

## Changing glacial lakes and associated outburst floods risks in Nanda Devi Biosphere Reserve, Indian Himalaya

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**Abstract** Glacial lakes and associated outburst floods (GLOFs) have increased in the Himalayan region due to climate change during the last century that has led to huge losses to society. Therefore, the present study was undertaken to map glacial lakes, their increasing extent, and associated damage potential in Nanda Devi Biosphere Reserve (NDBR), Indian Himalaya. The glacial lakes were mapped on Landsat TM (3 November, 2009 and 6 November 2010) and Landsat MSS satellite images (15 November 1976 and 26 October 1979) to assess their changing area. Potential GLOFs sites have been identified and studied for their damage potentials using site characteristics and past occurrence of GLOFs. A total of 35 lakes were mapped, of which 14 lakes are located at more than 4500 m. The size and damage potentials of lakes have increased. Some lakes grew so much that they merged to form a big lake. All of these are potential GLOFs and can cause severe damage to society.

**Key words** glacial lakes inventory; glacial lake outburst flood; climate change; Indian Himalaya

### INTRODUCTION

Major glacio-hydrological changes have taken place in glacial and periglacial mountain regions in response to climate change due to their higher level of sensitivity (Barry 1990, Couture and Pollard 2007, Mal and Singh 2013). The high altitude mountain areas sensitively react to climate change due to the propensity for melting of surface and sub-surface ice (Huggel *et al.*, 2002). As a result, certain geomorphic processes and events including glacial de-buttressing, slope failures and glacial lake outburst flood (GLOF) events have accelerated on recently deglaciated foreland, periglacial and further downstream regions (Quincey *et al.* 2005). These failures frequently turn out to be catastrophic to human society (Evans and Clague 1994) and their ill effects are often felt further downstream, e.g. GLOFs events and associated debris flow (Huggel *et al.* 2004). Such examples appear to be common across the Himalayan and other mountain ranges (Huggel *et al.* 2004, Bisht *et al.* 2002, 2011, Sah *et al.* 2005, Bajracharya *et al.* 2007, NDMA 2009).

Glacial lakes are common phenomena in mountain regions (Huggel *et al.* 2002). As per the estimates of Mool *et al.* (2001) and ICIMOD and APN (2005), there are more than 6100 glacial lakes, covering an area of about 790 km<sup>2</sup> in the Hindu-Kush-Himalayan (HKH) Mountains. The Indian Himalayan Mountains alone have about 582 glacial lakes that cover an area of about 402 km<sup>2</sup>. The area and number of glacial lakes have increased in the Himalayan region due to climate change during the last century (Sah *et al.* 2005). However, there are not many studies about changing area of glacial lakes. The assessment of increasing glacial lakes and their interlinkages with GLOFs are of great importance in view of their great potential for causing major catastrophes to human society (Huggel *et al.* 2004). These lakes have been increasingly observed to breach out, leading to outburst floods and debris flows (Fujita *et al.* 2007). Consequently, assessing the increasing size of glacial lakes and their flooding risk becomes vitally crucial (Dobhal *et al.* 2013). Therefore the present study was undertaken to map glacial lakes, their increasing extent and associated damage potentials in Nanda Devi Biosphere Reserve (NDBR), Indian Himalaya. The NDBR is located in Uttarakhand state of India and lies between the geographic coordinates of 79°13'E to 80°17'E longitudes and 31°04'N to 30°06'N latitudes.

### DATA SOURCES AND METHODOLOGY

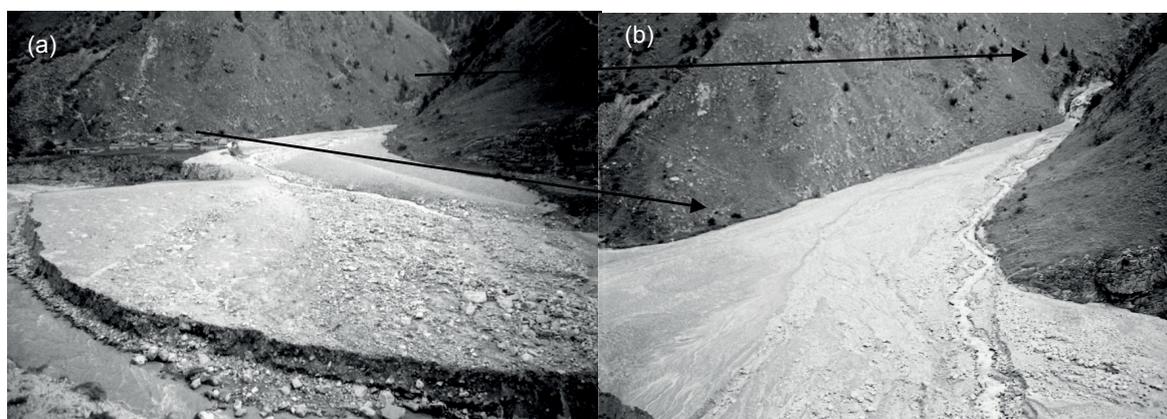
A complete inventory of glacial lakes was conducted in NDBR through mapping on the recent Landsat TM5 satellite images (3 November 2009 and 6 November 2010) (based on Huggel *et al.* 2004, Quincey *et al.* 2005, Sah *et al.* 2005) in combination with ASTER GDEM2 elevation data. Some of the areas

(lakes) were not visible in one satellite image due to heavy snow conditions, thus the image from the previous year was used to complete the inventory. The lakes were characterized for their elevation, latitude and longitude, types and area coverage based on Landsat satellite data and Digital Terrain Model (DTM). The elevation information of lakes has been determined from ASTER GDEM2 for the centroids of the lakes' polygons. Lakes located at more than 3500 m above m.s.l. and in glacial and periglacial areas were considered as glacial lakes. The lakes were classified into many types such as cirque lake, supraglacial lake, subglacial lake, end-moraine dammed, lateral-moraine dammed, medieval-moraine dammed and glacial ice-blocked based on their site characteristics. Major lakes were remapped on earlier MSS satellite images (15 November 1976 and 26 October 1979) to assess their changing characteristics using a change detection method. The increased area of glacial lakes, higher elevations, their types and locations are considered the results and indications of climate change. A few potential GLOFs sites have been studied for their damage potential using their site characteristics such as elevation, slope angle, lake types, etc. following Fujita *et al.* (2008). Assessment of damage potential of glacial lakes has been done in relation to previously occurred GLOFs in the study area. Some of the already occurred GLOFs in the study area originated from very small lakes, some of which could not even be identified on satellite images. Five GPS-aided field visits, along with intense site photography, were also made to different areas for verification of results. The field photographs were synchronized with GPS readings in order to provide them with latitude and longitude information. It helped to identify glacial lakes and slope failure events on satellite images. In addition, relevant literature, including research papers, monographs and research reports have also been consulted.

## RESULTS AND DISCUSSION

### Evolution of GLOFs in NDBR

The study suggests that the study region has a rich history of failures of glacial lakes and associated damage (Table 1). The Badrinath region in Alaknanda River valley has particularly experienced lake failures. However, these events have remained under-documented due to inaccessibility of Himalayan mountains (Srinivasan, 2013). Recently, a GLOF event was properly reported for the first time, i.e. Kedar *Tal* glacial lake outburst (17 June 2013) above the Kedarnath Shrine (Uttarakhand), as it hit the major pilgrim centre, i.e. Kedarnath and caused unprecedented damage. The GLOF claimed more than 5000 people and caused great damage to many settlements downstream including Kedarnath town and Rambara (Dobhal *et al.* 2013). In most cases, these events remain unreported, e.g. Gankhwi *Gad* outburst flood (2003) in Dhauri Ganga valley and many others. The moraine-dammed glacial lake on Gankhwi *Gad* in glacial foreland region of Gankhwi glacier outburst in 2002 and 2003, lead to heavy debris flow downstream and severe devastation of human property (Bisht *et al.*, 2011). The Siagari village in Dhauri Ganga Valley was completely buried under debris material (Fig. 1). This GLOF occurred from a very small glacial lake and washed out an entire village. GLOFs from larger lakes have potential to cause great damages to society.

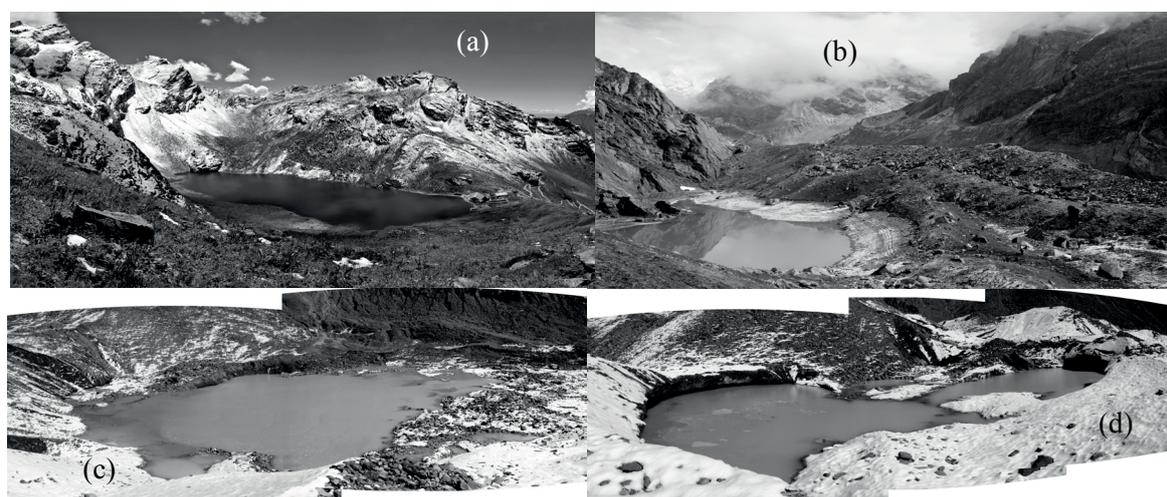


**Fig. 1** (a) GLOF led debris flow in Gankhwi *Gad* (photo supplied by Prof. MPS Bisht), (b) The Siagari village was completely destroyed.

**Table 1** State of major GLOFs events in NDBR.

Year	Areas	Causes and main event
April 1979 <sup>2</sup> ; Feb–March 2002 <sup>1</sup>	Bamni Village near Badrinath	Avalanches blocked Alaknanda River and lake was formed, which later breached above Bamni village near Badrinath.
20 July 1970 <sup>3</sup> and <sup>4</sup>	Hanuman Chatti near Badrinath and to Hardwar	About 275 mm rainfall (in few hours) caused landslide that blocked river creating temporary lakes. Alaknanda and Dhauli Ganga raised 30–60 and by 15–20 m, respectively that burst out causing considerable loss of life (381).
14 July 2007 <sup>2</sup>	Alakapuri Glacier and Badrinath	Glacio-fluvial sediments blocked Alaknanda River that burst out. A large area of Lakshmi Van and hanging bridge at Mana were washed away.
1968 <sup>3</sup> and 1970 <sup>3</sup>	Reni Village, Chamoli, Uttarakhand	The lake of about 40 m height in Rishi Ganga developed due to landslide led damming of Rishi Ganga River. The lake breached in July 1970 causing extensive damage.
2002–2003 <sup>2</sup>	Saigari Village	Gankhwi River was blocked by sediments and debris. GLOF occurred in 2002 and 2003 and completely destroyed the Saigari village in Dhauli Ganga valley.

Source: <sup>1</sup>Bisht *et al.* 2002, <sup>2</sup>2011; <sup>3</sup>NDMA 2009; <sup>4</sup>Gulia 2007.



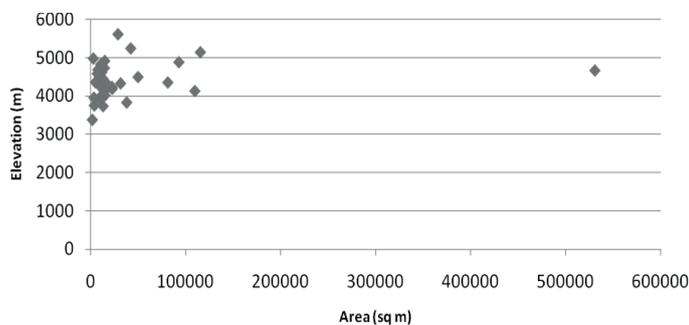
**Fig. 2** Types of glacial lakes. (a) Cirque lake near Hemkund Sahib, (b) lateral moraine-dammed lake on Bankund glacier (June 2010, photo supplied by Ashutosh), (c) end-moraine dammed lake in foreland of Milam glacier (October 2009) and (d) supraglacial lake in ablation zone of Milam glacier (October 2009).

### Inventory and distribution of glacial lakes

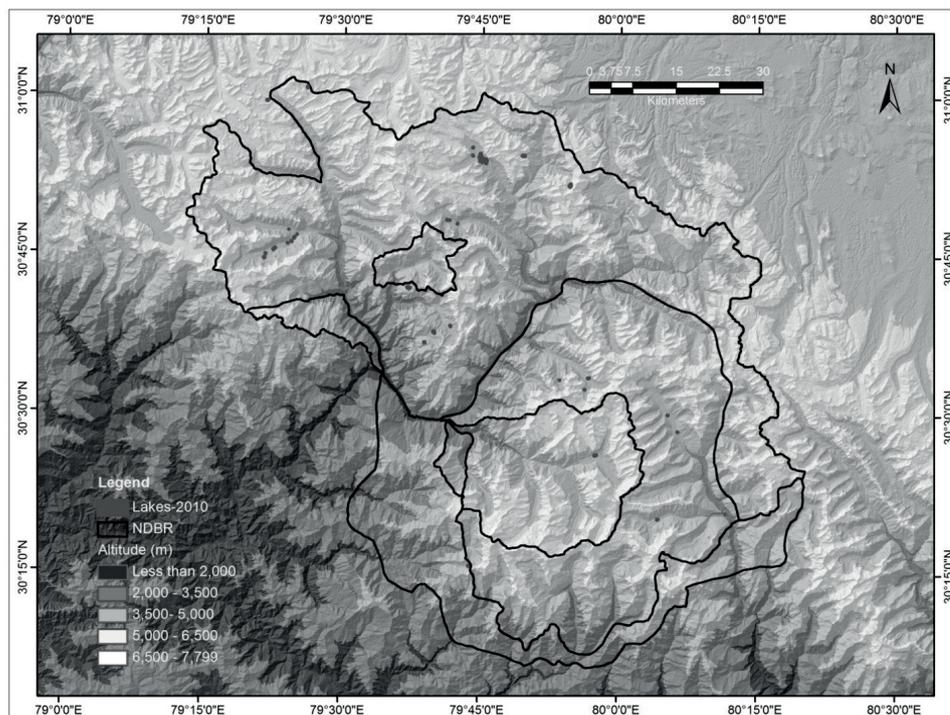
A total of 35 lakes could be identified and mapped on satellite images belonging to various types, including end-moraine dammed, cirque, lateral-moraine dammed, glacial-ice blocked and supraglacial lakes (Fig. 2). The criteria for the typology of lakes are their site characteristics. However, a few lakes in Saraswati River catchment could not be mapped, due to heavy snow cover and coarse spatial resolution (30 m) of satellite images. These lakes are clearly visible on Google Earth maps. Of the total 35 mapped lakes, 17 are supraglacial lakes, five cirque lakes, four lateral-moraine dammed, three end-moraines dammed and six are of other types. A few of the lakes are very large in size.

An unnamed lake on East Kamet glacier (supraglacial cum end-moraine) is the largest (531 028.52 m<sup>2</sup>) glacial lake in NDBR. The other large lakes are Sitkeng (115 176.91 m<sup>2</sup>), Hemkund (109 344.23 m<sup>2</sup>), Geldhura (92 522.72 m<sup>2</sup>) and Kagbhusandi (80 868.38 m<sup>2</sup>). Of these, Sitkeng and Geldhura are end-moraine dammed type lakes and others belong to cirque types. The altitude and area of lakes are closely related. All the lakes are larger than 1270 m<sup>2</sup> and most of them are located at high altitudes (>4000 m) (Fig. 3). Three lakes are located at more than 5000 m above msl, 11 between 4500 to 5000 m, 14 between 4000 to 4500 m and 7 are below 4000 m. The highest altitude lake (unnamed, 5622 m) is located at the base of Saraswati peaks of Saraswati River watershed and is of supraglacial

type. The other two lakes at very high altitudes ( $> 5000$  m) are cirque (Unnamed\_saraswati) and end-moraine dammed (Sitkang) types, respectively. The elevation of lakes increases towards the northern margins of NDBR (Fig. 4). Presence of different types of glacial lakes in higher elevations is an indication of glacial retreat caused by climate change.



**Fig. 3** Scatter plots of area of glacial lake vs elevation. The area of glacial lakes has been derived from Landsat satellite TM5 images of 3 November 2009 and 6 November 2010 and elevation from ASTER GDEM2 Image.



**Fig. 4** Spatial distribution of glacial lakes in various altitudinal zones of NDBR, as mapped on Landsat 5 TM satellite images (3 November 2009 and 6 November 2010) (Background-ASTER GDEM2 Image).

### Increasing extent of glacial lakes and associated outburst flood risks

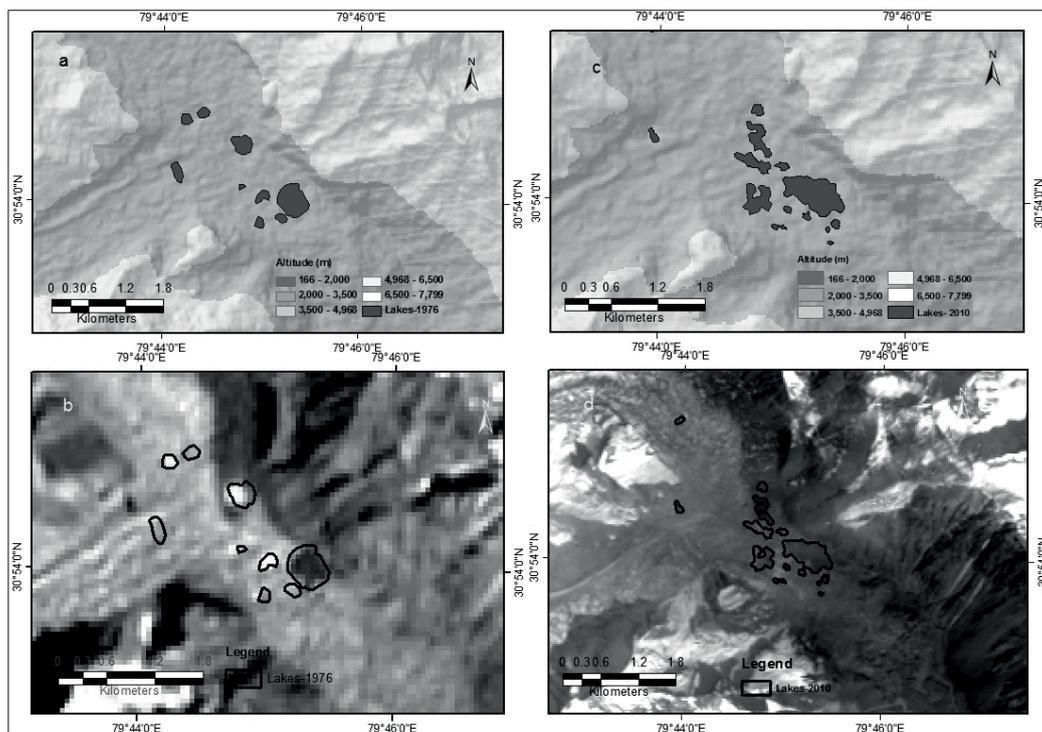
The formation and development of glacial lakes are associated with the process of deglaciation and deglaciated foreland caused by climate change (Quincey *et al.* 2005, Fujita *et al.* 2008). The area and volume of water in glacial lakes increases due to increased water supply from retreating glaciers (Mool *et al.* 2001). All the remapped glacial lakes have been observed to increase over the period of 1976 and 2010 (Table 2). Unnamed lakes on East Kamet glacier, Sitkeng, Geldhura and Hemkund lakes significantly increased by areas of 79 952.2, 30 430.9, 29 543.9 and 27 948.7 m<sup>2</sup>, respectively. There was minimal expansion observed in the area (6573.8 m<sup>2</sup>) of Kagbhusandi, the fourth largest lake of NDBR. Geldhura lake has expanded rapidly but at a lower rate than the two largest lakes. There were some small lakes on East Kamet glacier that expanded to the extent that they merged

and formed a big lake (Fig. 5). All the increasing glacial lakes are potential future GLOFs sites owing to their fragile physiographic and geomorphic conditions and will cause huge damage due to their association with nearby human settlements.

**Table 2** Changing extents of glacial lakes– few representative examples from NDBR.

Name	Lake Type	Area (m <sup>2</sup> ) 1976	Area (m <sup>2</sup> ) 2010	Change (m <sup>2</sup> )
Kagbhusandi	Cirque	74294.56	80868.38	6573.8
Sitkang	End_Moraine_Dammed	84745.99	115176.91	30430.9
Un-named_(Kamet_gl)	Supraglacial_End_Moraine_Dammed	451076.36	531028.52	79952.2
Hemkund_lake	Cirque	81395.56	109344.23	27948.7
Un-named_(Nanda_devi_gl)	Lateral_Moraine_Dammed	28104.94	49482.81	21377.9
Gel_dhura	End_Moraine_Dammed	62978.82	92522.72	29543.9
Un-named_(Satopant_gl)	Lateral_Moraine_Dammed	21336.30	31082.11	9745.8

Source: Calculated from Landsat MSS (1976) and TM images (3 November 2009 and 6 November 2010).



**Fig. 5** Changing extent of an unnamed supraglacial-cum-endmoraine dammed lake and increasing potential of GLOF on East Kamet glacier. (a) lake in 1976 on Landsat MSS 1976, and (b) lake in 2010 on Landsat TM 2010.

Kagbhusandi (80 868.38 m<sup>2</sup>) and Hemkund (109 344.23 m<sup>2</sup>) lakes are also such high altitude (4363 m) increasing cirque lakes that are potential hazards for settlements located in downstream areas of the Laxman Ganga catchment. The lakes are frequently affected by avalanches activities that produce waves in lake. The larger waves may sometimes overtop the lake outlet or lead to its breaching, draining the area located further downstream. Sometimes, lakes grow in size to an extent that the terminal moraines fail to hold the water and breach out (Mool *et al.*, 2001; Quincey *et al.*, 2005). Such breaching and failures produce huge flooding of water and debris flow, and cause unprecedented damage to downstream areas and settlements. The human settlements of Ghangaria,

Bhundyar, Pulna and Govind Ghat are located downstream of lakes and are risk prone. These settlements will be completely washed away if the lakes breach out, as in case of Gankhwi *Gad* burst flood. There are already many such un-documented cases in NDBR.

## CONCLUSION

The climate change has deglaciated higher elevations of mountains across the world. Consequently, glacial lakes have increased in number and their size expanded continuously. These glacial lakes have been increasingly observed to breach out and cause unprecedented damage to society. Some of the growing lakes have become potential GLOFs sites. These are an additional source of damage to human society that has come up in recent years as a result of climate change. GLOFs are occurring on a regular basis leading to huge damages. It is therefore needed to carryout complete assessment of potential GLOFs in order to provide the community and society a better warning and management system.

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