Bulletin of Geography. Physical Geography Series, No. 25 (2023): 51–62
http://doi.org/10.12775/bgeo-2023-0009

Glacier retreat and proglacial lake dynamics of Darma Valley, Central Himalaya, India

Masoom Reza*[a], Ramesh Chandra Joshi[b], Chandra Nabiyal[c], Mamta Negi

Kumaun University, Department of Geography, DSB Campus, Nainital, Uttarakhand India

*E-mail: hreza896@gmail.com; masoomreza@kunainital.ac.in

[a]https://orcid.org/0000-0002-9706-1103, [b]https://orcid.org/0000-0001-9824-7156, [c]https://orcid.org/0000-0002-5017-6632

Abstract. The physiography and climate of the Higher Himalayas are uniquely characterised. Some phenomenal changes, such as variability of glacier cover, lake area and glacier retreat are dynamic and are inevitable due to global temperature rises. This study is conducted using remote-sensing data. A total of 17 glaciers are mapped using Sentinel-2 (2020), Landsat 5 (1994) and Corona declassified (1966) data. In 1966, the total area of glaciers was 74.309±0.1478 km^2, which decreased to 72.072±0.370 km^2 in 2020. The estimated total loss of glacier area in 54 years (1966–2020) is 2.236±0.016 km^2. The average total retreat of terminii in 54 years is 439.30±13.795 m and the annual retreat is 7.91±0.255 m. In the same valley, six major glacial lakes were also observed to extend their surface, with the most expanding lake (GLK – 5) expanding by 2,010.7 ±30.26% in 54 years.

Key words:
glacial area loss,
terminus retreat,
pro-glacial lake,
uncertainty assessment,
corona declassified imagery

Introduction

The Himalaya is one of the most important regions in Asia and plays a significant role in the hydrological cycle by providing water for major rivers throughout the year. Changes in global climate have impacted snow cover, glacial lake (GLK) formation and glacier retreat. From 1950 to 1980, the rate of glacier retreat slowed, but it has accelerated since 1980 (Mauri 2022). The World Glacier Service reported a decrease in glacier ice, noting that each glacier has lost an amount of ice equivalent to nearly 25 metres of liquid water or 27.5 metres of ice from its surface (Rebecca 2020). Although climate change has also affected alpine areas globally, the observations reported by researchers are complex and difficult to interpret. Snow cover trends show varied patterns: in the Indus basin, snow cover increased, whereas it decreased in the Ganges and Brahmaputra basins between 2000 and 2011 (Singh et al. 2014). A study by the Chinese Academy of Sciences, examining 46,928 glaciers, revealed that 5.5% of the glacier area has been lost in the last 24 years (Ratna et al. 2008). Glacier retreat is not constant within a region. Therefore, long-term data are crucial for understanding how glaciers respond to climate change (Hoelzle et al. 2003). A 45-year study (1975–2020) in the Nujiang-Salween River Basin revealed an average annual rate of change of –0.62%. The most significant change occurred in glacier area between 5290 m and 5540 m in elevation, which accounted for 40% of the total shrinkage in the basin (Xuan et al. 2022). Glacier-area changes vary across the Himalaya. Over the past six decades, the average rate of area change has increased in the western and eastern Himalayas, while it has either decreased or remained stable in the central Himalaya (Bolch et al. 2019). This research delves into the phenomena of glacier retreat and proglacial lake dynamics spanning a 54-year period, from 1966 to 2020. The primary aim is to identify the dynamics of glacial coverage, extent and lake dimensions through the analysis of remote-sensing data. Another important task is the uncertainty analysis of the remote-sensing data used. The data produced prove invaluable in comprehending the transformations within the glacier landscape of Darma Valley.

Study area

The Darma Valley, situated in the Pithoragarh district of Uttarakhand – a state in the Himalayan region in India, spans a notable geographical area (Fig. 1). The spatial extent ranges from 30°34'22" to 30°03'52.15"N latitude and from 80°14'45.6" to 80°43'52.68" longitude. This expanse corresponds to a total geographical area of 1,110.37 km^2 (Fig. 1). The valley is distinguished by its two primary rivers, the Darma and the Lissar, both of which originate from the glaciers of the Darma Valley. These rivers converge at the village of Tidang, beyond which point they are collectively referred to as the Dhauliganga East River. The altitude of the glaciers in the valley spans between 3,473 and 5,879 metres above mean sea level.

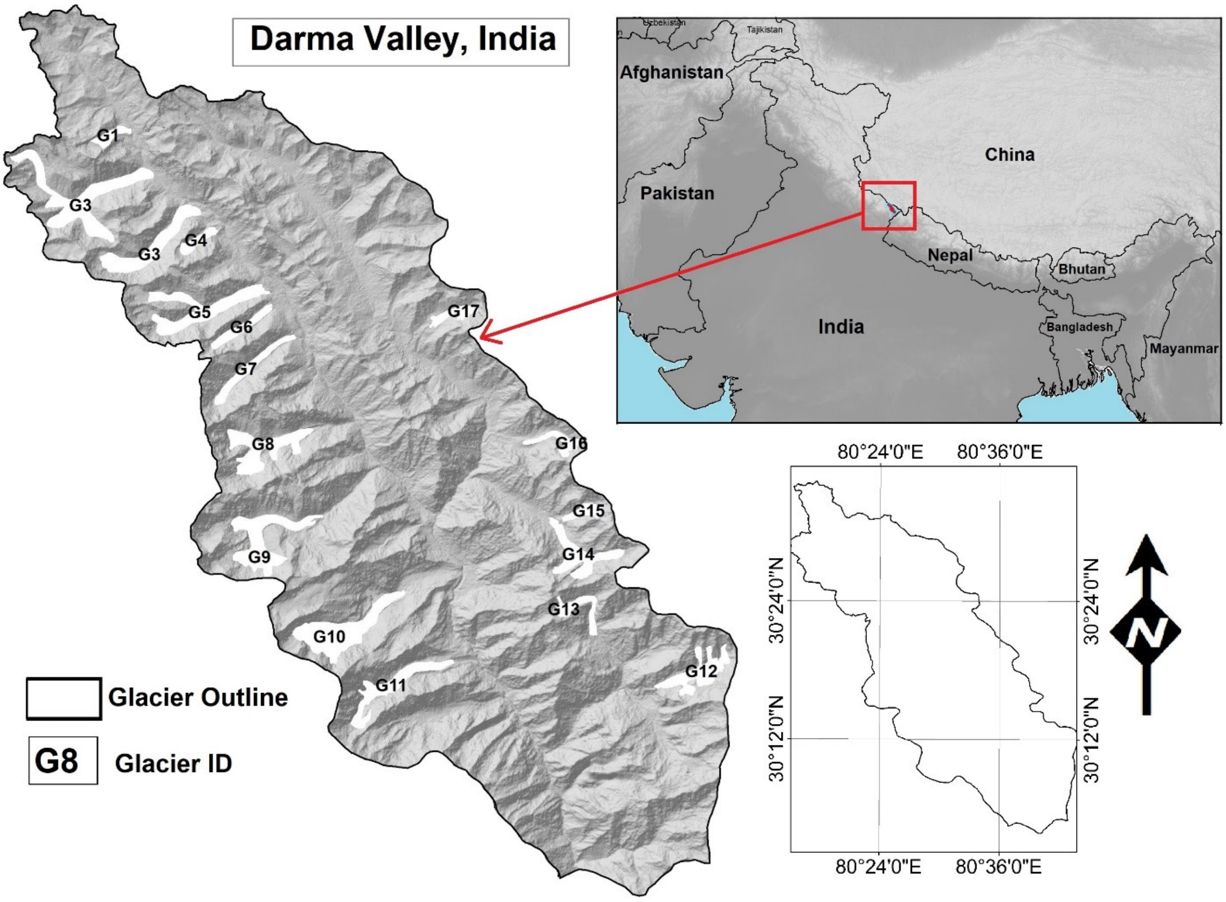

Fig. 1. Location of study area (DEM Source – Alos Palsar)

Materials and methods

Data

In this study, mapping of the glacier boundary and glacial lakes was carried out using various remote-sensing data sources, including declassified Corona KH-4A imagery, Landsat-5, Sentinel-2, and Alos Palsar DEM (see Table 1).

The declassified Corona KH-4A imagery, available on the USGS website (https://earthexplorer.usgs.gov/), offers a spatial resolution of 2.7–4 metres. These panchromatic images, provided as stereo pairs, were utilised from November 8, 1966. For image correction, 8 to 16 ground control points were selected from Google Earth for a section of the glacier area, and co-registration of all cropped images was performed in ArcMap using the georeferencing tool with a horizontal shift of 3.5 m.

High-resolution Sentinel-2 data, available at 10-m resolution (RGB & NIR), can be accessed on the European Space Agency (ESA) website (https://scihub.copernicus.eu/) and the USGS website. The data from October 18, 2020 were downloaded from the ESA website and processed using the SNAP-3 toolbox.

The Landsat-5 Thematic Mapper (TM) data, with an average spatial resolution of 30 metres, are freely available on the USGS website. The imagery used in this study dates from October 25, 1994.

The Alos Palsar DEM, freely downloadable from the Alaska Satellite Facility (https://asf.alaska.edu/) (ASF 2015), has a resolution of 12.5 m. It was employed to extract endpoints and elevations.

Google Earth Pro imagery was used to overlay the extracted glacier boundary and glacial lake data to compare with the current scenario.

All the above-mentioned remote-sensing data were systematically processed using the SNAP toolbox and ArcGIS software 10.2.2. The tools included *Co-registration* (to reduce registration error between images), *Clipping* (to extract glacier area), *Resample* (to match resolution), *Resolution merge* (to get clear texture), *Image Enhancement* (to increase brightness and clarity), and *On-screen Digitisation* (to extract glaciers outline as a vector file).

Uncertainty assessment

Inherent in remote-sensing data are sources of error and uncertainty in the measurement of glacier area, glacier terminus and glacier lake area. The primary sources of error are sensor resolution, co-registration error and digitisation error in the extraction of information. The uncertainty associated with measurement is calculated as shown below:

Glacier area change uncertainty (Ua)

The uncertainty in areal extent 'Ua' for each glacier was measured using the buffer method as described

Table 1. Satellite data used in the study

Date of Acquisition	Sensor and Scene ID	Resolution m	Swath km	Purpose
6 Nov 1966	**Corona - KH-4A** DS1048-1134DA111 DS1037-1007DA077_77 DS1037-1007DA078_78 DS1037-1007DF079_79	2.7–4	19.7 x 267	Glacier outlines, Glacier retreat
25 Oct 1994	**Landsat – 5 -TM** LT05_L2SP_145039_19941025_20200913_02_T1	30	185	Glacial lake outlines
18 Oct 2020	**Sentinel -2- MSI** L1C_T44RMU_A027801_20201018T052219	10	290	Glacial lake outlines, Glacier outlines, Glacier retreat
15 Jun 2007	**Alos Palsar** AP_07405_FBD_F0590_RT1 AP_07405_FBD_F0600_RT1	12.5	25	Contour

by Granshaw and Fountain (2006). This is a widely used and recommended for estimating uncertainty. It involves applying a buffer of up to one pixel size around the glacier margin (Granshaw and Fountain 2006; Bolch et al. 2010; Paul et al. 2013). In this approach, a buffer with a width equal to the digitisation error (0.5 pixels) was created. The uncertainty was then calculated as the average ratio of original glacier areas to areas enlarged by the buffer.

$$E_a = \sqrt{\left(\frac{Ob_a}{Tg_a}\right)^2}$$

E_a represents the error in the glacier boundary. In this context, Ob_a is the buffer area of an individual glacier, and Tg_a is the total area of the individual glacier.

To estimate the uncertainty of glacier area change (ϕ_Δ) for all the time intervals of this study, the average uncertainty of area extent of all the glaciers for various data scenes was utilised. The uncertainty in area change was estimated according to the law of error propagation using a specific formula, as outlined by Mir et al. (2017) as:

$$\phi_\Delta = \sqrt{\phi_1^2 + \phi_2^2}$$

ϕ_Δ represents the total uncertainty in all data pertaining of glacier area change, where ϕ_1 and ϕ_2 denote the uncertainties in the glacier outlines in *time frame 1* and *time frame 2*, respectively.

Glacial Lake Area Uncertainty (Ul)

Uncertainties in digitised glacial lakes from satellite imagery are calculated based on the pixel resolution and the outline (p) of the glacial lake. Given that each lake polygon was manually digitised, the estimated error in manual mapping is ~0.5 pixels (Fujita et al. 2009). This estimate is based on the nature of raster images, where pixels at the edges of two features can blend with pixels from both target and non-target features. As a result, the maximum area error in digitising the outline of a glacial lake is estimated to be ~0.5 edge pixels (Wang et al. 2020). It is assumed that the lake polygon follows a regular or Gaussian error distribution. Consequently, the error of the lake outline was calculated within one standard deviation (1σ), as per the equation provided by Hanshaw and Bookhagen (2014) and Paul et al. (2013).

$$Error\ (1\ \sigma) = (P\ /G) \cdot 0.6872\ \cdot G2/2$$

$$eP = \frac{Error\ (1\sigma)}{l_a} \times 100$$

where p is the perimeter of the glacial lake (m), G represents the spatial resolution of a satellite imagery, the coefficient 0.6872 is under 1σ, eP denotes the relative error of the glacial lake, and l_a signifies the total area of the glacial lake, as detailed by Wang et al. (2020).

Glacier Terminus Change Uncertainty (Ut)

Uncertainty in the change in glacier terminus can be measured from the error found in satellite imagery. The following formula is used to calculate uncertainty in glacier terminus:

$$U_t = \sqrt{Le_1^2 + Le_2^2} + \mu$$

U_t represents the uncertainty in glacier terminus, where 'Le_1' and 'Le_2' are the linear error/image resolutions of images and μ is the registration error. The above formula is proposed by Hall et al. (2003) and Wang et al. (2009).

The change in terminus of a glacier is measured by considering the flowline or centreline of the glacier. The centreline of the glacier is manually extracted using contours created through a digital elevation model. Therefore, the error in elevation model also incorporated into the formula. In this formula, dt represents the uncertainty in elevation data, and el denotes the error in elevation data, specifically referring to the one-sided dimension of a pixel.

$$dt = \sqrt{el^2}$$

By adding equation 6 and equation 7, we get:

$$U_t = \sqrt{Le_1^2 + Le_2^2} + \mu + (\sqrt{el^2})$$

or

$$U_t = 2\sqrt{Le_1 + Le_2 + el} + \ \mu$$
$$U_t = 2\sqrt{4_1 + 10_2 + 12.5} + \ 3.5$$
$$U_t = 13.795$$

Results

Glacier boundary delineation and change

The most accurate and widely adopted method for mapping glaciers involves manual digitisation of glaciers in satellite imagery. This approach contains fewer errors compared to automatic extraction methods. Glacier outlines are delineated using data from Corona (1966) and Sentinel-2 (2020), and changes in size are determined by comparing the data from two time points for each glacier, obtained through manual digitisation. The uncertainty in the area change for each glacier is calculated by using special formulae (referred to as *Eq. 1* and *Eq. 2*). In this study, a total of 17 glaciers were delineated (see: Fig. 2). In 1966, the combined area of all observed glaciers was 74.309 ±0.370 km^2, which decreased to 72.072 ±0.370 km^2 by 2020 (Table 2). Over the 54-year period from 1966 to 2020, there was a total decrease of 2.236 ±0.016 km^2 in glacier area, which constitutes 3.01±0.712% of total glacier area. The average annual decrease was 0.056 ±0.013% (Figs. 2 and 3).

Glacier terminus retreat

Glacier length reduction due to ice loss at the terminus is a key factor in understanding glacier responses to climate change. Besides global climate change, regional differences in topography and climate also contribute to the variability of glacier retreat. In this study, the terminal retreat of all 17 glaciers was monitored for the years 1966 and 2020. The average total retreat of all glaciers over this 54-year period is 426.93±13.79 m, with the annual rate calculated to be 7.91±0.255 m. For all glaciers, the greatest retreat was observed in glacier G10, at 1,429.74 m, and the smallest retreat was noted in glacier G16, at 12.3 m (Table 3 and Fig. 4). Glacier G10, which experienced the highest retreat, is located on a steep slope, having its terminus at an elevation of 3,501 m and extending up to 5,709 m at the glacier head. Glacier G16, showing the least retreat, has its terminus at 4,320 m and extends to the glacier head at 5,595 m.

Table 2. Change pattern in glacier area of Darma Valley in 54 years

Glacier ID	Glacier Area 1966 (km^2)	E_a (km^2)	eP ($ø^1$)	Glacier Area 2020 (km^2)	E_a (km^2)	eP ($ø^2$)	▲ in Size (km^2)	Change in%	Error in ▲ (km^2)	Tot-eP ($ø^1$+$ø^2$)
G1	1.235	±0.0103	±0.83	1.149	±0.025	±2.17	-0.086↓	-6.967	-0.0026	±3.00
G2	10.349	±0.0064	±0.06	10.090	±0.016	±0.16	-0.258↓	-2.496	-0.0006	±0.22
G3	5.812	±0.0059	±0.10	5.781	±0.015	±0.26	-0.031↓	-0.539	-0.0001	±0.36
G4	1.322	±0.0097	±0.73	1.270	±0.025	±1.99	-0.051↓	-3.886	-0.0014	±2.72
G5	7.019	±0.0071	±0.10	6.945	±0.018	±0.26	-0.074↓	-1.049	-0.0003	±0.36
G6	1.953	±0.0102	±0.52	1.944	±0.025	±1.29	-0.009↓	-0.459	-0.0002	±1.81
G7	2.641	±0.0107	±0.41	2.606	±0.027	±1.03	-0.035↓	-1.332	-0.0005	±1.43
G8	6.032	±0.0071	±0.12	5.938	±0.018	±0.30	-0.094↓	-1.557	-0.0004	±0.42
G9	7.498	±0.0064	±0.08	7.422	±0.015	±0.21	-0.076↓	-1.013	-0.0002	±0.29
G10	9.147	±0.0043	±0.05	8.548	±0.010	±0.12	-0.599↓	-6.545	-0.0010	±0.16
G11	4.950	±0.0086	±0.17	4.711	±0.021	±0.45	-0.238↓	-4.819	-0.0015	±0.63
G12	4.819	±0.0088	±0.18	4.765	±0.022	±0.45	-0.054↓	-1.122	-0.0003	±0.64
G13	2.041	±0.0118	±0.58	1.956	±0.031	±1.58	-0.084↓	-4.130	-0.0018	±2.16
G14	4.861	±0.0076	±0.16	4.634	±0.019	±0.40	-0.228↓	-4.684	-0.0013	±0.56
G15	1.425	±0.0090	±0.63	1.364	±0.022	±1.59	-0.061↓	-4.260	-0.0013	±2.22
G16	1.680	±0.0124	±0.74	1.673	±0.031	±1.82	-0.007↓	-0.409	0.0005	±2.56
G17	1.526	±0.0116	±0.76	1.275	±0.031	±2.45	-0.251↓	-16.438	-0.0081	±3.21
TOTAL	**74.309**	**±0.1478**	**0.199**	**72.072**	**±0.370**	**0.513**	**-2.236**↓	-3.009	**- 0.016**	**±0.712**

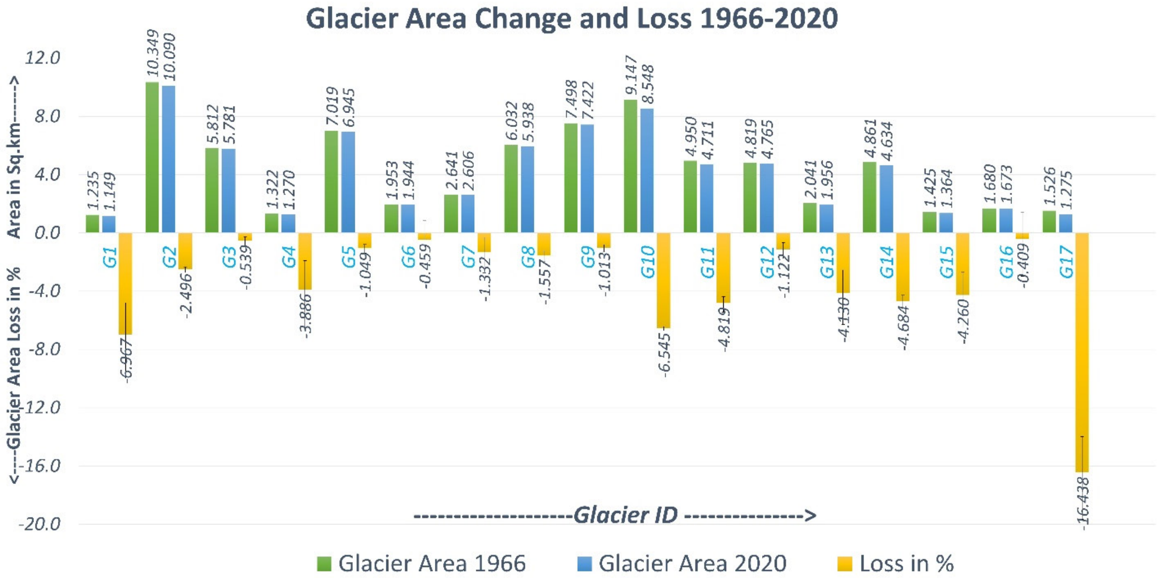

Fig. 2. Changing pattern of glacier area and loss in percentage (black line shows error)

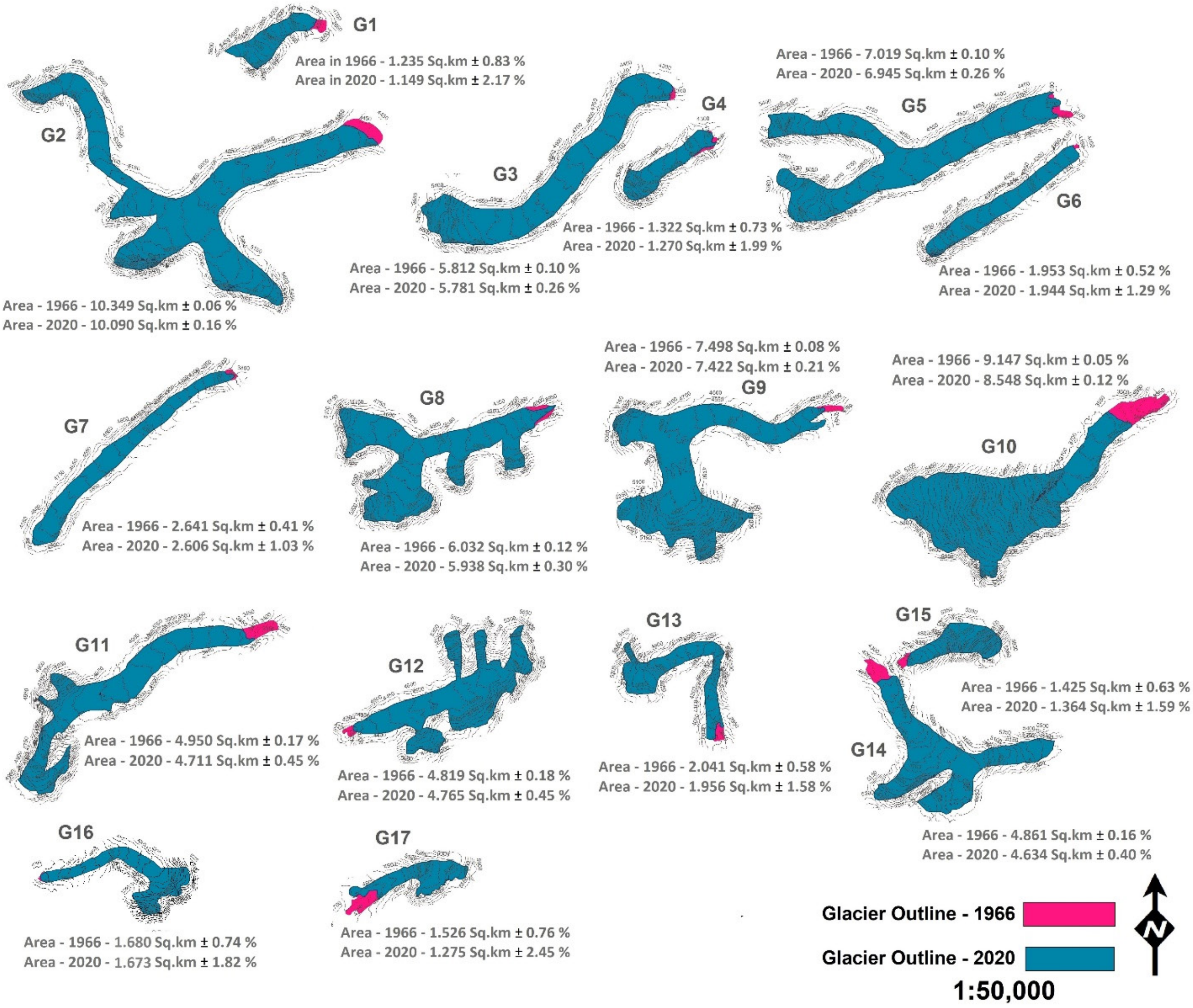

Fig. 3. Glacier outlines for the years 1966 and 2020 and glacier area change in 54 years

Table 3. Total retreat (1966–2020) and annual retreat of Darma glaciers, Uttarakhand

Glacier ID	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	Average
Total Retreat (m)	317.79	465.64	86.33	31.89	433.82	161.79	281.74	506.44	471.78	1,429.74	892.53	236	364.91	592.96	181.55	12.31	733.37	426.93 ±13.79
Annual Retreat	5.89	8.62	1.6	0.59	8.03	2.99	5.22	9.38	8.74	26.48	16.53	4.37	6.76	10.98	3.36	0.23	13.58	7.91 ±0.255

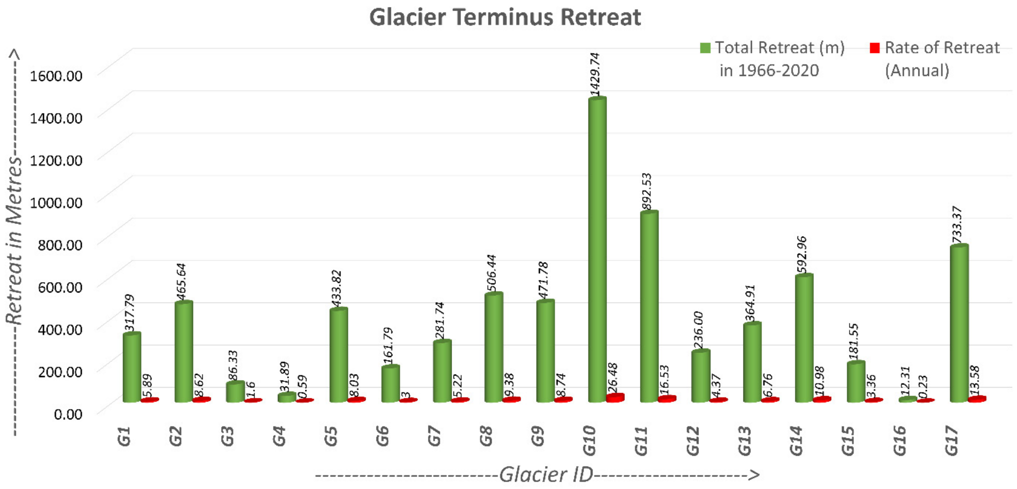

Fig. 4. Annual and total retreat of glacier (1966–2020) of Darma glaciers, Uttarakhand

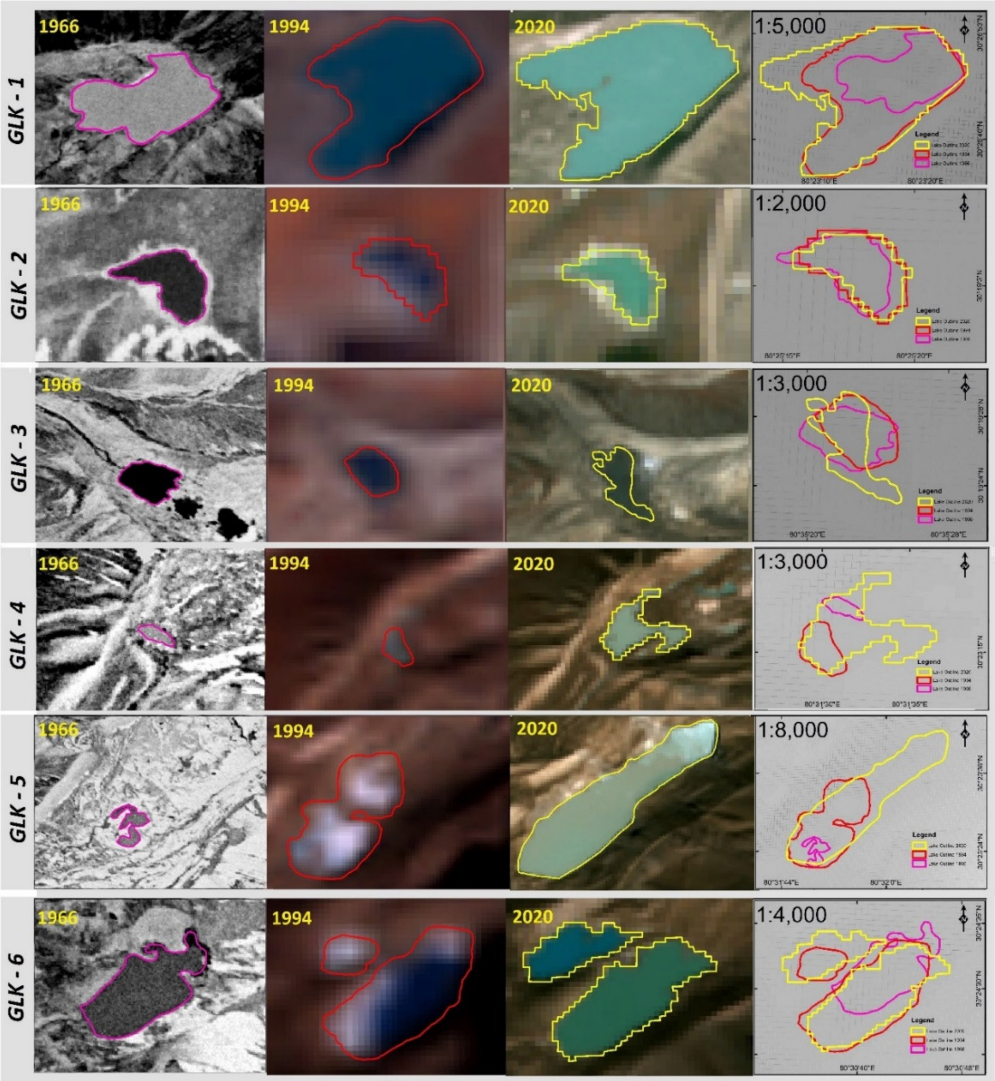

Fig. 5. Changes in glacial lake area from 1966 (Corona Imagery) to 1994 (Landsat 5) and 2020 (Sentinel-2) (Scale ratio produced with output size of 6 × 5 inches layout) (Source: own elaboration)

Glacial lakes

As the glaciers retreat, the morainic landscape becomes exposed or lakes form near the glacier tongue, sometimes posing a danger to downstream populations. Constant monitoring is crucial in glacial environments to mitigate such a threat. Although there have been numerous studies on mapping glacial lakes and their evolution in the Himalayas, a precise method for identifying the potentially hazardous lakes has still not been developed. In this study, six major glacial lakes were identified (Fig. 5) by manually digitising the rectified images of 1966, 1994 and 2020. Of all the identified glacial lakes, lake No. GLK-1 (Fig. 6) is located at an elevation of 4,750 m. Its size has increased by 184.84% during the period from 1966 to 2020. Among all glacial lakes, GLK-5 is the most expanding lake, having expanded to 2,010.7±30.26%, followed by GLK-4, expanding to 1057.4±78.64%. Lake GLK-5 formed by the merging of many small supra-glacial lakes at the margin of the glacier or within the glacier body. GLK-2 and GLK-3 are almost constant in growth (Table 4 and Fig. 5).

Discussion

In this study, Glacier G10, being the longest glacier among all glaciers, exhibited the largest area change (–0.599 km^2 ±0.16%), and is located in a steep-slope topography with an elevation range of 3,501 to 5,709 m. Among the 17 observed glaciers, G16 experienced a very small area loss of 0.007 km^2 ±2.56%, while G10 had the highest loss of 0.599 km^2 ±0.16%. Overall, a change of –3.01 ±0.712% was observed, equating to 0.056 ±0.013% annually. In addition to the effects of climate change on glacier retreat, glacier disintegration due to topography is one of the factors that increased the retreat rate.

Comparison with other glacierised high mountains in the Himalayan regions

During 1994 to 2021 in Himachal Pradesh, glacier area loss was 1.678% annually, with the decadal trend ranging from 2.31% in 1994–2001 to 1.398% in 2011–2021 (Rajat et al. 2022). The Himalayan lake-terminating glaciers rapidly retreated due to periodic frontal ice loss; during the period 1989 to 2018, glaciers showed annual retreat of 51.7 metres, equating to a total 5 km shortening of the tongue, experienced high interannual fluctuation with periods of fast and slow movement (Liu et al. 2020). Within the Chenab basin, an exhaustive analysis encompassing 324 glaciers between 1962 and 2002 revealed a concerning 11% reduction in overall glacier area. Subsequently, a follow-up study focusing on 238 glaciers during 2001–2011 documented an additional 1.1% loss. These findings underscore an escalated annual deglaciation rate

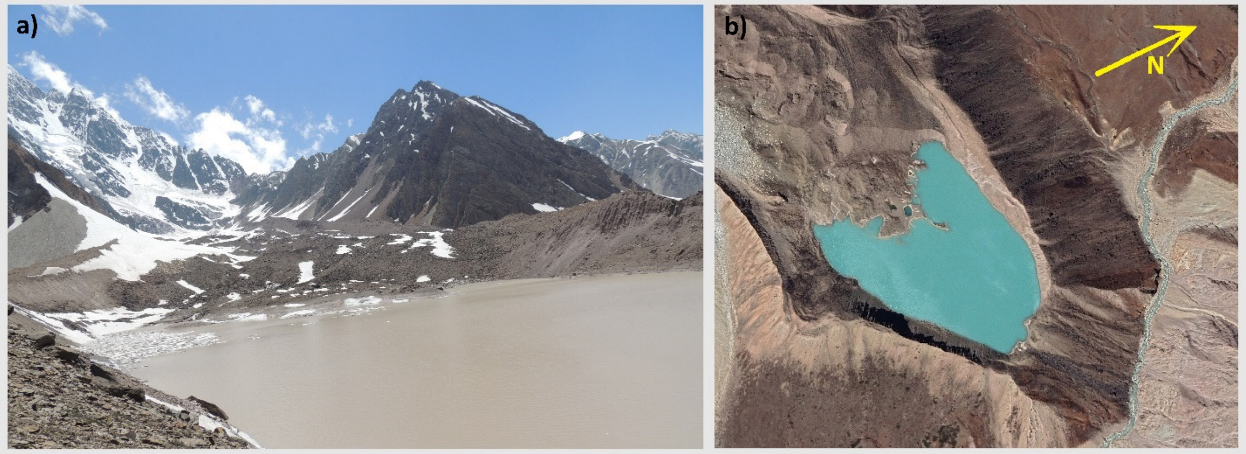

Fig. 6. Glacial Lake 1, locally known as Chho Mapang: a) ground photo taken in 2020; b) current imagery available in Google Earth. Chho Mapang, a moraine dammed glacial lake, formed prior to 1966. In the Corona imagery from 1966, its actual size was 43,965.67 ±1,366.70 m^2, and by 2020, it had increased to 124,354.17 ±7,105.72 m^2, marking a total change of 182.8% over 54 years.

Table 4. Geometrical changes in glacial lake

Glacial lake ID	Lake area -1966 (m^2)	Error (1 σ) (m^2)	eP ($ø^1$)	Lake area -1994 (m^2)	Error (1 σ) (m^2)	eP ($ø^2$)	Lake area -2020 (m^2)	Error (1σ) (m^2)	eP ($ø^3$)	Total ▲ in area (m^2)	Total error in ▲ (m^2)	▲ in%	Tot-eP ($ø^1+ø^2+ø^3$)
GLK -1	43,965.67	±1,366.70	±3.11	105,897.45	±10,077.58	±9.52	124,354.17	±7,105.72	±5.71	80,388.50↑	±14,742.47	182.84	±18.34
GLK -2	5,824.97	±500.90	±8.60	3,954.90	±1,807.69	±45.71	6,607.14	±1,483.72	±22.46	782.17↑	±600.42	13.43	±76.76
GLK -3	11,078.02	±604.95	±5.46	11,016.28	±2,721.60	±24.71	11,162.39	±2,419.64	±21.68	84.37↑	±43.74	0.76	±51.84
GLK -4	1,425.37	±230.67	±16.18	4,638.88	±1,902.12	±41.00	16,497.34	±3,539.39	±21.45	15,071.97↑	±11,852.74	1,057.4	±78.64
GLK -5	6,694.97	±898.13	±13.41	83,599.68	±10,089.33	±12.07	141,313.94	±6,754.48	±4.78	134,618.97↑	±40,740.26	2,010.7	±30.26
GLK -6	23,824.24	±1,114.91	±4.68	43,928.30	±7,676.29	±17.47	47,000.01	±5,995.48	±12.76	23,175.78↑	±8,090.82	97.28	±34.91

surpassing previous observations (Brahmbatt et al. 2017). Within the Miyar basin of the Indus drainage system, a comprehensive evaluation of 29 glaciers between 1989 and 2014 revealed a notable 4% deglaciation. This translates to an average annual loss of 0.16% across the observed period (Patel et al. 2018). A study of the Borohoro Mountains in the Tian Shan Range in China reported a decrease in glacier area at a rate of 0.61 ±0.01% per year (Li 2020). In the Hindu Kush Mountains in Afghanistan, glaciers loss was ~15% (0.6% annually) of the total glaciated area in the last 25 years during 1990 to 2015 (Joya et al. 2021). A similar long-term study of Garhwal region of the Uttarakhand Himalaya conducted by Bhambri et al. (2011) concluded that glacier area had decreased by 4.6 ±2.8% in 38 years. Another study, conducted by Salerno et al. (2017) in Sagarmatha National Park, Nepal, concluded that there was a decrease in glacier area of 4.9% between 1950 and 1990. Tibet experienced a similar loss during 1991 to 2013, while the glacier area in the Depuchangdake region of north-western Tibet decreased by 3.9% (Li et al. 2016). Additionally, a study in the Chinese region of the Sikeshu River basin in the Tienshan Mountains reported a 0.38% loss over four decades, and an average annual glacier terminus retreat of 4.9 m between 1964 and 2004 (Wang et al. 2015). Contrasting the aforementioned studies, investigations within Darma valley unveiled a comparatively modest annual reduction in glaciated terrain from 1966 to 2020. Analysis of 17 glaciers of surface areas ranging from 1.23 to 10.39 km^2 revealed an annual deglaciation rate for the valley at 0.056±0.013%. A study of the Karlik Shan in the eastern Tien Shan Mountains found a 0.13% annual decrease in glacier area from 1971 to 1992, which increased to 0.27% from 1992 to 2002, correlating with a rise in summer temperatures (Yetang Wang et al. 2009). From 1968 to 1999, the northern slope of Karakoram in the Yarkand Basin observed an annual loss of glacier area of 0.13% (Liu et al. 2006). Ren et al. (2017) reported that many glaciers on the southern slope of the Himalaya are retreating, with the retreat rate increasing recently. They also noted that, since the 1960s, the average retreat rate on the north slope of Qomolangma (Mount Everest) has been 5.5–9.5 m·a^{-1} and on Xixiabangma it is 4.0–5.2 m·a^{-1}. The air temperature over the Hindu Kush Himalaya warmed at a rate of 0.2° per decade from 1951 to 2014, and even faster at 0.5° per decade at elevations above 4,000 metres (Padma 2020).

According to Kulkarni et al. (2014), the thickness of glacial ice in the Himalaya has decreased by an estimated 19±7 m over the past four decades. This temperature rise has led to the thinning of glaciers, the loss of glacial cover and the formation of glacial lakes. A recent study of the western Himalayas shows that the area of glacial lakes has increased by 44% (Kumar et al. 2021). Research by Gobinda and Raj (2016) on 356 glacial lakes in the Uttarakhand Himalaya, using 2013 data (LISS-IV), identified that eight glacial lakes are critical in terms of their potential for outburst floods. The study observed rapid changes in glacial lakes over 54 years, noting that all the lakes surveyed are moraine reservoirs continuously receiving water from glacial melt. Lakes closer to glaciers, particularly those near glacier termini, have experienced more significant areal changes (Zhang et al. 2015a, b).

Similar studies in other glacierised regions/ high-mountain regions of the world

A similar study from the Central Andes reports that glaciated areas in the Juncal Basin declined by a total of 46±5% (or 0.76±0.08% annually) between 1956 and 2015 (Pereira and Veettil 2019). In the Rheinwald region of Switzerland, an 18% reduction in glacier area was observed for the period from 1985 to 1999, equating to 1.3% per year, noting a change in non-uniform geometry (Paul et al. 2004). In the Canadian Rocky Mountains, a study recorded a 40±5% decrease in glacier area (0.46±0.06% per year) between 1919 and 2006; it was also mentioned that, out of 523 glaciers, 17 had disappeared and 124 had fragmented (Tennant et al. 2012). Similarly, in the Mount Agrı Ice Cap, a decrease in total area of 29% (0.82% annually) was observed between 1976 and 2011, with an annual rate of 0.07 km^2 (Sarikaya 2012). For glaciers in the Bernina Group (Italy), the estimated change in glacier area during 1954–2007 was −36.5 ±2.4% (−0.688 ±0.04% annually) (D'Agata et al. 2020). In the Caucasian Mountain system, an annual glacier area changes of −1.16% was reported for the period from 2000 to 2020, with variations across its northern and southern slopes and between its western, central and eastern regions. The eastern Great Caucasus experienced the highest annual change at −1.82% (Leevan et al. 2022).

Conclusion

Historical Corona images are extremely useful for delineating glacial boundaries and glacial lakes due to their high spatial resolution. Nevertheless, the more recent Sentinel-2 MSI data, with a spatial resolution of 10 m, have also proven very useful for comparison against old data. By utilising two data frames from 1966 and 2020, it has been possible to evaluate over a 54-year period. In this study, 17 major glaciers, along with their retreat, and six major glacial lakes are analysed using remote-sensing data. During the study period of 1966 to 2020, the total loss of glacier area was calculated at 3.01±0.712%, and the largest increase in lake area was observed at 2,010.7±30.26%. Manual extraction of information has been successful in mapping and analysis because satellite data with considerable spatial resolution are openly accessible. An uncertainty analysis has also been carried out to enhance the accuracy of the results. However, it is acknowledged that the results are not completely free of error.

Acknowledgement

The authors are highly obliged and grateful for receiving the facility of the available infrastructure in the Department of Geography, Kumaun University, Nainital to carry out this work. We also thank the U.S. Geological Survey, the European Space Agency, and the Alaska Facility for providing data from Sentinel-2, Landsat, Alos Palsar DEM, and Corona. We would also like to acknowledge Google for Google Earth Pro data. Mr Masoom Reza is a recipient of doctoral fellowship (RFD/2021-22/GEN/ENV/300) from the Indian Council of Social Science Research, New Delhi and gratefully acknowledges support from this organisation.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author's Contribution

Data design: MR, RCS, data collection: MR, CN, MN, statistical analysis: MR, RCS, results interpretation: MR, RCS, manuscript preparation: MR, RCS, literature review: MR, RCS, MN.

References

ASF DAAC, 2015, ALOS PALSAR_Radiometric_Terrain_Corrected_low_res; Includes Material © JAXA/METI 2007. Accessed through ASF DAAC 28 November 2020. DOI: 10.5067/JBYK3J6HFSVF.

BAJRACHARYA SR, MOOL PK and SHRESTHA BR, 2008, *Global Climate Change and Melting of Himalayan Glaciers*. ICIMOD. The Icfai's University Press, India.

BHAMBRI R, BOLCH T, CHAUJAR R and KULSHRESHTHA S, 2011, Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. *Journal of Glaciology* 57(203): 543-556. DOI: https://doi.org/10.3189/002214311796905604.

BRAHMBHATT R, BAHUGUNA I, RATHORE B, KULKARNI A, SHAH R, RAJAWAT A and KARGEL J, 2017, Significance of glacio-morphological factors in glacier retreat: a case study of part of Chenab basin, Himalaya. *Journal of Mountain Science* 14: 128-141. DOI: 10.1007/s11629-015-3548-0.

BOLCH T, MENOUNOS B and WHEATE R, 2010, Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sensing of Environment* 114(2010): 127–137. DOI: https://doi.org/10.1016/j.rse.2009.08.015.

BOLCH T, JOSEPH MS, SHIYIN L, FAROOQ MA, YANG G, STEPHAN G, WALTER WI, ANIL K, HUILIN L, ADNAN AT, GUOQING Z and YINSHENG Z, 2019, Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region. In: P. Wester, A. Mishra, A. Mukherji, & A. Shrestha (Eds.), The Hindu Kush Himalaya Assessment. Springer. DOI: https://doi.org/10.1007/978-3-319-92288-1_7.

D'AGATA C, DIOLAIUTI G, MARAGNO D, SMIRAGLIA C and PELFINI M, 2020, Climate change effects on landscape and environment in glacierized Alpine areas: Retreating glaciers and enlarging forelands in the Bernina group (Italy) in the period 1954–2007. *Geology, Ecology, and Landscapes* 4(1): 71-86. DOI: 10.1080/24749508.2019.1585658.

GRANSHAW F and FOUNTAIN AG, 2006, Glacier change (1958–1998) in the North Cascades National Park Complex, Washington, USA. *Journal of Glaciology* 52(177): 251-256. DOI: 10.3189/172756506781828782.

HALL DK, BAYR KJ, SCHONER W, BINDSCHADLER RA and CHIEN JYL, 2003, Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893–2001). *Remote Sensing of Environment* 86(4): 566–577. DOI: 10.1016/S0034-4257(03)00134-2.

HANSHAW MN and BOOKHAGEN B, 2014, Glacial areas, lake areas, and snow lines from 1975 to 2012: Status of the Cordillera Vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru. *The Cryosphere* 8: 359–376. DOI: https://doi.org/10.5194/tc-8-359-2014.

HOELZLE M, HAEBERLI W, DISCHL M and PESCHKE W, 2003, Secular glacier mass balances derived from cumulative glacier length changes. *Global and Planetary Change* 36(4): 295-306. DOI: https://doi.org/10.1016/S0921-8181(02)00223-0.

JOYA E, BROMAND MT, MURTAZA KO and DAR RA, 2021, Current glacier status and ELA changes since the Late Pleistocene in the Hindu Kush Mountains of Afghanistan. *Journal of Asian Earth Sciences* 219: 104897. DOI: https://doi.org/10.1016/j.jseaes.2021.104897.

JI X, CHEN Y, JIANG W, LIU C and YANG L, 2022, Glacier area changes in the Nujiang-Salween River Basin over the past 45 years. *Journal of Geographical Sciences* 32(6): 1177-1200. DOI: 10.1007/s11442-022-1991-8.

KULKARNI AV and KARYAKARTE Y, 2014, Observed Changes in Himalayan Glaciers. *Current Science* 106(2): 237-244.

KUMAR V, MEHTA M and SHUKLA T, 2021, Spatially resolved estimates of glacial retreat and lake changes from Gepang Gath Glacier, Chandra Basin, Western Himalaya, India. *Journal of the Geological Society of India* 97: 520–526. DOI: https://doi.org/10.1007/s12594-021-1718-y.

LEVAN G, TIELIDZE, GENNADY A. NOSENKO, TATIANA E. KHROMOVA, & FRANK PAUL, 2022, Strong acceleration of glacier area loss in the Greater Caucasus between 2000 and 2020. *The Cryosphere* 16: 489–504. DOI: https://doi.org/10.5194/tc-16-489-2022.

LI Y, 2020, Glacier Changes and Their Linkage to the Climate-Topographic Context in the Borohoro Mountains, Tian Shan 1977–2018. *Water* 12(5): 1502. DOI: https://doi.org/10.3390/w12051502.

LINDSEY R, 2020, Climate Change: Mountain glaciers. Understanding Climate. Climate.gov. Science & Information for A Climate-Smart Nation. Available at: https://www.climate.gov/news-features/understanding-climate/climate-change-mountain-glaciers (Accessed: 11 July 2022).

LIU S, DING Y, SHANGGUAN D, ZHANG Y, LI J, HAN H, WNAG G and XIE C, 2006, Glacier retreat as a result of climate warming and increased precipitation in the Tarim river basin, northwest China. *Annals of Glaciology* 43: 91-96. DOI: 10.3189/172756406781812168.

LIU Q, MAYER C, WANG X, & NIE Y, WU K, WEI J and LIU S, 2020, Interannual flow dynamics driven by frontal retreat of a lake-terminating glacier in the Chinese Central Himalaya. *Earth and Planetary Science Letters* 546: 116450. DOI: 10.1016/j.epsl.2020.116450.

LI Z, TIAN L, WU H, WANG W, ZHANG S, ZHANG J and LI X, 2016, Changes in glacier extent and surface elevations in the Depuchangdake region of northwestern Tibet, China. *Quaternary Research* 85. DOI: 10.1016/j.yqres.2015.12.005.

MAURI SP, 2022, Recent Global Glacier Retreat Overview. Global Retreat, North Cascade Glacier Climate Project. Available at: https://glaciers.nichols.edu/glacier_retreat/ (Accessed: 12 July 2022).

MIR RA, JAIN SK, JAIN SK, THAYYEN SK JAIN, THAYYEN RJ and SARAF AK, 2017, Assessment of Recent Glacier Changes and Its Controlling Factors from 1976 to 2011 in Baspa Basin, Western Himalaya. *Arctic, Antarctic, and Alpine Research* 49(4): 621-647. DOI: 10.1657/AAAR0015-070.

PADMA TV, 2020, A future of retreating glaciers in the Himalayas. *Eos*, 101. DOI: https://doi.org/10.1029/2020EO147437.

PATEL LK, SHARMA P, FATHIMA TN and THAMBAN M, 2018, Geospatial observations of topographical control over the glacier retreat, Miyar basin, Western Himalaya, India. *Environmental Earth Sciences*, 77: 190. DOI: 10.1007/s12665-018-7379-5.

PAUL F, KÄÄB A, MAISCH M, KELLENBERGER T and HAEBERLI W, 2004, Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters* 31(21): L21402. DOI: https://doi.org/10.1029/2004GL020816.

PAUL F, BARRAND NE, BAUMANN S, BERTHIER E, BOLCH T, CASEY K, FREY H,JOSHI SP, KONOVALOV V, LE BRIS L, MÖLG N, NOSENKO G, NUTH C, POPE A, RACOVITEANU A, RASTNER P, RAUP B, SCHARRER K, STEFFEN S and WINSVOLD S, 2013, On the accuracy of glacier outlines derived from remote-sensing data. *Annals of Glaciology* 54(63): 171-182. DOI: 10.3189/2013AoG63A296.

PEREIRA SFR and VEETTIL BK, 2019, Glacier decline in the Central Andes (33°S): Context and magnitude from satellite and historical data. *Journal of South American Earth Sciences* 94: 102249. DOI: https://doi.org/10.1016/j.jsames.2019.102249.

RAJ KB and KUMAR KV, 2016, Inventory of Glacial Lakes and its Evolution in Uttarakhand Himalaya Using Time Series Satellite Data. *Journal of the Indian Society of Remote Sensing*, 44: 959-976.

RAJAT S, SINGH BR, PRAKASH C, ANITA S, 2022, Glacier retreat in Himachal from 1994 to 2021 using deep learning. *Remote Sensing Applications: Society and Environment* 28: 100870. DOI: https://doi.org/10.1016/j.rsase.2022.100870.

RATNA BS, MOOL PK and SHRESTHA BR, 2008, *Global Climate Change and Melting of Himalayan Glaciers*. ICIMOD. The Icfai's University Press, India

REN J, JING Z, PU J and QIN X, 2017, Glacier variations and climate change in the central Himalaya over the past few decades. *Annals of Glaciology* 43: 218-222. DOI: 10.3189/172756406781812230.

SARIKAYA MA, 2012, Glacier loss on Mount Agri (Ararat) and its climatic significance. *Quaternary International* 11: 279-280. DOI: 10.1016/j.quaint.2012.08.1383.

SALERNO F, BURASCHI E, BRUCCOLERI G, TARTARI G and SMIRAGLIA C, 2008, Glacier surface-area changes in Sagarmatha national park, Nepal, in the second half of the 20th century, by comparison of historical maps. *Journal of Glaciology* 54(187): 738-752. DOI: https://doi.org/10.3189/002214308786570926.

SINGH SK, RATHORE BP, BAHUGUNA IM, AJAI, 2014, Snow cover variability in the Himalayan-Tibetan region. *International Journal of Climatology* 34(2): 446–452. DOI: https://doi.org/10.1002/joc.3697.

TENNANT C, MENOUNOS B, WHEATE R, and CLAGUE JJ, 2012, Area change of glaciers in the Canadian Rocky Mountains, 1919 to 2006. *The Cryosphere* 6: 1–12. DOI: 10.5194/tc-6-1-2012.

WANG Y, HOU S and LIU Y, 2009, Glacier changes in the Karlik Shan, eastern Tien Shan, during 1971/72–2001/02. *Annals of Glaciology* 50(53): 39-45. DOI: 10.3189/172756410790595877.

WANG L, WANG F, LI Z, WANG W, LI H and WANG P, 2015, Glacier changes in the Sikeshu River basin, Tienshan Mountains. *Quaternary International* 358: 153-159.

ZHANG G, YAO T, XIE H, WANG W and YANG W, 2015a, An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global and Planetary Change* 131: 148-157. DOI: 10.1016/j.gloplacha.2015.05.013.

ZHANG Y, HIRABAYASHI Y, LIU Q and LIU S, 2015b, Glacier runoff and its impact in a highly glacierized catchment in the southeastern Tibetan Plateau: Past and future trends. *Journal of Glaciology* 61(228): 713-730. DOI: 10.3189/2015JoG14J188.

Received 11 July 2023
Accepted 4 December 2023