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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 322 in 2018, with a growth rate of 21.4%. The area has increased from 18.84 Km^2 in 1990 to 22.11 Km^2 in 2018 with a growth rate of 14.7 percent. The newly formed glacial lakes, including supra glacial 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 1.1°C, whereas T_{min} increased to 0.7°C from 1990 to 2018. 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 GLOFs and developing a mechanism for continuous monitoring and management of lakes in the study region.

1. Introduction

Glacial lakes are bodies of water strongly influenced by the presence of glaciers [23] and/or retreating processes of a glacier [17]. Globally, climate variability has a significant influence on the downwasting of glaciers [11, 54] as a result of forming new glacial lakes or increasing the spatial extent of existing lakes [71, 74, 10, 47]. With shrinking Himalayan glaciers, the high-altitude lakes in the region are continuously evolving and growing in number and size [77, 16, 45, 6, 2]. Himalayan glacier recession is largely attributed to the impact of changing global climate [12, 7, 57, 36, 34, 65; 42,13] and topographic regimes [57]. The continuous shrinkage of glaciers, as reported in the Central Himalayas, could trigger glacial lake expansion in the future [34]. The accelerated rate of glacial lake expansion increases the risk of outbursts of glacial lakes [76, 63, 68]. 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) [52]. GLOF events pose a serious threat to nearby communities and built infrastructure [54, 50, 31, 75]. 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 [38].

There have been several instances of GLOF events in the past striking the Himalayan region [31, 27, 69, 73, 4, 18]. 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 [28]; Nagma Pokhari (Nepal) in 1980 [8, 53]; Zhangzangbo (Tibet) in 1981 [35, 72]; Dig Tsho in 1985 [64]; and Lugge Tsho (Bhutan) in 1994 [44, 69]. The recent event was an outburst flood that struck a village (Gaya) in Ladakh, India in 2014 [38]. 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 [51, 29].

To carry out an updated inventory and understanding the spatiotemporal dynamism of glacial lakes is the first important step for monitoring and assessing GLOFs in a region [24, 47, 67].T hese multitemporal inventories serve as a baseline for studying the evolution, disappearance, and identification of potentially dangerous glacial lakes [41] as well as modeling GLOFs using various hydrodynamic models. In the Himalayan region, numerous inventories have been carried out by different authors according to their purpose of study. For example, [13] prepared an inventory of 958 glacial lakes (size > 500 m^2) for Himachal Pradesh (areal coverage 9.6 ± 0.3 Km^2) using the LISS IV data. [47] carried out a multitemporal inventory of glacial lakes in the central Himalayas using Landsat series of data. [62] mapped 2168 glacial lakes covering a total area of 127.61 Km^2 in the Koshi basin of central Himalayas. [34] prepared and developed a detailed inventory of 1541 glacial lakes in the Nepal Himalayas with areal coverage of approximately 80.95 ± 15.25 Km^2. 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 [78,79, 31] 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.

Table 1
Glacial lake inventory studies in the Himalayan region.

S. No	Study	Minimum size	Satellite/Sensor/ resolution	No of lakes	Area of lakes Km^2
1.	Bhambri *et al.*, (2015)	0.0005	Resourcesat-2 LISS IV/5	1266	7.59
2.	Shrestha *et al.*, (2017)	0.003	Landsat TM/ETM+/30	2168	127.61
3.	Khadka *et al.*, (2018)	0.003	Landsat TM/OLI	1541	80.95
4.	Bhambri *et al.*, (2018)	0.01	Resourcesat-2 LISS IV/5	147	5.12
5.	Begam *et al.*, (2019)	0.15	Landsat TM/ETM+/OLI/30	--	37.9
6.	Wang et al., 2020	0.005	Landsat TM/ETM+/OLI/30	30121	2080.12
7.	Chen et al., 2021	0.008	Landsat TM/ETM+/OLI/30	15348	1395.733
8.	Present Study	0.001	Landsat TM/ETM+/OLI/30	322	22.11

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°20´-34°50´N & 73°55´- 75°35´E) is in the Union Territory of Jammu and Kashmir, India,[39, Fig. 1). Kashmir Valley has an area of approximately 15,948 square kilometers. [21, 3] report 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) [5] 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 [21, 15]. Lakes formed during the time of deglaciation preceded by cold conditions in the Kashmir Himalayas [48]. 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 [57]. The altitude of the study area ranges from 1065 m asl to 5441 m asl, in which the majority of glacial lakes (e.g., proglacial type) are situated at 3800 m asl to 4300 m asl.

3. Methodology

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 [37, 14,59, 55]. Landsat images of 30 m resolution and the Advanced Space-borne Thermal Emission & Reflection Radiometer – Digital Elevation Model (ASTER DEM, 30 m) downloaded from the web portal[1] 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 portal[2] and used for the current study. Glacial lakes show minor changes in the post-monsoon season with limited cloud and snow cover [60]. 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 [41]; 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 2018 of the Pehalgam observatory was analysed to understand climate as a possible influencing factor for glacial lake changes in the study area.

Table 2 Satellite data used

Date of Pass	Satellite & Sensor	Bands & Wavelength (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.

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) [1, 37, 25, 26, 70].

In the present study, we used the normalized difference water index NDWI – first proposed in 1996 by McFeeters – using a semiautomated method similar to [29] for delineation of glacial lake outlines (Figure 2; Equation 1).

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

*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 [24]. A few mountain-shadowed areas were mistaken as lakes due to the same spectral reflectance and topographic effects [62, 34]. 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 (Figure 3).

Further correction was performed through a visual interpretation technique using ArcGIS 10.2 [34, 58, 46, 76, 60, 67]. 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 inventories for 2010, 2000 and 1990 were prepared to obtain the final database to observe glacial lake expansion in the study area.

Uncertainty analysis

In the present study, glacial lakes were identified, delineated, and mapped to observe changes in spatial extent using multidate/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 [41]. 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 co-registration 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 [41, 42]. 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 [75, 42] 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 is the coregistration error of the images to the base image in equation (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 equation (3), as suggested by Yao et al., 2006.

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

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 km^2 (0.3%) for TM and ETM+ and 0.0025 Km^2 (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 (42,41, 82].

4. Results And Discussion

4.1. Glacial lakes 2018

Using Landsat (OLI) imagery from 2018 with 30 spatial resolution, a total of 322 glacial lakes were identified in the UJB, with a total calculated area of approximately 22.11 km^2. The area of the glacial lakes varied from 0.001 km^2 to 1.65 Km^2 with an average size of 0.06Km^2. Glacial lakes in the region were classified as (1) proglacial lakes connected to glaciers, (2) proglacial lakes not connected to glaciers and (3) supraglacial lakes based on their hydrologic connection to the glacial watershed. A total of 208 glacial lakes were classified as not connected to glaciers, with an overall surface area of approximately 11. 84 km^2), which constitute approximately 64.59% and 53.55% of the total number and area, respectively. Nonglaciers fed (not connected to glaciers) accounted for 93 (28.88%) of the total lake area in the region and 9.95 km^2 (45%) of the total lake area. Supra-glacial lakes have been observed to be fewer in number and in area, i.e., 21 and 0.32 km^2, respectively (Fig. 4). Glacial lakes in the region are not evenly distributed, and 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 majority of the glacial lakes are small in size, i.e., less than 0.1 km^2 contributes 269 of the total number and 5.67 km^2 of the total area, which are 83.54% and 25.64%, respectively. Lakes with sizes greater than 0.1 km^2 constitute only 54 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 km^2 are considered dangerous because they possess an enormous volume of water to cause a flash flood in the downstream region [80, 81]. The details of the glacial lakes greater than 0.1 km^2 in the study region are mentioned in Table 6. All glacial lakes in the study area are located at an elevation range between 2700–4500 m asl. 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.

Table 6

Characteristics of glacial lakes with sizes > 0.1 km^2.

S. No	Local name	latitude	Longitude	GLIMS_Lake_ID	Watershed	Area Km^2	Elevation (m)	Type	Length	Width
1	Dudh Nag	75.320	34.192	G034192E75320N	Lidder	0.102	3704	NC	512.130	253.290
2	Raman Sar	75.143	34.361	G034361E75143N	Sind	0.102	3925	C	497.790	271.630
3		75.177	34.646	G034646E75177N	Sind	0.105	4208	NC	506.000	217.960
4	Chiti chhan Sar	74.913	34.470	G034470E74913N	Madhumati	0.112	3807	NC	561.190	271.270
5	Yamhar Sar	75.151	34.208	G034208E75151N	Sind	0.113	3763	C	498.040	301.820
6	Chohar Nag	75.469	33.754	G033754E75469N	Arapal	0.115	3894	NC	399.760	461.640
7		74.561	33.528	G033528E74561N	Rambiahra	0.123	4053	NC	430.250	386.070
8	Chiamar Sar	74.876	34.380	G034380E74876N	Erin	0.126	3711	C	592.890	388.240
9	Chand Sar	75.117	34.156	G034156E75117N	Lidder	0.126	3917	NC	368.750	391.710
10	Sursyar	74.523	33.735	G033735E74523N	Dodhganga	0.127	4024	C	526.340	328.950
11		74.593	33.505	G033505E74593N	Rambiahra	0.131	4041	NC	557.600	274.310
12	Kotori Sar	74.605	33.522	G033522E74605N	Rambiahra	0.131	3803	NC	603.760	249.650
13		74.906	34.489	G034489E74906N	Madhumati	0.133	4061	C	554.030	378.790
14	Andaun Sar	74.932	34.452	G034452E74932N	Sind	0.135	3854	NC	640.450	304.600
15	Tson	75.216	34.063	G034063E75216N	Lidder	0.137	3685	NC	594.910	278.260
16	Kaul Sar	74.944	34.385	G034385E74944N	Sind	0.139	3685	NC	682.280	317.440
17	Barani Sar	74.574	33.530	G033530E74574N	Rambiahra	0.151	3913	NC	550.450	375.730
18		74.435	33.829	G033829E74435N	Ferozpur	0.152	4006	C	750.450	289.510
19	Daman Sar	74.416	33.866	G033866E74416N	Ferozpur	0.153	3912	NC	467.960	424.220
20	Bramsar	74.850	33.502	G033502E74850N	Vaishav	0.155	3574	C	519.250	385.250
21	Watal Sar	74.986	34.457	G034457E74986N	Sind	0.158	3715	C	972.620	290.210
22	Logul Sar	74.908	34.448	G034448E74908N	Sind	0.172	3941	NC	569.140	363.570
23	Chandan Sar	74.542	33.550	G033550E74542N	Rambiahra	0.173	3872	NC	523.620	350.000
24	Handil Sar	75.205	34.202	G034202E75205N	Lidder	0.183	3668	NC	783.760	268.000
25	Chhumhai Sar	75.160	34.093	G034093E75160N	Lidder	0.188	3886	NC	770.840	402.200
26		75.372	34.184	G034184E75372N	Sind	0.188	4253	C	557.360	297.840
27	Sona Sar	75.275	34.234	G034234E75275N	Lidder	0.191	3799	NC	909.800	312.450
28	Sona Sar	75.475	34.067	G034067E75475N	Lidder	0.191	3697	C	961.490	248.280

S. No	Local name	latitude	Longitude	GLIMS_Lake_ID	Watershed	Area Km^2	Elevation (m)	Type	Length	Width
29	Sorus Nag	75.378	33.953	G033953E75378N	Lidder	0.202	3617	NC	469.750	490.000
30	Charl Nag	75.389	33.929	G033929E75389N	Lidder	0.210	4012	C	1001.160	300.910
31	Goli Sar	74.565	33.540	G033540E74565N	Rambiahra	0.224	3923	NC	571.680	528.340
32	Nandan Sar	74.526	33.559	G033559E74526N	Rambiahra	0.271	3816	NC	912.740	401.440
33	Pam Sar	74.451	33.820	G033820E74451N	Ferozpur	0.285	3962	C	1008.150	339.790
34	Sarbal Sar	74.873	34.392	G034392E74873N	Erin	0.288	3522	NC	1044.620	438.960
35	Nabler Sar	74.819	34.548	G034548E74819N	Madhumati	0.316	3843	NC	1214.650	346.060
36	Krishan Sar	75.103	34.397	G034397E75103N	Sind	0.321	3783	NC	922.840	479.100
37	Patalwan Sar	74.827	34.537	G034537E74827N	Madhumati	0.324	3891	NC	973.260	545.690
38	Laksukh Sar	74.554	33.537	G033537E74554N	Rambiahra	0.324	3971	NC	1007.250	323.060
39	Har Nag	75.377	34.139	G034139E75377N	Sind	0.333	3675	NC	1098.600	410.750
40	Salnai Sar	74.892	34.444	G034444E74892N	Madhumati	0.356	3814	C	992.650	440.620
41	Dhaklar Sar	74.624	33.509	G033509E74624N	Rambiahra	0.362	3905	C	932.130	575.800
42	Nund Kol	74.935	34.418	G034418E74935N	Sind	0.389	3459	C	1314.800	338.810
43	Gadsar	75.058	34.422	G034422E75058N	Sind	0.403	3722	C	870.830	626.450
44	Madmatti Sar	74.921	34.493	G034493E74921N	Madhumati	0.409	3841	C	1316.640	504.590
45	Mar Sar	75.114	34.144	G034144E75114N	Lidder	0.451	3788	NC	1180.800	489.120
46	Bodh Sar	74.428	33.841	G033841E74428N	Ferozpur	0.472	3919	C	1555.440	574.640
47	Vishan Sar	75.119	34.388	G034388E75119N	Sind	0.480	3632	C	1083.540	712.350
48	Shesh Nag	75.497	34.093	G034093E75497N	Lidder	0.553	3546	NC	1118.000	745.030
49	Bhag Sar	74.583	33.519	G033519E74583N	Rambiahra	0.730	3893	NC	1507.630	659.330
50	Tar Sar	75.151	34.140	G034140E75151N	Lidder	0.872	3800	NC	1733.570	601.200
51	Konsar Nag	74.769	33.512	G033512E74769N	Vaishav	1.376	3463	C	2912.750	645.230
52	Gangabal Lake	74.924	34.432	G034432E74924N	Sind	1.654	3534	C	2754.890	840.150

C = Lakes connected to glacier

NC = Lakes not connected to glacier

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 Km^2), 267 (19.31 ± 0.02), 310 (21.03 ± 0.02), and 322 (22.11 ± 0.002 km^2) glacial lakes identified and mapped in 1990, 2000, 2010, and 2018, respectively. The total lake area has increased by 3.27 ± 0.013 Km^2 (14.8%) in last three decades. The total area has increased by 0.10 Km^2 ± 0.013 for glacial lakes with size ≤ 0.01, 1.22 Km^2 ± 0.013 with size > 0.10 Km^2 and ≤ 1.0 Km^2 and 0.27 ± 0.013 Km^2 with size > 1.0 Km^2 from 1900–2018 (Table 3, Fig. 5). Hence, the small glacial lakes have contributed less to the total area change, i.e., expanded more slowly than the large ones, similar to what [47] reported in the Central Himalayan region. The smaller lakes are so dynamic that they appear and disappear over time (Table 3, Fig. 5), as confirmed by [62].

Table 3
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-.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	322	22.11	69	3.27

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., 55 > 14 over time. The newly formed glacial lakes, therefore, have a small contribution to lake expansion in the Kashmir Himalaya. (Table 4), similar to the Central Himalayas reported by [47].

Table 4
Newly formed glacial lakes and extinct lakes from 1990 to 2018

Year	**Total**	**Total**	**Newly Formed**		**Disappeared**		**Existing**		
	Number	**Change Area (km^2)**	**Number**	**Km^2**	**Number**	**Km^2**	**Number**	**Change Km^2**	**Contribution of the area change (%)**
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	322	+ 1.08	9	0.13	3	0.06	307	1.01	93.51

The study reveals that the proglacial lakes connected to glaciers showed greater expansion in comparison to supraglacial and proglacial lakes not connected to glaciers, the latter being dynamic in nature. The growth in terms of area as relates to proglacial lakes connected to glaciers increased by 2.70 km^2 (82.56%) from 1990 to 2018 (Table 5). The proglacial lakes not connected to glaciers show lower expansion rates, i.e., 6.42% of an overall increase in lake area.

Table 5
Total increase in the area of major glacial lake types from 1990–2018

Type	**Increasing Area (Km^2)**	**Percentage (%)**
Proglacial lakes connected to glacier	2.70	82.56
Supraglacial lakes	0.36	11.01
Proglacial lakes not connected to glacier	0.21	6.42
Total	3.27	100.00

4.3. Altitudinal differences

Altitude is an important controlling factor for the change in surface area of glacial lakes (Tartari et al., 2008). All the identified glacial lakes in the study region were normally distributed between 2700 m asl and 4500 m asl. The majority of them, particularly proglacial lakes not connected to glaciers and supraglacial lakes, were concentrated in the elevation range of 3800 m asl – 4300 m asl. This is largely due to an enabling environment and peculiar geomorphological setting for glacier lake development in the study region. Hence, maximum glacial lake changes (≥ 91%) occurred at elevations between 3800 m asl 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.

4.4. Field investigations

Field measurements of high-altitude lakes are difficult to accurately ascertain in steeply edged mountainous remote areas[26]. 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.

Figure 6 Photographs taken during the flied 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) field DGPS observations.

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. 7a-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.

4.5. Climate change in the region

The meltwater of glaciers makes a significant contribution to glacial lake growth in the Himalayan region [47], in which proglacial lakes show an obvious increase in expansion with increasing meltwater [16, 20, 19, 26]. The climatic variables (e.g., temperature and precipitation) of the Kashmir valley show substantial changes from 1980–2014 [61], with an increase in mean maximum and minimum temperatures and annual precipitation showing a downward trend from 1980 to 2018 [58]. The observed extreme warm temperatures in the past have resulted in the remarkable retreat of glaciers in the Western Himalayas [49, 22, 15, 32). Understanding that assessing climate change impact on glacial lakes is a tedious process and cannot singly be a reason for glacial lake expansion [26], 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 [33].

Our study used historical meteorological data from Pehalgam station from 1990 to 2018 to analyze the temperature and precipitation trends in the Kashmir valley. The study revealed that minimum and maximum temperatures in the Jhelum Basin have shown an increasing trend. T_{max} showed an increase of 1.1°C, whereas T_{min} increased to 0.7°C from 1990 to 2018 (Fig. 7a, b). 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. Although there can be various underlying causes for such changes, climatic variability appears to be a steeling force 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 [31, 2]. Glaciers and glacial lakes in the Jhelum Basin of the Kashmir Himalayas are vital sources to the headwaters of the Indus River basin and support hydropower generation, irrigation, domestic uses and tourism in downstream areas [21]. With the increasing temperatures in the Himalayan region, glaciers are melting, thus resulting in the negative mass balance of glaciers. Thus, this led to the formation and expansion of various types of glacial lakes. An extreme warming trend that has developed in the western Himalayas has resulted in significant glacier retreat [15, 22, 61]. Glacial lakes in the study area have shown a significant increasing trend over the study period. The total count of lakes as well as their spatial extent showed a discernible increase. The number increased from 253 in 1990 to 322 in 2018, with a growth rate of 21.4%. The area has increased from 18.84 Km^2 in 1990 to 22.11 Km^2 in 2018 with a growth rate of 14.7 percent. The newly formed glacial lakes, including supra glacial lakes, were greater in number than the lakes that disappeared over the study period. Similar to other parts of the Himalayan region, the analysis of the climatic variables (temperature and precipitation) reveals that glacial lake expansion in the study region is also the outcome of the increasing temperatures and decreasing precipitation trends. If the same trend continues in the future, glaciers will shrink more, which may result in the further expansion of glacial lakes. Therefore, the number of potentially dangerous glacial lakes in the region is increasing.

Field investigation is not possible for all glacial lakes because of the tough terrain and harsh weather conditions. In this backdrop, remote sensing-based studies in conjunction with GIS and GPS play an important role in monitoring such glacial lakes in a regular time interval. In the present study, we managed to carry out field surveys on a limited number of lakes with limited investigation due to a lack of instrumentation. In addition, due to the inaccessibility and paucity of hydrometeorological data networks, the hydrological and meteorological phenomena in the Kashmir Himalayan region have been poorly investigated [56]. Therefore, we suggest an in-depth study of rapidly expanding glacial lakes and the analysis of meteorological parameters to understand the influence of the changing climate on the rapid expansion of glacial lakes in the 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 Km^2 in 1990 to 22.11 Km^2 in 2018 with a growth rate of 14.7%. The number increased from 253 in 1990 to 322 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 m asl

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 are freely available at https://doi.org/10.5281/zenodo.5016511.

Declarations

Data availability: All data generated or analysed during this study are included in this published article.

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Declaration of competing interest

The authors have no conflicts of interest to declare that they are relevant to the content of this article.

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Footnotes

[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

[4] www.earthexplorer.usgs.gov