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Multi-Decadal Expansion of Potentially Dangerous Glacial Lakes in Central-Eastern Nepal (1992-2024): Remote Sensing Assessment and GLOF Hazard Implications

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Abstract. Glacial lakes in the Himalayan regions are expanding rapidly under ongoing climate change, intensifying the risk of Glacial Lake Outburst Floods (GLOFs). This study quantifies multi-decadal area changes (1992-2024) in four Potentially Dangerous Glacial Lakes (PDGLs), Thulagi, Lumding Tsho, Hongu 2, and Lower Barun, located in central-eastern Nepal, using Landsat 5 and Landsat 8 satellite imagery processed within the Google Earth Engine (GEE) cloud platform. Lake boundaries were delineated from post-monsoon (October-November) median composites using the Normalized Difference Water Index (NDWI; threshold = 0.3), supplemented by manual delineation where topographic shadow conditions compromised automated extractions. Area uncertainties were computed using the standard half-pixel buffer method. Non-parametric Mann-Kendall trend tests with Sen's slope estimator were applied to all lake area time series to evaluate the statistical significance and rate of expansion. Sub-period regression analysis was used to assess acceleration in lake growth. Empirical area-volume scaling was applied to estimate changes in impounded water volume. All four lakes exhibited statistically significant, monotonically increasing area trends over the 32-year study period (Mann-Kendall tau = 1, $p < 0.001$ for each lake). Lower Barun exhibited the highest expansion rate (Sen's slope = 0.063 km^2 yr^{-1}), growing from 0.77 ± 0.053 km^2 in 1992 to 2.76 ± 0.13 km^2 in 2024 (a 258% increase), with post-2010 expansion accelerating by a factor of 1.35. Lumding Tsho showed a strongly accelerating growth trajectory ($R^2 = 0.96$) with a post-2010 rate that more than doubled. The combined estimated additional water volume stored across all four lakes since 1992 approaches 608.6×10^6 m^3, representing a GLOF hazard of exceptional and growing scale. The approach demonstrates a scalable and reproducible framework for long-term glacial lake monitoring and hazard assessment, applicable across data-sparse high mountain environment.

Keywords: Glacial lakes, Thulagi, Lumding Tsho, Hongu 2, Lower Barun, Google Earth Engine

1 Introduction

The cryosphere of the Himalayas is undergoing accelerated transformation under anthropogenic climate change. Globally, glacial lake volume and area increased by approximately 48% and 51% respectively from 1990 to 2018, representing one of the most dramatic landscape-scale responses to warming documented in the satellite era (Shugar et al., 2020). Even if global temperatures were stabilised today, glaciers would continue to lose mass for several decades due to the long adjustment time of the cryosphere to climate change (Lee & Romero, 2023),

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ensuring that proglacial lakes will continue forming and expanding regardless of near-term mitigation efforts. The region is particularly exposed to these changes: its complex topography, steep elevation gradients, and strong orographic controls create conditions in which small climatic perturbations can trigger large geomorphological responses (Bajracharya et al., 2015).

Glacier extent in the Himalayan region is the largest outside the polar regions, supporting freshwater resources for approximately 2 billion people at risk of water stress across South and Southeast Asia. However, accelerated glacier mass loss; estimated at 65% in the HKH region over recent decades, is fundamentally altering the hydrological regimes of downstream river systems (ICIMOD, 2023). As glaciers retreat, they expose over-deepened bedrock basins or leave behind moraine-dammed depressions that fill with meltwater, forming proglacial lakes. These lakes grow as their parent glaciers retreat further, accumulating enormous volumes of water behind naturally unstable ice-cored or debris moraine dams. A sudden failure of these dams, whether triggered by ice calving, seismic activity, extreme precipitation, or slope instability, can release catastrophic outburst floods that sweep through steep valley systems with a little warming, threatening communities, infrastructure, and hydropower assets many kilometres downstream (Duan et al., 2023; Shugar et al., 2020).

Nepal is among the most GLOF-exposed nations on Earth. With 47 Potentially Dangerous Glacial Lakes (PDGLs) identified, of which 21 lie entirely within Nepal's borders, the country faces a disproportionate share of global GLOF risk (ICIMOD, 2011). Recent inventories document the scale of change: from 2000 to 2020, 499 new glacial lakes formed in Nepal, 139 vanished, and the net increase in lake area reached 19.46 km^2 with an additional 403.07 × 10^6 m^3 of impounded water (Hu et al., 2022). In the broader Hindukush-Karakoram region, glacial lake numbers increased by 9.31% and total area expanded by 10.09% between 1990 and 2010 alone (Kumar et al., 2025). These aggregate statistics, however, obscure the site-specific dynamics that are essential for hazard-targeted risk management.

Among Nepal's most hazardous lakes, Thulagi, Lower Barun, Lumding Tsho, and Hongu 2 have been consistently identified in GLOF hazard assessments as warranting priority attention (Bajracharya et al., 2020; Chen et al., 2025). Thulagi is directly upstream of existing hydropower infrastructure; Lower Barun has undergone explosive growth driven by continuous calving from a debris-covered glacier and poses cascade flood risk to areas downstream (Gantayat et al., 2024; Maskey et al., 2020); Lumding Tsho has a short moraine dam adjacent to steep hanging ice (Bajracharya et al., 2020); and Hongu 2 is part of a cluster of rapidly evolving lakes in the Hongu Valley (Byers et al., 2013; Komori, 2006). Recognising this hazard profile, all four lakes have been selected under a Green Climate Fund (GCF)-supported initiative for lake lowering and ecosystem-based stabilisation (UNDP, 2025).

Previous remote sensing studies have examined subsets of these lakes, notably Haritashya et al. (2018) for Thulagi and Lower Barun using multi-decadal Landsat data, and Gantayat et al. (2024) for the evolution of Lower Barun specifically, providing valuable insights into glacial lake distribution and change. However, several high-risk lakes, including Lumding Tsho and Hongu 2 remain comparatively under-represented in detailed long-term analyses. Existing studies often focus on individual sites or short time periods, lack methodological consistency,

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and rarely quantify uncertainties or assess non-linear growth dynamics such as acceleration (Bajracharya et al., 2020; Gantayat et al., 2024; Maskey et al., 2020). As a result, there is limited understanding of how rapidly these potentially dangerous lakes are evolving and whether their expansion is intensifying over time. Addressing this gap is essential for developing robust, comparable, and process-informed assessments of glacial lake hazards.

This study therefore aims to: (i) quantify multi-decadal area changes and asssociated uncertainties for selected high-risk glacial lakes using a consistent Landsat-based framework; (ii) characterise the temporal dynamics, and non-linear growth behaviour including potential acceleration; (iii) estimate changes in stored water volume using empirical scaling relationships; and (iv) evaluate implications for evolving GLOF hazards in glacierized mountain regions.

2 Study Area

The study area encompasses three adjacent Himalayan sub-catchments in central-eastern Nepal: the Upper Marsyangdi (Thulagi), the Dudh Koshi (Lumding Tsho and Hongu 2), and the Barun (Lower Barun) basins. Each span steep altitudinal gradients from subtropical/temperate mid-hills to high alpine and nival zones where glacier and moraine-dammed lakes have developed (Bajracharya et al., 2020; Bocchiola et al., 2020; Sigdel et al., 2022). The regional hydroclimate is dominated by the South Asian summer monsoon, which delivers approximately 70% of annual precipitation between June and September, creating a pronounced wet season contrasted with cold, dry winters (Bocchiola et al., 2020; Mudbhari et al., 2022; Pepin et al., 2022). These characteristics make the basins highly sensitive to changes in monsoon intensity, snowmelt timing, and glacier mass balance, jointly controlling seasonal streamflow, sediment delivery, and the likelihood of hydro-geomorphic hazard events (Bookhagen & Burbank, 2010; Neupane et al., 2015).

Figure 1 shows the locations of the three sub-catchments and the four study lakes.

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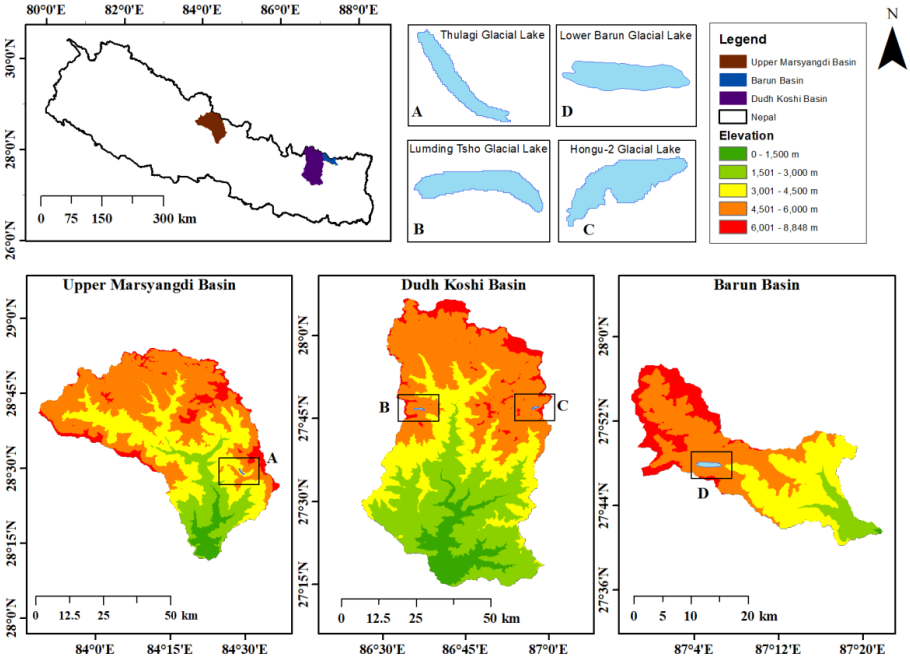

Figure 1: Three Himalayan sub-catchments, Upper Marsyangdi, Dudh Koshi, and Barun Basin, showing the locations of the four study lakes

2.1 Upper Marsyangdi and Thulagi Glacial Lake

The upper Marsyangdi sub-basin contains extensive debris-covered glaciers and several moraine-dammed proglacial lakes fed by glacier melt and avalanche input from high ridges (Bajracharya et al., 2020). Mean annual precipitation is highly variable with elevation, ranging from approximately 400 mm yr^{-1} at the highest and most arid sites to over 3200 mm yr^{-1} at lower, wind-exposed slopes, with the bulk falling during the monsoon season (Mudbhari et al., 2022).

Thulagi glacial lake is a moraine-dammed proglacial lake at the terminus of Thulagi glacier in the Upper Marsyangdi region, situated at approximately 4,050 m a.s.l. Bathymetric surveys have documented a maximum depth of approximately 76 m and an estimated volume of 36.1×10^6 m^3 (Haritashya et al., 2018). A breach of the moraine dam would have direct downstream consequences for existing hydropower facilities and downstream communities in the Marsyangdi valley.

2.2 Dudh Koshi: Lumding Tsho and Hongu 2

The Dudh Koshi sub-basin drains the southern flanks of the Everest-Makalu arc, spanning the full Himalayan elevation range from approximately 500 m to 8,848 m, and contains numerous glacier termini and proglacial lakes that modulate seasonal discharge (Nepal, 2016). Observed temperature and precipitation trends suggest warming

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and increasing extreme precipitation frequency, with direct implications for glacier mass balance, lake expansion, and downstream flood risk (Bocchiola et al., 2020)

Lumding Tsho is a proglacial lake formed at the terminus of Lumding glacier at an elevation of approximately 4,846 m a.s.l. (Ives et al., 2010). It is situated at approximately 27° 46' 59" N, 86° 57' 25" E, where steep slopes, nearby hanging glacier ice, and relatively short moraine dam contribute to a high monitoring priority ranking (Bajracharya et al., 2020; Chen et al., 2024). Remote sensing inventories have consistently listed Lumding Tsho among the lakes with the most rapid areal increases in Nepal (Hu et al., 2022).

Hongu 2 is located at the Hongu valley, a part of a cluster of actively evolving glacial lakes in the Makalu-Barun region. Historical records indicate that glacier termini in the Hinku and Hongu valleys have been retreating at approximately 70 m yr^{-1} since the 1950s-1970s (Komori, 2006), and a neighbouring lake, Chamlang South Pokhari has been expanding at a rate of 0.117 km^2 yr^{-1} from 1964 to 2010 (Byers et al., 2013), providing regional context for the rapid dynamics observed at Hongu 2.

2.3 Barun and Lower Barun Glacial Lake

The Barun sub-basin is located east of the Everest region within Makalu-Barun National Park. It contains the largest moraine-dammed lakes and most extensive debris-covered glaciers in eastern Nepal.

Lower Barun glacial lake lies in eastern Nepal's Mahalangur Himalaya at approximately 4,550 m a.s.l., close to the Makalu Massif (Gurung et al., 2021; Haritashya et al., 2018). It is dammed by an ice-cored moraine to the east and fed by a debris-covered glacier to the west, which continuously supplies icebergs through calving. Field measurements indicate a maximum depth of approximately 205 m and a volume of approximately 112.3×10^6 m^3, making it one of the deepest and most voluminous lakes in the Nepal Himalaya. It faces compound hazard risks from rock and ice avalanches on nearby steep slopes and potential cascade GLOF scenarios (Maskey et al., 2020).

3 Data and Methodology

3.1 Data Sources

Landsat 5 Thematic Mapper and Landsat 8 Operational Land Manager (OLI) imagery at 30 m spatial resolution were accessed via Google Earth Engine (GEE) (Williams et al., 2006). The study period spans 1992-2024. Landsat 7 ETM+ was deliberately excluded because the Scan Line Corrector (SLC-off) failure in May 2003 produced systematic data gaps of approximately 22% per scene (Scaramuzza et al., 2004), which would introduce artificial discontinuities in long-term boundary extraction. All imagery was accessed as Top of Atmosphere (TOA) reflectance. Post-monsoon periods (October-November) were selected for each year to minimize cloud cover and seasonal snowpack interference on lake delineation (Wangchuk & Bolch, 2020). Imagery was restricted to less than 20% cloud cover, and annual post-monsoon median composites were generated to further reduce cloud and shadow effects (Hermosilla et al., 2023; Jin et al., 2023). Annual composites were calculated at four-year intervals

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from 1992; where suitable imagery was unavailable (2012-2013), the nearest available alternative year (2014) was substituted.

3.2 Glacial Lake Delineation and Area Extraction

Lake boundaries were delineated from post-monsoon Landsat median composites using the Normalized Difference Water Index (NDWI):

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

where, NIR is Near Infrared band

A pixel threshold of 0.3 (Gu et al., 2007; McFeeters, 2013) was applied to classify water pixels. All pixel areas meeting the threshold were summed to estimate annual lake area in km^2. For scenes where accurate automatic delineation was compromised by topographic shadow effects on NDWI, particularly in narrow glacially-scoured valleys, GIS-based manual delineation was applied. For validation, Sentinel-2 imagery at 10 m spatial resolution (available from 2017 onwards) was used to independently delineate lake boundaries for the 2024 epoch, providing cross-sensor accuracy assessment of the Landsat NDWI-derived boundaries for the most recent time step (Wangchuk & Bolch, 2020).

3.3 Area Uncertainty Quantification

Mapping uncertainty for Landsat derived lake areas was quantified using the half-pixel buffer method (Fujita et al., 2009; Paul et al., 2013; Rounce et al., 2017).

$$\Delta A = \frac{p}{2} \times L \quad (2)$$

where p is the pixel size (30 m) and L is the lake perimeter (m). Perimeter lengths were extracted from the GIS-delineated lake polygons for each time step. Representative uncertainty values for the 1992 and 2024 epochs are presented in Table 1.

3.4 Volume Estimation

The empirical area-volume (A-V) power-law scaling relationship of Cook & Quincey (2015) was applied:

$$V = 0.104 \times A^{1.42} \quad (3)$$

where V is the estimated lake volume (km^3) and A is the lake surface area (km^2). This relationship was developed from a global compilation of glacial lake bathymetry data (Huggel et al., 2002) and has been widely applied for preliminary volume assessment in the Himalayas (Cook & Quincey, 2015; Shugar et al., 2020). Volume estimates

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are reported as order-of-magnitude indicators, and for lakes where field measurements exist (Thulagi and Lower Barun), the scaling estimates are compared against field data to calibrate interpretation.

3.5 Statistical Analysis

3.5.1 Mann-Kendall trend test and Sen's slope

The non-parametric Mann-Kendall (MK) trend test was applied to all lake area time series to evaluate the statistical significance of trends without assuming a normal distribution (Kendall & George, 1990; Mann, 1945). The MK test is recommended for cryospheric time series because it is robust to non-normality, outliers, and missing values (Yue et al., 2002). Sen's slope estimator was used as the trend magnitude estimator (Sen, 1968). Both tests were conducted at the 95% confidence level.

The MK test statistic S is:

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sgn(x_j - x_k) \quad (4)$$

with variance,

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (5)$$

where.....

The standardized test statistic Z was used to test the hypothesis of no trend at $p < 0.05$.

3.5.2 Sub-period trend analysis

To quantify post-2010 acceleration in lake expansion, linear regression was performed separately for the 1992-2010 and 2010-2024 sub-periods for each lake, and the ratio of sub-period slopes was calculated as the acceleration factor.

4 Results

4.1 Glacial Lake Area Change (1992-2024)

All four glacial lakes exhibited statistically significant positive area trends over the 1992-2024 study period. Mann-Kendall test results confirm perfect monotonic increasing trends for every lake (tau = 1, Z = 3.65, p = 2.63×10^{-4}). Key results are summarized in Table 1.

Table 1: Lake area statistics, uncertainty, Mann-Kendall results, and linear fit (1992-2024)

Lake	Area 1992 (km^2 ± uncertainty)	Area 2024 (km^2 ± uncertainty)	% Change	Sen Slope (km^2 yr^{-1})	Linear Slope (km^2 yr^{-1})	R^2

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Thulagi	0.75 ± 0.009	0.97 ± 0.013	≈ 29.3%	0.005	0.0053	0.88
Lumding Tsho	0.70 ± 0.007	1.53 ± 0.013	≈118.6%	0.025	0.025	0.97
Hongu 2	0.46 ± 0.05	1.09 ± 0.094	≈137%	0.02	0.018	0.91
Lower Barun	0.77 ± 0.053	2.76 ± 0.13	≈258%	0.063	0.063	0.98

Lower Barun showed the greatest absolute and proportional expansion, growing from 0.77 ± 0.053 km^2 to 2.76 ± 0.13 km^2, a 258% increase over 32 years. Lumding Tsho exhibited persistent and highly linear upward growth, reaching 1.53 km^2 by 2024 (R^2 = 0.97). Hongu 2 showed a characteristic step-change growth pattern: modest expansion from 1992 to approximately 2005, followed by a sudden area increase between 2006 and 2007, then slowest absolute growth but the highest linear fit (R^2 = 0.88), indicating uninterrupted steady gradual expansion throughout.

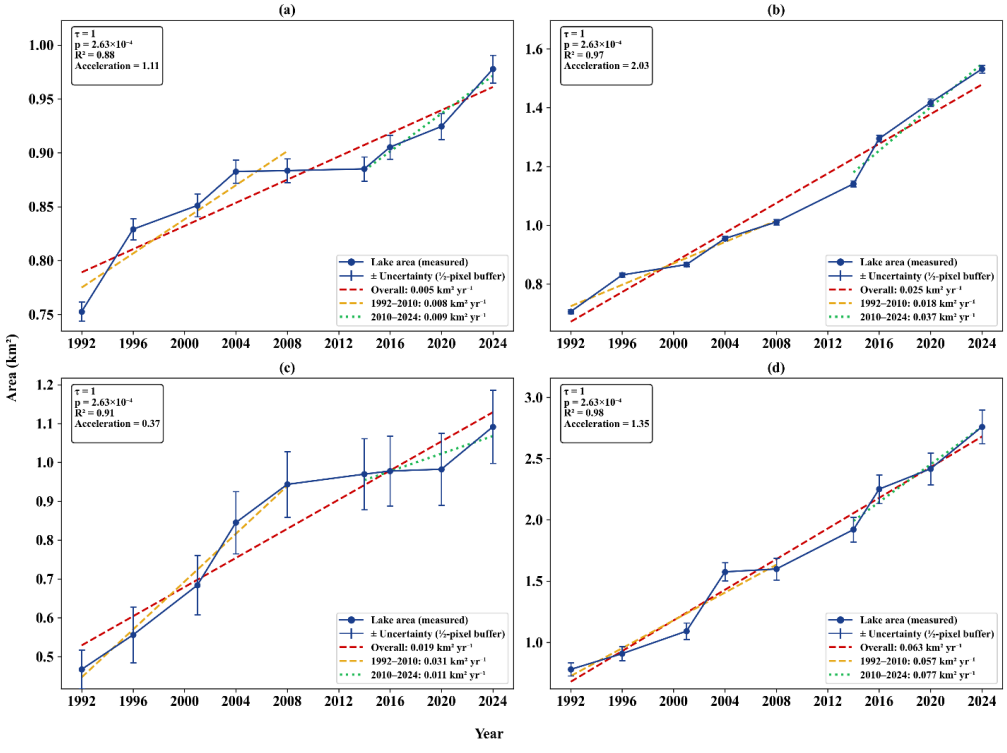

Figure 2: Lake area time series (1992-2024) for (a) Thulagi, (b) Lumding Tsho, (c) Hongu 2, and (d) Lower Barun, with Mann-Kendall confirmed trend lines and sub-period regression segments

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4.2 Sub-Period Acceleration Analysis

To assess whether lake expansion rates are accelerating or stabilising, linear regression was performed separately for the 1992-2010 and 2010-2024 sub-periods. (Table 2).

Table 2: Sub-period trend analysis comparing 1992-2010 and 2010-2024 lake expansion rates

Lake	Slope 1992-2010 (km^2 yr^{-1})	Slope 2010-2024 (km^2 yr^{-1})	Acceleration factor	Interpretation
Thulagi	0.0079	0.0087	1.11	Modest acceleration
Lumding Tsho	0.018	0.037	2.03	Marked acceleration
Hongu 2	0.030	0.011	0.37	Post-event decceleration
Lower Barun	0.056	0.076	1.35	Marked acceleration

Lower Barun's post-2010 expansion rate (0.077 km^2 yr^{-1}) was more than double the pre-2010 rate (0.57 km^2 yr^{-1}), an acceleration factor of 1.35. Hongu 2 showed a marked post-2010 deceleration (0.37), consistent with the abrupt 2006-2007 growth event representing a discrete threshold crossing after which growth stabilized at a larger extent. Thulagi showed a modest post-2010 acceleration of 11%, while Lumding Tsho showed the most pronounced acceleration with a 2.03-fold increase post-2010.

4.3 Spatial Dynamics of Lake Expansion

Temporal mapping of lake boundaries confirms significant and directional growth in all four lakes. Spatial analysis of boundary shift vectors reveals that all lakes expand preferentially in the upvalley direction, directly towards and into the space progressively vacated by retreating glacier termini. In Lower Barun, the 2024 lake boundary extends approximately 1.1 km further up-glacier compared to the 1992 extent. In Lumding Tsho, the northern boundary facing the glacier terminus shows the greatest displacement, while the lateral moraine-constrained margins are comparatively stable.

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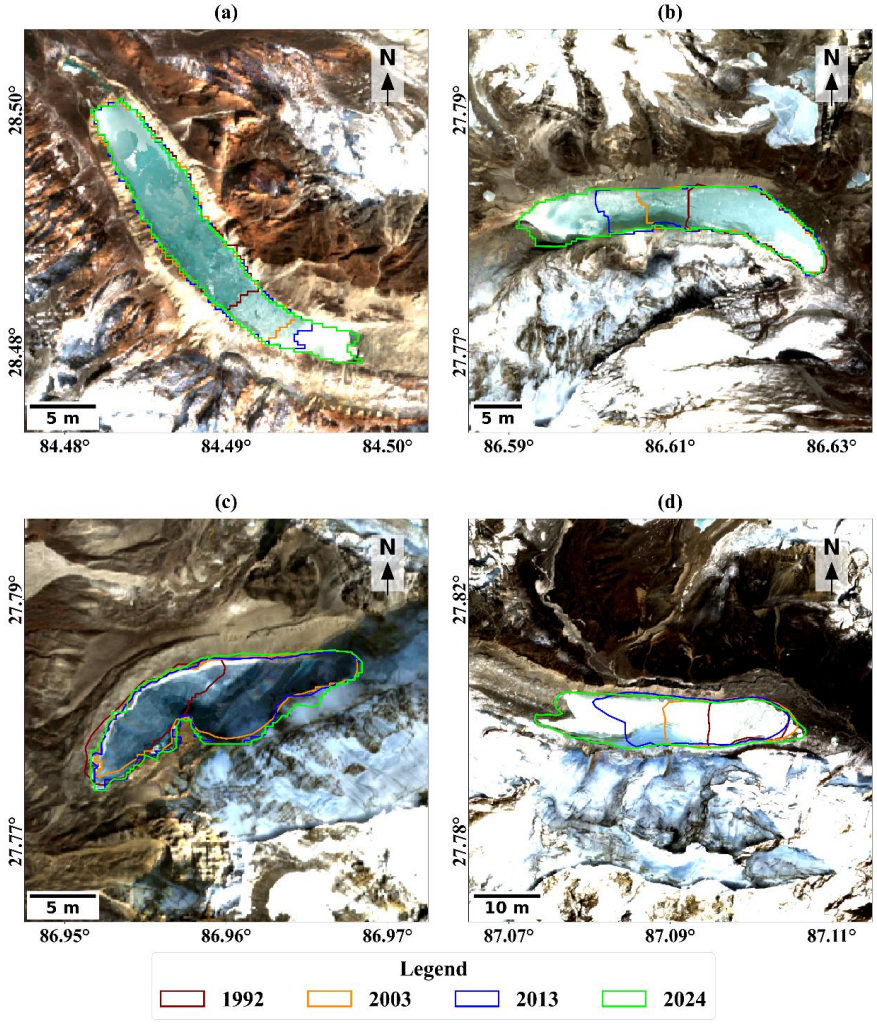

Figure 3: Multi-temporal lake boundaries (1992, 2000, 2010, 2024) overlaid on 2024 Sentinnel-2 imagery for (a) Thulagi, (b) Lumding Tsho, (c) Hongu 2, and (d) Lower Barun

4.4 Estimated Volume Change

Empirical area-volume scaling using the Cook & Quincey (2015) relationship ($V = 0.104 \times A^{1.42}$) provides order-of-magnitude estimates of the water volume accumulated since 1992 (Table 3).

Table 3: Estimated lake volumes using Cook & Quincey (2015) empirical scaling

Lake	$Area_{1992}$ (km^2)	V_{1992} ($\times 10^6$ m^3)	$Area_{2024}$ (km^2)	V_{2024} ($\times 10^6$ m^3)	ΔV ($\times 10^6$ m^3)
Thulagi	0.75	69.1	0.97	99.6	+30.5

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Lumding Tsho	0.70	62.7	1.53	190.2	+127.5
Hongu 2	0.46	34.5	1.09	117.4	+82.9
Lower Barun	0.77	71.7	2.76	439.4	+367.7
Combined	2.68	238	6.35	846.6	+608.6

For lakes with field-measured volumes, the scaling equation overestimates the surveyed 2018 volume for Thulagi (field: 36.1×10^6 m^3; scaling: ~80×10^6 m^3). This overestimation is expected for Thulagi, which occupies a relatively shallow, moraine-constrained basin. For Lower Barun (field: 112.3×10^6 m^3; in 2018), the 2024 scaling estimate of 439.4×10^6 m^3 reflects the substantial post-survey growth and is broadly consistent with the observed calving-driven volume increase documented by Gantayat et al. (2024). Volume estimates should be treated as indicative order-of magnitude values. Nevertheless, the combined additional water volume across the four lakes since 1992 (~608.6×10^6 m^3), equivalent to approximately 60 times the estimated flood volume of the destructive 1985 Dig Tsho GLOF (Vuichard & Zimmermann, 1987), underscores the scale of GLOF hazard potential these systems collectively represent.

5 Discussion

5.1 Lake Expansion in the Context of regional Himalayan Trends

The statistically significant expansion of all four study lakes over 32 years is consistent with broad patterns documented across the HKH region. Shugar et al. (2020) reported a 51% increase in global glacial lake area from 1990 to 2018, and studies focused specifically on Nepal document rapid lake proliferation in recent decades (Hu et al., 2022; Kumar et al., 2025). The range of areal expansion rates across the four lakes, from Thulagi's modest 29.3% growth to Lower Barun's explosive 258% increase reflects the diversity of controls on proglacial lake dynamics in the Himalaya, including glacier hypsometry, debris cover, moraine geometry, and basin topography (Carrivick & Tweed, 2013; Rounce et al., 2017). Notably, all four lakes show monotonic trends of increasing area with zero reversals over 9 timesteps between 1992 and 2024, a result that points to consistent, uninterrupted physical forcing throughout the study period rather than episodic or oscillatory dynamics.

The post-2010 acceleration documented at Lower Barun (1.35 rate increase) is particularly major. Gantayat et al. (2024) identified continuous glacier calving and increasing ice-cliff area at Lower Barun as primary drivers of its accelerating expansion, with calving dynamics sensitive to lake thermal structure and glacier geometry. This mechanism produces acceleration that outpaces what would be expected from atmospheric forcing alone, and explains why the post-2010 rate change is more pronounced at Lower Barun than at the other three lakes.

5.2 Divergent Growth Patterns and Site-Specific Controls

The contrasting growth trajectories across the four lakes underscore the importance of site-specific analysis in GLOF hazard assessment. Thulagi's slow expansion reflects the narrow geometry of the Upper Marsyangdi basin and the relatively smaller, less dynamic nature of the Thulagi glacier. Haritashya et al. (2018) documented a

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gradual increase from 0.4 km^2 in the early 1970s to 0.9 km^2 by 2017, consistent with our finding of 0.97 km^2 by 2024, confirming continuity of this gradual trend over five decades.

Hongu 2's step-change growth between 2006 and 2007 suggests a threshold event, likely an ice-calving episode, subaqueous moraine adjustment, or a sudden meltwater influx, that abruptly enlarged the lake before stabilization. The post-2007 deceleration factor of 0.37 indicates that the lake is now expanding towards a new, constrained equilibrium after the discrete threshold-crossing event consumed the available accommodation space within the existing moraine basin. This pattern highlights how gradual climate-driven glacier retreat can produce punctuated, threshold-driven lake responses when geomorphological boundaries are crossed (Carrivick & Tweed, 2013).

Lumding Tsho's steady, uninterrupted expansion rate, with no sign of deceleration, is consistent with its hazardous configuration described by Bajracharya et al. (2020): a lake pinned between steep slopes and hanging glacier ice, fed by continuous meltwater, with a relatively short and potentially vulnerable moraine dam. An accelerating Sen's slope of 0.025 $km^2\ yr^{-1}$ and a post-2010 acceleration factor of 2.03 indicates that Lumding Tsho expansion is gathering pace, with the rate of growth increasing through the study period.

5.3 Volume Implications for GLOF Hazard

The estimated additional water volume accumulated across the four lakes since 1992 approaches 608.6 × 10^6 m^3, more than tripling their baseline combined volume. The individual volume increase at Lower Barun alone (~367.7 × 10^6 m^3) represents a hazard of exceptional scale: the 1985 Dig Tsho GLOF, which caused catastrophic damage to downstream infrastructure, villages, and the Manche Small Hydro project, involved an estimated flood volume of only 5-10 × 10^6 m^3 (Richardson & Reynolds, 2000). Even allowing for inherent uncertainties in the A-V scaling, the order-of-magnitude increase in impounded water at Lower Barun represents a fundamentally different hazard class from documented events in Nepal. The Lumding Tsho volume increase (+127 × 10^6 m^3), concentrated behind a short moraine dam adjacent to hanging ice as described by Bajracharya et al. (2020), similarly represents an extreme potential hazard given the dam's structural characteristics.

These volume estimates reinforce the scientific evidence and provide the quantitative water-volume context that hazard exposure modelling requires. Future work integrating these volume estimates with hydrodynamic GLOF routing models, as applied by Maskey et al. (2020) for Thulagi and Lower Barun, should update the routing analyses with the substantially larger 2024 lake volumes presented here.

5.4 Methodological Limitations

Several methodological limitations apply to this study. First, NDWI-based lake delineation at 30 m Landsat resolution carries inherent uncertainty, quantified here using the standard half-pixel buffer method. The perimeter-based uncertainty values in Table 1 represent pixel-level geometric uncertainty; additional uncertainty may arise from inter-annual variation in water surface levels due to seasonal drawdown or infill, which is partially controlled by restricting analysis to post-monsoon (October-November) composites when lake levels are near their seasonal maximum.

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Second, the 2012-2013 data gap due to Landsat 7 SLC-off failure required substitution of 2014 imagery, introducing a slightly uneven temporal spacing. This does not affect the monotonic trend result but should be noted in interpreting sub-period regression coefficients.

Third, the area-volume scaling of Cook & Quincey (2015) carries substantial uncertainty for individual lakes, particularly those in highly over-deepened basins. Field-measured volumes for Thulagi and Lower Barun confirm the scaling equation overestimates shallow, confined basins (Thulagi), while performing more consistently for deep, calving-fed systems (Lower Barun). Volume estimates should therefore be treated as order-of-magnitude indicators, and high-resolution bathymetric surveys are recommended to refine these values ahead of detailed GLOF routing modelling.

Fourth, this study does not include quantitative glacier retreat mapping. Qualitative evidence for the casual link between glacier retreat and lake expansion is supported by published literature (Byers et al., 2013; Gantayat et al., 2024; Haritashya et al., 2018; Maskey et al., 2020), and the spatial dynamics of up-valley lake boundary expansion (Section 4.3) are consistent with glacier-driven expansion. Future work should incorporate glacier area change mapping, using field-validated glacier outlines rather than indices based on satellite imagery alone, which are unreliable for debris-covered glaciers that constitute a large fraction of total ice area at these sites.

6 Conclusion

This study presents the most comprehensive multi-decadal analysis to date of the four potentially dangerous glacial lakes in central-eastern Nepal, integrating lake area change, uncertainty quantification, volume estimation, and sub-period acceleration analysis within a unified remote sensing and statistical framework spanning 1992 to 2024.

All four lakes exhibit statistically significant monotonic expansion confirmed by Mann-Kendall trend tests (tau = 1, $p = 2.63 \times 10^{-4}$). Lower Barun has undergone the most dramatic transformation: +258% areal growth, a post-2010 acceleration factor of 1.35, and an estimated additional impounded water volume of $+367.7 \times 10^6$ m^3. Lumding Tsho maintains an undiminished linear expansion rate (Sen's slope = 0.025 km^2 yr^{-1}) with no sign of geometric constraint, representing the most persistently growing hazard among the four lakes. Hongu 2 experienced a discrete threshold-crossing growth event around 2006-2007 followed by slower growth at around 0.37 of the previous rates. Thulagi continues steady expansion with a 1.11 post-2010 modest acceleration. The combined estimated volume increases across all four lakes since 1992 approaches 608.6×10^6 m^3.

These findings collectively validate the scientific basis to support the following specific prioritisations: (i) urgent lake lowering at Lower Barun given its explosive post-2010 acceleration and exceptional volume increase; (ii) sustained monitoring of Lumding Tsho given its undiminished linear expansion and vulnerable moraine dam configurations; (iii) continued area monitoring of Thulagi with attention to its structurally sensitive ice-cored moraine dam; and (iv) trigger-event focused early warning monitoring of Hongu 2, given its demonstrated capacity for episodic, threshold-driven expansion.

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Future work should incorporate high-resolution bathymetric surveys to refine volume estimates, field-validated glacier outline mapping using SAR and thermal infrared methods to quantify debris-covered ice loss, and updated cascade GLOF hydrodynamic modelling using the current 2024 lake volumes presented here.

Code and data availability

The Google Earth Engine code and Python analysis used in this study were developed entirely by authors. Landsat imagery w as accessed via Google Earth Engine (https://earthengine.google.com) and Sentinel-2 image was accessed via the Copernicus Open Access Hub (https://copernicus.eu), both of which are publicly available.

Author Contributions

AG conceptualized the study, designed the methodology, developed all Google Earth Engine and Python analysis codes, performed the data processing, conducted the statistical analysis, and led the writing manuscript. SM, TB, RK, and AD contributed to manuscript preparation, writing, and editing. KA and DP provided scientific review, supervision, and critical revision of the manuscript. All authors reviewed and approved the final version.

Competing Interests

The authors declare that they have no conflict of interest.

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References

Bajracharya, S. R., Maharjan, S. B., Shrestha, F., Guo, W., Liu, S., Immerzeel, W., & Shrestha, B. (2015). The glaciers of the Hindu Kush Himalayas: current status and observed changes from the 1980s to 2010. *International Journal of Water Resources Development*, *31*(2), 161–173. https://doi.org/10.1080/07900627.2015.1005731

Bajracharya, S. R., Maharjan, S. B., Shrestha, F., Sherpa, T. C., Wagle, N., & Shrestha A.B. (2020). *Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet autonomous region of China, and India*. International Centre for Integrated Mountain Development and United Nations Development Programme.

Bocchiola, D., Manara, M., & Mereu, R. (2020). Hydropower potential of run of river schemes in the himalayas under climate change: A case study in the dudh koshi basin of Nepal. *Water (Switzerland)*, *12*(9). https://doi.org/10.3390/W12092625

Bookhagen, B., & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research: Earth Surface*, *115*(3). https://doi.org/10.1029/2009JF001426

https://doi.org/10.5194/egusphere-2026-2402
Preprint. Discussion started: 13 May 2026

Byers, A. C., McKinney, D. C., Somos-Valenzuela, M., Watanabe, T., & Lamsal, D. (2013). Glacial lakes of the Hinku and Hongu valleys, Makalu Barun National Park and Buffer Zone, Nepal. *Natural Hazards*, *69*(1), 115–139. https://doi.org/10.1007/s11069-013-0689-8

Carrivick, J. L., & Tweed, F. S. (2013). Proglacial lakes: character, behaviour and geological importance. *Quaternary Science Reviews*, *78*, 34–52. https://doi.org/10.1016/J.QUASCIREV.2013.07.028

Chen, H., Liang, Q., Zhao, J., & Maharjan, S. B. (2024). *Assessing national exposure and impact to glacial lake outburst floods considering uncertainty under data sparsity*. https://doi.org/10.5194/hess-2023-260

Chen, H., Liang, Q., Zhao, J., & Maharjan, S. B. (2025). Assessing national exposure to and impact of glacial lake outburst floods considering uncertainty under data sparsity. *Hydrology and Earth System Sciences*, *29*(3), 733–752. https://doi.org/10.5194/hess-29-733-2025

Cook, S. J., & Quincey, D. J. (2015). Estimating the volume of Alpine glacial lakes. *Earth Surface Dynamics*, *3*(4), 559–575. https://doi.org/10.5194/esurf-3-559-2015

Duan, H., Yao, X., Zhang, Y., Jin, H., Wang, Q., Du, Z., Hu, J., Wang, B., & Wang, Q. (2023). Lake volume and potential hazards of moraine-dammed glacial lakes - A case study of Bienong Co, southeastern Tibetan Plateau. *Cryosphere*, *17*(2), 591–616. https://doi.org/10.5194/tc-17-591-2023

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., & Sharma, R. R. (2009). Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. *Environmental Research Letters*, *4*(4). https://doi.org/10.1088/1748-9326/4/4/045205

Gantayat, P., Sattar, A., Haritashya, U. K., Ramsankaran, R. A. A. J., & Kargel, J. S. (2024). Evolution of the Lower Barun lake and its exposure to potential mass movement slopes in the Nepal Himalaya. *Science of the Total Environment*, *949*. https://doi.org/10.1016/j.scitotenv.2024.175028

Gu, Y., Brown, J. F., Verdin, J. P., Wardlow, B., Gu, Y., Brown, J. F., Verdin, J. P., & Wardlow, B. (2007). A five-year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States. *Geophysical Research Letters*, *34*(6). https://doi.org/10.1029/2006GL029127

Gurung, N., Thakuri, S., Chauhan, R., Ghimire, N. P., & Ghimire, M. (2021). Dynamics of Lower-Barun Glacier and Glacial Lake and its GLOF Susceptibility Using Geospatial Analysis and Modelling. *Jalawaayu*, *1*(2), 57–77. https://doi.org/10.3126/jalawaayu.v1i2.41012

Haritashya, U. K., Kargel, J. S., Shugar, D. H., Leonard, G. J., Strattman, K., Watson, C. S., Shean, D., Harrison, S., Mandli, K. T., & Regmi, D. (2018). Evolution and controls of large glacial lakes in the Nepal Himalaya. *Remote Sensing*, *10*(5). https://doi.org/10.3390/rs10050798

Hermosilla, T., Francini, S., Nicolau, A. P., Wulder, M. A., White, J. C., Coops, N. C., & Chirici, G. (2023). Clouds and Image Compositing. *Cloud-Based Remote Sensing with Google Earth Engine: Fundamentals and Applications*, 279–302. https://doi.org/10.1007/978-3-031-26588-4_15/FIGURES/12

Hu, J., Yao, X., Duan, H., Zhang, Y., Wang, Y., & Wu, T. (2022). Temporal and Spatial Changes and GLOF Susceptibility Assessment of Glacial Lakes in Nepal from 2000 to 2020. *Remote Sensing*, *14*(19). https://doi.org/10.3390/rs14195034

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., & Paul, F. (2002). Remote sensing based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps. *Canadian Geotechnical Journal*, *39*(2), 316–330. https://doi.org/10.1139/t01-099

ICIMOD. (2011). *Glacial Lakes and Glacial Lake Outburst Floods in Nepal*.

ICIMOD. (2023). Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. In R. Chettri, N. Adve, C. Wickramagamage, & K. Shrestha (Eds.), *Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook*. ICIMOD. https://doi.org/10.53055/icimod.1028

Ives, J. D., Shrestha, R. B., & Mool, P. K. (2010). *Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment*.

https://doi.org/10.5194/egusphere-2026-2402
Preprint. Discussion started: 13 May 2026

Jin, H., Fang, S., & Chen, C. (2023). Mapping of the Spatial Scope and Water Quality of Surface Water Based on the Google Earth Engine Cloud Platform and Landsat Time Series. *Remote Sensing*, *15*(20). https://doi.org/10.3390/rs15204986

Kendall, & George, M. (1990). *Rank correlation methods*. Internet Archive. https://archive.org/details/rankcorrelationm0000unse/page/n1/mode/2up

Komori, J. (2006). Glacial Lake Expansion and Present Situation in Hinku and Hongu Regions, Eastern Nepal and Bhutan Himalaya. *Journal of Geography (Chigaku Zasshi)*, *115*(4), 531–535. https://doi.org/10.5026/jgeography.115.4_531

Kumar, A., Mal, S., Schickhoff, U., & Dimri, A. P. (2025). Basin-scale spatio-temporal development of glacial lakes in the Hindukush-Karakoram-Himalayas. *Global and Planetary Change*, *245*, 104656. https://doi.org/10.1016/J.GLOPLACHA.2024.104656

Lee, H., & Romero, J. (2023). Climate Change 2023 Synthesis Report IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. *IPCC*, 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245. https://doi.org/10.2307/1907187

Maskey, S., Kayastha, R. B., & Kayastha, R. (2020). Glacial Lakes Outburst Floods (GLOFs) modelling of Thulagi and Lower Barun Glacial Lakes of Nepalese Himalaya. *Progress in Disaster Science*, *7*. https://doi.org/10.1016/j.pdisas.2020.100106

McFeeters, S. K. (2013). Using the Normalized Difference Water Index (NDWI) within a Geographic Information System to Detect Swimming Pools for Mosquito Abatement: A Practical Approach. *Remote Sensing 2013, Vol. 5, Pages 3544-3561*, *5*(7), 3544–3561. https://doi.org/10.3390/RS5073544

Mudbhari, D., Kansal, M. L., & Kalura, P. (2022). Impact of climate change on water availability in Marsyangdi river basin, Nepal. *Quarterly Journal of the Royal Meteorological Society*, *148*(744), 1407–1423. https://doi.org/10.1002/QJ.4267

Nepal, S. (2016). Impacts of climate change on the hydrological regime of the Koshi river basin in the Himalayan region. *Journal of Hydro-Environment Research*, *10*, 76–89. https://doi.org/10.1016/j.jher.2015.12.001

Neupane, R. P., White, J. D., & Alexander, S. E. (2015). Projected hydrologic changes in monsoon-dominated Himalaya Mountain basins with changing climate and deforestation. *Journal of Hydrology*, *525*, 216–230. https://doi.org/10.1016/j.jhydrol.2015.03.048

Paul, F., Barrand, N. E., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S. P., Konovalov, V., Le Bris, R., Mölg, N., Nosenko, G., Nuth, C., Pope, A., Racoviteanu, A., Rastner, P., Raup, B., Scharrer, K., Steffen, S., & Winsvold, S. (2013). On the accuracy of glacier outlines derived from remote-sensing data. *Annals of Glaciology*, *54*(63), 171–182. https://doi.org/10.3189/2013AoG63A296

Pepin, N. C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., Palazzi, E., Seibert, P., Serafin, S., Schöner, W., Terzago, S., Thornton, J. M., Vuille, M., & Adler, C. (2022). Climate Changes and Their Elevational Patterns in the Mountains of the World. In *Reviews of Geophysics* (Vol. 60, Number 1). John Wiley and Sons Inc. https://doi.org/10.1029/2020RG000730

Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International*, *65–66*, 31–47. https://doi.org/10.1016/S1040-6182(99)00035-X

Rounce, D. R., Watson, C. S., & McKinney, D. C. (2017). Identification of hazard and risk for glacial lakes in the Nepal Himalaya using satellite imagery from 2000-2015. *Remote Sensing*, *9*(7). https://doi.org/10.3390/rs9070654

Scaramuzza, P., Micijevic, E., & Chander, G. (2004). *SLC Gap-Fill Methodology*.

https://doi.org/10.5194/egusphere-2026-2402
Preprint. Discussion started: 13 May 2026

539 Sen, P. K. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. *Journal of the American*
540 *Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

541 Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R.,
542 Betts, R. A., Harrison, S., & Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990.
543 *Nature Climate Change 2020 10:10*, *10*(10), 939–945. https://doi.org/10.1038/s41558-020-0855-4

544 Sigdel, K. P., Ghimire, N. P., Pandeya, B., & Dawadi, B. (2022). Historical and Projected Variations of
545 Precipitation and Temperature and Their Extremes in Relation to Climatic Indices over the Gandaki River
546 Basin, Central Himalaya. *Atmosphere*, *13*(11). https://doi.org/10.3390/atmos13111866

547 UNDP. (2025). *Green Climate Fund approves $36.1 million to help Nepal protect lives and livelihoods from*
548 *glacial flood risks | United Nations Development Programme*. https://www.undp.org/nepal/press-
549 releases/green-climate-fund-approves-361-million-help-nepal-protect-lives-and-livelihoods-glacial-flood-
550 risks

551 Vuichard, D., & Zimmermann, M. (1987). The 1985 Catastrophic Drainage of a Moraine-Dammed Lake,
552 Khumbu Himal, Nepal: Cause and Consequences. *Source: Mountain Research and Development*, *7*(2),
553 91–110. https://doi.org/10.7892/boris.72507

554 Wangchuk, S., & Bolch, T. (2020). Mapping of glacial lakes using Sentinel-1 and Sentinel-2 data and a random
555 forest classifier: Strengths and challenges. *Science of Remote Sensing*, *2*.
556 https://doi.org/10.1016/j.srs.2020.100008

557 Williams, D. L., Goward Samuel, & Arvidson, T. (2006). Landsat: Yesterday, Today, and Tomorrow.
558 *Photogrammetric Engineering & Remote Sensing*, *72*(10), 1171–1178. 10.14358/PERS.72.10.1171

559 Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The influence of autocorrelation on the ability to detect
560 trend in hydrological series. *Hydrological Processes*, *16*(9), 1807–1829. https://doi.org/10.1002/hyp.1095

561

562