds 2000; Petrakov et al. 2011; Govindha Raj et al. 2012; TanDong et al. 2010; Govindha Raj 2010). It is reported that the expanding glacial lakes have created a great potential threat for glacial lake outburst floods (GLOFs), which is a serious geomorphological hazard pertaining to catastrophic discharge of stored water from the glacial lake (Richardson and Reynolds 2000; Clague and Evans 2000; Benn et al. 2012; Westoby et al. 2014; Worni et al. 2014). Further, bursting of floods from moraine-dammed glacial lakes carries a considerable amount of debris brought about by precipitous topography and the unstable clast, which intensifies the effect of hazard (Daoming 1988). The high-velocity water masses developed due to the bursts are capable of eroding and carrying the huge amounts of sediments (Breien et al. 2008). GLOFs are perhaps one of the most devastating processes that can cause loss of human life and destruction of property (Govindha Raj et al. 2013). Several studies related to GLOF disasters in different parts of the globe have been carried out, for examples, 15 outburst floods in Nepalese Himalaya (Kattelmann 2003; Bajracharya et al. 2006; Richardsons and Reynolds 2000), 35 outburst floods in the Karakoram (Ashraf et al. 2012), over 21 GLOFs in Peru's Cordillera Blanca (Carey 2005, 2008) and over 40 GLOFs in Chinese Himalaya and Nyainqêntanglha ranges (Wang and Zhang 2013). Major instances of GLOF events include breaching of Palcacocha lake, Peru Cordillera in 1941 (Carey 2005, 2008), Cirenmaco lake in the Himalayan region of China in 1981, Dig Tsho lake in 1985 and breaching of Tam Pokhari lake in the Nepalese Himalaya in 1998, and Luggye Tso in the Bhutan Himalaya in 1994 (Kaltenborn et al. 2010; Osti et al. 2011). As the phenomenon of GLOFs is directly associated to climate change and deglaciation (Shrestha and Aryal 2011), it is expected that the impact of GLOFs is likely to be extended further as glaciers continue to recede in the coming decades (Carey et al. 2012).

Till date, satellite remote sensing has been widely used for the estimation of change in glacier lakes (Wessels et al. 2002; Bajracharya et al. 2007; Bolch et al. 2008; Gardelle et al. 2011). The studies conducted in the Hindu Kush Himalaya (HKH) have reported the existence of < 8000 glacial lakes and 209 potentially vulnerable lakes in terms of GLOFs, out of which 30 lakes are present in India (Bajracharya et al. 2007), 77 lakes are in China (Bajracharya et al. 2007), 26 lakes are in Nepal (Ives et al. 2010), 24 lakes are in Bhutan (Kattelmann 2003) and 52 lakes are in Pakistan (Ashraf et al. 2012). The latest remote sensing-based observations have showed that there are 116 potentially dangerous lakes, out of 329 moraine-dammed lakes in Chinese Himalaya (Shijin et al. 2015).

Furthermore, the in situ-based investigations of glacial lakes are limited in the Indian Himalaya due to their remote locations, harsh climate and there is often a shortage of field-based information on the lake water depth (Wang et al. 2010). Therefore, most of the studies have used some empirical relationships between glacial lake volume and area for studying these lakes (Evans 1986; Huggel et al. 2004; Yao et al. 2012). Bathymetric investigations of glacial lakes are mostly confined to the Nepal and Bhutan Himalaya. In Nepalese Himalaya, bathymetric investigations have been carried out for Tsho Rolpa glacial lake (Yamada 1998; Shrestha et al. 2004), Imja glacial lake and Thulagi glacial lake (Yamada 1992; ICIMOD 2011). According to the surveys of 1993 and 1994, the stored water volume of Tsho Rolpa glacial lake was 71 million m^3 corresponding to a maximum depth of 132 m (Mool et al. 2001). However, the recent bathymetric volume of Tsho Rolpa glacial lake is estimated to 92.4 × 10^6 m^3 in 2002 (Shrestha et al. 2004). Similarly, the bathymetric investigation of Imja glacial lake has revealed an area of 0.60 km^2 with a storage volume of 28 × 10^6 m^3 in 1992 (Yamada 1992), which has expanded to 1.01 km^2 with the storage capacity of 35.5 × 10^6 m^3 corresponding to a maximum depth of 96.5 m in 2009 (ICIMOD 2011). Further, the bathymetric investigation of Thulagi glacial lake has reported the storage volume of 35.3 × 10^6 m^3, registering an increase from 31.75 × 10^6 m^3 in 1995 (ICIMOD 2011).

In Sikkim Himalaya, a total of 320 glacial lakes have been reported to exist. (Govindha Raj et al. 2013). Of these, a total of 14 glacial lakes are potentially dangerous in terms of GLOFs (Mool and Bajracharya 2003; Govindha Raj et al. 2012). A study on the risk assessment of Shako Cho lake, a glacier fed lake in North Sikkim, has suggested that the lake is highly critical in terms of GLOF (Worni et al. 2013). Similarly, remote sensing-based hazard assessment of South Lhonak lake (SLL) suggested a high outburst probability (Govindha Raj et al. 2013). It is observed that SLL is one of the fastest growing glacial lakes in Sikkim Himalaya. The exponential growth of the lake in terms of its size within a few decades has created a threat of GLOF. In this study, we have carried out systematic remote sensing study on the dynamics of expansion of the SLL from 1976 to 2016 and in situ estimation of bathymetric volume of this lake. Further, on the basis of measured volume and area of SLL, we propose a new volume–area empirical relationship to calculate the storage capacity of moraine-dammed glacial lakes in the Himalaya.

2 Materials and methods

2.1 Study area

South Lhonak lake (SLL) (27°54.741′N and 88°11.857′E) is a moraine-dammed glacial lake located in the north district of Sikkim, India. It takes 3 days trek from Thangu village, North Sikkim to reach the lake. The lake is east to west elongated and situated at the tongue of South Lhonak glacier at an elevation of 5200 masl in the Lhonak valley (Fig. 1). The headwaters of the valley are formed by the valley glaciers, viz. South Lhonak glacier, North Lhonak glacier and Lhonak glacier.

2.2 Remote sensing data analysis

In the present study, we used multi-temporal images of different satellite products (Landsat MSS, Landsat TM, IRS LISS III and IRS LISS IV) from the year 1976 to 2016 to map the expansion of SLL (Table 1). Only cloud-free satellite images were taken into consideration for mapping. All the satellite images listed in Table 1 were registered to 1990 Landsat TM scene, which is used as a reference image. To register the images, common and clearly identifiable 10–14 tie points were determined (Yao et al. 2012). A second-order polynomial model was used to wrap the images to a reference image (1990 Landsat TM scene). The registration errors were 16.75 m, when registering the Landsat MSS to Landsat TM image; 83.50 m, when registering 2000 LISS III to Landsat TM image; 62.70 m, when registering 2011 LISS III image to Landsat TM image; 26.22 m, when registering 2013 LISS III image to Landsat TM image; 124.64 m, when registering LISS IV to Landsat TM image; and 14.25 m, when registering Landsat TM to Landsat TM image.

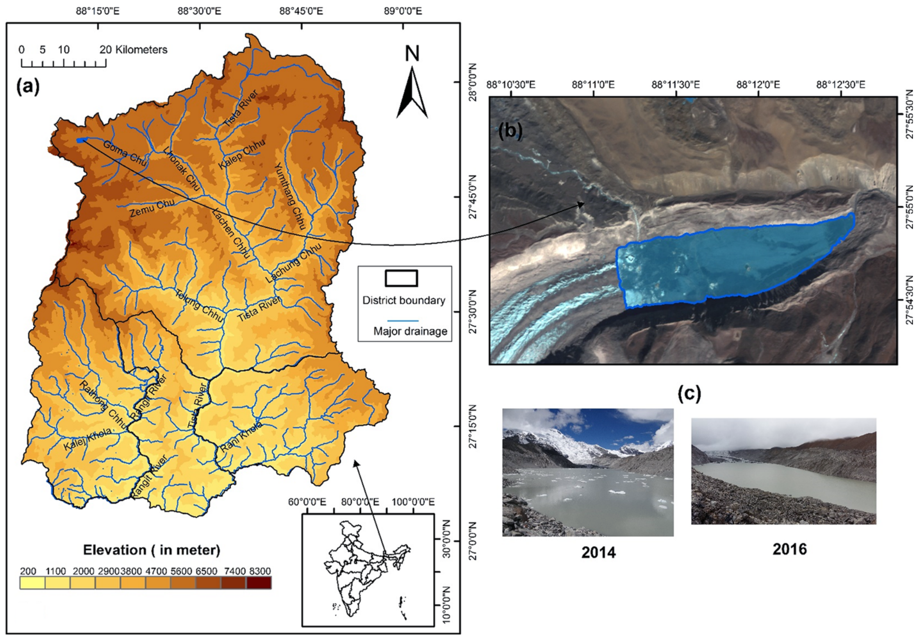


Fig. 1 **a–c** Location map of the study area, showing the major drainage in Sikkim Himalaya **(a)**, present South Lhonak lake (SLL) depicted through IRS LISS IV satellite image 2016 **(b)** and field photographs of SLL taken in 2014 and 2016 **(c)**

The NDWI (Normalize Difference Water Index) of McFeeters (1996) was used to differentiate and delineate glacial lake area from the Landsat images (Huggel et al. 2002; Bolch et al. 2008; Fujita et al. 2009; Nie et al. 2013). The threshold value of zero was considered to differentiate surface water body from the raw digital Landsat values, wherein all positive values were classified as water and the negative values as non-water bodies (Sarp and Ozcelik 2017). Further, digitization and mapping of lake area were carried out by visual interpretation (Khanal et al. 2015). After the preprocessing of satellite images, *Arc GIS 9.3* software was used for digitization of lake boundaries to estimate the changes in area and length of the lake from 1976 to 2016.

Errors in the satellite images mapped for area and length of the lake are mainly controlled by the image resolution and registration error (Hall et al. 2003; Yao et al. 2012). The dimensional error in the area and length changes was determined by the following formula (Williams et al. 1997).

$$d = \sqrt{\sum_{1}^{n} \lambda^2} + \sqrt{\sum_{1}^{n} \varepsilon^2} \tag{1}$$

where d is the linear dimension error, λ is the original pixel resolution of each image (given in Table 1) and ε is the registration error. The accuracy was measured as ± 129 m for Landsat MSS, ± 116 m for 2000 LISS III, ± 95 m for 2011 LISS III, ± 59 m for 2013 LISS III images, ± 132 m for LISS IV image and ± 54 m for Landsat TM.

Finally, changes in the areal extent of SLL were measured by calculating error using the formula given by Hall et al. (2003).

Table 1 Details of satellite products with their measurement accuracy used for mapping South Lhonak lake (SLL)

Satellite/sensor	Scene/product ID	Imagery date	Spatial resolution (m)	Measurement accuracy (± km^2)	Source
Landsat MSS	LM21490411976353XXX03	Dec 18, 1976	80	0.0207	USGS-Earth Explorer (https://earthexplorer.usgs.gov)
Landsat TM	ETP139R41_5T19901105	Nov 5, 1990	28.5	0.0031	-do-
IRS LISS III	–	Jan 19, 2000	23.5	0.0054	NRSC, Hyderabad
IRS LISS III	122530451	Nov 20, 2011	23.5	0.0045	-do-
IRS LISS III	–	Jan 13, 2013	23.5	0.0027	-do-
IRS LISS IV	173831651	Nov 17, 2016	5.8	0.0015	-do-

MSS multi-spectral scanner, *TM* thematic mapper, *IRS* Indian remote sensing and *LISS* linear imaging self-scanning sensor

$$a = A \times \left(\frac{2d}{x}\right) \tag{2}$$

where a is the desired uncertainty in the area, $A = x^2$, where x is the linear side dimension of image (original pixel resolution) and d is the error in linear dimension from Eq. 1. The measurement accuracy was ± 0.0207 km^2 for Landsat MSS, ± 0.0054 km^2 for 2000 LISS III, ± 0.0045 km^2 for 2011 LISS III, ± 0.0027 km^2 for 2013 LISS III, ± 0.0015 km^2 for LISS IV image and ± 0.0031 km^2 for Landsat TM.

2.3 Bathymetric survey

Bathymetric surveys of SLL were carried out twice, i.e. 28th–30th August 2014 and 28th August 2016 during the summer ablation season (Fig. 2a, b). Depth measurement of the lake was carried out with Echo sounders (Hondex PS-7 and Hondex HE-770) using a rubber boat. The echo sounders work on the principle of ultrasonic waves that are transmitted by the transducer directly to the lake bottom and then reflection from the lake bottom is received by the instrument as a depth value. For this, we followed the instruction manual of echo sounders to measure depth of the lake. The Hondex PS-7 works at the frequency of 200 kHz (depth range: 0.6–80 m; beam angle: 24°), whereas Hondex HE-770 has a dual frequency of 50 kHz and 200 kHz (beam angle: 24°) covering the depth range of 3–500 m. We collected three-dimensional coordinate data (*x, y,* and depth) from the total of 321 discrete points using a handheld Global Positioning System (Trimble Juno 3D TNJ32; accuracy: 1–3 m). Due to frequent calving of ice bodies causing huge waves in the lake, we did not record data near the glacier terminus. Finally, in order to confirm the accuracy of the data recorded by echo sounders, approximately 10 random points were measured inside the lake with a measuring rope. The estimated mean error was 2–3 m.

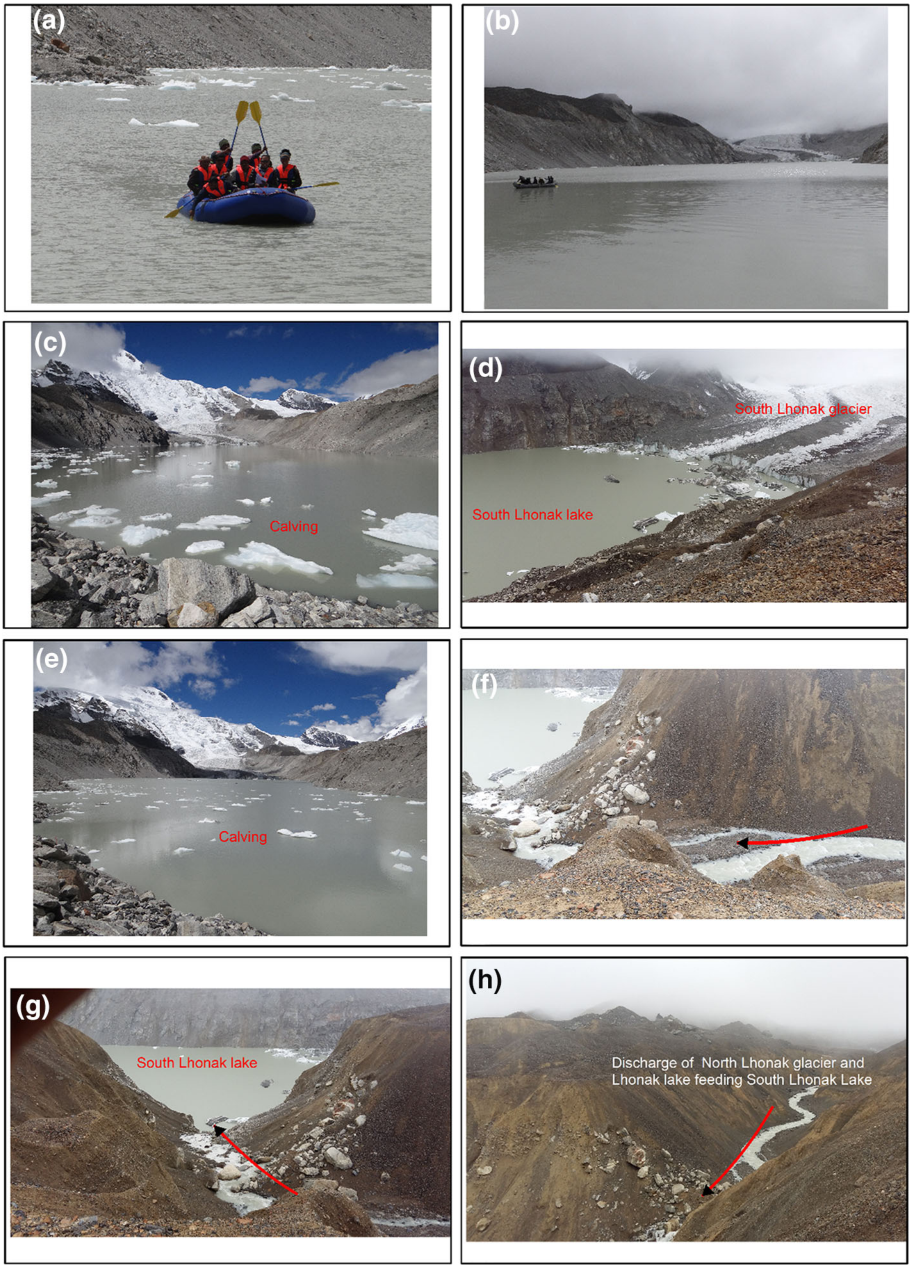


Fig. 2 **a**–**h** The field investigation of SLL carried out in the year 2014 and 2016. Bathymetry survey carried out in 2014 **(a)** and 2016 **(b)**, substantial calving of SLL in both the observational periods **(c**–**e)**, North Lhonak glacier and Lhonak lake draining meltwater to South Lhonak lake **(f**–**h)**

2.4 Bathymetric data analysis

The collected data on depth of lake from the different sites were processed in *Arc GIS 9.3* software. The contours of lake depth (isobaths) were generated at 5-feet interval using “Natural Neighbour Interpolation (NNI)”, and these contours were further used to generate the bathymetric map of SLL. For the estimation of stored volume of the lake, Conic equation (Eq. 3) was used (Kendra and Singleton 1987; Taube 2000).

$$V = \left[\frac{d}{3}\right]\left(A_1 + A_2 + [A_1A_2]^{0.5}\right) \tag{3}$$

where V is the storage volume, A_1 is the surface area of the lake at elevation 1, A_2 is the surface area of the lake at elevation 2 and d is the difference in depth between points 1 and 2.

3 Results

3.1 Lake morphometry

The important morphometric characteristics recorded for the lake based on repeated field as well as remote sensing observations are given in Table 2. SLL is a glacial moraine-dammed lake with a freeboard of 6–7 m. We have not seen any potential avalanche site (PAS) in the study area. The lake is in direct contact with South Lhonak glacier, and a substantial calving of ice bodies during field observations has been observed (Fig. 2c–e). The lake is east to west elongated with a free-flowing outlet.

3.2 Expansion of SLL

The multi-temporal satellite data analysis revealed that the SLL continuously expanded over the period of four decades (1976–2016). The lake was a small supraglacial glacial lake in 1960s (Govindha Raj et al. 2013), which expanded to 2.415 ± 0.132 km in length

Table 2 Present morphometric status of SLL

Sl no.	Lake characteristics	Morphology
1	Type of lake	Glacial lake
2	Lake area (km^2)	1.31
3	Lake length (km)	2.41
4	Type of dam	Moraine-dammed
5	Dam height from lake level (m)	16.33
6	Dam width (m)	592.67
7	Dam height–width ratio	0.031
8	Freeboard (m)	6–7
9	Active snow avalanche site	Almost absent
10	Lake level (masl)	5200
11	Outlet condition	Free flow
12	Lake direction (towards outlet)	East facing
13	Contact with parent glacier	Yes

Table 3 Multi-temporal lake area changes/expansion estimated for SLL

Year	Area (in km^2)	Change in area (in km^2)	Length of lake (in km)	Change in length of lake (in km)
1976	0.20 ± 0.0207	–	0.779 ± 0.129	–
1990	0.42 ± 0.0031	0.22	1.161 ± 0.054	0.382
2000	0.70 ± 0.0054	0.28	1.435 ± 0.116	0.274
2011	1.13 ± 0.0045	0.43	2.106 ± 0.095	0.671
2013	1.22 ± 0.0027	0.09	2.210 ± 0.059	0.104
2016	1.31 ± 0.0015	0.09	2.415 ± 0.132	0.205

in 2016. The lake area substantially increased from 0.20 ± 0.020 to 1.31 ± 0.001 km^2 since 1976 (Table 3). Spatial changes in the lake boundary were recorded to be highly significant ($R^2 = 0.97$) due to glacier retreat (Fig. 3a–g). The average rate of lake expansion was found to be 0.027 km^2/year. However, the rate of lake expansion was recorded substantially high (0.038 km^2/year) during the last 16 years (2000–2016). The length of the lake also increased from 0.779 ± 0.129 km (1976) to 2.415 ± 0.132 km (2016). Significant length change has been observed towards the west side and is attributed to the glacier melting and ice calving from the snout.

3.3 Lake bathymetry

The bathymetric study carried out on SLL during two melting seasons (2014 and 2016) showed that the lake area was 1.31 ± 0.001 km^2. The storage volume of the lake measured was 65.81 ± 2.5 million m^3 with the maximum depth of 131 ± 2.5 m. With 65.81×10^9 L of stored water, SLL was recorded as one of the largest lakes in Sikkim Himalaya (Fig. 4). The longitudinal profile generated through bathymetric data of SLL showed the maximum depth of 120–131 ± 2.5 m, which was measured between the distances of 0.60–0.90 ± 0.014 km away from the glacier terminus (Fig. 5).

3.4 Volume–area empirical relationship

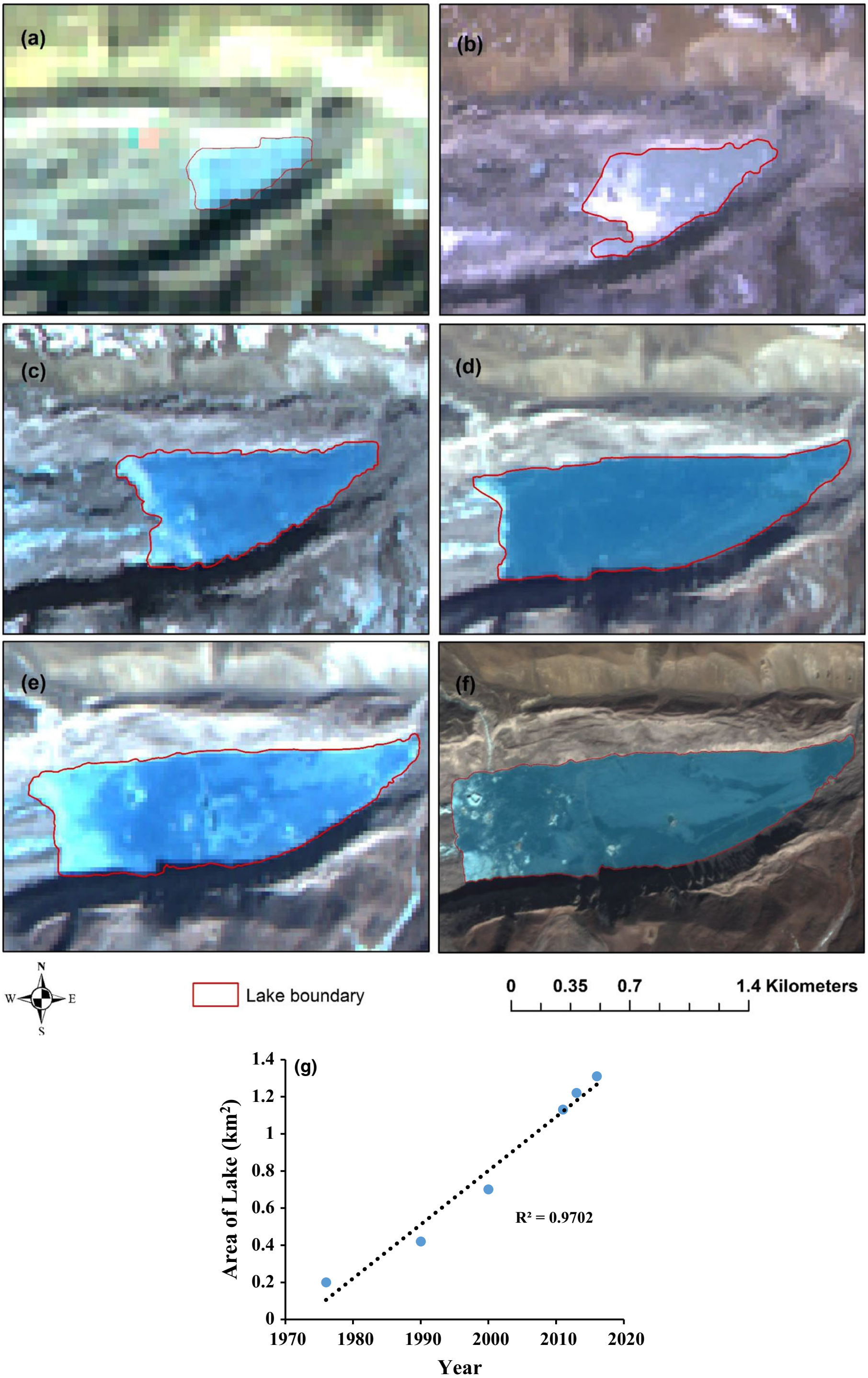
Based on the measured volume and vector layer of all the lake boundaries derived from the multi-temporal satellite images listed in Table 1, we proposed an empirical relation between lake volume and area of SLL (Fig. 6), as under;

$$V = 0.0522 \times A^{1.1766} \left(R^2 = 0.99\right) \quad (4)$$

where V is the volume, A is the area and R^2 is the coefficient of determination.

Using Eq. (4), and equations proposed by Huggel et al. (2004) and Yao et al. (2012), we calculated the volume of only those lakes of Himalaya that had reported data on volume. Our results correspond well with the measured volume of moraine-dammed glacial lakes of the Himalaya. Further, our findings showed a more accurate estimation of volume for the glacial lakes of the Himalaya with minor error (Table 4) as compared to the equation developed by Huggel et al. (2004) and Yao et al. (2012).

Fig. 3 **a**–**g** Shoreline changes of SLL estimated through different year satellite sensors. Time series expansion of lake is studied for the year 1976 **(a)**, 1990 **(b)**, 2000 **(c)**, 2011 **(d)**, 2013 **(e)** and 2016 **(f)**. The expansion of lake area from 1976 to 2016 **(g)** ▶


(a)
(b)
(c)
(d)
(e)
(f)
N
W
E
S
Lake boundary
0 0.35 0.7 1.4 Kilometers
(g)
Area of Lake (km²)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1970 1980 1990 2000 2010 2020
Year
R² = 0.9702

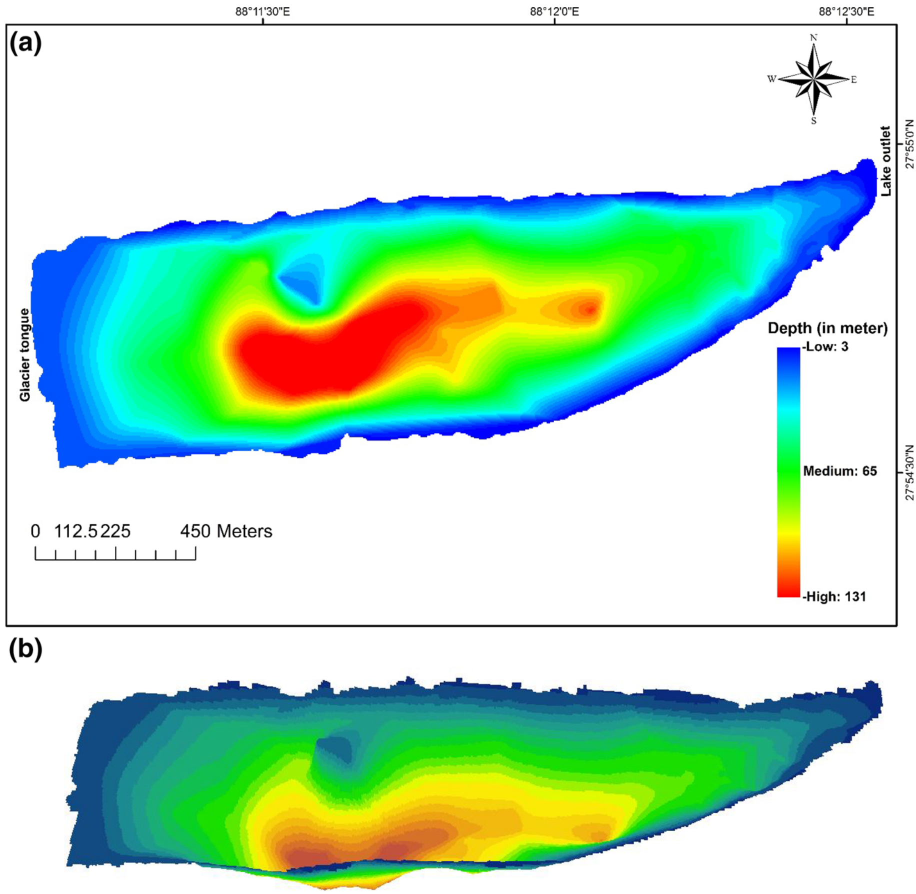


Fig. 4 In situ-based bathymetric map **(a)** and 3D view of SLL developed from bathymetric depth profiles **(b)**

3.5 Additional meltwater contribution to SLL

Besides receding of South Lhonak glacier, satellite images revealed the presence of water channels (streams) flowing towards SLL that are originating from North Lhonak glacier and Lhonak glacier at a distance of about 2.5 km above from SLL. The area around SLL was connected with South Lhonak glacier, Lhonak glacier and North Lhonak glacier. Apart from SLL, we recorded another developing glacial lake due to the melting of Lhonak glacier. We observed that North Lhonak glacier and Lhonak lake were also the main source in contributing meltwater to the SLL. The satellite-based observation was validated during the field survey in 2016 (Fig. 2f–h).

4 Discussion and conclusions

Climate warming has accelerated the glacier melts and contributed in forming proglacial lakes in the Himalaya. Many glacier lakes have been reported to have developed in the Himalaya as a result of glacier melting (Iwata et al. 2002; Jha and Khare 2016; Bajracharya

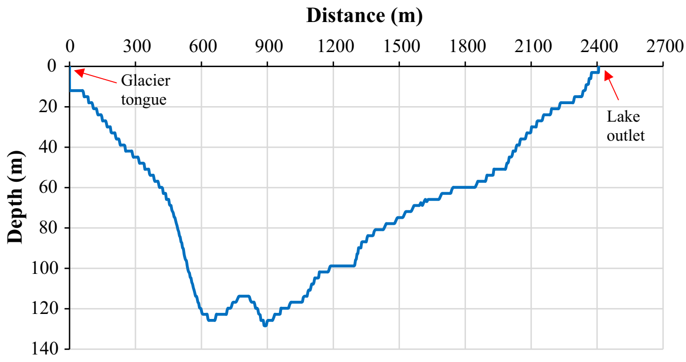
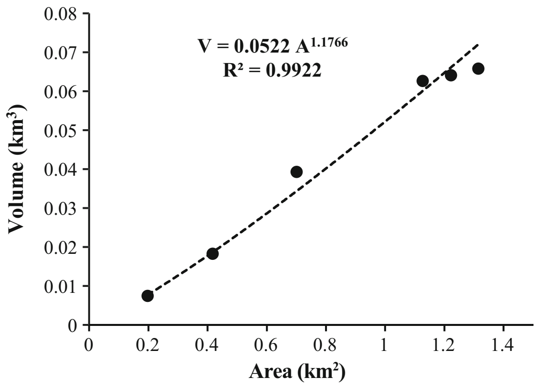


Fig. 5 Longitudinal profile of SLL generated from bathymetric depth measurements

Fig. 6 Relationship between volume and area of SLL for the period 1976–2016



and Mool 2009). The overall rise in annual temperature in the eastern Himalaya is reported to be of 0.01–0.04 °C (Sharma et al. 2009) and the warming rate is found to be the highest during winter (Chettri et al. 2010). Sikkim Himalaya, an integral part of eastern Himalaya, is reported to have impacted by the climate warming with a significant increase in temperature from the past and warmer winter (Sharma and Shrestha 2016). With this ongoing rise in temperature in Sikkim Himalaya, SLL has expanded tremendously as a result of glacier melting. Sudden flood during summer and autumn have been reported from the higher Himalaya (Qinghua 1991), advocating towards a special attention be taken especially during the peak discharge season.

Remote sensing application has played an important role in detecting and understanding the dynamics of glacial lakes. In the present study, we used the multi-temporal satellite images to understand the lake expansion process. However, changes in moraine dam height and the lake level still require field investigation, as there is a low accuracy of satellite-based digital elevation models (DEMs) (Fujita et al. 2008). During this study, we observed a significant expansion in the area of SLL during 1976–2016. However, the highest expansion rate of 0.038 km^2/year of SLL has been reported during the recent time (2000–2016). Therefore, it is pertinent to state that climate warming has a substantial impact on melting glaciers and lake expansion process in Sikkim Himalaya.

The importance of bathymetric investigation in the Himalaya, viz., Tsho Rolpa glacial lake, Imja glacial lake and Thulagi glacial lake in Nepalese Himalaya (Yamada 1992, 1998; Shrestha et al. 2004; Mool et al. 2001; ICIMOD 2011) are well established.

Table 4 Comparison of measured and calculated lake volumes for moraine-dammed glacial lakes in the Himalaya

Glacial lake	Area (km^2)	Measured volume (10^6 m^3)	Equation 4		Equation proposed by Yao et al. (2012)		Equation proposed by Huggel et al. (2004)	
			Calculated volume (10^6 m^3)	Error (%)	Calculated volume (10^6 m^3)	Error (%)	Calculated volume (10^6 m^3)	Error (%)
Tsho Rolpa′	1.39	76.60	76.90	0.39	66.97	− 12.57	54.97	− 28.24
Tsho Rolpa*	1.76	97.7	101.51	3.90	83.42	− 14.62	76.85	− 21.34
Thulagi[□]	0.76	31.80	37.79	18.84	38.19	20.09	23.32	− 26.67
Imja©	0.60	28.00	28.62	2.21	30.65	9.46	16.67	− 40.46
Imja[+]	0.86	35.8	43.71	22.09	42.84	19.66	27.79	− 22.37
Imja[$]	1.21	63.80	65.32	2.38	58.86	− 7.74	45.14	− 29.25
Tampokhari′	0.47	21.25	21.47	1.03	24.42	14.92	11.79	− 44.52
Raphstreng Tsho[§]	1.380	66.83	76.25	14.09	66.53	− 0.44	54.41	− 18.58
Longbasaba[ε]	1.219	64.00	65.88	2.94	59.26	− 7.41	45.60	− 28.75
Gelhaipuco′	0.548	25.45	26.72	4.99	28.71	12.81	14.66	− 42.39

Measured volumes are based on in situ bathymetric surveys. Error in volume estimation refers to the difference between calculated and measured value divided by the measured value

Symbols indicate the different literature sources as ′Mool et al. (2001), *Shrestha et al. (2004), [□]Mool (1995), ©Yamada and Sharma (1993), [+]Sakai et al. (2003), [$]Somos-Valenzuela et al. (2013), [§]Bhargava (1995) and [ε]Yao et al. (2012)

However, in Indian part of the eastern Himalaya, glacier melting and formation of moraine-dammed lakes are also a widespread fact (Worni et al. 2013; Govindha Raj et al. 2013; Basnet et al. 2013). Despite the importance, there are no records of in situ bathymetric investigation of glacial lakes in the eastern Himalaya. Bathymetric analysis of SLL shows an increased size of 1.31 ± 0.001 km^2 with the total storage volume of 65.81 ± 2.5 million m^3 corresponding to the maximum depth of 131 ± 2.5 m, which can pose a great threat to the entire settlements and development in the downstream areas.

Furthermore, for the first time in Indian Himalaya, we proposed an empirical equation (Eq. 4) for the volume–area relationship in SLL. This empirical equation is based on measured lake volume and areal information recorded during different periods. Comparatively, the equation (Eq. 4) gives more accurate estimates of glacial lake volume with minor error as compared to the formula suggested by Huggel et al. (2004). Moreover, Eq. 4 estimates more accurate glacial lake volumes than the recent volume–area relationship proposed in Tibetan region by Yao et al. (2012). However, the inclusion of field-based bathymetric data of a few glacial lakes could refine the volume–area relationship in the Indian Himalaya. The present volume–area relationship can be extensively used to calculate the storage capacity of similar moraine-dammed glacial lakes in Indian Himalaya.

We observed a substantial calving of ice bodies in SLL during both the field surveys (Fig. 2c–e), which further contributes to the lake expansion. At present, we found that SLL is directly attached to South Lhonak glacier (Fig. 2c, d). Therefore, ice melts in the glacier are likely to enhance the calving of ice bodies and thus accelerate glacier retreat and expansion of lake (Kirkbride 1993; Rohl 2006). Further, the meltwater of North Lhonak glacier and Lhonak lake draining towards the SLL is also a major concern, which contributes to SLL expansion (Fig. 2f–h) and may induce the risks of GLOF in near future.

The GLOFs have become frequent in the Himalaya during recent decades (Mool 1995; Walder and Costa 1996; Sakai et al. 2000; Iwata et al. 2002; Bajracharya et al. 2006; Wang et al. 2008). The Kedarnath disaster in Central Himalaya, India, is the recent example of GLOF event, which claimed lives of many people and caused massive damages of infrastructure and property (Dobhal et al. 2013; Allen et al. 2015). Therefore, study of lake outbursts is of prime importance. However, it is a challenging task due to the limits imposed by high altitudes, the remoteness of locations and short accessible period (Bajracharya and Mool 2009). It is suggested that effective and sustainable mitigation strategies are required at the earliest stage to tackle such events. In Nepalese Himalaya, the first-ever mitigation of GLOF from a potentially dangerous Tsho Rolpa glacial lake (4580 masl) was attempted through lowering the lake water level by 3 m by constructing a gated canal in 1999 (Shrestha et al. 2001, 2004; Chalise et al. 2005) and lake siphoning in 1995 (Rana et al. 2000). In the Himalaya, lake water levels can be lowered by 5 m with a simple siphoning technique (Grabs and Hanisch 1993). Siphons are suitable for installation at remote places and carry the minimum risk of causing catastrophic failure; we recommend lake siphoning at SLL in order to minimize the risk of pressure developed to the moraine damming the lake, due to calving of ice bodies. It also helps in reducing the water level and even controls water waves produced due to the calving. Further, controlled deepening and widening of outlet channel can also help in reducing the water level of the glacial lakes in the Himalaya.

In Lhonak valley, there are other proglacial lakes that are in process of formation due to the melting of the glaciers. We also suggest construction of check dams in the suitable areas downstream. Check dams can be effectively used to control the outburst flow and can be effectively used to check the water velocity during the floods. Further, an early warning system (EWS) is very essential in minimizing the impending threats of GLOF to downstream (Shrestha and Nakagawa 2014; Govindha Raj et al. 2013) as has been installed in Tsho Rolpa glacier lake (Rana et al. 2000). We recommend the installation of effective and robust EWS with a real-time satellite-based information system (Kattelmann and Watanabe 1997; Grabs and Hanisch 1993) to measure the sudden fluctuation in water level in SLL.

The present study is extremely important for the hydrodynamic modelling for flood simulation of glacial lakes. Further the present findings can help policymakers and governments to formulate the effective strategies and policies in reducing disaster risks and mitigating plan to minimize the threat of GLOFs in Sikkim Himalaya.

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