AI-Driven Climate Intelligence for Climate Risk Prediction and Decision Making

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Chapter 8

Tracking Vegetation Dynamics After a Glacial Lake Outburst Flood (GLOF): A Multi-source Data Analysis from Sikkim Himalaya

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Summary

Glacial Lake Outburst Floods (GLOFs) are increasingly recognized as high impact climate driven hazards in the Himalaya, yet their ecological consequences, particularly forest loss and post disturbance vegetation trajectories, remain poorly quantified. The catastrophic outburst of South Lhonak Lake during 3–4 October 2023 in North Sikkim triggered one of the most severe GLOFs events in the Eastern Himalaya, causing extensive geomorphic damage along the Teesta River basin. This study evaluates spatio-temporal patterns of GLOF induced forest disturbance using a multi-source, multi temporal optical remote sensing framework. Pre and post event Sentinel-2A imagery (2023–2026) was integrated with Survey of India 1:50,000 toposheets, Forest Survey of India (FSI) forest density data (2019), SRTM 30 m digital elevation data, and Hansen Global Forest Loss datasets (2000–2024). Vegetation dynamics were evaluated using multi temporal NDVI analysis within a geomorphic and forest structural context to differentiate event driven impacts from background deforestation. Results indicate a substantial and progressive increase in forest loss following the GLOF, with the affected forest area expanding from 166.2 ha (4.1% forest cover) in 2023 to 254.8 ha (6.3%) in 2026, resulting in a net loss of 88.5 ha over three years. Moderate Dense Forest experienced the highest loss (62.3 ha), followed by Scrub Forest (49.5 ha) and Open Forest (35.4 ha), while Very Dense Forest also declined by 26.3 ha, underscoring the severity of disturbance. Forest loss was highly corridor controlled, concentrated along riparian zones, floodplains, terraces, and confined valley reaches. Continued degradation observed in 2026 imagery suggests prolonged ecological impacts driven by sediment instability and secondary geomorphic processes. The findings demonstrate that GLOFs functions not as a single event disturbance but as multi-year ecological regime shift, highlighting the integrate ecological indicators into post disaster risk and restoration planning.

Keywords: Glacial Lake Outburst Flood (GLOF); forest loss; Sentinel-2; riparian disturbance; Teesta River basin

1. Introduction:

The increasing frequency of landslides and associated hydro geomorphic hazards in recent decades has emerged as a serious concern for both human populations and natural ecosystems in the Indian biodiversity hotspots. Several extreme events underscore this alarming trend, including the Chooralmala landslide in Wayanad, Kerala (2024); the catastrophic failure of the Teesta III hydropower project in Sikkim triggered by a Glacial Lake Outburst Flood (GLOF) from South Lhonak Lake (2023); widespread landslides within the Kali Tiger Reserve, Karnataka, following an extreme rainfall event (2021); and the devastating Kedarnath floods in Uttarakhand (2013). In addition, recent disasters such as large scale land subsidence and slope instability in Joshimath, Uttarakhand (2023), and the rainfall induced floods and landslides across Himachal Pradesh (2023) further highlight the growing influence of climate driven extremes, glacier retreat, and unregulated infrastructure development on slope instability across mountainous regions of India.

Glacial Lake Outburst Floods (GLOFs) are increasingly recognised as one of the most consequential hydro-geomorphic hazards in high-altitude regions under contemporary climate change. Accelerated glacier retreat across the Himalaya has led to the rapid expansion and coalescence of moraine-dammed lakes, significantly increasing both the probability and magnitude of devastating outburst floods (Carrivick & Tweed, 2016; Sattar et al., 2025). While the impacts of such events on human lives, infrastructure, and hydropower systems are often immediately visible and widely reported, their ecological consequences particularly forest loss and long-term ecosystem disruption remain poorly quantified and conceptually underrepresented in hazard research.

Natural vegetated mountain river corridors perform critical ecological functions, including slope stabilisation, regulation of sediment fluxes, micro-climatic buffering, and habitat connectivity across steep altitudinal gradients. In the Himalaya, riparian and valley-floor vegetation such as forests, Grasslands and scrub are important given their role in mitigating erosion and sustaining biodiversity in ecologically fragile landscapes. However, GLOF-driven disturbances differ fundamentally from more commonly studied drivers of forest change such as logging, fire, or cyclones. Rather than generating discrete patches of canopy loss, GLOFs typically act through high-energy hydraulic stripping, massive sediment deposition, and prolonged geomorphic instability, resulting in linear, process-controlled patterns of forest damage and delayed tree mortality (Zhang et al., 2025).

The Glacial Lake Outburst Flood of 3 October 2023, originating from the catastrophic collapse of South Lhonak Lake in North Sikkim, represents a landmark event for understanding such climate-amplified disturbance regimes in the Eastern Himalaya. The event was one of the most severe GLOFs to occur in the Himalayas in recent decades (Zhang et al., 2025). Triggered by the collapse of a large volume of lateral moraine and associated landslide into the lake, the cascade released tens of millions of cubic metres of water and mobilised extraordinary sediment loads, producing a high-velocity flood wave that propagated over 380 km downstream along the Teesta River system (Mohanty et al., 2026; Sattar et al., 2025). The complete destruction of the Teesta Stage-III hydropower dam at Chungthang became the most visible symbol of the disaster; less visible, but equally consequential, were the extensive impacts on forested riverbanks, terraces, and lower valley slopes throughout the basin.

Recent post-event analyses demonstrate that the South Lhonak GLOF initiated a complex hazard cascade, including channel widening, bank erosion, aggradation, and the triggering of dozens of secondary landslides along the Teesta valley (Zhang et al., 2025). These processes directly affected forest ecosystems through multiple pathways: immediate uprooting of trees, burial of standing forests beneath thick sediment layers, destabilisation of root systems due to channel incision, and increased susceptibility to delayed slope failures during subsequent monsoon seasons. Such compound disturbances create long-term "ecological legacies," in which forest structure and composition remain altered for years or decades after the initial flood (Sattar et al., 2025; Times of India, 2025).

Despite the scale of these impacts, forest loss associated with the 2023 Teesta GLOF is largely absent from official deforestation statistics and forest inventory reports. Conventional forest monitoring frameworks, including national forest cover assessments, are poorly suited to capturing buried forests, partially damaged stands, or delayed post-disturbance mortality. As a result, there is no single authoritative estimate of forest loss attributable to the event, highlighting both a methodological and conceptual gap in disaster ecology assessments. Advances in Earth observation science offer new opportunities to address this gap through the integration of multi-source and multi-temporal datasets. High-resolution optical imagery from sensors such as Sentinel-2, Landsat derived tree loss data enables and forest cover density type analysis of vegetation trajectories. When combined with digital elevation models, topographical maps, vegetation indices, and time-series analysis, these datasets facilitate a process-based understanding of forest disturbance.

In this context, the Teesta basin offers a particularly instructive case study for such an approach. Characterised by steep relief, diverse forest types ranging from subtropical broadleaf to sub-alpine conifer systems, and extensive hydropower development, the basin represents a highly coupled natural–anthropogenic system. Identifying forest loss in this context therefore requires a temporally explicit, multi-sensor framework capable of capturing both immediate impacts and evolving post-disaster trajectories. This chapter aims to systematically capture vegetation loss and associated ecological impacts resulting from the 2023 South Lhonak Glacial Lake Outburst Flood (GLOF) in the Teesta river basin using a multi-temporal, multi-sensor optical remote-sensing framework supported by topographic and ancillary datasets. Specifically, it seeks to (i) map the spatial patterns of forest disturbance, (ii) pre and post vegetation dynamics, and (iii) assess vegetation density type loss. By foregrounding forests as critical, yet often overlooked, components of GLOF impact zones, the chapter seeks to contribute to more integrated assessments of climate-driven mountain hazards and to inform future restoration and risk-governance strategies in the Himalaya and beyond.

2. Study Area

2.1 Geographic Setting

The study focuses on the Teesta River basin in the eastern Himalaya, with particular emphasis on the river corridor downstream of South Lhonak Lake in the Indian state of Sikkim. The Teesta River originates from glacial and periglacial systems near the Indo-Tibetan boundary at elevations exceeding 5,000 m and flows southward through Sikkim before entering West Bengal and Bangladesh. Within Sikkim, the river passes through steep, deeply incised valleys characterised by narrow floodplains, high relief energy, and frequent mass-movement activity, making the basin highly sensitive to cryosphere-related hazards such as GLOFs and landslides (Mohanty et al., 2026; Zhang et al., 2025). South Lhonak Lake, located at approximately 5,200 m above sea level, is a moraine-dammed proglacial lake that expanded rapidly in the decades preceding the 2023 outburst due to sustained glacier retreat. The glacial lake failure on 3–4 October 2023 generated a high-magnitude flood wave that reached Chungthang approximately 60–70 km downstream within a short time window and propagated through the Teesta valley with exceptional erosive force (Sattar et al., 2025). This geomorphic connectivity makes the Teesta basin particularly suitable for corridor-based analysis of forest disturbance using multi-temporal satellite imagery. Details of study area map shown in Figure 1.

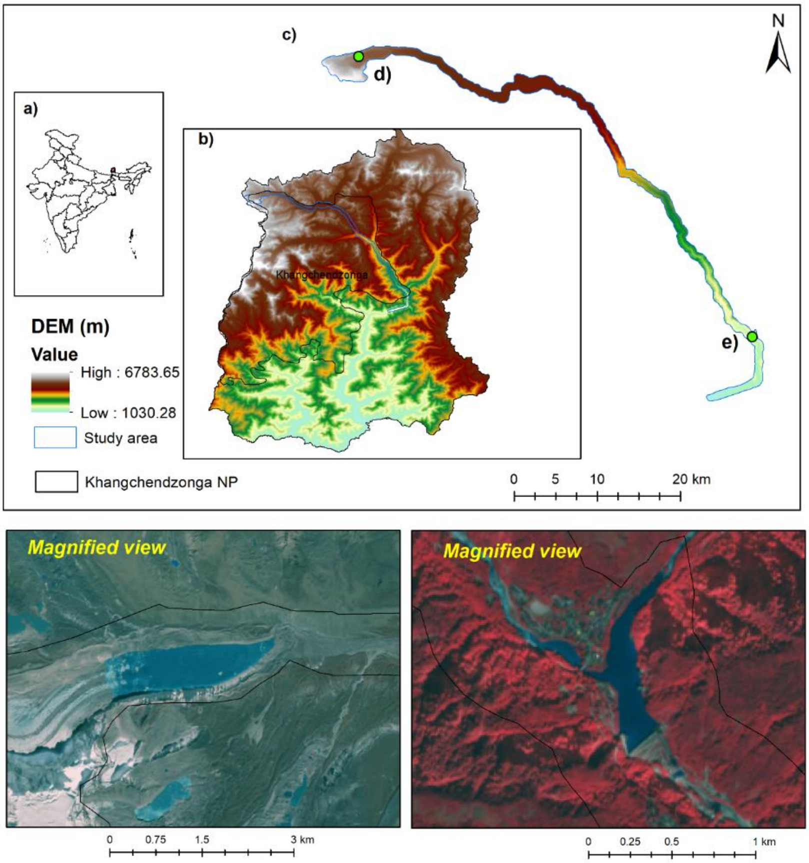

Figure 1. Study area maps showing: (a) the location of Sikkim within India; (b) the 30 m resolution SRTM Digital Elevation Model (DEM) illustrating elevation gradients across Sikkim, along with the boundary of Khangchendzonga National Park; and (c) the study area boundary with a magnified view highlighting the South Lhonak Lake (left) and the Teesta III Dam (right), based on satellite imagery acquired on 5 November 2022.

The Teesta basin experiences a monsoon-dominated climate, with roughly 70–80% of annual precipitation occurring between June and September. Precipitation increases sharply downstream and with decreasing elevation, while the upper basin is influenced by snowfall and glacial melt processes. Importantly, the October 2023 GLOF occurred outside the core monsoon period, highlighting the role of cryosphere-driven extremes as independent disturbance agents in Himalayan river systems (Sattar et al., 2025). Hydrologically, the basin is regulated by a combination of natural flow variability and extensive hydropower development. Multiple dams and diversions along the Teesta alter sediment continuity and channel morphology, thereby influencing how flood energy is translated into geomorphic and ecological impacts.

2.3 Forest Distribution and Ecological Characteristics

The Teesta basin contains a wide range of forest types distributed along a steep altitudinal gradient, from subtropical broadleaf forests at lower elevations (300–800 m), through temperate mixed and oak–conifer forests, to sub-alpine scrub and krummholz communities at higher elevations. Riparian forests along the Teesta and its tributaries form narrow but ecologically significant corridors that support bank stability, sediment regulation, and habitat connectivity. These forests are particularly vulnerable to extreme flood events due to their proximity to active channels and terraces. Post-event assessments indicate that the 2023 GLOF caused extensive uprooting of riparian vegetation, burial of standing forests under coarse sediment, and destabilisation of forested slopes adjacent to eroded riverbanks. Unlike clear-cutting or fire-driven disturbances, these impacts often remain spectral-ambiguous in the immediate aftermath, making time-series optical analysis essential for detecting delayed canopy decline and recovery patterns.

3. Methodology

3.1 Satellite Optical Data: Sentinel-2 MSI

3.1.1 Data Selection and Temporal Windows

Multi-temporal optical imagery from the Sentinel-2A MultiSpectral Instrument (MSI) was used as the primary dataset for forest condition and disturbance analysis (www.dataspace.copernicus.eu). Sentinel-2 data were selected due to their high spatial resolution (10 m), better temporal resolution, and suitability for vegetation index computation in complex terrain.

Three key temporal windows were defined:

- **Pre-GLOF baseline:** Sentinel-2A scenes acquired prior to 4 October 2023, representing stable pre-disturbance forest conditions.
- **Immediate post-GLOF period:** Sentinel-2 scenes from late 2023, capturing short-term vegetation response, canopy removal, and sediment-covered forest surfaces.
- **Extended post-GLOF period:** Sentinel-2 imagery from 2025 and, used to evaluate delayed forest mortality, early recovery patterns, and secondary disturbance effects.

Only cloud-free or minimally cloud-influenced scenes were selected, with images visually inspected to ensure consistency across seasons and illumination conditions.

3.1.2 Vegetation Indices and Forest Change Detection

Normalized Difference Vegetation Index (NDVI) was computed for all selected Sentinel-2 using red (Band 4) and near-infrared (Band 8) bands. NDVI layers were generated for: pre-GLOF conditions, immediate post-GLOF conditions, and latest available imagery representing longer-term post-GLOF effects. NDVI differencing and comparative analysis were used to identify areas of abrupt vegetation loss, gradual decline, and partial recovery. Attention was given to linear disturbance patterns aligned with river corridors, which are characteristic of GLOF-driven ecological impacts rather than anthropogenic deforestation.

3.2 Topographic Data: SRTM DEM

A 30 m resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (NASA Shuttle Radar Topography Mission (SRTM) 2013) was used to characterise terrain controls on forest disturbance patterns. Derived terrain variables included elevation, slope, and valley confinement, which were used to: interpret spatial variability in flood impact intensity, distinguish valley-floor from slope-associated forest damage, and identify geomorphically sensitive zones prone to erosion and sediment deposition. The DEM provided the topographic framework for integrating optical disturbance patterns with underlying geomorphic processes. This study also used the high-resolution Google earth Pro images for understanding the various land cover details (**https://www.google.com/earth/**).

3.3 Forest Cover and Density Type Data

Forest density information from the **Forest Survey of India (FSI) 2019** dataset was integrated to classify forests into standard density categories (very dense, moderately dense, and open forest). This enabled assessment of whether disturbance patterns showed preferential impacts on specific forest density classes (Forest Cover density and type 2019). The FSI dataset also served as an authoritative baseline for interpreting forest condition prior to the GLOF.

3.4 Cartographic Reference: SOI Toposheets:

Survey of India (SOI) 1:50,000 scale topographic maps were used as cartographic reference data for: validating forest type distribution, identifying historical river alignment and valley features, and providing contextual information on settlements, roads, and landforms. These maps were particularly useful in areas where satellite interpretation was affected by shadow or rugged terrain.

3.5 Global Forest Change Data and Integration

The Hansen et al. Global Forest Change dataset (2000–2024) was used to identify long-term tree cover loss trends within the study area. This dataset provided a valuable historical framework to differentiate: pre-existing deforestation patterns, background forest loss unrelated to the GLOF, and areas where post-2023 changes represented anomalous disturbance. To ensure relevance to current conditions, the Hansen dataset was updated and refined using post-2023 Sentinel-2 imagery, allowing detection of newly affected forest areas not yet captured in global loss products. The details of the datasets used in the study are provided in Table 1.

Table 1. Datasets Used in the Study and Their Spatial and Temporal Characteristics

Dataset	Source	Spatial Resolution	Temporal Coverage	Role in Analysis

Sentinel -2A MSI	ESA	10 m	Pre-Nov 2022; Post-Oct 2023; and Feb-2026	NDVI, forest disturbance mapping
SRTM DEM	NASA	30 m	Static	Terrain, valley confinement
Forest cover (FSI) 2019	https://indiawris.gov.in/wris/#/geoSpatialData	1:50k equivalent	2019	Baseline forest condition
SOI Toposheets	Survey of India	1:50,000	Historical	Forest type & landscape reference
Global Forest Change	Hansen et. al.	30 m	2000–2024	Long-term tree loss trends
Updated forest status	Sentinel-2A	10 m	2024–2026	Post-GLOF refinement

3.6 Attribution of Forest Loss to the GLOF

Attribution of forest loss to the 2023 GLOF was based on spatial, temporal, and geomorphic criteria, including: coincidence with the post-GLOF time window, linear alignment along river corridors, proximity to floodplains, terraces, and eroded banks, and absence of similar disturbance signals in pre-2023 imagery. This integrative approach facilitated the separation of GLOF-driven forest impacts from background deforestation and other land-use changes.

While the use of multi-temporal optical imagery enables robust assessment of vegetation dynamics, limitations remain due to cloud cover during the immediate post-event period and challenges in distinguishing buried forests from exposed sediment surfaces. These constraints were mitigated through careful scene selection, time-series comparison, and integration of structural, density, and topographic datasets.

4. Results and Discussions

4.1 Overall Distribution of Forest Disturbance

Multi temporal analysis of Sentinel-2A imagery reveals that forest loss associated with the 2023 South Lhonak Glacial Lake Outburst Flood (GLOF) is spatially heterogeneous and strongly corridor controlled, rather than being uniformly distributed across the Teesta Basin. Disturbance patterns are predominantly concentrated along the active river channel, floodplains, low terraces, and confluence zones, forming elongated linear patches that contrast sharply with the polygonal deforestation patterns identified elsewhere in the basin using long term forest loss datasets. Similarly, Swarada et al. (2024) examined landslide induced deforestation in the Western Ghats using a comprehensive multi source geospatial framework and demonstrated that post landslide disturbances, including increased land surface temperature (LST), landscape fragmentation, and topsoil loss, collectively alter local microclimatic conditions.

Comparison between pre-GLOF (pre-October 2023) and immediate post-GLOF imagery shows abrupt NDVI reduction along several tens of kilometres of the Teesta River corridor downstream of Chungthang. These areas correspond to zones of direct flood impact, including channel widening, bank erosion, and sediment deposition. In contrast, upland forest areas removed from the river corridor exhibit relatively stable NDVI values, indicating that large-scale forest disturbance was spatially constrained by valley morphology rather than rainfall-driven slope wash alone.

4.2 Linear Forest Disturbance Along Riparian and Valley Floor Zones

The most pronounced forest loss is observed in riparian and valley-floor forests, where NDVI decrease is abrupt and sustained across multiple post-event time steps. Sentinel-2 derived NDVI differencing indicates complete or near-complete vegetation removal in narrow belts adjacent to the active channel, consistent with hydraulic stripping and uprooting of trees during peak flood discharge. Field interpretation supported by SOI toposheets and SRTM-derived valley confinement analysis suggests that narrow gorge sections experienced higher intensity forest removal than wider valley reaches. In these confined sections, flow energy was concentrated, resulting in extensive scour of riverbanks and removal of mature riparian stands. In contrast, wider valley sections show evidence of forest burial rather than total removal, with reduced but non-zero NDVI values indicative of sediment-covered vegetation rather than immediate canopy loss.

The multi temporal NDVI maps derived from Sentinel-2A imagery illustrate a clear and progressive increase in non green (low NDVI) areas within and around the GLOF impacted reach of the Teesta River corridor. The pre event condition (Figure 2 a; 05 November 2022) is characterized by continuous moderate to high NDVI values, indicating relatively intact riparian and valley floor vegetation with limited exposure of bare substrate. Vegetation is well distributed along the river margins, with narrow channel width and minimal disturbance signatures.

In contrast, the post GLOF imagery acquired on 26 October 2023 (Figure 2 b) shows a noticeable expansion of low NDVI zones, particularly along the active river channel and adjacent floodplain surfaces. These areas reflect widespread removal of vegetation due to high energy flood flows, hydraulic stripping, debris flow, bank erosion, and initial sediment deposition. The disturbance pattern is strongly linear and corridor controlled. The 17 February 2026 imagery (Figure c) further reveals continued expansion and persistence of low NDVI areas, despite temporal separation from the primary GLOF event. The magnified views (Figures d–f) clearly demonstrate widening of the river channel, reactivation of successive landslides along valley slopes, and extensive sediment burial of previously vegetated surfaces. These processes have inhibited vegetation recovery and resulted in delayed canopy decline and conversion of forested pixels into non vegetated or sparsely vegetated surfaces. The persistence of low NDVI values in 2026 indicates prolonged ecological stress driven by unstable sediments, altered hydrology, and repeated slope failures, rather than rapid post event recovery Figure 2.

Overall, the NDVI trajectories confirm that the South Lhonak GLOF initiated a multi year disturbance regime, transforming riparian and valley floor ecosystems through channel expansion, landslide reactivation, and sediment redistribution, leading to progressive and spatially structured vegetation loss. These areas are important ecologically, as buried forests may not immediately register as “lost” in standard forest-cover assessments but represent functionally degraded systems with altered regeneration potential.

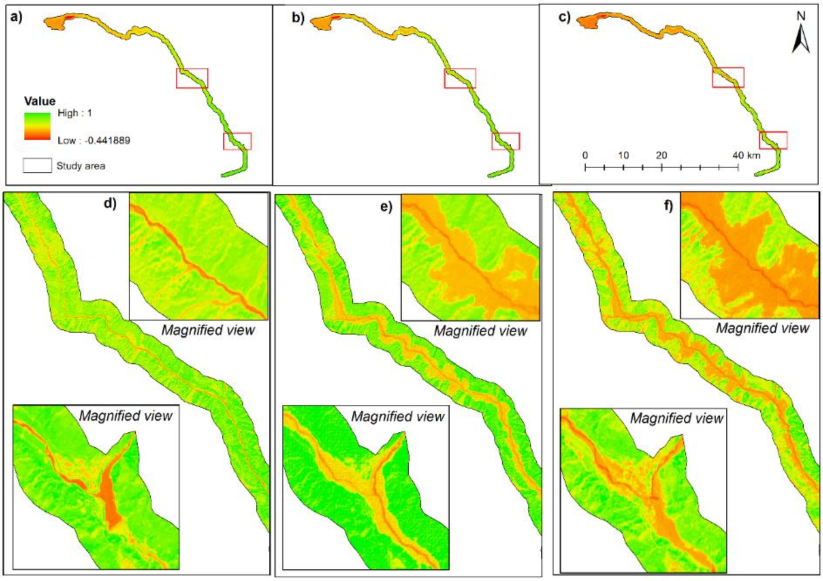

Figure 2. Multi temporal Normalized Difference Vegetation Index (NDVI) maps illustrating vegetation dynamics in the GLOF impacted reach of the Teesta River basin. Panels (a–c) show NDVI conditions on 05 November 2022 (pre GLOF), 26 October 2023 (post GLOF), and 17 February 2026 (post disturbance phase), indicating a progressive increase in non vegetated (low NDVI) surfaces. Panels (d–f) present magnified views highlighting the expansion of low NDVI zones associated with river channel widening, sediment deposition, debris flow, and successive

landslide reactivation, resulting in sustained vegetation loss across riparian and valley floor.

4.3 Impacts on Forest Density

Overlay analysis using the Forest Survey of India (FSI) 2019 forest density classification indicates that a total of 4029.7 ha, representing 41.3% of the study area, is under forest cover. Among the forest density classes, Very Dense Forest (VDF), Moderately Dense Forest (MDF), Open Forest (OF), and Scrub Forest (SF) account for 10.9%, 16.2%, 10.5%, and 3.7% of the total geographical area, respectively.

Assessment of forest loss induced by the South Lhonak GLOF event in North Sikkim between 2023 and 2026 reveals a substantial and progressive increase in disturbance across the impacted forested landscape. In 2023, forest loss accounted for 1.6% of the total geographical area, which increased to 2.5% by 2026. This corresponds to 4.1% and 6.3% of the total forest cover, respectively, across all forest density classes. Detailed analysis shows that VDF loss increased from 60.5 ha in 2023 to 86.7 ha in 2026, representing a loss of 2.5%. MDF experienced a higher proportional loss of 3.9%, increasing from 105.8 ha to 168.0 ha during the same period, followed by Open Forest, which recorded a loss of 3.5%.

Scrub Forest exhibited the highest relative loss, with a decline of 13.6% between 2023 and 2026, increasing from 34.8 ha to 84.4 ha. Overall, the total forest area affected by loss increased from 166.2 ha in 2023 to 254.8 ha in 2026, resulting in a net forest loss of 88.5 ha over the three year period. Among the vegetation types, MDF experienced the greatest absolute loss, followed by Scrub Forest (49.5 ha) and Open Forest (35.4 ha). Notably, VDF typically characterized by greater ecological stability also suffered a loss of 26.3 ha, underscoring the intensity, severity, and degree of damage along with spatial reach of the GLOF induced disturbance. Details of spatio-temporal changes in various forest types depicted in Figure 3.

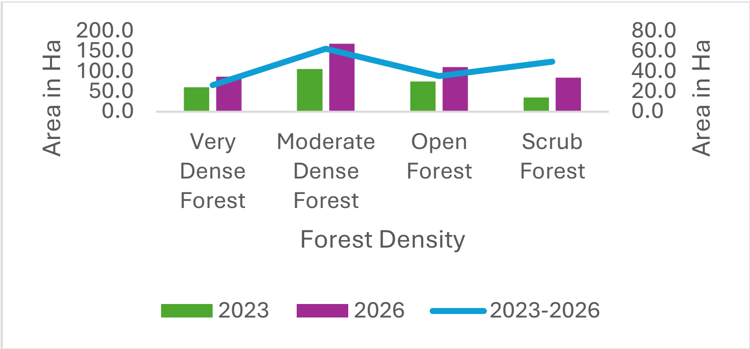

Figure 3. Spatio temporal variation in forest loss across major forest density classes in North Sikkim following the South Lhonak Glacial Lake Outburst Flood (GLOF) event.

The observed pattern of forest loss reflects the combined effects of high-energy floodwaters, channel erosion, slope failure, debris flow, and sediment deposition associated with the GLOF. The explicit loss of Moderate Dense and Open Forests suggests that forests with lower canopy cohesion and root strength are particularly vulnerable to sudden hydrological extremes in undulated Himalayan terrain. The substantial increase in scrub forest loss may indicate degradation of previously forested areas, where dense vegetation has been removed or converted into sparsely vegetated or unstable surfaces. Notably, the loss of Very Dense Forest underscores severe ecological damage, as such forests are generally resilient and only impacted under extreme disturbance. Overall, the results demonstrate that the GLOF triggered widespread forest loss across multiple vegetation classes in North Sikkim, emphasizing the need for post-disaster ecological restoration, long-term monitoring, and integration of GLOF risk into forest and watershed management planning.

4.4 Temporal Trajectories: Immediate vs Delayed Forest Loss

Comparison between immediate post-2023 imagery and 2026 Sentinel-2 data demonstrates that forest loss associated with the GLOF is not limited to the initial impact window. Several areas that exhibited only moderate NDVI decline immediately after the flood show further deterioration in 2026, suggesting delayed mortality caused by root exposure, prolonged waterlogging, slope destabilisation, or repeated monsoon-season reactivation of disturbed surfaces. Conversely, limited signs of early regrowth are observed on exposed gravel bars and low-lying deposition surfaces, indicated by slight NDVI recovery. However, this regrowth is largely confined to pioneer vegetation or invasion and does not represent recovery of pre-existing forest structure. A study by Swarada et al., (2024) indicates colonisation of invasive alien plant species in a post landslide event in the Western Ghats.

4.5 Distinguishing GLOF-Driven Loss from Background Deforestation

Integration of Hansen Global Forest Change data (2000–2024) indicates that most GLOF-affected forest areas do not coincide with long-term deforestation hotspots in the basin. Where overlap exists, updated Sentinel-2 analysis shows a sharp acceleration of forest loss after 2023, reinforcing attribution of disturbance to the GLOF rather than ongoing anthropogenic clearing. This combined approach allows separation of episodic, event-driven forest loss from gradual land-use change, highlighting the distinct spatial signature of GLOF-induced ecological disturbance (**Figure 4**).

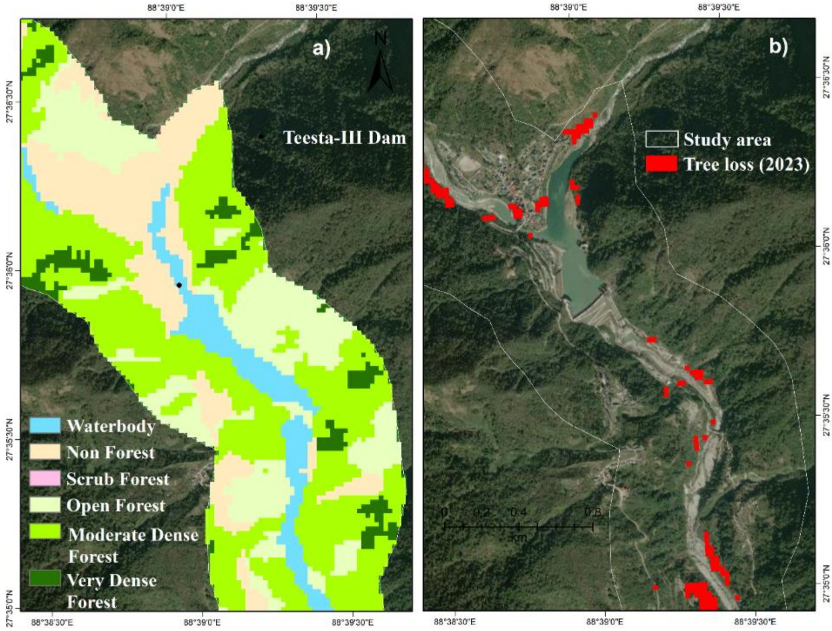

Figure 4. (a) Spatial distribution of major forest cover density classes based on Forest Survey of India data, and (b) Hansen Global Forest Change tree loss dataset highlighting forest loss during 2023 in and around the Teesta III dam environs.

4.6 Limitations and Uncertainty

There are uncertainties associated with the persistent cloud cover and shadow effects in undulated Himalayan terrain with limited availability of cloud-free optical imagery, particularly immediately after the GLOF. The optical indices such as NDVI cannot always distinguish between sediment deposition, vegetation and exposed sediment, possibly under capturing forest loss. Finally, attribution of delayed forest decline to the GLOF becomes increasingly uncertain with time due to interacting influences of monsoon rainfall, slope instability, and anthropogenic pressures. Despite these constraints, the integration of multiple datasets and temporal windows enhances confidence in identifying dominant spatial patterns of GLOF-driven forest disturbance.

5. Conclusions:

This study underscores the critical value of integrating multi source datasets to evaluate vegetation dynamics associated with glacial lake outburst flood (GLOF) events. By comparing pre and post GLOF vegetation trajectories, our analysis extends beyond the conventional hydro geological and hazard centric perspectives that dominate existing GLOF research. The results reveal a substantial escalation in forest disturbance, with the total impacted forest area increasing from 4.1% in 2023 to 6.3% in 2026, corresponding to a net forest loss of 2.2% over a three year period based on FSI 2019 forest cover. This loss is primarily attributed to the combined effects of flood driven erosion, extensive sediment deposition, and the reactivation of slope instabilities, leading to large scale conversion of forest and scrublands and pronounced lateral expansion of the river channel.

The observed patterns highlight the long term ecological implications of GLOF events, particularly the destabilization of riparian and valley floor ecosystems that are highly vulnerable to repeated geomorphic disturbances. The findings emphasize the need to incorporate ecological indicators into post-disaster assessments and risk mitigation frameworks. To reduce the impacts of future landslides and secondary disturbances, targeted restoration measures focusing on soil stabilization, bioengineering techniques, and the reestablishment of site-appropriate native vegetation are strongly recommended. Such ecosystem-based interventions are essential for enhancing slope resilience, limiting further forest degradation, and supporting sustainable landscape recovery in high mountain river basins.

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