CLIMATE-RESILIENT DAMS AND HYDROPOWER INFRASTRUCTURE INTEGRATING ENVIRONEMENTAL SUSTAINABILITY IN PLANNING AND DEVELOPMENT

Climate Change Impact on the Himalayan Cryosphere: Glacier Studies and Risk Assessment

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Resilient India - Disaster Free India

Contents

- Climate change is for real- Global and India scenario
- Impacts
- Glacial lakes in the Indian Himalayas
- Anatomy of GLOF threat
- Case studies- Sikkim and Chamoli
- Lake monitoring
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- Key Implementation Challenges
- Strategic Framework for Resilience

Climate Change is for REAL
Cues from IPCC AR6

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ESTD. 1927
NEW DELHI

IPCC WGI Interactive Atlas: Regional synthesis

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SELECT VISUALIZATION

MAP | REGIONS | COMBINATIONS

- Russian Far East (RFE)
- East Asia (EAS)
- East Central Asia (ECA)
- Tibetan Plateau (TIB)
- **South Asia (SAS)**
- South East Asia (SEA)

AUSTRALASIA

- Northern Australia (NAU)
- Central Australia (CAU)
- Eastern Australia (EAU)
- Southern Australia (SAU)
- New Zealand (NZ)

CENTER & SOUTH AMERICA

- Southern Central America (SCA)
- North-Western South America (NWS)
- Northern South America (NSA)
- South American Monsoon (SAM)

Landslide	Medium confidence of increase	—
Fire weather	Medium confidence of increase	—
SNOW AND ICE		
Snow, glacier and ice sheet	High confidence of decrease	Downward trend without attribution
Permafrost	High confidence of decrease	Downward trend without attribution
Lake, river and sea ice	High confidence of decrease	—
COASTAL		
Relative sea level	High confidence of increase	Upward trend without attribution
Coastal flood	High confidence of increase	—
	High confidence of	

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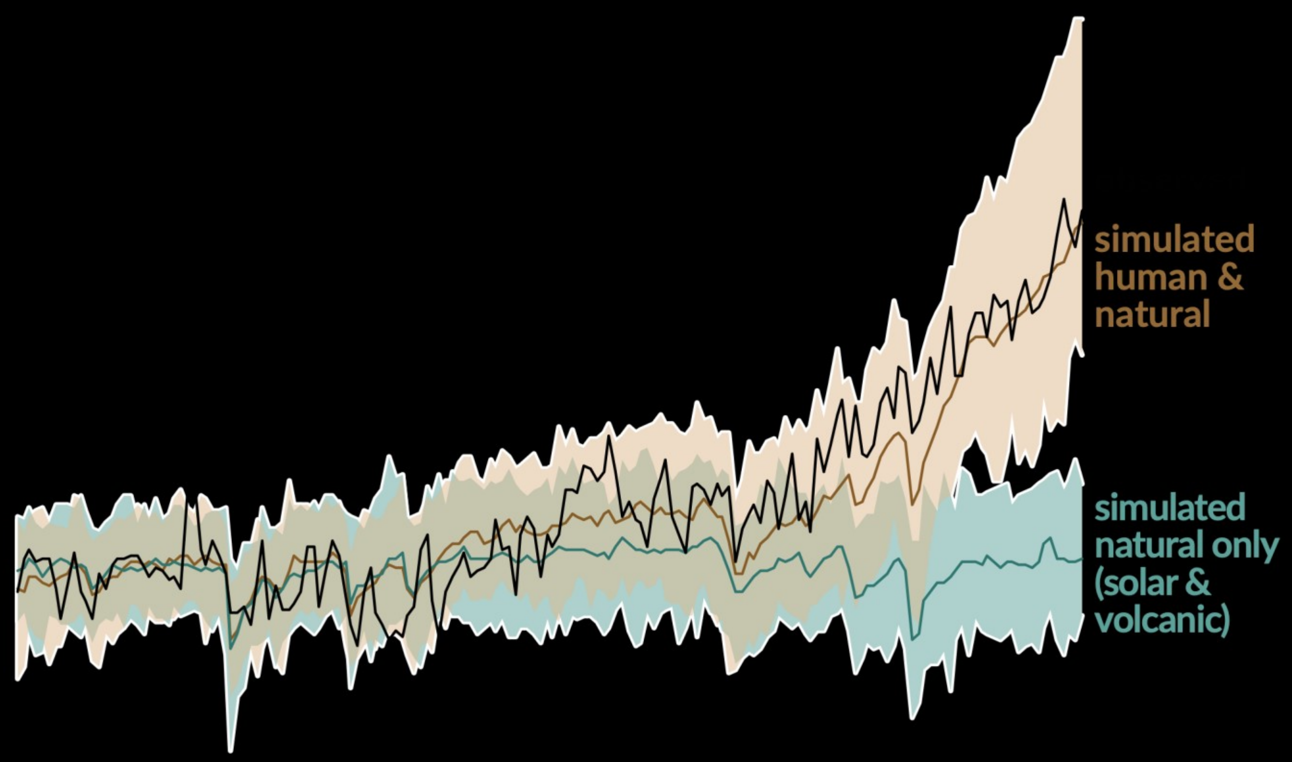
Change in globa **observed** and s **human & natural** **only** **natural** factors

The climate is warming because of human activities

- Current warming of 1.1°C
- Natural factors are not causing this warming



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HMA | HKH

0.32°C

Warming per decade in HMA (vs 0.16°C global average).

21.1 Gt/year

Glacier mass loss (2000–2019).

~70%

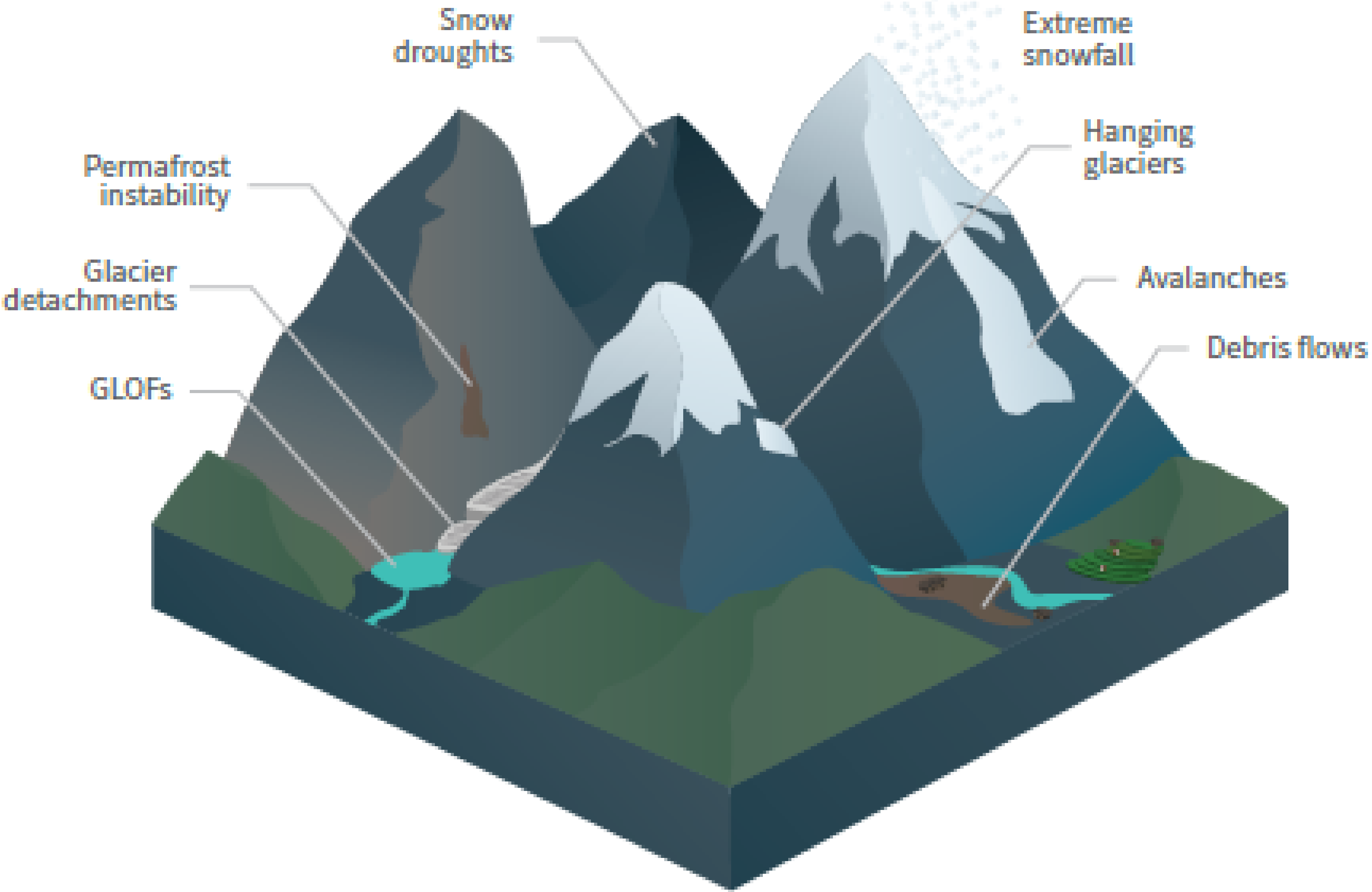
Projected glacier shrinkage by 2100 under high emissions (RCP 8.5).

Li, D., Lu, X., Walling, D.E. *et al.* High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nat. Geosci.* **15**, 520–530 (2022). https://doi.org/10.1038/s41561-022-00953-y

- **Human-induced climate change** has led to accelerated warming of the Himalayas and the Tibetan Plateau at a rate of **0.2 °C per decade during 1951–2014** (High confidence).
- **High-elevation areas (altitude > 4 km),** in particular, underwent amplified **warming at a rate of about 0.5 °C per decade**.
- Many areas in the HKH, except the high-elevation Karakoram Himalayas, **experienced significant decline in wintertime snowfall and glacier retreat in recent decades**.
- **Future warming** in the HKH region, which is projected to be in the range of **2.6–4.6 °C by the end of the twenty-first century**, will further exacerbate the snowfall and glacier decline leading to profound hydrological and agricultural impacts in the region.

R. Krishnan et al. (eds.), Assessment of Climate Change over the Indian Region, https://doi.org/10.1007/978-981-15-4327-2_11

The Impacts



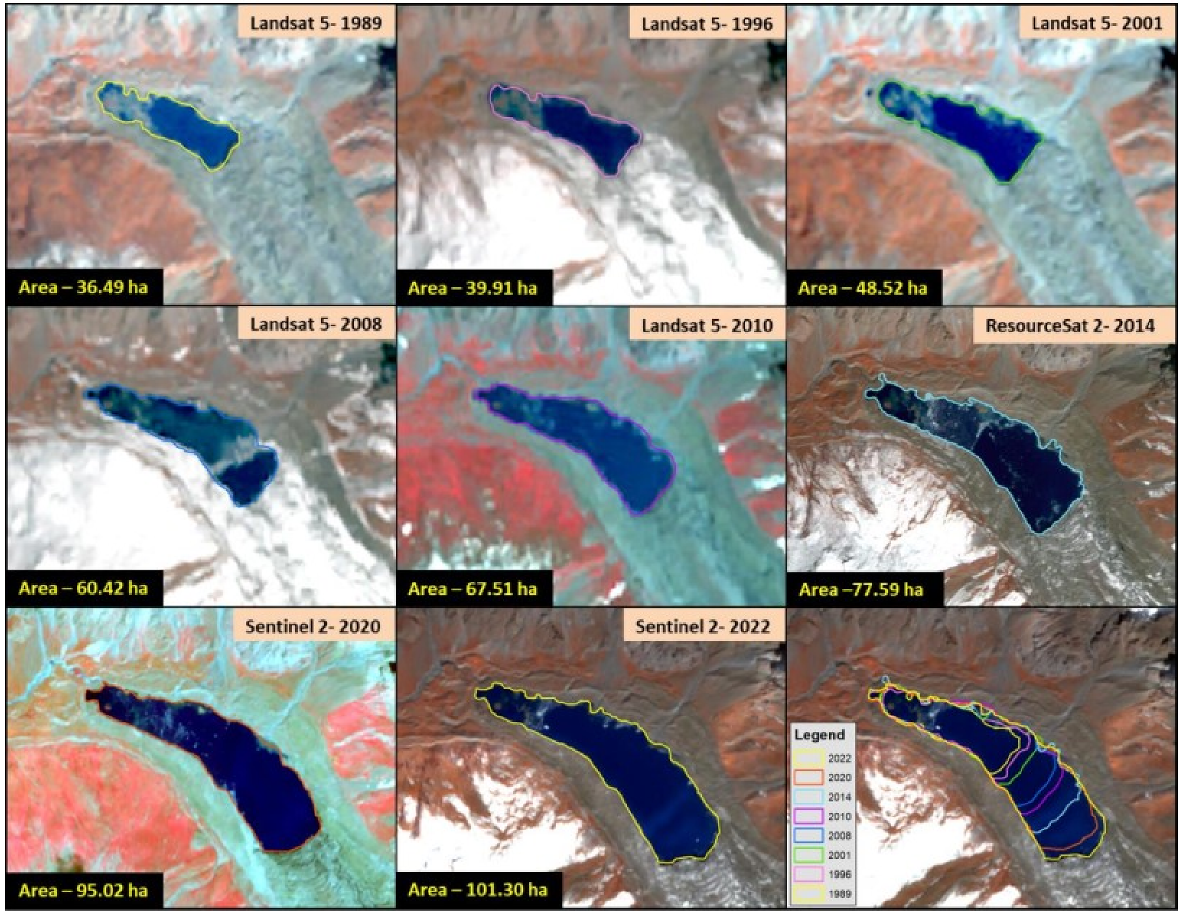
Wester, P., Chaudhary, S., Chettri, N., Jackson, M., Nepal, S., & Steiner, J. F. (2023). Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. International Centre for Integrated Mountain Development (ICIMOD). https://doi.org/10.53055/ICIMOD.1028

Glacial Lake Inventory – State wise

State/UT	Glacial Lakes (NRSC-ISRO)
Ladakh	3,219
Arunachal Pradesh	2,188
Sikkim	733
Jammu & Kashmir	546
Himachal Pradesh	537
Uttarakhand	347
Total	**7,570**
Map Source: NRSC Glacial Lake Atlas	

Pamir

Development of Glacial Lake
(Ghephang Gath GL, Lahul & Spiti District,HP)



Long-term changes in Ghepang Ghat Glacial Lake water spread area

The Cascade of Risk: From Warming to Resilience.

1. The Trigger

Atmospheric warming (0.32°C/decade) destabilizes the cryosphere (glaciers/permafrost).

2. The Cascade

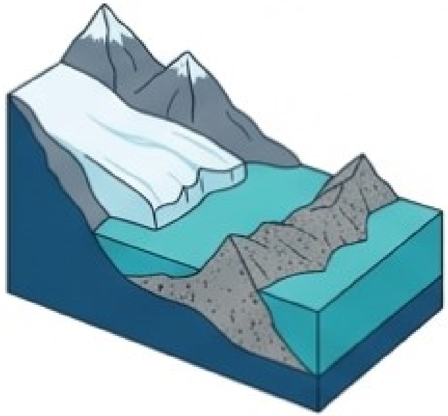
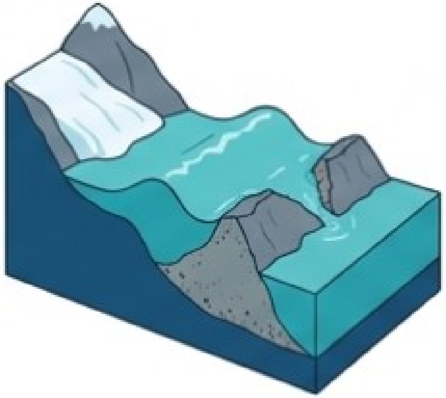
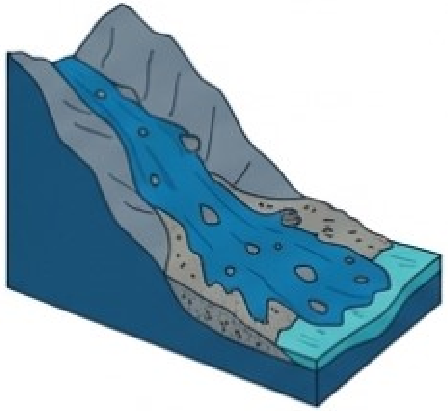
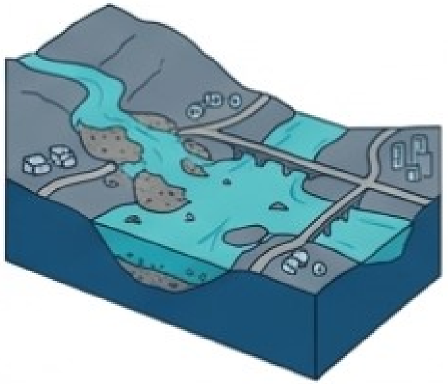
Meltwater forms unstable lakes → Slopes collapse → Outburst floods (GLOFs/LLOFs) mobilise massive sediment loads.

3. The Impact & Response

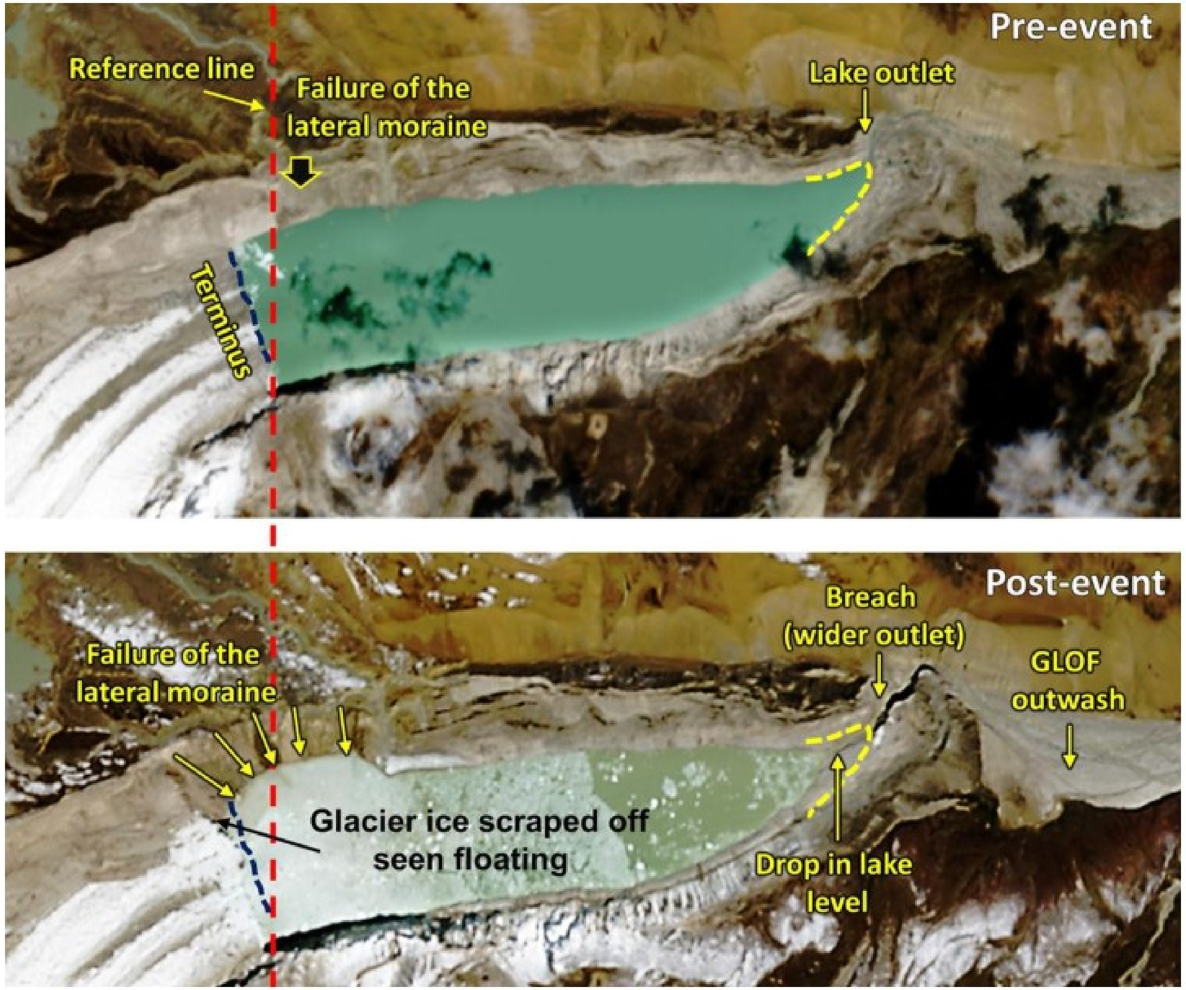
Hydropower and communities are threatened; survival requires the 5-Step GLOF Risk Reduction (GLOFRR) Framework.

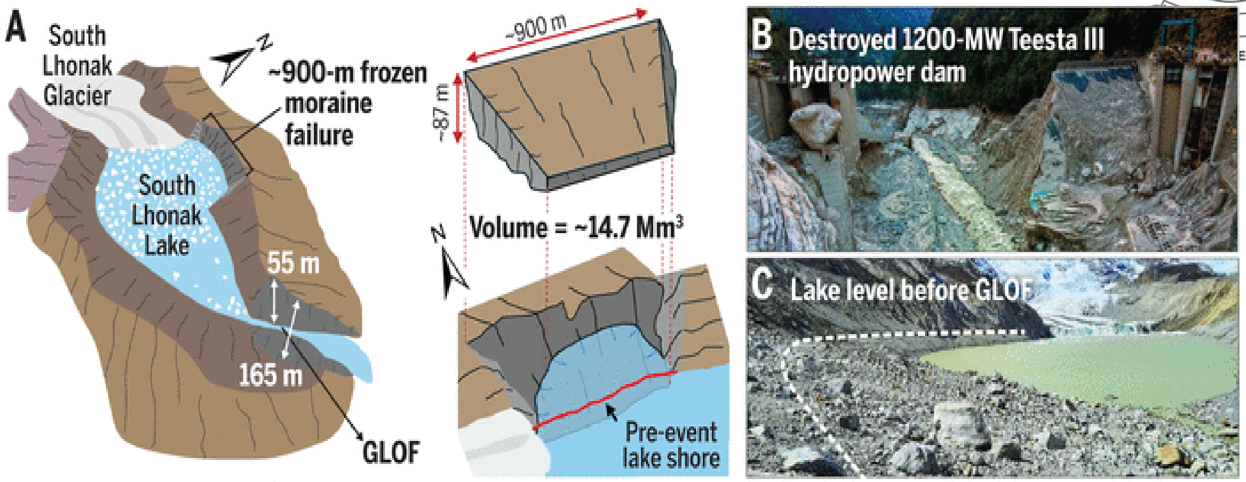
Core Assertion: *Climate change is not just melting ice; it is destabilizing the landscape itself, threatening the energy security Resilience requires shifting from reactive disaster management to proactive engineering and policy integration.*

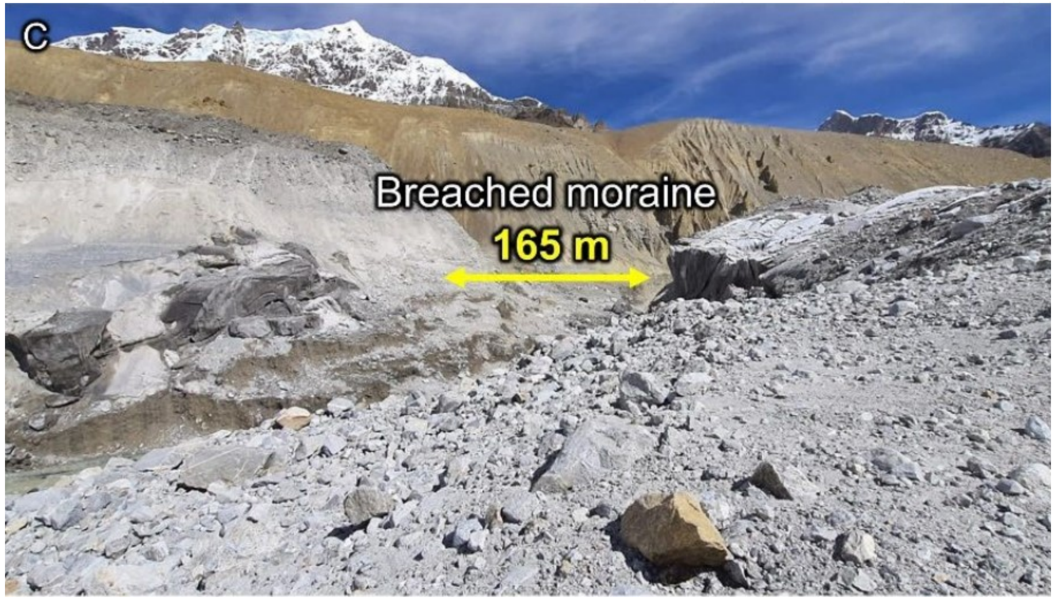
Anatomy of a Threat: GLOFs

Step 1: **Glacial Lake Formation** →	Step 2: **Triggering Event** →	Step 3: **Dam Breach** →	Step 4: **Flood Propagation** →	Step 5: **Impact**
				
A glacial lake forms at the snout of a glacier, often dammed by ice or moraine.	Ice Avalanche, Extreme Weather, Landslides, Earthquake	An ice or moraine dam fails due to the pressure caused by water, debris, or external triggers.	The released water flows downstream with debris, eroding riverbanks and depositing sediments.	Severe damage to downstream communities, infrastructure, and ecosystems.

Sikkim GLOF- 2023



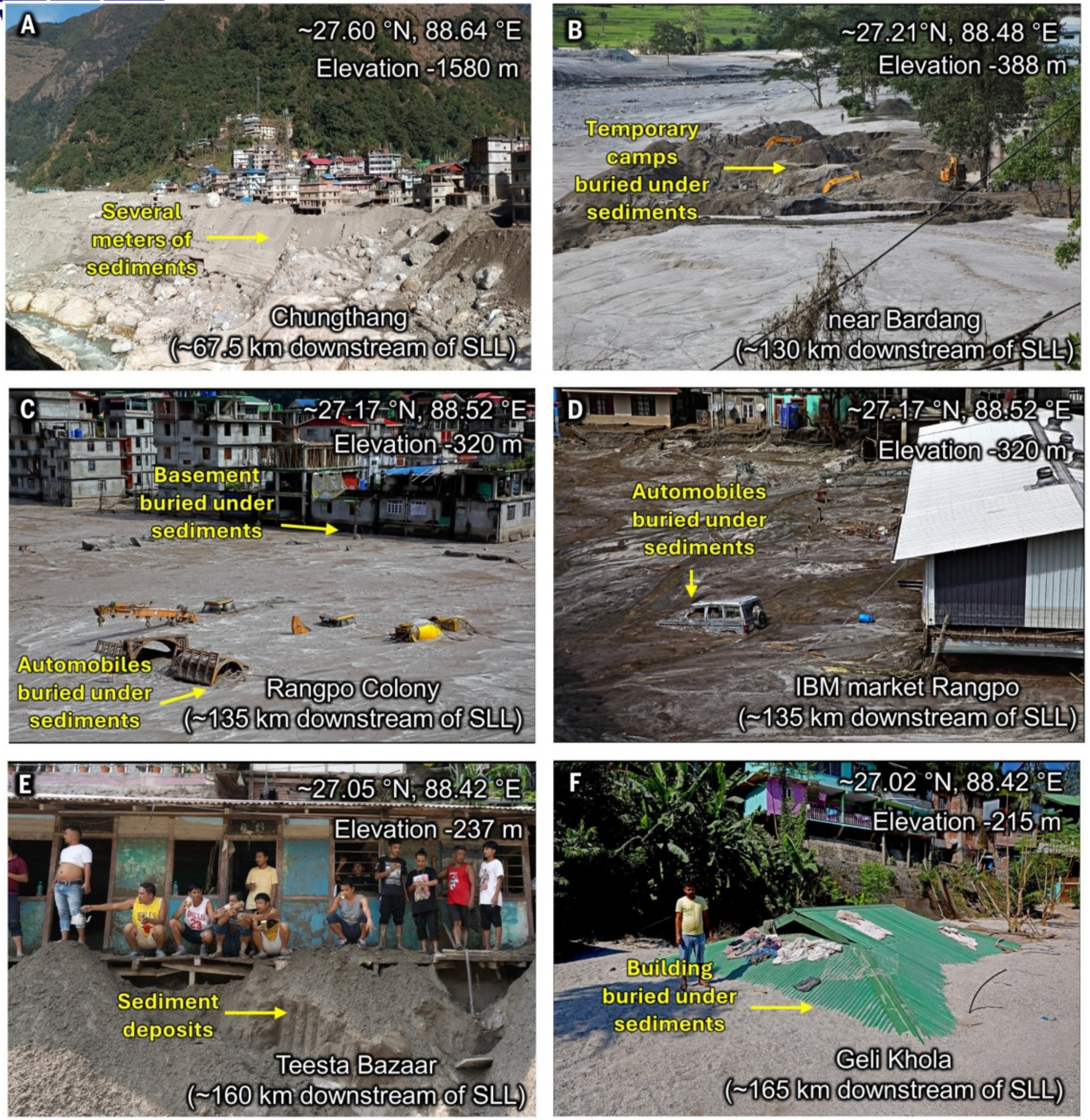




https://www.thehindu.com/sci-tech/energy-and-environment/south-lhonak-lake-flood-teesta-dam-climate/article67503729.ece

Sattar et al., (2025). The Sikkim flood of October 2023: drivers, causes, and impacts of a multihazard cascade. *Science*, *387*(6740), eads2659. https://www.science.org/doi/10.1126/science.ads2659

Sikkim GLOF- 2023

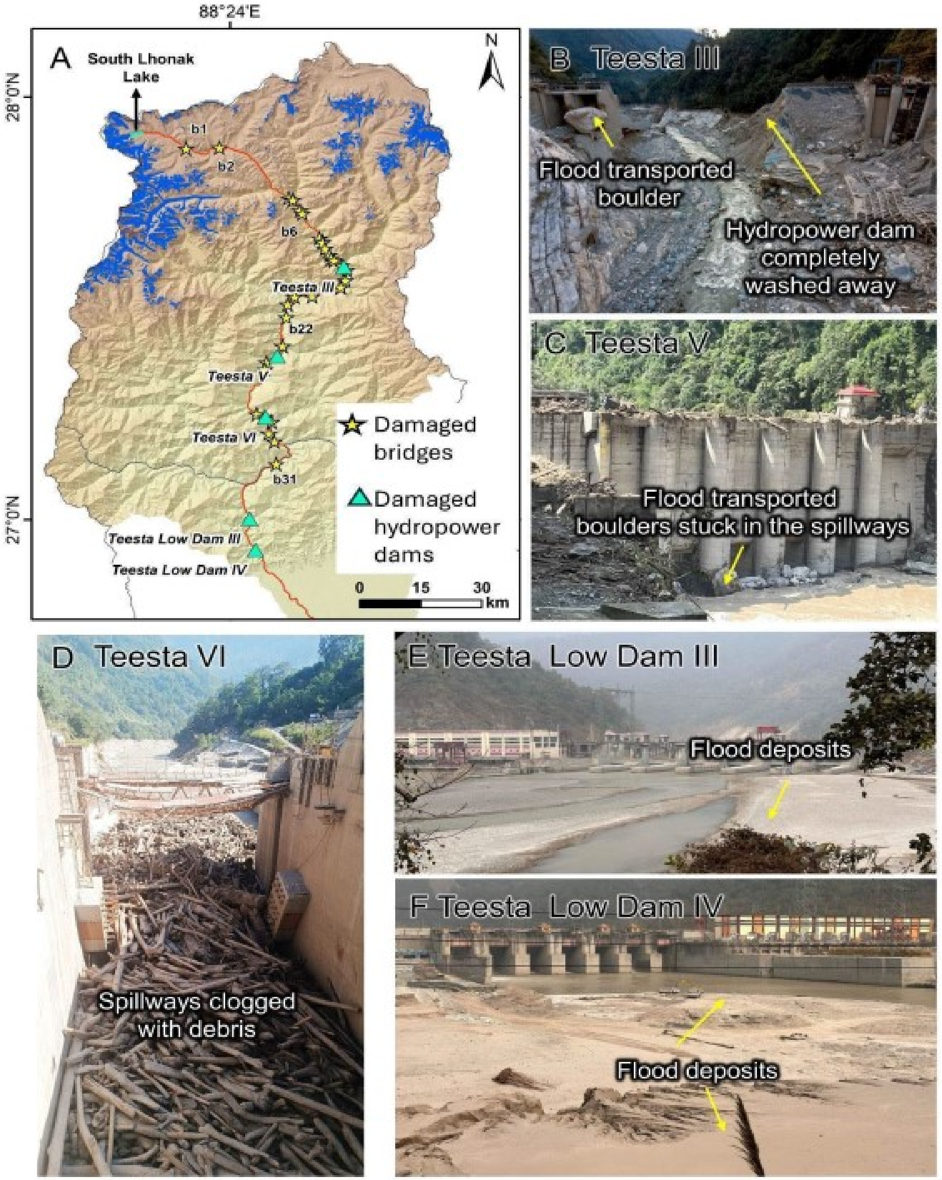


Field photographs taken along the Teesta River showing erosion caused by the 3rd October 2023 GLOF cascade

Sattar et al., (2025). The Sikkim flood of October 2023: drivers, causes, and impacts of a multihazard cascade. *Science*, *387*(6740), eads2659. https://www.science.org/doi/10.1126/science.ads2659

Sikkim GLOF- 2023

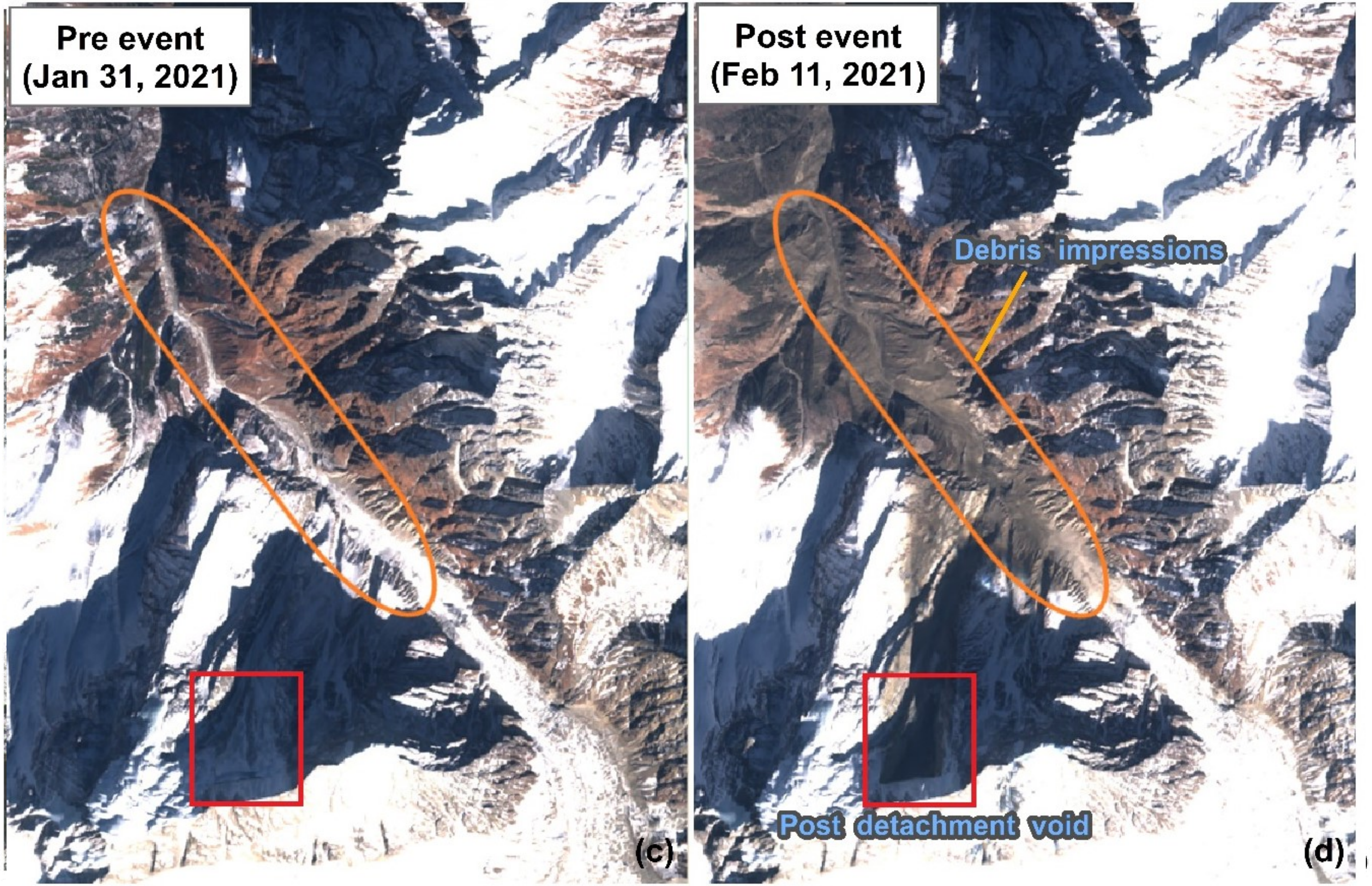
Field photographs showing the bridges damaged by the GLOF cascade along the Teesta River. Each panel provides the following details: latitude and longitude (top center), elevation (top right corner), and locality name (bottom left).



(A) Map showing the locations of the damaged bridges and hydropower projects along the Teesta River. (B-F) Post-GLOF field photographs showing impact on five hydropower projects: Teesta III, Teesta V, Teesta VI, Teesta Low Dam III, and Teesta Low Dam IV. P

Deriving important flow characteristics during the

Release depth chosen (m)



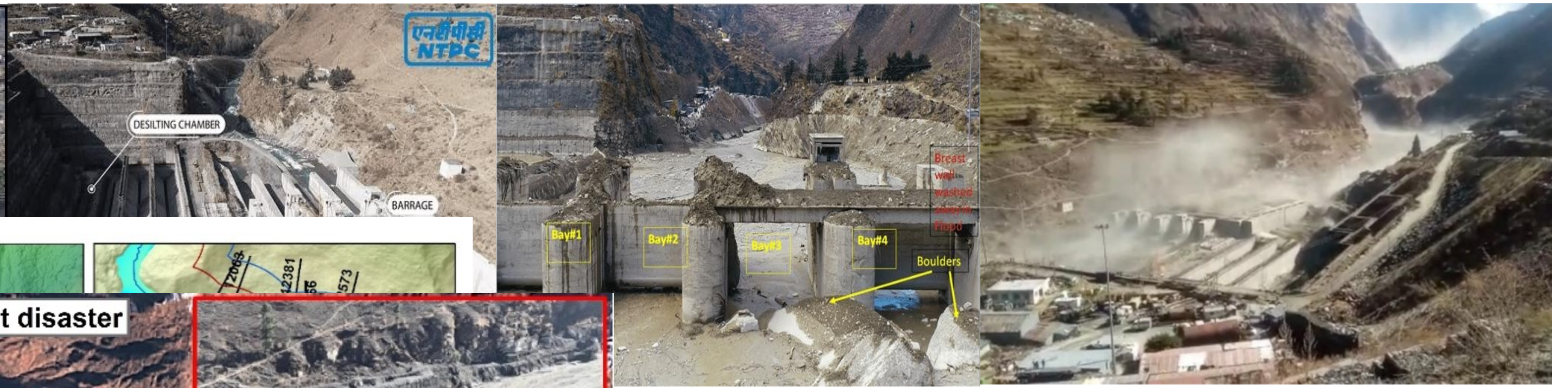
imagery

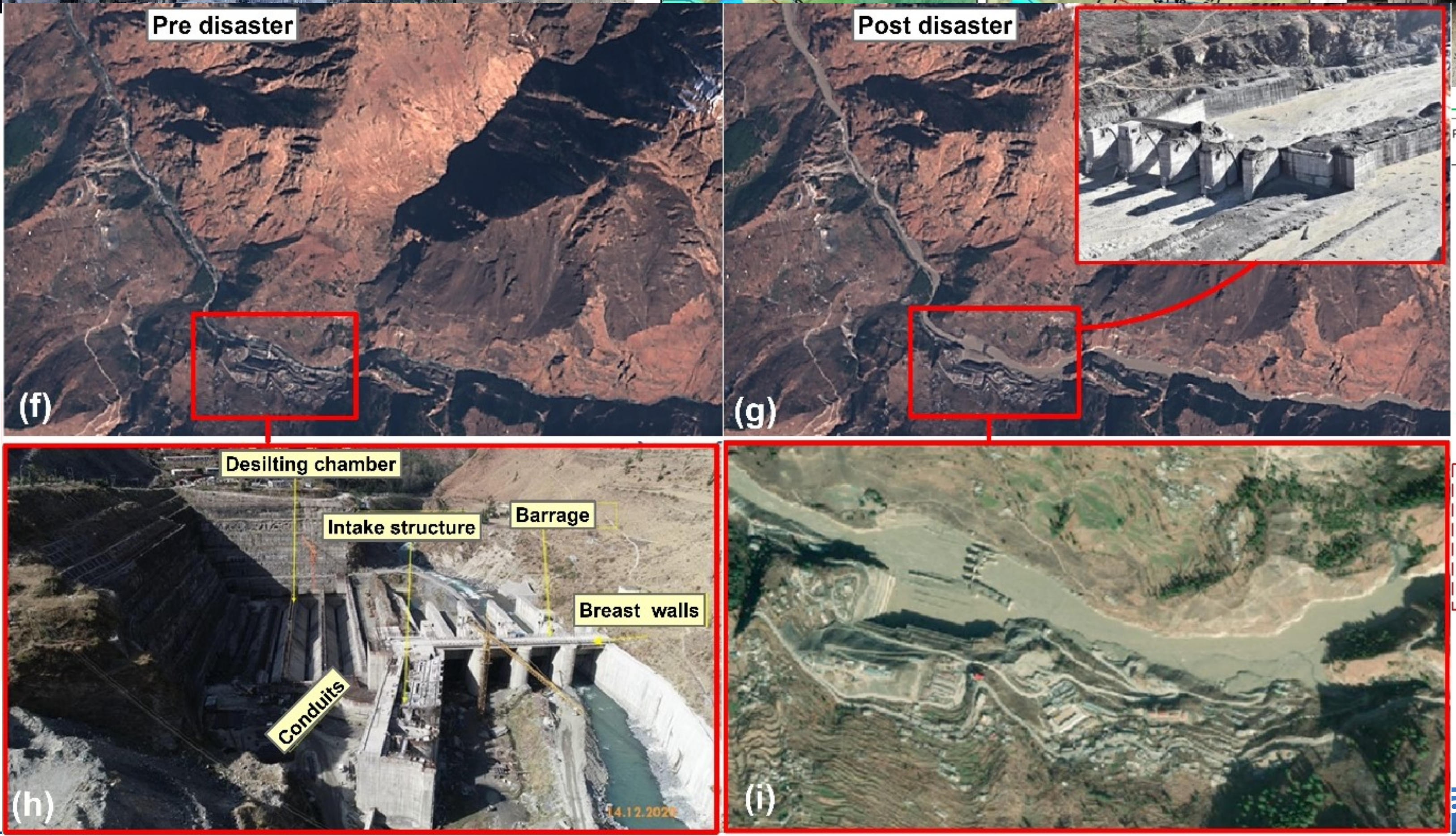
›atial footprint of
›bris
ınout distance
›eposition volume

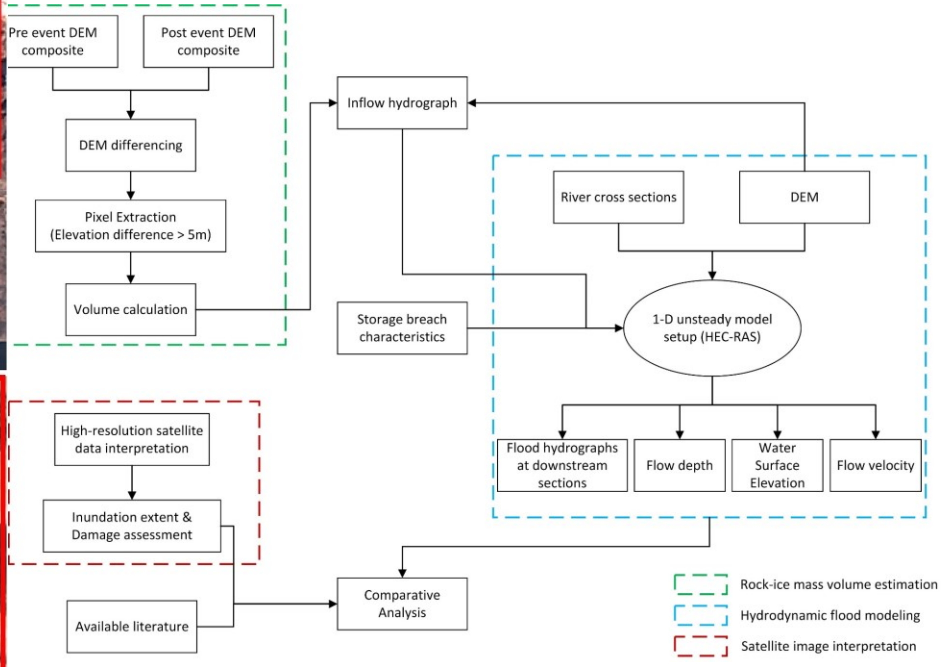
μ Dry coulomb type friction

ξ Viscous turbulent friction

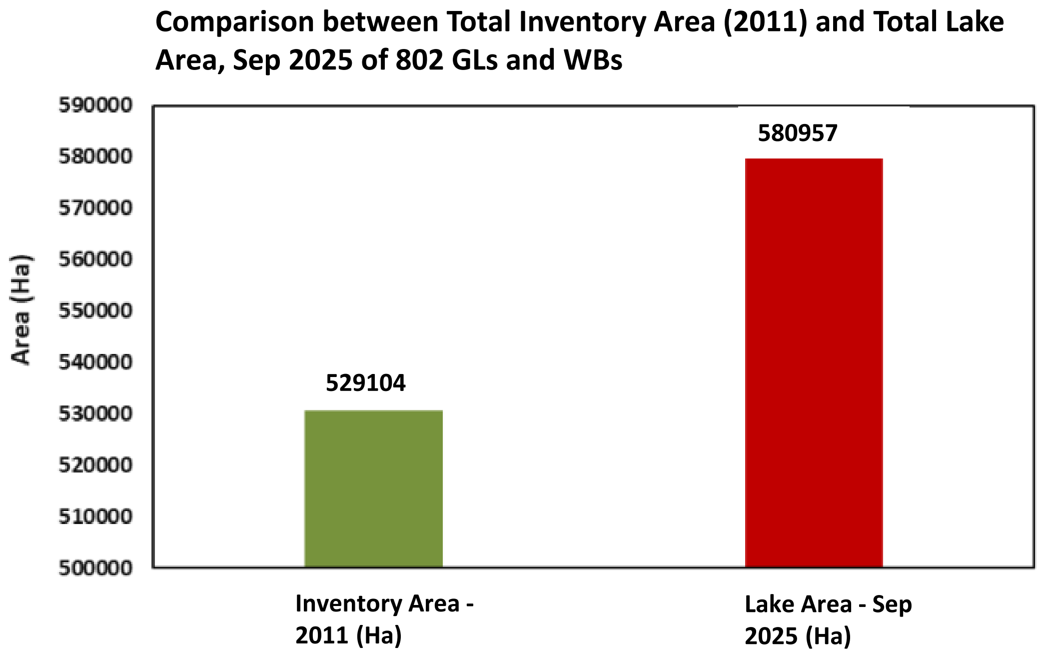
Comprehensive assessment of the Chamoli flash flood event through Hydrodynamic Modeling





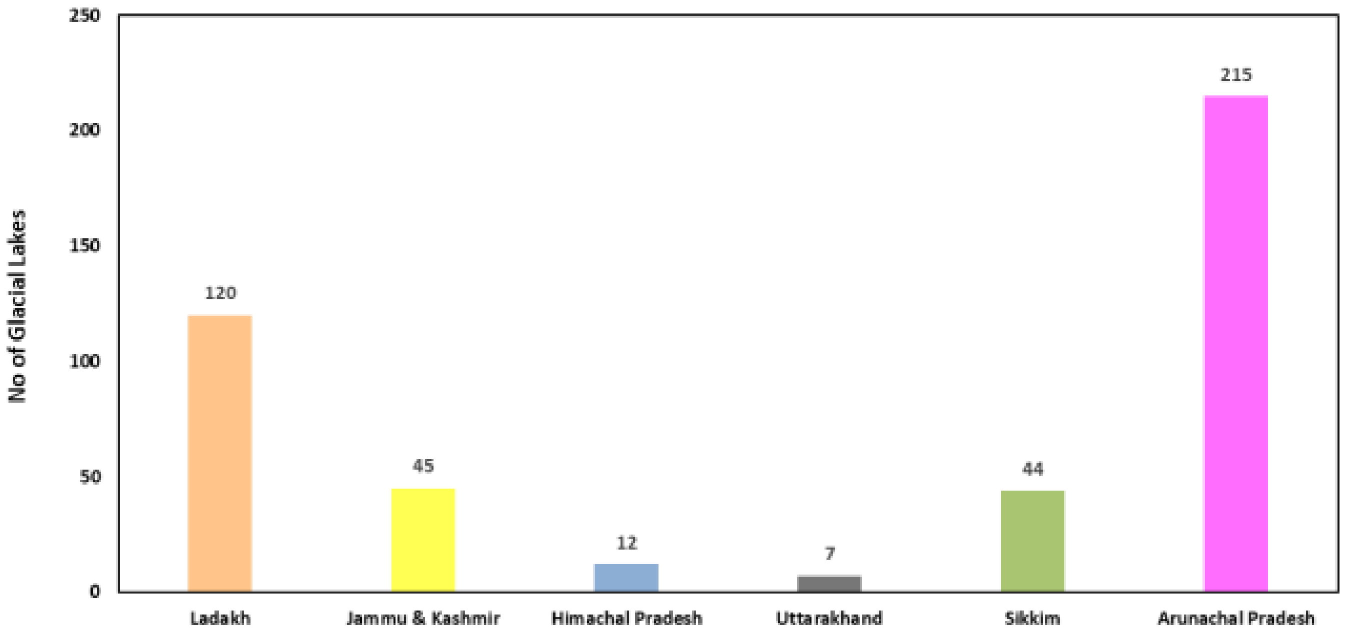


Central Water Commission (CWC) report (August 2025)



Glacial lakes and other water bodies in the Himalayan region have expanded by 9.8 per cent over the past 14 years

CWC monitors **2,843 glacial lakes** and water bodies using high-resolution Sentinel-2 Multi-Spectral Imagery (MSI) and Sentinel-1 Synthetic Aperture Radar (SAR) data (Microwave
Imagery through Google Earth Engine. Of these, **443 glacial lakes located within India showed**



https://cwc.gov.in/en/glacial-lakeswater-bodies-himalayan-region

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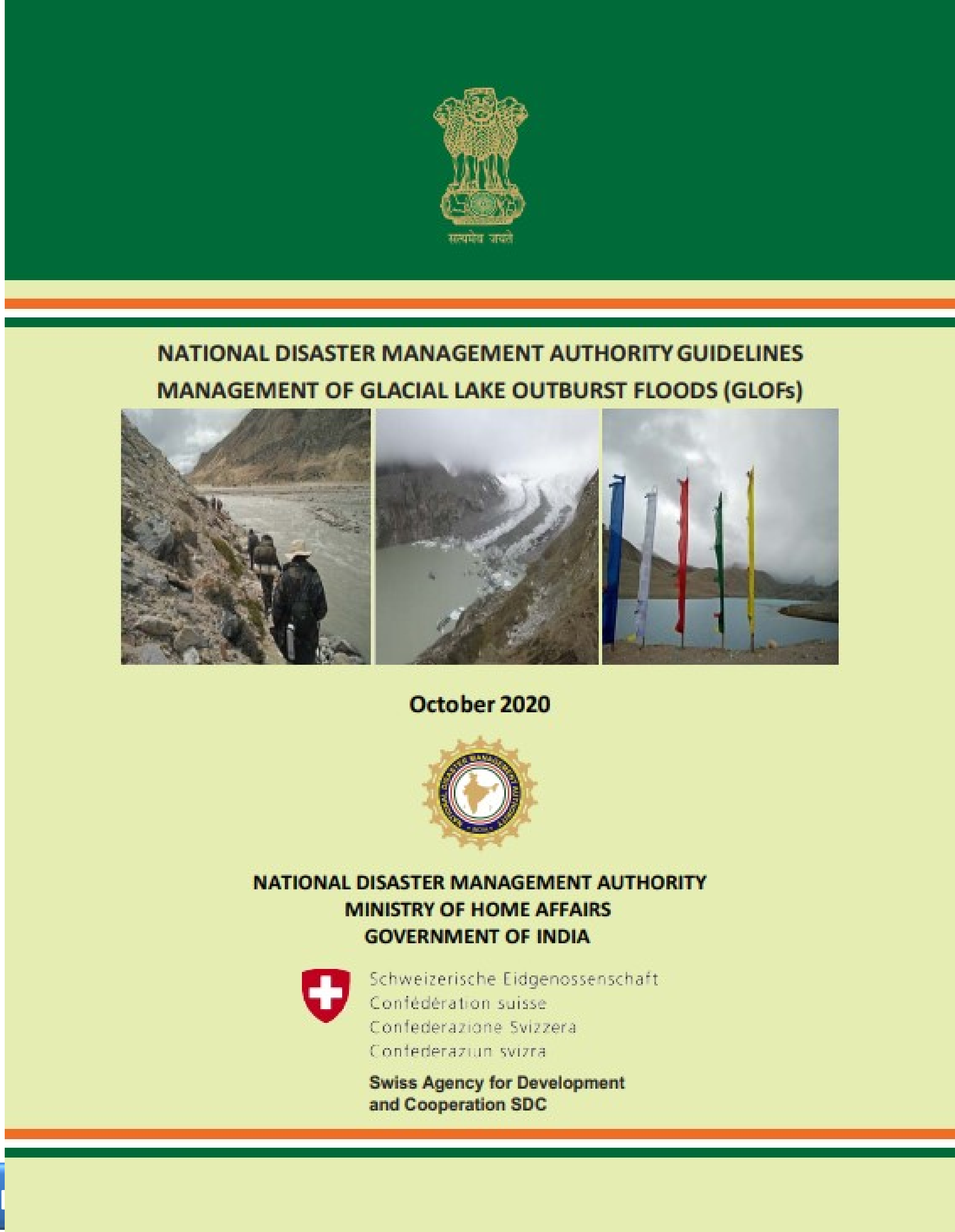
NDMA 2020 Guidelines: Pillars

- Standardized identification & mapping of dangerous lakes
- Early Warning Systems (risk knowledge, monitoring, dissemination, response)
- Structural & non-structural mitigation; mainstreaming into development
- Capacity-building of institutions; community preparedness & drills

https://ndma.gov.in/sites/default/files/PDF/Guidelines/Guidelines-on-Management-of-GLOFs.pdf



Overview

- CHAPTER 1: THE CONTEXT
- CHAPTER 2: HIMALAYAN GEO-ENVIRONMENT AND CRYOSPHERE
- CHAPTER 3: HAZARD & RISK ZONATION MAPPING
- CHAPTER 4: MONITORING, RISK REDUCTION & MITIGATION MEASURES
- CHAPTER 5: AWARENESS & PREPAREDNESS
- CHAPTER 6: CAPACITY DEVELOPMENT
- CHAPTER 7: RESPONSE
- CHAPTER 8: RESEARCH AND DEVELOPMENT
- CHAPTER 9: REGULATION AND ENFORCEMENT
- CHAPTER 10: IMPLEMENTATION OF THE GUIDELINES

Identifying and quantifying the hazard

1. Building an **inventory of glacial lakes**
2. Flag the **potentially dangerous ones**
3. The guidelines list **criteria** like:
    a) lake size and depth (bigger lakes hold more water = bigger flood)
    b) condition of the moraine dam (is it narrow? tall? Does it contain ice cores that could melt and weaken it?
    c) How much freeboard – i.e., buffer height – exists before water overtops?).
    d) Signs of instability – for example, active hanging glaciers above the lake (which could calve or avalanche into it) or past occurrences of surges.

4. **Hazard zonation mapping** evaluates: if this lake bursts, **which areas downstream would flood**?
→ The terrain model is used to predict how far the flood would reach. The output is a hazard map delineating high-hazard zones (likely to be inundated deeply or with high velocity), moderate and low hazard zones.

5. **Risk assessment** comes by **adding exposure and vulnerability**. We need to overlay the hazard map with what lies in those zones: Are there villages? Major bridges or highways? Farmlands? Hydropower projects?

Hazard and Risk zonation

- For the top-priority lakes, the guidelines urge **detailed ground surveys**.
- **Remote sensing** gives a snapshot, but nothing beats **field data** for accuracy.
- Teams should measure how deep the lake is, examine the dam material (rock size, signs of seepage or cracks), and install instruments if possible.
- **In situ weather and stream gauges** upstream can provide early signs (like lake level rise or rainfall thresholds that might trigger a landslide into the lake).
- **Local communities** can contribute as well – often, villagers know if a lake's outlet stream has suddenly dried or changed color (which might mean the lake is leaking or a blockage occurred).
- **Traditional knowledge and past events**, even if anecdotal, can fill data gaps. Overall, hazard and risk assessment is the foundation of GLOF management – it tells us where to act before a disaster strikes.

Government Priority-NGRMP

Meeting of **Sub-Committee of National Executive Committee (SC-NEC)** under the Chairmanship of Union Home Secretary was held on **18th October 2023** to consider the proposal of National Glacial Lake Outburst Flood (GLOF) Risk Mitigation Programme (NGRMP).

High Level Committee Meeting under the Chairmanship of Hon'ble Home Minister was held on **25th July 2024** and in the meeting proposal of NDMA was approved for the States of **Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh** at the total cost of **Rs. 150 Cr.**

The Programme will be implemented with a budget of ₹150 crores (comprising Rs. 135 crores from NDMF and 15 crores as States' share, during April 2023 to March 2026 (Table A).

Sl. No.	State/ UT	Centre share (Rs. in Cr.)	State Share (Rs. in Cr.)	Total Budget
1.	Himachal Pradesh	31.5	3.5	35
2.	Uttarakhand	27	3	30
3.	Sikkim	36	4	40
4.	Arunachal Pradesh	40.5	4.5	45
	Total	135	15	150

Key Implementation Challenges

- Non-uniform hazard mapping & limited field validation; dynamic lakes
- Access & maintenance in harsh terrain; telemetry and power reliability
- Last-mile alerting in remote valleys; multilingual communications
- Local capacity gaps; sustained funding for O&M beyond pilots
- Balancing development with safety; integrating risk into planning

Strategy 1: Hazard & Risk Assessment Standardized Inventory (15% Budget)

- **Institutionalize** a living, **GIS-enabled glacial lake database** (central + state nodes)
- **Annual updates** via optical + SAR; UAV bathymetry & dam-condition surveys for priority lakes
- **Uniform risk ranking** → valley-scale

Strategy 2: Monitoring & Early Warning Systems (35% Budget)

- **Automation**
  - Lake level, weather, seismic sensors; satellite telemetry; threshold-based alerts
- **Dissemination**
  - Sirens, SMS/app in local languages; radio; CAP integration
- **Community**
  - Village GLOF wardens; quarterly drills; citizen-science

Strategy 3: Mitigation measures: Targeted Engineering & Nature-based Measures (40% Budget)

- Prioritize a **shortlist of critically high-risk lakes** for siphoning/spillways/dam strengthening
- **Downstream energy-dissipating structures** and safe havens on high ground
- **Bioengineering & vegetation for slope/moraine stabilization**

Strategy 4: Community Preparedness, Planning & Policy (10% Budget)

- Embed **GLOF scenarios into land-use, hydropower and road design standards**
- **Local contingency plans** with mapped evacuation routes & shelters
- **Sustained funding:** integrate with climate adaptation windows; public-private

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A Strategic Framework for Resilience

The 5-Step GLOF Risk Reduction (GLOFRR) Framework

1. Risk Assessment
- Identifying Vulnerable Lakes
- Hazard Level Mapping

2. Monitoring
- Remote Sensing
- Field Surveys
- Modeling

3. Mitigation Strategies
- Engineering
- Drainage
- Ecosystem Restoration

4. Community Engagement
- Awareness
- Education
- Stakeholder Involvement

5. Policy Formulation
- Climate Adaptation
- Regulatory Frameworks
- Regional Collaboration

> “Managing this risk requires a holistic approach that bridges the gap between physical science, engineering, and public policy.”

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A framework for building GLOF-resilient communities

Emphasizing vulnerability assessment, early warning systems, awareness programs, resilient infrastructure, and collective actions.

https://doi.org/10.1038/s44304-025-00097-0

Recommendations and future needs to create climate change-resilient hydropower systems

- **Expand satellite and ground-based mapping and monitoring networks** for the climate, glaciers and permafrost, glacial lakes, paraglacial landscapes, unstable slopes, erosion rates and sediment yields
- **Understand the cascading links** between climate change, glacier retreat and permafrost thaw, slope instability, evolution of glacial lakes and landslide-dammed lakes, lake outburst floods and downstream impacts
- **Predict future fluvial sediment loads and reservoir sedimentation in response to a changing climate** and the associated evolving glacial, paraglacial and fluvial processes
- **Develop forward-looking and sustainable sediment management solutions** to minimize reservoir sedimentation and turbine abrasion
- **Establish real-time early-warning systems using seismic signals and enhance social awareness** and drills and response strategies, especially for HPPs under construction, to minimize human and infrastructure losses
- **Further enhance transboundary cooperation by establishing data-sharing schemes** and adopting joint-operation strategies to better cope with hazards and optimize sediment flushing
- **Assess the long-term trade-offs** of using hydropower as an adaptation solution for climate change, including the economic effects on hydropower generation of changing run-off, sediment load and hazard, the environmental effects on ecosystem fragmentation and biodiversity, societal effects on population migration and the reduction in greenhouse gas emissions contributed by hydropower
- **Promote the inclusion of indigenous and local knowledge** in policy, governance and management and secure local gains from dam and reservoir construction

Li, D., Lu, X., Walling, D.E. *et al.* High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nat. Geosci.* **15**, 520–530 (2022). https://doi.org/10.1038/s41561-022-00953-y

Adaptation is the Only Path Forward

Inevitability: Degradation will continue for decades.

Resilience: Pivot from crisis management to resilience by design.

Integration: Combine engineering, science, and community knowledge.


Thank You