Geospatial Early-Warning Indicators and Climate-Driven Dynamics of Thyanbo Glacial Lake, Nepal: A Remote-Sensing Based GLOF Assessment

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Key words: Remote sensing, Glacial Lake Outburst Floods (GLOFs), Climate change, Early-warning systems, Spatio-temporal analysis, SDG 13

SUMMARY

Thyanbo Glacial Lake in the Thame region of eastern Nepal experienced a destructive glacial lake outburst flood (GLOF) on 16 August 2024, displacing over 130 people and damaging homes, hotels, a school, and a health post. This study investigates the short-term lake dynamics and climatic conditions preceding the event using multi-temporal Sentinel-2 satellite imagery (2017–2024) and satellite-derived climate data. Lake area was delineated using the Normalized Difference Water Index (NDWI) and Modified NDWI (MNDWI), and lake volume was estimated using an established empirical area–volume relationship. Temperature and precipitation data were analyzed to assess their influence on meltwater input and lake expansion. Results indicate that while the lake remained relatively stable between 2017 and 2023, a rapid increase in lake area and estimated volume occurred during summer 2024, coinciding with elevated temperatures and intensified monsoon precipitation. The lake reached its maximum extent approximately two weeks before the outburst. Following the GLOF event, lake area decreased by more than 70% and estimated volume declined by nearly 80%, indicating extensive drainage and geomorphic reconfiguration. The findings demonstrate that satellite-based monitoring can provide practical early-warning signals even for glacial lakes previously considered low risk. The study highlights the role of geospatial technologies in strengthening early-warning systems, supporting disaster risk reduction, and advancing climate-resilient planning in mountain regions, contributing directly to Sustainable Development Goal 13 (Climate Action).

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1. INTRODUCTION

Glacial lakes in the Himalayan region are expanding due to glacier retreat and rising temperatures, increasing the likelihood of glacial lake outburst floods (GLOFs) (Bajracharya & Shrestha, 2011; Shugar et al., 2020). GLOFs represent a major hazard in high-mountain environments, frequently causing loss of life, damage to infrastructure, and long-term impacts on downstream valleys (Richardson & Reynolds, 2000; Kargel et al., 2010). In Nepal, repeated GLOF events have affected settlements, hydropower facilities, and transportation corridors, highlighting growing vulnerability to climate-driven hazards. Most GLOF monitoring efforts in the Himalaya have focused on large, well-known glacial lakes, while smaller and medium-sized moraine-dammed lakes that appear stable over long periods are often considered low risk. Recent events demonstrate that such lakes can fail rapidly under short-term climatic extremes, revealing limitations in existing hazard classification and early-warning approaches (Cook & Quincey, 2015; Woolway et al., 2020).

Thyanbo Glacial Lake, located in the Thame region of eastern Nepal, exemplifies this challenge. On 16 August 2024, the lake experienced a destructive outburst flood that damaged multiple structures and displaced approximately 135 people (ICIMOD, 2024). Prior to this event, the lake was not classified as highly dangerous. This study applies satellite-based monitoring to analyses short-term lake dynamics and climatic conditions preceding the outburst, demonstrating how geospatial technologies can support early-warning interpretation and disaster risk reduction in Himalayan mountain regions.

2. RESEARCH METHODOLOGY

2.1 Overview of Methodological Framework

The methodological workflow integrates multi-temporal Sentinel-2 imagery, spectral water index analysis, empirical area–volume estimation, and climatic anomaly analysis to assess short-term lake dynamics and early-warning indicators (Bisht et al., 2025). The overall workflow is illustrated in Figure 1.

2.2 Study Area

Thyanbo Glacial Lake is located in the Solukhumbu District of eastern Nepal within the high-mountain Himalayan region. The lake is situated at an elevation exceeding 4,500 m above mean sea level and is dammed by unconsolidated moraine material. The surrounding terrain is characterized by steep slopes, active geomorphological processes, and extensive glacial coverage as shown in Figure 2. The lake drains into a steep downstream valley hosting settlements, trekking routes, and local infrastructure. Prior to 2024, Thyanbo Glacial Lake was not categorized among Nepal's most critical GLOF threats, highlighting the challenge of identifying hazardous lakes under rapidly changing climatic conditions.

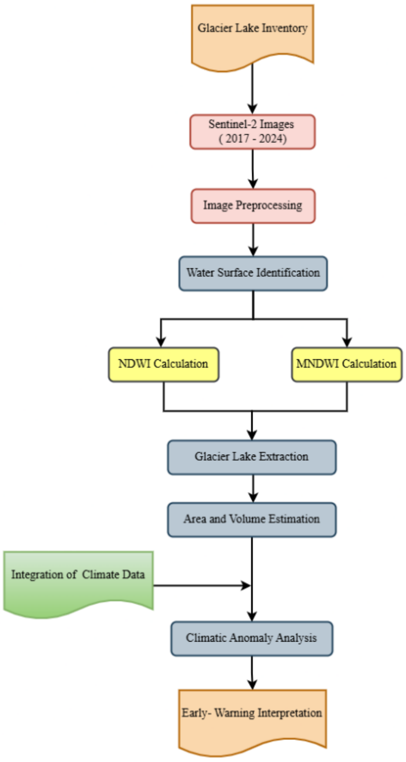

Figure 1. Methodological workflow for satellite-based GLOF early-warning assessment.

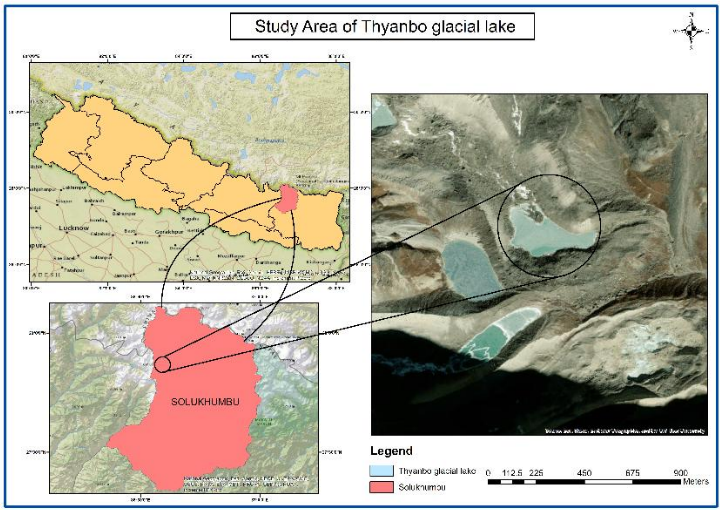

Figure 2.Thyanbo glacial lake situated in the Thame region of Solukhumbu District, Koshi Province, Nepal

2.3 Data Acquisition

Multi-temporal Sentinel-2 Level-2A imagery accessed from Copernicus Open Access Hub (https://browser.dataspace.copernicus.eu/) covering the period 2017–2024 was used to analyses lake dynamics. Images were selected during cloud-free periods and processed using standard atmospheric correction and spatial referencing procedures. Temperature and precipitation data were collected from NASA POWER (https://power.larc.nasa.gov/).

2.4 Lake Area Delineation

Thyanbo Glacial Lake was delineated using the Normalized Difference Water Index (NDWI) and Modified Normalized Difference Water Index (MNDWI). NDWI and MNDWI were calculated using the following equations:

$$\mathrm{NDWI} = \frac{\mathrm{Green} - \mathrm{NIR}}{\mathrm{Green} + \mathrm{NIR}}$$

$$\mathrm{MNDWI} = \frac{\mathrm{Green} - \mathrm{SWIR}}{\mathrm{Green} + \mathrm{SWIR}}$$

Both indices typically range from −0.1 to +1, where higher positive values indicate water surfaces and negative values correspond to non-water features (Xu, 2006). Lake boundaries were extracted through manual digitization of the NDWI and MNDWI outputs in QGIS to ensure accurate delineation of the water surface. From the extracted lake polygons, lake area and perimeter were calculated for each observation year.

2.5 Lake area and volume Estimation

Lake surface area was calculated using both NDWI- and MNDWI-derived lake outlines. NDWI generally captures slightly larger water extents due to its sensitivity to shallow or mixed pixels, whereas MNDWI reduces confusion from bright land surfaces, snow, and debris (Xu, 2006; Gautam et al., 2015). In high-altitude glacial terrain, MNDWI may underestimate true water boundaries due to shadowing and debris cover (Wigmore & Mark, 2017). Accordingly, both indices were used to assess temporal consistency and uncertainty in lake area estimates.
Lake volume was estimated using an established empirical area–volume relationship expressed as:

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

where V is lake volume (m^3) and A is lake area (m^2). This power-law relationship has been widely applied in glacial lake studies and reflects the non-linear scaling between lake surface area and mean depth (Cook et al., 2015; Shugar et al., 2020). As bathymetric data were unavailable and the relationship is not site-specific, the resulting volume estimates are interpreted as first-order approximations and are used primarily to analyses relative temporal changes and pre- and post-outburst contrasts.

2.6 Integration of Temperature and Precipitation Data

Temperature and precipitation data were analyzed to characterize seasonal melt conditions and short-term climatic variability preceding the 2024 outburst event. These datasets were integrated with satellite-derived lake area and volume estimates to examine temporal correspondence between summer warming, monsoon precipitation, and observed lake expansion. This combined analysis provides contextual evidence for assessing how short-term climatic anomalies may have influenced meltwater input, lake-level fluctuations, and pre-outburst instability, supporting early-warning interpretation and downstream risk assessment.

3. RESULTS

3.1 Spatio-Temporal Changes in Lake Area and Volume (2017-2024)

Analysis of multi-temporal Sentinel-2 imagery shows that Thyanbo Glacial Lake remained relatively stable between 2017 and 2023, with lake surface area varying between approximately 32,881 m² and 41,758 m² (Figure 3(a) – 3(c)).

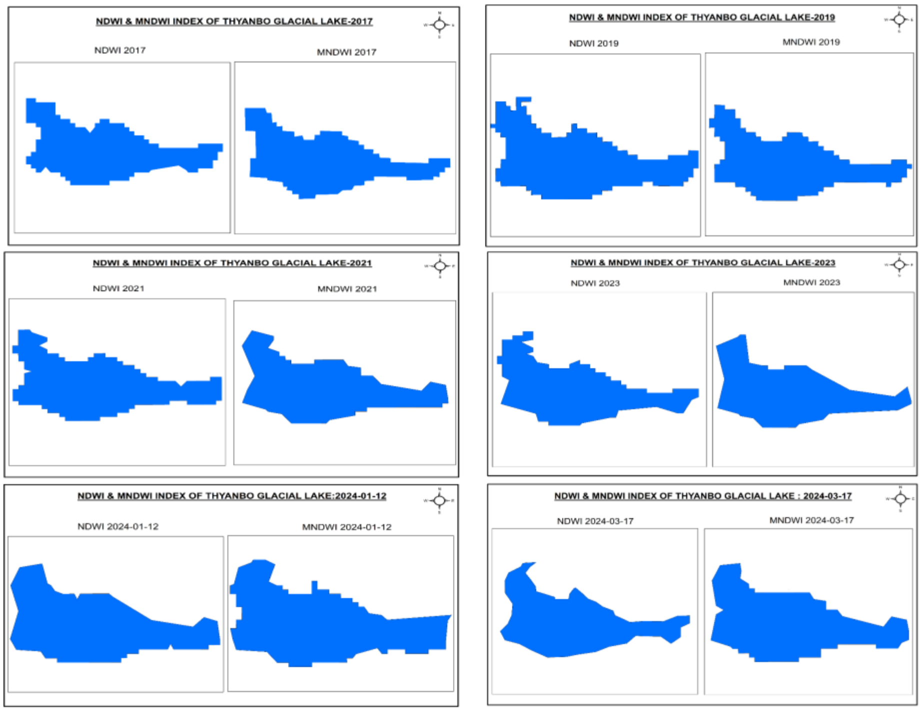

Figure 3 (a). Spatiotemporal map of NDWI and MNDWI from 2017 to 2024 March.

During this period, only gradual interannual fluctuations were observed, indicating no pronounced long-term expansion trend.

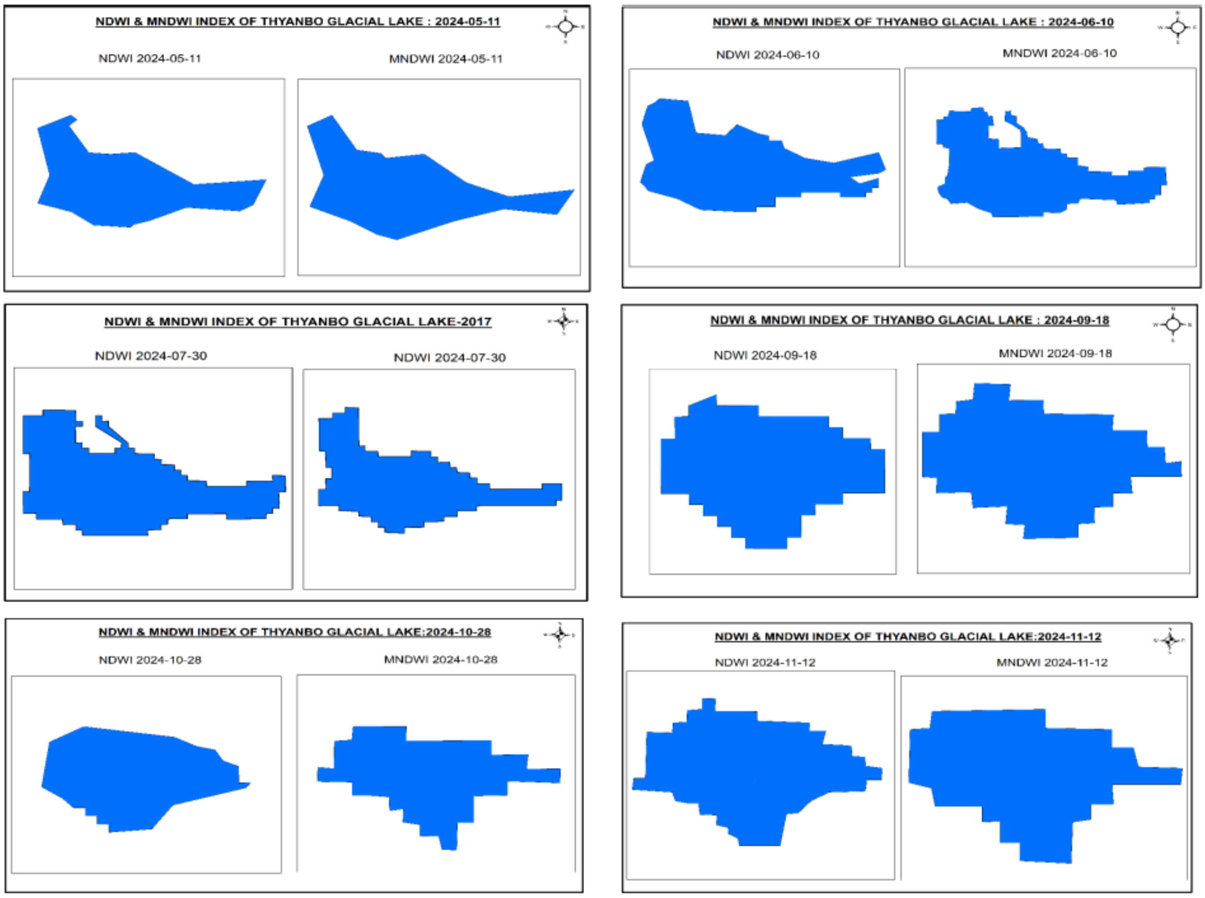

Figure 3 (b). Spatiotemporal map of NDWI and MNDWI from 2024-05-11 to 2024-11-12.

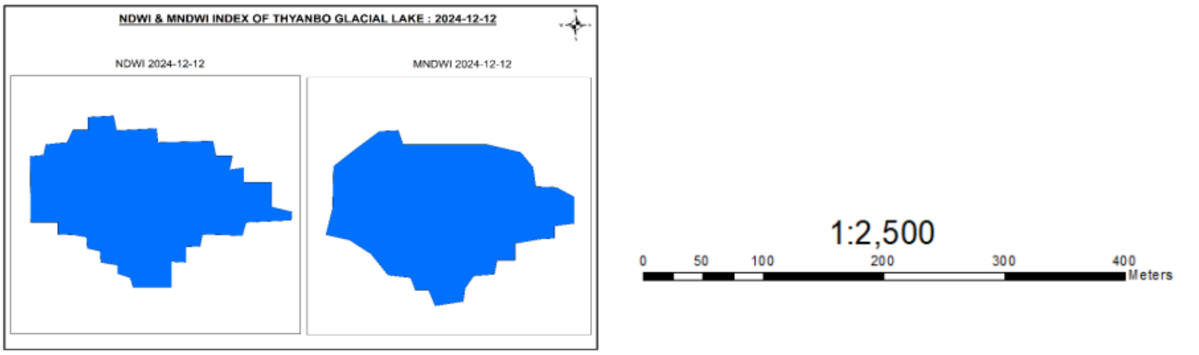

Figure 3 (c): Spatiotemporal map of NDWI and MNDWI of 2024-12-12.

In contrast, a marked change occurred in 2024. Rapid lake growth was detected during the pre-monsoon and monsoon months, culminating in a maximum lake area of approximately 43,902 m² on 30 July 2024 as shown in figure 4. This peak occurred around two weeks prior to the outburst event. Following the GLOF on 16 August 2024, lake area declined sharply by more than 70%, reflecting extensive drainage and post-event geomorphic modification of the lake basin.

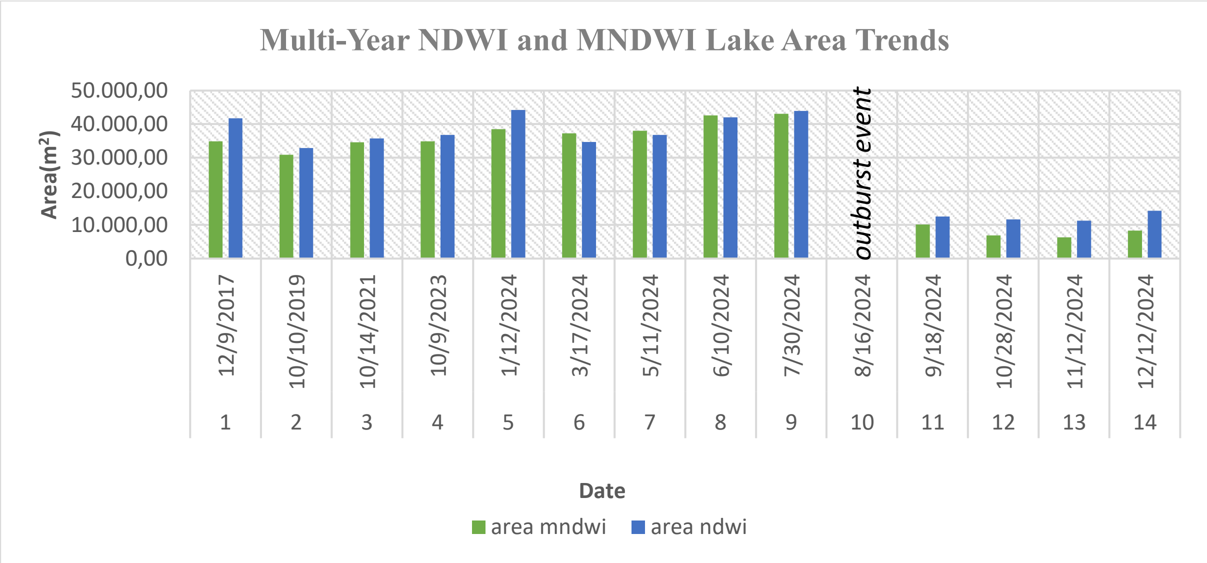

Figure 4. Temporal changes in lake area.

Estimated lake volume followed trends similar to lake area. Volumes ranged between approximately 118 × 10^3 m^3 and 159 × 10^3 m^3 during 2017–2023, increasing sharply in 2024 to a maximum of approximately 169 × 10^3 m^3. After the outburst, estimated volume declined by nearly 80%, reflecting rapid water release as shown in figure 5.

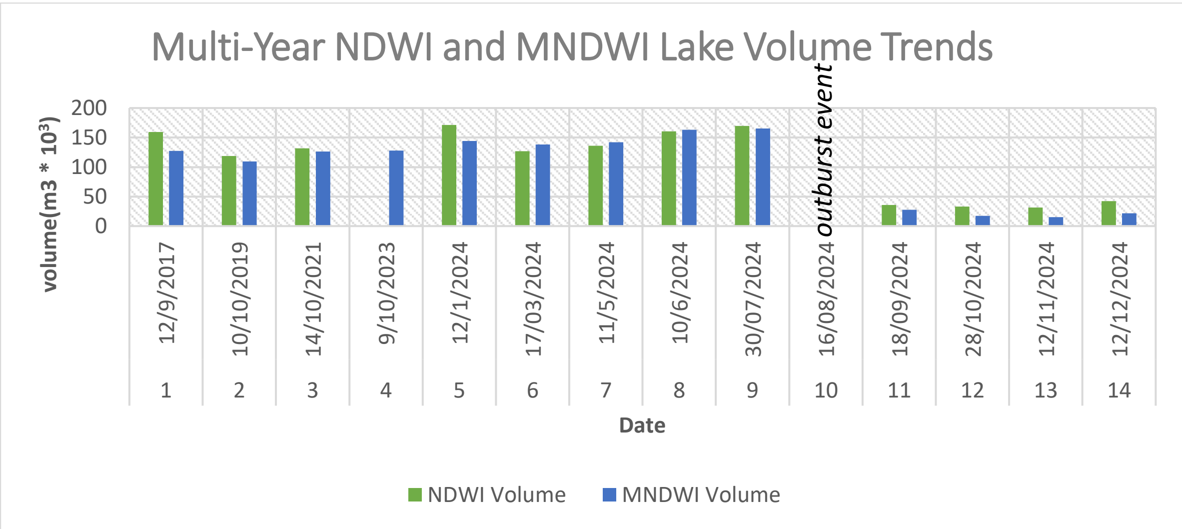

Figure 5. Temporal changes in lake volume.

3.2 Climatic Conditions Preceding the GLOF

Satellite-derived climate data indicate that summer 2024 was characterized by elevated air temperatures and intensified monsoon precipitation compared to the 2017–2023 baseline (Figure 6 and 7). Mean summer temperatures exceeded 5 °C during the period of rapid lake expansion, while precipitation totals increased substantially during the monsoon months. The timing of these climatic anomalies closely coincided with observed increases in lake area and volume, suggesting enhanced glacier melt and increased inflow to the lake during the weeks preceding the outburst (Bisht et al., 2025).

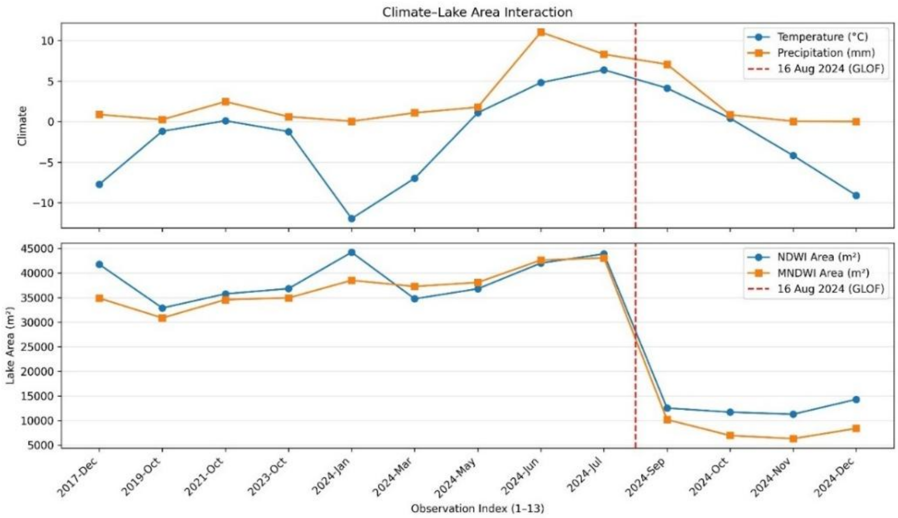

Figure 6. Temporal variation of climatic variables and lake area at Thyanbo Glacial Lake.

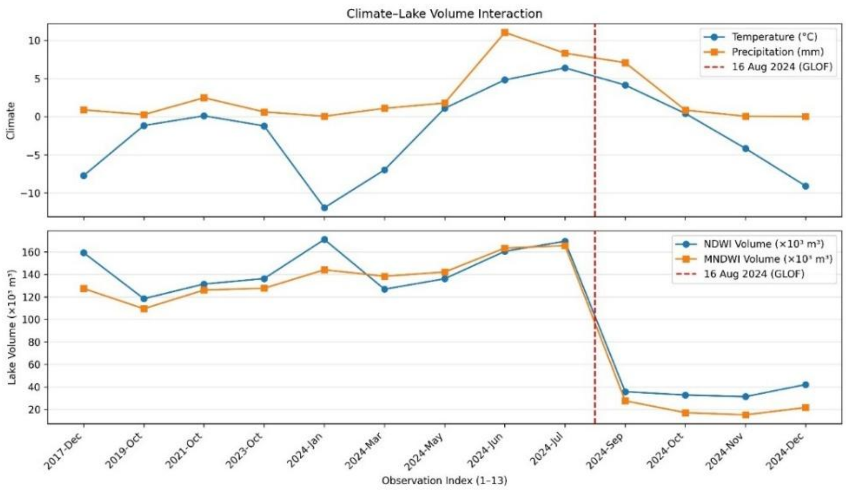

Figure 7. Temporal variation of climatic variables and lake volume at Thyanbo Glacial Lake.

4. DISCUSSION

The 2024 outburst of Thyanbo Glacial Lake demonstrates that short-term climatic extremes can rapidly destabilize glacial lakes that appear stable over long periods, challenging conventional approaches to GLOF hazard classification. The results show that elevated summer temperatures and intensified monsoon precipitation in 2024 coincided with a rapid increase in lake area and estimated volume. These conditions likely enhanced glacier melt and runoff, leading to accelerated lake filling and increased hydrostatic pressure on the moraine dam, ultimately contributing to failure.

A key contribution of this study is the identification of clear, satellite-detectable early-warning indicators preceding the outburst. The lake reached its maximum area and estimated volume approximately two weeks before the GLOF, followed by rapid drainage. This short lead time is critical from an operational perspective, as it demonstrates that freely available Sentinel-2 imagery combined with simple spectral water indices (NDWI and MNDWI) can reveal anomalous lake behavior prior to failure. Such signals are particularly valuable in remote Himalayan regions where in-situ monitoring infrastructure is limited or absent.

The Thyanbo event also highlights the limitations of static glacial lake hazard inventories, which often rely on long-term lake size or growth trends to define risk. Lakes classified as low risk may still experience rapid destabilization under short-term climatic forcing. This underscores the need for continuous, dynamic monitoring frameworks that integrate satellite-derived lake metrics with climatic information to support early-warning systems and timely decision-making.

Although uncertainties remain due to the use of empirical area–volume relationships and the lack of bathymetric data, the observed relative changes in lake area and volume provide robust insight into pre- and post-outburst dynamics. From a practical standpoint, this approach offers a scalable and cost-effective tool for national mapping agencies, survey departments, and disaster management authorities tasked with monitoring glacial lake hazards and improving preparedness in high-mountain environments. The results demonstrate how satellite-based lake monitoring can function as an operational early-warning component within broader GLOF risk management frameworks

5. CONCLUSION

This study demonstrates the effectiveness of satellite-based monitoring for identifying early-warning indicators of glacial lake instability. Analysis of Thyanbo Glacial Lake shows that rapid lake expansion driven by short-term climatic extremes preceded the 2024 GLOF by approximately two weeks, providing a detectable warning signal prior to failure. The findings highlight that glacial lakes previously considered low risk can undergo rapid destabilization when exposed to extreme climatic conditions.

Integrating multi-temporal satellite imagery, spectral water indices, and climatic data enables timely detection of hazardous lake behavior and strengthens early-warning systems in data-scarce mountain regions. Such geospatial approaches support disaster risk reduction, inform hazard preparedness, and enhance climate-resilient planning for vulnerable downstream communities. The study contributes directly to Sustainable Development Goal 13 (Climate Action) and underscores the critical role of geospatial intelligence in managing climate-induced hazards in the Himalayas.

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BIOGRAPHICAL NOTES

Bhuwan Singh Bisht holds a Bachelor's degree in Geomatics Engineering and is currently an Instructor at the Land Management Training Center (LMTC), Government of Nepal. He is also serving as the Vice President of the Nepal Geomatics Engineering Society (NGES). His professional and research interests include remote sensing, geographic information systems (GIS), GNSS and surveying, glacial lake outburst floods (GLOFs), satellite-based early-warning systems, and the application of geospatial technologies for disaster risk reduction and climate-resilient planning in Himalayan regions. He is actively involved in academic training, professional capacity building, and applied geospatial research in Nepal.

Bimal Joshi is a Diploma holder in Surveying from the Land Management Training Center (LMTC), Nepal, and is currently a student of Geomatics Engineering. His academic and professional interests include surveying, GIS, satellite image analysis, and the application of geospatial technologies for environmental monitoring and climate-related hazard assessment in mountainous regions.

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