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Changes of Glacier Lakes Using Multi-Temporal Remote Sensing Data: A Case Study from India

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Abstract

The present study used the potential of Landsat multispectral data and ASTER-DEM data to identify the changes of glacier lakes in part of Chandra basin and surrounding of Himachal Pradesh of India from 1989 to 2013. The Barashigri, Chotashigri, Hamtahand Parvati glacier are the major glaciers within the area. The Landsat data of TM (1989 and 2009), ETM+ (2001) and OLI-TIRS (2013) sensors having different band combinations were analysed to monitor variation in the glacier lakes and area of glaciers and terminus whereas ASTER-DEM data was used for relief information. Glaciers terminus and glacial lakes were identified and mapped using false-colour composites (FCC) with band combinations of red, near-infrared (NIR) and shortwave infrared (SWIR), and a true-colour composite of red, green and NIR, of Landsat TM/ETM+ images and normalized difference water index (NDWI) methods. It is observed that the number of lakes in the study area increased by 18.69% during the past 34 years while it was increased from 68 in 1989 to 89 in 2013. During the analysis, it is also found that the snow and glacier covered area within this period is also reduced from 1,317.39 to 1,125.59 km^2.

Keywords: Glacier lakes, Landsat, ASTER-DEM, glacier terminus, NDWI, FCC.

Introduction

A glacial lake is demarcated as a water mass present in adequate amount and encompassing with a free surface in, under, besides, and/or in front of a glacier and instigated by glacier actions (Campbell 2005). Glacier lakes are the utmost clear and might have been the major significance of climate change and glacier thinning in the Himalaya (Khare, et al., 2016). Due to increase in the rate of the retreating glaciers, the lakes are increasing in areal extent and water storage capacity in the glaciated topography of the Himalaya area. Changes in the areal extent of glacial lake surface water may occur due to several factors i.e. progressive unveiling of the lake basin by sediments, climate change, tectonic movement triggering uplift or subsidence, and the development of stream faults (Mercier, et al., 2002; Goerner, et al., 2009; Jawak, et al., 2015). Some of the glaciers have retreated due to climate warming, not only disturbing water resources and hydrological processes, but also affecting the development of glacial lakes in earlier studies (Yao, et al., 2010).

Warming of climate has instigated change in the Himalayan environment such as lowering of glacier surfaces, glacier front retreat etc. (Skvarca, et al., 1998; Scambos, et al., 2000; Parkinson, 2002; Cook, et al., 2005). Most of the Himalayan glaciers have retreated recently, leaving behind large number of glacial lakes. In the Indian Himalayan region, the first glacial lake outburst floods (GLOF) event was reported when the 1926 flood, released by the Shyok glacier in Jammu and Kashmir, destroyed Abudan village and the surrounding land 400 km (downward) from the outburst source. Recent flash flood in Kedarnath, is the most remarkable incident in Indian history till today. Kedarnath GLOF event produces a need to update the analysis of glacial lakes hazard assessment for understanding the

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future GLOF hazards (Dobhal, et al., 2013). Researchers have proposed suitable indicators to qualitatively assess breach probabilities of glacial lake outburst floods (GLOFs) according to lake characteristics. These factors mostly include the freeboard of the lake, dam type and geometry, parent glacier and lake basin settings, which can be calculated through satellite data (Clague, Evans 2000; Richardson, Reynolds, 2000; Huggel, et al., 2004; Wang, et al., 2013).

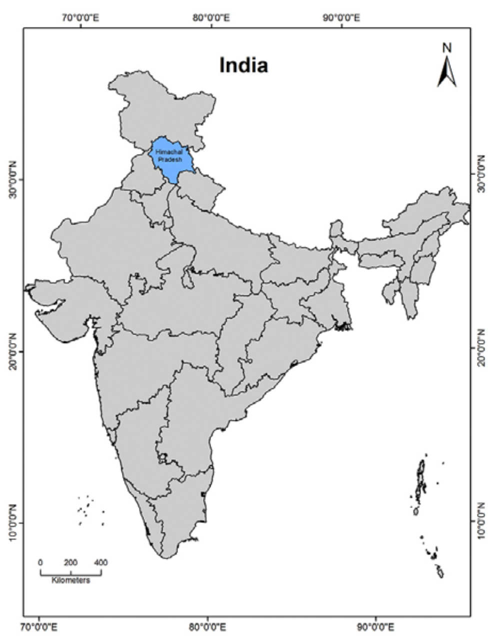
The detection of glacial lakes is a key step in the study of their hazard potential and in the preclusion of unexpected catastrophes. Remote sensing data has established to be the best tool to delineate the glacial lakes of very high elevated, cold climate and uneven topographic situations, making it a tedious, hazardous and time taking process to monitor by traditional survey methods (Govindha Raj, et al., 2013). Delineation and mapping of glacial lakes in Himalaya (Kulkarni, 1996; Randhawa, et al., 2005) can be done by using false colour composites (FCC) combination in remote sensing data.

The integrated used of remote sensing with geographic information systems (GIS) technologies offers strong advantages for first and at least qualitative hazard evaluation of glacier lakes (Huggel, et al., 2002a). Many researchers attempted detailed inventoryof glaciers and glacial lakes focusing largely on Himalayan region (Yamada, Sharma 1993; Bolch, et al., 2008; Fujita, et al., 2008; Fujita, et al., 2013; Komori, 2008; Nathawat, et al., 2008; Wang, et al., 2013; Worni, et al., 2013; Wang, et al., 2014; Bhambri, et al., 2011, 2012; Rai, et al., 2009, 2013, 2016; Rai, et al., 2017). Bolch et al. (2008) used automatic detection method of glacial lake using a Normalized Difference Water Index (NDWI) on Imja Glacial Lake. Lichtenegger et al. (2008) studied the variations of Imja Lake of Nepal using microwave remote sensing data. Racoviteanu et al. (2008b) discussed normalise difference snow index (NDSI) method for glacier terrain mapping of Sikkim Himalaya. Molnia (2009) worked on TERRA-ASTER image to detect glacial lakes of Afghanistan. Thompson et al. (2010) worked through Differential GPS survey for mapping the various perimeters of major glacial lakes. The International Centre for Integrated Mountain Development (ICIMOD) provided a first level assessment of glacial lakes in some parts of the Indian Himalayan area (Mool and Bajracharya 2003).The inventory done by Sah et al. (2005) from multi-temporal remote sensing data displays 127 glacial lakes in the Uttarakhand Himalaya. As recommended by Kargel et al. (2005), glacier and glacial lake development are likely to be very different between the eastern parts of the Himalayan range where the large majority of glaciers are retreating while the western part glacier changes are slower (Gardelle, et al., 2011).

The purpose of this paper is to give an overview of the distribution and recent development of glacial lakes in the Chandra basin and surrounding region of Himachal Pradesh of India. To attain this objective, a set of Landsat satellite images of 1989, 2001, 2009 and 2013 has been used.

Study area

The study area is located in India, precisely in Lahul and Spiti district of Himachal Pradesh. The area also covers a small portion of Kullu and Kinnaur district. Itex tends from the Shivalikhills in the south to the



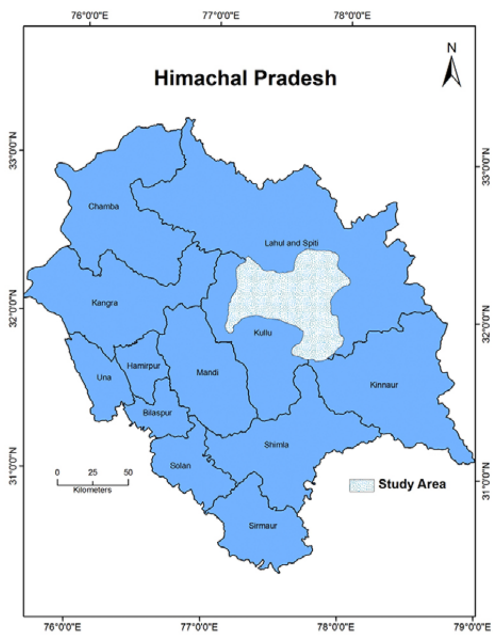


Figure 1. Location of the study area

Greater Himalayan ranges in the north. Geographically the study area is situated between 31°44'8.9” to 32°27'42.191” north latitude and 77°7'32.103” to 78°1'4.6” east longitude. The area is compact in shape and almost mountainous with altitude varying from 1,081 to 6,582 meters covering a geographical area of 3,944km^2 (Fig.1).

Material and methods

To avoid cloud cover during the monsoon and ensure minimal snow coverage, satellite images acquired in the October season were selected. Limited remote sensing data was available annually due to seasonal snow and cloud cover. Hence the glacial lake layer is generated by digitization of the lakes from the orthorectified Landsat data of different time periods through visual interpretation and validation. Due to the dimensional inconsistency of the lakes in satellite images, glacial lakes can be extracted as a point shape file with attribute data (Wang, et al., 2014; Chen, et al., 2007).

Delineation of glacier lakes were carried out using Landsat TM (16th October, 1989 and 1st October, 2009), ETM+(18th October, 2001) and Landsat, OLI-TIRS (October, 2013) satellite data (spatial resolution of 36 m, 30 m and 15 m respectively) which were downloaded from the Earth Explorer (Internet).

DEM produced using Advanced Spaceborne Thermal Emission and Reflection Radiometer sensor (ASTER) of 30m resolution has been used in this study. ASTER is an imaging instrument that is flying on the TERRA satellite launched in December 1999 as part of NASA's Earth Observing System (EOS).Its resolution ranges from 15 to 90 m, dependent on the wavelength.

Normalized Difference Water Index (NDWI) using Near Infrared (NIR) and green channels of Landsat data can delineate and enhance water bodies and lakes (Mcfeeters,1996). Glacial lakes were automatically identified using the Normalized Difference Water Index (NDWI= [NIR-Blue]/[NIR+Blue]). This method has been successfully used for water bodies extraction (Randhawa, et al., 2005). The NDWI performed slightly better than the band ratio (GREEN/NIR) (Bolch, et. al., 2008). The result shows that the identification of glacial lakes using the NDWI led to accurate results. This also confirmed findings of earlier studies (Bolchet, et al., 2008). The pro-glacier lakes present in front of the glacier terminus exhibiting bright tone with fine texture in contrast to coarse and mottled texture over glacier surface helped in defining the lower limits of the glaciers (Pandey, et al., 2012). Methodology flow chart for the inventory of glacier lakes in the study area is shown in the Fig. 2. As a consequence of spectral reflection, some shadowed areas are misinterpreted as glacial lakes. These areas have been identified with the help of ASTER- DEM; the DEM was overlapped with NDWI image and the result was, that the glacial lake seemed as black spot tone. After that, manual demarcation of lakes has been carried out. Each location of glacial lake was digitized using GIS platform. Representation of the types of glacial lakes is shown in the Fig. 3.

In Himalayan terrain due to the near vertical acquisition of the satellite image, hill shadows create troubles in recognition of the water bodies. Hill shade

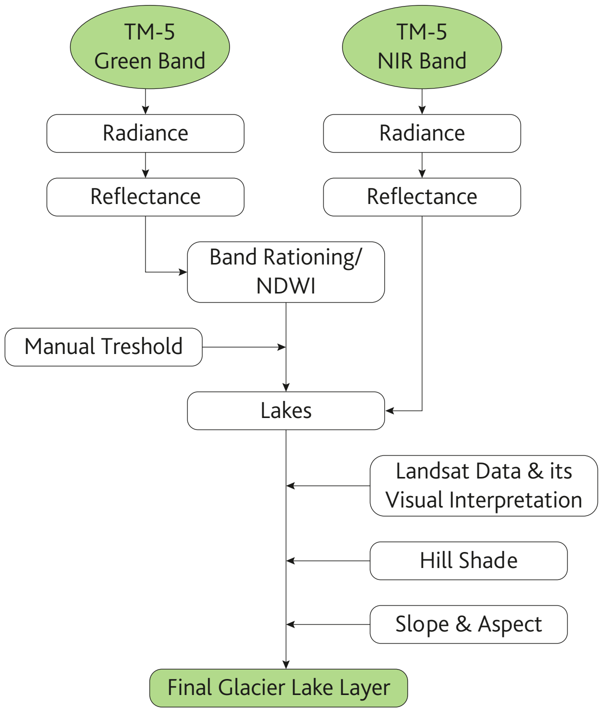


Figure 2. Methodology flow chart for the inventory of glacier lakes in the study area

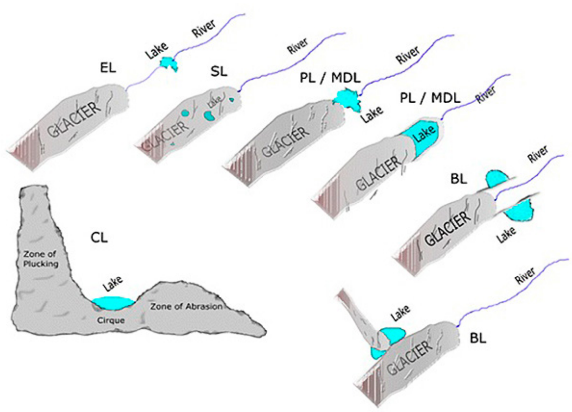


Figure 3. Representation of the types of glacial lakes. Supra glacial lake SL, Proglacial lake (PL), Erosion lake (EL), Cirque lake (CL), Moraine-dammed lake (MDL), Blocked lake (BL)
Source: Govindha Raj, Kumar 2016

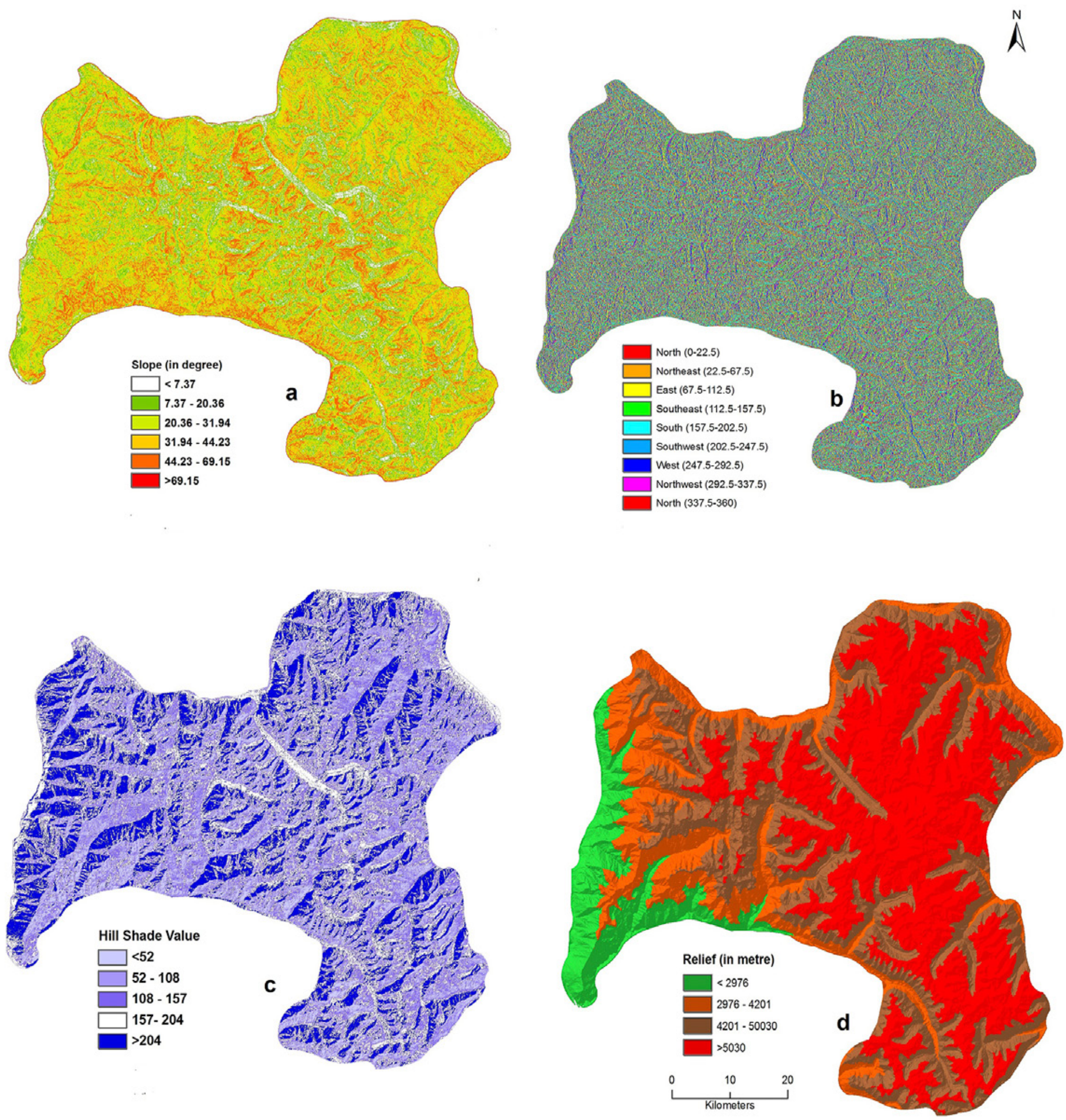


Figure 4. Different topographic thematic maps generated using ASTER DEM; Slope map (a), aspect map (b), hill shade image (c) and relief map (d) of the study area

image generated from ASTER DEM was used to differentiate lakes (Fig. 4). Slope map and aspect map generated from ASTER DEM are also used for visual interpretation of glaciers and for classifying the glacier lakes in combination with optical remote sensing data i.e. Landsat-TM, ETM+ and OLI-TRS (Fig. 4). Hill shade and Relief map of the study area is also shown in the Fig. 4.

Wessels et al. (2002) also discussed the automatic classification of glacial lakes. Using the four bands in the VNIR (visible near infrared) and MIR (Middle Infrared) of ASTER data, and computed two ratios (R1 and R2) to distinguish (i) water surfaces from non-water surfaces and (ii) glacier or snow from water surface, among classified water surfaces.

$$R1=B_{Green}/B_{NIR} \quad (i)$$

$$R2=B_{NIR}/B_{MIR} \quad (ii)$$

where, Bi is the ASTER spectral band. However, this algorithm is not robust enough to be applied to images whose channels slightly differ from the ASTER sensor.

Table 1. Details of the Landsat satellite data specification

Date of Pass	Satellite and Sensor	Bands and Wavelength (µm)	Raw/Path	Spatial Resolution (m)	Cloud Cover
16 Oct. 1989, 1 Oct. 2009	Landsat TM	0.45-0.52(Blue-B1) 0.52-0.60(Green- B2) 0.63-0.69(Red-B3) 0.76-0.90(VNIR- B4) 1.55-1.75(SWIR- B5) 10.4-12.5(TIR-B6) 2.08-2.35(SWIR- B7)	147/38	30	No
18 Oct 2001,	Landsat ETM+	T M Bands (0.50-0.90) and Pancromatic band	147/38	30, 15 (Panchromatic)	No
21 Oct. 2013	Landsat (L8OLI- TIRS)	T M Bands (0.50-0.90) and Pancromatic band	146/38	30, 15 (Panchromatic)	No

Using LANDSAT images to study glacier hazards in the Swiss Alps, Huggel et al. (2002b) applied the NDWI (Normalized Difference Water Index, Eq. (3)) to classify glacial lakes, taking advantage of the low water reflectance in the NIR band. However, by using this method, glacial lakes could be misinterpreted as shadow area.

$$NDWI = B_{NIR}-B_{Blue} / B_{NIR} + B_{Blue}$$

Through satellite dataset (LANDSAT-TM and ETM+), the automatic classification has been performed, both with ratios R1and R2, and with NDWI.

All the information about data and source are summarized in the Table1.

Results and discussion

A glacial lake is defined as a water mass existing in a sufficient amount and extends with a free surface. The glacial fluctuation causes the formation and enlargement of glacial lakes in many high mountainous regions (Richardson, Reynolds, 2000; Govindha Raj, et.al., 2013; Yao, et.al., 2010). The sudden tectonic events can causes glacial lake outburst flood (GLOF) which can extensively damage the ecology and economy of the region. Lake Identification based on ASTER was slightly more accurate than of Landsat as the comparison with the referenced data. The automated lake identification can be problematic with turbid lakes and lakes with partial ice cover/icebergs, and in shadow areas. In these cases, an improvement based on visual interpretation had been performed with the help of DEM. The prominent location of the glacial lakes is an important element to categorize them in different categories (Govindha Raj, Kumar, 2016). Locations of lakes with glacier buffer, morphological landscapes, moraines, outwash plains, etc. are measured to classify the lakes. Almost all the lakes in the study area are above altitude of 4,000 m and below 6,000 m.

The study shows the recession in the glacier in terms of area and volume during 25 years. The snow and glacier covered area has been reduced from 1,317.39 to 1,125.56 km^2 from 1989 to 2013. In present study, a total of 89 glacial lakes of various categories are identified in the satellite data of 2013 while it was only 68 in the Landsat TM data of 1989 (Fig. 5 and Table 2). The valley of Barashigri glacier and Parvati glacier shows huge increase in number and area of glacial lakes especially supraglacial lakes. Due to lack of snow free data and data of same season, the actual and exact number and location of glacial lakes may vary in the field. The distribution of glacial lakes in 1989, 2000, 2009, and 2013 are displayed in the Fig. 5. Snow and glacier covered area are delineated through Landsat data of 1989 and 2013 and are represented in the Fig. 6.

Table 2. Type and number of glacial lakes in the study area

Glacial lakes	1989	2001	2009	2013
Blocked lake (BL)	02	04	05	07
Cirque lake (CL)	12	12	13	14
Erosion lake (EL)	05	05	04	02
Moraine- dammed lake (MDL)	07	08	10	08
Pro-glacial lake (PL)	02	07	04	03
Supraglacial lake (SL)	40	43	48	55
Total	68	79	84	89

Glacier lakes are categorized into six types namely erosion lakes, cirque lakes, blocked lake, moraine-dammed lakes, proglacial lakes and supra glacial lake.

Erosion lakes (EL) are the water bodies developed in depressions through glacial erosion and occupy

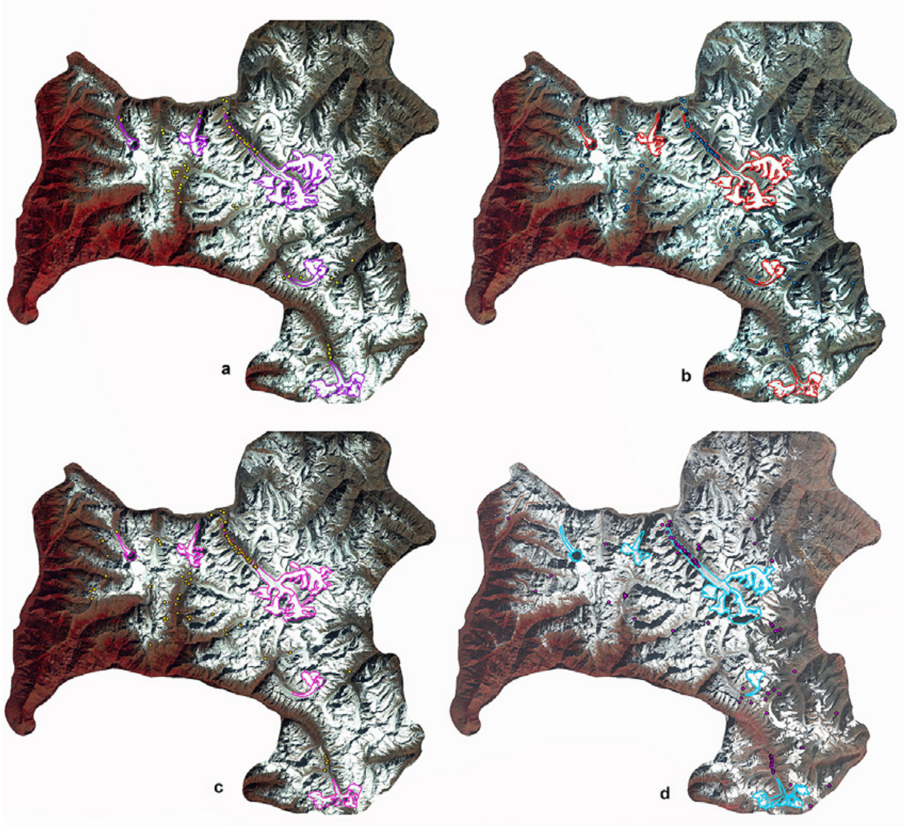


Figure 5. Distribution of glacier lakes as identified in (a) 1989, (b) 2001, (c) 2009 and (d) 2013

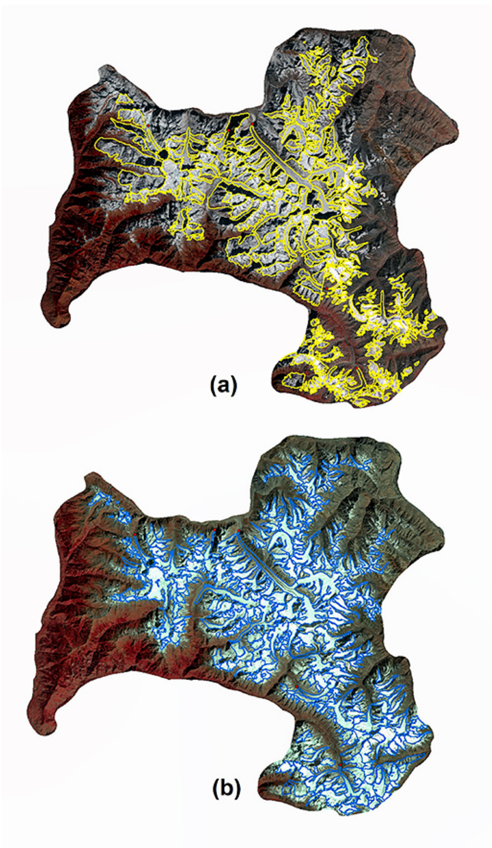


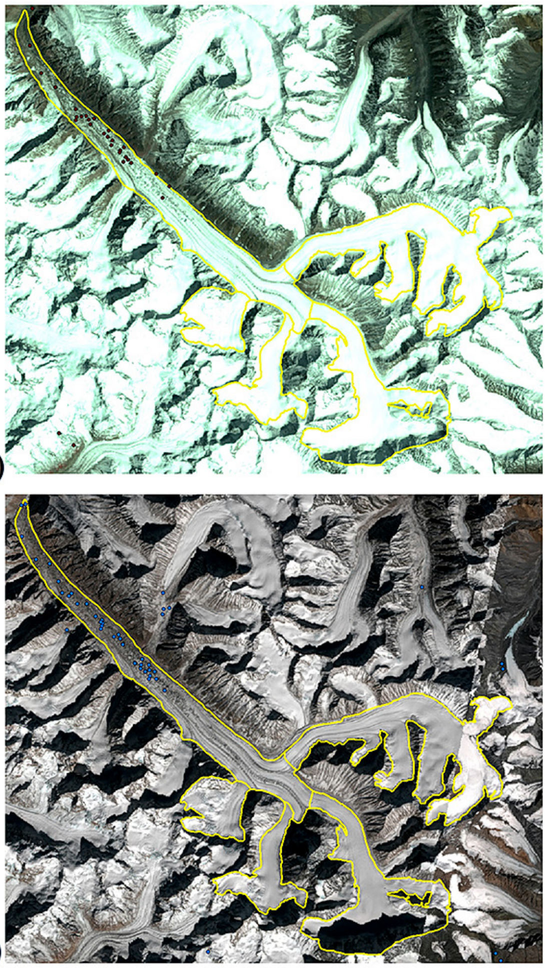
Figure 6. Snow and Glacier Covered Area in (a) 1989 and (b) 2013

the limited lateral extent in the deglaciated valley and outwash plain (Govindha Raj, Kumar, 2016). Wang et al. (2014) measured erosion lakes as periglacial lakes, since these lakes are not in direct relations with main valley glaciers. Through satellite data of 1989, 6 erosion lakes were identified, whereas it was only 2 in 2013.

Cirque lakes (CL) are developed due to snow melt water accumulation in the evacuated cirque. It can be recognized on the basis of location of lakes that are close to the mountain peaks where cirques develops. Their identification is possible through GIS software along with DEM for the 3-dimensional perspective view (Govindha Raj, Kumar, 2016). During the visual interpretation and digital analysis of the satellite data, it is clearly seen, that the 12 cirque lakes were detected in 1989 whereas 2 new lakes has been developed during 14 years.

Identification of supra glacial (SL) lakes can be easily done in the Landsat data through their high contrast with the glacier ice and debris covered area. Shifting, merging, draining and vanishing are distinctive characteristics of supra glacial lakes (Govindha Raj, Kumar, 2016). Merging of supraglacial lakes can lead to produce moraine-dammed lakes (MDL). These lakes are more dynamical and vary in time and space; its life is unpredictable (Benn, et al., 2001). Number of supraglacial lakes (SL) in the study area in-

(a)



(b)

Figure 7. Supraglacial lakes in Barashigri glacier in (a) Landsat TM (1989) and (b) OLI-TIRS (2013) satellite data

creased to 43, 48 and 55 in 2001, 2009 and 2013 respectively in comparison to 40 in 1989. The distribution of proglacial lake (PL) at the terminus of Barashigri glacier. Location of supraglacial (SL) lakes on NDWI images is represented in the Fig.7. Supraglacial lakes formed in Barashigri glacier valley is continuously increasing in number. As the time passes and glacier retreat increases, lakes become larger and when the size is too large to hold, some kind of tectonic activity might trigger the event of GLOF in the valley.

Blocked lakes (BL) instigates due to obstruction of lakes by glaciers and the moraines. These lakes are made due to glaciers and other objects including the main valley glacier or its moraines obstructive the branch valley, the tributary glacier blocking the main valley glacier, and the lakes formed through snow avalanches break down and debris flow blocked from main or branch valley or even lakes developed due to landslides incidences. It can cause GLOF and debris flow. During the analysis of the satellite data and NDWI images, 2 blocked lakes (BL) were identified in 1989 whereas 7detected in 2013.

Through this study, it is very clear that glacier dynamics have a control over the formation and growth of the lakes.

Pro-glacial lakes (PL/ MDL) are ice-contact lakes arising near to the terminus/snout of a glacier. These lakes can be easily delineated in Landsat satellite data based on the high contrast appearance and colour variation with the glaciers. Moraine-dammed lakes (MDL) come under the group of pro-glacial lakes (PL). Pro-glacial lakes (PL) increase their sizes in accordance with the retreating of the glacier terminus. In the retreating process of a glacier, glacier ice tends to retreat faster in the terminus part of the glacier surrounded by lateral and terminal moraines. As a result, many supraglacial lakes (SL) and pro-glacial lakes (PL) are formed on the glacier terminus. These lakes sometimes become large lakes by binding with each other and deepen in further and finally bounded by a moraine dam. A number of moraine dammed pro-glacial lakes (PL) had no vent drainage and are closed to the parent glacier and growing laterally by down wasting the glacier (Govindha Raj, Kumar, 2016). Many pro-glacial lakes (PL) are ice-core moraine dammed or ice dammed and show stable characteristics. These lakes are susceptible for GLOF. The temporal satellite data shows that 7 MDL in 1989 and however one new MDL was developed regarding 2013 data.

After the analysis, 8 potential MDL were detected in this study. These lakes can generate anoption to break the lakes and destroy the downstream area. The government administration should take themas a thoughtful step in order to defend a serious destruction and they can execute additional detailed study of this area. Analysis shows 3 pro-glacial lakes (PL) in 2013 whereas it was 2 in 1989. Kulkarni (2011) reported that the climate change is responsible for the glacial retreat, negative mass balance, early melting of seasonal snow cover and wintertime increase in stream runoff in the Indian Himalaya.The impression of climate change on glacial environments could be the reason for the accelerated growth of glacial lakes in the Himalayan region.

The information about the type and number of glacial lakes in the area under study in four different years is given in the table 2.

Conclusion

The recent rate in the glaciers retreat and thinning has caused the evolving of new glacial lake in the glaciated region of the Himalaya. The integration of visual image interpretation and digital image analysis of remote sensing data with a Geographic Information System (GIS) can enable us very significant methods for the glacier lakes study. This study shows that the presence of 89 glacial lakes in 2013 among five different categories in the study area while it was 68 in 1989. Under substantial climate warming and glacier shrinkage over the past 24 years in the study area, the number of glacial lakes increased by 23.59% This study also shows loss of 14.55% snow and glacier area between 1989-2013. It was found that due to shrinkage in glacier area, few glaciers have been fragmented from its tributary glaciers. This has resulted in the reduction of the total glacier extent but conversely increases in the number of glaciers. Continuous growth of glacial lake area could possibly increase the frequency and damage of GLOFs or debris flows in the Himalayan region and may give rise to additional risks in the nearby future. Henceforth appropriate mapping and monitoring of glaciers is very vital for the water resources development and for the purposes of natural disaster mitigation of high altitude regions. Passive remote sensing images are the main input of the inventory of glacier lakes but related climatic conditions makes the data inadequate for application. Therefore, active remote sensing data like microwave or RADAR data have to be of bigger significance for such type of study in Himalayan glaciated terrain.

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