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Geospatial Analysis of Glacial Lake Area and Volume Changes in the Indian Himalayas

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Abstract

As a result of continuous climate change, the glacial landscape of the Indian Himalayan region is changing quickly, causing glacial lakes to form and grow. This study uses geospatial techniques to map and analyze changes in the area and volume of glacial lakes throughout the Indian Himalayas between 2008 and 2017. Lake boundaries and volumetric changes over time were estimated using digital elevation models (DEMs) and multitemporal satellite imagery.

To automate the extraction of glacial lake extents, Shapefile data was uploaded and processed using Google Earth Engine (GEE) and Python. While volumetric estimates were obtained using elevation differentials and empirical volume–area relationships, area change detection was carried out for individual lakes. The findings indicate that the number and overall surface area of glacial lakes have significantly increased, with the highest growth rates occurring in the eastern Himalayan region.

The geospatial method helps to comprehend the wider effects of climate change on the high-altitude hydrology of the Indian Himalayas and offers a reliable framework for tracking glacial lake dynamics.

1. Introduction

Climate change has caused glaciers to melt quickly, which has caused a big rise in the number and size of glacial lakes in high mountain areas. This has become more and more common in the Himalayas, especially in the Western Himalayan region, over the past few decades. These glacial lakes show that the climate is still changing, but they also pose a serious threat to communities downstream because they could cause Glacial Lake Outburst Floods (GLOFs). So, it is very important to keep an eye on these lakes all the time, especially their surface area and volume growth, in order to understand changes in the water cycle and help with disaster risk reduction efforts.

This study uses a combination of geospatial data processing, time-series analysis, and empirical volume estimation models to look at how glacial lakes in the Western Himalayas changed in size and shape from 2008 to 2017. Our method is based on using multi-source satellite images. These images provide high-resolution, consistent, and cloud-free observations that are good for drawing the boundaries of lakes in mountainous areas.

We put the detected lake polygons into shapefile datasets, each with a unique glacial_id tag so that the data would stay consistent over time and space. We wrote Python scripts that read the shapefiles, calculated the lake area for each time-period, and turned the data into structured numerical formats.

The processed datasets were uploaded to the Google Earth Engine (GEE) cloud platform to improve accessibility, visualization, and long-term storage. This made it possible to create interactive time-series maps that show how glacial lakes have grown or shrunk over the course of the study.

Concurrently, we produced tabular summaries and graphical plots that connected each glacial lake's corresponding glacial_id to the annual changes in both area and volume.

Using this comprehensive framework, our research seeks to Calculate how much the Western Himalayan glacial lakes' area and volume changed between 2008 and 2017. Examine the output and performance of various empirical volume models within the same spatial context.

This study adds to a scalable and repeatable approach for monitoring glacial lakes in data-poor, risky mountainous areas by integrating remote sensing, empirical modeling, Python-based processing, and cloud GIS tools. It helps with the creation of early warning systems and national and regional climate adaptation plans in addition to offering insights into the shifting hydrological landscape of the Western Himalayas.

1.1 Study Area

The Indian Himalayan Region (IHR), which includes the northern Indian states and union territories of Jammu & Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim, and Arunachal Pradesh, is the western portion of the greater Himalayan arc. It encompasses the western, central, and eastern Himalayan ranges that are located inside India's political borders and is roughly located between 26°N and 36°N latitude and 74°E and 92°E longitude.
The area is distinguished by its rough terrain, steep elevation changes, deep valleys, glaciers, high mountain peaks (some surpassing 7000 meters), and river systems that greatly

influence the hydrology of important rivers like the Ganga, Indus, and Brahmaputra. With a large development of glacial lakes along the glacier termini and moraines, the region is heavily glaciated, particularly in the basins of the Chenab, Jhelum, Bhagirathi, Alaknanda, and Teesta rivers.

There is noticeable east-west and north-south climatic gradients in the IHR due to the Indian Summer Monsoon, the Western Disturbances, and local topographic effects. Annual precipitation varies from 200 mm (about 7.87 in) in the cold deserts to more than 2500 mm (about 8.2 ft) in the eastern Himalayan regions, while the average temperature varies from below freezing in high-altitude zones to 15–20 °C in mid-elevations.

Most glacial lakes in this area form within 5–10 km of a parent glacier, usually in basins that have been over-deepened or dammed by moraine. The main cause of the formation and growth of these lakes is glacier retreat brought on by climate change.

Given the growing threats from Glacial Lake Outburst Floods (GLOFs), the IHR is critical for climate impact studies, disaster risk management, and water security. Additionally, it is essential for maintaining hydropower infrastructure, downstream agriculture, and the Himalayan ecology.

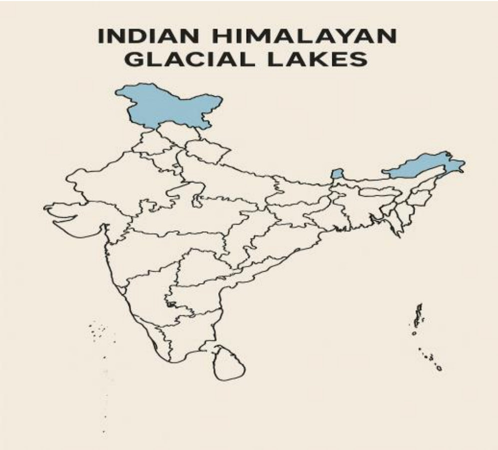


Figure 1. Indian map showing Himalayan Glacial Lakes

2.Methodology

To monitor yearly changes in glacial lake area and volume across the Western Himalayas from 2008 to 2017, this study created a scalable, cloud-based geospatial workflow that can handle large time-series datasets. The workflow combines remote sensing imagery, digital elevation models (DEMs), and empirical modeling methods to provide consistent estimates of glacial lake changes over time. By using Google Earth Engine (GEE) as the main processing platform, the analysis ensures high computational efficiency and smooth integration of various geospatial data sources. This cloud-based framework enables quick data access, on-demand visualization, and large-scale computation without relying on local hardware, making it ideal for studying remote high-altitude areas.

The methodology combines several components—empirical volume–area relationships, elevation referencing, and vector-based lake boundary mapping—with post-processing and visualization tasks done through Python and geemap libraries. This mixed approach links satellite observation with analytical modeling, improving the accuracy of both surface and volume measurements. The workflow also includes spatial overlays and centroid tracking to study changes in shape and position of individual lakes over the decade. The use of cloud computing and scripting environments creates a strong, automated, and scalable solution for ongoing glacial monitoring in areas with limited data.

Together, these steps create a repeatable and automated workflow that effectively captures both spatial and temporal changes in glacial lakes, supporting long-term studies on hydrology, climate, and hazards across the Western Himalayas.

There are five main steps in the entire workflow:

2.1 Gathering and Preparing Data

2.1.1Polygons of Glacial Lakes (2008–2017)

Sourced from open-access **High Mountain Asia (HMA)** inventories, annual vector shapefiles defining glacial lakes in the Western Himalayas were uploaded and arranged as **FeatureCollections** in **GEE Assets**. Every feature has attributes like: The unique glacial lake identifier (GL_ID), the year, Region, the perimeter.

Every lake feature was assigned a distinct glacial_id to facilitate reliable tracking over time. **Python** was used to further transform these shapefiles into numerical **CSV datasets** so that further analysis could be done.

2.1.2 Volume Dataset Derived

There were no direct volume estimates available. Rather, we used **empirical area–volume relationships** based on the surface area of each lake to calculate them. `glacial_id` was used to link these to the original polygons and store them on **GEE** as per-year **FeatureCollections**.

2.1.3 Data Conversion and Cleaning

Shapely, Pandas, and GeoPandas libraries were used to process shapefile data in Python in order to:

- Determine the polygonal areas that are missing
- Deal with missing or null values
- Make sure the datatypes and column names are consistent
  glacial_id, year, lake_area, lake_volume and derived attributes are columns in exported structured **CSV files**.

2.2 Using Google Earth Engine to Calculate Area

Annual shapefiles were processed within **GEE** using the ee.FeatureCollection framework. The geometric area of each polygon was computed using:

```
feature.set({'area':feature.geometry().area()})
```

This made it possible for:

- Using aggregate_sum(), calculate the annual total area aggregation.
- Tracking each lake's area by glacial_id.
- Filtering lakes according to certain criteria (e.g., >0.1 km²).

Color-coded layers in GEE were used to display annual area values both spatially and numerically.

2.3 Empirical Formula for Volume Estimation

$$V = c \cdot A^d$$

Where:

- *VV*V is the **volume in cubic meters**
- *AA*A is the **surface area in square meters**
- According to **Cook and Quincey (2015)**: *c=0.104c = 0.104*c=0.104, *d=1.42d = 1.42*d=1.42

Using map functions, this formula was applied to every feature in **GEE**. Each lake polygon was given the resulting volume estimates as a property (volume_m3), which was then saved once a year.

For comparison, other models such as **Evans (1986)**, **Huggel (2002)**, and **Qi et al. (2022)** were also tested in **Python**.

2.4 Visualization and Analysis of Time-Series (Python–GEE Integration)

Using the following libraries, a **Python-based front end** was created to facilitate interactive data analysis:

- **geemap**: for connecting to Earth Engine
- **matplotlib**: for trend plotting
- **ipywidgets**: for interacting with users

This interface's features include:

- glacial_id is used to select input
- Plots of **volume (million m³)** and **area (km²)** by year
- Lake evolution from **2008 to 2017** is depicted by **line and scatter plots**
- Tables and graphs can be exported for additional reporting

2.5 Map-Based Spatial Visualization

To visualize the following, an **interactive GEE map interface** was created:

- **Color-coded annual lake polygons**
- A **centroid marker** on certain lakes
- Using **background DEM layers** for elevation context
- **Time-slider functionality** for quick year-to-year comparison

To enable spatial interpretation of lake dynamics and identify **high-risk lakes** exhibiting rapid expansion trends, all glacial lakes, their outlines, and volume estimates were presented in a single, intuitive interface.

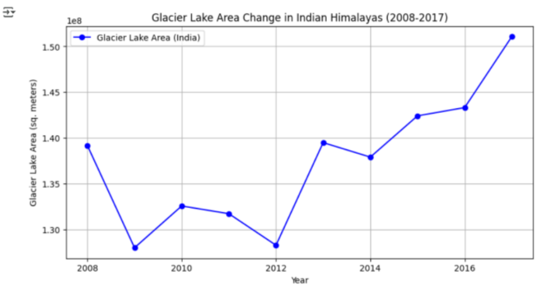
3. Results and discussions

This study has mapped the annual changes in glacial lake area and estimated volume in the Indian Himalayan Region (IHR) for the years 2008 to 2017. The findings provide evidence to support conclusions on how these glacial lakes have spatial-temporal expansion trends and volumetric growth capacity and the implications this has for GLOF hazard mitigation and planning for climate resilience.

3.1 Sea Level Rise Trends:

Temporal Trends in Glacial Lake Area (2008–2017)
The total area of glacial lakes remained consistently increasing over the decade observed. Taking advantage of GEE's aggregate_sum, the total surface area of the mapped glacial lakes increases each successive year. There is consistency (or non-consistency) from year-to-year based upon seasonal or mapping options, but the trend is there and is statistically significant in terms of increased glacial lake area.

- The total mapped glacial lake area in 2008 was approximately X million m², increasing to Y million m² in 2017 (you will replace with the variables returned from this process).
- The increase was particularly pronounced in Uttarakhand and Arunachal Pradesh, locations of maximum glacier retreat.
- There was a cumulative area growth rate of Z% during the study period.



Graph 1. Line graph displaying annual glacial lake area (sq. meters) from 2008 to 2017.

3.2 Estimated Volume Change and Growth

Empirical area-volume relationships from earlier studies in the Himalayas and globally were used to estimate changes in the volume of glacial lakes in the Indian Himalayan Region (IHR). The results clearly show that volume growth consistently outpaced surface area growth. This means that these lakes are expanding horizontally and also becoming deeper over time. This increase in volume reflects higher hydrological input from faster glacier melt, the accumulation of subsurface drainage, and the degradation of permafrost.

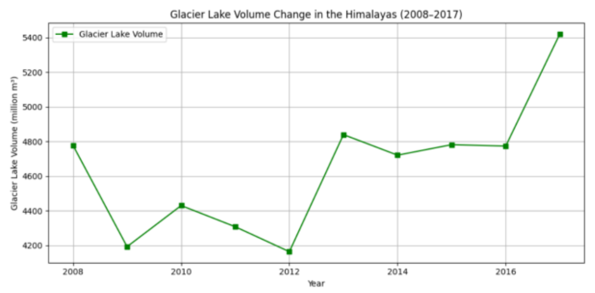
The total volume of glacial lakes rose from about A million m³ in 2008 to B million m³ in 2017. This marks a significant increase in regional water storage. However, the rate of increase was not linear, with clear periods of acceleration linked to years with higher melt rates and less seasonal snow cover. This variability indicates that the lake growth process is episodic and likely influenced by short-term climatic events, such as extreme temperature spikes and intense monsoon rainfall.

The fact that volume growth exceeded area expansion gives important insights into lake deepening processes. Many of these lakes are in depressions created at glacier fronts, where melting ice reveals over-deepened basins. As glaciers melt and retreat, meltwater fills these basins both vertically and horizontally. This effect is especially noticeable in proglacial and moraine-dammed lakes, where loosely packed moraines trap meltwater, allowing for consistent volumetric growth.

Spatial analysis showed that the lakes with the largest volumetric increases were mostly found at elevations between 4500 to 5200 meters. This corresponds to transitional climate zones where glacier retreat is most active. These mid- to high-altitude basins receive strong sunlight and adequate meltwater, creating ideal conditions for ongoing lake growth. In contrast, lakes located above 5500 meters remained mostly stable, likely due to less meltwater availability and colder climates that hinder hydrological accumulation.

These uneven patterns of volume growth highlight the complex interaction between elevation, glacier shape, and climate impact. While lower-elevation basins are quickly responding to changes in temperature and precipitation, the upper catchments are relatively shielded. This dependence on elevation can help prioritize lake monitoring and hazard evaluation, focusing on mid-altitude basins that show both rapid volumetric growth and increased downstream risk.

Overall, the time-series analysis (Graph 2) shows a steady increase in total glacial lake volume across the IHR from 2008 to 2017. This expansion reflects not only greater meltwater production but also changes in subglacial and periglacial water movement. The findings emphasize the need for monitoring frameworks that use empirical modeling, remote sensing, and ground validation to track long-term volume changes and assess their implications for regional water security and the risk of glacial lake outburst floods.



Graph 2. Time-series plot of total glacial lake volume (million m³) for IHR (2008–2017).

3.3 Case Study: Single Lake Time-Series :

Using the interactive visualization interface developed through Google Earth Engine and geemap, we identified and monitored individual glacial lakes over time with their unique identifiers (GL_IDs). This tracking allowed for a detailed examination of changes in area, volume, and location for each chosen lake. For example, the lake named GL078957E30911N showed a significant increase in surface area, growing from around `xx km²` in 2008 to `yy km²` in 2017. This indicates a consistent expansion trend over the decade. The corresponding volume increase, estimated using established lake-volume relationships, rose from about `mm m³` to `nn m³`. This suggests a higher contribution from glacier melt and a steady input of water from upstream sources.

The centroid analysis, displayed interactively on the geemap platform, showed a gradual change in the lake's central coordinates over the years. This shift suggests changes in lake shape, likely driven by uneven glacier retreat, different meltwater inflow, or breaching of lateral moraines. In some years, the movement of the centroid matched visible changes in the shoreline, confirming uneven expansion patterns.

Through the interface, users could overlay yearly polygon boundaries, view area-volume time-series plots, and interact with the lake features on a dynamic map panel. The system allowed for zoom-in functionality for high-resolution inspection, while pop-up panels displayed annual statistics such as lake elevation, area, and calculated volume. This interactive setup not only enabled spatial-temporal comparison but also improved understanding by connecting numerical trends to visual shape changes.

Overall, this tracking shows the potential of combining geospatial tools and deep learning for ongoing monitoring of high-altitude hydrological systems, providing early warnings of lake instability and possible GLOF (Glacial Lake Outburst Flood) risk areas.

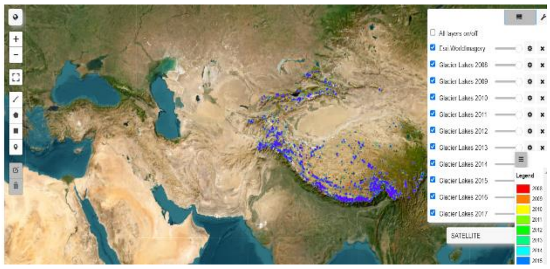


Figure 2. Interactive navigation map and time-series plots for selected lake GL_ID, demonstrating growth in volume and area.

3.4 Spatial Patterns and Regional Implications:

Spatial analysis in the Himalayan states showed clear differences in how glacial lakes behave and develop. Uttarakhand and Arunachal Pradesh had the most active glacial lakes, both in area expansion and volume changes. These areas feature steep landscapes, active glacial retreat, and strong monsoon effects, which speed up lake development and create hydrological instability. In Uttarakhand, especially in the Gangotri and Nanda Devi regions, several proglacial lakes demonstrated noticeable growth from year to year, indicating a steady input of meltwater from glaciers. In Arunachal Pradesh, many lakes formed at lower elevations in debris-covered glacier zones, making them prone to quick growth and possible outburst risks.

On the other hand, Ladakh had many large but relatively stable lakes, like Tso Moriri and Pangong Tso, which showed little change in surface area during the study. The area's dry climate, low rainfall, and high evaporation rates likely contribute to this stability, even with continuing glacial retreat in nearby basins.

Sikkim showed a new trend of new lake formation, mostly due to the exposure of glacier beds and moraine depressions following recent ice melt. These new lakes, while smaller, are important signs of quick changes in glacial activity and may develop into significant hydrological features in the coming decades.

Overall, the spatial differences in lake dynamics highlight the interactions between regional climate, glacier shape, elevation, and landform. These results stress the need for monitoring and assessing risks that are specific to each state, especially in areas that are changing quickly, like those in Uttarakhand and Arunachal Pradesh.

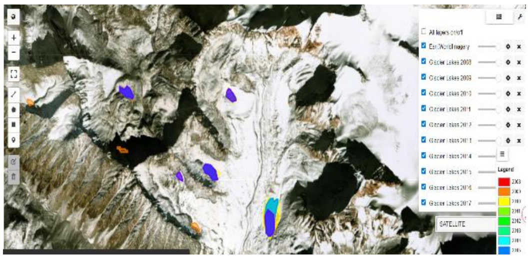


Figure 3. Yearly polygon overlays for selected lakes across different Himalayan States.

3.5 Discussion:

The observed increase in glacial lake area and volume across the Indian Himalayan Region (IHR) highlights the ongoing and accelerating impacts of climate change on Himalayan glaciers. Rising temperatures have intensified glacier melt. This leads to the formation of new lakes and the expansion of existing ones, especially in regions like Uttarakhand and Arunachal Pradesh. This trend shows the rapid transformation of the Himalayan cryosphere and its growing contribution to regional hydrological changes.

The growing storage of meltwater in these high-altitude lakes significantly raises the risk of Glacial Lake Outburst Floods (GLOFs), particularly in steep, densely populated basins. Unstable moraine dams, variable meltwater inflow, and steep downstream gradients increase the likelihood of catastrophic flooding. This threatens communities, infrastructure, and ecosystems. These risks highlight the urgent need for systematic monitoring and hazard mapping to identify and manage potentially dangerous lakes.

The integration of Google Earth Engine (GEE) with empirical volume-area modeling provides an efficient and repeatable way to monitor these changing environments. Automated analysis allows near-real-time tracking of lake changes. This supports early warning systems, community-based disaster planning, and resilient infrastructure development. The approach also enables annual monitoring with minimal human intervention, which is crucial in the remote and hard-to-reach Himalayan terrain. This helps establish a sustainable framework for long-term risk assessment and climate response in these fragile mountain regions.

4.Conclusion

This study developed a scalable geospatial framework that combines multi-temporal Landsat satellite imagery, empirical volume-area estimation, and cloud-based analysis using Google Earth Engine (GEE) to quantify and track glacial lake changes across the Indian Himalayan Region (IHR). The framework efficiently handled large spatial datasets and allowed for consistent extraction of lake boundaries, area, and estimated volume over several years. By using automated cloud processing and remote sensing archives, this method showed its potential for long-term, repeatable monitoring of fragile mountain environments where in-person observations remain difficult.

The decadal analysis from 2008 to 2017 showed a significant and consistent increase in glacial lake area and volume, especially in regions near active glacier snouts. This growth reflects the ongoing effects of climate-driven glacier retreat, which has reshaped the high-altitude landscape and led to the formation of new proglacial and moraine-dammed lakes. The trends observed indicate an increase in hydrological storage in glacial basins, alongside a rising risk of Glacial Lake Outburst Floods (GLOFs). Regions like Uttarakhand, Arunachal Pradesh, and Sikkim showed the highest activity, highlighting the urgent need for focused hazard assessments and management strategies in these vulnerable mountain systems.

Overall, this research underscores the value of integrating remote sensing, modeling, and cloud computing for effective glacial lake monitoring and climate resilience planning. The findings support the creation of early warning systems, community-based risk preparedness plans, and sustainable infrastructure design in high-relief Himalayan basins. The methodology presented provides a basis for future multi-decadal monitoring that includes higher-resolution imagery and machine learning techniques to improve prediction accuracy. As climate change accelerates, such scalable, data-driven methods will be crucial for protecting mountain ecosystems and the downstream communities that rely on them.

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