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Research Article

Spatio-temporal change analysis of glacial lakes in Himachal Himalayas using geospatial technology

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Abstract
Extreme weather events, such as cloud bursts, temperature inversions, and landslides, along with the effects of global warming, act as catalysts for snowmelt and contribute to the expansion of existing glacial lakes in mountainous regions like the Himalayas of Himachal Pradesh, India. The additional water load in these glacial lakes, caused by snowmelt and extreme rainfall events, can lead to glacial lake outburst floods (GLOFs), a phenomenon that is both difficult to map and inaccessible. These GLOF events pose significant hazards to the region and its inhabitants. Therefore, it is crucial to map and monitor glacial lakes using remote sensing and geographic information system (GIS) techniques. The present research focuses on the spatio-temporal mapping of glacial lakes in a part of Himachal Pradesh, India, utilizing Landsat satellite time series data from 1980 to 2017. The years 1980, 1990, 2000, 2010, and 2017 were selected for mapping using the well-known normalized difference water index (NDWI > 0.25) in the earth resource data analysis system (ERDAS) modeler. Results indicated a continuous increase in both the number and extent of glacial lakes during the study period. In 1980, there were 102 glacial lakes covering an area of 222.8 hectares. By 2017, the number of glacial lakes had increased to 783, covering an area of 955.6 hectares. It was observed that while some lakes appeared and others disappeared during the study period, the appearance of lakes was more prominent in higher elevation ranges (4000-5500 meters), making this a potentially vulnerable altitude zone for GLOF hazards. The study provides a foundation for further monitoring of lake dynamics and identifying possible GLOF-prone areas, offering valuable information for policymakers involved in the management of hilly habitats and for researchers globally.

Keywords
Glacial lake outburst flood, Normalized difference water index, Landsat, Time series, Automatic extraction water index, modified normalised difference water index, Global climate change.

1.Introduction
Himalaya is a major physiographic region not only in India but also in the world and home to many glaciers [1]. Its area above the snow line is covered with ice throughout the year. The melting of glaciers in response to recent impacts of global warming produces young glacial lakes in the Himalayan region. It has been observed that the Himalayan region is sensitive to global climate changes [2, 3] and thus has the potential to produce more young glacial lakes shortly. It has also been recorded that the temperature of the Himalayan region has increased with varying ranges of 0.15-0.60°C [4] and this variability in the range of temperature causes the glacial retreat [5, 6]. It has discovered that warming has increased in the higher altitudes of the Himalayas [7].

In the Chamoli district of Uttarakhand, India, historical trend analysis of climatic parameters, land surface temperature (LST), and physical landscape change indicates alarming consequences in the future [7]. As a result, the elevation-dependent warming potential to alter glacier equilibrium and snow line has been processed at a faster pace in recent years. The process of retreating of Glaciers leads to the evolution and growth of different types of lakes in the Himalayan region and makes the area hazard-prone [8, 9].

There have been recognised about 9000 glacial lakes in the Himalayan region which are probably the highest in the world and among them, 200 lakes have been identified as potentially hazardous to the hilly habitat. A total of 40 glacial lakes have resulted in the

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event of glacial lake outburst flood (GLOF) over the past four decades [10].

As per the report of the international centre for integrated mountain development (ICIMOD), there are about 3,252 glaciers and 2,323 glacial lakes in Nepal, of which 20 were observed as perilous [11]. In Bhutan, there are about 677 glaciers and 2,674 glacial lakes out of which 24 glacial lakes are identified as dangerous [10]. The ICIMOD also explains the formation of glacier lakes in the region of Hindu Kush Himalaya [10]. There have been identified more than 8000 glacial lakes in this region, of which 200 glacier lakes are identified as potentially hazardous. Observed that glaciers are retreating at a faster rate in the Mount Everest region, ultimately resulting in the formation of new glacial lakes [12]. A study related to the mapping of glaciers and glacial lakes in the Himalayan region was carried out by using linear imaging self-scanner (LISS) - III data over ten years (2000/01/02 - 2010/11) time span. The study reported that 87% of glaciers are stable while 12% revealed retreating of glaciers and only 1% of glaciers showed advancement of the snout [13]. Glacial lakes inventory has been examined by Space Applications Centre – Indian Space Research Organisation (SAC-ISRO) in the Himalayan region (including Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh) using LISS III and LISS IV data on 1:50000 scale. There were about 4699 glacial lakes mapped using various methods, in which nearly 1966 lakes were separated as an identical database because of the size constraint of mapped lakes. The GLOF area can be mapped through simple on-screen digitisation or automatically using satellite image-based inputs (such as imageries, indices etc.)

Previous research studies indicated that the glacial lakes can be very dangerous to the adjacent downstream areas and their regular monitoring is important to manage disastrous events like GLOFs [14]. The dynamicity of GLOF can be determined by many factors such as mass movement and rapid ice melting in the lake, heavy rainfall, dam failure, earthquake, and overflow due to the rising level of the lake etc. The GLOF abolishes every natural and artificial infrastructure [15, 16]. However, one cannot stop and predict the event of GLOF, but the damages caused by GLOFs can be minimized through proper pre-planning using up-to-date data and advanced monitoring systems like remote sensing and geographic information system (GIS). It is also possible by studying previously occurred GLOF events and predictive modelling. The research works carried out on GLOF showed variance in results due to distinct methodologies and data sources.

Challenges of the previous studies include the unavailability of cloud-free and snow-free scenes to map glacial lakes, field surveys in rouged and inaccessible terrain to validate the data and shadowed areas in hilly terrain leading to misclassification of glacial lakes [12]. The GLOF areas are very remote, and it is very hard to map and monitor such areas physically. It has been observed that a lot of research work on glaciers has been carried out in recent decades using GIS and Remote Sensing techniques which signifies it is a prominent tool for GLOF assessment [17].

Different methods and different time frames are presented with varying datasets by the researchers and there is no integration of these studies together so that they can be analysed on one platform, finally, there is no study available for a long-time frame which can be compared with an earlier scenario in Himachal Pradesh state.

This work has identified the potentially vulnerable lakes to GLOF hazards in the study area, and the glacial lakes were mapped with all the parameters responsible for GLOF. The objective of this study was to review the methods and approaches adopted in previous studies and to find a suitable method that provides an accurate count of current glacial lakes, supported by 37 years of data from the literature. This detailed study of glacial lakes in Himachal Pradesh helps researchers and planners regulate developmental activities in the vicinity of GLOF-vulnerable areas. Using Landsat satellite data from 1980 to 2017, glacial lakes were extracted based on indices, including the number and area of sub-basins, altitude, and category type in Himachal Pradesh, India.

The organization of the rest of the manuscript is as follows: Section 2 explains the previous research conducted on the Glacial Lake mapping techniques and inventories. Section 3 explains the study area, material and methodology used in this study. The findings and explanations of the results are presented in Section 4 and discussion in Section 5. Finally, the conclusion is stated in Section 6.

2.Literature review

The automatic extraction of water bodies has been familiarized in the form of the normalized difference water index (NDWI) by [18] which is potentially accurate and efficient in mapping glacial lakes required to assess the GLOF hazard. It uses reflected near-infrared radiation and visible green light to enhance the presence of water features while eliminating soil and terrestrial vegetation features. It is based on a normalised ratio of green and near infra-red (NIR) bands and it has been improved by removing error pixels [19] and is known as modified normalised difference water index (MNDWI) which uses short wave infra-red (SWIR) instead of NIR band. Some other techniques are also there in the form of the normalised difference snow index (NDSI) for snow mapping and the normalised difference pond index (NDPI) for water body mapping [20]. Which provides another index i.e. automatic extraction water index (AWEI) for the satellite-based water feature extraction method which has shown to have a stable optimal threshold value [21]. Layer stacking of spectral indices method also exists [22] and is compared for the water feature extraction. Announced a new technique for the automated mapping of glacial lakes in high-altitude areas of Asia using Landsat-8 data [23].

NDWI and Landsat data is used to analyse that the number of glacier lakes in the western Himalayas increased from 120 to 128 over a thirty-year [24]. The surface elevation change, glacier velocity, and glacial lake area information that were already available analysed to characterize the history of 352 land- and lake-terminating glaciers in three Himalayan sub-regions between 2000 and 2019 [25]. These results demonstrate that, even in cases where lakes are well-established on Himalayan glaciers, the influence of ice-contact lakes propagates up-glacier across only the lowermost 30% of the hypsometric distribution. A group of fifteen global climate models that use four shared socio-economic pathway (SSP) scenarios and the most recent coupled model intercomparison project (CMIP6) data and the open global glacier model (OGGM), a modelling system that explicitly simulates glacier dynamics, to estimate the formation timing for each of the 2,700 biggest potential glacial lakes (>0.1 km2) in high mountain Asia (HMA) and to model glacier development up to 2100 [26]. The study focused on the causes, distribution, and evolution of glacial lakes at the regional scale in the Himalayan Mountain range. They studied lake growth and its influencing characteristics using Landsat thematic mapper (TM) and operational land imager (OLI) photos, Google Earth imageries, Shuttle radar topographic mission (SRTM) digital elevation model, and aphrodite climate data [27]. Another study has made use of high-resolution indian remote sensing LISS IV data, Google Earth in conjunction with ALOS PALSAR DEM, and NDWI multi-temporal Landsat data multi-spectral sensor (MSS), TM, enhanced thematic mapper (ETM) +, and OLI) [28]. A glacier lake database for the Dibang River Basin for the year 2020 using remote sensing data products. The surficial changes in glacial lakes larger than 0.1 km2 were investigated using the multi-temporal Landsat series data [29].

The study displays the fast-growing glacial lakes in the Himalayas of Nepal [30]. The study examined the changes in the glaciers and glacial lakes of the upper ganga basin (UGB) over a 24-year, from 1990 to 2014, using multi-temporal satellite data [31]. Quantified subaqueous mass loss from the replacement of ice with lake water and estimated the volume change of glacial lakes over the greater Himalayas using multi-temporal satellite data and an empirical area-volume connection [32].

In Himachal Pradesh, there are 271 glacial lakes which meet the requirement of mapping [33] of glacial lakes. The Sutlej and Chenab basin's glacier lakes have also been mapped [34] using LISS IV and Landsat data for the years 2011, 2012, 2013, 2014 and 2015 [35]. A frontal change study was carried out on 2 glaciers of the Ravi River basin in Himachal Pradesh [36]. There has been a lot of work on GLOF in other Himalayan states [37, 38] however, case studies on Himachal Pradesh state are limited though having a maximum number of lakes under high priority of risk after Sikkim [37]. Despite these statistics and studies, the long-term changes in the glacial lakes have not been attempted earlier using Landsat data over this region.

The prediction and monitoring of GLOF can be achieved by establishing geo-enabled early warning systems. This type of effort can be helpful to minimize the loss of life, property, and other damages in downstream areas. This again signifies the importance of monitoring the GLOFs for conservation, water management, and for avoiding damages. Therefore, the present study is being carried out for the identification and mapping of glacial lakes and detects the long-term change in the size, number, and pattern of expansion of glacier lake area during the last five decades having an emphasis on glaciers and glacial lakes of Himachal Pradesh. The key objectives of the study were to map the glacial lakes of Himachal Pradesh over five decades using Landsat satellite data for GLOF assessment, assess the long-term changes in the number and area of glacial lakes, and identify GLOF-prone areas in Himachal Pradesh.

3.Materials and methods

Study Area

The state of Himachal Pradesh, located in the northern part of India between latitudes 30˚ 22’ 40’’ N and 33˚ 12’ 40’’ N and longitudes 75˚ 45’ 55’’ E and 79˚ 04’ 20’’ E (https://himachal.nic.in), has been selected for the present research work (*Figure 1*). It has been observed from the literature that Himachal Pradesh is a GLOF-prone area [33, 38]. It is equally vulnerable to GLOF as other Himalayan states i.e. Jammu and Kashmir, Uttarakhand, Sikkim, Arunachal Pradesh etc. [39].

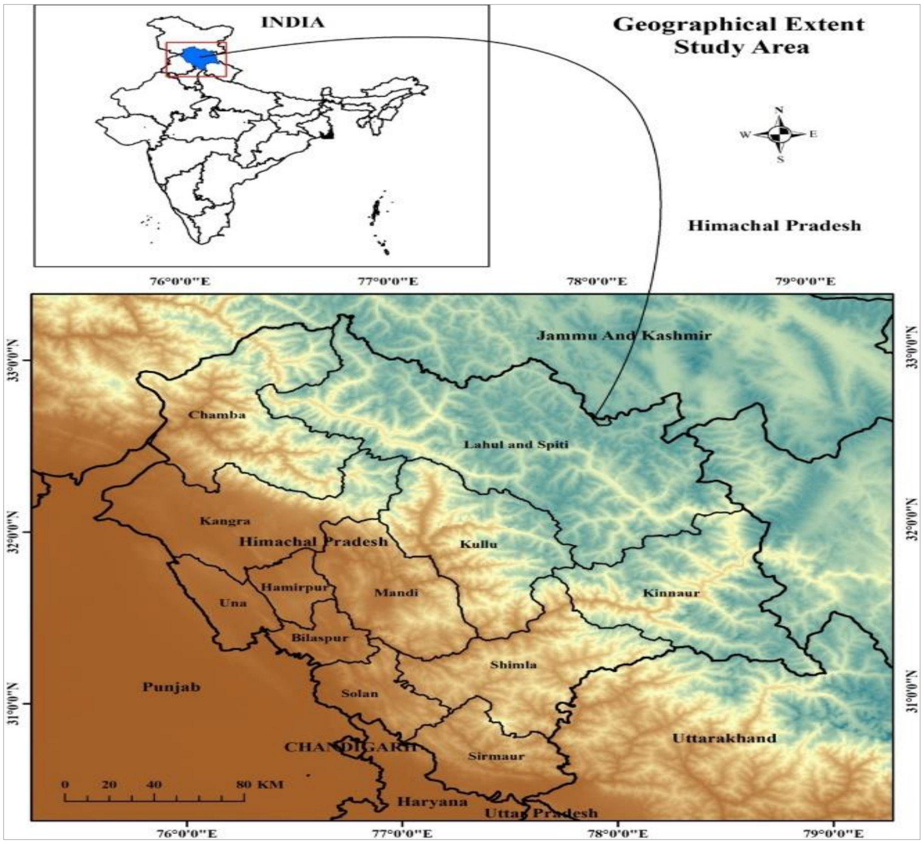

Figure 1 Study area location

The study area is bordered by the state of Jammu & Kashmir to the north, Punjab to the west and southwest, and shares boundaries with Haryana and Uttarakhand to the south and southeast. Himachal Pradesh, predominantly a hilly state, covers a total geographical area of 55,673 km². The state boasts a forest cover of approximately 66.52%, making it one of the richest reservoirs of biological diversity in India. Due to significant variations in altitude, the region experiences a wide range of average temperatures, from 28 to 32 °C. The climate is cold in the upper regions and humid in the lower parts of the state. The average annual rainfall in Himachal Pradesh is 1,469 mm, which is higher than the national average of 1,100-1,200 mm. The major rivers in the state include the Satluj, Ravi, Beas, and Parbati. Prominent lakes in the region include Renuka, Rewalsar, Khajjiar, Dal, Beas Kund, Dasaur, Bhrigu, Prashar, Mani-Mahesh, Chandra Tal, Suraj Tal, Kareri, Serolsar, Gobind Sagar, and Nako.

Data and Methodology

The methodology is presented through a flow chart shown in *Figure 2*. The study utilizes extensive satellite data from the Landsat platform (Landsat 2, 3, 5, 7, and 8) to achieve the required objective. The Landsat is a joint database of the National Aeronautics and Space Administration (NASA) and United States Geological Survey (USGS) which provides the longest continuous record of Earth’s surface in the world. The data essential for the present study has been downloaded from the web link https://earthexplorer.usgs.gov/ in the form of Level 1 Terrain processed data. The details of the satellite data used are provided in *Table 1*.

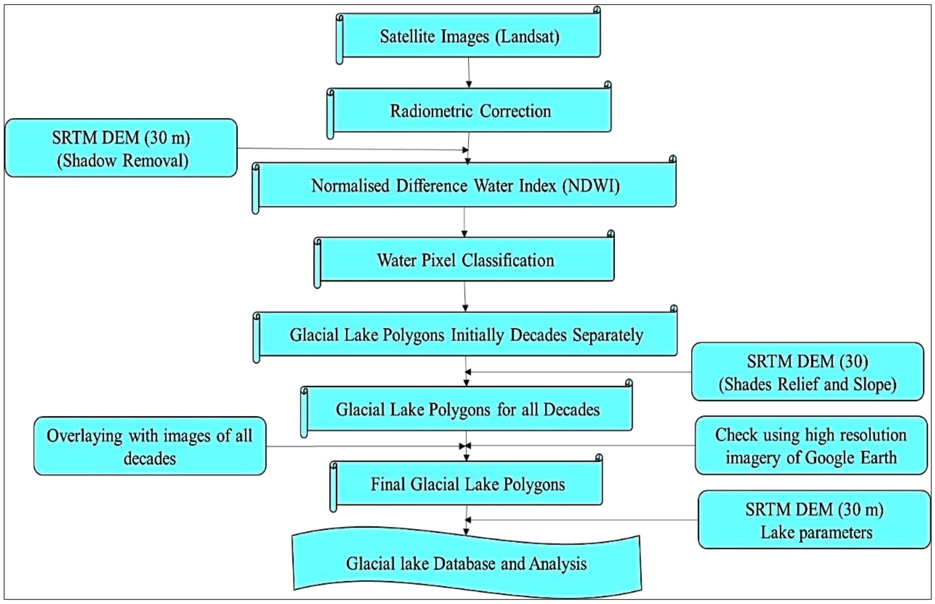

Figure 2 Methodology flow chart

Table 1 Various series of landsat satellite data used in the current study

Landsat 8 Data		**Landsat 5 Data**		**Landsat 7 Data**		**Landsat 5 Data**		**Landsat 3 Data**	
Path/ Row	**Date**	**Path/ Row**	**Date**	**Path/ Row**	**Date**	**Path/ Row**	**Date**	**Path/ Row**	**Date**
146037	13-11-2016	146037	07-09-2009	146037	10-08-2000	146037	05-12-1989	157038	03-10-1980
146038	13-11-2016	146038	13-11-2010	146038	12-11-2000	146038	05-12-1989	157039	03-10-1980
146039	02-12-2017	146039	15-12-2010	146039	27-10-2000	146039	05-12-1989	158037	28-10-1979
147037	06-10-2017	147037	22-10-2011	147037	15-10-2000	147037	16-11-1991	158038	28-10-1979
147038	06-10-2017	147038	22-10-2011	147038	15-10-2000	147038	16-11-1991	158039	22-10-1980
147039	06-10-2017	147039	01-11-2009	147039	15-10-2000	147039	16-11-1991	159037	23-10-1980
148037	30-11-2017	148037	23-10-2009	148037	22-10-2000	148037	17-11-1989	159038	23-10-1980
148038	30-11-2017	148038	23-10-2009	148038	22-10-2000	148038	17-11-1989	-	-

3.1Satellite data preprocessing

Landsat-2 & Landsat -3 data have been used for the year 1980. For the years 1990 & 2000, Landsat -5 data has been used. Landsat -7 data has been used for the year 2010 and further Landsat -8 series data has been used for the year 2017. Landsat-3 data has a spatial resolution of 60 meters, while Landsat 5, 7, and 8 have a spatial resolution of 30 meters. The temporal resolution of Landsat satellite data is 16 days, with the satellite passing over the equator between approximately 10:00 am and 10:25 am. These datasets were downloaded in zip format and then extracted, allowing for the entire dataset to be layer-stacked with all bands used for visualization and indices calculation. Consistency in the season and month across all decades was maintained during the download process. All the satellite data has been transformed from digital number (DN) to top of atmosphere (ToA) reflectance using a series of formulae [40, 41] given in forthcoming sections.

ToA reflectance can be computed using OLI band data which is obtained from the reflectance rescaling coefficients provided in the product metadata file. The transformation from DN to ToA reflectance [ρ'_λ], without rectification for solar angle, is accomplished using the Equation 1 [42]:

$$\rho'_{\alpha} = M_p \times Q_{cal} + A_p \pi r^2 \quad (1)$$

Where, M_p *and Ap* stand for the band-specific additive and multiplicative rescaling factors obtained from the metadata, respectively. Q_{cal} is the quantified and rectified standard product pixel values.

ρ'_{λ} does not contain a rectification for the Sun angle; hence, the ToA reflectance value with a correction [ρ_{λ}] for the Sun angle is obtained by Equation 2:

$$\rho_{\lambda} = \rho'_{\lambda}/sin\theta_{SE} \quad (2)$$

θ_{SE} is the local Sun elevation angle available in the metadata.

All the data was registered with the decadal data of the same path row so that the change in geometry could be corrected within the 0.5-pixel limit. It reduced the error in the decadal change of the areal extent of features (*Figure 2*). These scenes were then mosaiced together to make single images for the whole of Himachal Pradesh. All the processes were done in earth resources data analysis system **(**ERDAS) software. This single image is not suitable for indices calculation because of spectral difference.

3.2Water bodies identification based on water indices

The tool in the ERDAS modeller is used to build the model for batch processing from layer stack to indices calculation. This is customizable tool where the condition can be put according to requirement and can give the input and output options. All the indices were of float type. All the Landsat 8 images have been processed for NDWI as suggested by [18]. The NDWI in Equation 3 is obtained by using ERDAS Modeller and MNDWI in Equation 4 is computed by using both SWIR bands of the Landsat 8 scene.

$$NDWI = [G - NIR]/[G + NIR] \quad (3)$$

$$MNDWI = [G - SWIR]/[G + SWIR] \quad (4)$$

$$NDVI = [NIR - R]/[NIR + R] \quad (5)$$

Normalised difference vegetation index (NDVI) in Equation 5 is given by [43] and further evaluated by [44, 45] is also used to differentiate the vegetation from water bodies. There are two other indices named AWEI and modified advanced water extraction index (MAWEI) for shadowed and non-shadowed data suggested by [21] using the ERDAS Modeler in Equation 6, 7, 8 and 9.

$$AWEI_{nsh} = [4 \times (B3 - B6) - (0.25 \times B5) + [2.75 \times B7] \quad (6)$$

$$AWEI_{sh} = [B2 + 2.5 \times B3 - 1.5 \times (B5 + B6) - [.25 \times B7] \quad (7)$$

$$MAWEI_{nsh} = AWEI_{nsh}/[B3 + B5 + B6 + B7] \quad (8)$$

$$MAWEI_{sh} = AWEI_{sh}/[B2 + B3 + B5 + B6 + B7] \quad (9)$$

All of the formulas (Equation 6, 7, 8 and 9) have been applied to the Landsat 8 satellite data of the year 2017 image-wise and then analyzed for water body extraction based on the threshold method reported by [46].

3.3Threshold-based glacial lake extraction

For the thresholding process, major glacial lakes with varying spectral signatures—such as shallow, deep, muddy, and supraglacial lakes—were selected. These signatures were used to calculate the threshold for each scene across all decades, based on the study by [46], to identify the optimal threshold. The threshold values varied for each scene, likely due to differences in land-use classes, atmospheric conditions, sensor types, and the specific dates within the season. The indices and related thresholds used are provided in *Table 2.* NDWIs derived from different band combinations (visible, near-infrared, or SWIR) might yield varying results, and NDWI thresholds can fluctuate depending on the proportions of subpixel water/non-water components. These are common challenges encountered in such analyses [47]. The procedure to use NDWI for different applications was also recommended. The NDWI threshold varied between dates, whether the data was corrected or uncorrected. A comparison revealed significant disparities between the two types of thresholds. Approximately 90% of this discrepancy can be attributed to temporal variables, including sun-target-satellite geometry and atmospheric conditions [48].

Table 2 Decade-wise threshold for various indices reported in the literature and identified here in this study

Indices	**Identified threshold values in the current study**					**Reported threshold values in the earlier studied**	**Reference**
	1980	1990	2000	2010	2017		
NDVI	-0.02	-0.03	-0.13	-0.10	-0.06	−0.29, (-0.09 to -0.10)	[49, 50]
NDWI	0.21	0.08	0.35	0.24	0.16	> 0.38, 0.05(OLI) – 0.15(TM), 0.144 to 0.153 for Reflectance	[48–51]

Indices	Identified threshold values in the current study					Reported threshold values in the earlier studied	Reference
	1980	1990	2000	2010	2017		
						0.004 to 0.281 for DN, ≥ 0.3 with Zonal St. in ⩽0.3	
MNDWI	-	0.52	0.56	0.55	0.17	0.35, 0.20(OLI) – 0.31(TM)	[49, 50]
MNDWI7	-	0.61	0.62	0.61	0.19	0.5	[49]
AWEIsh	-	0.49	0.78	0.65	0.30	0.11, 0	[49, 50]
AWEInsh	-	0.79	1.21	0.98	-0.25	0.18, 0	[49, 50]

3.4Basin and sub-basin extraction

By using digital elevation model, drainage pattern is generated in remote sensing software by using stream order. Basin and sub-basins were obtained following the Geological Survey of India (GSI) guideline [52, 53]. The basins were generated on a fifth-order basis of drainage pattern.

4.Results

4.1Thresholds for glacial-lake extraction

The threshold values for glacial lakes identified in this study exhibited considerable variability compared to previously reported thresholds. For example, the NDVI threshold ranged from < -0.13 to -0.02, which is within the range reported by [50], but slightly lower than the values reported by [49]. Similarly, the NDWI threshold for water extraction ranged between > 0.16 and 0.35, aligning with the limits reported by [48, 50, 51]. The values for MNDWI and MNDWI7 were consistently higher across all years except for 2017. Additionally, the thresholds for AWEIsh and AWEInsh were found to be higher than the reported values (*Table 1*).

The variability in thresholds may be attributed to factors such as sun-target-satellite geometry, inter-sensor radiometry, and atmospheric conditions [48]. As [49] suggested, MNDWI and AWEI may not effectively distinguish water from shadows and snow, making NDWI and NDVI better options for further analysis. Consequently, NDWI images and thresholds have been used for further analysis and glacial lake identification.

4.2Spatial distribution of glacial lakes and their characteristics

The year-wise spatial distribution of glacial lakes is illustrated in *Figure 3*. The mapping results indicate that in 2017, Himachal Pradesh had 783 glacial lakes, covering an area of 955.6 hectares (*Figure 4*). Small-sized lakes (<0.1 ha) were few in number (10) during the 1980s but gradually increased to 246 by 2017 (*Figure 5a* and *5b*). The highest number of lakes in 2017 was found in the size range of 0.1 to 0.5 hectares. Samudra Tapu Lake, with an area of 135.34 hectares, was identified as the largest glacial lake in Himachal Pradesh. The average size of the mapped glacial lakes was 1.22 hectares.

Most of the lakes in the Himachal Himalaya are situated at elevations between 2,896 meters and 5,872 meters above mean sea level. The average altitude of the mapped lakes was 4,715 meters, with about 95% of the lakes located above 4,000 meters (*Figure 6*). The data shows a consistent trend of area expansion from 1980 to 2017, suggesting a possible effect of warming in higher elevation zones.

The analysis of Landsat data confirms the presence of 610 glacier-fed lakes and 173 non-glacier-fed lakes. Glacier-fed lakes are nourished by glacial melt, snowmelt, and precipitation, and have at least one glacier feeding them. In contrast, non-glacier-fed lakes depend solely on snowmelt or precipitation. Among the 610 glacier-fed lakes, 111 were supraglacial lakes with an average area of 0.24 hectares, 236 were end moraine lakes with an average area of 2.44 hectares, 215 were other moraine-dammed lakes with an average area of 1.03 hectares, and 48 were unconnected lakes. Non-glacier-fed lakes include those formed by glacier erosion, debris dams, and lateral moraine dams.

The spatial distribution of glacial lakes was also analyzed based on basin boundaries. As shown in *Figure 4*, the Spiti basin had the largest number of lakes, followed by the Beas, Bhaga, Parvati, and Ravi basins, accounting for 13.5%, 11.4%, 10.7%, 10.6%, and 10.3% of the total lakes in Himachal Pradesh, respectively. The Jahnvi basin had the fewest glacial lakes, with just 1.5% of the total. In terms of area distribution, the Chandra basin had the largest coverage, followed by Ravi, Beas, Spiti, and Baspa, with 32.8%, 10.6%, 8.9%, and 7.2% of the total area, respectively, while the Jahnvi basin had the smallest coverage at 0.7%. The Beas, Bhaga, Parvati, and Spiti basins are predominantly characterized by moraine-dammed lakes. The Chandra basin not only showed the largest coverage of glacial lakes but also had a higher number of lakes, indicating its vulnerability to GLOFs (*Figure 4*). *Figure 5a* and *5b* illustrate the year-wise variations in the number and area of glacial lakes based on their size. Although large lakes were fewer in number, they accounted for 80% of the total mapped area of glacial lakes.

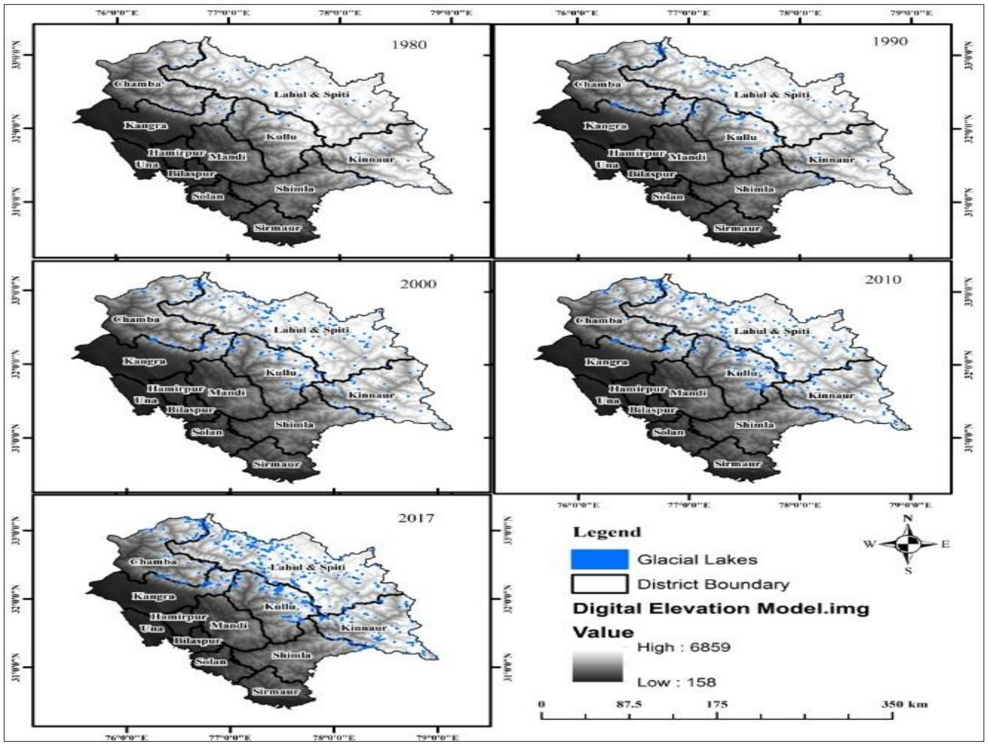

Figure 3 Spatial distribution of Decade-wise glacial lakes

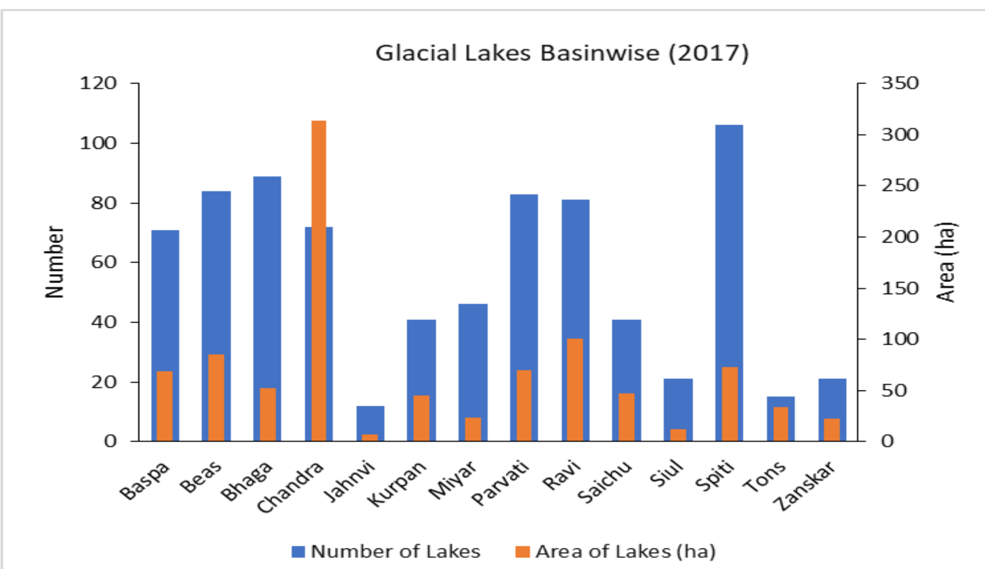

Figure 4 Area and number of glacial lakes basin-wise

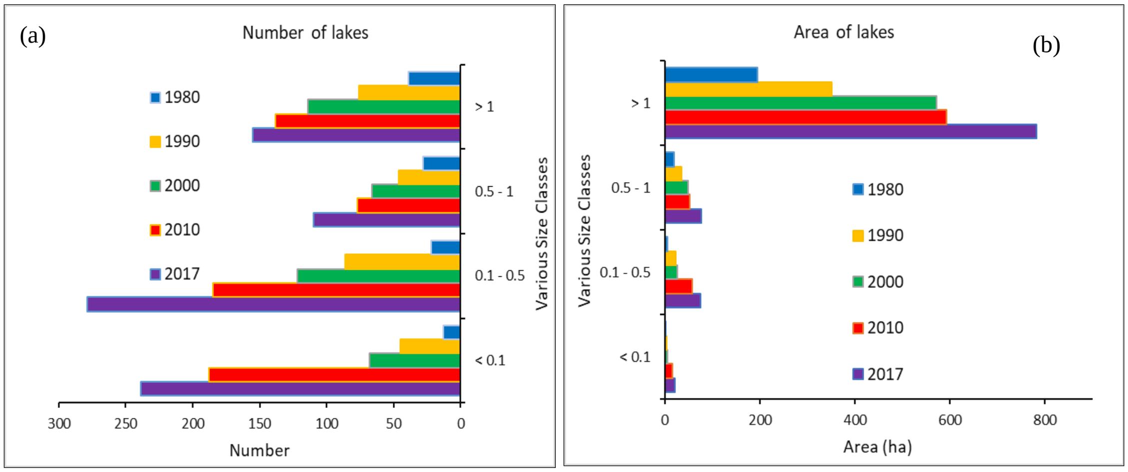

Figure 5 Number (a) and Area (b) of Glacial lakes in various size classes

The increase in the number of small lakes between 2010 and 2017 is showing the effect of warming and the origin of new lakes probably in response to the melting of glaciers. It was also found that the number of lakes had increased from 1980 to 2017 in all the categories (based on size) of lakes (*Figure 5a*). The year-wise distribution of glacial lakes concerning elevation and types was also analyzed. The most dominant type of glacial lake was moraine dam lakes and mainly distributed between 4000-5500 m elevation ranges (*Figure 6a*). A similar trend was observed in the area coverage of lakes (*Figure 6b*).

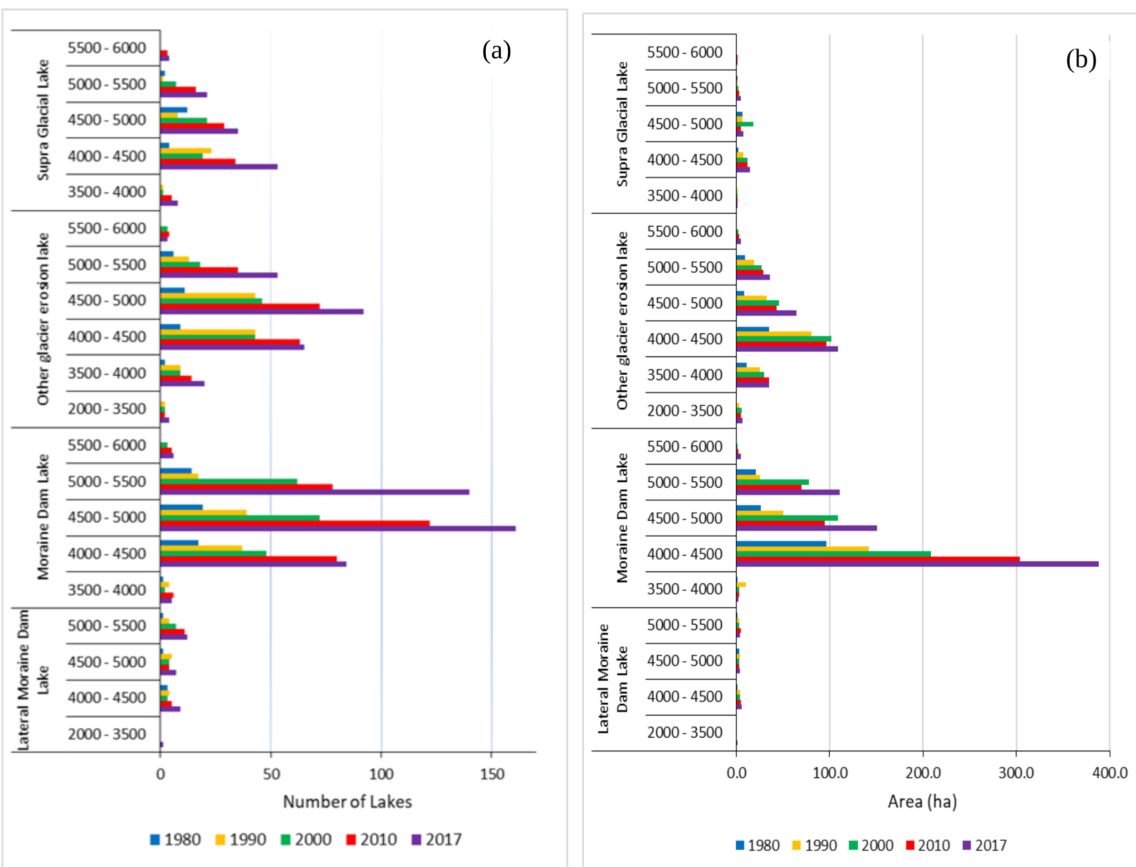

Figure 6 Decadal Area (a) and Number (b) of glacial lakes w.r.t Altitude range and lake type

4.3Trends of glacial lakes development

The trend of glacial lake development in Himachal Pradesh highlights the growth of glacial lakes in numbers as well as area from 1980 to 2017.

- The results of mapping showed that the decade of 1980-90 noticed the highest growth in numbers and area of glacial lakes where the number of glacial lakes has increased by 14.8% per year and the area expanded by 8.6% per year from 1980 to 1990s.
- From 1980 to 1990 decade a declining trend of growth was recognised in glacial lakes. The areal expansion growth rate of lakes was noticed at 4.6% per year. Whereas the growth rate in the number of new lakes was observed to be 5.6% per year.
- In subsequent decades (1990 – 2010) a marginal growth in the expansion of the area of glacial lakes was noticed. The area of glacial lakes expanded by 5.9% per year. But the growth rate in the number of new lakes touches 1% per year.
- The glacial lakes increased by 3.3% per year in area during the decade 2010-2017 which represents that the number of lakes were growing very fast. This increasing change was probably due to the increase in Moraine Dam Lake and supraglacial lakes. These two factors are chiefly responsible for the growth in numbers and area of glacial lakes.
- *Figure 6* presents the decadal changes in the area and number of glacial lakes with respect to altitudinal ranges and lake types. Supraglacial lakes, which are ponds located on the surface of a glacier, showed the most significant increase within the 4000–5500-meter elevation range in the study area.
- The increase in the number and area of Moraine Dam Lakes (the lakes formed after the prevention of the flow of meltwater from the valley on the Moraine terminal) was again the maximum over the same altitudinal ranges (4500-5500 m).
- Other glacial erosion lakes were the highest in both number and area over the altitudinal range between 4000-5500 m.

Figures 7, 8 and *Table 3*, show the fluctuations in the number and area of glacial lakes from 1980 to 2017. The spatial distribution of glacial lakes which appeared (green), disappeared (red) and sustained (blue) during the study period are presented in *Figure 7*.

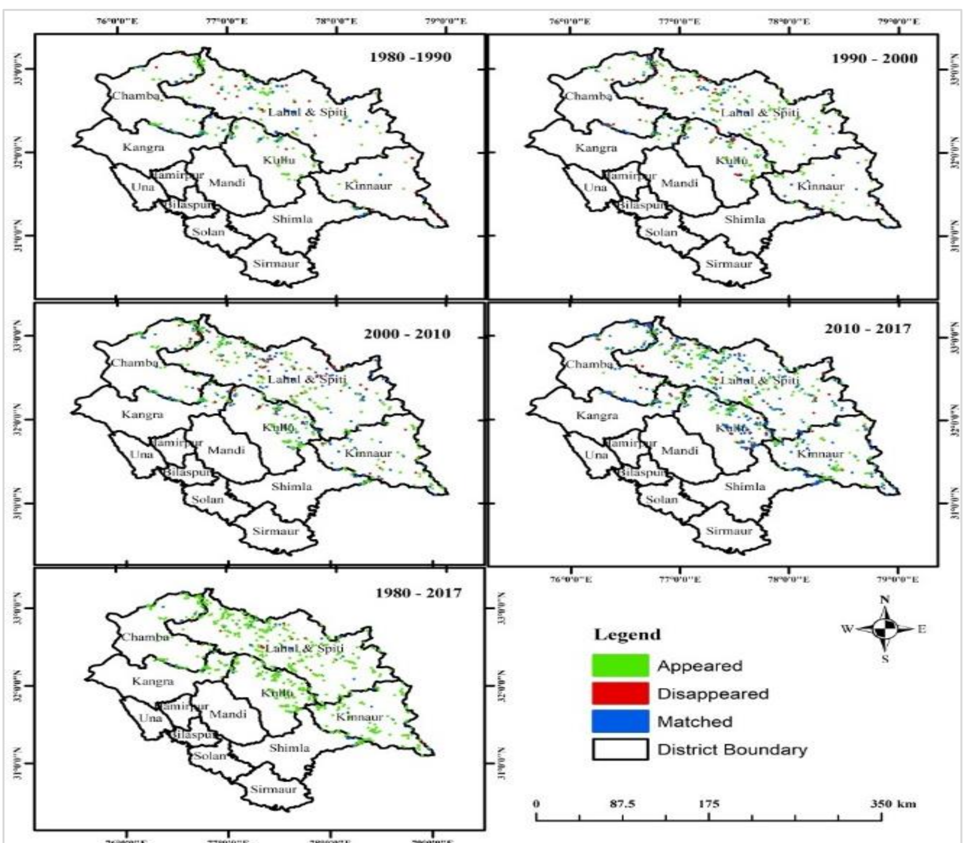

Figure 7 Spatial distribution of glacial lakes which are appeared and disappeared

- Decade-wise appeared and disappeared glacial lakes and related area dynamics showed maximum fluctuations in the elevation range of 3500-5500 m (*Figure 8*).
- In between the years **1980 to 1990**, the maximum gain in a number of glacial lakes was 79 at the 4000-4500 m altitude range and the maximum loss in number was 18 at the 4500-5000 m altitude range.
- The maximum area gain was 43.1 ha in the 4000-4500 m altitude range and the maximum area loss (11.6 ha) in the 5000-5500 m altitude range.
- In between the years **1990 to 2000**, the maximum gain in several glacial lakes was 74 and the maximum loss was 36 at the same 4000-4500 m altitude range while the area gain was 68.6 ha maximum in the 4500-5000 m altitude range.
- In between the years **2000 to 2010**, the maximum gain in several glacial lakes was 123 with an area gain of 41.8 ha and the maximum loss in glacial lakes was 39 at the altitude range of 4500-5000 m.
- In between the year **2010 to 2017**, the maximum gain in several glacial lakes number was 105 with an area gain of 35.1 ha at the 5000-5500 m altitude range and the maximum number loss in number was 48 at the 4000-4500 m altitude range with an area loss of 14.8 ha.
- The overall scenario showed that the maximum glacial lakes developed between 4500-5000 m altitude range and the maximum number of lakes were also lost between 4500-5000 m altitude range (*Figure 8*).
- Since most of the fluctuation is observed around 4500-5000 m, it has a great potential for the GLOFs events (*Figure 9*).

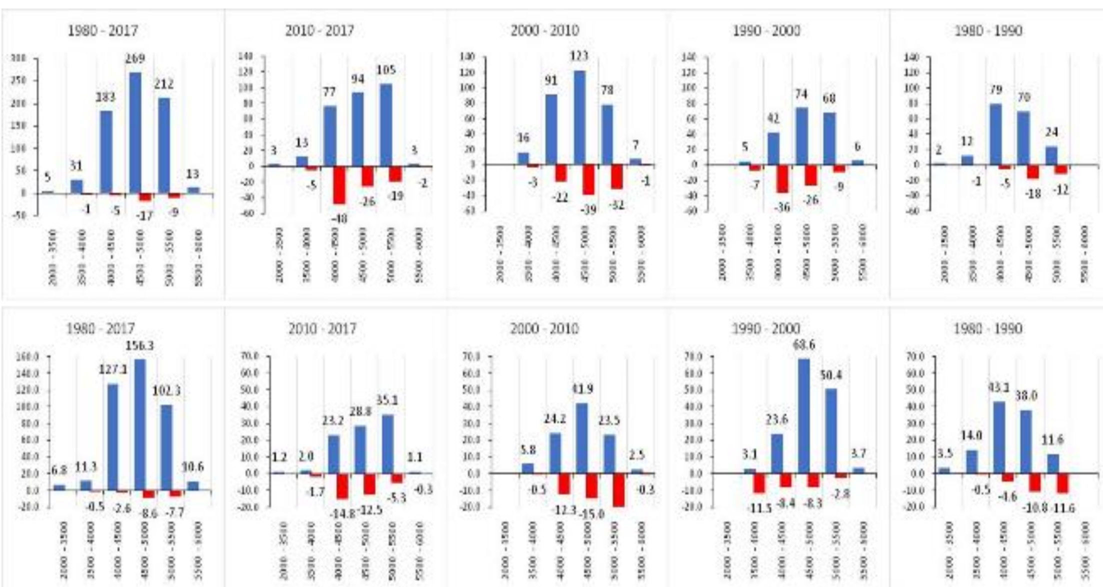

Figure 8 Decade wise appearance and Disappearance of Glacial Lakes in Number and Area

Table 3 Fluctuation in the number and area (ha) of glacial lakes during 1970-2017 on a basin and sub-basin scale

Basin	Sub-Basin	2017		2010		2000		1990		1980	
		Count	Area	Count	Area	Count	Area	Count	Area	Count	Area
Beas	Beas	84	85.2	75	58.5	52	64.2	40	28.9	6	8.0
	Parvati	83	69.5	63	44.2	34	42.7	22	27.4	5	11.0
Chenab	Bhaga	89	52.8	62	33.0	38	28.9	31	21.2	17	11.0
	Chandra	72	313.9	38	270.9	30	196.8	20	152.9	10	109.7
	Miyar	46	23.9	42	13.5	27	20.2	20	17.0	5	4.4
	Saichu	41	46.8	40	32.4	27	34.9	24	25.2	8	8.2
	Siul	21	12.0	18	9.8	10	8.2	7	3.2	4	3.2
Indus	Zanskar	21	22.0	12	17.3	15	23.0	4	9.4	5	5.9
Ravi	Ravi	81	101.1	67	82.4	48	76.8	48	62.6	15	21.7
Satluj	Baspa	71	69.1	41	43.7	20	34.7	6	10.7	8	5.9
	Kurpan	41	45.4	29	21.8	10	14.7	4	3.9		
	Spiti	106	73.0	78	56.0	51	73.3	18	26.4	11	13.1
Yamuna	Jahnvi	12	6.6	9	3.3	3	10.3	2	5.8	3	6.1

Basin	Sub-Basin	2017		2010		2000		1990		1980	
		Count	**Area**	**Count**	**Area**	**Count**	**Area**	**Count**	**Area**	**Count**	**Area**
	Tons	15	34.2	14	30.8	5	25.6	7	19.3	5	14.7
Grand Total		**783**	**955.6**	**588**	**717.6**	**370**	**654.4**	**253**	**414.0**	**102**	**222.8**

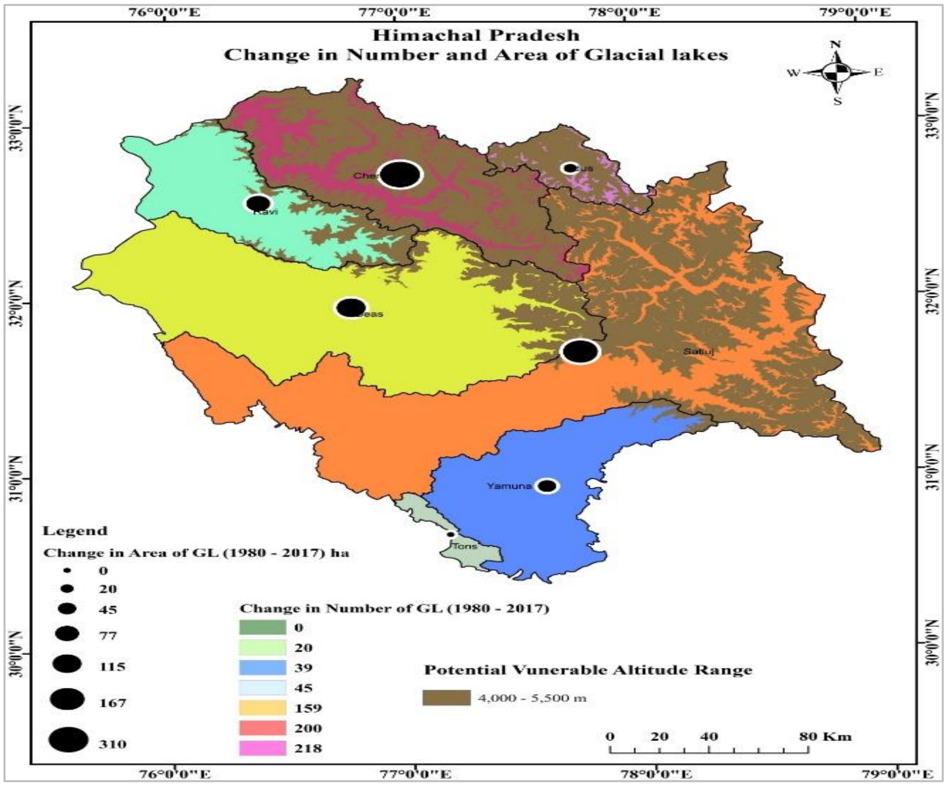

Figure 9 The most vulnerable area for changes in glacial lakes and GLOFs events

5.Discussion

The present study has been carried out for the times-series mapping of glacial lakes number and area from the year 1980 to 2017 in Himachal Pradesh using Landsat satellite series with a resolution of 30 m (2017, 2010, 2000 & 1990) and 60 m (1980).

- The number and area of these lakes were found to be increasing rapidly. The major category seen to have increased is moraine dam glacial lakes both in terms of number and area, also mentioned by different studies [28, 36,54–56].
- Some glacial lakes have disappeared, and new glacial lakes have also emerged during the study period depending on the changes that occurred in elevation and ambient temperature.
- The major change in the number and area of glacial lakes was seen in the 4000-5500 m elevation range. Basin-level analysis indicated that the Chandra basin had the maximum area of glacial lakes having the 2 largest moraine dam lakes in it and the Spiti basin had a maximum number of glacial lakes. Other studies [34, 35, 54, 57, 58] also found that increment in this range and Chandra basin of the study area.
- Out of 269 numbers of glacial lakes appeared from 1980 -2017, of which 123 glacial lakes have appeared in the 2000- 2010 decade alone indicating the effect of recent global climate change and temperature increase on the glacial lake's regions.
- A total increase of 156.3 hectares in the area of glacial lakes was observed from 1980 to 2017, with the largest increase of 68.6 hectares occurring during the 1990-2000 decade, indicating the formation of small lakes. Similar studies have also reported an increase in these categories of lakes [28, 36, 54–56].
- The change in the number of glacial lakes interpreted in this study has helped to visualize the increase in overall lake areas in recent decades implying climatic factors and warming beyond the normal scenario in the elevation range of 4500m to 5500m.

Limitations

During the study, one of the main challenges was locating satellite images captured within specific time intervals that would minimize temporal differences. Ensuring temporal consistency is crucial when analyzing changes in glacial lakes over several decades, as variations in the timing of image acquisition can introduce discrepancies in the data. Factors such as seasonal changes, weather conditions, and the availability of cloud-free images further complicated the process. A complete list of abbreviations is listed in *Appendix I*.

6.Conclusion and future work

Though the number and area of these lakes were found to be increasing rapidly in the study area where disappearance of glacial lakes is also found decade-wise that needs further investigation of the exact reasons behind the disappearance of lakes at higher altitudes. This study also encourages the in-depth study of long-term climatic changes in the study area such as a time series analysis of minimum and maximum temperature variation, precipitation patterns and tectonic reasons that have led to the appearance and disappearance of several Glacial Lakes.

Nevertheless, more fluctuations in the number and area are directly related to GLOF events thus this study helped to understand the areas vulnerable to GLOFs i.e. the elevation range 4000-5500 m in the study area. The data generated in this study can be used with Land-use land cover, geology, geomorphology, soil type, and meteorology for further research to find the potential GLOF events through a multi-criteria analysis. The results from this study stir up the requirement for Glacial Lake monitoring to be done from time to time in this hilly state to manage and map the areas vulnerable to future GLOF hazards thereby planning mitigation methods. This data can be used as base for identifying the site for installation of early warning system to avoid GLOF hazard.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

The data used in the study will be provided by the corresponding author upon reasonable request.

Author’s contribution statement

Parmod Kumar and Swati Sharma: Methodology, formal analysis and investigation, writing - original draft preparation. **I.M. Bahuguna and Partibha**: Writing - review and editing, supervision.

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Appendix I

S. No.	Abbreviation	Description
1	AWEI	Automatic Extraction Water Index
2	CMIP6	Coupled Model Intercomparison Project
3	DN	Digital Number
4	ERDAS	Earth Resources Data Analysis System
5	ETM	Enhanced Thematic Mapper
6		
7	GIS	Geographic Information System
8	GLOF	Glacial Lake Outburst Flood
9	GSI	Geological Survey of India
10	HMA	High Mountain Asia
11	ICIMOD	International Centre for Integrated Mountain Development
12	LISS	Linear Imaging Self-Scanner
13	LST	Land Surface Temperature
14	MNDWI	Modified Normalised Difference Water index
15	MSS	Multi-Spectral Sensor
16	NASA	National Aeronautics and Space Administration
17	NDPI	Normalised Difference Pond Index
18	NDSI	Normalised Difference Snow Index
19	NDVI	Normalised Difference Vegetation Index
20	NDWI	Normalised Difference Water Index
21	NIR	Near Infra-Red
22	OGGM	Open Global Glacier Model
23	OLI	Operational Land Imager
24	SAC-ISRO	Space Applications Centre – Indian Space Research Organisation
25	SRTM	Shuttle Radar Topographic Mission
26	SSP	Socio-Economic Pathway
27	SWIR	Short Wave Infra-Red
28	TM	Thematic Mapper
29	ToA	Top of Atmosphere
30	UGB	Upper Ganga Basin
31	USGS	United States Geological Survey