Research

Spatiotemporal dynamics of glacial lakes (1990–2018) in the Kashmir Himalayas, India using Remote Sensing and GIS

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Abstract

This study is perhaps the first attempt to use satellite data (1990–2018) to analyze spatiotemporal changes in glacial lakes over the Kashmir Himalayas supplemented by field studies. Landsat images were used to delineate the spatial extent of glacial lakes at four-time points, i.e., 1990, 2000, 2010 and 2018. The total count of lakes as well as their spatial extent showed a discernible increase. The number increased from 253 in 1990 to 324 in 2018, with a growth rate of 21.4%. The area has increased from 18.84 ± 0.1 km² in 1990 to 22.13 ± 0.12 km² in 2018 with a growth rate of 14.7%. The newly formed glacial lakes, including supraglacial lakes, were greater in number than the lakes that disappeared over the study period. All glacial lakes are situated at elevations of 2700 m asl and 4500 m asl. More than 78% of lake expansion in the study region is largely due to the growth of existing glacial lakes. Through area change analysis, our findings reveal that certain lakes show rapid expansion needing immediate monitoring and observation. The analysis of the meteorological variables reveals that minimum and maximum temperatures in the Jhelum basin have shown an increasing trend. $T_{\max}$ showed an increase of 1.25 °C, whereas $T_{\min}$ increased to 0.7 °C from 1980 to 2020. On the other hand, precipitation has shown a decreasing trend, which can be attributed to one of the major causes of glacier recession and the expansion of glacial lakes in the Upper Jhelum basin. Consequently, this study could play a significant role in devising a comprehensive risk assessment plan for potential Glacial Lake Outburst Floods (GLOFs) and developing a mechanism for continuous monitoring and management of lakes in the study region.

Keywords Climate change · Glacial Lake expansion · Remote sensing · Landsat imageries · GLOFs · Kashmir Himalaya · India

1 Introduction

Glacial lakes are bodies of water strongly influenced by the presence of glaciers [1] and/or retreating processes of a glacier [2]. Globally, climate variability has a significant influence on the downwasting of glaciers [3, 4] as a result of forming new glacial lakes or increasing the spatial extent of existing lakes [5–8]. With shrinking Himalayan glaciers, the high-altitude

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Table 1 Glacial Lake inventory studies in the Himalayan region

S. No	Study by	Minimum size	Satellite/sensor/resolution	No of lakes	Area of lakes km ²	Study region
1	[73]	0.0005	Resourcesat-2 LISS IV/5	1266	7.59	Uttarakhand
2	[53]	0.003	Landsat TM/ETM+/30	2168	127.61	Koshi basin
3	[19]	0.003	Landsat TM/OLI	1541	80.95	Nepal Himalaya
4	[18]	0.01	Resourcesat-2 LISS IV/5	147	5.12	Himachal Pradesh
5	[93]	0.15	Landsat TM/ETM+/OLI/30	–	37.9	Central & Eastern Himalaya
6	[74]	0.005	Landsat TM/ETM+/OLI/30	30,121	2080.12	High Mountain Asia
7	[55]	0.008	Landsat TM/ETM+/OLI/30	15,348	1395.733	High Mountain Asia
8	Present study	0.001	Landsat TM/ETM+/OLI/30	322	22.11	Kashmir Himalaya

lakes in the region are continuously evolving and growing in number and size [9–15]. Himalayan glacier recession is largely attributed to the impact of changing global climate [16–24] and topographic regimes [22]. The continuous shrinkage of glaciers, as reported in the Central Himalayas, could trigger glacial lake expansion in the future [19]. The accelerated rate of glacial lake expansion increases the risk of outbursts of glacial lakes [25–28]. Furthermore, the development of dangerous glacial lakes and the risk of outburst flooding in mountainous regions are unarguably critical concerns for South Asian countries (e.g., Nepal, China, Pakistan, Bhutan, and India) [29]. GLOF events pose a serious threat to nearby communities and built infrastructure [4, 30–32]. This was evident in the case of the 2014 Gaya GLOF event that caused destruction in terms of agricultural losses, damage to immediate infrastructure and channel defences, the major reason being the lake's potential to outburst and subsequent sudden downstream draining [33].

There have been several instances of GLOF events in the past striking the Himalayan region [30, 34–39]. The well documentation of such multiple extreme weather events acts as historic evidence to identify Himalayas as GLOF high-risk regions, e.g., Nare (Nepal) in 1977 [40]; Nagma Pokhari (Nepal) in 1980 [11, 41]; Zhangzangbo (Tibet) in 1981 [42, 43]; Dig Tsho in 1985 [44]; and Lugge Tsho (Bhutan) in 1994 [38, 45]. The recent event was an outburst flood that struck a village (Gaya) in Ladakh, India in 2014 [33]. Remote sensing has been largely a potent method for constant monitoring and timely detection of GLOFs over inaccessible mountain-bound regions, as it guides us to investigate a large area [46, 47].

To carry out an updated inventory and understanding the spatiotemporal dynamics of glacial lakes is the first important step for monitoring and assessing GLOFs in a region [6, 48, 49]. These multitemporal inventories serve as a baseline for studying the evolution, disappearance, and identification of potentially dangerous glacial lakes [50–52] as well as modelling GLOFs using various hydrodynamic models. In the Himalayan region, numerous inventories have been carried out by different authors according to their purpose of the study. For example, an inventory of 958 glacial lakes (size > 500 m²) for Himachal Pradesh (areal coverage 9.6 ± 0.3 km²) using the LISS IV data [18], a multitemporal inventory of glacial lakes in the Central Himalayas using Landsat series of data [6], mapping of 2168 glacial lakes with area 127.61 km² in Koshi basin of Central Himalayas [53], and an inventory of 1541 glacial lakes in the Nepal Himalayas with area 80.95 ± 15.25 km² [19]. Various studies that have focused on the inventories of glacial lakes in the Himalayan region are summarized in Table 1. However, to date, no exhaustive study has focused on the glacial lakes of the Jhelum Basin in particular, except for a few noteworthy studies [30, 54, 55] that have mapped some of the glacial lakes in the upper Jhelum Basin of the Kashmir Himalayas. Thus, there has been a gap in knowledge over the most recent decades. With the geographic importance of the Jhelum Basin, an updated glacial lake inventory and an analysis of spatiotemporal dynamism are needed.

To address this need, in the current study, spatiotemporal changes in glacial lakes were observed through time series Landsat imageries of the Kashmir Himalaya from 1990 to 2018. Consequently, the results were linked to the changing climatic regimes and glacier recession to understand the influence of climate change and glacier fluctuations on the expansion of glacial lakes. This is a step towards better and continuous monitoring of lake expansion in the study area, which is critical for GLOF hazard mitigation.

Fig. 1 Location map showing glacial lakes in the Kashmir Himalaya

2 Study area

Kashmir Valley is oval-shaped and has a dramatic landscape with several glaciers and glacial lakes spread over lofty mountains. Flanked by the Pir Panjal Mountains in the southwest and the Greater Himalayan range in the northeast, the study region (between $32^{\circ} 20' - 34^{\circ} 50' \text{ N}$ & $73^{\circ} 55' - 75^{\circ} 35' \text{ E}$) is in the Union Territory of Jammu and Kashmir, India^{1,2} (Fig. 1). Kashmir Valley has an area of approximately 15,948 square kilometers³ [56]. Dar et al. [57] and Ahmed et al. [58] reported that the Pir Panjal range obstructs southwestern monsoons from entering the valley, shaping the climate of the Kashmir region to a more arid-windy type in comparison to the tropical type in other parts of India. Kashmir Valley experiences four seasons: spring, summer, autumn and winter) [59] with annual average precipitation and temperature, i.e., 710 mm, 13.5°C , while receiving enormous precipitation during winter months (December–February) due to western disturbances [57, 60]. Lakes formed during the time of deglaciation preceded by cold conditions in the Kashmir Himalayas [61].

There are large reserves of glaciers and glacial lakes in North Kashmir that also contribute to the Jhelum River. Jhelum is one of the main tributaries of the Indus basin and acts as a lifeline to the Kashmir valley [22]. The altitude of the study area ranges from 1065 to 5441 m asl.

¹ <https://www.britannica.com/place/Vale-of-Kashmir>.

² https://en.wikipedia.org/wiki/Kashmir_Valley.

³ http://jkforest.gov.in/geo_area.html.

Table 2 Satellite data used

Date of pass	Satellite & sensor	Bands & wave-length (μm)	path/row	Spatial resolution (m)	Repeat cycle (days)	Cloud cover
14 Oct. 1990	Landsat TM	6	149/36	30	16	No
09 Oct. 2000	Landsat TM	6	149/36	30	16	
18 Oct. 2010	Landsat ETM+	8	149/36	30	16	
04 Oct. 2018	Landsat L8 (OLI)	9	149/36	30	16	

Thematic Mapper TM. Enhanced Thematic Mapper ETM. Operational Land imager OLI

3 Methodology

3.1 Datasets

Landsat data have been extensively utilized for the purpose of delineation and mapping glacial lakes due to their free availability, 30 m resolution and wide area coverage [62–65]. Landsat images of 30 m resolution and the Advanced Spaceborne Thermal Emission & Reflection Radiometer—Digital Elevation Model (ASTER DEM, 30 m) downloaded from the web portal were used in the present study (Table 2). The Landsat images hosted by the Global Land Survey (GLS) data system of the United States Geological Survey (USGS) were downloaded from their web portal⁴ and used for the current study. Glacial lakes show minor changes in the post-monsoon season with limited cloud and snow cover [66]. Landsat scenes used in the study were from the post-monsoon season with less cloud coverage (< 10%) or were cloud-free. The Landsat images from 1990 to 2018 were used to prepare glacial lake inventories for area change analysis. Validation of glacial lake boundaries for 1990 was performed using the Survey of India (SOI) toposheet 1979, Scale 1:50,000. The SOI toposheets alone are less reliable for change detection analysis [50]; hence, the Landsat TM (1990) scene has been used as a base image for glacial lake area change.

To validate the glacial lake outlines, Google Earth imagery of high resolution was used because of the comparatively coarser resolution of the Landsat data. The time series of meteorological data (e.g., temperature and precipitation) from 1980 to 2020 of the Pehalgam weather station was analysed to understand climate as a possible influencing factor for glacial lake changes in the study area.

3.2 Glacial lake mapping

A number of methods (processing satellite imagery) have been used for mapping glacial lakes over time. The two commonly used methods are automated and semiautomated methods, e.g., the normalized difference water index (NDWI) [25, 63, 67–69]. In the present study, we used the normalized difference water index NDWI—first proposed in 1996 by McFeeters [70] using a semiautomated method similar to [46] for delineation of glacial lake outlines (Fig. 2; Eq. 1).

$$NDWI = \frac{BNIR - Bblue}{BNIR + Bblue} \quad (1)$$

*BNIR and Bblue are reflectance in the near infrared and blue bands, respectively.

Pixel identification pertaining to the lakes was performed based on NDWI values in the range of −0.60 to −0.85 [48]. A few mountain-shadowed areas were mistaken as lakes due to the same spectral reflectance and topographic effects [19, 53]. Misclassification could occur due to near similarities between glacial lakes from frozen lakes and snow cover because of peculiar surface conditions. The pixels identified as mountain shadows were removed from ASTER DEM-derived values for slope, aspect and hill shade in NDWI images to overcome misclassification of lakes because of topographic effects.

Further correction was performed through a visual interpretation technique using ArcGIS 10.2 [19, 28, 49, 66, 71, 72]. Through this process, the first glacial lake layer in 2018 was prepared. The glacial lake outlines were overlaid with Google Earth imagery for validation and later crosschecked with the toposheet glacial lake inventory generated from SOI toposheet 1979 at a scale of 1:50,000. Corrections, if any, were taken on priority. Subsequently, glacial lake

⁴ www.earthexplorer.usgs.gov.

Fig. 2 Flowchart showing the process of glacial lake mapping for area change detection

inventories for 2010, 2000 and 1990 were prepared to obtain the final database to observe glacial lake expansion in the study area (Fig. 2).

3.3 Glacial lake classification

Classification of glacial lakes plays an important role to know the location and to understand the origin and evolution of glacial lakes. Glacial lake characteristics which include phases of lake formation, constituents of dam material, glacier proximity, moraines, outwash plains and other geomorphological features should be taken into consideration at the time of classification of glacial lakes [73]. Although, numerous approaches of glacial lake classification [6, 49, 55, 66, 68, 74–77] are present in the scholarly literature. However, as of now there has been no internationally accepted method for the classification system of glacial lakes. In the present study classification of glacial lakes was carried out by using methodology as suggested by [55, 66, 74, 78] with certain modifications. Subsequently, glacial lakes were classified into three major types as:

1. Unconnected glacial lakes: lakes that are not connected or directly-fed by the glacier e.g., glacier erosion lakes (cirque erosion lake, glacier trough valley erosion lake and other glacier erosion lakes).
2. Supraglacial lakes: lakes that are formed on the surface of the glacier.
3. Proglacial lakes: lakes which are generally dammed by moraines and are in contact with the glacier or in the vicinity of the glacier. Here in this study lakes which are directly fed by the glaciers are also classified in this category as in case of Refs. [55, 74].

Fig. 3 a and b showing number and area of glacial lake type

3.4 The uncertainty analysis

In the present study, glacial lakes were identified, delineated, and mapped to observe changes in spatial extent using multirate/multisensor remote sensing data. Uncertainties in glacial lake mapping occur mainly due to image coregistration, area delineation and editing using manual interpretation. As a result, thorough consideration of errors is required to determine the accuracy and relevance of the findings. High-resolution satellite imagery would be the most precise way to assess the errors related to glacial lake outlines [50]. However, high-resolution satellite data were not available for the present research work. Therefore, we used Landsat satellite data in conjunction with high-resolution Google Earth imagery to maintain the accuracy of glacial lake boundaries. The primary errors of coregistration and lake outlines that could have resulted in various levels of accuracy were considered in this study. Most of the Landsat scenes have similar resolutions. The glacial lakes are clear on almost all the scenes utilized in the study with less snow and cloud cover, and the manually delineated lake boundaries were checked two times simultaneously by a single operator.

Initially, Landsat ETM+ images were merged with Pan images with high resolution to create a high-resolution pansharpened image by employing the methodology suggested by [21, 50]. All other images were coregistered with the pansharpened ETM+ image within 7.5 m for TM and OLI images, using it as the base map. Consequently, after the image coregistration, geometrical rectification of all images was carried out with the same projected coordinate system of WGS 1984 UTM Zone 43. The remote sensing uncertainty formula [21, 32] was used to estimate the terminus change uncertainty (U).

$$U = \sqrt{a^2 + b^2 + \sigma} \quad (2)$$

where a and b are the resolutions of the image and σ is the co-registration error of the images to the base image in Eq. (2). We estimated a terminus accuracy of 47.3 m for Landsat TM and ETM+ and 49.6 m for OLI images.

The uncertainties related to lake area have also been estimated through Eq. (3), as suggested by Yao et al. [8].

$$U_{\text{area}} = 2UV \quad (3)$$

where U and V are the glacier area uncertainty and pixel resolution, respectively.

In this way, the area uncertainties of the glacial lakes were found to be 0.003 km² (0.3%) for TM and ETM+ and 0.0025 km² (0.25%) for OLI images. Thus, the overall uncertainty was estimated to be 0.005 km² (0.55%), which are well or below the previously reported acceptable ranges [21, 50, 79].

Fig. 4 Showing types of glacial lakes. **a–c** Proglacial Lakes. **d, e** Supraglacial Lake and **f** unconnected glacial lakes

4 Results and discussion

4.1 Glacial lakes in 2018

Using Landsat (OLI) imagery from 2018 with 30 m spatial resolution, a total of 324 glacial lakes were identified in the UJB, with a total calculated area of approximately 22.11 km². The area of the glacial lakes varied from 0.001 to 1.65 km² with an average size of 0.06 km². Glacial lakes in the region are not evenly distributed, the majority of glacial lakes are located in the Sindh and Lidder catchments of the basin, accounting for almost 68% of the total lakes. The Gangabal lake located in Sind watershed possesses the highest area of 1.67 km², whereas lowest area was found to be 0.001 Km² for Dont-Sar Lake in Vaishav catchment.

Of the total glacial lakes mapped for the year 2018, 76 are proglacial lakes (generally moraine dammed, ice dammed lakes and other moraine dammed lakes fed by the glacier) 241 unconnected glacial lakes that are not fed by the glaciers (Cirque lakes and other erosion lakes) and 7 glacial lakes were identified as supraglacial lakes (developed on the surface of glaciers) (Fig. 3a). Unconnected glacial lakes cover the highest area 13.42 km² which is approximately 61% of the total area of glacial lakes in the basin. Proglacial lakes and supraglacial lakes accounts 8.64 km² (39%) and 0.07 km² (0.3%) of the total area respectively (Fig. 3b). The representation of glacial lake types is depicted in (Fig. 4).

The majority of the glacial lakes are small in size, i.e., less than 0.1 km² contributes 271 of the total number and 5.67 km² of the total area, which are 83.64% and 25.64%, respectively. Lakes with sizes greater than 0.1 km² constitute only 52 in number but contribute 16.54 km² of area, which is approximately 75% of the total surface area of the glacial lakes in the study region. Lakes with an area > 0.1 km² are considered dangerous because they possess an enormous volume of water to cause a flash flood in the downstream region [80, 81]. Among 52 lakes greater than 0.1 km² 19 are proglacial lakes and 33 are unconnected glacial lakes. The details of the glacial lakes greater than 0.1 km² in the study region are mentioned in Table 3. All glacial lakes in the study area are located at an elevation range between 2700–4500 m asl. The majority of glacial lake area, i.e., 68%, is concentrated in the elevation zone of 3650–4150 m.

Table 3 Characteristics of glacial lakes with sizes > 0.1 km²

S. No	Local name	Latitude	Longitude	GLIMS_Lake_ID	Watershed	Area Km ²	Elevation (m)	Type	Length (m)	Width (m)
1	Dudh Nag	34° 11' 31.75"	75° 19' 12.96"	G034192E75320N	Lidder	0.102	3704	PGL	512.130	253.290
2	Raman Sar	34° 21' 39.60"	75° 08' 34.80"	G034361E75143N	Sind	0.102	3925	PGL	497.790	271.630
3	–	34° 38' 45.60"	75° 10' 37.20"	G034646E75177N	Sind	0.105	4208	UCL	506.000	217.960
4	Chitti chhan Sar	34° 28' 12"	74° 54' 46.80"	G034470E74913N	Madhumati	0.112	3807	UCL	561.190	271.270
5	Yamhar Sar	34° 12' 28.80"	75° 09' 03.60"	G034208E75151N	Sind	0.113	3763	PGL	498.040	301.820
6	Chohar Nag	33° 45' 14.40"	75° 28' 08.40"	G033754E75469N	Arapal	0.115	3894	UCL	399.760	461.640
7	–	33° 31' 40.80"	74° 33' 39.60"	G033528E74561N	Rambiahra	0.123	4053	UCL	430.250	386.070
8	Chiamar Sar	34° 22' 48"	74° 52' 33.60"	G034380E74876N	Erin	0.126	3711	PGL	592.890	388.240
9	Chand Sar	34° 09' 21.60"	75° 07' 01.20"	G034156E75117N	Lidder	0.126	3917	UCL	368.750	391.710
10	Sursyar	33° 34' 06.00"	74° 31' 22.80"	G033735E74523N	Dodhganga	0.127	4024	PGL	526.340	328.950
11	–	33° 30' 18.00"	74° 35' 34.80"	G033505E74593N	Rambiahra	0.131	4041	UCL	557.600	274.310
12	Kotori Sar	33° 31' 19.20"	74° 36' 18.00"	G033522E74605N	Rambiahra	0.131	3803	UCL	603.760	249.650
13	–	34° 29' 20.40"	74° 54' 21.60"	G034489E74906N	Madhumati	0.133	4061	UCL	554.030	378.790
14	Andaun Sar	34° 27' 07.20"	74° 55' 55.20"	G034452E74932N	Sind	0.135	3854	UCL	640.450	304.600
15	Tson	34° 03' 46.80"	75° 12' 57.60"	G034063E75216N	Lidder	0.137	3685	UCL	594.910	278.260
16	Kaul Sar	34° 23' 06.00"	74° 56' 38.40"	G034385E74944N	Sind	0.139	3685	UCL	682.280	317.440
17	Barani Sar	33° 31' 48.00"	74° 34' 26.40"	G033530E74574N	Rambiahra	0.151	3913	UCL	550.450	375.730
18	–	33° 49' 44.40"	74° 26' 06.00"	G033829E74435N	Ferozpur	0.152	4006	UCL	750.450	289.510
19	Daman Sar	33° 51' 57.60"	74° 24' 57.60"	G033866E74416N	Ferozpur	0.153	3912	UCL	467.960	424.220
20	Bramsar	33° 30' 07.20"	74° 51' 00.00"	G033502E74850N	Vaishav	0.155	3574	PGL	519.250	385.250
21	Watal Sar	34° 27' 25.20"	74° 59' 12.66"	G034457E74986N	Sind	0.158	3715	PGL	972.620	290.210
22	Logul Sar	34° 26' 52.80"	74° 54' 28.80"	G034448E74908N	Sind	0.172	3941	UCL	569.140	363.570
23	Chandan Sar	33° 33' 00.00"	74° 32' 31.20"	G033550E74542N	Rambiahra	0.173	3872	UCL	523.620	350.000
24	Handil Sar	34° 12' 07.20"	75° 12' 18.00"	G034202E75205N	Lidder	0.183	3668	PGL	783.760	268.000
25	Chhumhai Sar	34° 05' 34.80"	75° 09' 36.00"	G034093E75160N	Lidder	0.188	3886	UCL	770.840	402.200
26	–	34° 11' 02.40"	75° 22' 19.20"	G034184E75372N	Sind	0.188	4253	PGL	557.360	297.840
27	Son-Sar	34° 14' 02.40"	75° 16' 30.00"	G034234E75275N	Lidder	0.191	3799	UCL	909.800	312.450
28	Sona Sar	34° 04' 01.20"	75° 28' 30.00"	G034067E75475N	Lidder	0.191	3697	PGL	961.490	248.280
29	Sorus Nag	33° 57' 10.80"	75° 22' 40.80"	G033953E75378N	Lidder	0.202	3617	UCL	469.750	490.000
30	Charl Nag	33° 55' 44.40"	75° 23' 20.40"	G033929E75389N	Lidder	0.210	4012	UCL	1001.160	300.910
31	Goli Sar	33° 32' 24.00"	74° 33' 54.00"	G033540E74565N	Rambiahra	0.224	3923	UCL	571.680	528.340
32	Nandan Sar	33° 33' 32.40"	74° 31' 33.60"	G033559E74526N	Rambiahra	0.271	3816	UCL	912.740	401.440
33	Pam Sar	33° 49' 12.00"	74° 27' 03.60"	G033820E74451N	Ferozpur	0.285	3962	UCL	1008.150	339.790
34	Sarbal Sar	34° 23' 21.20"	74° 55' 22.80"	G034392E74873N	Erin	0.288	3522	UCL	1044.620	438.960
35	Nabler Sar	34° 32' 52.80"	74° 49' 08.40"	G034548E74819N	Madhumati	0.316	3843	UCL	1214.650	346.060
36	Krishan Sar	34° 23' 49.20"	75° 06' 10.80"	G034397E75103N	Sind	0.321	3783	UCL	922.840	479.100
37	Patalwan Sar	34° 32' 13.20"	74° 49' 37.20"	G034537E74827N	Madhumati	0.324	3891	UCL	973.260	545.690

Table 3 (continued)

S. No	Local name	Latitude	Longitude	GLIMS_Lake_ID	Watershed	Area Km ²	Elevation (m)	Type	Length (m)	Width (m)
38	Laksukh Sar	33° 32' 13.20"	74° 33' 14.40"	G033537E74554N	Rambiahra	0.324	3971	UCL	1007.250	323.060
39	Har Nag	34° 08' 20.40"	75° 22' 37.20"	G034139E75377N	Sind	0.333	3675	PGL	1098.600	410.750
40	Salnai Sar	34° 26' 38.40"	74° 53' 31.20"	G034444E74892N	Madhumati	0.356	3814	PGL	992.650	440.620
41	Dhaklar Sar	33° 30' 32.40"	74° 37' 26.40"	G033509E74624N	Rambiahra	0.362	3905	PGL	932.130	575.800
42	Nund Kol	34° 25' 04.80"	74° 56' 06.00"	G034418E74935N	Sind	0.389	3459	PGL	1314.800	338.810
43	Gadsar	34° 25' 19.20"	75° 03' 28.80"	G034422E75058N	Sind	0.403	3722	PGL	870.830	626.450
44	Madmatti Sar	34° 29' 34.80"	74° 55' 15.60"	G034493E74921N	Madhumati	0.409	3841	UCL	1316.640	504.590
45	Mar Sar	34° 08' 38.40"	75° 06' 50.40"	G034144E75114N	Lidder	0.451	3788	UCL	1180.800	489.120
46	Bodh Sar	33° 50' 27.60"	74° 25' 40.80"	G033841E74428N	Ferozpur	0.472	3919	PGL	1555.440	574.640
47	Vishan Sar	34° 23' 16.80"	75° 07' 08.40"	G034388E75119N	Sind	0.480	3632	PGL	1083.540	712.350
48	Shesh Nag	34° 05' 34.80"	75° 29' 49.20"	G034093E75497N	Lidder	0.553	3546	UCL	1118.000	745.030
49	Bhag Sar	33° 31' 08.40"	74° 34' 58.80"	G033519E74583N	Rambiahra	0.730	3893	UCL	1507.630	659.330
50	Tar Sar	34° 08' 24.00"	75° 09' 03.60"	G034140E75151N	Lidder	0.872	3800	UCL	1733.570	601.200
51	Konsar Nag	33° 30' 43.20"	74° 46' 08.40"	G033512E74769N	Vaishav	1.376	3463	PGL	2912.750	645.230
52	Gangabal Lake	34° 25' 55.20"	74° 55' 26.40"	G034432E74924N	Sind	1.654	3534	PGL	2754.890	840.150

UCL Unconnected glacial lakes, PGL proglacial lakes

Table 4 Glacial Lake count and area in 1990, 2000, 2010 and 2018

Area range (km ²)	1990		2000		2010		2018		1990–2018 Change	
	Count	Km ²	Count	Km ²	Count	Km ²	Count	Km ²	Count	Km ²
≤ 0.01	103	0.49	112	0.57	110	0.60	121	0.59	18	0.10
0.01–0.05	77	1.70	82	1.92	124	2.94	115	2.68	38	0.98
0.05–0.10	25	1.72	25	1.84	27	2.01	34	2.42	09	0.70
0.10–1.0	46	12.20	46	12.23	47	12.52	50	13.42	04	1.22
> 1.0	02	2.73	02	2.75	02	2.96	02	3.00	0	0.27
Total	253	18.84	267	19.31	310	21.03	324	22.11	71	3.27

Fig. 5 a, b show area changes in two major glacial lakes within the study area**Table 5** Newly formed glacial lakes and extinct lakes from 1990 to 2018

Year	Total number	Total change area (km ²)	Newly formed		Disappeared		Existing		Contribution of the area change (%)
			Number	km ²	Number	km ²	Number	Change km ²	
1990	253	–	–	–	–	–	–	–	–
2000	267	+0.47	10	0.15	4	0.08	253	0.40	85.10
2010	310	+1.72	36	0.47	7	0.10	260	1.36	79.06
2018	324	+1.09	11	0.13	3	0.06	307	1.01	93.51

4.2 Glacial lake expansion (1990–2018)

The glacial lakes in the Kashmir Himalayas evolved and increased in number and size over time, particularly from 1990 to 2018, with 253 (18.84 ± 0.02 km²), 267 (19.31 ± 0.02), 310 (21.03 ± 0.02), and 324 (22.13 ± 0.002 km²) glacial lakes identified and mapped in 1990, 2000, 2010, and 2018, respectively. The total lake area has increased by 3.28 ± 0.013 km² (14.8%) in last three decades. The total area has increased by $0.10 \text{ km}^2 \pm 0.013$ for glacial lakes with size ≤ 0.01 , $1.22 \text{ km}^2 \pm 0.013$ with size > 0.10 km² and ≤ 1.0 km² and 0.27 ± 0.013 km² with size > 1.0 km² from 1900–2018 (Table 4, Fig. 5). Hence, the small glacial lakes have contributed less to the total area change, i.e., expanded more slowly than

Table 6 Total increase in the area of major glacial lake types from 1990–2018

Type	Number		Area Km ²		Change (1990–2018)	
	1990	2018	1990	2018	Number	Area Km ²
Proglacial lakes	57	76	6.36	9.04	19	2.68
Supra-glacial lakes	1	7	0.003	0.07	6	0.067
Unconnected glacial lakes	195	241	12.49	13.02	46	0.53
Total	253	324	18.85	22.13	71	3.28

Fig. 6 Photographs taken during the field visit of the study area showing various types of glacial lakes: **a** supra-glacial lakes, **b**, **d** and **f** cirque lakes, **c** and **e** moraine and ice dammed glacial lakes and **g** on field DGPS observations

the large ones, similar to what [6] reported in the Central Himalayan region. The smaller lakes are so dynamic that they appear and disappear over time (Table 4, Fig. 5), as confirmed by [53].

More than 78% of existing glacial lakes show an obvious increase in the spatial extent over the 28-year study period. The processes of glacial lake area change were intricate, consisting of expansion in areas of larger glacial lakes as well as the appearance and disappearance of small glacial lakes. Newly developed glacial lakes were found three times more in number than glacial lakes that were extinct, i.e., $57 > 14$ over time.

The newly formed glacial lakes, therefore, have a small contribution to lake expansion in the Kashmir Himalaya. (Table 5), similar to the Central Himalayas reported by [6].

The study reveals that the proglacial lakes showed greater expansion in comparison to supraglacial and unconnected glacial lakes, the latter being dynamic in nature. Proglacial lakes increased lesser in number i.e., 19 as compared to the unconnected glacial lakes which have increased from 195 (12.49 km²) in 1990 to 241 (13.02 km²) in 2018. The unconnected glacial lakes show lower expansion rates, i.e., 0.53 km² (16.2%) of an overall increase in lake area. On the other hand, proglacial lakes have shown highest expansion rate of 2.68 km² (82%) over the period of 28 years. Supraglacial lakes are very less in the study area accounts 7 of the total number and 0.067 km² of the total area. The area of supraglacial lakes has increased from 0.003 km² to 0.07 km² from 1990 to 2018, thus showing an overall increase of 0.067 km² which is 2% of the total growth of area (Table 6).

4.2.1 Altitudinal differences

Altitude is an important controlling factor for the change in surface area of glacial lakes [58, 82]. All the identified glacial lakes in the study region were normally distributed between 2700 and 4500 m asl. The majority of them were

concentrated in the elevation range of 3800 m asl to 4300 m asl. This is largely due to an enabling environment and peculiar geomorphological setting for glacial lake development in the study region. Hence, maximum glacial lake changes ($\geq 91\%$) occurred at elevations between 3800 and 4300 m asl from 1990 to 2018. The area of glacial lakes has also shown variation in terms of different altitudinal ranges. Glacial lakes below 2900 m asl and above 4500 m asl share a minimum number and area of lakes, whereas the majority of the glacial lake area, i.e., 68%, is concentrated between the elevation zones of 3650–4150 m asl.

4.2.2 Field investigations

Field measurements of high-altitude lakes are difficult to accurately ascertain in steeply edged mountainous remote areas [68]. Field study experiences, however, still confirm the location, shape and size of such lakes. To supplement our study, we conducted a five (05) day field visit to glacial lakes in the study area from 7–11 October 2019.

During our visit, we could only identify a sizable number of glacial lakes due to inaccessibility issues and hostile conditions in the study region. We identified lakes broadly classified as supra glacial, cirque, moraine and ice dammed glacial lakes (Fig. 6a–f) and crosschecked them with the first glacial lake inventory prepared from Landsat images for 2018 to make corrections in lake outlines and obtain the final glacial lake inventory for 2018. Furthermore, various glacial lake parameters, such as latitude, longitude, and elevation, were taken using a differential global positioning system (DGPS). A laser distance meter (LDM) was used to calculate the length and width of the lakes. Various geomorphological parameters of lakes identified during the field investigation are presented in Fig. 6a–f. The main purpose of the field investigation of selected lakes was to validate the inventoried glacial lakes on the ground. The coordinates taken during the field visit of selected lakes showed a minor error in terms of location. The elevation on the ground and elevation derived from the DEM also showed a minor error of approximately 4–10 m. For example, Gangabal Lake, which is located in the Sind catchment, has an elevation of 3534 m derived from the DEM, whereas DGPS on the ground has shown an elevation of 3537 m. Similarly, Sheshnag in the Lidder catchment has a DEM-generated elevation of 3564 m, whereas it has shown 3573 m on the ground.

4.3 Possible causes of glacial lake changes

The meltwater of glaciers makes a significant contribution to glacial lake growth in the Himalayan region [6], in which proglacial lakes show an obvious increase in expansion with increasing meltwater [13, 68, 83, 84]. Ice or glacial melt water drives the expansion of proglacial lakes in the region. The climatic variables (e.g., temperature and precipitation) of the Kashmir valley show substantial changes from 1980–2014 [85], with an increase in mean maximum and minimum temperatures and annual precipitation showing a downward trend from 1980 to 2018 [72]. The observed extreme warm temperatures in the past have resulted in the remarkable retreat of glaciers in the Western Himalayas [60, 86–88]. Understanding that assessing climate change impact on glacial lakes is a tedious process and cannot singly be a reason for glacial lake expansion [68], the melting of glaciers in the Central Himalayas is exacerbated by the presence of increased light trapping particles (such as black carbon and dust) that may also contribute to the development of glacial lakes [89].

Our study used historical observed meteorological data from the Pahalgam weather station (2310 masl) for 1980 to 2020 obtained from the Indian Meteorological Department, Meteorological Centre Srinagar to analyse the temperature and precipitation trends in the study region. The analysis of climatic data revealed that the minimum and maximum temperatures have shown an increasing trend, whereas precipitation has shown a decreasing trend by using non-parametric Mann–Kendall test and Theil–Sen method at 95% of confidence level. $T_{\max}$ showed an increase of 1.25 °C, whereas $T_{\min}$ increased to 0.7 °C from 1980 to 2020 (Fig. 7a). $T_{\max}$ is increasing at the rate of 0.03 °C/year and $T_{\min}$ at 0.017 °C/year. On the other hand, precipitation has shown a decreasing trend – 1.69 °C/year (Fig. 7b), which can account for a major cause of glacier recession and subsequent lake expansion in the study region. Although there could be various underlying causes for such changes, climatic variability appears to be a possible cause for glacial lake changes in the study region.

5 Discussions

The Himalayan cryosphere acts as a major source of water for downstream regions and has important interconnections with ecosystems and socioeconomic benefits [9, 30]. Glaciers and glacial lakes in the Jhelum Basin of the Kashmir Himalayas are vital sources to headwaters of the Indus River basin and supports hydropower generation, irrigation, domestic

Fig.7 Trends in the essential climatic variables in the study area (1990–2018). **a** Annual minimum, maximum, average temperature. **b** Annual precipitation

uses and tourism in the downstream areas [57]. With increasing temperatures in the Himalayan region under the global climate change, glaciers are melting at an enhanced rate, leading to the formation and expansion of various types of glacial lakes.

The total count of glacial lakes mapped in the study region as well as their spatial extent showed a discernible increase. The number has increased from 253 in 1990 to 324 in 2018, with a growth rate of 21.4%. The area has increased from 18.84 km² in 1990 to 22.13 km² in 2018 with a growth rate of 14.7%. The newly formed glacial lakes, including supra glacial lakes, were greater in number than the lakes that have disappeared over time. Lake expansion is not limited to

the North-Western Himalayas, the phenomenon has also been witnessed in other parts of the Himalayan region and has been well documented in the scholarly literature, for example Central Himalayas have shown an expansion rate of 24% [90], Nepal 25% [19], Namco basin 16.7% [91], Koshi basin 31.5% [53], Entire Third Pole 23% [28], Chandra basin 41.41% [92] and Nepal and Bhutan 20–60% [68].

The classification of glacial lakes becomes problematic when there are several studies that classify/categorize lakes differently based on certain characteristics and no common consensus is developed to standardise a selection criterion and overcome such a problem. In the present study, we classified glacial lakes as (1) Unconnected lakes; (2) Proglacial lakes; and (3) Supra-glacial lakes after the methodology adopted by major studies such as [55, 66, 74, 78].

The analysis of climatic variables (temperature and precipitation) reveals that the minimum and maximum temperatures in the study region show an increasing trend, while as precipitation is showing a decreasing trend, as well as reported by [72, 85]. A persistent warming trend that has developed over the western Himalayas is seen as a major cause of glacier recession in the region [60, 85, 86]. The shrinking and thinning of glaciers may result in further expansion of glacial lakes, hence increasing the possibility of potentially dangerous glacial lakes in the region.

Glacier melt water is apparently a major contributor for glacial lake expansion in the study region. Nevertheless, the impact of climate change on glacial lakes is too complex a process to understand owing to certain limitations in terms of hydro-metrological data networks and glacier observation sites in the region, it is therefore a matter of future investigation whether climate change is singly responsible for glacial lake change in the study region.

6 Conclusions

The selected study sites in the Kashmir Himalayas have a complex and rugged topography in addition to the limited network of observational sites (e.g., meteorological and glaciological). This proves to be a major obstacle in conducting extensive field investigations and understanding the occurrences of dynamic environmental processes in the region.

This study systematically observes the spatiotemporal changes in glacial lakes across the Kashmir Himalaya from 1990–2018 using Landsat images supplemented by ground observations. The Landsat images with 30 m resolution used for four time points (1990, 2000, 2010, and 2018) make this entire process of glacial lake change detection more reliable by reducing any uncertainties.

This analysis further revealed that the overall glacial lakes pertaining to the present study showed a substantial increase in count and area through 1990–2018. Area has increased from 18.84 km² in 1990 to 22.13 km² in 2018 with a growth rate of 14.7%. The number increased from 253 in 1990 to 324 in 2018, with a growth rate of 21.4%. The already existing lakes have contributed more to area expansion than newly developed glacial lakes, with maximum changes occurring in the elevation range of 3800 m asl and 4300 masl.

Glacial lakes that are expanding at higher rates should be taken as case studies for potential GLOF events in the future. Consequently, continuous monitoring and observation specifically focused on area change, lake volumes and outburst scenarios/simulation studies. Furthermore, the development of integrated socio technology-driven early warning systems (EWSs) and the generation of public awareness may help us to reduce the risk of GLOF hazards in the region. The supplementary data related to this research article is freely available at <https://doi.org/10.5281/zenodo.5016511>.

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Declarations

Ethical approval All the ethical standards of research publishing were taken care of during this study.

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