



Brief Communication: Multisource Remote Sensing Detects Growing Himalayan Glacial Lake Outburst Flood Hazards

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Abstract:

Increasing outburst flood hazards from melting glaciers threaten Himalayan communities but are difficult to assess. On 16 August 2024, a catastrophic Glacial Lake Outburst Flood (GLOF) occurred unexpectedly in the Bhotekoshi River Valley, in the Mt. Everest region of Nepal. Using this disaster as an illustration, we demonstrate that combining new and legacy satellite remote sensing technologies for lake water level, turbidity, and extent can detect potential GLOF hazards and help identify these risks.

1. Introduction

On 16 August 2024, a catastrophic Glacial Lake Outburst Flood (GLOF) occurred unexpectedly in the Bhotekoshi River Valley, near Mt. Everest, Nepal. It was triggered by overtopping of a newly formed glacial lake, which cascaded into a neighboring lake, causing both to breach and drain suddenly into the valley. The GLOF (hereafter Thame GLOF) destroyed critical bridges and hydropower infrastructure; and a school, a hospital clinic, and ~40 homes in Thame (one of Nepal's oldest Sherpa communities, **Fig. 1**). The event disrupted the region's communications and trail systems for Mt. Everest at the start of the tourist season, an important source of income for the region. Ongoing post-GLOF hazards include landslides, riverbank erosion, and ground fissures in Thame. Societal damages include losses of property and income from the flood, and decades of future engineering issues due to abrupt deposition of a massive sedimentary valley train now moving 10s-100s of kilometers downstream (**Fig. 1d**).



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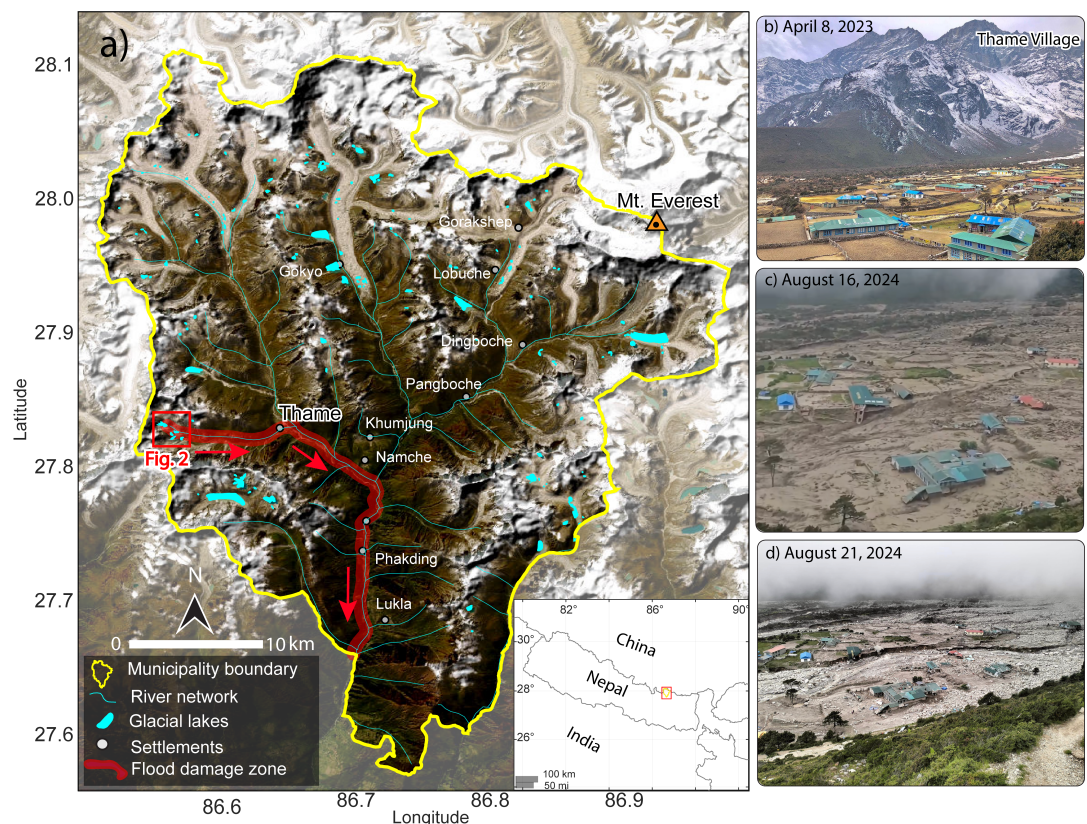


Figure 1. Study site **a)** Khumbu Pasang Lhamu municipality, Everest region, Nepal (yellow boundary), showing origin and path of the 16 August 2024 glacial lake outburst flood (GLOF), human settlements, other glacial lakes (cyan polygons) from Zhang et al. (2024) and rivers (cyan lines) and the background image is from Earthstar Geographics, World Imagery base map retrieved from MathWorks Mapping Toolbox. Red box shows location of GLOF origin (see **Fig. 2**), and the red arrows indicate flood flow direction and damage zone. Panels **b) - d)** show Thame Village (3820 m a.s.l.) before (8 April 2023), during (16 August 2024, 1:25 pm Nepal time), and **d)** after (21 August 2024) the GLOF disaster, including flood inundation (**c)** and sediment deposition (**d**).

GLOFs are a growing hazard in the Himalayas due to climate warming in High Mountain Asia (HMA) (Compagno et al., 2022; Furian et al., 2022; Zheng et al., 2021), which is occurring at twice the mean global average rate (Yao et al., 2022). Due to this warming, the region has experienced increased retreat and melting of glaciers (Miles et al., 2021; Yao et al., 2012) leading to ice-dammed lakes (Compagno et al., 2022) and newly formed proglacial lakes impounded behind moraines (Nie et al., 2017), which are susceptible to sudden drainage. Between 2000 and 2020, HMA proglacial lakes have grown by approximately +47% in number, +33% in area, and +42% in volume (Zhang et al., 2023). By the end of the 21st century HMA glacial lake volumes are projected to increase tenfold (Furian et al., 2022), and GLOFs to triple



(Zhang et al., 2024), one of the major cryospheric hazards. Globally, some 15 million people are already exposed to GLOF impacts (Taylor et al., 2023). While engineered mitigation measures are possible (Reynolds et al., 1998; UNDP, 2016), it is challenging to identify emerging GLOF hazards, as they commonly form in inaccessible mountainous areas. Using the 16 August 2024 Thame GLOF disaster for illustration, we demonstrate how optical and radar satellite remote sensing offer powerful tools for identifying emerging GLOF hazards in such areas.

2. Methods

A combination of high-resolution optical and radar satellite imagery was used to investigate five upstream glacial lakes before and after the Thame GLOF event. A historical archive of cloud-free historical Landsat optical imagery from 1991 to 2024 (30m resolution) was examined to determine the timing of the development of any new glacial lake(s) or growth of existing ones. Daily images from PlanetScope CubeSat satellite (~3 m resolution), captured before (15 August 2024) and after (17 August 2024) the flood event, were also analyzed. The Normalized Difference Water Index (NDWI) (McFeeters, 1996) was used to obtain the spatiotemporal evolution of lake area time series for LandSat. Sentinel-2, L2A cloud-free and likely snow-free imagery (10m resolution) acquired during the melt seasons (May1 – November31) of 2016-2024 taken were used to calculate the Normalized Difference Turbidity Index (NDTI) (Lacaux et al., 2007) to assess lake water turbidity. The melt season time window was extended to November 30 to compensate for data gaps caused by cloud cover. The Surface Water and Ocean Topography (SWOT) mission's Level 2 HR pixel cloud product (~22 m resolution) (SWOT L2_HR_PIXC) (Jet Propulsion Laboratory, 2023), PGO-version from science orbit on 29 June 2024 from pass 286 was used to investigate Water Surface Elevation (WSE) prior to the flood. SWOT PIXC products are pre-processed radar data corrected for radiometric, orbital, and co-registration requirements. SWOT pixel cloud 'height' data, which are geolocated and relative to the reference ellipsoid WGS84, was used. A model-based estimate of tides is applied to each SWOT height pixel separately, accounting for solid Earth (Cartwright and Edden, 1973; Cartwright and Tayler, 1971), load (Ray, 2013), pole (Wahr, 1985), and geoid (computed by EGM2008) (Pavlis et al., 2012), as these effects are expected to vary pixel by pixel. Each of these variables is provided in the SWOT product. Ultimately, orthometric and tide-corrected height was obtained. The WSE of open water PIXC classification was used and spatially averaged to obtain mean WSEs for lakes. Direct field observation images taken after the flood event were also analyzed to gain a better understanding of the event.

3. Results

3.1. Detection of newly forming glacial lakes from space

Examination of historical Landsat optical imagery (30m resolution) reveals a glacier in 1991 (**Fig. 2a**) that retreated and formed a new, unnamed proglacial lake by 2008 (**Lake 1, Fig. 2b**). From September 2008 to June 2024 this lake grew >1000% in area, unlike surrounding Lakes 2-5 which remained relatively stable over this time period. The time-series of lake area evolution of all five lakes is shown in **Fig. S1** in the supplement. On or near 16 August 2024 Lake 1 breached into Lake 5 which then also breached, releasing an estimated 380,000 cubic meters (Department of Hydrology and Meteorology, Nepal, 2024) of water down Bhotekoshi Valley.

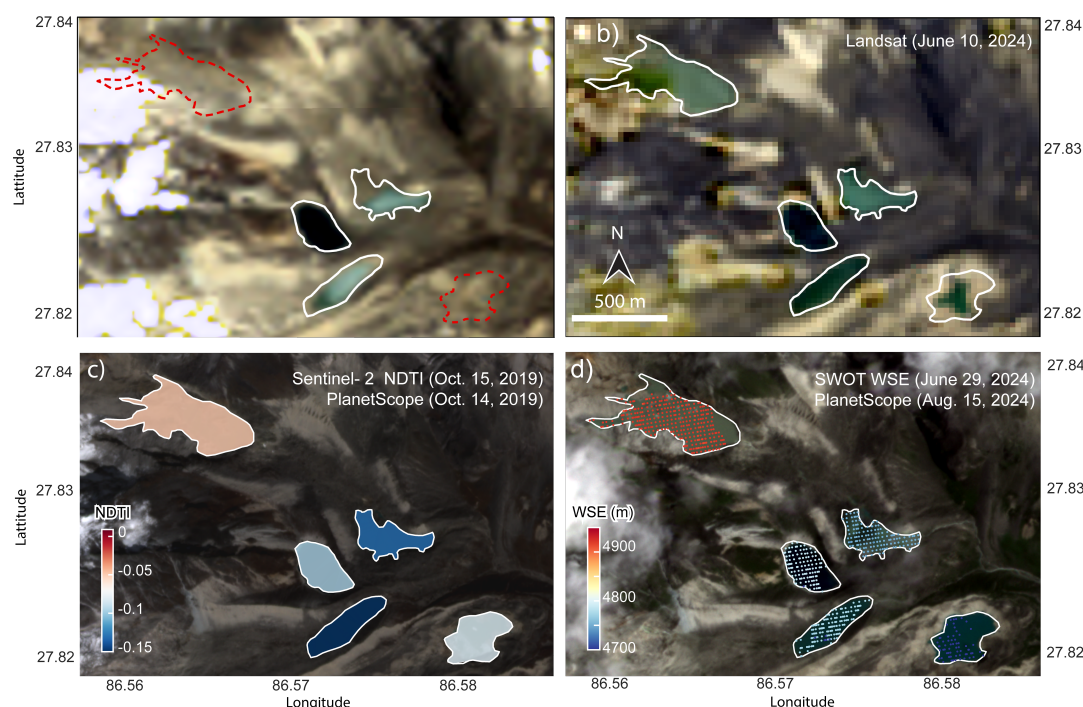


Figure 2. Closeups of GLOF origin (see red box in Fig. 1): **a)** 7 May 1991 Landsat image from US Geological Survey (USGS) showing debris-covered outlet glacier in a location of future Lake 1 (red dashed line, see also future Lake 4) together with stable **Lakes 2, 3, 5** (white polygons, from a cloud-free 15 August 2024 PlanetScope image from Planet Labs); **b)** 10 June 2024 Landsat image (from USGS), showing fully developed **Lake 1**, growth of **Lake 5** and appearance of **Lake 4**; **c)** Sentinel-2 (obtained from Copernicus Sentinel data) based Normalized Difference Turbidity Index (NDTI), from 15 October 2019, and a background PlanetScope image from 14 October, 2019 (courtesy: Planet Labs); **d)** SWOT water surface elevations from 29 June 2024 (SWOT PIXC product, pass 286 retrieved from NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC), and a background PlanetScope image obtained by Planet Labs for 15 August 2024, one day before the GLOF.

3.2. Water turbidity

Optical remote sensing provides further understanding of this GLOF event through observations of water turbidity and color. Proglacial lakes actively receiving glacial runoff are more turbid and have a milky blue color (due to high suspended sediment concentration from subglacial mechanical erosion) than lakes receiving water from snowmelt only (Hall, 2011). The remotely sensed NDTI (Lacaux et al., 2007) has values ranging from -1 to 1, with a lower (negative) value indicating clear water and a higher value indicating turbid water (Garg et al., 2020). NDTI retrievals from Sentinel-2 L2A (10m resolution) over the 2024 GLOF source area reveal the highest turbidity in Lake 1 (NDTI= -0.04) (Fig. 2c), suggesting receipt of meltwater from the retreating upstream glacier. This indicates increased melt and potential growth in lake extent. In contrast, Lakes 2-5 have lower turbidity (NDTI= -0.19 to -0.08) (Figure 2c).



3.3. Water surface elevations

Interferometric Synthetic Aperture Radar observations of WSE from the SWOT satellite (~20m resolution) reveal a large, ~170-meter pre-GLOF hydraulic head difference between Lake 1 and Lake 5 (4921 vs. 4750 m a.s.l.), the largest WSE difference in this area (**Fig. 2d**). This portends high stream power, bed shear stress, and erosive power in any channel connecting the two lakes (Whipple and Tucker, 1999). While not visibly connected prior to the 16 August 2024 GLOF, the flood quickly eroded a massive ~95-150 m wide channel (measurable in PlanetScope satellite imagery, 3.7 m resolution) connecting Lake 1 with Lake 5 and causing Lake 5 to also breach, and drain (**Fig. S2**). New SWOT observations thus enable mapping of hydraulic head and other hydrodynamic characteristics (slope, discharge, WSE fluctuations) to assess GLOF hazard potentials.

4. Discussions and Conclusions

Viewed collectively these three remote sensing technologies reveal: 1) formation and growth of an unnoticed proglacial lake hazard (from the historical Landsat archive); 2) affirmation this lake was receiving glacial meltwater (located immediately downstream of a receding glacier; high turbidity from Sentinel-2); and 3) high erosion potential should the lake overtop its basin (~170m WSE difference, from SWOT). While not a “smoking gun” that a GLOF would occur, the convergence of all three phenomena at a specific location and the ease with which they could be observed suggests that satellite remote sensing can help identify emerging GLOF risks in remote, mountainous areas. Landsat optical imagery has long been utilized for mapping glacial lake formation and extents (Bajracharya et al., 2020; Nie et al., 2017; Zhang et al., 2023). Our examination of Sentinel-2 observations for 89 lakes inside Khumbu Pasang Lhamu municipality (Fig.1) finds the highest NDTI values (-0.15 to -0.03) (**Supplementary Fig. S3**) in six proglacial lakes independently known to be receiving glacial meltwater (Bajracharya et al., 2020; Zhang et al., 2023) using Sentinel-2 from 2016-2023 (except 2017-18) using datasets from melt time period. WSE has not been measured to date with this spatial density, as measured by SWOT, and certainly not on a monthly scale. Early SWOT observations contain WSE retrievals for hundreds of lakes throughout the HMA region every 21 days (<https://podaac.jpl.nasa.gov/>).

GLOFs are a natural hazard endemic to glaciated mountain ranges such as the Himalayas, Andes, and the Alps (Emmer, 2024; Emmer et al., 2022; Huggel et al., 2002; Veh et al., 2020). Due to inaccessibility and remoteness, these hazards are often difficult to identify and monitor. Satellite programs such as Landsat, Sentinel-2, PlanetScope, and SWOT can help detect growing glacial lake outburst flood hazards at an early stage, aiding global efforts to mitigate potential climate hazards and impacts.



Data availability:

Landsat data were obtained from the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) on-demand interface, accessible through the USGS Earth Explorer portal (<https://earthexplorer.usgs.gov/>). Sentinel-2 data are provided by the European Space Agency (ESA) under the Copernicus program and can be accessed via the Copernicus Open Access Hub (<https://scihub.copernicus.eu/>). Surface Water and Ocean Topography (SWOT) mission data were accessed from NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC), available at <https://podaac.jpl.nasa.gov/>. PlanetScope datasets are available at (<https://www.planet.com/explorer/>). Produced lake area time series, NDTI of 84 lakes, and WSEs of lakes are available at Sherpa et al.(2025) <https://doi.org/10.5281/zenodo.14635544>.

Author contributions:

S.F.S. and L.C.S. conceptualized the opinion piece. S.F.S led the original manuscript writing, methodology, and investigation, and created the illustrations. B.W. carried out Landsat methods and analysis. L.C.S., B.W., and C.S. contributed reviews and editing of the manuscript and figures.

Competing interests: Authors declare no competing interests

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