# Integrating Multi-Source Remote Sensing and AHP-MCDA for GLOF Hazard Assessment of Major Glacial Lakes in Nepal

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**Keywords:** Glacial Lake Outburst Flood, Normalized Difference Water Index, Normalized Difference Snow Index, Analytic Hierarchy Process (AHP)

## SUMMARY

Potential risk assessment of Glacial Lake Outburst Flood (GLOF) plays an important role in flood risk management and aims to mitigate the hazards posed to the vulnerable communities. This research aims to evaluate the potential risk of GLOF hazards for the three largest glacial lakes in Nepal: Tsho Rolpa Lake, Imja Tsho Lake, and Thulagi Lake by integrating multi-source remote sensing datasets. The change in lake surface areas over time were delineated using Normalized Difference Water Index (NDWI) and Normalized Difference Snow Index (NDSI), along with digitization from high-resolution 3m PlanetScope imagery. The area of Tsho Rolpa Lake was calculated to be 1.648 km2 in 2022, with an error of 0.003 $km^2$ when validated with data from the Department of Hydrology and Meteorology, Nepal. The percentage of area change in Tsho Rolpa, Imja Tsho, and Thulagi lakes from 2016 to 2024, was observed to be 3.36%, 10.15%, and 5.221% respectively, over each 4-year interval. The lake surface velocity was determined through the offset tracking method using Sentinel-1 images, which resulted 0.816 m/day, 0.012 m/day and 0.345 m/day velocities for Tsho Rolpa, Imja Tsho and Thulagi respectively. These data, were combined with primary data such as precipitation, volume, slope and distance to the glacier, to perform AHP based MCDA in GIS, resulting in potential outburst risk values of 1.75 for Tsho Rolpa, 1.69 for Thulagi, and 1.43 for Imja Tsho.

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## 1. INTRODUCTION

Nepal is home to over 1,466 glacial lakes, many of which have expanded significantly in recent decades due to accelerated glacier melt, leading to heightened risks of GLOFs (Khadka et al., 2019). Research has been conducted to assess the risks of glacial lakes and those with the highest risks have been prioritized for further investigations (Peppa et al., 2020). For this study, the extent of risk in three of the largest glacial lakes in Nepal: Tsho Rolpa, Imja Tsho and Thulagi lake have been put into study. Tsho Rolpa, located in the Rolwaling Valley, is one of the largest glacial lakes in Nepal. Over recent decades, it has expanded significantly, raising concerns about its potential to cause a Glacial Lake Outburst Flood (GLOF) (Bajracharya et al., 2007). Similarly, Imja Tsho, situated near Mt. Everest in the Khumbu region, has also seen rapid growth in its area. Thulagi Lake, nestled in the Manang district, has also shown notable changes in size, which may pose risks to downstream communities. Nepal's topography and large glacial reservoirs make these lakes particularly vulnerable to outbursts, which can devastate downstream communities, infrastructure, and ecosystems (A. B. Shrestha & Aryal, 2011). To avoid or minimize loss of life and property, it is crucial to better understand glacial lake outbursts and their downstream impact (B. B. Shrestha & Nakagawa, 2014).

In recent decades, glacial lakes situated at the higher Himalaya region of Nepal are increasing rapidly, posing severe threats to communities downstream. This increased size of the glacial lakes has sparked concerns about the potential risk of Glacial Lake Outburst Floods (GLOFs). When these floods occur, they release large volumes of water and debris causing widespread destruction of human lives and property. Glacial lakes are dammed by unstable materials such as ice, debris and moraines, making them susceptible to failure from any internal or external triggering factors, such as melting of dead ice inside the dam, piping, avalanches, earthquakes, and heavy precipitation (Westoby et al., 2014). Therefore, monitoring the health and condition of these lakes is necessary for risk preparedness. Due to their remote locations and high altitude, monitoring these lakes is a very difficult task by traditional surveys (Mool, 1995). Remote sensing offers a useful tool for monitoring these lakes as most of the parameters related to glacial lakes can be studied using remote sensing (Bolch et al., 2008). We can observe changes in lake size, volume and the surrounding terrain over time using satellite images and geospatial analysis. Mapping of glaciers is an important part of the glacial lake hazard assessment as their position with respect to lakes, their slope and surface area play an important part in assessing glacial lake hazard (Aggarwal et al., 2016). The Normalized Difference Water Index, NDWI has been frequently employed in remote sensing studies to accurately delineate water bodies, including glacial lakes, as it enhances water features and reduces the influence of surrounding land cover (McFEETERS, 1996). The Normalized Difference Snow Index, NDSI another spectral index is used to distinguish snow from other land features, particularly in mountainous and snowy regions (Hall et al., 1995). While NDWI effectively identifies water bodies, it can misclassify snow and ice as water in glaciated regions. The use of NDSI alongside NDWI helps to reduce such misclassifications by clearly distinguishing between water and snow/ice, thus improving detection accuracy (Kulkarni et al., 2005).

The formula for calculating Normalized Difference Water Index, NDWI and Normalized Difference Snow Index, NDSI is given below:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \quad (1)$$

$$NDSI = \frac{(Green - SWIR)}{(Green + SWIR)} \quad (2)$$

As these lakes expand due to different causes like accelerated glacial melting, increased temperature and precipitation, increases the risk of sudden outburst since the natural dams that contain glacial lakes become increasingly unstable(Bajracharya et al., 2007) . Geographic information system (GIS) and Remote Sensing (RS) technology have been successfully used globally for the monitoring and assessment of glaciers, glacial lakes, and associated hazards (Rawat et al., 2023).Without systematic risk assessments, such as those facilitated by Multicriteria Decision Analysis (MCDA) combined with the Analytic Hierarchy Process (AHP), it is difficult to prioritize lakes for detailed investigations and mitigation efforts. AHP helps the decision-making process by assigning relative weights to factors such as lake volume, proximity to glaciers, and surrounding slope stability, enabling an evidence based and transparent evaluation of GLOF risks (Saaty, 2008). By using a combination of remote sensing data and GIS-based MCDA, we can identify lakes that are at high risk of bursting and assess the potential dangers they pose, enabling us to take action before disaster strikes.

The aim of the present study is to achieve the following objectives:

- To analyze the spatiotemporal changes in selected lakes from the year 2016 to 2024 AD.
- To generate key factors needed for GLOF assessment, including glacial lake velocity, lake expansion, slope and distance to glacier from satellite imagery.
- To assess the GLOF outburst risk of the lake using an AHP based multi-criteria decision-based method.

## 2. STUDY AREA AND DATA USED

### 2.1 Study Area

This study has selected three largest and potentially dangerous glacial lakes of Nepal, namingely Tsho Rolpa, Imja Tsho and Thulagi Lake. Tsho Rolpa Lake is located in the Rolwaling Valley of northeastern Nepal, within the Gaurishankar Conservation Area in the

Dolakha District between 27.845° to 27.875° N latitude and 86.462° to 86.493° E longitude and elevation of 4580 meters above the sea level. Similarly, Thulagi Lake, also known as Dona Lake, is a glacial lake located in the Manang District, within the Annapurna Conservation Area between 28.481° to 28.50° N latitude and 84.476° to 84.490° E longitude and elevation of 4050 meters above the sea level. Imja Tsho (also known as Imja Lake) is a glacial lake located in the Solukhumbu District of northeastern Nepal, within the Sagarmatha National Park, which is home to Mount Everest between 27.893° to 27.902° N latitude and 86.906° to 86.940° E longitude and elevation of 5010 meters above the sea level.

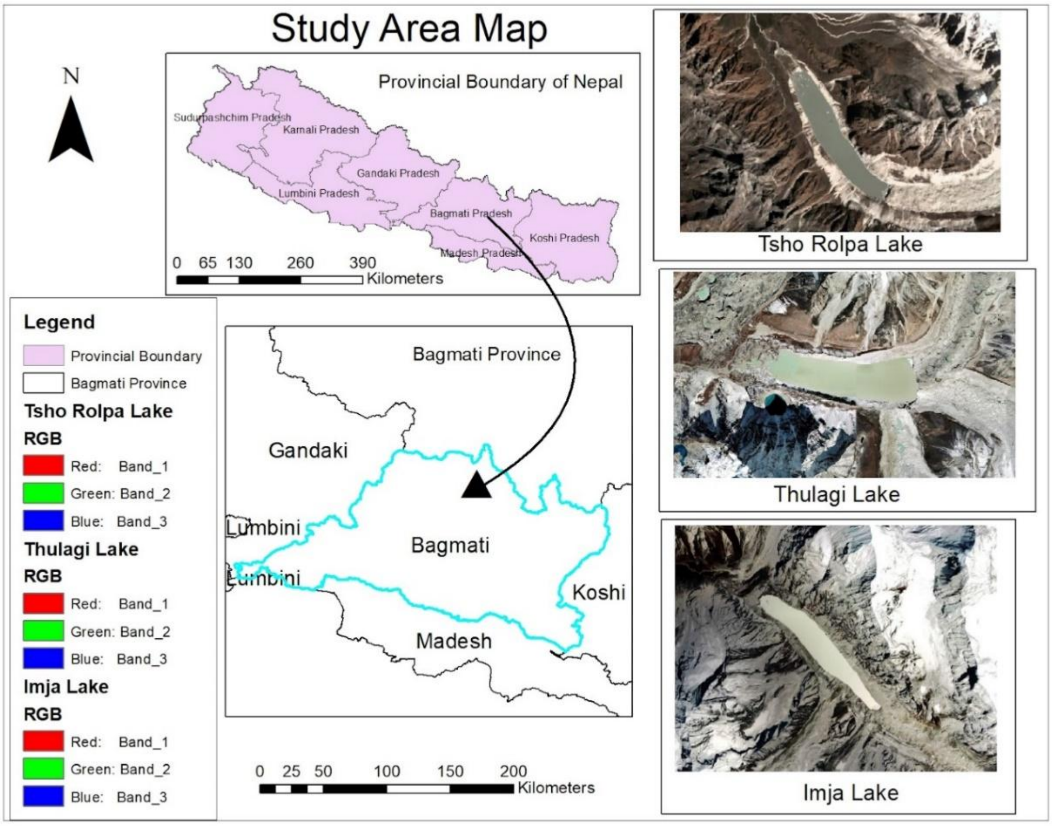



*Figure 1: Location map of selected lakes (Tsho Rolpa, Imja Tsho and Thulagi Lake) for GLOF outburst risk assessment)*

### 2.2 Data Used

Harmonized Sentinel-2 MSI images of spatial resolution 10m were used to calculate Normalized Difference Water Index (NDWI) and Normalized Difference Snow Index (NDSI) in the year 2016, 2020 and 2024. PlanetScope images of 3–4 m resolution with RGB bands: blue (455–515 nm), green (500–590 nm), and red (590–670 nm) were also assessed for the similar years (from Planet Labs: Satellite Imagery & Earth Data Analytics ) to assess temporal changes in the glacial lakes area from 2016 to 2024. Sentinel SAR images for the 2023 and 2024 were assessed for velocity determination.

| Datasets | Source | Resolution/Scale | Date |
|---|---|---|---|
| Harmonized Sentinel-2 | Copernicus Open Access Hub | 10 meters | 2016-2024 |
| PlanetScope images | Planet Labs | 3 meters | 2016-2024 |
| Precipitation Events | Department of Hydrology and Meteorology | | 2016-2024 |
| Digital Elevation Model (DEM) | Satellite Radar Topography Mission (SRTM) | 30 meters | 2024 |
| Synthetic Aperture Radar (SAR) images | Sentinel 1C | 30 meters | 2023 & 2024 |
| High Resolution Imagery | Google Earth | Varying Resolution | Different Dates |

*Table 1: Summary of datasets used for the study*

## 3. METHODOLOGY

This methodology employs a multi-source remote sensing and GIS-based Multi-Criteria Decision Analysis (MCDA) framework to assess potential Glacial Lake Outburst Flood (GLOF) hazards. The methodology comprises three distinct phases: Data Collection, Data Processing and Analysis, and MCDA based Risk Assessment. The methodology used for this study can be illustrated in the figure below.

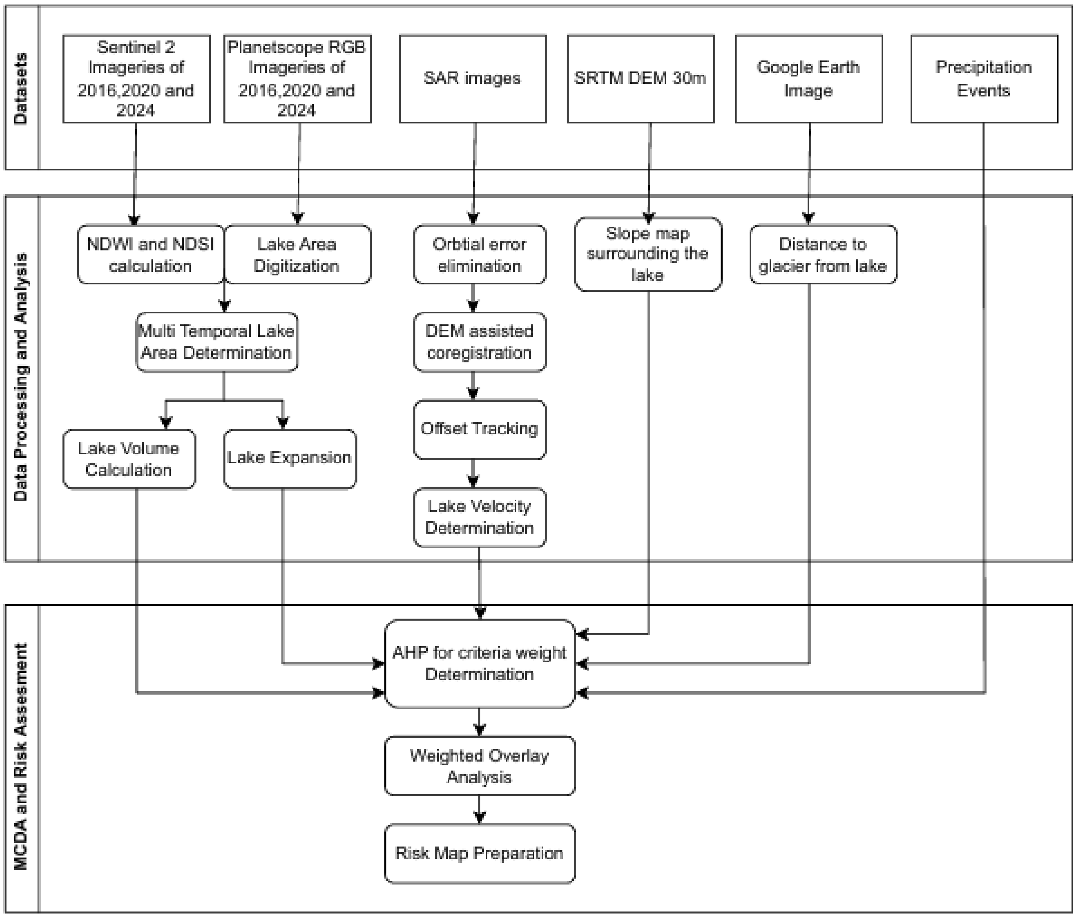



*Figure 2: Methodology flow chart depicting the steps followed for the GLOF risk assessment*

We synergized six different datasets: Sentinel 2 images, Planet imageries, Synthetic Aperture Radar (SAR) images, Digital Elevation Model (DEM), google earth image and precipitation data from the hydrological department to assess multi-temporal glacial lake dynamic using remote sensing techniques. These datasets were also used for preparing criteria for multicriteria decision analysis of potential risk assessment of the lakes.

## 3.1 Data Processing and Analysis

### 3.1.1 Lake Area Expansion and Volume Calculation

Normalized Difference Water Index (NDWI), the spectral index used to identify water bodies along with Normalized Difference Snow Index (NDSI) were calculated and map was prepared using harmonized sentinel 2 image at the study area for the year 2016, 2020 and 2024. Since the water at glacial lake are at frozen state for large period of the year, NDSI is also used to identify these lakes when at frozen state. The calculated NDWI and NDSI were digitized in GIS environment to delineate the lake area. High resolution planet scope imageries were also digitized to delineate the lake area for improved accuracy. The average area from these three digitization was used for further analysis.

Lake area expansion rate for each of three lake was calculated using area calculated from the digitization. The volume of lake was only calculated for the year 2024 using empirical relationship between glacial lake volume and its area as available in the study by (Huggel C, et al. 2002),

$$V = 0.104*A^{1.42} \qquad (3)$$

Where V represents the lake volume ($10^6$ $m^3$) and A represents the lake area ($km^2$).

3.1.2 Lake Velocity Determination

SAR images for the year 2023 and 2024 were used to determine the present glacial lake deformation velocity using esaSNAP software. The images were applied orbital correction to ensure precise alignment of pair of radar images. Then images undergo DEM assisted registration process to correct for topographic distortions in SAR images. Finally, offset tracking method is used to determine glacial lake velocity. Offset tracking involves measuring the displacement of features between two different SAR images. This is crucial for determining the velocity of surface movements. By accurately tracking these offsets, one can compute the rate of movement over time (Zou et al., 2009).

3.1.3 Slope map and Distance Analysis

Slope map surrounding the lake was prepared using Satellite Radar Topography Mission (SRTM) DEM to better understand the geomorphological context of the glacial lake. This was done using Surface slope spatial analysis in GIS environment. The distance from lake to its mother glacier, which is prominent criteria for the outburst risk assessment was also determined using google earth imageries.

### 3.2 MCDA and Risk Assessment

In order to assess the GLOF susceptibility, different parameters have been employed in the past studies pertaining to various parts of the Himalayan region(Aggarwal et al., 2016);(Che et al., 2014). However, there is no universal set of parameters to be used to determine glacial lake outbrust risk. The parameters for this study were identified and compiled through detailed literature review. The ranking and determination of class for criteria was also done in similar way. The selected factors with their class division, data source and reference is provided in the table below.

| Factors | Class | Rank | Data Source | Reference |
|---|---|---|---|---|
| Lake Area ($km^2$) | >0.5<br>0.5 - 0.1<br><0.1 | High<br>Medium<br>Low | Sentinel 2, Planetscope Imagery | (Aggarwal et al., 2016); (Washakh et al., 2019) |
| Lake Expansion (%) | >25%<br>10% - 25%<br><10 % | High<br>Medium<br>Low | Mutitemporal Satellite Data | (Bolch et al., 2008);(Che et al., 2014) |
| Distance between lake and glacier (m) | At snout<br>0-250<br>250-500 | High<br>Medium<br>Low | Google earth Imagery | (Che et al., 2014); (ICIMOD, 2011) |
| Lake volume ( $10^6$ $m^3$) | >$10^7$ $m^3$<br>$10^6$ $m^3$-$10^7$ $m^3$<br><$10^7$ $m^3$ | High<br>Medium<br>Low | Empirical Area Volume equation<br>$V = 0.104*A^{1.42}$ | (Huggel et al., 2002) |
| Lake Velocity (m/day) | >1m<br>0.5-1m<br><0.5m | High<br>Medium<br>Low | Sentinel 1 | (Ashraf et al., 2021) |
| Slope steepness Surrounding the lake | >30˚<br>15˚-30˚<br><15˚ | High<br>Medium<br>Low | SRTM DEM | (ICIMOD, 2011) |
| Precipitation events (monthly) | >100<br>50-100<br><50 | High<br>Medium<br>Low | Department of Hydrology and Meterology, Nepal (2024) | |

*Table 2: Factors selected for Risk assessment with their assigned classes*

Risk assessment of glacial lake is inherently a multi criteria decision making problem, since it involves evaluating multiple geospatial and environmental factors that influence outburst potential of the lake. These include lake area, expansion rate, proximity to the glacier, volume, surface velocity, slope of the surrounding terrain, and intensity of precipitation events. The Analytic Hierarchy Process (AHP), a widely used technique in MCDA, is suitable in this context as it facilitates pairwise comparison of multiple criteria, helps in reducing inconsistencies, and assigns priorities through pairwise comparison(Mandal et al., 2020). Therefore, the weightage criteria was determined using Analytic Hierarchy Process (AHP). This involves pairwise comparing of criteria to assess their relative importance in decision making. The final weightage of the criteria based on pairwise AHP comparison is tabulated in table 3.

| Criterion | Lake Area | Lake Expansion | Distance to Glacier | Lake Volume | Lake Velocity | Slope Surrounding Lake | Precipitation | Final Weightage |
|---|---|---|---|---|---|---|---|---|
| **Lake Area** | 1 | 3 | 3 | 5 | 5 | 5 | 7 | 0.335 |
| **Lake Expansion** | 1/3 | 1 | 2 | 5 | 5 | 5 | 7 | 0.219 |
| **Distance to Glacier** | 1/3 | 1/2 | 1 | 5 | 5 | 5 | 7 | 0.174 |
| **Lake Volume** | 1/5 | 1/5 | 1/5 | 1 | 1/3 | 3 | 5 | 0.080 |
| **Lake Velocity** | 1/5 | 1/5 | 1/5 | 3 | 1 | 3 | 3 | 0.096 |
| **Slope Surrounding Lake** | 1/5 | 1/5 | 1/5 | 1/3 | 1/3 | 1 | 3 | 0.070 |
| **Precipitation** | 1/7 | 1/7 | 1/7 | 1/5 | 1/3 | 1/3 | 1 | 0.026 |

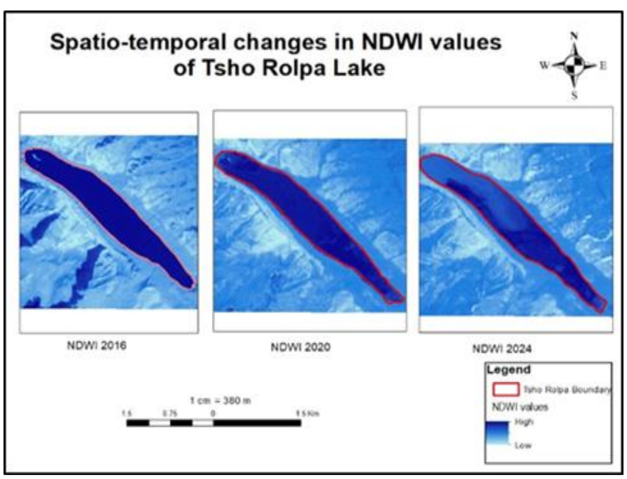
*Table 3: Weightage of the criteria determined using pairwise AHP comparison*

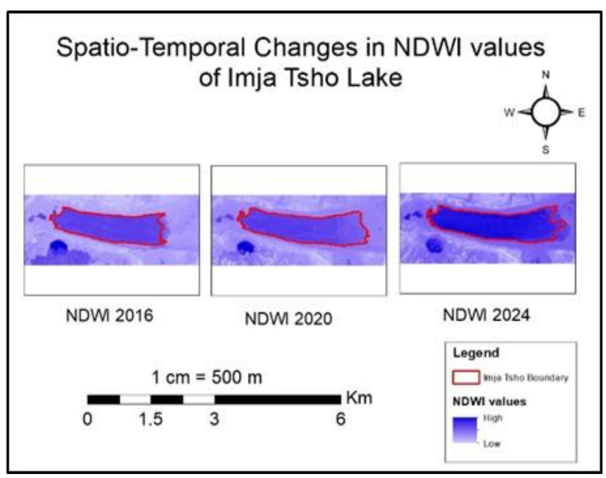
Based on these derived weightage of each criteria, weighted overlay analysis was performed in GIS environment to prepare the risk map for each of the lakes.

## 4. RESULT AND DISCUSSION

### 4.1 Glacial lake area change

Two of spectral indices to detect water and snow, Normalized Difference Water Index (NDWI) and Normalized Difference Snow Index (NDSI) were calculated to prepare following maps for the year 2016, 2020 and 2024. Similarly, high resolution 3m planetscope satellite imagery were also digitized to calculate the area of glacial lake boundary area for the same time period.



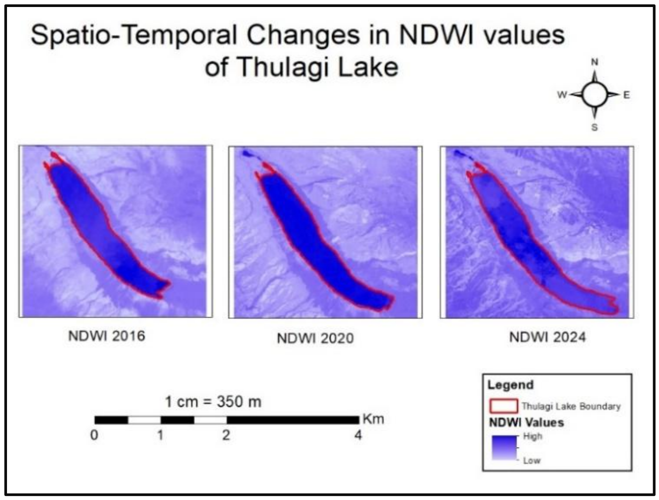



*Figure 3: NDWI map showing glacial lake area in the year 2016, 2020 and 2024*

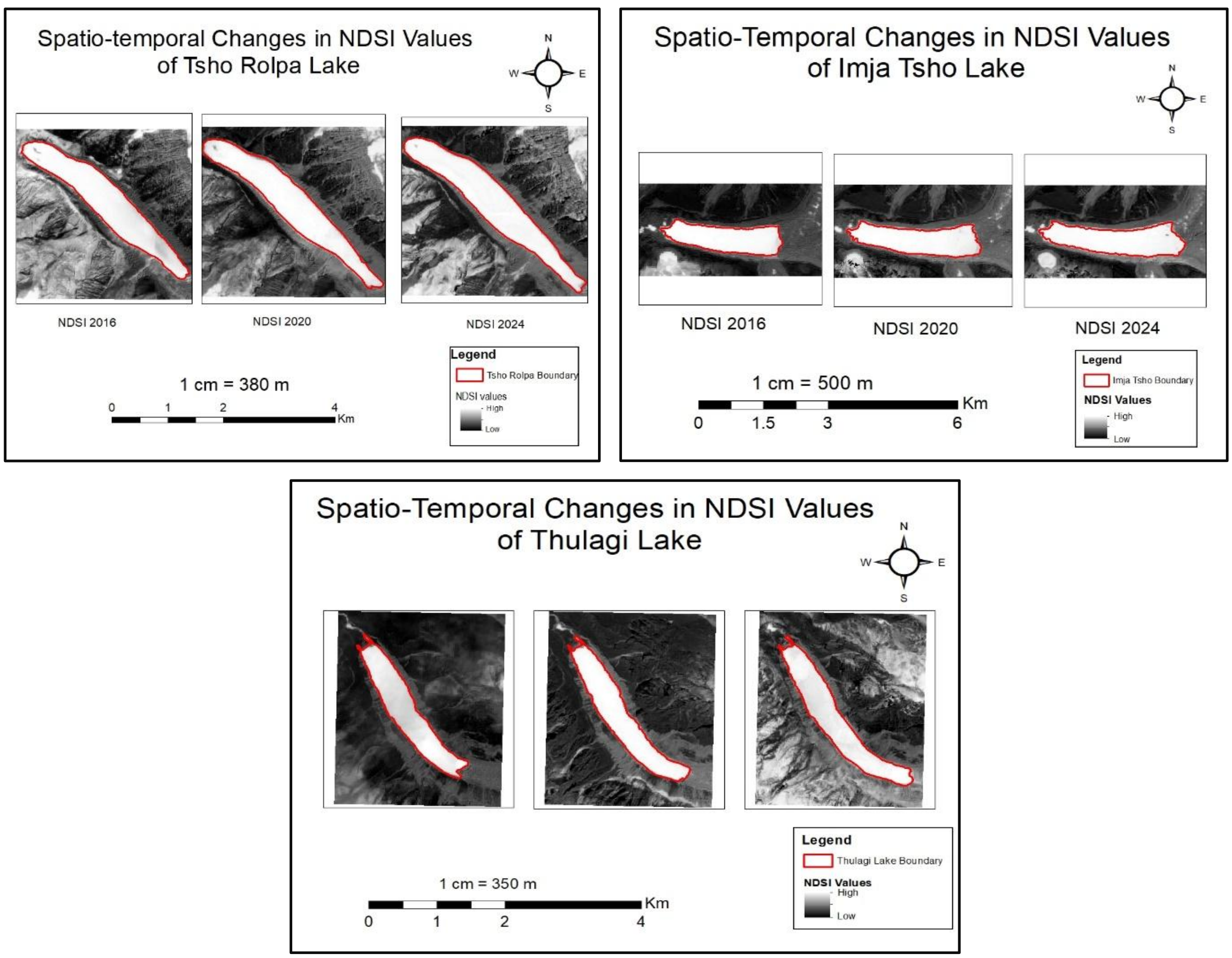



*Figure 4: NDSI map showing glacial lake area in the year 2016, 2020 and 2024*

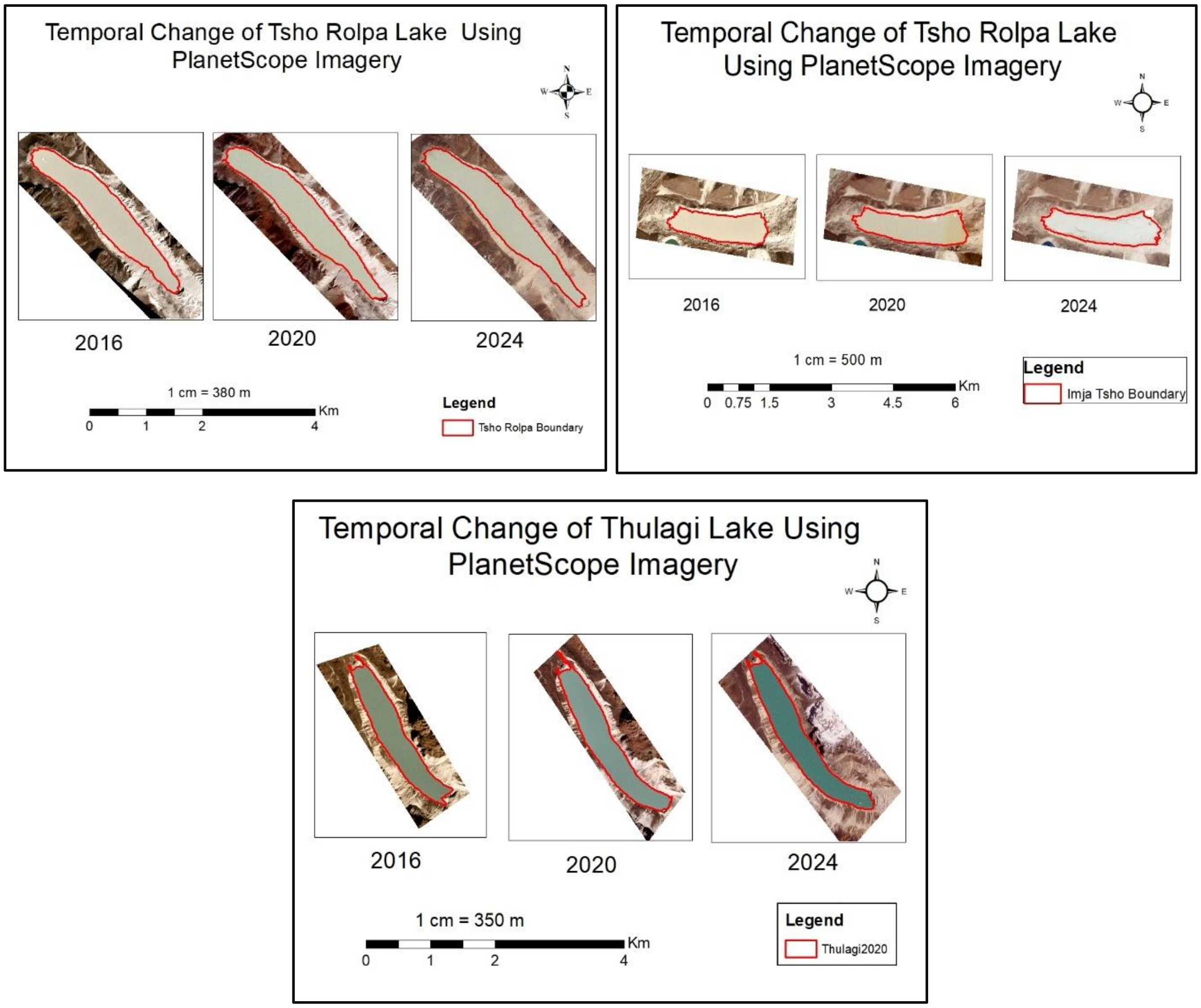



*Figure 5: Map showing glacial lake area in the year 2016, 2020 and 2024 using digitized planetscope imagery*

The dark red color in the above maps suggest the lake area and it has been increasing from 2016 to 2024. Furthermore the area of Lake Boundary from NDSI, NDWI and digitization from planet image has been calculated and summarized in the table below for Tsho Rolpa, Imja Tsho and Thulagi Lake respectively.

| Year | Area ($km^2$)From NDWI | Area ($km^2$)From NDSI | Area ($km^2$)From planet | Percentage Change |
|---|---|---|---|---|
| 2016 | 1.5229 | 1.5147 | 1.598 | |
| 2020 | 1.5676 | 1.5679 | 1.632 | 2.84 |
| 2024 | 1.664 | 1.6593 | 1.655 | 4.46 |

| Year | Area (km²)From NDWI | Area (km²)From NDSI | Area ($km^2$) From Planet | average |
|---|---|---|---|---|
| 2016 | 1.32 | 1.3014 | 1.361 | 1.327 |
| 2020 | 1.544 | 1.472 | 1.561 | 1.526 |
| 2024 | 1.6 | 1.589 | 1.633 | 1.607 |

| Year | Area (km²)From NDWI | Area (km²)From NDSI | Area (km2) From Planet | average |
|---|---|---|---|---|
| 2016 | 0.924 | 0.904 | 0.888 | 0.905 |
| 2020 | 0.96 | 0.934 | 0.968 | 0.954 |
| 2024 | 1.015 | 0.993 | 0.999 | 1.002 |

*Table 4: Tables showing area of Tsh oRolpa, Imja Tsho and Thulagi Lake respectively derived from different Indices*

### 4.2 Validation and Limitation

While this study provides a comprehensive GLOF risk assessment using multi-source remote sensing and AHP-MCDA, several limitations must be acknowledged. Among the three glacial lakes studied—Tsho Rolpa, Imja Tsho, and Thulagi, only Tsho Rolpa had recent field-based area measurements available from the Department of Hydrology and Meteorology (DHM) for the year 2022. When compared with the average of NDWI, NDSI, and PlanetScope-based delineation for Tsho Rolpa in 2022, the observed error margin was only 0.003 km², which supports the accuracy of our remote sensing approach for this lake. Field measurements for Imja Tsho and Thulagi Lake were not available from DHM, and primary data collection could not be conducted due to logistical and financial constraints. To assess the internal consistency among the lake area estimates derived from NDWI, NDSI, and PlanetScope imagery, the Root Mean Square Error (RMSE) was calculated using the mean of the three values as a reference. As shown in Table 5, the RMSE values generally decreased over time, likely due to enhanced data quality and clearer seasonal observations. Future work should aim to incorporate field campaigns and finer-scale temporal datasets to enhance the robustness and validation of glacial lake hazard assessments.

| Lake | **2016** | **2020** | **2024** |
|---|---|---|---|
| Tsho Rolpa | 0.0442 | 0.0368 | 0.0046 |
| Imja Tsho | 0.0249 | 0.0386 | 0.0182 |
| Thulagi | 0.0158 | 0.0141 | 0.0094 |

*Table 5: Root Mean Square Error (RMSE in km²) of lake area from NDWI, NDSI, and PlanetScope imagery*

A Glacial Lake Outburst Flood (GLOF) risk map was prepared using criteria and weights derived from Tables 2 and 3. The risk values were reclassified into three categories during the weighted overlay analysis: high risk (2), medium risk (1), and low risk (0). The analysis resulted in potential outburst risk values of 1.75 for Tsho Rolpa, 1.69 for Thulagi Lake, and 1.43 for Imja Tsho. These values were subsequently normalized to percentile risk to allow for better comparative analysis, as shown below:

| Lake Name | Risk Value | Normalized Risk |
| --- | --- | --- |
| Tsho Rolpa | 1.75 | 0.875 |
| Thulagi | 1.69 | 0.845 |
| Imja Tsho | 1.43 | 0.715 |

The normalized risk values for Tsho Rolpa (0.875), Thulagi (0.845), and Imja Tsho (0.715) are relatively close to 1, suggesting that all three lakes exhibit notable susceptibility to potential outburst events. These results indicate that while the lakes vary in relative risk, they collectively warrant continued observation and further validation through field-based studies. However, the present assessment relies solely on remotely sensed inputs and expert-derived AHP weightings; therefore, field verification of lake conditions, moraine stability, and hydrodynamic behavior remains a key limitation. This emphasizes the importance of integrating long-term monitoring with remote sensing approaches for improved hazard assessment. Future work should incorporate bathymetric surveys, moraine stability assessments, and hydrodynamic modelling to enhance the accuracy of GLOF hazard estimates and support evidence-based risk management for downstream communities.

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