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Assessment of Continuous Growth of Glacial Lakes in the Teesta River Basin Using Semi-Automated Geospatial Approach

A. K. Shukla*†, I. Ahmad*, S. K. Jain and M. K. Verma***
*Department of Civil Engineering, National Institute of Technology, Raipur, Raipur-492 010, Chhattisgarh, India
**Centre of Excellence in Disaster Mitigation & Management, IIT Roorkee-247667, Uttarakhand, India
†Corresponding author: A.S. Shukla; amitkrshukla01@gmail.com

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ABSTRACT

Global warming is one of the primary causes contributing to melting glaciers and shrinking of glaciers moth. Because of the glacier retreat, more lakes increase the risk of flooding in people's homes and lives. Several studies on the surging glaciers have been conducted by researchers using various techniques, as well as with the aid of multiple models like the Normalized Differential Water Index (NDWI). The Number of glacial lakes is increasing in the Himalayan region due to climate change (rise of the temperature). Some glacial lakes are potentially dangerous so monitoring is very necessary. It is necessary to evaluate such vulnerable lakes. Therefore, current work is carried out to identify such glacial lakes present in the Teesta River Basin (Eastern Himalaya). Spatiotemporal Landsat data for the last four decades at intervals of ten years from 1990 to 2020 has been considered which was cloud-free and spatial resolution of 30 meters. The dataset mentioned above was used for lake identification and delineation. The findings indicate the presence of lakes with respective areas of 275 (18.90 km^2), 337 (24.92 km^2), 295 (22.96 km^2), and 419 (31.44 km^2). It has also been observed that the growth rate is increasing with approximate water spread from 1990 to 2000 (+129%), 2000 to 2010 (+106%), and 2010 to 2020 (+136%). The present study aimed to identify such glacial lakes based on their water spreading area, which is an essential step followed in the study of GLOF (Glacial Lake Outburst Flood) as it will be helpful in the identification of hazardous lakes. In that study, we found that eleven glacial lakes are in the potentially dangerous category situated in the upper Teesta Basin due to the presence of glaciers, which gives a clear reason for the time-to-time assessment of such lakes. By the conducted study it has been observed that the number of glacial lakes has increased, due to which water spread has also increased in the area. It can also be demonstrated that GIS (Geographical Information System), along with remote sensing, is one of the best tools for assessing and monitoring such change detection and differentiation of hazardous glacial lakes in the cryosphere, along with the supporting data.

INTRODUCTION

India's natural border with China is defined by a range of Himalayan Glacier Mountains surrounding it in the northeast. With a combined snow area of around 60000 km2, these mountain ranges extend a 2000 km stretch (Kaab et al. 2012, Khadka et al. 2018 & 2019, Maskey et al. 2020). In the Himalayan region, much research found that glaciers and snow areas have decreased in the last few decades. However, with every passing year, these glaciers are retreating by 0.4% per year (Bolch et al. 2012). These glaciers provide food for about 1.3 billion people in Asian nations, which make up about one-fourth of the world's population. In addition, the flow of naturally soured water into the connecting rivers, which are then used for residential, industrial, and irrigating purposes, satisfies the need for water for flora and animals residing in southern Asia. It has been observed that many glaciers are melting around the world due to climate change. An intergovernmental institute named The International Centre for Integrated Mountain Development (ICIMOD) is an organization that contributes toward conservation and sustainable developments related to the Hindukush Mountain region. ICMOD has created an inventory of glaciers and glacial lakes for the Himalayan area at regular intervals. It has been revealed that, as the glaciers are thinning and shrinking, the glacier's mouth is receding.

Consequently, depression areas separate from glaciers, and after years, these areas become known as glacial lakes, which are growing both in number and size (Mool et al. 2001). Glacial lakes are formed as the meltwater collects in areas with depressions that are surrounded by moraines and ice on retreating glaciers. Mainly such glacial lakes are formed in glaciated, and very few of them are found in non-glaciated regions.

The glaciers are receding year after year, which results in the formation and expansion of glacial lakes consistently. Many lakes are considered to be hazardous, as they provide the possibility of catastrophic events. Cryospheric sciences are therefore studied by scholars to broaden their knowledge and contribute to the efforts of the local community, non-governmental organizations, and the government. Many articles are available that explain the mechanism involved in the evolution of these glacial lakes and the factors regulating it (Reynolds 2000, Benn et al. 2012, Thompson et al. 2016). Different researchers have classified Glacial lakes into different types and groups. ICIMOD in the Hindu Kush Himalayan region has classified the lakes into five categories based on their occurrence and process of formation, which is: glacial erosion lake, moraine-dammed lake, ice-blocked lake, Supraglacial Lake, and subglacial lake (Shukla et al. 2018). Glacial erosion lake is the type of lake located at the snout of the retreated glacier formed by the eroded glacier, which is again classified into cirque lake, glacial valley lake, and another glacial erosion lake. Moraine dammed lakes are the type of waterbody that lies between the Moraine ridge and glacier due to the obstruction created by the Moraine. These types of lakes can be divided into three types based on the formation location: End-Moraines, Lateral Moraines, and Moraines Thaw Lake, ice-blocked lakes, including advancing glacier-blocked lakes, and other glacier-blocked lakes, supraglacial and subglacial lake (Dhar et al. 2010). While most glacial lake characteristics can be investigated using remote sensing and GIS techniques, it offers a helpful method for keeping track of all these lakes (Bolch et al. 2012). The primary factors affecting glacial lakes, including the volume and number of lakes and other geometrical aspects like mass, size, length, and width, can be monitored using geospatial data (Reynolds 2000). Numerous studies have shown the significance of remote sensing in monitoring glacier lakes and creating their inventory (Huggel et al. 2002). Remote sensing is typically the sole method that can be used to monitor and map these glaciers. Glacier dynamics and remote sensing have been extensively studied in research. Nevertheless, even though the threshold of NDWI is the most commonly used index for glacial lake mapping, other supporting ground truth verification can be considered important.

The Hindu Kush Himalayan's hydrological conditions at higher altitudes in the catchments can be significantly impacted by these changes in glaciers and snow cover due to climate change (Kargel et al. 2005, Scherler et al. 2011, Brun et al. 2017, Debnath et al. 2018). Additionally, vegetation and fauna were negatively impacted; ensuing changes in run-off owing to glacier melt will have an indirect or direct impact on approximately a fifth of the world's population (Clague & Evans 2000, Huggel et al. 2004, Garg et al. 2021).

Per one of the research studies, it has been estimated that by the year 2100, 1/3 of the country's whole Himalayan forest will have vanished due to cattle grazing and deforestation (). The Easter Sikkim Himalayas (Present research work) have to significant rapid growth of glacial lakes and decreases the glacier coverage area (Benn et al. 2012, Khadka et al. 2020). A considerable amount of glaciated area decreases by around 2.5% in the Teesta River basin, and Moraine and debris cover the formation of glacial lakes in the non-glaciated area (Bolch et al. 2012, Basnett et al. 2013, Shukla et al. 2018). Most of the glacial lakes are formed in the upper part of the Sikkim Himalayan because these areas are covered by snow (Nie et al. 2013, Aggarwal et al. 2016). As a result of rising global temperatures brought on by increased global warming, Himalayan glaciers' snow and ice are melting, forming new glacial lakes and increasing the volume of already-existing lakes (Bolch et al. 2012, Veh et al. 2020, Chowdhury et al. 2021), which can be hazardous and result in Glacier Lake Outburst Floods (Abdul et al. 2018, Rajak et al. 2022). This is the main reason for concern GLOF. GLOFs are a serious environmental issue. A glacial lake, often blocked by ice or moraine, releases water suddenly due to glacier melting, landslides, or avalanches. Massive floods in valleys and river basins can threaten human populations, infrastructure, and ecosystems due to rapid water flow downstream. GLOFs are important in glacier-covered regions like the Himalayas and the Andes. A GLOF has long-term socio-economic effects as well as physical impairment. GLOF risk reduction requires glacial lake monitoring and early warning systems. Understanding glacial lake dynamics and taking early steps can improve resilience in sensitive mountainous locations and mitigate climate change's effects on glacial habitats.

The ICIMOD evaluated the glacial lake at the first level for the. Indian Himalayan region (Mool & Bajracharya 2003, Budhathoki et al. 2013). According to research from 2003, Sikkim, which has an area of roughly 20.20 km^2, has about 266 glacial lakes in the eastern Himalayas. They classified a total of 14 glacial lakes as being particularly susceptible. Due to its topographical and lithological features, northern India, along with the Himalayan ranges, experiences disasters like landslides and floods more frequently than other regions (Salerno et al. 2012, Bolch et al. 2012, Basnett et al. 2013, Allen et al. 2016). One similar catastrophe happened in June 2013 in Kedarnath, Uttrakhand; torrential rains caused dam movement that spread to the nearby habitation area, destroying the hamlet and surrounding areas (Dobhal et al. 2013, Martha et al. 2014, Das et al. 2015, Allen et al.

2015, Iwata 2000, Sakai & Fujita 2010, Zhang et al. 2011). Moreover, the frequency of GLOF occurrences suddenly increased in the second half of the 20th century (Bajracharya et al. 2002, Koirala et al. 2017). To analyze these temporal changes using spatial data, which are occurring in the Himalayan glaciers, the current study was carried out (Shrestha & Balla 2011, Koirala et al. 2017). The Teesta basin was delineated for the analysis, primarily covered with high mountain ranges, many glaciers, and lakes. Lakes were indicated for each year of the temporal Landsat series data from 1990 to 2020 (Srivastava et al. 2022), which were then overlaid to analyze the overall regional change (Jain & Mir 2019).

Remote sensing tools/models like the NDWI are often used to measure and keep an eye on the amount of water in different areas (Mitkari et al. 2017, Watson et al. 2018, Jaiswal & Jhariya 2020). NDWI is found by using pictures taken from space or the air since water absorbs light in the near-infrared range and reflects light in the visible range. This measure is very helpful for separating bodies of water, seeing how water levels change, and keeping an eye on trends in aquatic ecosystems. Researchers and environmental scientists use NDWI to look into water flow patterns, track how climate change affects water supplies, and judge the health of wetlands (Magsar et al. 2021). It can be used for more than just monitoring the environment. For example, it can be used to help farmers handle crops by showing how wet the soil is (Gong et al. 2020). NDWI is also very important for crisis management because it helps make maps of areas that are flooded after natural disasters like hurricanes or floods. Additionally, NDWI is a useful and flexible instrument in the field of remote sensing that makes it easier to understand and control water resources around the world.

This study aims to identify the newly formed glacial lakes for the last forty years and demarcate them with the help of spatial datasets. Firstly, differentiation is done using the spatial data available for the required years using the techniques of remote sensing and GIS; once the inventory of lakes is identified, different algorithms, including NDWI and NDSI, are applied for the validation of marked lakes. Finally, the categorization of lakes It was done based on the covered area and elevation.

STUDY AREA

The Teesta Basin is situated in the northeast of the country, covering the entire state of Sikkim, a part of the Eastern Himalayan that lies between the boundaries of Nepal and Bhutan (Basnett et al. 2013, Raj et al. 2013). The basin has a total area of about 8141.59 km2 with a geographical extent between 27°04’52” and 28°08’26” N latitude and 88°00’57” and 88°55’50” E longitude (shown in Fig. 1). The Teesta River, which is a tributary of the Brahmaputra, originates from Chhombo Chhu. Khangchung Chho glacial lake is 5281 meters (Abdul Hakeem et al. 2018) in the northeastern corner of Sikkim. Several tributaries, including the ZemuChhu, Lachung Chhu, Rangyong Chhu, Dik Chhu, Rani Khola, Rangpo Chhu, and Rangit River, then join it. The whole basin lies between 6500 to 813 meters above sea level. Based on a report from the 2011 Census, the overall recorded population of Sikkim was about 610,577, which is an increase of 13% compared to 2001 (Aggarwal et al. 2017). Due to its topographic conditions, glaciers, and other related features, Sikkim is categorized in Zone IV of the Indian seismic chart, which means that it has a high risk of an earthquake with higher intensity (Murthy 2004, Sharma et al. 2012, Aggarwal et al. 2017).

CLIMATE

The climate of Sikkim Himalaya varies with its elevation variation; hence, it can be classified into five types, starting with lower elevation. First comes the subtropical zone, which lies up to 1000 meters. Second comes the warm temperate zone found between the elevation of 1000 and 2000 meters middle Sikkim Himalayan range (2000-25000 meters) comes under the cold temperate zone. The fourth one is the cold zone between 2500 and 4000 meters, and the topmost part of the Himalayas comes under the Frigid Zone with its elevation above 4000 meters (Meetei et al. 2007, Tsering et al. 2019). Sikkim Himalayas has a variety of plant and animal species, and the major glaciated portion of the basin is in the Northern part (SC Mukhopadhyay 1982 and Tsering et al.2019). It has more than 400 glacial lakes. Out of these, most of them lie above 4500-meter elevation. Mean annual rainfall varies from 2000 to 4000 mm due to altitude (Census, 2011). Precipitation and Melted water are the primary sources of water supply to the Teesta River (SC Mukhopadhyay 1982 and Tsering et al. 2019). Temperature varies from 1.5°C to 9.5°C at a lower altitude, with its maximum temperature recorded during the month of July-Aug (21°C-26°C) and minimum during December to January between 6°C 8°C (Census, 2011).

MATERIALS AND METHODS

Materials

For the present work, Alos Palsar DEM with a resolution of 12.5 meters has been used for watershed delineation and drainage map; the broad basin has been divided into nine sub-basins based on major tributaries. This dataset is freely available to download from https://search.asf.alaska.edu/. In

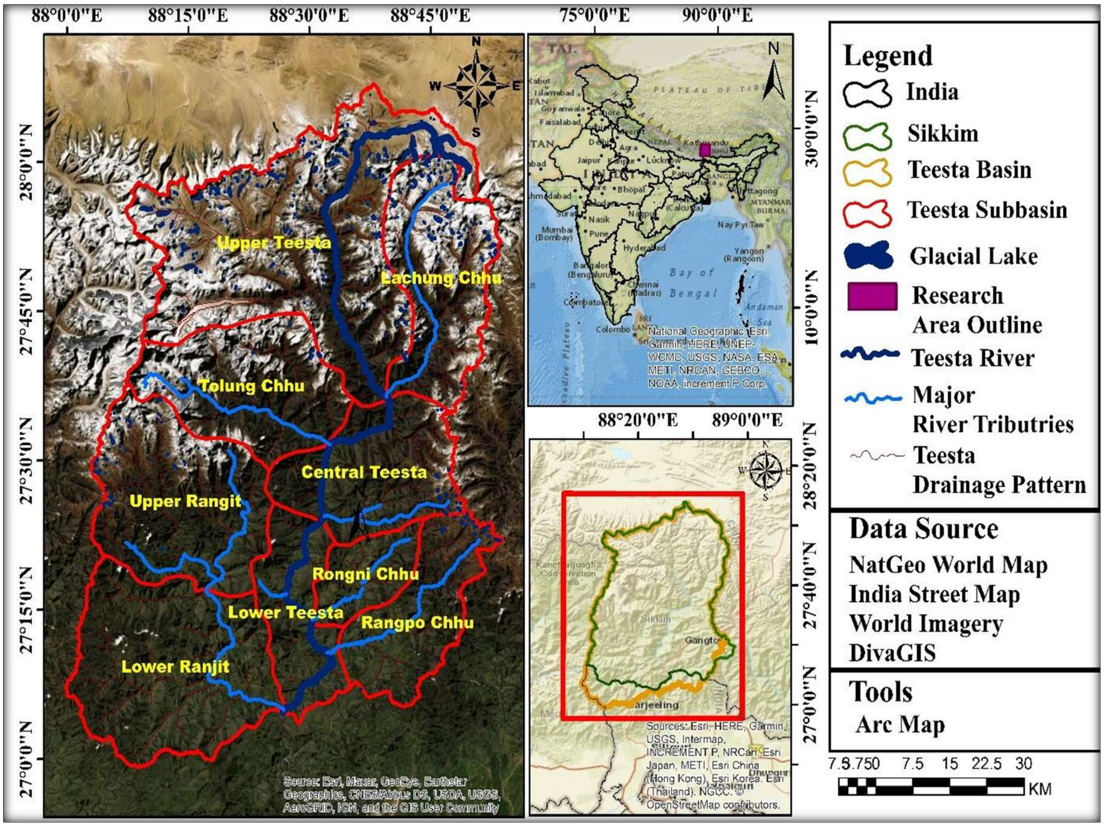

Fig. 1: The study area.

Table 1: List of satellite data used in glacial lake inventory.

Satellite/Sensor	Type of Data	Resolution	Source	Remark
AlosPalsar (Hi-Resolution terrain Data)	DEM	12.5 meter	https://search.asf.alaska.edu/	Watershed delineation and Drainage network
Landsat Series (TM, MSS & OLI/TIRS)	Optical Imagery	Vary from 30 meters to 80 meters	https://earthexplorer.usgs.gov/	Demarcation of glacial lake
Google Earth	Image Landsat/ Copernicus	1 meter	https://earth.google.com/	Validate and identify glacial lake

addition, Google Earth images, which are high-resolution data of approximately 1 meter, have been downloaded using SAS Planet software for lake identification. In contrast, Landsat TM, ETM, and OLI/TIRS data with a spatial resolution of 30 and a panchromatic band of 15 meters, respectively, have been downloaded from https://earthexplorer.usgs.gov/ used as primary data (given in Table 1) for differentiation of lakes for different time series.

Methodology

Geospatial techniques for watershed delineation and investigation of glacial lakes are used by many pieces of research prominently as they allow for the preparation of a watershed boundary, which includes downloading topographic terrain data and its pre-processing using a predefined algorithm for mosaicking, clipping, and re-projecting. After that, other required steps are done as a part of post-processing with the help of algorithms like r.watershed and r.outlet under QGIS software.

Once the delineation process is completed, different indexes or algorithms are predefined (Wessels et al. 2002, Govindaraj et al. 2013). An index like NDVI and NDWI is being used, which recognizes different objects on the surface based on the reflectance as every object has its properties, which can be classified using for the identification and delineation of

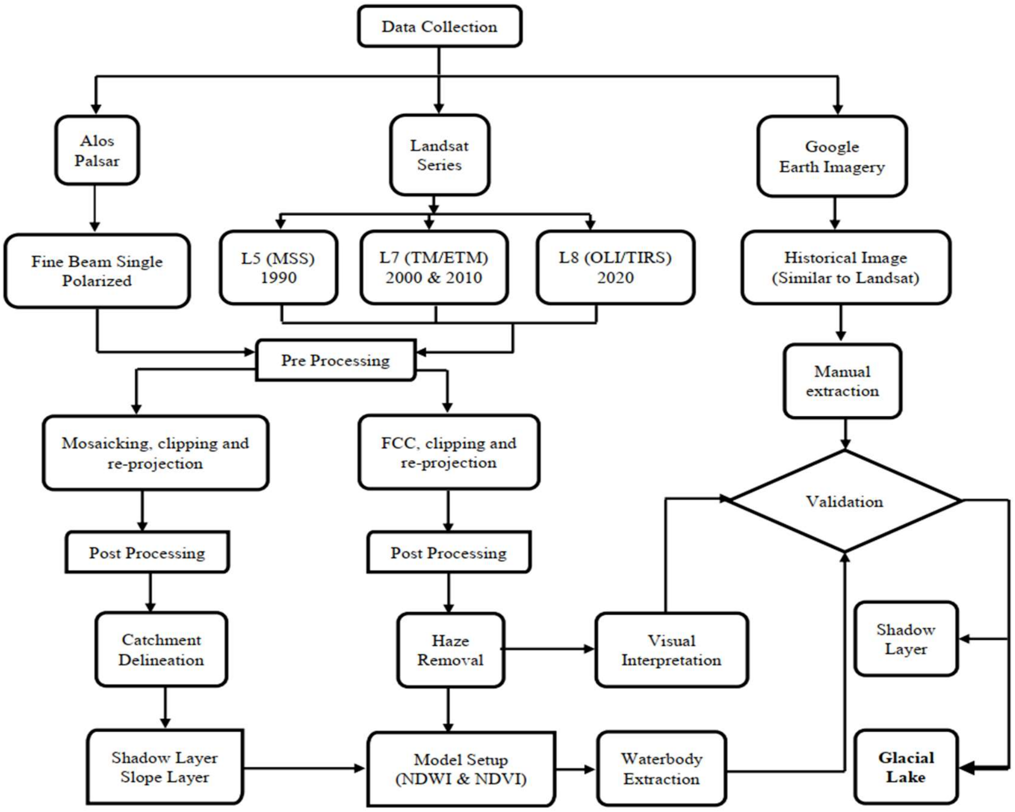

Fig. 2: Flow diagram of methodologies.

glacial lakes. A detailed process adopted is given in Fig. 2.

Identification of Glacial Lakes

The high-resolution Google Earth data allowed for the identification of glacial lakes that are located inside the basin. Through the use of the SAS Planet software, the imagery has been downloaded. After that, the basin was divided into 10 by 10-kilometer grids, and a fishnet was made for the basin, which was then superimposed on the map of the lake that had been downloaded.

Demarcation of Glacial Lakes

Landsat data, which is the most extended time series data available, has been used to demarcate the glacial lakes for the different years 1990, 2000, 2010, and 2020; data for these years has pre-processed, i.e., false-color composite, re-projection, and clip the area of interest, and the lakes were demarcated using the technique of visual interpretation to achieve the maximum accuracy due to variation in the due to the variation of terrain shadow appear which affects the actual pixel value, therefore, resulting in inaccurate digital interpretation.

NDVI

NDVI is the numerical formula for calculating the vegetation cover using the visible bands from satellite imagery (Scanlon et al. 2002, Kunkel et al. 2011). It measures the reflectance value from the leaves and gives the overall vegetation cover on the surface (Malo & Nicholson 1990). Algorithms use NIR and Red band for calculating the vegetation cover where the subtraction of NIR from the red band is divided by the addition of NIR and red. The formula for NDVI is given in Eq.1 (Tucker 1979).

$$\mathrm{NDVI} = \mathrm{NIR} - \mathrm{Red}/\mathrm{NIR} + \mathrm{Red} \qquad \ldots(1)$$

Whereas NIR represents the near infrared band, while RED represents the red band Calculated values from the index range from -1 to +1, where the low values represent there like barren land or rocks, the moderate value represents shrubs or discrete vegetation, while the area with high values shows the maximum vegetation cover (shown in Table 2) (Karaburun 2010, Chouhan & Rao 2011, Xie et al. 2010, Ramachandra et al. 2014, Kumar et al. 2020).

Digital Number (DN) to Spectral Irradiance

Radiance depends on the targeted object; hence, it can be

Table 2: NDVI classification range.

NDVI Range	Feature
-1.0 to 0	Water, Snow, and Cloud
0 to 0.2	Barren land, Built up & Rock
0.2 to 1.0	Vegetation

explained as the ratio of upward flux from the surface to the total incoming flux reaching the surface (Markham & Barker 1987, Govindha Raj et al. 2013, Jaiswal & Jhariya 2020). The value of Top of Atmospheric (TOA) spectral radiance (Lλ) was determined by multiplying multiplicative Rescaling factor OLI bands; Lλ is proportional to its digital number (DN), which can be computed using the formula (Eq.2) (Markham & Barker 1987, Govindha Raj et al. 2013, Jaiswal & Jhariya 2020).

$$L\lambda = Gain\lambda \times DN\lambda \times Bias\lambda \qquad \ldots(2)$$

Where,

Lλ = spectral radiance calculated in (mW cm72 sr71 mm71 counts71),

Gainλ = calibration coefficient from sensor (mW cm72 sr71 mm71 counts71),

DNλ = digital number of a pixel in a particular band (counts) and

Biasλ = Calibration offset of the sensor band (mW cm72 sr71 mm71).

Spectral Irradiance to Reflectance

Reflectance properties of any object are highly variable and are the ratio of the upward flux reflected energy from the

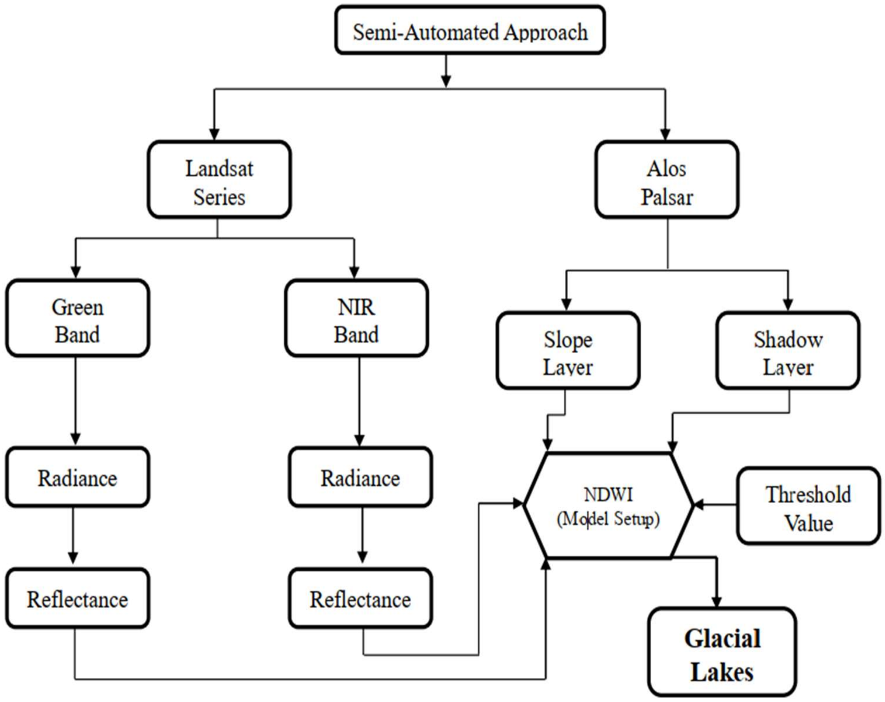

Fig. 3: Semi-automated geospatial approach for extraction of glacial lakes.

Table 3: Earth-Sun Distance in Astronomical Units (Source: L7 Data User Handbook).

Day of Year	Distance	Day of Year	Distance	Day of Year	Distance	Day of Year	Distance	Day of Year	Distance
1	0.98331	74	0.99446	152	1.01403	227	1.01281	305	0.99253
15	0.98365	91	0.99926	166	1.01577	242	1.00969	319	0.98916
32	0.98509	106	1.00353	182	1.01667	258	1.00566	335	0.98608
46	0.98774	121	1.00756	196	1.01646	274	1.00119	349	0.98426
60	0.99084	135	1.01087	213	1.01497	288	0.99718	365	0.98331

surface to the total inward flux reaching the surface (Govindha Raj et al. 2013). For extracting the reflectance values, the converted radiance values will be used; the reflectance is the ratio of the satellite-derived radiance to its equivalent solar radiance (see Fig. 3) (Govindha Raj et al. 2013, Jaiswal & Jhariya 2020). Therefore, spectral reflectance for the dataset was calculated using the formula (See Eq.3).

$$\rho\lambda = \frac{\pi L\lambda d2}{Esun\lambda Cos\Theta S} \quad \ldots(3)$$

Where:

$\rho\lambda$ = Unitlessplanetary reflectance

π = Mathematical constant approximately equal to 3.14159

$L\lambda$ = Spectral radiance at the sensor's aperture (from earlier step)

d = Earth-Sun distance in astronomical units interpolated from values given in (Table 3)

ESUNλ = Mean solar exo-atmospheric irradiances (Table 4)

θs = Solar zenith angle in degrees

Validation of Glacial Lakes Using NDWI

Normalize Difference water index (NDWI) as used for extracting the water feature, which is done by maximizing the reflectance value of green wavelength and minimizing the reflectance value of NIR (Eq.4) by the water feature, which results in an enhanced water feature with a positive pixel value.

$$NDWI = \frac{Green-NIR}{Green+NIR} \quad \ldots(4)$$

Where Green represents the reflectance from the green band (band 3 for Landsat 8), and NIR represents the reflectance from the near-infrared band (band 5 for Landsat 8) using the MINMAX algorithm for the pixel distribution (Radiometric resolution, gray sheds in each band). This index uses the reflectance value from the Green and NIR band, where the wavelength from the green band is maximized, representing the pixel of water. While the reflectance from NIR is absorbed to minimize the reflectance from the NIR_{band} (Mcfeeters 1996, Sarkar et al. 2020).

Table 4: ETM+ Solar Spectral Irradiances Source: L7 Data User Handbook).

Band	Watts/(m²*µm)
1	1970
2	1842
3	1547
4	1044
5	225.7
7	82.06
8	1369

When comparing NDWI results with Google Earth or other satellite imagery provided by Google, it's important to note that the accuracy of the match depends on various factors. NDWI is sensitive to atmospheric conditions, sensor characteristics, and the type of surface cover. Google Earth uses a combination of satellite and aerial imagery that may have different resolutions and acquisition times. If the NDWI results match well with the water features visible on Google Earth, it suggests that the index is effectively identifying water bodies in the study area. However, discrepancies can arise due to factors like cloud cover, shadows, or changes in land cover over time. It's always a good practice to validate remote sensing results with ground truth data or additional sources to ensure the reliability of the findings.

RESULTS AND DISCUSSION

Sub-basins were created for the whole Teesta basin coming into India, based on which seven sub-basins were formed. The lakes were identified using the visual interpretation technique, which was then verified using DWI. A description of such inventory lakes is given in Table 5, which signifies the continuous increase in the area of lakes with higher elevation and area. Based on the identified lakes, it can be observed that the upper Teesta sub-basin, located northwest of the upper portion of the basin, has the highest number of lakes because of the higher number of glaciers surrounding the area. In contrast, the Lonchung Basin adjacent to the Upper Teesta Basin is located northeast of the basin and has been observed as the sub-basin with the second-highest number of lakes.

Most glacial lakes were found in the Upper Teesta basin and Lanchhu basin due to glaciers around the sub-basin (Fig. 1 & Fig. 5). The cause behind the formation of such lakes is snowmelt from the surrounding glaciers, which results in increased water quantity in lakes. In contrast, due to retreating glaciers, several new lakes are formed. In addition, the shifting of moraines with the period and nature of the glacier regime also participates in glacial lake formation. Based on the available research done and the obtained result illustrate that there was a significantly smaller number of the glacial lakes found in the lower part of the basin, which was not vulnerable because of it is they are well connected with drains without the moraines obstructing the water flow from the lake into the stream. However, due to the constant melting of glaciers, the number of lakes and the lake area is also increasing, which can be explained by the results, which show the maximum number of lakes present at the altitude

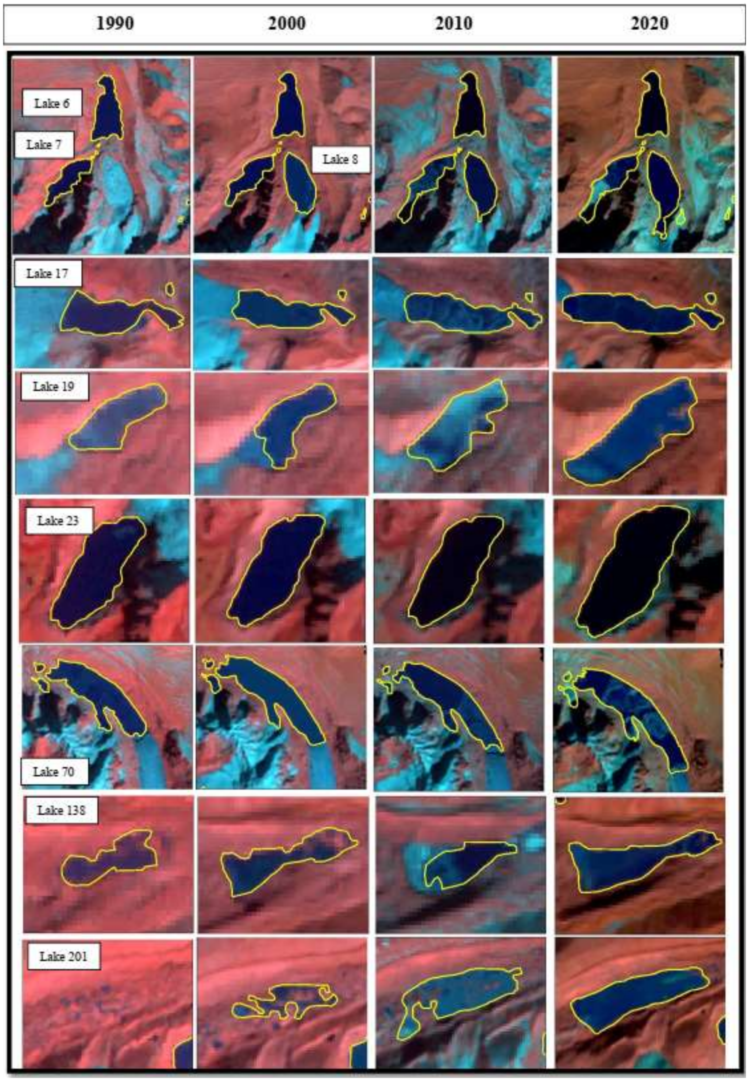

Fig. 4: Glacial Lake from 1990 to 2020.

Table 5: Inventory of Glacial Lake based on water spread area.

Area Range (sqm)	Year 1990		Year 2000		Year 2010		Year 2020	
	No	Area (sqm)	No	Area (sqm)	No	Area (sqm)	No	Area (sqm)
<1000	0	0	4	3523.74	0	0	5	4,805
1000-5000	30	102822	41	141938.71	29	94,986	50	1,64,272
5000-10000	46	3,30,948	45	3,35,816	47	3,26,469	73	5,43,852
10000-50,000	119	29,82,675	154	37,93,760	134	33,72,102	174	43,10,312
50,000-1,00,000	38	28,66,059	38	29,21,080	37	28,33,765	55	40,35,602
1,00,000-5,00,000	35	65,88,200	45	84,60,906	38	70,23,263	51	1,07,59,799
>5,00,000	7	60,35,329	10	88,65,595	10	93,12,357	11	1,16,19,832
Total	275	1,89,06,032	337	2,45,22,619	295	2,29,62,942	419	3,14,38,474

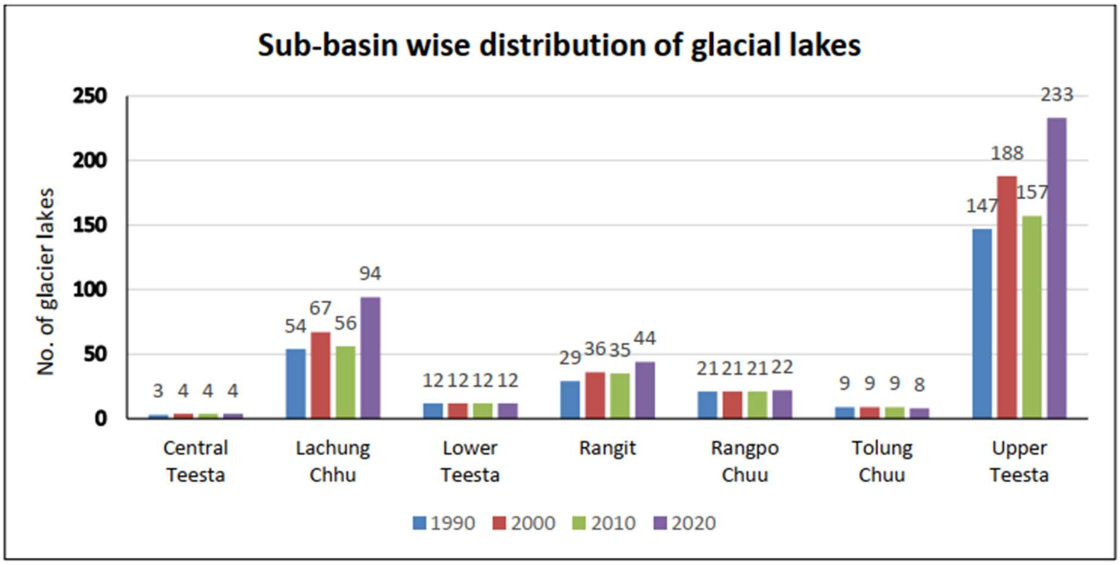

Fig. 5: Sub-basin-wise distribution of glacial lakes.

Table 6: Percentage change of glacial lake.

Lake ID	Year (Area in m^2)				Difference rate 1990-2000	Difference rate 2000-2010	Difference rate 2010-2020
	1990	2000	2010	2020			
6	110673	113423	111709	115627	2.45	1.52	3.45
7	749213	805752	953129	1003817	7.27	16.76	5.18
8	0	106536	112155	129748	--	5.14	14.55
17	411593	476937	437324	476937	14.71	8.67	8.67
19	393589	572566	678492	825073	37.05	16.93	19.50
23	106189	99116	198507	306082	6.89	66.79	42.64
70	569296	593223	579880	598522	4.12	2.27	3.16
138	154501	170099	163917	191009	9.61	3.70	15.27
198	87272	167705	110196	348238	63.09	41.39	103.85
201	0	250273	518487	845961	--	69.78	48.00

Table 7: Elevation zone-wise number of glacial Lake.

Elevation Zone	No .of lake
<3500	3
3500-4000	11
4000-4500	72
4500-5000	104
>5000	229

of 5000 or above with almost 90% of glaciers and glacier mountains. Several glacier lakes are at the snout, which during the summer season, melt as a cause of retreating glaciers. An example of such a glacier lake is Lake No. 23 in 2020 (Fig. 4). Few of the new small glacial lakes are formed near pre-existing lakes due to the melting glaciers; Lake Number 9 in the year 1990 can be the super-fitted example of such a lake, which has been now separated into a new lake with Lake Number 392 in the year 2020 (Fig. 4). Such lakes formed due to the erosional activity in glaciers are known as glacial erosion lakes. As a result of retreating glaciers, a few new lakes formed between 2000-2020, which were not there in 1990. Other glacial lakes, Lake Number. Also feeds a few lakes. 06 is an example of a lake getting its water from Lakes Number 7 & 8 (see Table 6), which are again glacial erosion lakes located at the snot, and due to the effect of the retreating glacier, they are on the continuous increase for water spread area. Hence, the study demonstrated that glaciers. Retreats are the major reason behind the increasing volume and number of glacial lakes.

By the above-performed study can also be observed that the number of lakes is higher at the higher elevation of 5000 meters (Table 7); an increase in the area of the lake has also been observed, which may be due to the melting glaciers caused majorly due to the human-induced activity. A few lakes had a higher increase rate than others, due to which some of these can be considered vulnerable, depending on other parameters like elevation, depth, volume, and moraines surrounding them, a few of which are shown in Tables 5, 6 & 7.

CONCLUSION

Based on the findings of the research that was conducted, it is feasible to arrive at the following conclusion: the utilization of data received through remote sensing and GIS in conjunction with one another has proven to be very effective in identifying glacier lakes. In addition, using the temporal data that is readily available, it is possible to deduce information relating to historical changes in the glacial lakes, which may then be used effectively to determine which lakes are at risk. To distinguish snow from water and vegetation, the utilization of NDWI and NDVI is of utmost importance. This is because it is extremely challenging to successfully differentiate the features based just on visual perception, as features cast shadows on one another. A study that was conducted over ten years and covered forty years found that glacial lakes in the Upper Teesta basin and the Rongpo basin, which is located in the upper western section of the Teesta basin extension and lies between altitudes of 4500 and 5000 meters, had been expanding at an alarming rate.

As a direct consequence of the climatic regimes in which they are located, the glacial lakes that have been documented display varying rates of area increase. By suggesting that the procedure be carried out on a time basis, it is possible that the remote sensing and GIS approaches that are utilized for GLOF might be utilized more efficiently. This makes it possible to conduct a better assessment as well as an analysis of change detection. As a consequence of this, the information can be utilized to keep track of the variations that are occurring in the quantity and size of these lakes that are forming as a consequence of the development and retreat of glaciers (Table 7). Also, keep an eye on lakes that have a habit of growing their water spread area from year to year while being restricted by things like moraines or other obstacles, and if at all possible, do surveys using an unmanned aerial vehicle (Raaj et al. 2021). In addition, the newly formed lake can be graded according to its vulnerability, which will depend on a variety of circumstances, so that the appropriate preventative measures can be put into place in the further downstream region.

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