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

Rayees Ahmed1 · Gowhar Farooq Wani1 · Syed Towseef Ahmad1 · Riyaz Ahmad Mir2 · Mansour Almazroui3,4 · Sanjay K. Jain5 · Pervez Ahmed1

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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. $T_{\text{max}}$ showed an increase of 1.25 °C, whereas $T_{\text{min}}$ 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...
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.

### 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 km² | 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 |
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° 20ʹ–34° 50ʹ N & 73° 55ʹ–75° 35ʹ 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 kilometers\(^3\) [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\(^4\) [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.

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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.
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).

\[
NDWI = \frac{BNIR - Bblue}{BNIR + Bblue}
\]

*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

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                  | No          |
| 18 Oct. 2010 | Landsat ETM+      | 8                       | 149/36   | 30                     | 16                  | No          |
| 04 Oct. 2018 | Landsat L8 (OLI)  | 9                       | 149/36   | 30                     | 16                  | No          |

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

4 www.earthexplorer.usgs.gov.
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].
3.4 The 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 [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 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 [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).

\[ U = \sqrt{a^2 + b^2 + \sigma} \]  

(2)

where a and b are the resolutions of the image and \( \sigma \) 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].

\[ U_{area} = 2UV \]  

(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 km\(^2\) (0.55\%), which are well or below the previously reported acceptable ranges [21, 50, 79].

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

| Number | Area Km\(^2\) |
|--------|-------------|
| Proglacial lakes | 76 |
| Supra-glacial lakes | 21 |
| Unconnected glacial lakes | 7 |

| Number | Area Km\(^2\) |
|--------|-------------|
| Proglacial lakes | 8.64 |
| Supra-glacial lakes | 13.42 |
| Unconnected glacial lakes | 0.07 |
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.

Fig. 4  Showing types of glacial lakes. a–c Proglacial Lakes. d, e Supraglacial Lake and f unconnected glacial lakes
| S. No | Local name | Longitude | Latitude | Area Km$^2$ | Length (m) | Width (m) | Type |
|-------|------------|-----------|----------|-------------|------------|-----------|------|
| 1     | Duddh Nag  | 34° 11' 31.75" | 75° 19' 12.96" | 0.102 | 3704 | 512.130 | PGL |
| 2     | Raman Sar  | 34° 21' 39.60" | 75° 08' 31.80" | 0.102 | 3225 | 497.790 | PGL |
| 3     | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 4208 | 506.000 | UCL |
| 4     | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 561.190 | UCL |
| 5     | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 6     | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 7     | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 8     | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 9     | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 10    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 11    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 12    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 13    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 14    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 15    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 16    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 17    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 18    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 19    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 20    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 21    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 22    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 23    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 24    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 25    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 26    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 27    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 28    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 29    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 30    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 31    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 32    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 33    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 34    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 35    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 36    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
| 37    | Chitthian Sar | 34° 28' 12.84" | 75° 10' 31.20" | 0.105 | 3807 | 496.040 | UCL |
Table 3 (continued)

| S. No | Local name     | Latitude   | Longitude   | GLIMS_Lake_ID       | Watershed | Area Km² | 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      | Liddier   | 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    | Bhag Nag       | 34° 05' 34.80" | 75° 29' 49.20" | G034093E75497N      | Liddier   | 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      | Liddier   | 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
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 ± 0.02 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 km² ± 0.013 for glacial lakes with size ≤ 0.01, 1.22 km² ± 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
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 glacier lake development in the study region. Hence, maximum glacial lake changes (≥ 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. $T_{\text{max}}$ showed an increase of 1.25 °C, whereas $T_{\text{min}}$ increased to 0.7 °C from 1980 to 2020 (Fig. 7a). $T_{\text{max}}$ is increasing at the rate of 0.03 °C/year and $T_{\text{min}}$ 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
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

Fig. 7 Trends in the essential climatic variables in the study area (1990–2018). a Annual minimum, maximum, average temperature. b Annual precipitation
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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 tem-
peratures 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 investiga-
tion 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 sys-
tems (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

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References

1. Fitzsimons S, Howarth J. Glaciolacustrine. In: Menzies J, Van der Meer JM. Past glacial environments, 2nd edn. Elsevier; 2018. p. 309–34. https://doi.org/10.1016/B978-0-08-100524-8.00009-9.

2. Campbell JG, Pradesh H. Inventory of glaciers and glacial lake and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of India, Pakistan and China/Tibet Autonomous Region. International Centre for Integrated Mountain Development (ICIMOD), GP O. Box, 3226; 2005.

3. Benn D, Lehmkuhl F. Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. Quatern Int. 2000;65:15–29. https://doi.org/10.1016/S1040-6182(99)00034-8.

4. Richardson S, Reynolds J. An overview of glacial hazards in the Himalayas. Quatern Int. 2000;65:31–47.

5. Bajracharya S, Mool P. Growth of hazardous glacial lakes in Nepal. In: Proceedings of the JICA regional seminar on natural disaster mitigation and issues on technology transfer in south and southeast Asia, 30; 2005. p. 131–48.

6. Nie Y, Liu Q, Liu S. Glacial lake expansion in the central Himalayas by landsat images, 1990–2010. PLoS ONE. 2013;8(12):e83973.

7. Worm R, Stoffel M, Huggett C, Volz C, Casteller A, Luckman B. Analysis and dynamic modeling of a moraine failure and glacial lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). J Hydrol. 2012;444:134–45.

8. Yao T, Li Z, Yang W, Guo X, Zhu L, Kang S, et al. Glacial distribution and mass balance in the Yarlung Zangbo River and its influence on Lakes. Chin Sci Bull. 2010;55(20):2072–8.

9. Ahmed R, Ahmad ST, Wani GF, Ahmed P, Mir AA, Singh A. Analysis of landuse and landcover changes in Kashmir valley, India—a review. Geojournal. 2021. https://doi.org/10.1007/s10708-021-10465-8.

10. Bahuguna IM, Rathore BP, Brahmbhatt R, Sharma M, Dhar S, Randhawa S, et al. Are the Himalayan glaciers retreating? Curr Sci. 2014;106(7):1008–13.

11. Bajracharya SR, Mool PK, Shrestha BR. The impact of global warming on the glaciers of the Himalaya. In: Proceedings of the international symposium on geodisasters, infrastructure management and protection of world heritage sites; 2006. p. 231–42.

12. Bajracharya SR, Mool PK, Shrestha BR. Impact of climate change on Himalayan glaciers and glacial lakes: case studies on GLOF and associated hazards in Nepal and Bhutan. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD); 2007.

13. Bolch T, Pieczonka T, Benn DJ. Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. Cryosphere. 2011;5(2):349–58.

14. Muhammad S, Tian L, Nusser M. No significant mass loss in the glaciers of Astore Basin (North-Western Himalaya), between 1999 and 2016. J Glaciol. 2019;65(250):270–8.

15. Zhou Y, Li Z, Li J. Slight glacier mass loss in the Karakoram region during the 1970s to 2000 revealed by KH-9 images and SRTM DEM. J Glaciol. 2017;63(238):331–42.

16. Bajracharya SR. Impacts of climate change on Himalayan glaciers and glacial lakes: case studies on GLOF and associated hazards in Nepal and Bhutan. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD); 2007.

17. Berthier E, Arnaud Y, Kumar R, Ahmed S, Wagnon P, Chevallier P. Remote sensing estimates of glacier mass balances in the Himalach Pradesh ( western Himalaya, India). Remote Sens Environ. 2007;108(3):327–38.

18. Bhambrri R, Misra A, Kumar A, Gupta A, Vurma A, Tiwari S. Glacier lake inventory of Himachal Pradesh. Himalayan Geol. 2018;39:1–33.

19. Khadka N, Zhang G, Thakuri S. Glacial lakes in the Nepal Himalaya: inventory and decadal dynamics (1977–2017). Remote Sens. 2018;10(12):1913.

20. Kulkarni AV, Rathore BP, Singh SK, Bahuguna IM. Understanding changes in the Himalayan cryosphere using remote sensing techniques. Int J Remote Sens. 2011;32(3):601–15.

21. Mir RA, Jain SK, Jain SK, Thayyen RJ, Saraf AK. Assessment of recent glacier changes and its controlling factors from 1976 to 2011 in Baspa basin, western Himalaya. Arct Antarct Alp Res. 2017;49(4):621–47.

22. Romsheo SA, Dar RA, Rashid I, Marazi A, Ali N, Zaz SN. Implications of shrinking cryosphere under changing climate on the streamflows in the Lidder catchment in the Upper Indus Basin, India. Arct Antarct Alp Res. 2015;47(7):627–44.

23. Wagnon P, Linda A, Arnaud Y, Kumar R, Sharma P, Vincent C, et al. Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, a new benchmark glacier in the western Himalaya. J Glaciol. 2017;53(183):603–11.

24. Ahmad ST, Ahmad R, Wani GF, Sharma P, Ahmad P. Glacier mass changes in Sind basin (1990–2018) of North-western Himalayas using earth observation data. Model Earth Syst Environ. 2021. https://doi.org/10.1007/s40808-021-01246-w.

25. Agarwal A, Tatala S. Assessment of volume changes in East Rathong glacier, Eastern Himalaya. Int J Geoinform. 2013;9(1):73–82.

26. Valenzuela SM, Mckinney DC, Rounce DR, Byers AC. Changes in Imja Tscho in the Mount Everest region of Nepal. Cryosphere. 2014;8(5):1661–71.

27. Watanabe T, Lamsal D, Ives JD. Evaluating the growth characteristics of glacial a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal. Norwegian J Geogr. 2009;63(4):255–67.

28. Zhang G, Yao T, Xie H, Wang W, Yang W. An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. Glob Planet Change. 2015;131:148–57.
1. Allen SK, Rastner P, Arora M, Huggel C, Stoffel M. Lake Outburst and debris flow disaster at Kedarnath, June 2013: hydro meteorological triggering and topographic predisposition. Landslides. 2016;13(6):1479–91.
2. Carrick JL, Tweed FS. A global assessment of the societal impacts of glacier outburst floods. Glob Planet Change. 2016;144:1–16.
3. Gunj JP. The Shyok flood, 1929. Himal J. 1930;23:45–47.
4. Ives JD. Glacial lake outburst floods and risk engineering in the Himalaya: a review of the Langmoche disaster, Khumbu Himal, 4 Aug. 1985. ICIMOD occasional paper/International Centre for Integrated Mountain Development; no.10; 1986.
5. Pant RK, Agrawal DP, Krishnamurthy RV. Scanning electron microscope and other studies on the Karewa Beds of Kashmir India: scanning electron microscopy in the study sediments Norwey. Geo Abstracts; 1978. p. 257–82.
6. Bhardwaj A, Singh MK, Joshi PK, Singh S, Sam L, Gupta RD, Kumar R. A lake detection algorithm (LDA) using Landsat 8 data: a comparative approach in glacial environment. Int J Appl Earth Obs Geoinf. 2015;38:150–63.
7. Li J, Sheng Y. An automated scheme for glacial lake dynamics mapping using Landsat imagery and digital elevation models: a case study in the Himalayas. Int J Remote Sens. 2012;33(16):1594–213.
8. Robson BA, Nuth C, Dahl SO, Hölbling D, Strozzi T, Nielsen PR. Automated classification of debris-covered glaciers combining optical, SAR and topographic data in an object-based environment. Remote Sens Environ. 2015;170:372–87.
9. Roy D, Wulder M, Loveland T, Woodcock C, Allen R, Anderson M, et al. Landsat-8: Science and product vision for terrestrial global change research. Remote Sens Environ. 2014;145:154–72.

29. Raj K, Kumar KV. Inventory of glacial lakes and its evolution in Uttarakhand Himalaya using time series sattelite data. J Indian Soc Remote Sens. 2016;44(6):959–76.
30. Ives JD, Shrestha RB, Mool PK. Formation of glacial lakes in the hindu Kush-Himalayas and GLOF risk assessment. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD); 2010.
31. Quinecy DJ, Lucas RM, Richardson SD, Glasser NF, Hambrey MJ, Reynolds JM. Optical remote sensing techniques in high-mountain environments: application to glacial hazards. Prog Phys Geogr. 2005;29(4):475–505.
32. Yao T, Thompson L, Yang W, Yu W, Gao Y, Guo X, Joswiak D. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nat Clim Chang. 2012;2:663–7.
33. Majeed U, Rashid I, Sattar A, Allen S, Stoffel M, Nusser M, Schmidt S. Recession of Gaya Glacier and the 2014 glacial lake outburst flood in the Trans-Himalayan region of Ladakh, India. Sci Total Environ. 2020;756:144007–9.
34. Allen SK, Rastner P, Arora M, Huggel C, Stoffel M. Lake Outburst and debris flow disaster at Kedarnath, June 2013: hydro meteorological triggering and topographic predisposition. Landslides. 2016;13(6):1479–91.
35. Carrick JL, Tweed FS. A global assessment of the societal impacts of glacier outburst floods. Glob Planet Change. 2016;144:1–16.
36. Gunj JP. The Shyok flood, 1929. Himal J. 1930;23:45–47.
37. Ives JD. Glacial lake outburst floods and risk engineering in the Himalaya: a review of the Langmoche disaster, Khumbu Himal, 4 Aug. 1985. ICIMOD occasional paper/International Centre for Integrated Mountain Development; no.10; 1986.
38. Watanabe T, Rothacher D. The 1994 Luggethso glacial lake outburst flood, Bhutan Himalaya. Mt Res Dev. 1996;16(1):77–81.
39. Yamada T, Sharma C. Glacier lakes and outburst floods in the Nepal Himalaya. IAHS Publ Publ Int Assoc Hydrol Sci. 1993;218:319–30.
40. Higaki D, Sato G. Erosion and sedimentation caused by glacial lake outburst floods in the Nepal and Bhutan Himalayas. Glob Environ Res. 2012;16(1):71–6.
41. Richardson SD, Quinecy DJ. Glacier outburst floods from Gulklin Glacier, Upper Hunza Valley, Pakistan. EGU; 2009. 12871.
42. Khanal NR, Mool PK, Shrestha AB, Rasul G, Ghimire PK, Shrestha RB, Joshi SP. A comprehensive approach and methods for glacial lake outburst flood risk assessment, with example from Nepal and the transboundary area. Int J Water Resour Dev. 2015;31(12):219–37.
43. Xu D. Characteristics of debris flow caused by outburst of glacial lake in Boqu river, Xizang, China, 1981. GeoJournal. 1988;17(4):569–80.
44. Vuichard D, Zimmermann M. The 1985 catastrophic drainage of moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences. Mt Res Dev. 1987;7(2):91–110.
45. Motegi M. GLOF sediments and geology of river terraces in WangdPhodhrang district, Bhutan. J Geogr (ChigakuZasshi). 2001;110(1):17–31.
46. Huggel C, Kaab A, Haeberrli W, Teyssiere P, Paul F. Remote sensing based assessment of hazard from glacier outbursts: a case study in Swiss Alps. Can Geotech J. 2002;39(2):316–30.
47. Quinecy DJ, Richardson SD, Luckman A, Lucas RM, Reynolds JM, Hambrey MJ, Glasser NF. Early recognition of glacial lake hazards in Himalaya using remote sensing datasets. Glob Planet Change. 2007;56(1–2):137–52.
48. Frey H, Huggel C, Paul F, Haeberrli W. Automated detection of glacial lakes based on remote sensing in view of assessing associated hazard potential. Frey Schriften der Geography und Raumforschung. 2010:45:261–72.
49. Wang W, Xiang Y, Gao Y, Lu A, Yao T. Rapid expansion of glacial lakes caused by climate and glacier retreat in central Himalayas. Hydrol Process. 2015;29(6):859–74.
50. Mir RA, Majeed Z. Frontal recession of Parkachik Glacier between 1971–2015, Zanskar Himalaya using remote sensing and field data. Geocarto Int. 2018;33(2):163–77.
51. Mool P, Wangda D, Bajracharya S, Kunzang KA, Gurung DR, Joshi SP. Inventory of glaciers, glacial lakes and glacial lake outburst floods: monitoring and early warning system in the Hindu Kush-Himalayan Region-Bhutan. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD); 2001.
52. Zhang G, Yao T, Piao S, Bolch T, Xie H, Chen D, et al. Extensive and drastically different alpine lake changes on Asia’s high plateaus during the past 4 decades. Geophys Res Lett. 2017;44(1):252–60.
53. Shrestha F, Gao X, Khanal NR, Mahrajan SB, Shrestha RB, Wu LZ, et al. Decadal glacial lake changes in the Koshi basin, Central Himalaya, from 1977 to 2010, derived from Landsat Images. J Mt Sci. 2017;14(10):1969–84.
54. Rao BS, Gupta A, Guru N, Maheshwari SR, Raju PV, Rao VV. Glacial lake atlas of indus river Basin. National Remote Sensing Centre, ISRO: Hyderabad; 2020. p. 1–273.
55. Chen F, Zhang M, Guo H, Allen S, Kargel JS, Haritashya UK, Watson CS. Annual 30 m dataset for glacial lakes in High Mountain Asia from 2008 to 2017. Earth Syst Sci Data. 2021;13(2):741–66.
56. Hussain M. Geography of Jammu and Kashmir. New Delhi: Rajesh Publications; 2002.
57. Dar RA, Romshoo SA, Chandra R, Ahmed I. Tectono-geomorphic study of the Karewa Basin of Kashmir Valley. J Asian Earth Sci. 2014;92:143–56.
58. Ahmed R, Wani GF, Ahmad ST, Sahana M, Singh H, Ahmed P. A Review of glacial lake expansion and associated glacial lake outburst floods in the Himalayan Region. Earth Syst Environ. 2021. https://doi.org/10.1007/s41748-021-00230-9.
59. Bagnolus F. Bioclimatic types of South-East Asia. White Town: Institute Francais de Pondicherry; 1959.
60. Bhuyiyani MR, Kale VS, Pawar NJ. Climate change and the precipitation variations in the northwestern Himalaya: 1886–2006. Int Climalot J R Meteorol Soc. 2010;30(4):355–548.
61. Pant RK, Agrawal DP, Krishnamurthy RV. Scanning electron microscope and other studies on the Karewa Beds of Kashmir India: scanning electron microscopy in the study sediments Norwey. Geo Abstracts; 1978. p. 257–82.
62. Bhardwaj A, Singh MK, Joshi PK, Singh S, Sam L, Gupta RD, Kumar R. A lake detection algorithm (LDA) using Landsat 8 data: a comparative approach in glacial environment. Int J Appl Earth Obs Geoinf. 2015;38:150–63.
63. Li J, Sheng Y. An automated scheme for glacial lake dynamics mapping using Landsat imagery and digital elevation models: a case study in the Himalayas. Int J Remote Sens. 2012;33(16):1594–213.
64. Robson BA, Nuth C, Dahl SO, Hölbling D, Strozzi T, Nielsen PR. Automated classification of debris-covered glaciers combining optical, SAR and topographic data in an object-based environment. Remote Sens Environ. 2015;170:372–87.
65. Roy D, Wulder M, Loveland T, Woodcock C, Allen R, Anderson M, et al. Landsat-8: Science and product vision for terrestrial global change research. Remote Sens Environ. 2014;145:154–72.
66. Salerno F, Thakuri S, Agata CD, Smiraglia C, Manfredi CE, Viviano G, Tartari G. Glacial Lake distribution in the Mount Everest region: Uncertainty of measurement and conditions of formation. Glob Planet Change. 2012;92:30–9.
67. Gao BC. NDWI-A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sens Environ. 1996;58(3):257–66.
68. Gardelle J, Arnaud Y, Berthier E. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. Glob Planet Change. 2011;75(1–2):47–55.
69. Worni R, Huggel C, Stoffel M. Glacier Lakes in the Indian Himalayas- From area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. Sci Total Environ. 2013;468:71–84.
70. McFeeters SK. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. Int J Remote Sens. 1996;17(7):1425–32.
71. Murtaza KO, Romshoo SA. Recent glacier changes in the Kashmir Himalayas, India. Geocarto Int. 2017;2:188–205.
72. Chevutri A, Dimri AP, Thayyen RJ. Climate change over Leh (Ladakh), India. Theor Appl Climatol. 2018;131(1–2):531–45.
73. Prakash C, Nagarajan R. Glacial lake changes and outburst flood hazard in Chandra basin, North-Western Indian Himalaya. Geomat Nat Haz Risk. 2018;9(1):337–55.
74. Begam S, Sen D. Mapping of moraine dammed glacial lakes and assessment of their areal changes in the central and eastern Himalayan using satellite data. J Mt Sci. 2019;16(1):77–94.