



Climatic drivers of the 2024 Thyanbo Glacial Lake Outburst in Nepal deciphered using Sentinel-2 NDWI/MNDWI analysis

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Abstract

Thyanbo Glacial Lake in the Thame region of Nepal experienced a destructive outburst flood on 16 August 2024, displacing more than one hundred people and damaging homes, hotels, a school, and a health post. This study examines the climatic and hydrological conditions that contributed to the event using multi-temporal satellite imagery from 2017 to December 2024. Lake area and volume were estimated using the Normalized Difference Water Index (NDWI) and Modified NDWI (MNDWI), while temperature and precipitation records were analysed to assess their influence on melt-water input and lake expansion. From 2017 to 2023, the lake remained relatively stable, with areas ranging from 32,881 to 41,758 m² and volumes from 118×10³ to 159×10³ m³. A pronounced shift occurred in 2024, when rising temperatures and intensified monsoon rainfall drove rapid lake growth. By 30 July 2024, the lake reached its maximum extent (43,902 m²) and volume (169×10³ m³), coinciding with summer temperatures exceeding 5°C and a marked increase in rainfall. Following the 16 August outburst, lake area declined by more than 70% and volume by nearly 80%, indicating extensive drainage and geomorphic reconfiguration. Overall, the findings show that short-term climatic extremes, superimposed on long-term warming, contributed to moraine failure and the resulting Glacial Lake Outburst Floods (GLOFs). The study underscores the value of combining spectral water indices with climatic trends to detect early warning signals. These results highlight the need for improved real-time lake monitoring, integration of local weather observations, and targeted hazard preparedness for downstream communities. Continuous satellite-based surveillance is essential for anticipating future GLOFs risks in rapidly changing Himalayan environments.

Keywords: Remote Sensing Analysis, Spectral Water Indices, Glacier–Lake Monitoring, Climate Change Impacts, Glacial Lake Outburst Floods (GLOFs)

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1 Introduction

The Himalayan region hosts numerous glaciers and glacial lakes formed in response to glacier retreat and atmospheric warming (Bajracharya and Shrestha, 2011; Shugar et al., 2020). As glaciers thin and recede, melt-water accumulates behind moraine or ice dams, forming glacial lakes that may fail suddenly as glacial lake outburst floods (GLOFs). GLOFs represent one of the most severe cryospheric hazards in high-mountain environments, causing loss of life, infrastructure damage, and long-term geomorphic change in downstream valleys (Richardson and Reynolds, 2000; Kargel et al., 2010). In Nepal, past GLOF

events have repeatedly affected settlements, hydropower facilities, agricultural land, and transportation networks, indicating increasing exposure of mountain communities to climate-related hazards.

Previous GLOF research in the Himalayas has largely focused on large, well-known glacial lakes such as Imja and Tsho Rolpa, which exhibit sustained long-term growth and have been classified as potentially dangerous (Shugar et al., 2020). In contrast, small to medium-sized moraine-dammed lakes that appear stable over long periods have received comparatively less attention and are often considered low-risk. Recent GLOF events, however, demonstrate that such

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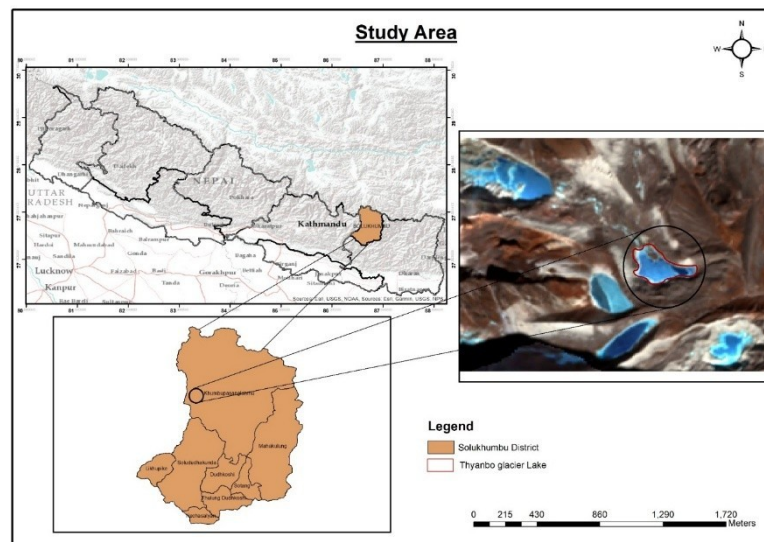


Fig. 1. Location of study area in the Himalayas, the Thyanbo glacial lake situated in the Thame region of Solukhumbu District, Koshi Province, Nepal.

lakes may fail following short-term climatic forcing, even in the absence of pronounced long-term expansion (Woolway et al., 2020). Consequently, the key knowledge gap addressed in this study concerns the limited understanding of short-term pre-event processes leading to GLOF initiation, particularly during the weeks to months immediately preceding failure (Cook and Quincey, 2015; Shugar et al., 2020).

Thyanbo Glacial Lake is located within a steep, high-mountain basin and is impounded by a moraine dam composed of unconsolidated glacial debris. The surrounding terrain is characterized by exposed rock faces and debris slopes, indicating a geomorphic setting sensitive to hydrological loading and rapid lake-level changes. On 16 August 2024, Thyanbo Glacial Lake in the Thame region experienced a destructive outburst flood that swept away at least 14 structures, including a primary school, a health clinic, hotels, and residential buildings (ICIMOD, 2024). Additional assessments reported the destruction of 12 houses, the displacement of approximately 135 people—including nearly 40 children—and at least one missing person (The Kathmandu Post, 2024; Farsight Nepal, 2024; Aawaaj News, 2024). This event highlights the hazard posed by glacial lakes that were not previously considered highly dangerous.

This study employs Sentinel-2 satellite imagery and established water indices, including the Normalized Difference Water Index (NDWI) and Modified NDWI (MNDWI), to analyse changes in lake area and volume before and after the 2024 outburst (Xu, 2006; Du et al., 2016). While these methods are well established, the novelty of this work lies in its event-based analysis focusing on short-term lake dynamics and climatic conditions immediately preceding failure. By integrating satellite-derived lake metrics with temperature and precipitation data, this study aims to improve understanding of the role of short-term climatic variability in triggering GLOFs. Accordingly, the objectives are to: (1) quantify changes in lake area and volume before and after the August 2024 GLOF; (2) examine temperature and pre-

cipitation conditions during summer 2024 relative to 2017–2023; (3) analyse short-term lake expansion patterns prior to the outburst; and (4) assess possible triggering mechanisms of the 2024 Thyanbo GLOF based on combined lake and climatic evidence.

2 Materials and Methods

2.1 Study Area

Thyanbo glacial lake is situated in the Thame region of Solukhumbu District, Koshi Province, Nepal, as shown in Fig. 1. The lake lies in a remote high-mountain region with Thame village being the nearest settlement. It is located at approximately 27.83° N and 86.60° E at an elevation of about 4,750 m above mean sea level.

2.2 Research Methodology

Methodological workflow adopted for this research is presented in Fig. 2. The workflow includes water surface extraction using NDWI and MNDWI, estimation of lake area and volume, accuracy assessment based on Sentinel-2 false-color composite (FCC) imagery, and integration of climatic anomaly analysis to evaluate short-term pre-event lake dynamics.

2.3 Data acquisition

The datasets used in this study, including satellite imagery and climatic records along with their sources, are summarized in Table 1.

All Sentinel-2 imagery for the period 2017–2024 was pre-processed through geometric correction and cloud masking.

2.4 Feature Extraction

Thyanbo Glacial Lake was delineated using both Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI). Sentinel-2 images were acquired for the period 2017–2024, using Band 3

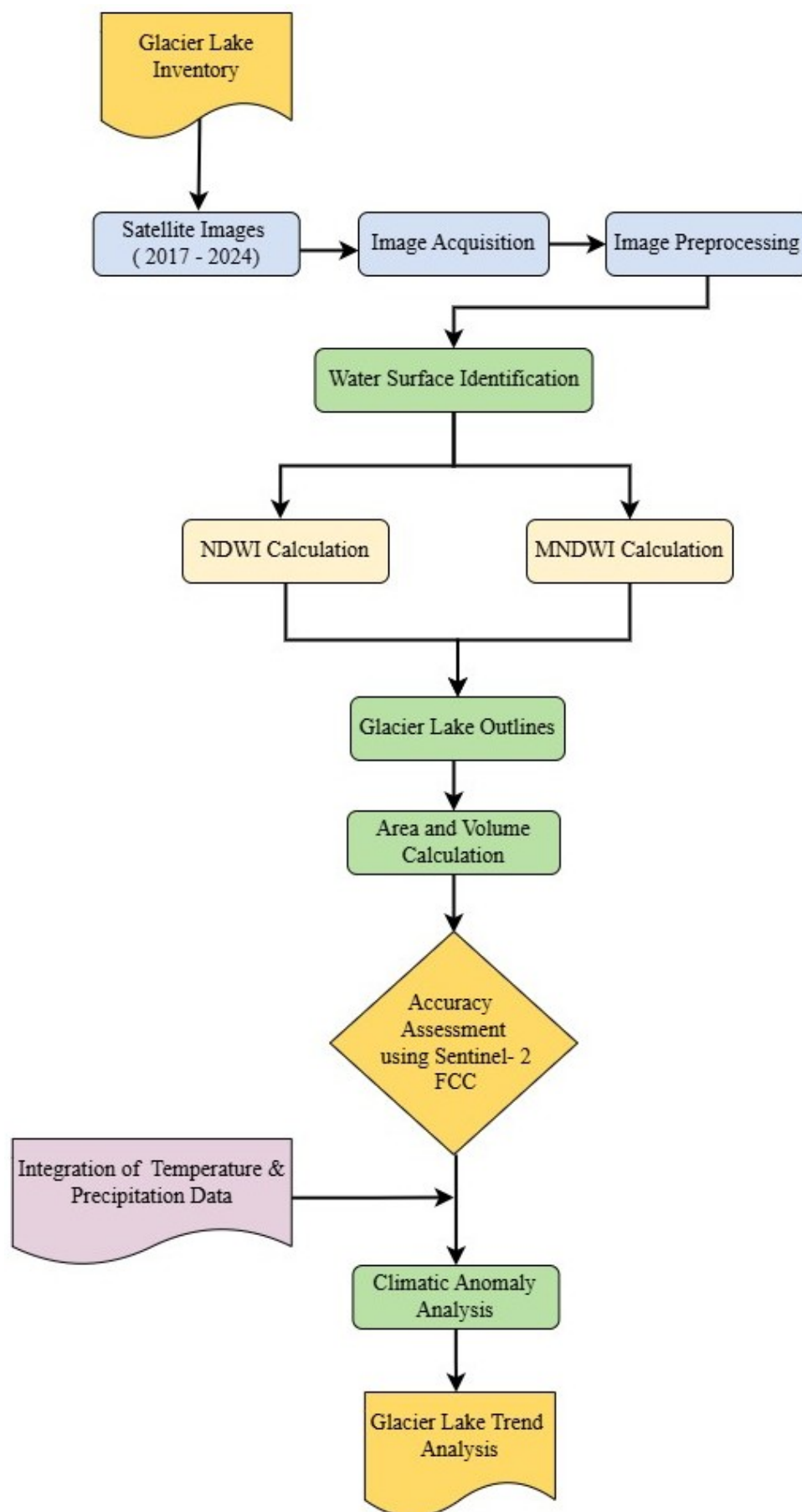


Fig. 2. Working methodology.

Table 1. Datasets and characteristics.

SN	Data Type	Source	Date
1	Satellite Image (Sentinel-2)	Copernicus Open Access Hub (https://browser.dataspace.copernicus.eu/)	2017–2024
2	Temperature/ Precipitation	NASAPOWER (https://power.larc.nasa.gov/)	2017–2024

(Green, 10 m), Band 8 (NIR, 10 m), and Band 11 (SWIR, 20 m). To ensure spatial consistency for index calculation, Band 11 was resampled to a 10 m spatial resolution and all bands were processed on a common 10 m grid prior to computing NDWI and MNDWI. NDWI and MNDWI were calculated from the Sentinel-2 using the following equations:

$$\begin{aligned}\text{NDWI} &= \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \\ \text{MNDWI} &= \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}}\end{aligned}$$

Both NDWI and MNDWI values typically range from -0.1 to +1, where positive values close to 1 indicate water presence, and negative values represent bare soil, vegetation, or other non-water features (Xu, 2006). After calculating NDWI and MNDWI, the water bodies were digitized in QGIS to delineate the lake boundaries accurately. From the digitized features, lake area and perimeter were computed for each year, providing a quantitative assessment of temporal and spatial changes.

2.5 Area Calculation

The lake area was calculated using both NDWI and MNDWI indices. NDWI often captures slightly larger water extents because it is more sensitive to shallow, turbid, or mixed water pixels. MNDWI reduces confusion from bright land surfaces, snow, or built-up features but in high-altitude glacial terrain, where shadows, debris cover, and mixed pixels are common, it may underestimate true water boundaries (Wigmore and Mark, 2017; Xu, 2006; Gautam et al., 2015).

2.6 Volume Estimation

The volume of the lake was estimated using an empirical relationship between lake area and volume, expressed as:

$$V = 3 \times 10^{-7} A^{1.239}$$

where V = lake volume (m^3) and A = lake area obtained from NDWI- and MNDWI-based water masks (m^2). This power-law relationship has been widely applied to glacial lakes and reflects the non-linear scaling between lake surface area and mean depth (Cook and Quincey, 2015; Shugar et al., 2020). The coefficient represents a generalized regression-based scaling derived from measured glacial lake datasets rather than a site-specific calibration. As this relationship is not explicitly calibrated for Himalayan glacial lakes and bathymetric data are unavailable, the resulting volume estimates carry uncertainty related to basin morphology and dam geometry. Therefore, the derived volumes are interpreted as first-order approximations and are used primarily to assess relative temporal changes and pre- and post-outburst contrasts rather than absolute water storage.

2.7 Accuracy Assessment

Accuracy assessment was conducted to evaluate the reliability of lake water extraction using NDWI and MNDWI. Due to the absence of field-based observations and contemporaneous very high-resolution imagery for 2024, visual interpretation of Sentinel-2 False Color Composite (FCC) imagery was adopted as the reference dataset, an approach commonly applied in high-mountain environments where direct ground truth is unavailable (Congalton, 1991). Four cloud-free Sentinel-2 images acquired on 10 June, 30 July, 28 October, and 12 December 2024, representing early summer, pre-outburst peak, post-outburst, and recovery stages, were selected for validation. For each date, lake boundaries were manually digitized from FCC imagery (NIR–Red–Green) and converted into binary reference rasters, assigning values of 1 to water and 0 to non-water pixels. NDWI and MNDWI outputs were similarly converted into binary water masks using a consistent threshold, following established water-mapping practices (Du et al., 2014).

A 100 m buffer was generated around the lake perimeter to capture shoreline and adjacent non-water areas where classification uncertainty is typically highest. Within this buffer, stratified random sample points were generated to ensure balanced representation of water and non-water classes. Raster values from the reference and classified datasets were extracted at these locations and used to construct confusion matrices (Florath et al., 2022). Standard accuracy metrics, including overall accuracy, producer's accuracy, and user's accuracy for the water class, were computed separately for NDWI and MNDWI to quantitatively assess classification performance and enable comparison between the two indices.

2.8 Intergradation of Temperature and Precipitation data

Temperature and precipitation records were analysed to characterise seasonal melt conditions and short-term climatic variability preceding the outburst event. The combined climatic datasets were used to examine temporal correspondence between summer warming, monsoon precipitation, and observed changes in lake area and volume. This integrated analysis provides context for evaluating how short-term climatic anomalies may have influenced meltwater input, lake-level fluctuations, and pre-outburst instability, thereby supporting interpretation of potential climatic contributions to the 2024 GLOF and its downstream impacts.

3 Results and Discussion

3.1 Spatiotemporal analysis of NDWI and MNDWI

Spatial maps were generated using NDWI and MNDWI for multiple observation dates to illustrate changes in the extent and boundaries of lake. These maps visually high-

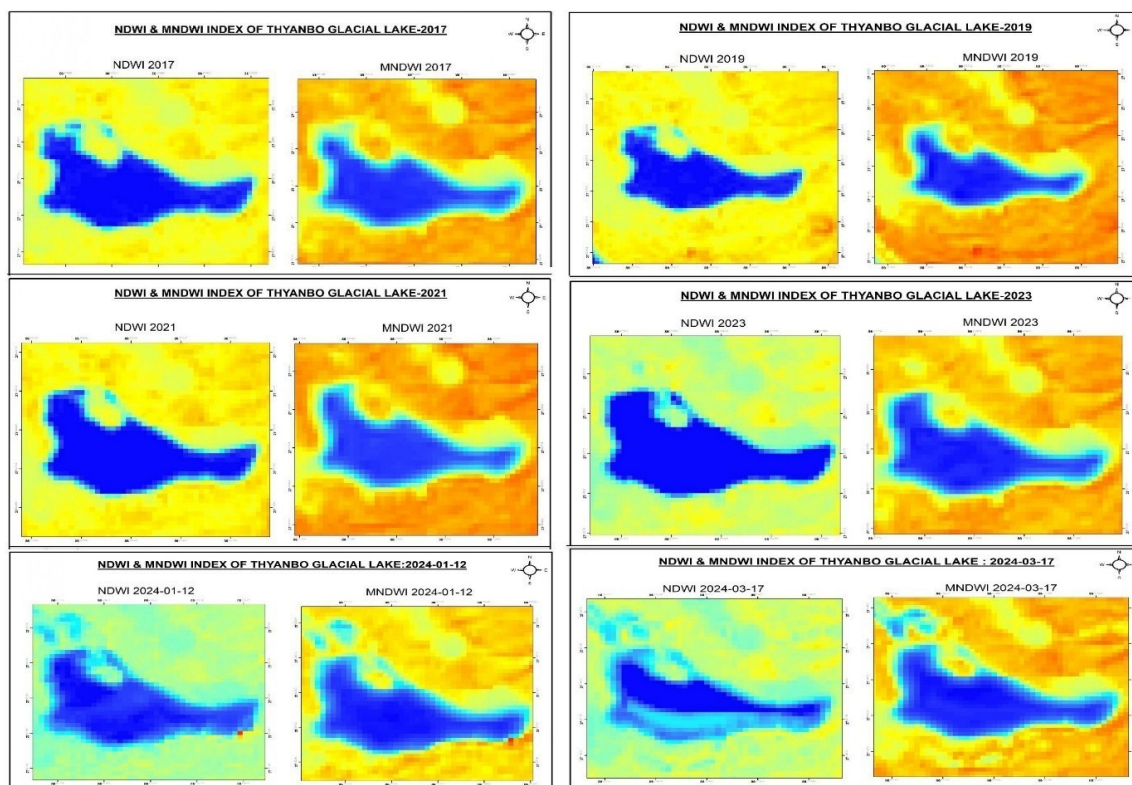


Fig. 3(a). Spatiotemporal map of NDWI and MNDWI from 2017 to 2024 March.

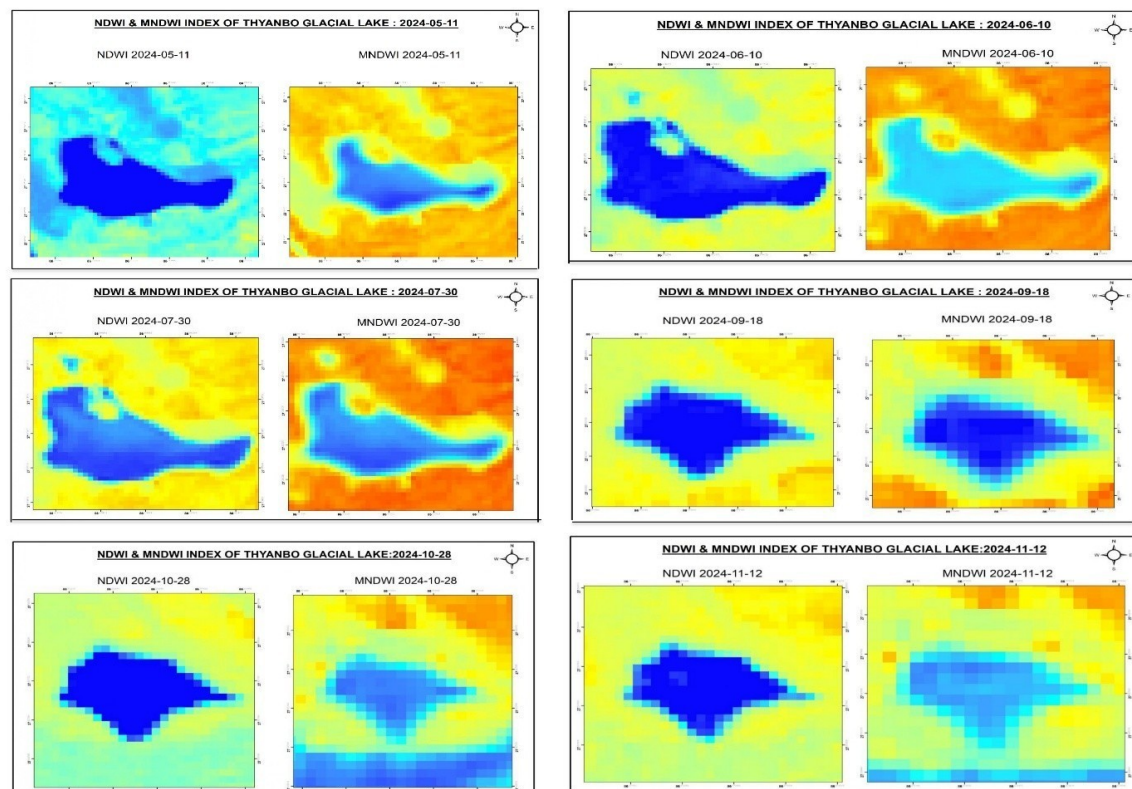


Fig. 3(b). Spatiotemporal map of NDWI and MNDWI from 2024-05-11 to 2024-11-12 (Legend and scale in next page.).

light temporal variations in lake morphology. Comparison of the two indices allows assessment of their respective responses to glacial lake dynamics, particularly during

the pre- and post-outburst periods, as shown in Fig. 3(a)–Fig. 3(c).

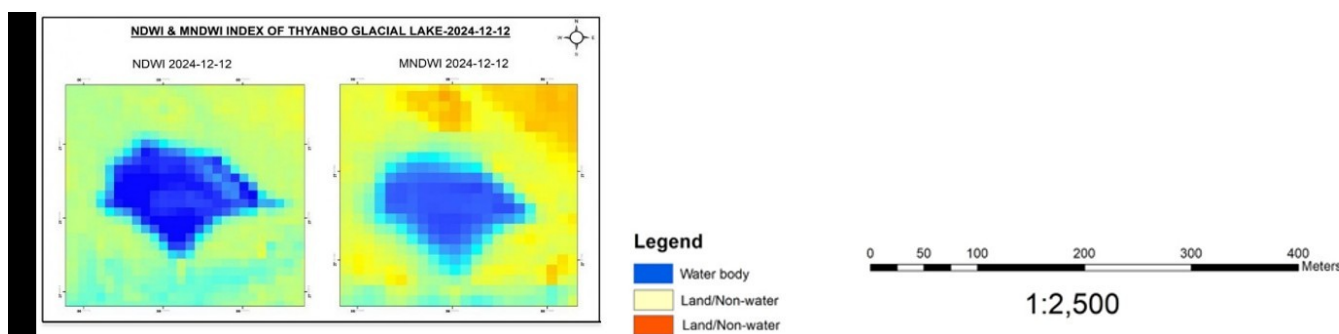


Fig. 3(c). Spatiotemporal map of NDWI and MNDWI of 2024-12-12.

Table 2. Multi-temporal lake area estimates based on NDWI and MNDWI, including percentage changes from 2017 to 2024.

SN	Date	NDWI Area (m ²)	Change in Area (%)	NDWI Rate (m ² /day)	MNDWI Area (m ²)	Change in Area (%)	MNDWI Rate (m ² /day)
1	12/9/2017	41,758.22	—	—	34,882.21	—	—
2	10/10/2019	32,880.60	−21.24	−11.71	30,864.08	−11.52	−5.30
3	14/10/2021	35,763.40	8.76	3.92	34,585.48	12.05	5.06
4	9/10/2023	36,826.82	2.97	1.47	34,936.40	1.01	0.48
5	12/1/2024	44,228.90	20.09	77.92	38,513.30	10.25	37.65
6	17/03/2024	34,752.76	−21.45	−145.79	37,274.64	−3.22	−19.06
7	11/5/2024	36,791.78	5.87	37.07	38,085.08	2.17	14.74
8	10/6/2024	42,019.65	14.22	174.26	42,627.76	11.93	151.42
9	30/07/2024	43,902.46	5.01	37.66	43,082.75	1.06	9.10
10	18/09/2024	12,515.58	−71.5	−627.74	10,169.35	−76.38	−658.27
11	28/10/2024	11,683.19	−6.64	−20.81	6,920.66	−31.94	−81.22
12	12/11/2024	11,264.33	−3.58	−27.92	6,284.69	−9.18	−42.40
13	12/12/2024	14,281.73	26.82	100.58	8,367.75	33.07	69.44

3.2 Temporal Dynamics of Thyanbo Glacial Lake Area

The temporal analysis of Thyanbo Glacial Lake from 2017 to 2024 reveals distinct phases of expansion and contraction captured by both NDWI and MNDWI. NDWI consistently mapped larger lake extents due to its higher sensitivity to mixed pixels, whereas MNDWI produced more conservative boundaries. From 2017 to 2023, the lake remained relatively stable, with NDWI-derived areas ranging from approximately 36,000 to 41,700 m² and MNDWI-derived areas from about 34,800 to 34,900 m². During the 2024 melt season, both indices recorded an increase in lake area, reaching 43,902 m² (NDWI) and 43,082 m² (MNDWI) by 30 July. Table 2 summarizes the multi-temporal lake areas derived from both indices, while Table 3 highlights the lake area between 2017 with immediately before and after the outburst. Changes in area (%) were calculated relative to the immediately preceding observation date, and rates of change (m²/day) were computed using the actual number of days between consecutive image acquisition dates.

Both NDWI and MNDWI captured a distinct phase of lake expansion between June and July 2024, followed by a sharp contraction after the outburst event, demonstrating their effectiveness for monitoring short-term glacial lake dynamics. Although the absolute percentage increase was moderate, the expansion occurred over a short early-summer interval and exceeded typical seasonal growth observed in previous years. Following the 16 August GLOF, lake area declined abruptly by more than 70% (NDWI) and 76% (MNDWI), with only limited refilling observed in the subsequent months. Fig. 4 illustrates the multi-year trends in lake area derived from both indices.

To verify that the mapped maximum lake extent was not influenced by monsoon-season cloud cover or cloud shadow, a Sentinel-2 true color composite acquired on 30 July 2024 is presented in Fig. 5.

3.3 Temporal Dynamics of Thyanbo Glacial Lake Volume

Thyanbo Lake volume, estimated using an empirical area–volume relationship, showed stable conditions from 2017–2023 (NDWI: 118.47×10^3 – 136.33×10^3 m³; MNDWI: 109.54×10^3 – 127.72×10^3 m³). In 2024, both indices captured strong seasonal variability, with rapid growth from May to July and a pre-outburst peak on 30 July (NDWI: 169.50×10^3 m³; MNDWI: 165.59×10^3 m³). After the 16 August GLOF, lake volume dropped sharply—about 79% (NDWI) and 83% (MNDWI)—indicating major drainage and moraine failure. Limited refilling from September to December marks early stabilization of the post-event basin. Overall, NDWI and MNDWI consistently revealed the pronounced pre-GLOF buildup and abrupt post-GLOF contraction.

Table 4 summarizes the multi-temporal NDWI- and MNDWI-based volume changes, while Table 5 compares 2017 volumes with the dates immediately surrounding the outburst. Percentage change is calculated relative to the immediately preceding observation date, and volume change rates (m³/day) are computed using the actual number of days between consecutive image acquisition dates.

Fig. 6 presents the multi-year NDWI and MNDWI lake volume trends. Overall, both NDWI and MNDWI consistently captured the strong pre-outburst volume buildup

Table 3. Comparison of lake area between 2017 and the dates immediately before and after the 2024 outburst event.

SN	Period	NDWI Area (m ²)	Change from 2017 (%)	NDWI Rate (m ² /day)	MNDWI Area (m ²)	Change from 2017 (%)	MNDWI Rate (m ² /day)	Remarks
1	12/9/2017	41758.22	-	-	34882.21	-	-	Initial measurement
2	10/6/2024	42,019.65	0.63	0.11	42,627.76	22.20	3.14	Early summer rise, signs of lake expansion
3	30/07/2024	43,902.46	5.14	37.66	43,082.75	23.50	9.10	Pre-outburst peak (17 days before outburst)
4	16/08/2024					GLOF Event		
5	28/10/2024	11,683.19	−72.03	−357.99	6,920.66	−80.15	−401.80	Post-outburst drainage
6	12/11/2024	11,264.33	−73.03	−27.92	6,284.69	−81.98	−42.40	Post-outburst stabilization and erosion
7	12/12/2024	14,281.73	−65.79	100.58	8,367.75	−76.00	69.44	Post-GLOF refilling / stabilization

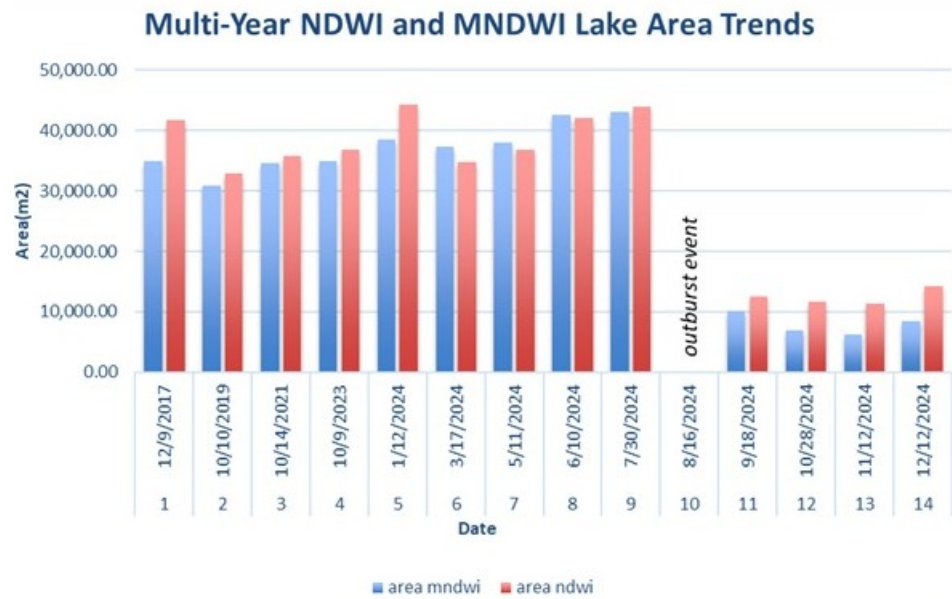


Fig. 4. Multi-year NDWI and MNDWI lake area trends.

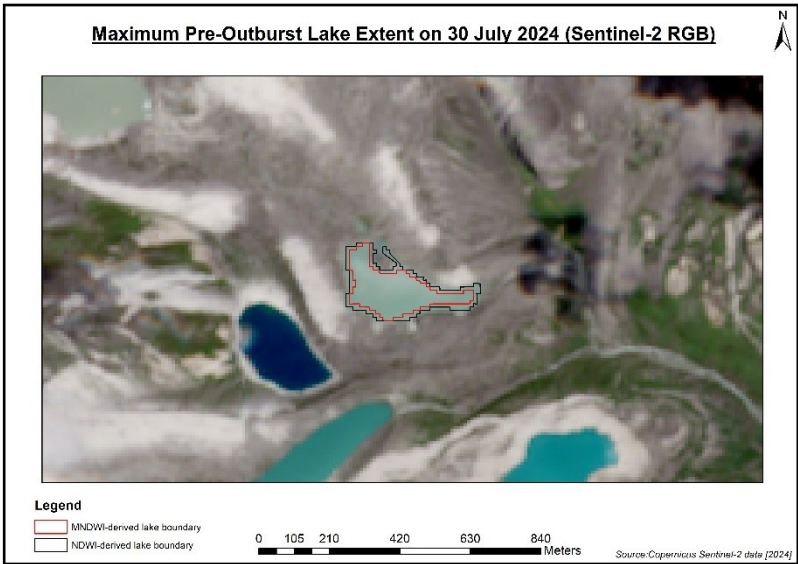


Fig. 5. Sentinel-2 Level-2A true color composite (RGB) from 30 July 2024 showing the maximum pre-outburst extent of Thyabho Glacial Lake with the NDWI/MNDWI-derived boundary overlaid.

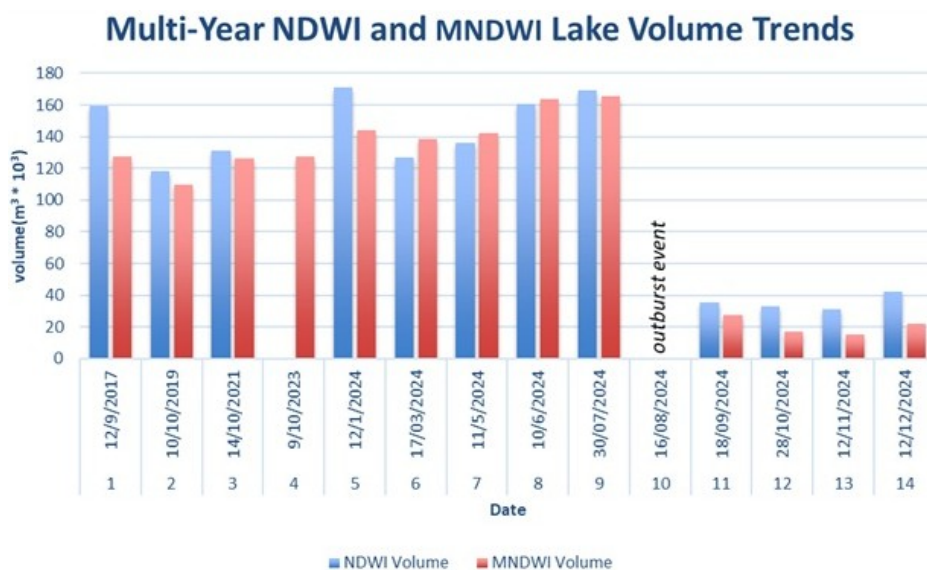
from June to July and the abrupt contraction after the event. These results highlight the effectiveness of satellite-derived volume estimation in tracking lake evolution and providing early indications of potential instability.

Table 4. Multi-temporal lake volume estimates derived from NDWI and MNDWI with corresponding percentage changes from 2017 to 2024.

SN	Date	NDWI Volume (m ³ × 10 ³)	NDWI Change (%)	NDWI Rate (m ³ /day)	MNDWI Volume (m ³ × 10 ³)	MNDWI Change (%)	MNDWI Rate (m ³ /day)
1	12/9/2017	159.30	–	–	127.47	–	–
2	10/10/2019	118.47	–25.60	–53.87	109.54	–14.10	–23.65
3	14/10/2021	131.47	11.00	17.69	126.13	15.10	22.57
4	9/10/2023	136.33	3.70	6.70	127.72	1.30	2.19
5	12/1/2024	171.06	25.50	365.58	144.11	12.80	172.53
6	17/03/2024	126.88	–25.80	–679.69	138.39	–4.00	–88.00
7	11/5/2024	136.17	7.30	168.91	142.13	2.80	68.00
8	10/6/2024	160.54	17.90	812.33	163.42	15.00	709.67
9	30/07/2024	169.50	5.60	179.20	165.59	1.30	43.40
10	18/09/2024	35.80	–78.90	–2674.00	27.68	–83.30	–2758.20
11	28/10/2024	32.87	–8.20	–73.25	17.18	–37.90	–262.50
12	12/11/2024	31.42	–4.40	–96.67	15.25	–11.20	–128.67
13	12/12/2024	42.16	34.20	358.00	21.74	42.60	216.33

Table 5. Comparison of lake volume between 2017 and the dates immediately before and after the 2024 outburst event.

SN	Period	NDWI Volume (m ³ × 10 ³)	Change from 2017 (%)	NDWI Rate (m ³ /day)	MNDWI Volume (m ³ × 10 ³)	Change from 2017 (%)	MNDWI Rate (m ³ /day)	Remarks
1	12/9/2017	159.30	–	–	127.47	–	–	Initial measurement
2	10/6/2024	160.54	0.78	0.50	163.42	28.0	14.61	Early summer rise, signs of lake expansion
3	30/07/2024	169.50	6.40	179.20	165.59	29.92	43.40	Pre-outburst peak (17 days before outburst)
4	16/08/2024							<i>GLOF Event</i>
5	28/10/2024	32.87	–79.36	–1,868.63	17.18	–86.53	–2,036.44	Post-outburst drainage
6	12/11/2024	31.42	–80.27	–96.67	15.25	–88.04	–128.67	Post-outburst stabilization and erosion
7	12/12/2024	42.16	–73.54	358.00	21.74	–82.95	216.33	Refilling & stabilization

**Fig. 6.** Multi-year NDWI and MNDWI lake volume trends.

3.4 Accuracy assessment of NDWI and MNDWI classifications

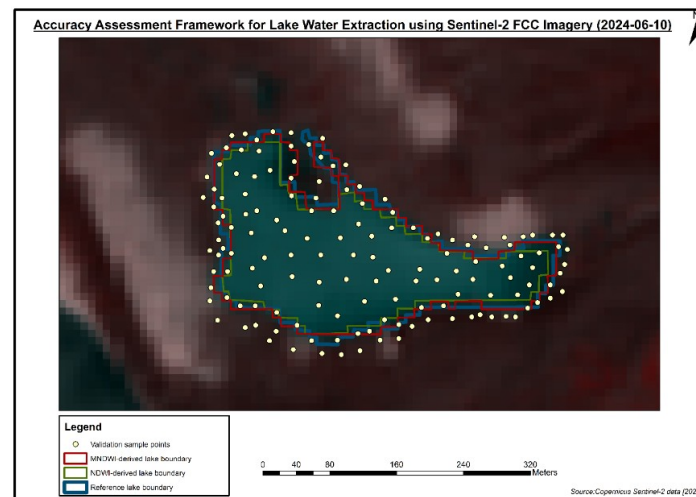
The quantitative accuracy metrics derived from confusion matrix analysis are summarized in Table 6. A total of 146, 147, 126, and 132 validation sample points were used for the Sentinel-2 images acquired on 10 June, 30 July, 28 October, and 12 December 2024, respectively, ensuring adequate representation of both water and non-water classes for each validation date. An example of the accuracy assessment framework, including FCC-derived reference data,

NDWI and MNDWI lake boundaries, and validation sample points for 10 June 2024, is shown in Fig. 7. Across all four validation dates, NDWI achieved overall accuracies ranging from 84.2% to 91.3%, with corresponding Cohen's Kappa coefficients between 0.69 and 0.81, indicating substantial to near-perfect agreement with the FCC-derived reference data. For the water class, producer's accuracy ranged from 69.7% to 88.1%, while user's accuracy ranged from 86.7% to 100.0%, demonstrating a strong capability of NDWI to correctly identify lake water pixels with limited commission error.

Table 6. Accuracy assessment of NDWI and MNDWI water classifications using Sentinel-2 FCC reference data (2024).

Date (2024)	Index	TP	FP	FN	TN	Overall Accuracy (%)	Producer's Accuracy – Water (%)	User's Accuracy – Water (%)	Kappa (κ)
10-Jun-24	NDWI	53	0	23	70	84.20	69.70	100.00	0.69
	MNDWI	68	8	8	62	89.00	89.50	89.50	0.78
30-Jul-24	NDWI	54	3	12	78	89.80	81.80	94.70	0.79
	MNDWI	31	0	35	81	76.20	47.00	100.00	0.49
28-Oct-24	NDWI	39	5	6	76	91.30	86.70	88.60	0.81
	MNDWI	19	0	26	81	79.40	42.20	100.00	0.48
12-Dec-24	NDWI	52	8	7	65	88.60	88.10	86.70	0.77
	MNDWI	38	1	21	72	83.30	64.40	97.40	0.65

TP = True Positive (water correctly classified), TN = True Negative (non-water correctly classified), FP = False Positive (non-water misclassified as water), FN = False Negative (water misclassified as non-water); κ = Cohen's Kappa coefficient.

**Fig. 7.** Accuracy assessment framework for lake water extraction using Sentinel-2 FCC imagery (10 June 2024).

MNDWI produced overall accuracies between 76.2% and 89.0%, with Kappa values ranging from 0.48 to 0.78, corresponding to moderate to substantial agreement. MNDWI consistently exhibited high user's accuracy for the water class (89.5%–100.0%), reflecting low false-positive rates. However, its producer's accuracy was lower (42.2%–89.5%), indicating increased omission of shallow or debris-influenced water pixels, particularly during post-outburst and recovery phases.

Overall, the multi-temporal accuracy assessment demonstrates that NDWI provides a more sensitive representation of glacial lake water extent under dynamic conditions, while MNDWI yields a more conservative classification with reduced false positives but higher omission errors. The complementary performance of the two indices supports their combined use for robust interpretation of short-term glacial lake dynamics before and after the 2024 Thyanbo GLOF.

3.5 Climatic Controls: Temperature and Precipitation Trends

Temperature records from 2017 to 2023 indicate conditions that were generally near or below the freezing point, with only occasional marginally positive values, thereby, limiting meltwater input and keeping the lake stable. In early 2024, very cold winter temperatures caused contraction, but a rapid warming trend from April to July—peaking at 6.38°C—drove strong glacier melt and continu-

ous inflow as shown in Table 7. By 30 July, just 17 days before the outburst, the lake reached its maximum extent, indicating rising hydrostatic pressure. Temperatures dropped again after mid-August, supporting post-GLOF stabilization. Precipitation followed a similar pattern. While previous years showed low rainfall, 2024 recorded a sharp rise from April to July, with 11.02 mm in June and 8.30 mm in July. This wet period, combined with warming, likely accelerated inflow and weakened the moraine through saturation. Rainfall decreased sharply after the outburst. Together, the strong warming and wetting signals in early–mid 2024 align closely with the rapid lake expansion and likely contributed to the 2024 GLOF. Temperature is reported as absolute values (°C), while precipitation is expressed in both absolute amounts (mm) and percentage change, as percentage change is physically meaningful for precipitation but not for temperature near the freezing point. Climate–lake interactions were assessed using combined lake and climate plots.

Fig. 8 presents the relationship between climatic variables and lake area, with the upper panel showing temporal variations in air temperature and precipitation and the lower panel illustrating NDWI- and MNDWI-derived lake area changes. Similarly, Fig. 9 displays climatic variability in the upper panel and the corresponding NDWI- and MNDWI-derived lake volume changes in the lower panel. Together, these figures highlight the temporal association between climatic variability and changes in lake area and volume observed prior to the 2024 GLOF.

Table 7. Temporal variation of lake temperature and precipitation..

SN	Year	Month	Temperature (°C)	Precipitation (mm)	Change in Precipitation (%)	Remarks
1	2017	December	−7.72	0.88	–	Cold winter; minimal melting, stable lake.
2	2019	October	−1.17	0.26	−70.50	
3	2021	October	0.11	2.47	850.00	
4	2023	October	−1.22	0.62	−74.90	Marginally above freezing.
5	2024	January	−11.93	0.05	−91.90	
6	2024	February	−11.50	0.15	200.00	Very cold winter conditions.
7	2024	March	−6.97	1.09	626.70	
8	2024	April	−3.12	0.48	−56.00	Gradual warming begins.
9	2024	May	1.09	1.78	270.80	Transition toward melt season.
10	2024	June	4.81	11.02	519.10	Start of strong meltwater inflow.
11	2024	July	6.38	8.30	−24.70	Rapid warming and rainfall surge.
12	2024	August	5.42	6.12	−26.30	Peak melting; lake at highest volume (16 days before outburst).
13	2024	September	4.13	7.06	15.30	Outburst period; rapid drainage.
14	2024	October	0.41	0.85	−88.00	Post-outburst; moderate rainfall, cooling trend.
15	2024	November	−4.17	0.05	−94.10	Cooling and reduced rainfall.
16	2024	December	−9.08	0.01	−80.00	Early winter conditions.
						Cold post-monsoon period.

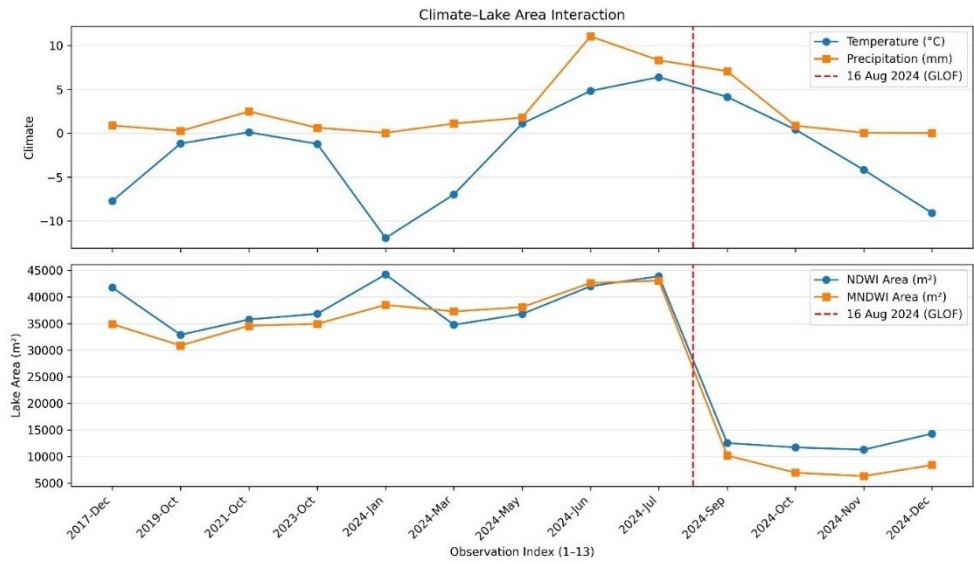


Fig. 8. Temporal variation of climatic variables and lake area at Thyanbo Glacial Lake.

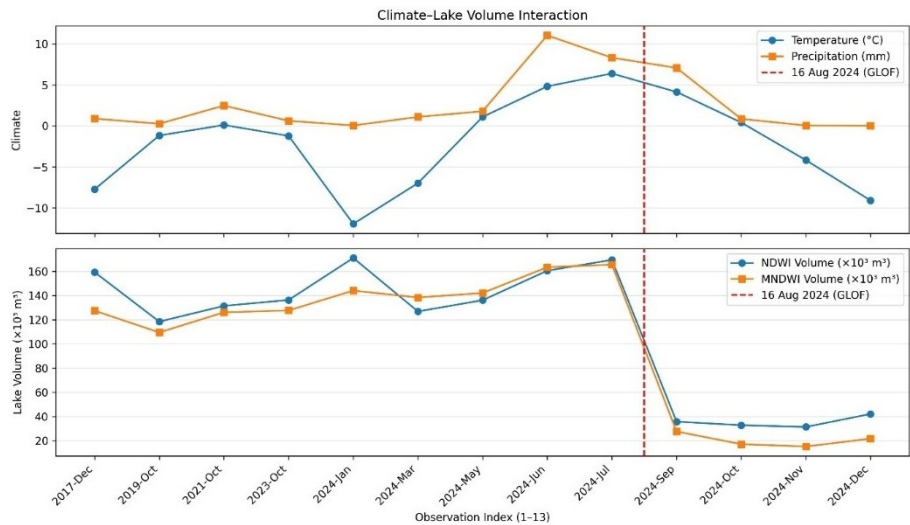


Fig. 9. Temporal variation of climatic variables and lake volume at Thyanbo Glacial Lake.

3.6 Climatic Anomalies Prior to the 2024 GLOF

The summer of 2024 exhibits a clear departure from climatic conditions observed during the 2017–2023 period. Temperatures increased steadily from May to July 2024, transitioning from near-freezing conditions in April (-3.12°C) to sustained positive temperatures in May (1.09°C) and June (4.81°C), and reaching a peak in July (6.38°C). Concurrently, monsoon precipitation intensified, increasing from 1.78 mm in May to 11.02 mm in June and remaining elevated in July (8.30 mm). These warm and wet conditions coincided with rapid lake expansion and the maximum pre-outburst lake extent observed on 30 July 2024, approximately 17 days prior to the GLOF. Although long-term linear correlations between climatic variables and lake geometry remain weak, the short-term concurrence of elevated temperatures and enhanced precipitation during May–July 2024 suggests that these climatic anomalies increased meltwater input and hydrostatic loading on the moraine dam, thereby preconditioning the lake for failure. This behavior is consistent with the threshold-driven nature of GLOF processes, where short-lived climatic extremes can induce sudden instability. The 2024 Thyanbo GLOF is therefore interpreted as the outcome of hydrological and climatic preconditioning rather than a single definitive trigger. Sustained meltwater inflow and intensified monsoon precipitation during early summer likely elevated lake levels and increased hydrostatic pressure on the moraine dam. However, Himalayan GLOFs are often initiated by dynamic triggers, such as ice or rock avalanches impacting the lake and generating displacement waves capable of overtopping or breaching the moraine. Visual inspection of Sentinel-2 imagery did not reveal clear evidence of a large landslide or hanging-glacier collapse immediately preceding the event; nevertheless, monsoon cloud cover and spatial resolution limitations prevent the exclusion of smaller-scale slope failures or ice calving. Consequently, the outburst is best interpreted as a threshold-driven failure resulting from the combined influence of short-term climatic forcing, rapid lake expansion, and inherent moraine instability.

4 Conclusion

This study demonstrates that short-term climatic anomalies, particularly elevated summer temperatures and intensified monsoon precipitation, played a critical role in driving the rapid expansion of Thyanbo Glacial Lake prior to the August 2024 outburst. Multi-temporal analysis using NDWI and MNDWI revealed sustained lake growth during June and July 2024, culminating in a pronounced expansion only 17 days before the GLOF, indicative of accelerated meltwater inflow and increasing hydrostatic pressure on a structurally fragile moraine dam. Following the outburst, the lake underwent an abrupt reduction in both area and volume, losing more than 75% of its stored water. Subsequent cooling and reduced precipitation during September–December 2024 contributed to partial stabilization of the post-event basin. NDWI consistently captured more extensive lake boundaries due to its sensitivity to mixed pixels, whereas MNDWI produced more conservative estimates by suppressing marginal and debris-influenced water areas.

Overall, the 2024 Thyanbo GLOF is best interpreted as a threshold-driven failure resulting from the combined effects of short-term climatic forcing, rapid lake expansion, and inherent geomorphic instability of the moraine dam, rather than a single isolated trigger. These findings highlight the importance of continuous satellite-based monitoring, integration of near-real-time climate data, and coordinated geomorphological and hydrodynamic assessments to strengthen GLOF risk evaluation and support early-warning and downstream hazard preparedness in the Himalayan region.

Conflict of Interest

The authors declare that there are no known conflicts of interest associated with this publication.

CRediT statement

Bhuwan Singh Bisht: Conceptualization, Methodology, Investigation, Data analysis, Writing - original draft, and editing. **Bimal Joshi:** Methodology, Validation, Data analysis, Writing - original draft and Visualization. **Soniya Koirala:** Data curation and reviewing draft manuscript. **Sabita Sapkota:** Investigation and reviewing draft manuscript. **Harish Bhatt:** Data analysis and reviewing draft manuscript.

Data availability

All data used in this study are derived from freely available open-access sources, which are fully cited within the manuscript. Additional processed datasets can be made available from the corresponding author upon reasonable request.

AI-Assistance Disclosure

No AI tool was used for data analysis, interpretation, or drawing of conclusions. All responsibility for the content rests with the authors.

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