



Updated Inventory of Glacial Lakes in Teesta Basin Using Remote Sensing Data for Use in GLOF Risk Assessment

K. Abdul Hakeem¹ · S. Abirami² · V. V. Rao¹ · P. G. Diwakar¹ ·
V. K. Dadhwal¹

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Abstract Detailed inventory of glacial lakes in a Glacial Lake Outburst Flood (GLOF) prone area is vital for disaster mitigation. Availability of cheaper high resolution satellite data from Indian remote sensing satellites enables us to create up-to-date inventory for use in prioritisation of glacial lakes for GLOF risk assessment. Earlier inventories show presence of more glacial lakes in Brahmaputra basin in Indian Himalaya. Teesta River is one of the tributary of Brahmaputra and previous studies have shown that the inventory of glacial lakes in Teesta basin varies from 143 to 320. In the present study, the inventory carried out using satellite data of years 2000, 2007 and 2014 show presence of 301 (25.789 km²), 302 (26.081 km²) and 644 (29.706 km²) glacial lakes in Teesta basin respectively. The steep increase in number of lakes in the latest inventory is primarily due to the finer spatial resolution of satellite data used. Analysis of water spread area of glacial lakes at different altitudes shows that most of the lakes in the higher altitudes are small in size. It is observed that more than 66% of lakes are in the altitude beyond 4500 m and of

size less than 50,000 sqm (5 ha). Out of 301 glacial lakes inventoried during 2000, water spread area of 6 lakes have decreased in 2014 and 31 lakes have shown increase in area. Out of these 31 lakes, 17 lakes are classified as end moraine dammed lakes and among them, 14 are located in Upper Teesta sub-basin and in higher altitudes (beyond 5000 m). The prioritisation of these lakes for GLOF risk needs to be carried out with detailed field investigation.

Keywords Glacial Lake · GLOF · Teesta · Disaster · Remote sensing · Risk assessment

A Glacial Lake Outburst Flood (GLOF) is a type of outburst flood that occurs when the dam containing a glacial lake fails. Failure can happen due to erosion, a build-up of water pressure, an avalanche of rock or heavy snow, an earthquake or cryoseism, volcanic eruptions under the ice, or if a large enough portion of a glacier breaks off and massively displaces the waters in a glacial lake at its base. Catastrophic failure of the containing ice or glacial sediment can release this water over periods of minutes to days. Peak flows as high as 15,000 m³/sec have been recorded in such events (<http://en.wikipedia.org> 2016). Apart from landslides and river erosion, the mountainous Himalayan region is also quite susceptible to disastrous hazards due to GLOF (Mool et al. 2001). Downstream impacts of these GLOFs are reported to be highly destructive in nature and to lead to long-term secondary environmental degradation in the valleys, both physically and socio-economically. A report by International Centre for Integrated Mountain Development (ICIMOD) lists 34 GLOF events that have occurred in Nepal, TAR/China, and Bhutan (Ives et al. 2010). The importance of this situation has magnified over the past century due to increased population, and the

✉ K. Abdul Hakeem
abdulhakeem_k@nrsr.gov.in

S. Abirami
abiramiselvi@gmail.com

V. V. Rao
vvrao@nrsr.gov.in

P. G. Diwakar
pgdiwakar@nrsr.gov.in

V. K. Dadhwal
vkdadhwal@nrsr.gov.in

¹ National Remote Sensing Centre, ISRO, Hyderabad 500 037, India

² Centre for Water Resources, Anna University, Chennai 600 025, India

increasing number of glacial lakes that have developed due to glacier retreat. The study of glacial lakes is also very important for the planning and implementation of any water resources development projects. Glaciers and glacial lakes are generally located in remote areas, where access is through tough and difficult terrain. Satellite remote sensing offers several unique advantages like quick data collection, reliability, more accurate, repetitive collection, geometric integrity and digital storage, which makes it an ideal tool for mapping, inventorying and monitoring the glacial lakes. The unprecedented disaster that occurred in Kedarnath during June, 2013 showed that how sudden burst of a small lake can create havoc, resulting in huge loss of life (Rao et al. 2013). This makes it vital to have a detailed inventory of glacial lakes in a disaster prone area. Recent availability of cheaper high resolution satellite data from Indian remote sensing satellites enables us to create up-to-date inventory of glacial lakes for use in prioritisation of these lakes for GLOF risk assessment. This communication describes the data used, methodology and salient features of the latest inventory of glacial lakes carried out in Teesta basin and also compare the same with scenario in the beginning of the millennium.

Many studies have been carried out for inventorying glacial lakes in different parts of the Himalayan region. ICIMOD has carried out inventory of glaciers and glacial lakes in the Himalayan regions in cooperation with other organisations (Ives et al. 2010). It has created a comprehensive inventory and GIS database of glaciers and glacial lakes in Nepal and Bhutan using available maps, satellite images, aerial photographs, reports, and field data on different scales. Along with national partner institutions, ICIMOD has also carried out similar studies in parts of India (Himachal Pradesh, Sikkim and Uttarakhand), and a few basins in China (<http://www.icimod.org> 2016). Space Applications Centre (SAC), ISRO has mapped glacial lakes in Himalayan region (SAC 2011).

Three major river basins are draining into India from Himalayas, namely, Indus, Ganga and Brahmaputra. Earlier inventories show presence of more glacial lakes in Brahmaputra basin (Abdul Hakeem and Siva Sankar 2013). Teesta River is one of the tributary of Brahmaputra and originates at Chhombo Chhu glacial lake and Khangchung Chho glacial lake at an elevation of 5280 m in the north eastern corner of the Sikkim. The Teesta basin is vulnerable to landslides and river erosion due to great elevation differences, steeply sloping terrain, and fragile geological conditions. The Teesta basin lies between 27°04'52" and 28°08'26" N latitude and 88°00'57" and 88°55'50" E longitude and it covers entire state of Sikkim. The basin is surrounded by Tibetan Plateau in the north, Chumbi Valley of Tibet and Bhutan in the east, Darjeeling district of West Bengal in the south and Nepal in the west. There are 7 sub-

basins namely Central Teesta, Lachung Chhu, Lower Teesta, Rangit, Rangpo Chhu, Tolung Chhu and Upper Teesta under Teesta basin (Fig. 1).

ICIMOD study conducted in 2003 shows presence of 266 glacial lakes in the Sikkim Himalaya, with an area of 20.20 km² (Gabriel Campbell 2005). The study also concludes that though the area of Teesta River basin is comparatively very small but the number of lakes and potential GLOF is very high compared to other study region. Centre for Inter-Disciplinary Studies of Mountain & Hill Environment, University of Delhi, while conducting carrying capacity study of Teesta basin, mapped 313 glacial lakes covering an area of 21.5 km² using LISS III data of 2000. Another study conducted using satellite data (LISS III, 24 m resolution) of 2010 shows an inventory of 320 glacial lakes (Raj et al. 2013). A recent study using LISS III data for the year 2011 accounted 143 glacial lakes in Teesta basin (Aggarwal et al. 2016). These studies reveal that there are some inconsistencies in inventory of glacial lakes in Teesta basin. The reasons that could be attributed are availability of appropriate date of satellite data (cloud free and snow free), ineffective interpretation (automatic, semi-automatic or visual) of satellite data due to hill shadow, physical lake condition or terrain condition, etc. In view of this and to have a consistent database on glacial lake in Teesta basin, a study was carried out using latest satellite data from Resourcesat-2 LISS-IV. In order to understand the glacial lake dynamics over time, historic satellite data of year 2000 and 2007 (Landsat 7/ETM) were also used in this study. The list of satellite data used is given in Table 1.

Since the study area is highly undulating mountainous terrain, orthorectification of satellite data is necessary. Orthorectification of LISS-IV image was carried out using ERDAS Imagine "Orthorectification without using GCP" module. Cartosat-1 digital elevation model (CartoDEM) and Rational Polynomial Coefficient (RPC) file of Resourcesat-2 were used as inputs for orthorectification. Glacial lakes were delineated based on the visual interpretation of satellite data, using spectral band combination of false colour composite (FCC) of NIR, Red, Green bands in Red, Green, Blue channels respectively. Segmented image based on NIR reflection and standard indices were also used to aid in identifying glacial lakes. Glacial lakes appear in dark blue to black colour in false colour composite, whereas frozen lakes appear in white colour. Appropriate image enhancement techniques were used to highlight the glacial lakes for improving the interpretation (Fig. 2). The inventoried glacial lakes were also classified based on their type, such as cirque lake, debris dammed lake, end moraine dammed lake, lateral moraine dammed lake, other lake fed by glacial melt, supraglacial lake and water body. The water spread area for each glacial lake in all the years (2000, 2007 and 2014) were calculated along

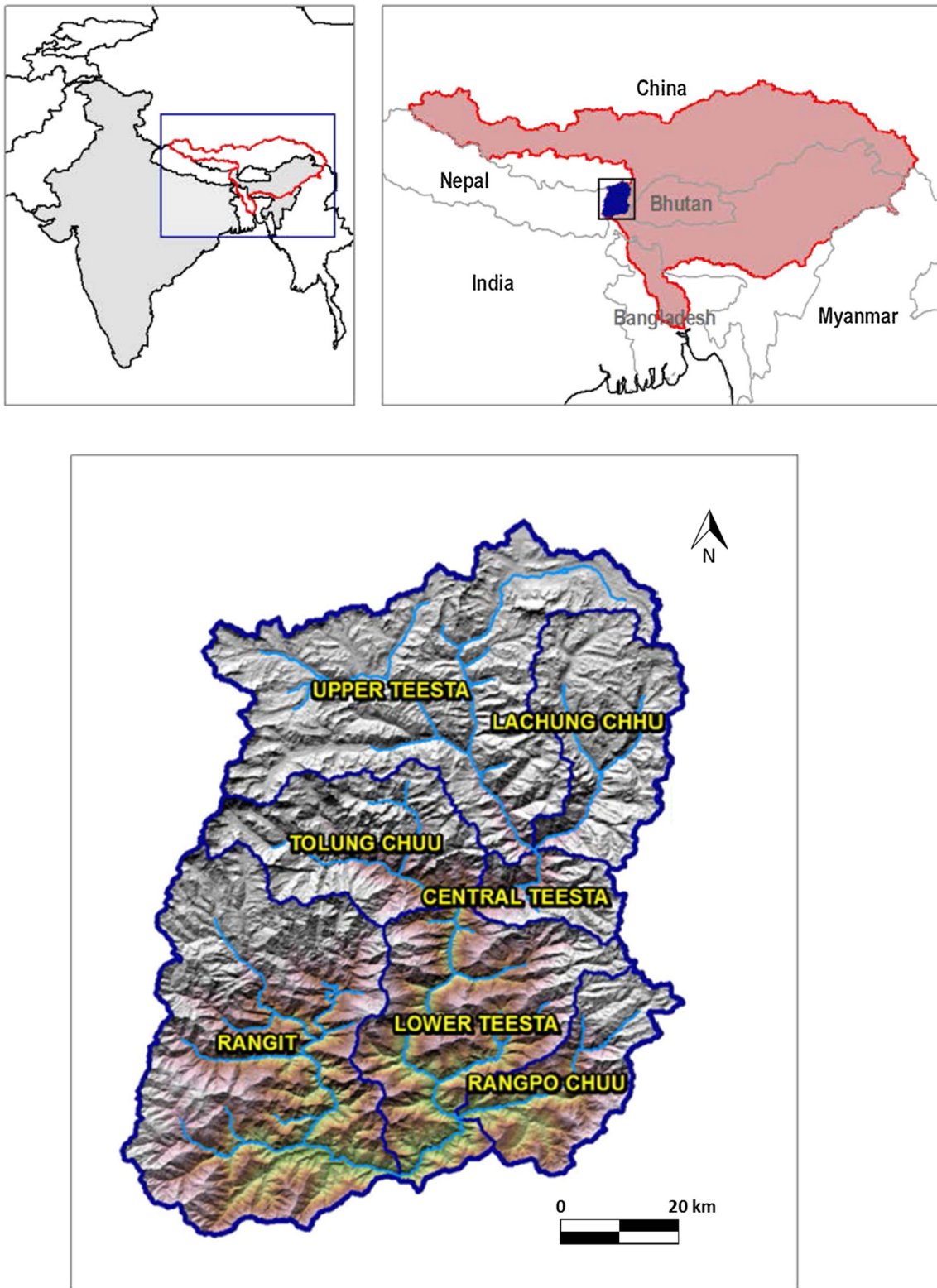


Fig. 1 Location map showing Teesta basin

with their length, breadth and azimuth (orientation) using GIS tools. The elevation of each lake was measured using CartoDEM. The average elevation of lake water spread is

computed to get the elevation of the lake. This elevation was used to categorise the lakes based on altitude. All glacial lakes are identified with unique identifier indicating

the basin and sub-basin details and toposheet reference and all the attribute data for each lake is stored in a GIS database. Typically, in the unique id “BTSCT_78A14_001”, ‘B’ refers to Brahmaputra, ‘TS’ refers to Teesta, ‘CT’ refers to Central Teesta, ‘78A14’ refers to the 1:50,000 scale toposheet number and the last three character refers to the sequential number for each lake within the toposheet.

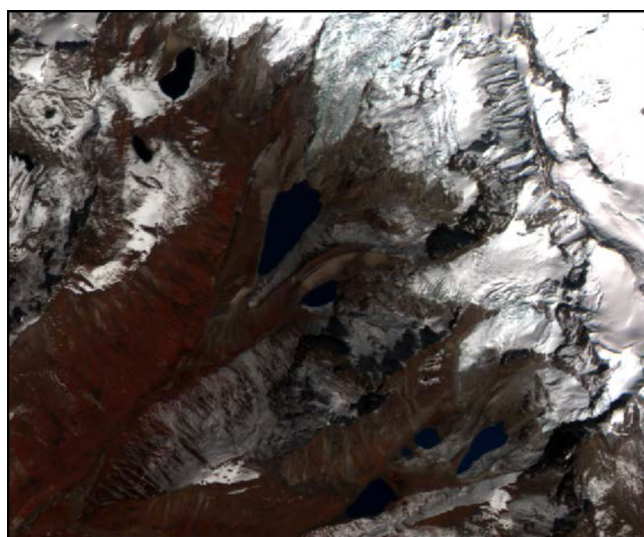
The inventory of glacial lakes using satellite data of year 2000, 2007 and 2014 shows presence of 301 (25.789 km²), 302 (26.081 km²) and 644 (29.706 km²) glacial lakes in Teesta basin respectively. The steep increase in number of

glacial lakes in the latest inventory is primarily due to the difference in spatial resolution of the satellite data used in these years (LISS-IV–5.8 m and ETM–28.5 m). Glacial lakes with water spread area of minimum 5000 sqm only could be mapped using ETM (2000 and 2007), whereas glacial lakes as small as 500 sqm were mapped using LISS-IV data. However, when compared based on the water spread area, the number of glacial lakes with area more than 5000 sqm is 420 during 2014 against 301 during 2000 (Table 2). The sub-basin wise distribution of glacial lakes is shown in Fig. 3. It is observed that Upper Teesta and Lachung Chhu sub-basins have more glacial lakes than other sub-basins. The distribution of glacial lakes based on type is shown in Fig. 4. Most of the cirque lakes and supraglacial lakes that are identified in 2014 data are in small in size with water spread area less than 5000 sqm. It is also observed that almost all the glacial lakes that are inventoried during 2000, 2007 and 2014 are in the higher altitudes (beyond 4000 m) as can be seen from the Fig. 5. Analysis of glacial lakes (of 2014 inventory) of different sizes with reference to elevation shows that most of the lakes in the higher altitudes are small in size (Table 3). It is observed that more than 66% of lakes are in the altitude beyond 4500 m and of size less than 50,000 sqm (5 ha).

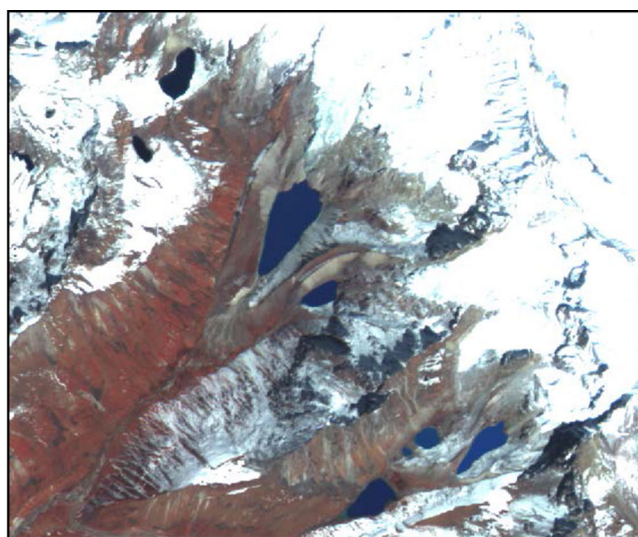
Out of 301 glacial lakes inventoried during 2000, water spread area of 6 lakes have decreased in 2014 and 31 lakes have shown increase in size. However, none of the end or lateral moraine dammed lakes have decreased in size. Out of the 31 lakes with increase in water spread area, 17 lakes are classified as end moraine dammed lakes that are located near the glacier snout. Among them, 14 glacial lakes are found in Upper Teesta sub-basin and located in higher altitudes (beyond 5000 m).

Table 1 List of satellite data used in glacial lake inventory

S. No.	Satellite/Sensor	Path	Row	Date of acquisition
1	Resourcesat-2/LISS-IV	106	051 D	06-Oct-2014
2	Resourcesat-2/LISS-IV	107	051 C	11-Oct-2014
3	Resourcesat-2/LISS-IV	107	052A	11-Oct-2014
4	Resourcesat-2/LISS-IV	107	052 B	4-Nov-2014
5	Resourcesat-2/LISS-IV	107	052 C	11-Oct-2014
6	Resourcesat-2/LISS-IV	107	052 D	4-Nov-2014
7	Resourcesat-2/LISS-IV	107	052 A	20-Nov-2011
8	Landsat 7/ETM	139	41	14-Dec-2007
9	Landsat 7/ETM	139	41	8-Nov-2000



Normal image



Enhanced image

Fig. 2 Image enhancement for improved interpretation of glacial lakes

Table 2 Inventory of glacial lake based on water spread area

Area Range (sqm)	Year 2000		Year 2007		Year 2014	
	No	Area (sqm)	No	Area (sqm)	No	Area (sqm)
<1000	–		–		27	20,693
1000–5000	–		–		197	540,809
5000–10,000	3	20,070	5	37,537	107	766,533
10,000–50,000	194	4770,063	193	4717,093	205	4913,711
50,000–1,00,000	45	3288,267	46	3342,830	45	3293,095
1,00,000–5,00,000	49	8709,900	48	8700,182	52	9483,485
>5,00,000	10	9001,407	10	9283,673	11	10,688,232
Total	301	25,789,707	302	26,081,315	644	29,706,558

Fig. 3 Sub-basin wise distribution of glacial lakes

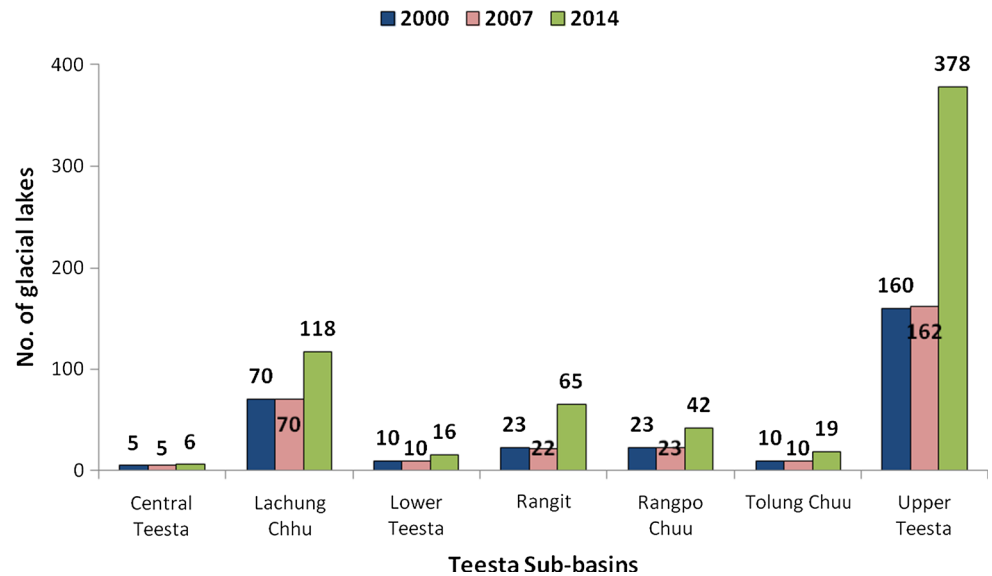
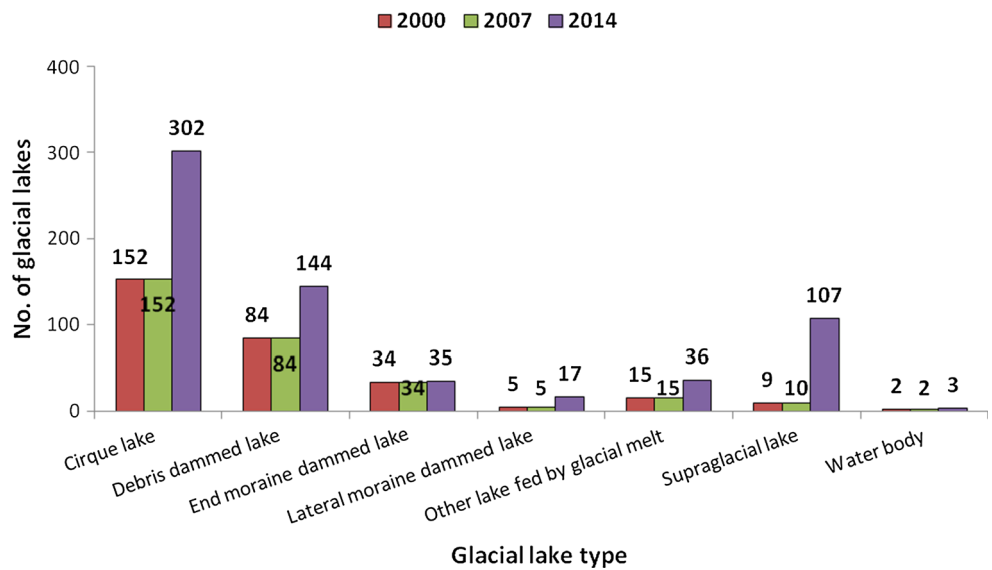
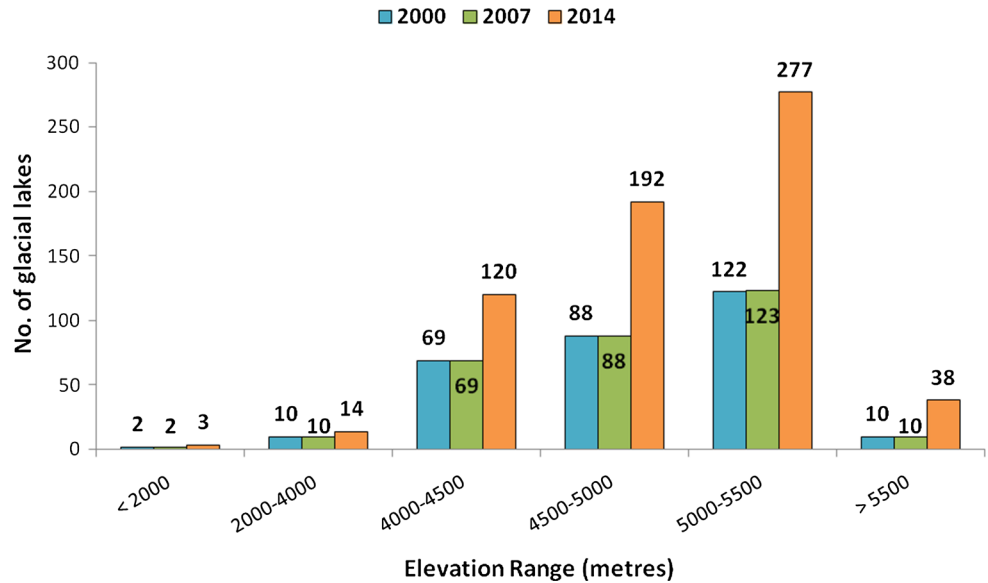


Fig. 4 Distribution of glacial lakes based on type



Some of the glacial lakes in Teesta basin with significant increase in water spread area in 2014 when compared to 2000 are listed in Table 4. The snapshots of satellite

image for some of these lakes are shown in Fig. 6. The prioritisation of these lakes for GLOF risk needs to be carried out with additional information as described

Fig. 5 Elevation range wise distribution of glacial lakes**Table 3** Distribution of glacial lakes with reference to size and altitude

Area range (sqm)	Elevation range (m)						Total
	<2000	2000–4000	4000–4500	4500–5000	5000–5500	>5500	
<1000	–	–	2	7	17	1	27
1000–5000	–	2	22	62	88	23	197
5000–10,000	1	1	27	32	42	4	107
10,000–50,000	1	5	49	66	77	7	205
50,000–1,00,000	1	2	12	11	18	1	45
1,00,000–5,00,000	–	4	8	14	24	2	52
>5,00,000	–	–	–	–	11	–	11
Total	3	14	120	192	277	38	644

Table 4 Glacial lakes with significant increase in water spread area

Lake Id/Glacial Lake type	Latitude (°N)	Longitude (°E)	Elevation (m)	Area (ha)			Increase in area from 2000 to 2014 (%)
				2000	2007	2014	
BTSUT_78A1_031/End moraine dammed lake	27.9125	88.19581	5194	72.6	93.7	129.0	77.7
BTSUT_78A1_024/Supraglacial lake	27.822	88.24837	5407	17.8	25.5	68.0	282.4
BTSUT_77D12_039/End moraine dammed lake	28.0059	88.71296	5241	110.9	110.9	116.5	5.0
BTSUT_78A13_004/End moraine dammed lake	27.9903	88.81558	5262	166.3	166.3	172.4	3.7
BTSUT_78A1_045/End moraine dammed lake	27.9195	88.15887	5446	58.3	65.4	82.3	41.1
BTSRG_78A2_024/End moraine dammed lake	27.5332	88.08558	4813	31.6	31.6	37.5	18.5

above, through detailed field investigation. GLOF simulation modelling could be done for vulnerability assessment of the potentially dangerous lakes.

This study demonstrates the usefulness of remote sensing data for generating information on glacial lakes in Himalayas over different time period. The temporal

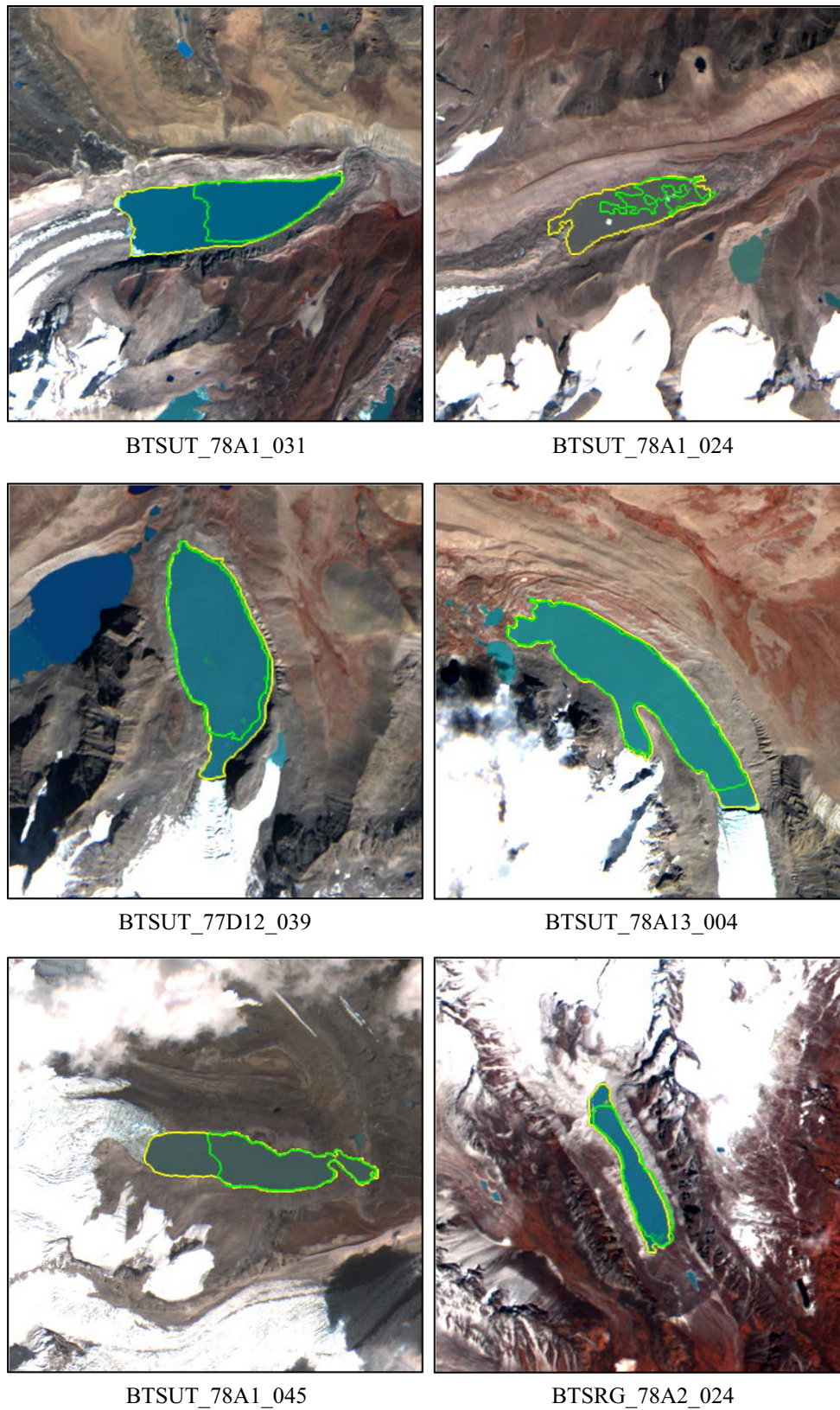


Fig. 6 Satellite image with water spread boundary in 2000 (*green*) and 2014 (*yellow*) for selected lakes (colour figure online)

information on water spread area of glacial lakes, lake type, and glacier characteristics derived from satellite data along with collateral information from field and other sources could be efficiently used to prioritise and identify potentially dangerous glacial lakes in entire Himalaya. There is scope for considering additional parameters for ranking of the lakes in addition to what have been suggested in this study. It is recommended that similar studies can be taken up in other sub-basins of Brahmaputra basin and also other basins in the Himalayas for ranking of potentially dangerous lakes, in order to mitigate the effect of GLOF in future. It is also recommended that based on ranking, early warning systems could be established for highly potential dangerous lakes by use of geospatial and communication technologies.

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