Review of glacial lake inventories in the Sikkim Himalaya

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ABSTRACT

This article aims to review the existing research associated with the preparation of glacial lake inventories in the Sikkim Himalaya, to understand their evolution over the past two decades and analyse them. The number and areal extent of glacial lakes has been increasing in the Sikkim region due to climate change and global warming in the Himalayas. This makes glacial lakes vulnerable to the occurrence of Glacial Lake Outburst Floods (GLOF). This review analyses the findings from 30 research studies of glacial lakes, including key parameters, such as temporal coverage, criteria for lake delineation (including minimum size thresholds), lake typology criteria, remote sensing data sources, and methodologies employed for glacial lake identification and also the GLOF analysis. The review highlights inconsistencies such as variations in data sources, automatic or semi-automatic mapping technique, minimum size criteria and need for expert interpretations. The study finds that Normalised Difference Water Index (NDWI) based identification of glacial lake is the most preferred technique with visual interpretation. It is also observed that the source of water for a glacial lake is the prominent typological criterion for both glacial lake mapping and GLOF analysis. This study highlights the possibility of preparing a comprehensive inventory of glacial lakes having at least 0.0036 km^2 area from 1962. Such inventory may further improve our understanding of glacial lake dynamics and facilitate an effective GLOF risk analysis in the Sikkim region.

KEYWORDS

Glacial lake inventory; Glacial lake outburst flood (GLOF); satellite data; typology of glacial lakes; proglacial lakes

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1. Introduction

A lake is termed a glacial lake if and only if its origin is related to glacier action. Formally, glacial lakes are defined as the lakes whose origin is due to glacial processes, unlike other lakes, formed due to processes like tectonic, volcanic, landslide, fluviatile, and aeolian activities and organic material, which are usually found in the high-altitude regions of the mountain environment (Iturrizaga 2014). Several processes like glacier erosion, transport or accumulation, lead to the formation of the glacial lakes. Proglacial lakes are one of the prominent glacial lakes, which are formed mainly due to deglaciation, leaving an empty space to be filled as a lake or the merging of several supraglacial lakes at the terminus of the glacier, or glacial melt being collected at the depression created during the previous glacial extent maxima (ICE Age) (Huss et al. 2017). The high-altitude regions of the Himalayas and other glaciated mountain ranges, such as the Alps or Andes, are abundant with proglacial lakes. Under the influence of a warming climate and due to special geological and geomorphological preconditions (Emmer and Cochachin 2013), these proglacial lakes may become vulnerable to Glacial Lake Outburst Flood (GLOF). Therefore, understanding the past and present status of these proglacial lakes is the key to studying the process of their origin and evolution. The preparation of an inventory of glacial lakes in the region of Sikkim Himalaya is the prominent step to such a study.

Inventory is defined as an ensemble of information containing geographic location, area, length, orientation, elevation, and classification of the entity (World Glacier Inventory). Local geology, geomorphology and existing climatic conditions affect the formation and evolution of the glacial lakes, and therefore, they are crucial to be studied while preparing an inventory of glacial lakes. The Eastern Himalaya is a seismically active zone (Das et al. 2024), and the rate of temperature rise in its high-altitude (3–7 km) and low-altitude (0–3 km) regions is significantly higher in the last 45 years (Desinayak et al. 2023). This, combined with high-altitude (above 3000 m a.s.l.) proglacial lakes in the Sikkim Himalaya, makes them vulnerable to GLOF. Under the influence of climate change, the health of the glaciers is drastically deteriorating with the increase in the extent and number of proglacial lakes across the region (Mohanty and Maiti et al. 2021; Gaikwad et al. 2025). Kovanda (2024) analysed 2939 GLOFs (occurred across the world since the beginning of the 20th century) and highlighted that GLOFs occur most frequently in summer due to increased melting, with glacial-dammed lakes primarily affected by positive temperatures and moraine/bedrock-dammed lakes by heavy precipitation, especially during rainy seasons in regions like the Central Andes. A GLOF event can have a catastrophic impact including the loss of life, damage to the local ecology and property, and destruction of hydropower plants (Chowdhury et al. 2025). Preparation of inventories is a crucial first step to understand the present status of the proglacial lakes in the Sikkim Himalaya, and therefore, researchers have been actively studying this area and developing several inventories over several years (Tab. 1).

With the development of remote-sensing technology in recent decades, the monitoring of these glacial lakes and associated glaciers has become much easier. Further, the availability of several free satellite datasets has incentivised researchers to map such remote glacial lakes, which would be difficult to monitor, as they are difficult to access physically. To date, several inventories of glacial lakes in the Himalayan region have been prepared using several satellite images (Ives et al. 2010; Campbell and Pradesh 2005; NWIA/SAC/ISRO 2010 and 2012; Govindha Raj et al. 2013; Worni et al. 2013; Schmidt et al. 2020; Das et al. 2024; Mohanty and Maiti 2021; Chen et al. 2021; Gaikwad et al. 2025; Song et al. 2025). These inventories provide important data for several research objectives, including GLOF analysis (Aggarwal et al. 2017; Mohanty and Maiti 2021). Several factors that vary include mapping methodology, the use of satellite images, expert knowledge or interpretation capability, and their purpose, like GLOF analysis (Mohanty and Maiti 2021) or glacial lake extent change monitoring (Banerjee and Bhuiyan 2023). The time series is the most prominent criterion on which most of these datasets vary (Mohanty et al. 2023; Kaushik et al. 2024; Gaikwad et al. 2025). Therefore, the main aim of this study is to understand the evolution of glacial lake inventory in the Sikkim region over the past 25 years and simultaneously assess their quality and limitations.

2. Study area

Sikkim lies in the northeastern region of India. Geographically the region lies above sea level from ~280 m up to 8586 m (Kumar and Sharma 2023) and ~ 40% of the total state area is cryosphere, consisting of glaciers, glacial lakes and permafrost (Kumar and Sharma 2023) (Fig. 1). The region has nearly 100 glaciers, having different sizes, among which Zemu Glacier (~26 km) is the largest glacier (Kumar et al. 2020). Teesta River is a major tributary of Brahmaputra River and originates in the northeastern corner of Sikkim at Chhombo Chhu glacial lake and Khangchung Chho glacial lake, which are situated at an elevation of 5280 m. The Teesta river system comprises several 7 tributaries; among them, Rangit is the major tributary (Abdul Hakeem et al. 2018; Sharma et al. 2019). These rivers are fed with mostly precipitation from the southwest monsoon, along with snow and glacier melt. Several dams have been built on these rivers for hydropower generation and irrigation purposes. With the change in climatic conditions, the retreat of glaciers and potential occurrences of GLOF events pose a threat to these river systems.

Sikkim Himalaya has young folded mountains of the Himalayan system with rugged terrain and steep slopes (~43% area). Lithology of the area broadly suggests three major rock constituents, which are half-schistose, gneissose and Precambrian rocks like schists and phyllites (NWIA/SAC/ISRO 2010). The slopes of this region are very prone to erosion and weathering due to the presence of schists and phyllites. Such a possibility of soil erosion makes the area susceptible to landslides. The region is also sensitive to seismic activity (seismic active zone IV), which is high in terms of earthquake intensity (Aggarwal et al. 2017; Gaikwad et al. 2025), as it is situated in the young Himalayan mountain.

Sikkim's climate varies dramatically with altitude, mostly influenced by the southwest monsoon, having nearly 35–40% snow cover even in summer with limited influence of westerlies and easterlies (Kumar et al. 2020; Basnett et al. 2013). The precipitation season largely extends from May to October, covering summer and monsoon. Heavy monsoon rains usually happen in July and August, which may trigger landslides in the Sikkim region. While most inhabited areas enjoy a temperate climate with mild summers and cool winters, the high-altitude north experiences prolonged snowfall and freezing temperatures. Kumar et al. 2020 suggest accelerated warming in the last two decades by analysing the minimum temperature.

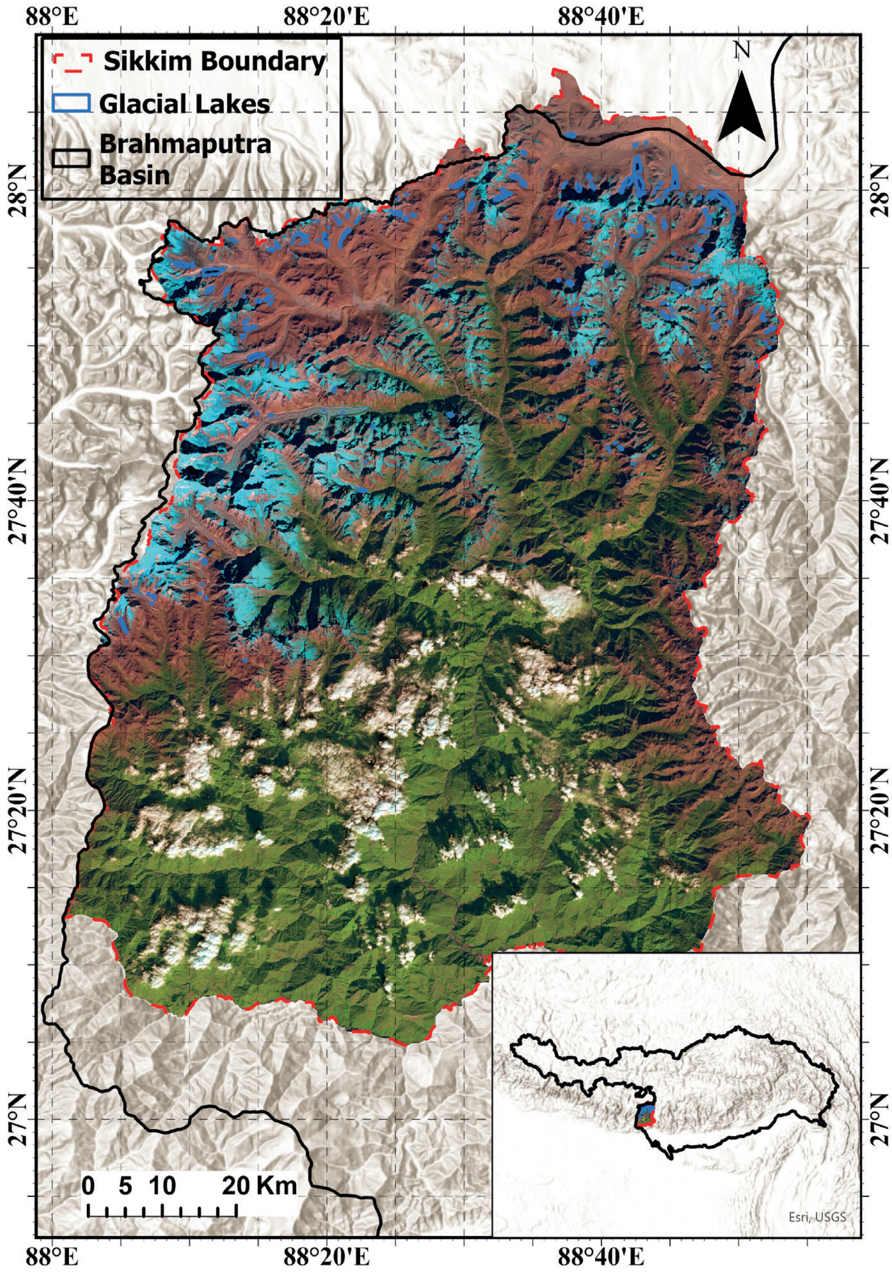

Fig. 1 The study area is situated in the Sikkim Indian Himalayan region, with the large number of glacial lakes, distributed across the glaciated region, which is displayed on the background image of False colour composite of Landsat data.

Precipitation does not show any particular trend from 1961 to 2017 (Kumar et al. 2020).

3. Methodology and data

Several studies account for glacial lake monitoring to understand their spatial and temporal variation, and therefore, preparation of an inventory is critical to the study. A basin-based research focused towards GLOF analysis also ends up preparing an inventory of the glacial lakes, including all the parameters associated with an inventory. Therefore, in the current study, the main focus was to identify the studies related to glacial lakes carried out from the early 2000s and filtered them on the criterion like the location of the study, i.e., Sikkim region or Teesta basin region, inventory preparation, glacial lake change study and GLOF analysis. With the rise of the threat of GLOF occurrence under the influence of climate change, the study of glacial lake monitoring of Sikkim region was initially picked up by some big organisations like International Centre for Integrated Mountain Development (ICIMOD) (Ives et al. 2010), Aisa-Pacific Network (APN) (Campbell and Pradesh 2005) and Space Applications Centre (SAC) (NWIA/SAC/ISRO 2010 and 2012) during the early 2000s. In later decades of the 2000s, mapping and monitoring of glacial lakes have been widely carried out by several researchers across the Himalayas, including Sikkim region (Tab. 1). The compiled research includes categorisation on the basis of mapping strategies like the use of satellite images, strategies for mapping involving automatic, manual or semi-automatic methodology, the typology of the glacial lakes for glacial lake extent change study or GLOF analysis, along with the methodology followed for GLOF analysis. Consideration of the minimum area for identifying glacial lakes and further considering them for GLOF analysis is also analysed in this study. The study highlights the factors affecting the GLOF analysis utilised by these researchers. Since temporal variation of the glacial lake extent significantly affects GLOF analysis and therefore has also been included in this study along with the years of mapping (Tab. 1).

4. Review of lake inventories

The current study thoroughly investigates the previous 30 such studies (Tab. 1) and highlights a comprehensive overview of these studies focusing on glacial lake inventories and GLOF analysis as well as glacial lake extent change in the Sikkim Himalaya. Nearly half (~14) of the inventories have been prepared for the world (Shugar et al. 2020; Song et al. 2025), High Mountain Asia (HMA) (Chen et al. 2021; Zhang et al.

Tab. 1 Since the early 2000s, the researchers have been preparing a glacial lake inventory focusing on the Sikkim region or the whole/partial Himalayan region for analysing glacial lake extent change or GLOF analysis. [*Publication: Red colour is for across the Indian Himalayas, and the rest are limited to only Sikkim region, Purpose of the study: Broad purposes of the study are (i) Inventory (Cyan), (ii) GLOF Analysis (Red) and (iii) Lake monitoring and analysis (Purple), Area: Inventories with minimum area threshold (Cyan or otherwise), Broadly the Typology is categorised in five classes based on various criteria (legend similar to Fig. 4).*] * lake created after the occurrence of a landslide based blocking of the flowing stream, ** land that is temporarily or permanently covered with water, *** depression filled with water and has less area, and **** glacial lake with no direct attachment to the glacier terminus.

Publication	Time series	No. of lakes	Purpose of the study	Area (km^2)	Studied lakes and their typology (Category of lakes)
Ives et al. 2010	2000	266	Inventory	0.10000	Glacial lakes
Campbell and Pradesh 2005	2000–2003	266	Inventory	0.10000	Glacial lakes: Erosion, Valley trough, Cirque, Blocked*, Moraine Dammed (Lateral Moraine and End Moraine Dammed lakes), and Supraglacial lakes.
NWIA/SAC/ISRO 2010	2005	359	Inventory	0.02250	Wetlands**: High altitude Wetlands (elevation > 3000m) 3000–4000m: 10 lakes 4000–5000m: 130 lakes >5000m: 119 lakes
NWIA/SAC/ISRO 2012	2006–2008	534	Inventory	0.02250	Wetlands**: High altitude Wetlands (elevation > 3000m) 3000–4000m: 6 lakes 4000–5000m: 323 lakes >5000m: 205 lakes
Govindha Raj et al. 2013	2005–2010	320	Inventory	0.10000	Glacial lakes: Moraine-dammed lakes, Blocked, Valley
Worni et al. 2013	2000–2002	8	Inventory	0.01000	Glacial lakes: Moraine-dammed lakes; Ice-dammed lakes
Zhang et al. 2015	1990, 2000, 2010	98	Inventory and GLOF analysis	0.00270	Glacial Lakes: Glacier-fed and Non-glacier-fed
Abdul Hakeem et al. 2018	2000, 2007, 2014	644	Inventory	0.00100	Glacial lakes: cirque lake, debris dammed lake, end moraine dammed lake, lateral moraine dammed lake, other lake fed by glacial melt, supraglacial lake and water body***.

Publication	Time series	No. of lakes	Purpose of the study	Area (km^2)	Studied lakes and their typology (Category of lakes)
Aggarwal et al. 2 017	1975, 1985, 1995, 2005, 2015	1104	Inventory and GLOF analysis	0.00100	Glacial lakes: Moraine-dammed, bedrock-dammed, combined dam, ice-dammed lakes, and non-specified lakes. Classified on the basis of Quantitative characteristics (Latitude, longitude, lake level elevation, lake area, Lake depth, lake volume, dam geometry and freeboard measurements) and Qualitative characteristics (lake type, watersheds, and direct connection with glacier).
Debnath et al. 2018	1988, 2001, 2014	68	Inventory	0.00300	Glacial lakes: Supraglacial, Ice scoured, Moraine-dammed, Proglacial lake and Tarn
Shukla et al. 2018	1975–2017	466	Inventory	0.00360	Glacial lakes: Supraglacial, pro/peri glacial lakes in contact with glacier, pro/peri glacial lakes NOT in contact with glacier and other glacial lakes
Maharjan et al. 2018. (ICIMOD)	2004–2007	401	Inventory	0.00300	Glacial lakes: 1) Moraine dammed lake: (a) End moraine (b) Lateral moraine (c) Other moraine 2) Ice dammed lake: (a) Supraglacial lake (b) Glacier Ice dammed lake 3) Bedrock dammed lake: (a) Cirque (b) Other bedrock-dammed lakes 4) Others
Garg et al. 2019	1991–2017	17	Glacier monitoring and analysis	0.00360	Glacial Lakes: 9 Proglacial lakes and 8 Supraglacial lakes
Shugar et al. 2020	1990–2018	48	Inventory	0.05000	Glacial lakes: area and elevation based classification
Wang et al. 2020	1990–2018	253	Inventory	0.00540	Glacial lakes: Glacier-fed and non-glacier-fed-lakes, supraglacial lakes, ice-contacted lakes and ice-uncontacted lakes****
Mohanty and Maiti 2021	1990–2019	165	GLOF analysis	0.01010	Glacial lakes: Glacier-fed, connected, moraine-dammed lake
Chanda and Biswas 2021	1990, 2000, 2017	282	Inventory and GLOF analysis	0.00005	Glacial lakes: Distance from the glacier, Growth of lakes, Elevation and Slope
Chen et al. 2021	2008–2017	242	Inventory	0.00810	Glacial lakes: Classified according to their position relative to the parent glacier or their formation mechanisms. Proglacial lakes, Supraglacial lakes, Unconnected lakes, Ice marginal lakes
Islam and Patel 2022	2000–2018	354	Inventory and GLOF analysis	0.00100	Glacial lakes: Area based classification
Verma and Ramsankaran 2022	2020	419	Inventory	0.01000	Glacial lakes
Banerjee and Bhuiyan 2023	1987–2020	406	Inventory and analysis	0.01000	Erosional lake, Supraglacial lake, Proglacial lake and Blocked lake, Area
Agarwal et al. 2023	1975–2017	14	Inventory and analysis	0.00500	Proglacial lakes; Area based categories: small: <0.2 sq. km, medium: 0.2–1 sq. km and large: >1 sq. km
Mohanty et al. 2023	1990, 2000, 2010, 2015, 2020	382	Inventory	0.01000	Glacial lakes: Glacier-fed, connected, moraine-dammed lakes
Kumar and Sharma 2023	1988–2018	12	Glacier monitoring and analysis	None	Glacial Lakes: Supraglacial lakes and proglacial lakes
Zhang et al. 2023	1990–2020	208	Glacier mass balance analysis	0.00360	Glacial lakes: Proglacial lakes, Supraglacial lakes and Non-ice contact glacial lakes
Kaushik et al. 2024	2015, 2017, 2020	231	Inventory and GLOF analysis	0.01000	Glacial lakes: Moraine dammed lake
Das et al. 2024	1990–2023	47	GLOF analysis	0.01000	Glacial lakes including Proglacial lakes, Lake area and volume
Gaikwad et al. 2025	1990, 2000, 2010, 2020	440	Inventory and GLOF analysis	0.02000	Glacial lakes: Based on dam formations: moraine-dammed, bedrock-dammed, ice-dammed, and other lake types
Song et al. 2025	1984–2020	244	Inventory	0.01000	Glacier Fed or Non-glacier Fed
Kumar et al. 2025	1990, 2000, 2010, 2020	363	Glacier Monitoring and analysis	0.01000	Moraine-dammed: End moraine-dammed lakes [M(e)], Lateral moraine-dammed lakes [M(l)], and other moraine-dammed lakes [M(o)], Bedrock-dammed lakes were divided into two categories: cirque lakes [B(c)] and other bedrock-dammed lakes [B(o)], and ice-dammed lakes: Supraglacial (S) and dam med by tributary glaciers [I(v)]

2023, etc.) or the partial Himalayan region (Ives et al. 2010, NWIA/SAC/ISRO 2012, Mohanty et al. 2023), including the Sikkim region. These inventories include all types of glacial lakes, including supraglacial as well as proglacial lakes, and they are categorised as per the user's requirement and their understanding.

4.1 According to time span

Time series analysis of the inventories prepared by several researchers highlights that a few inventories have been prepared since 1975 (Shukla et al. 2018; Agarwal et al. 2023). However, the majority of the inventories have been prepared from around 1990 (Zhang et al. 2015; Garg et al. 2019; Mohanty and Maiti 2021; Chanda and Biswas 2021; Zhang et al. 2023; Das et al. 2024; Gaikwad et al. 2025), including a few from 1988 (Kumar and Sharma 2023; Debnath et al. 2018) and 1987 (Banerjee and Bhuiyan 2023), covering a duration of nearly 30 years. In recent years, researchers have tried to look for the latest 20 years of the lake's extent change and therefore several inventories were prepared based on the early 2000s satellite data (Ives et al. 2010; Campbell and Pradesh 2005; Worni et al. 2013; Abdul Hakeem et al. 2018; Maharjan et al. 2018; Islam and Patel 2022) (Fig. 2).

The largest span for studying the Sikkim region was carried out for 40 years (Aggarwal et al. 2017). Another study by Agarwal et al. (2023) covers a temporal span of 42 years and spatially the whole of the Himalayas but has only 14 lakes in the Sikkim region. Three inventories have been prepared on the basis of a single year, each having a reference year as 2000, 2005 and 2020. Some inventories were prepared on the basis of a few years (i.e., combining 2–3 years) of data, the majority in the early 2000s. Several inventories were also prepared for the purpose of glacial lake extent change, covering nearly 5 to 10 year interval, among them, the majority were prepared later in the 2000s. Chowdhury et al. (2021) have studied only 4 glacial lakes of Sikkim region covering a time span from 1962 to 2018 for the purpose of GLOF analysis. Racoviteanu et al. (2015) studied the change in glaciers from 1962 to 2006 for Sikkim region, which suggests the possibility of mapping the whole Sikkim region and analysing over a large temporal range.

Several studies were carried out for a periodical analysis of the glacial lake extent change, inventory preparation or GLOF analysis, like Aggarwal et al. (2017), Mohanty et al. (2023) and Gaikwad et al. (2025), who carried out a decadal inventory; Debnath et al. (2018) with a period of 13 years; and Kaushik et

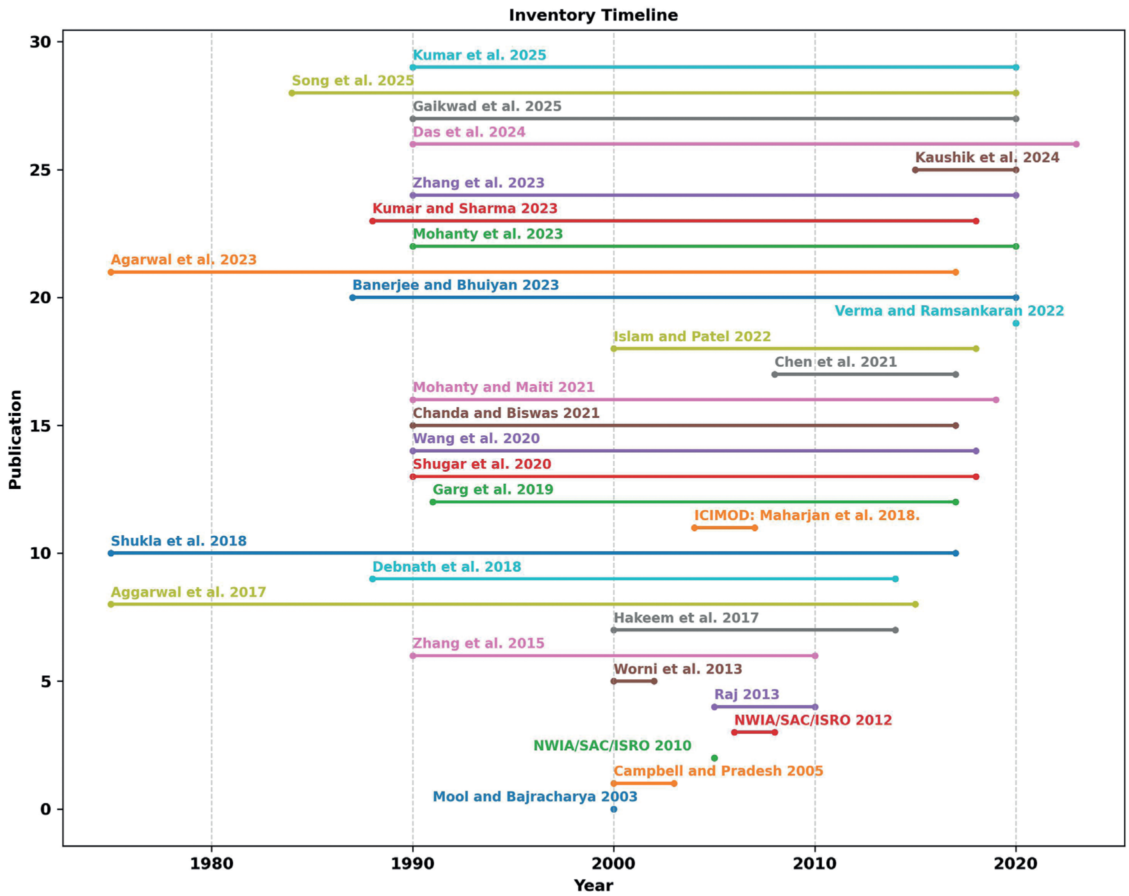

Fig. 2 The inventories were prepared by various researchers for monitoring and GLOF analysis of glacial lakes using satellite datasets, earliest from 1975 to recent, in the Sikkim Himalayan region.

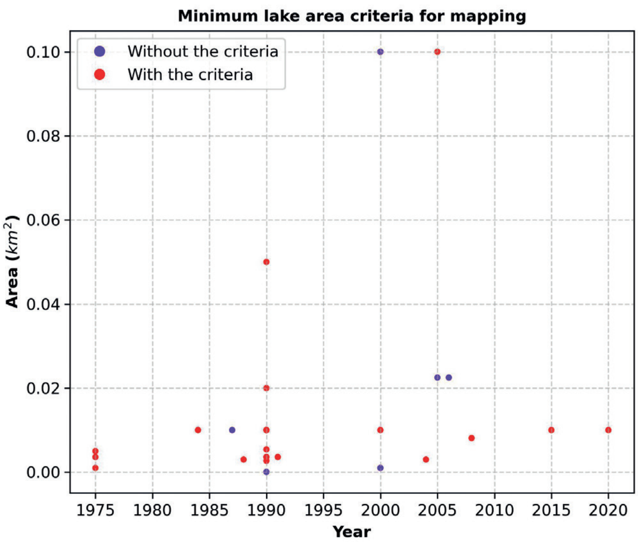

Fig. 3 The variation of the different minimum area criteria adopted by researchers for glacial lake mapping.

al. (2024) with an interval of nearly two years. Hazra and Krishna (2022) studied just one lake, Shako-Cho lake for its GLOF analysis but highlighted the possibility of finding a suitable dataset for mapping for the years 2000, 2005, 2009, 2015 and 2018. Shugar et al. (2020) and Song et al. (2025) have provided a global dataset of glacial lakes mapped from 1990 to 2018 and from 1984 to 2020, respectively.

4.2 Size of lakes and mapping uncertainty

Glacial lakes are of different sizes due to their varying formation stages, and among them, supraglacial lakes are mainly smaller than the proglacial lakes. In this study, we found that generally, the inventories are prepared with a minimum area-based criteria to map the glacial lakes (Tab. 1). It has also been observed that there is a large variation in the minimum area criteria, like 0.0036 km^2 (Garg et al. 2019), 0.0054 km^2 (Wang et al. 2020), 0.0081 km^2 (Chen et al. 2021) and 0.01 km^2 (Mohanty and Maiti 2021), in spite of utilising the same reference Landsat series data. The Landsat series is the most common satellite sensor used by the researchers for glacial lake mapping, irrespective of the purpose of their study (Tab. 1). Majorly, the researchers prefer the threshold to map glacial lakes to be <= 0.01 km^2 (Fig. 3). Researchers who have prepared their inventory not limited to Sikkim region follow a minimum area criteria, which range from 0.0027 km^2 (3 adjoining pixels of 30m) to 0.1 km^2, except two inventories (NWIA/SAC/ISRO 2010 and 2012).

4.3 Typology of lakes

In this study, the typology of the glacial lakes is usually based on the lakes' position relative to the parent glacier, which are namely, supraglacial lakes, proglacial lakes, unconnected lakes and ice marginal lakes and based on dam formation, which are namely, moraine-dammed, bedrock-dammed, and ice-dammed (Tab. 2) (Maharjan et al. 2018). Mapping of glacial lakes in the Sikkim region has been mainly carried out for the purpose of preparation of inventory (19 studies) and GLOF analysis (8 studies) (Fig. 4). The studies with the purpose of inventory have often defined the typology of the glacial lakes on the basis of the process of formation (Campbell and Pradesh 2005; Govindha Raj et al. 2013; Worni et al. 2013; Abdul Hakeem et al. 2018; Debnath et al. 2018; Maharjan et al. 2018) followed by "water source" to the lake (Shukla et al. 2018; Wang et al. 2020; Mohanty et al. 2023; Song et al. 2025) (Fig. 3). Similarly, in the case of GLOF analysis, the main typology criterion is the "process of formation" (Aggarwal et al. 2017; Kaushik et al. 2024; Gaikwad et al. 2025), followed by "water source" (Zhang et al. 2015; Mohanty and Maiti 2021), and then the relative position of the glacial lake with the nearest glacier (Das et al. 2024). Lakes are often classified on the basis of physical characteristics (like elevation or area of the lake) for purposes like preparing a glacial lake inventory as well as GLOF analysis (Tab. 1), but here two early inventories adopted physical characteristics like elevation and area of the lake as the prominent typology criteria (NWIA/SAC/ISRO 2010 and 2012). Two inventory preparation works (Ives et al. 2010; Verma and Ramsankaran 2022) did not follow any typology while mapping the glacial lakes. Erosional processes in the bedrock often lead to the formation of piedmont and cirque lakes where

Tab. 2 The typology of glacial lakes based on various criteria (modified based on Maharjan et al. 2018).

Typology criteria	Lake type	Lake sub-type
Process of formation	Moraine dammed lake	End-moraine dammed lake
		Lateral moraine dammed lake
		Other moraine dammed lake
	Ice dammed lake	Supraglacial lake
		Glacier Ice dammed lake
	Bedrock dammed lake	Cirque lake
		Other bedrock-dammed lake
	Combined lakes	
Source of water to lake	Glacier Fed	
	Not Glacier Fed	
Position relative to glacier	Supraglacial lake	
	Proglacial lake	
Physical characteristics of the lake	Area: Small, medium and large glacial lakes Altitude: High and low altitude glacial lakes	

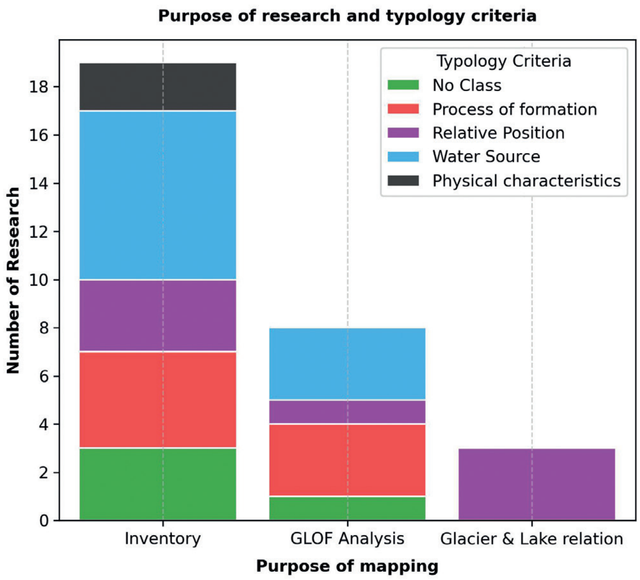

Fig. 4 The use of typology criteria for categorising glacial lakes vary significantly based on the purpose of mapping undertaken by various researchers.

glaciers were earlier present, which is also considered for the classification of the glacial lakes (Campbell and Pradesh 2005; Banerjee and Bhuiyan 2023). GLOF analysis many a time utilises multiple typologies to understand the vulnerability of lakes (Chen et al. 2021; Gaikwad et al. 2025).

4.4 Data selection and methodology of glacial lake identification

The selection of data for mapping is crucial for mapping precise glacial lake extent, which largely depends on the snow and cloud-free conditions, which usually happen at the end of the ablation period, i.e., September to December in the eastern part of the Himalaya (Mohanty et al. 2023). However, there is a small variation in the selection of reference data, which further leads to variation in the lake area. For example, the glacial lake extent for the year 1990 varies in the selection of date as well as numbers because Wang et al. (2020) selected the date roughly in between June and November, 1990; Zhang et al. (2015) considered 5th November, 1990; Zhang et al. (2023) considered 23rd September, 1992 and Mohanty et al. (2023) further added some lakes polygons over the mapped lakes by Zhang et al. (2015) using a satellite dataset from September to December of the year 1990, and Kumar et al. (2025) considered the ablation season of 1990 as the reference layer (Fig. 6). Preparation of an inventory requires precision in the delineation of the lake boundary, which can be achieved by several methodologies. The Normalised Difference Water Index (NDWI) has been quite often utilised for mapping of glacial lakes; however, the final lake extent is only achieved after manual correction using visual interpretation. Band ratio has also been utilised for highlighting the water bodies and further manually corrected for analysis (Campbell and Pradesh 2005; NWIA/SAC/ISRO 2010, 2012; Worni et al. 2013, etc.). This can be further analysed for the purpose of glacial lake monitoring/extent change analysis as well as GLOF analysis. The utilisation of manual or semi-automatic techniques are entirely dependent on the dataset used and the researchers expertise. The inventories utilise the earliest available satellite datasets, which are Hexagon KH-9 and Landsat 4 (MSS sensor). Corona, Hexagon KH-9 data have grayscale images and therefore it is only possible to map the boundary of the lakes with visual interpretation (Chowdhury et al. 2021; Schmidt et al. 2020). The Landsat series has one of the largest time spans (from 1982 to ongoing) of the data acquired over the study area and is therefore widely utilised for such research studies (Tab. 1) with a consistency of spatial resolution of 30 m.

4.5 GLOF analysis: adopted methodology and parameters

Glacial lakes mapped for either inventory or GLOF analysis always have a few general associated parameters, like the location of the lake (latitude and longitude), altitude, area and perimeter (Ives et al. 2010; Zhang et al. 2015; Chanda and Biswas 2021; Gaikwad et al. 2025) (Tab. 3). GLOF analysis is the most important criterion for mapping or preparing an inventory of these glacial lakes in Sikkim region. Tab. 3 summarises the uses of various parameters in GLOF analysis. Broadly, the various parameters which are affecting the occurrence of GLOF include morphological parameters of the lake and associated glacier, the lake's dam characteristics, physical conditions of the surrounding area in terms of occurrence of landslides, snow avalanches, and seismic activity, lake area change, the lake's proximity to the glacier, the lake's shape index highlighting the range of ellipticity from irregular shape to a circle (Kaushik et al. 2024), topographic potential suggesting the potential of occurrence of ice and/or rock avalanches (slope > 30°) (Kaushik et al. 2024), and downstream slope. Morphological parameters like area, perimeter, length and area change of glaciers and glacial lakes, along with glacier dams, are derived from optical data sets. The elevation, slope, aspect of the lake and glacier, and freeboard dimension of the dam, including height, are derived using a Digital Elevation Model (DEM) like SRTM, ASTER, Cartosat and ALOS PULSAR.

Analytical Hierarchy Process (AHP) is one of the most widely utilised methodologies for assigning the weights of the aforementioned parameters following another methodology, Fuzzy Analytical Hierarchy Process (FAHP). Islam and Patel (2022), and Worni et al. (2013) utilised the weights derived from other researchers for GLOF analysis. Threshold-based techniques have also been popular to identify potentially

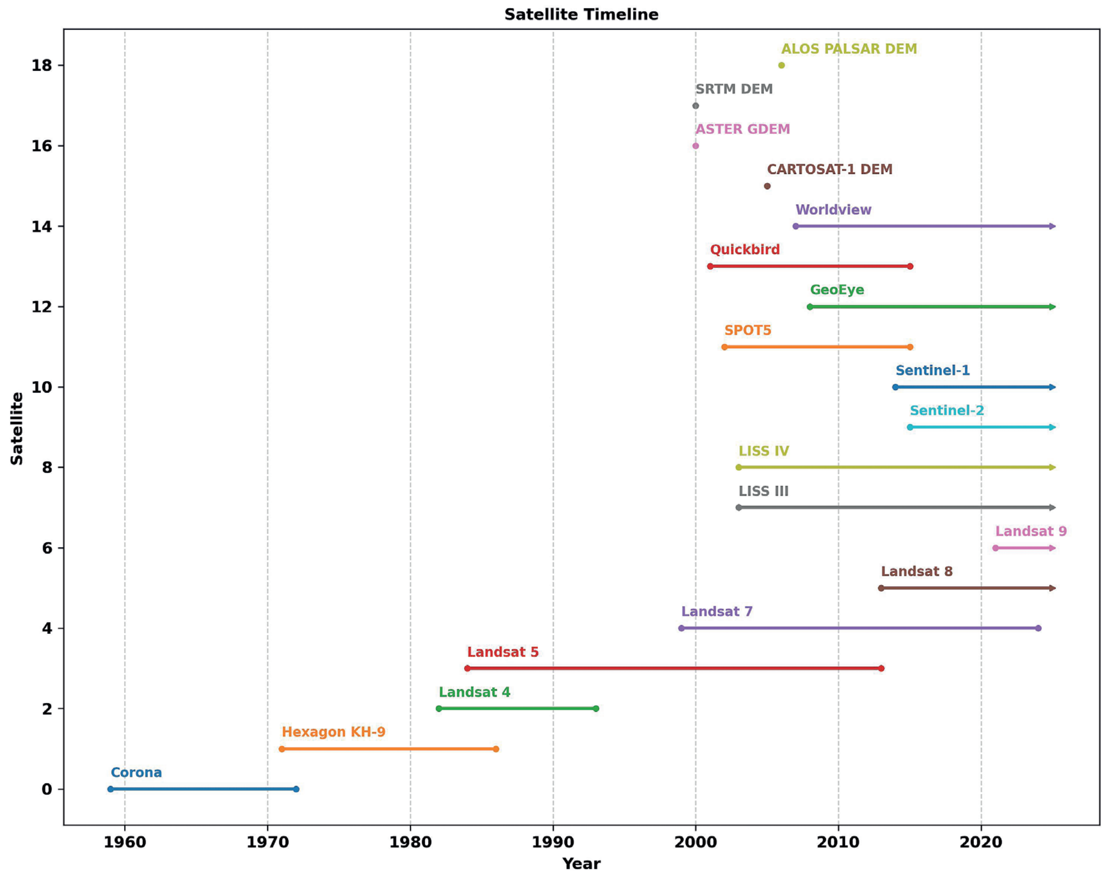

Fig. 5 Availability of satellite data for mapping of glacial lakes in the Sikkim region over past 60 years. Ongoing satellite missions are marked with an arrow.

Tab. 3 GLOF analysis and associated parameters utilised in the Sikkim region.

Publication	Methodology for GLOF Analysis	Parameters
Campbell and Pradesh 2005	Potentially dangerous lakes identification	Moraine dams, Rise of lake water level, Activity of supraglacial lakes, Position of lakes relative to glaciers, Glacial lake size, Dam conditions, Conditions of Associated Mother Glacier, Physical conditions of the surrounding area
Worni et al. 2013	Risk analysis using weight assignment	Dam type, Dam geometry, Freeboard and Potential for lake outburst impacts
Aggarwal et al. 2017	AHP	Area, Elevation, Length, Width, Volume, Type of the lake, Orientation of the lake, Freeboard level, Dam width-height ratio, Activity of the lake, Drainage type of the lake, Slope of the moraine walls, Growth in the lake area, Distance from the parent glacier, Distance of settlement, Geomorphology, like physical conditions of surroundings, and Seismic and tectonic factors
Chanda and Biswas 2021	Threshold based categorisation to identify hazardous lakes	Minimum elevation, Slope threshold, Distance from connecting stream or outlet, Distance from settlement area, Distance from the hydroelectric power projects, Growth of lakes, Distance from the glacier
Mohanty and Maiti 2021	AHP and Object Based Classification method	Lake size, Area change rate, Volume, Elevation, Proximal distance, Lake type, Lake aspect, Glacier calving frontal width, Glacier snout steepness, Avalanches, Landslide, Earthquake, Lake freeboard, Dam steepness, Dam height
Islam and Patel 2022	Weight assignment	Change in lake area, Slope difference between glacial snout and lake outlet, Connection/Proximity to Parent Glacier, Connection with river channel, Height of Dam, Availability of rocks for avalanches/rockfall, Distance from the basin outlet
Kaushik et al. 2024	AHP	Rate of lake change, Lake area, Downstream Slope, Total watershed area, Shape index, Topographical potential, Rate of lake change
Das et al. 2024	AHP and Fuzzy AHP	Glacial Lake Volume, Seismic Activity, Glacial Lake Area, Elevation, Avalanche, Rockfall, Slope, Distance from River, Rainfall
Gaikwad et al. 2025	FAHP	Volume of lake, Area change rate, Area of the mother glacier, Slope between lake and snout of the mother glacier, Distance between glacier and lake, Average Steep Lakefront Area angle

dangerous/hazardous lakes using several morphological and terrain parameters (Campbell and Pradesh 2005; Chanda and Biswas 2021).

5. Discussion

5.1 According to time span

There are several satellite data available now, and therefore, more periodic analysis are possible. The decadal changes from 1990 till 2020 are very common, but in order to understand the evolution of the glacial lakes, the year of formation is very crucial for the study. Such studies have widely exploited the Landsat series data (Tab. 1). The uses of high-resolution images are necessary to identify the various parameters of the lake dam and further improve the accuracy of the lake's extent. Similarly, DEM data is also important to derive the lake's dam parameters like slope, elevation, etc., and SRTM has been widely utilised for such studies. The sensors with high spatial resolution are advantageous for mapping small glacial lakes. Since several Corona (KH-4) images have been declassified and are available for Sikkim region, the time span for monitoring these glacial lakes can be increased. Chowdhury et al. (2021) have performed GLOF analysis for four glacial lakes in the Sikkim region and utilised the available 1962 data. Such analysis with a longer time span enhances the GLOF analysis. Another benefit of KH-4 data is that it is collected in high resolution, and therefore smaller glacial lakes can also be identified, and their evolution over recent years can also be effectively analysed. Schmidt et al. (2020) utilised the Corona images of 1969 to prepare an inventory of glacial lakes in the Ladakh region (Trans-Himalayan region), highlighting their further utility in GLOF analysis.

5.2 Size of lakes and mapping uncertainty

With the formation of glacial lakes and further undergoing evolution, the size can vary from a few square meters to several thousand square meters. The mapping of glacial lakes highly depends on the spatial resolution of the available satellite data. Gardelle et al. (2010) suggest that the minimum area of a glacial lake can be mapped using a satellite image which covers at least 4 pixels and satisfies the condition of the presence of at least one pure water pixel (i.e., a pixel whose reflectance is homogeneous and represents only one endmember). Several research studies carried out after 2011 have still been using either 9 pixels as a minimum size criteria, or some have no threshold, suggesting inconsistency in such a wide range of prepared datasets (Chen et al. 2021). Chen et al. (2021) suggest that at least 9 pixels should be considered for a lake polygon to define while keeping the area error under 50%. There is a variation in extent and/or number of mapped glacial lakes for the year 1990 by Zhang et al. 2015, Wang et al. (2020), Mohanty et al. (2021), and Zhang et al. (2023), as their date of reference satellite data may vary. Another reason for such variation may be due to the minimum size criteria. Zhang et al. (2023) establish that the maximum area of a lake can be up to 200 km^2.

While mapping the glacial lake, the mapping uncertainty is induced. The estimation of mapping uncertainty is dependent on the methodology followed along with the pixel's spatial resolution and other qualities of the available satellite data. Theoretically, the maximum area error in a glacial lake boundary is the half area of the boundary pixels because pure lake water body pixels are usually surrounded by mixed pixels (Zhang et al. 2015, Debnath et al. 2018, Shukla et al. 2018, Wang et al. 2020, Agarwal et al. 2023, Mohanty et al. 2023). The mapping error is inherent and specific to the spatial resolution of the satellite image and may be estimated using equation 1 (Zhang et al. 2015).

$$\%\ Mapping\ uncertainty = \frac{P * R * R * 100}{R * A * 2} \tag{1}$$

where,
P is the perimeter and A is the Area of the lake,
R is the spatial resolution of the satellite image.

The factor of 0.678 is sometimes multiplied by (1) to estimate the area uncertainty of an individual lake within one standard deviation (σ) (Song et al. 2025). A few of the researchers, like Gaikwad et al. (2025), Banerjee and Bhuiyan (2023), Chen et al. (2021), and Govindha Raj et al. (2013), have considered an uncertainty of 1 pixel on the edges of the glacial lake as the mapping uncertainty.

Considering the availability of high-resolution satellite images in recent times, the minimum size criteria can vary for the preparation of an inventory. However, while doing long-term time series analysis, the inventories are compared with one another, which may or may not be developed on the same resolution of the satellite images. While performing a glacial extent change analysis over a period, each glacial lake is considered as an entity and further analysed accordingly (Shukla et al. 2018). Considering the recent availability of higher resolution images, the precision of mapping is increasing but has a basic limitation in performing a time series analysis, as we have the majority of coarser resolution data. The comparative analysis should always include the error associated with mapping accuracy for both the conditions, same resolution based mapping and different resolution-based mapping.

5.3 Typology of lakes

Researchers choose the typology of lakes based on the purpose of analysis. A wide range of regional or local scale glacial lake extent change analysis or GLOF analysis requires preparation of an inventory. Such inventories may vary in attributing the various typologies of lakes, considering the expertise of researchers as well as the purpose of their limited study, which may include prominently the process of formation and physical characteristics (Tab. 2). GLOF based analysis specifically requires a few other important typologies of lakes to better understand the process, like the relative position of the glacial lake with the nearest glacier, the source of the water, dam type, etc.

Although such studies on glacial lakes have been carried out for many years, there is a lack of a standardised typology of lakes. Specifically, under the current warming climatic scenario, the increase in the occurrence of GLOF across the world requires inventories built with the necessary typology, which further helps in understanding the evolution of the lakes. The typology of a lake is based on the process of formation, position relative to glacier, source of water to the lake and physical characteristics of the lake, which explains the process of evolution of the glacial lakes, formation of the lakes and future of those lakes under various GLOF scenarios. Same type of lake can be categorised on the basis of various typologies of lakes, like proglacial lakes, which can be formed due to the damming of lateral moraines, and their source can be the glacier melt (Shukla et al. 2018; Wang et al. 2020). Similarly, cirque lakes are erosional lakes which are bounded by a bedrock dam and have the least vulnerability in terms of dam breaching (Campbell and Pradesh 2005; Abdul Hakeem et al. 2018; Maharjan et al. 2018). Considering such parameters simultaneously will be beneficial for GLOF analysis. Supraglacial lakes, which are mostly ice dammed lakes and occur on the glacier, are becoming crucial for GLOF analysis, and under current warming conditions, these are expanding at a large rate in the Himalayas (Mohanty and Maiti 2021). In some cases, several supraglacial lakes at the terminus of the glacier merge to form a proglacial lake; therefore, they are crucial in understanding the evolution of such proglacial lakes. Tab. 2 includes the major typology of lakes, highlighting the strength of the dams, which is an important criterion for GLOF analysis (Kaushik et al. 2024; Das et al. 2024; Gaikwad et al. 2025; Mohanty and Maiti 2021).

5.4 Data selection and methodology for identification

Correct identification and delineation of glacial lakes depend on the spatial resolution of the satellite data, along with snow and cloud-free conditions. Sikkim experiences such favourable conditions at the end of ablation, usually during September–December (Mohanty et al. 2023). Satellite-based investigation helps in the derivation of these parameters, but limits their accuracy due to their spatial resolution. LANDSAT provides the longest time series of available data for mapping the lake extent. The availability of KH-4 images at high resolution (~2.5 m) (Chowdhury et al. 2021) over Sikkim region provides an opportunity to make an inventory of glacial lakes with the largest possible time span (~60 years). DEM-based derived parameters like slope, aspect and elevation information for a glacier or lake's dam are crucial for GLOF analysis. Fujita et al. 2008 assessed the utility of SRTM and ASTER DEMs for glacial lake studies and established that relative accuracy is worse over moraines and hill slopes due to the narrow ridges and steep slopes. Despite of having several limitations, these DEMs provide reference information from 2000, and ASTER DEMs derived from optical stereo pair images may provide temporal information but have limitations due to the presence of clouds (Fujita et al. 2008). ALOS-PALSAR DEM and Cartosat DEM (Govindha Raj et al. 2013; Debnath et al. 2018; Das et al. 2024) are also gaining popularity in the GLOF analysis because of better spatial resolution. Similarly, the morphological parameters related to dimensional measurement, like area, length or proximity to the glacier, etc., also include mapping error due to mapping uncertainty along the boundary pixels (Chand and Sharma 2015). The availability of high-resolution images or DEMs helps in minimising such uncertainty and therefore various researchers have started using them (Mohanty et al. 2023; Das et al. 2024). However, freely available data for both optical and DEM are more popular among the researchers than the paid ones, in spite of having finer spatial resolution. Collectively, the dataset with longer time series and better spatial

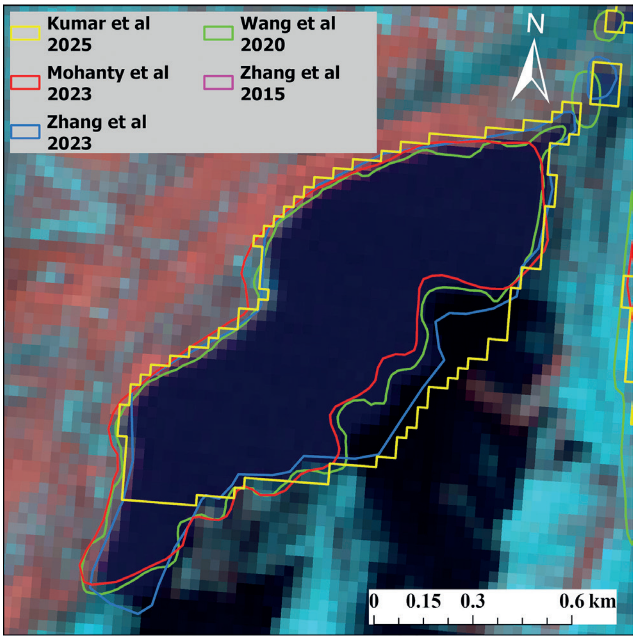

Fig. 6 The variation in glacial lake outline for the year 1990 corresponding to different researches are shown with False colour composite of Landsat 05, dated 20th Oct, 1990, where, Mohanty et al. (2023) have taken Zhang et al. (2015) as the reference layer (Not visible in the image).

Tab. 4 Selection of time and mapping criteria for defining the outline of the glacial lake boundary may lead to change in the variation of their number.

Publication	Time of mapping	Number of lakes	Mapping criteria (km^2)
Zhang et al. 2015	Nov, 1990	80	0.0027
Wang et al. 2020	Nov, 1990	229	0.0054
Zhang et al. 2023	Sep, 1992	192	0.0036
Mohanty et al. 2023	Nov, 1990	95	0.0100
Kumar et al. 2025	Ablation period, 1990	330	0.0036

resolution will be helpful in understanding the evolution of glacial lakes in the Sikkim region.

The NDWI-based identification is the most popular and established methodology to detect a water body (Gaikwad et al. 2025). However, shadow pixels of the image may also be categorised as water pixels, therefore limiting the capacity of the threshold-based water body delineation technique (Chen et al. 2021). Choosing a threshold for the identification of water pixels may also vary region to region, and therefore a general consensus has not been established among researchers. Such complications lead to the requirement of manual quality assessment (Zhang et al. 2023; Chen et al. 2021). The selection of different years' data (see section 4.4) and, at the same time, the mapping criteria like minimum lake area vary as 0.001, 0.0027, 0.0036, 0.0054 and 0.01km^2 for Aggarwal et al. (2017), Zhang et al. (2015), Zhang et al. (2023), Wang et al. (2020) and Mohanty et al. (2021), respectively, which influence the number of outlined lakes (Tab. 4) and their extent (Fig. 6), which may have been due to the aforementioned reasons.

5.5 GLOF analysis: adopted methodology and parameters

The recent occurrence of GLOF at South Lhonak Lake (Zhang et al. 2024; Sattar et al. 2025) has highlighted the necessity to investigate the prior research related to GLOF analysis methodology and associated parameters. Multiple-criteria decision-making (MCDM) methods like AHP and FAHP are the most common among such researchers for weight assignment to the various parameters affecting GLOF (Mohanty and Maiti 2021; Kaushik et al. 2024; Das et al. 2024; Gaikwad et al. 2025). Expert knowledge is a key factor in assigning the relative importance among the parameters for which weights are estimated using the aforementioned methods. It is very popular because it is most efficient and easy to replicate without much computational requirement (Gaikwad et al. 2025). Huggel et al. (2004) characterise the various parameters with qualitative probability, but it is still limited to the geography (Swiss Alps). However, further research advancement over recent years has improved the parameters selection for GLOF analysis (Emmer and Vilímek 2014; Emmer et al. 2022). The studies related to the Sikkim area include the parameters for GLOF analysis: lake and glacier area, area change, expansion rate, watershed area, downstream slope, shape index, slope, height of the lake outlet dam, rockfall or avalanche occurrences, proximity to glacier, and proximity to basin outlet. Satellite-based investigation helps in the derivation of these parameters without physically visiting the area but limits their accuracy due to the spatial resolution of the images (Section 5.4).

The parameter selection for GLOF analysis by researchers across the high mountain regions of the world is limited to remote sensing based derived parameters due to glacial lake inaccessibility. Emmer et al. 2022 have extensively worked on the parameters associated with GLOF analysis for the Andes and the Cordillera Blanca, Peru (Emmer et al. 2016). Emmer and Cochachin (2013) have studied in detail the failure mechanism of moraine dams in North America and the Himalayas, highlighting almost no difference in the failure mechanism except for the season of frequent occurrence of GLOF. All the researchers working in the Himalayas marginally vary in choosing the parameters for the GLOF analysis, like Worni et al. (2013), who do not consider the glacier's parameters and the watershed area, and similarly Gaikwad et al. 2025 also do not consider the watershed area. The interdependency of glacial lake vulnerability with the associated glacier is noticed by every researcher, and therefore proximity to the glacier, glacier and lake morphometric parameters, along with lake dam parameters, have been widely utilised for the assessment of GLOF analysis across the world (Emmer and Vilímek 2014).

6. Conclusion

Overall, the existing research on the glacial lakes in the Sikkim Himalaya demonstrates a wide range of inventory creation and significant enough research on GLOF analysis. These studies have been mostly dependent on the availability of satellite data due to the inaccessibility of the glacial lakes for physical mapping. The most reliable Landsat image with the longest time series has been widely utilised by the researchers. NDWI-based glacial lake identification is commonly implemented for the identification of glacial lakes, but their precision is further improved using manual correction. The typology criteria significantly vary for various purposes of research, where "sources of water" for the lake is the most common. Morphological, topographical, and environmental parameters associated with glaciers, glacial lakes and the surrounding area affect the GLOF analysis, and AHP is commonly utilised for estimation of their weights. An inventory with consistent mapping standards over a longer temporal coverage (possibly from 1962) over the Sikkim region can be prepared, which will be a better basis for the assessment of glacial lake vulnerability under the influence of continuous climate change.

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