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# *Snow and Ice Cover Change in the Earth's Third Pole: Implications for Future Water Resources*

**Fred Deng**

*BASIS International School Park Lane Harbour, Huizhou, China*
*fred.deng14199-biph@basischina.com*

***Abstract.*** The Tibetan Plateau, Earth's "Third Pole," holds critical glacial water reserves that sustain billions of people across Asia. Climate change drives widespread glacier retreat across the region, but melt rates vary sharply by location, creating a need for fine-scale local monitoring to support adaptive water management. This study quantifies annual late-summer changes in snow and ice cover in a 100 × 125 mile central Himalayan study area near Mount Everest, using Landsat 8 satellite imagery processed in Google Earth Engine with the Normalized Difference Snow Index. Year-to-year changes were measured via image subtraction for 13 intervals from 2013 to 2026, and linear regression with a t-test was used to evaluate long-term trends. Results show net annual snow and ice loss across all 13 year-to-year intervals, although the magnitude of loss varies widely from year to year. A slight negative trend in annual loss was not statistically significant ($p = 0.458$), indicating no clear statistically significant long-term change in the annual loss trend over the study period. These local findings complement regional assessments and support targeted water resource planning for communities dependent on Third Pole meltwater.

***Keywords:*** Glacial retreat, Third Pole, Google Earth Engine, Landsat, snow cover change

## 1. Introduction

The Tibetan Plateau, widely known as Asia's Water Tower, contains one of the world's largest concentrations of high-altitude glaciers outside the polar regions and forms the headwaters of major river systems that sustain billions of people across Asia (See Figure 1) [1]. Under ongoing global warming, widespread changes in snow and ice cover across the plateau have been well documented, but the magnitude and direction of these changes vary substantially by subregion, creating substantial uncertainty for local water resource planning.

Most regional assessments rely on glacier inventories at 5- to 10-year intervals, and fine-scale annual snow and ice over data for the central Himalayan region around Mount Everest remains relatively limited. Few studies have conducted year-over-year snow and ice cover change tracking paired with formal statistical testing for short-term trends in this specific area.

This study addresses two core research questions: first, what is the magnitude of annual late-summer snow and ice cover change in a 100 × 125 mile study area near Mount Everest from 2013 to 2026; second, is there a statistically significant linear trend in annual snow and ice cover change over the study period? Using Landsat 8 imagery processed via the Normalized Difference

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Snow Index on the Google Earth Engine platform, this study quantifies annual net change and evaluates trend significance. The results provide local-scale evidence to complement plateau-wide assessments and support basin-specific water resource adaptation strategies.

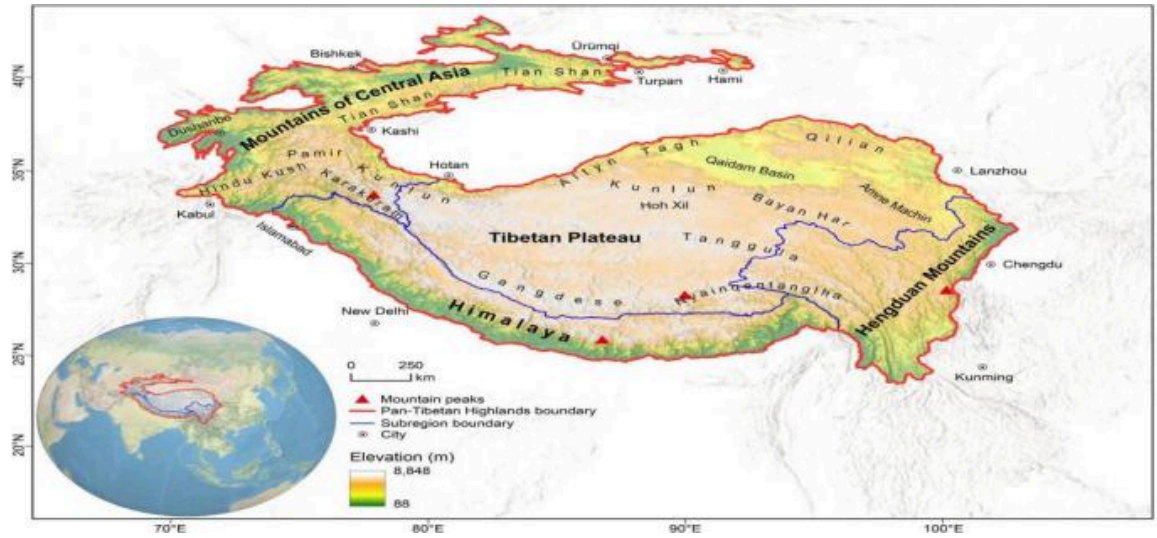



Figure 1. Geographical extent of the Tibetan Plateau and adjacent mountain regions [2]

*Note: The map delineates four sub-regions, the Tibetan Plateau, Himalaya, Hengduan Mountains and Mountains of Central Asia, and shows their combined scope defined as the "Pan-Tibetan Highlands."*

## 2. Literature review

### 2.1. Remote sensing of tibetan plateau glacier change

Satellite remote sensing has become a major method for large-scale and long-term glacier monitoring across the Tibetan Plateau. Zhao et al. conducted a 34-year (1988–2022) plateau-wide glacier mapping study using Landsat data processed on the Google Earth Engine platform, developing the adaptive glacier extraction index (AGEI) to produce glacier inventories every five years [3]. The study found that total clean glacier cover decreased by approximately one-third over the study period, with strong spatial heterogeneity: glaciers in the eastern and southeastern plateau experienced the greatest area loss, while some glaciers in the Karakoram Range showed slight growth, a pattern known as the "Karakoram anomaly." Temporally, most regions experienced rapid shrinkage in the 1990s, modest expansion between 2000 and 2010, and slowed or stable retreat after 2010. Rising air temperature was identified as the primary driver of melt, with increased spring precipitation moderating retreat in regions such as the Karakoram.

Spectral index methods applied to multispectral Landsat imagery, including the Normalized Difference Snow Index, are well established as standard tools for delineating snow and ice-covered areas in mountain environments [3]. However, most existing studies focus on multi-year interval changes rather than annual-scale variability, and few provide detailed year-over-year quantification of snow and ice over change for the Mount Everest subregion.

### 2.2. Glacial water resources and supply-demand risks

Changes in glacial extent and meltwater dynamics on the Tibetan Plateau have direct implications for water resource security across Asia. Wang et al. emphasized that the plateau's glacial reserves

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play a pivotal role in regulating regional water supply, and climate change is projected to progressively undermine this function over the 21st century [1]. Su et al. further analyzed supply and demand dynamics across China's 16 major glacier-fed basins, identifying four basins (Tarim, Junggar, Ili, and Zangxi) as the most critically dependent on glacier water due to large storage volume and high population reliance [4].

The study revealed distinct spatiotemporal mismatches: basins in the eastern Tianshan, eastern Qilian Mountains, and southeastern plateau will reach peak meltwater in the 2020s, before local population peaks around 2030, creating a compound risk of water shortage as supply declines while demand continues to rise. In contrast, basins such as the Tarim will not reach peak meltwater until the mid-to-late 21st century. The study also noted that including downstream nations' water needs dramatically amplifies the strategic importance of China's glacier resources, particularly in transboundary basins such as the Indus and Ganges. These findings highlight the need for local-scale snow and ice over data to support basin-specific water management and hazard mitigation.

### 2.3. Global climate governance and cryosphere protection

International climate governance frameworks shape the broader context for glacial protection and water resource adaptation. The Intergovernmental Panel on Climate Change (IPCC), a United Nations body, synthesizes peer-reviewed climate research into consensus assessment reports every 6 to 7 years, establishing the scientific evidence base for global climate action [5]. The IPCC does not prescribe specific policies, but its findings on cryosphere loss and water security risks directly inform international negotiations.

The Conference of the Parties (COP), the governing body of the UN Framework Convention on Climate Change, produces binding global climate agreements. The 2015 Paris Agreement, adopted at COP21, committed signatories to limiting global warming to well below 2 °C and pursuing a 1.5 °C target [6]. Limiting warming is particularly relevant to the Third Pole because greater warming is associated with substantially greater risks of glacier loss and disruptions to mountain water systems. While global mitigation targets aim to slow long-term glacial retreat, recent COP agendas have increasingly prioritized adaptation measures such as cross-border water cooperation and early warning systems, which are critical for transboundary glacier-fed river basins.

### 2.4. Research gap

Collectively, existing literature establishes a clear consensus of overall snow, ice, and glacier change across the Tibetan Plateau and its water resource implications. However, two key gaps remain. First, most plateau-wide studies use multi-year interval glacier inventories, lacking fine-grained annual-scale change data for specific subregions. Second, few studies focus explicitly on the Mount Everest area of the central Himalayas, and even fewer conduct formal statistical significance testing for short-term trends in annual snow and ice cover change. This study addresses these gaps by providing a 13-year time series of annual late-summer snow and ice cover change for a central Himalayan study area, paired with statistical trend analysis, to complement broader regional assessments.

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## 3. Data & methods

### 3.1. Google earth engine & landsat

This study uses satellite imagery accessed through Google Earth Engine (GEE), a cloud-based platform that provides access to large archives of geospatial data and allows researchers to conduct analysis directly on cloud-based servers without downloading large datasets. GEE hosts the full Landsat satellite archive and provides pre-processed surface reflectance products, and it has been widely used for glacier and snow-cover monitoring and change detection in remote sensing research [7].

The Landsat program, operated by NASA and the U.S. Geological Survey, has collected continuous Earth observation data since 1972. This project specifically uses Landsat 8 Collection 2 Level-2 Surface Reflectance imagery, which has a spatial resolution of 30 meters per pixel. Landsat 8 carries the Operational Land Imager (OLI) sensor, which captures data across multiple wavelength bands, including visible, near-infrared, and shortwave-infrared (SWIR) light. Each band serves a different purpose: visible bands show true-color appearance, while SWIR bands are critical for distinguishing snow from clouds because snow and ice generally have much lower reflectance in the SWIR than in the visible green band.

The study area is a slightly slanted rectangular region approximately 100 × 125 miles, centered approximately at 86.8°E, 27.45°N, encompassing Mount Everest 40 miles north of the center and the border of Tibet and Nepal. This region was selected because it contains representative alpine glaciers and seasonal snow cover of the Third Pole. All image processing and analysis was performed using JavaScript in the GEE Code Editor.

### 3.2. Sanity check: seasonal snow comparison

Before conducting decade-long trend analysis, a sanity check was performed to verify that the snow-mapping method produces physically reasonable results. The test compares snow cover between February (end of winter, maximum snow) and August (end of summer, minimum snow) of the same year, 2022. If the method works correctly, the August image should show substantially less snow than the February image.

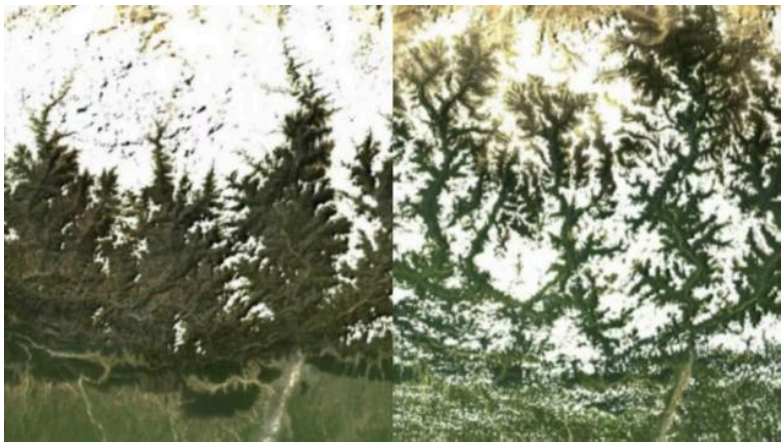


Figure 2. True-color Landsat 8 satellite images of the study area, February 2022 (left) and August 2022 (right)

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For each month, the least cloudy Landsat 8 scene was selected by sorting all images in the month by their CLOUD_COVER metadata value and taking the first result (Figure 2). Surface reflectance values were scaled using the official Landsat 8 Collection 2 scaling factors: reflectance = DN × 0.00002 − 0.2.

Snow and ice were mapped using the Normalized Difference Snow Index (NDSI), a commonly used spectral index for snow and ice identification in multispectral satellite imagery, calculated as [8]:

$$\mathrm{NDSI}=\frac{\mathrm{Green-SWIR1}}{\mathrm{Green+SWIR1}} \tag{1}$$

where Green corresponds to Landsat band SR_B3 and SWIR1 corresponds to band SR_B6. A threshold value of 0.4 was applied: pixels with NDSI greater than 0.4 were classified as snow or ice, while all other pixels were classified as non-snow. This threshold is standard in glacial remote sensing and effectively separates snow from clouds, water, and bare ground.

The February snow map was subtracted from the August snow map to produce a change image (Figure 3). In the resulting visualization, red pixels represent snow retreat (areas covered in February but not in August), blue pixels represent snow advance (areas covered in August but not in February), and white pixels show no change.

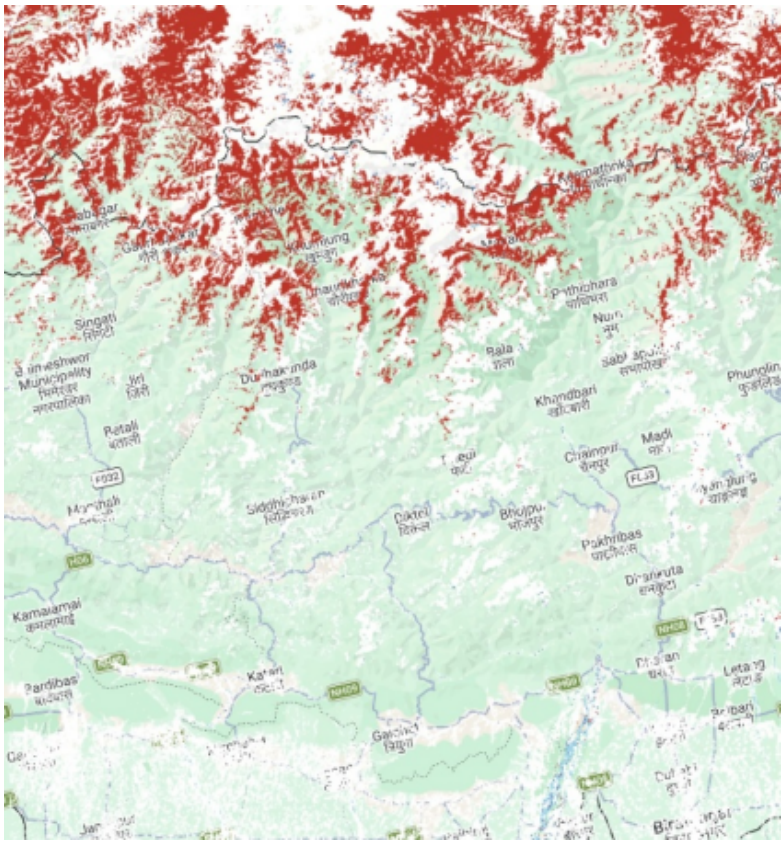



Figure 3. Seasonal snow cover change map derived by subtracting the February 2022 NDSI snow map from the August 2022 NDSI snow map and removing false colors

As expected, the change image was dominated by red, confirming widespread snow and ice cover loss from winter to summer. Visually, the August raw image appeared to contain extensive white areas due to cloud cover, but the NDSI algorithm correctly excluded clouds because they reflect

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similarly in both green and SWIR wavelengths, yielding NDSI values well below the 0.4 threshold. This result confirms that the NDSI-based method reliably distinguishes actual snow from cloud cover and produces reasonable seasonal patterns, validating the approach for use in multi-year trend analysis.

The code used to search, filter, and visualize Landsat 8 satellite imagery for the study area is available as a public Google Earth Engine script [9]. The code used for NDSI calculation, snow/ice classification, image subtraction, and pixel counting is available as a second public Google Earth Engine script [10].

## 4. Results

This section presents annual snow cover change results for the 100 × 125 mile study area between August 2013 and August 2026, derived using the NDSI-based image subtraction method described in Section 3.2. All comparisons use the least-cloudy August scene from each year, with the previous year's August scene subtracted to quantify net annual snow and ice over loss. Because this study uses Landsat i8 imagery, the analysis begins in 2013, resulting in 14 annual observations and 13 year-to-year intervals.

### 4.1. Annual snow retreat magnitudes

For each consecutive year pair, the total number of red pixels, which represented areas where snow/ice cover was present in the earlier August image but absent in the later August image, was counted across the full study area. All 13 annual comparisons yielded positive snow and ice cover-loss areas, meaning the study area experienced snow and ice loss in every year-to-year comparison relative to the prior August.

The magnitude of annual snow and ice cover loss varied widely from year to year. The smallest annual net retreat occurred in 2022–2023, with 375,533 red pixels, while the largest occurred in 2017–2018, with 3,914,294 red pixels—more than ten times the minimum value. Several years showed particularly high recover loss (over 2.5 million pixels: 2013–2014, 2015–2016, 2016–2017, 2017–2018, 2024–2025), while other years showed comparatively low cover loss (under 1 million pixels: 2014–2015, 2022–2023, 2023–2024).

### 4.2. Linear trend analysis

A line of best fit was calculated via linear regression to assess whether the magnitude of annual snow and ice cover loss showed a long-term linear trend over the study period (Figure 4). This analysis and the accompanying plot were generated using Python code in a Jupyter Notebook environment.

The fitted linear trend had a slope of −69,248 pixels per year, indicating a slight overall decrease in the amount of annual snow and ice cover loss across the period. The regression had an intercept of 141,846,907 pixels and a Pearson correlation coefficient (r) of −0.226. The R-squared value was 0.051, meaning only about 5 % of the year-to-year variation in snow cover loss can be explained by a simple linear time trend. The remaining 95 % of variation is driven by other year-to-year factors such as seasonal weather patterns, cloud cover differences, and snowfall variability.

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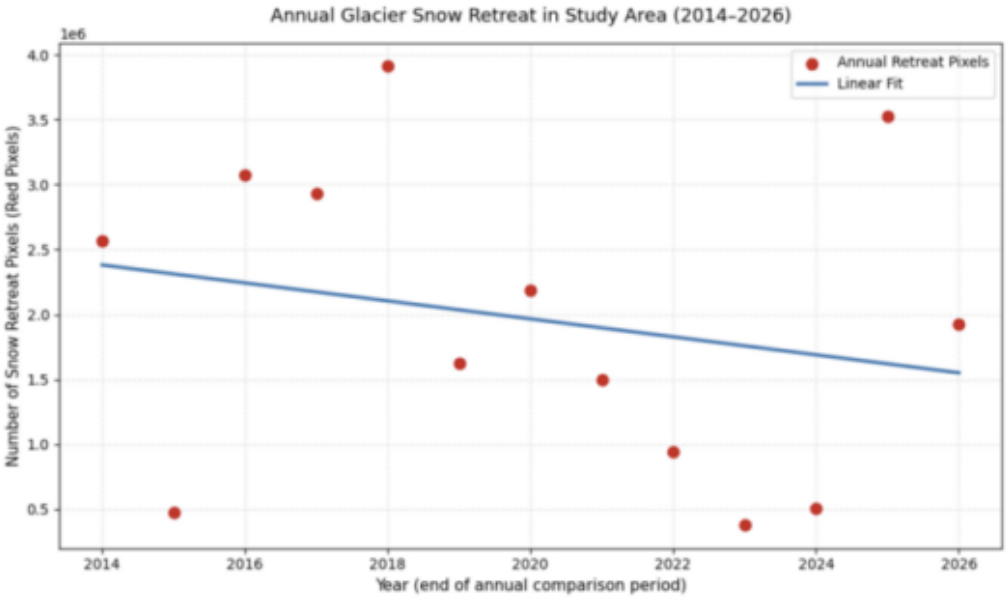



Figure 4. Plot of annual net snow retreat (red pixel count) in the study area over the time period from August 2013 to August 2026, with the blue line showing the linear line of best fit

### 4.3. Statistical significance testing

A two-tailed t-test for linear regression was performed to evaluate whether the observed negative slope was statistically distinguishable from zero. The null hypothesis stated that the true slope of the trend line equals zero (no consistent linear trend in annual snow and ice cover loss over time), and the alternative hypothesis stated that the true slope is not equal to zero.

The test returned a p-value of 0.4581, with a standard error of the slope of 90,046 pixels per year. Because the p-value is well above the standard significance threshold of 0.05, the null hypothesis cannot be rejected. This means there is no statistically significant linear trend in the magnitude of annual snow and ice cover loss across the 2013–2026 study period. The observed slight downward slope is within the range of random year-to-year variation and cannot be interpreted as a real directional trend.

All statistical calculations, plotting data, analysis code, and step-by-step explanations of linear regression and t-test concepts are available in a supplementary Jupyter Notebook [11].

## 5. Discussion

### 5.1. Main findings

This study quantified annual late-summer snow and ice cover change in a 100 × 125 mile central Himalayan study area near Mount Everest from August 2013 to August 2026. The most consistent finding is that the region experienced net snow and ice cover loss throughout the observation period, although the magnitude of loss varied substantially between years. This persistent but highly variable pattern suggests that late-summer snow and ice cover in the study area did not follow a stable year-to-year trajectory.

The magnitude of annual retreat showed substantial interannual variability, consistent with broader regional findings by Zhao, who documented highly uneven glacier change across the Tibetan Plateau [3]. Such variability may reflect differences in precipitation, snowfall accumulation,

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summer temperature, monsoon conditions, and other short-term environmental factors. Because these variables were not directly analyzed in this study, however, their individual contributions cannot be established from the present data. The linear regression analysis showed no statistically significant trend in annual snow and ice cover loss, indicating that the observed year-to-year fluctuations do not provide sufficient evidence for a consistent linear increase or decrease over the observation period.

In the context of Third Pole water resources, these results support the broader consensus that glacial water storage is declining across the Himalayan region [4]. Even without a statistically significant accelerating or decelerating trend, consistent annual net loss means the region is losing frozen water reserves each year, with cumulative impacts on downstream river flows over time.

### 5.2. Caveats

Two important limitations shape how these results should be interpreted.

First, the study area is not representative of the entire Third Pole region. The 100 × 125 mile analysis zone is focused narrowly on the Mount Everest area of the central Himalayas, covering only a small fraction of the full Tibetan Plateau and surrounding mountain ranges. As established in prior regional research, glacier change patterns differ dramatically across the Third Pole: glaciers in the eastern and southeastern plateau retreat fastest, while some glaciers in the Karakoram Range remain stable or even grow slightly [3]. The patterns observed in this single central Himalayan sub-region cannot be generalized to the entire plateau, to inland glacial basins, or to other parts of the Himalayan arc. Local topography, monsoon exposure, and elevation gradients can create very different snow and ice accumulation and melt dynamics even in adjacent basins.

Second, the 13-year study period is too short to capture long-term glacial trends. The analysis is limited to 2013–2026 by the availability of consistent Landsat 8 imagery for the region. Glacial change is a slow process that unfolds over decades and centuries, and a single decade is easily dominated by short-term natural climate variability, such as fluctuations in monsoon rainfall, winter snowfall totals, and individual summer heatwaves, rather than long-term anthropogenic warming. The high year-to-year swing in retreat magnitudes seen in the results reflects this short-term variability. A longer time series, ideally spanning multiple decades, would be required to detect a statistically significant long-term trend in retreat rate, if such a trend exists in this region.

## 6. Conclusion

Overall, this study provides a focused, local-scale examination of annual snow and ice change in the central Himalayan portion of the Earth's Third Pole, using a satellite remote sensing method validated against seasonal snow patterns. The core takeaway is that net glacial and seasonal snow loss is occurring consistently in this region, even though the rate of loss has not shown a statistically significant increase or decrease over the past 13 years.

These findings complement broader regional studies by documenting fine-grained annual variability that larger-scale assessments often average out. While plateau-wide studies give a critical big-picture view of Third Pole glacial change, local studies like this one help illustrate how those broader trends play out at the scale of individual mountain systems. For water resource planning, this kind of local data can help ground truth regional projections and support basin-specific management strategies. This is particularly critical because ongoing glacial loss increases the risk of both long-term water supply instability and acute climate-driven hydrogeological hazards such as glacial lake outburst floods for downstream mountain communities.

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Future work that expands the study area to cover more of the Himalayan arc and extends the time series back to earlier Landsat missions would help place these results in a wider spatial and temporal context. Such research would strengthen the evidence base for adapting water management to ongoing glacial change across the Third Pole.

## Acknowledgement

The author thanks Professor David M. Holland for his guidance and assistance across both parts of the computational analysis: writing and debugging the Google Earth Engine code for satellite image processing and snow cover change detection, as well as supporting the development of the Python Jupyter Notebook code for linear regression modeling, time series plotting, and the t-test for statistical significance. The author also acknowledges the Landsat program and the Google Earth Engine platform for providing open access to satellite imagery and cloud computing tools that made this study possible. Finally, the author appreciates the feedback and support provided throughout the research process.

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