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

Climate Change Impacts on the Himalayan Cryosphere and Extreme Hydro-Meteorological Events: Implications for Cascade Hazards, GLOF Risk, and Climate-Resilient Dam and Hydropower Infrastructure in the Eastern India

CENTRE FOR EARTH SCIENCES & HIMALAYAN STUDIES
CES & HS
ITANAGAR
GOVERNMENT OF ARUNACHAL PRADESH

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Highlights

Very few glaciers have been studied so far in Arunachal, glacier response and their impact remain to be a “white spot”.

The limited studies in the region are confined to limited geographical areas covering short periods of observation.

Systematic long-term scientific investigations of the glaciers are necessary to understand the complex behavior that controls the observed and anticipated changes.

Northeastern Himalaya are significantly losing their ice mass due to the ongoing global changes ,

646 Glaciers as of 2020 (*Murtem et al., 2023*) and a total of 1,532 Glacial Lakes as of 2018 (*Mal et al., 2020*) in four glaciated basin of Arunachal Himalaya; Out of four glacier basin of Arunachal Himalaya, only one glacier basin (Mago Chu Basin) is being studied by the CESHS for long term field-based dynamics studies.

Glacier Surface Area Comparison in Arunachal Pradesh (Murtem et al. 2023)

Basin	Year	No. of Glaciers	Total Glacier Area (km^2) representing the permanently frozen mass within the basin.
Western Arunachal-Manas Basin / Mago Chu	2017	52	57.66
Central Arunachal-Subansiri Basin	2022	49	67.85
Eastern Arunachal-Dibang Basin	2021	62	60.30
Western Arunachal-Kameng Basin	-	-	-
Total		163	185.81

Objectives

- To study the mass balance and dynamics of glaciers to understand differential responses within the region.
- To study the response of Eastern Himalayan cryosphere to the changing climate and its hydrological impacts.
- To study the evolution of glacial lakes and their GLOF potential.

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Study Area

Current Status:

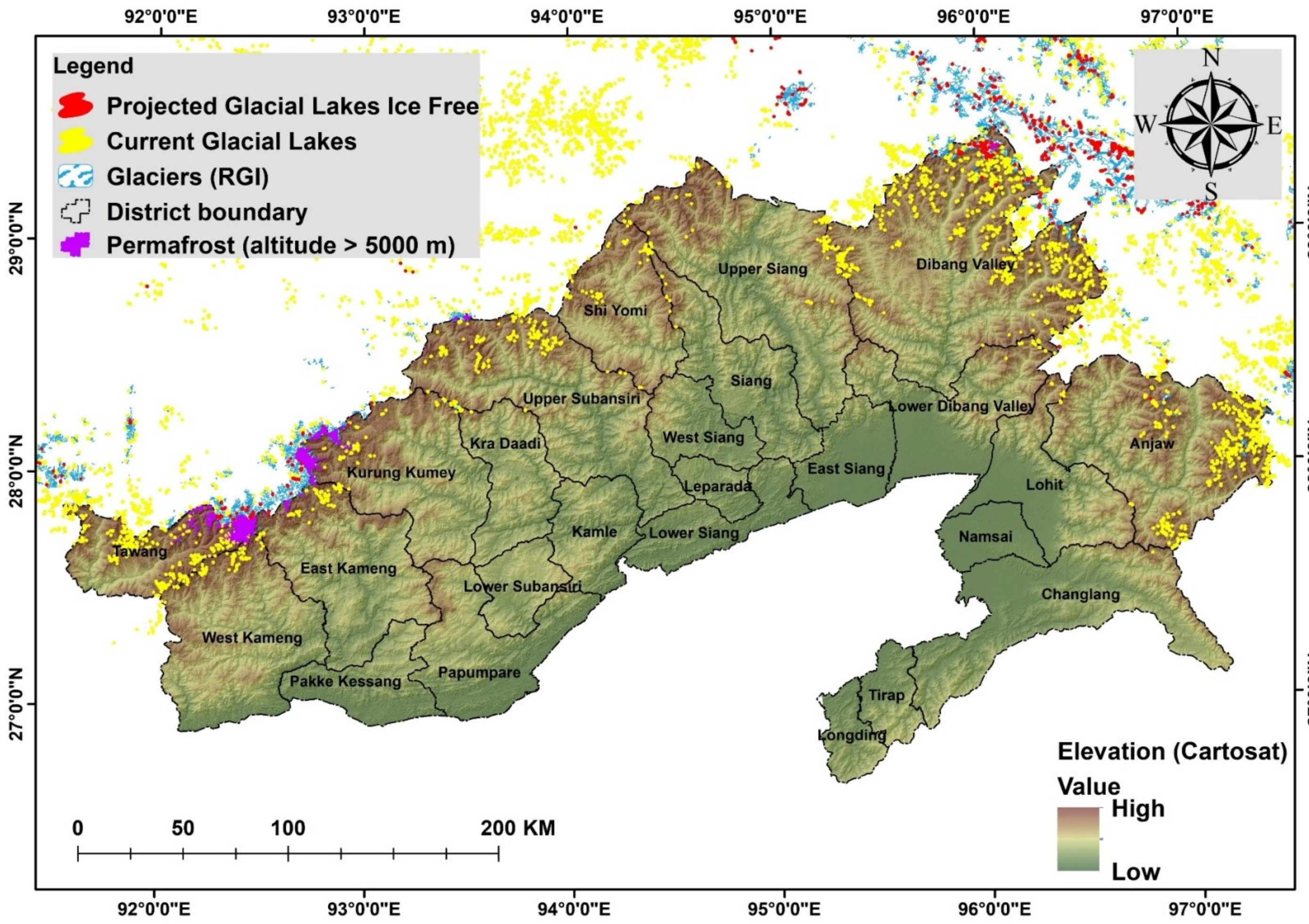
Glaciers, glacial lakes, permafrost experiencing unprecedented changes

Glacier Loss:

27 high-risk lakes (NDMA) threatening mainly Tawang and Dibang Valley

Climate Drivers:

1.6°C warming in last few decade (*Roy et al., 2021*), precipitation decline, more than million people at risk



Glacier Monitoring in Khangri Glacier, Tawang District

- Glacier dynamics and Mass Balance Studies
- Energy balance studies
- Hydrological balance/Runoff from glacierised and non –glacierised catchment /snow cover
- Glacial lakes Monitoring

Since 2023, CESHS has led Four scientific expeditions in collaboration with

- National Centre for Polar and Ocean Research (NCPOR)
- IIT Roorkee
- Northeast Regional Institute of Science and Technology (NERIST)

Other Notable Partners:
IIT Guwahati
Nagaland University

Major achievements include,

- Installation of Automatic Weather Stations (AWS)
- Installation Automatic Water Level Recording (AWLR) systems
- Launched operational mass balance programme on Khangri Glacier
- Surveyed 4 high-risk glacial lakes; 3 of category ‘B” and one of Category ‘A’ in 3rd & 4th during April–May 2025 & November-2025

A site has been selected for a prefabricated permanent base camp to support long-term field research.

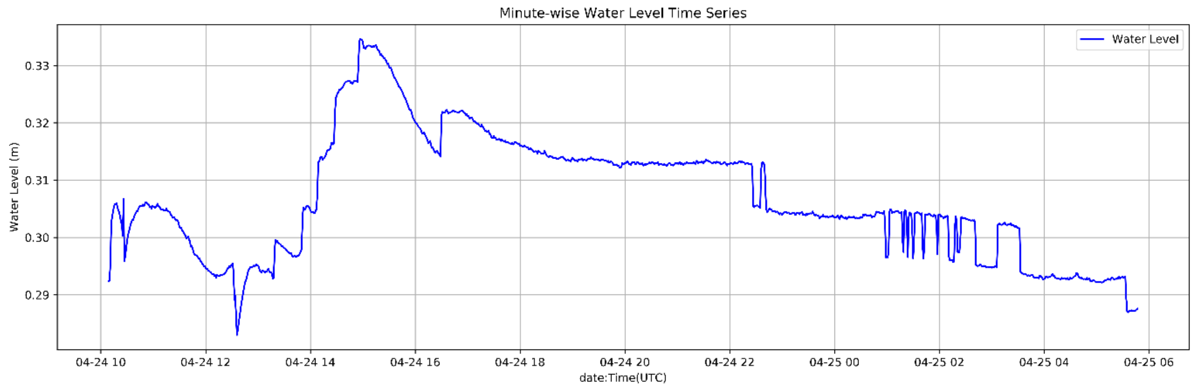
Khangri Glacier

Field Instrument Data

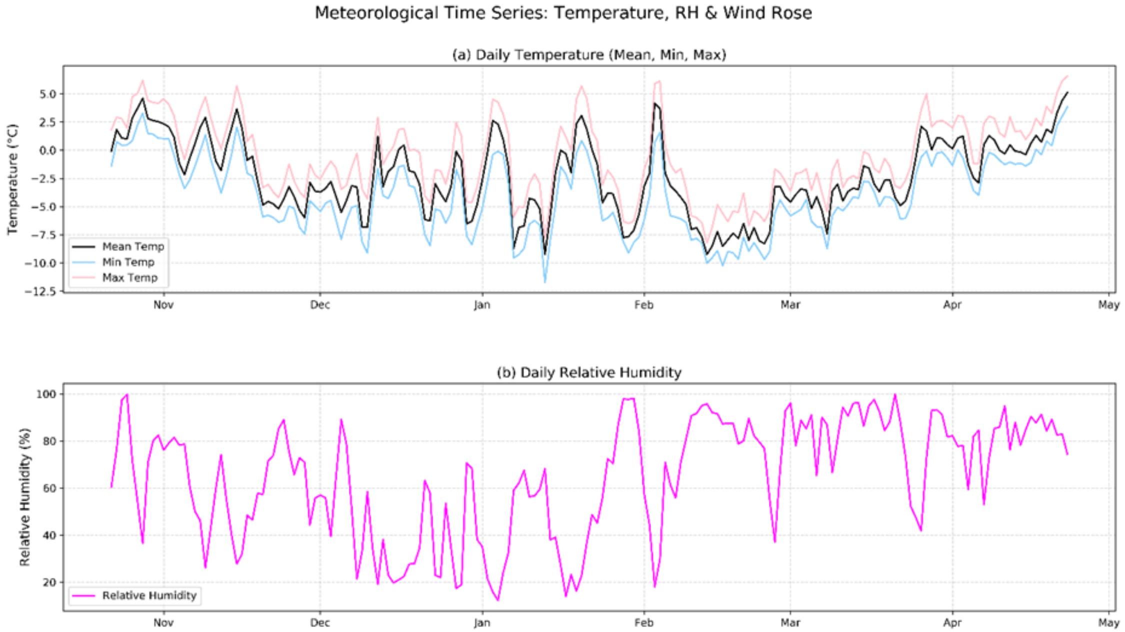
Glacier Mass Balance Data

Stake Number	Elevation (m)	Bamboo (cm)				Debris (cm)	Initial expose (cm)	Stake reading	Bambo	Total expos	Melt
		i	ii	iii	iiii		23-10-2024	22-04-2025		(cm)	23/10/2024 to 22/04/2025
I	4916	200	199	200		9	43	115	iii	115	72
II	4942	200	200	200		25	31	67	iii	67	36
III	4950	200	200			6	55	200	i	400	345
IV	4951	200	202	202	200	0	30	133	iiii	133	103
V	4969	200	201	201	200	0	30	82	iiii	82	52
VI	4985	200	200			0	11	40	ii	40	29

Glacier Discharge Data

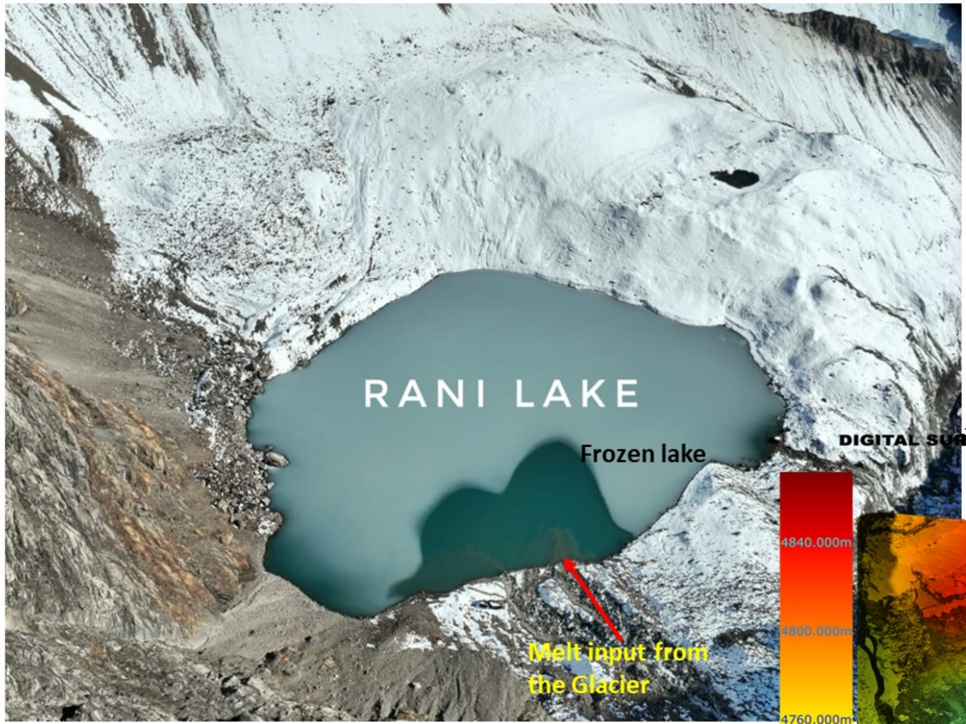


Meteorological Data



- Mean annual mass loss – 0.6m water equivalent
- Lost 4.6 Giga Ton of glacier mass between 2000 to 2019
- Mean thinning of 11.7m during last 20 years
- Lost approximately 6% of glacierized area

Survey of High-Risk Lakes

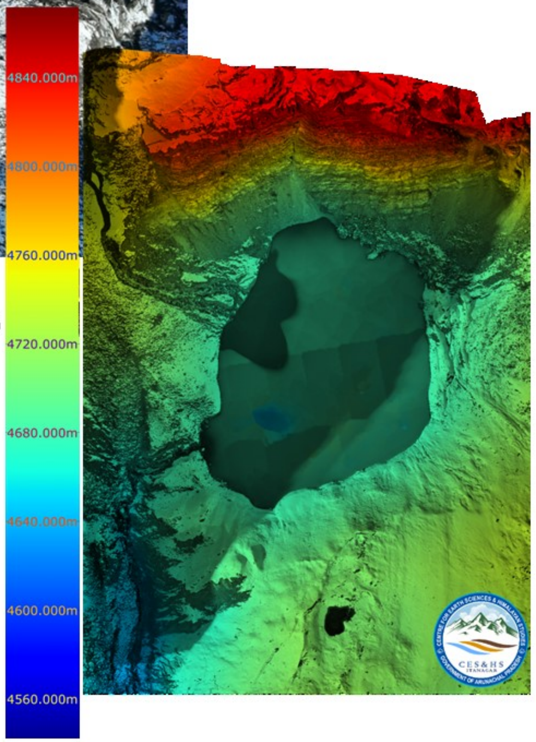


Drone based Photogrammetry for determination for lake dimension, area; Creation of Lake DSM; Moraine dam height,2D/3D profile; 3D model of the surrounding region etc.

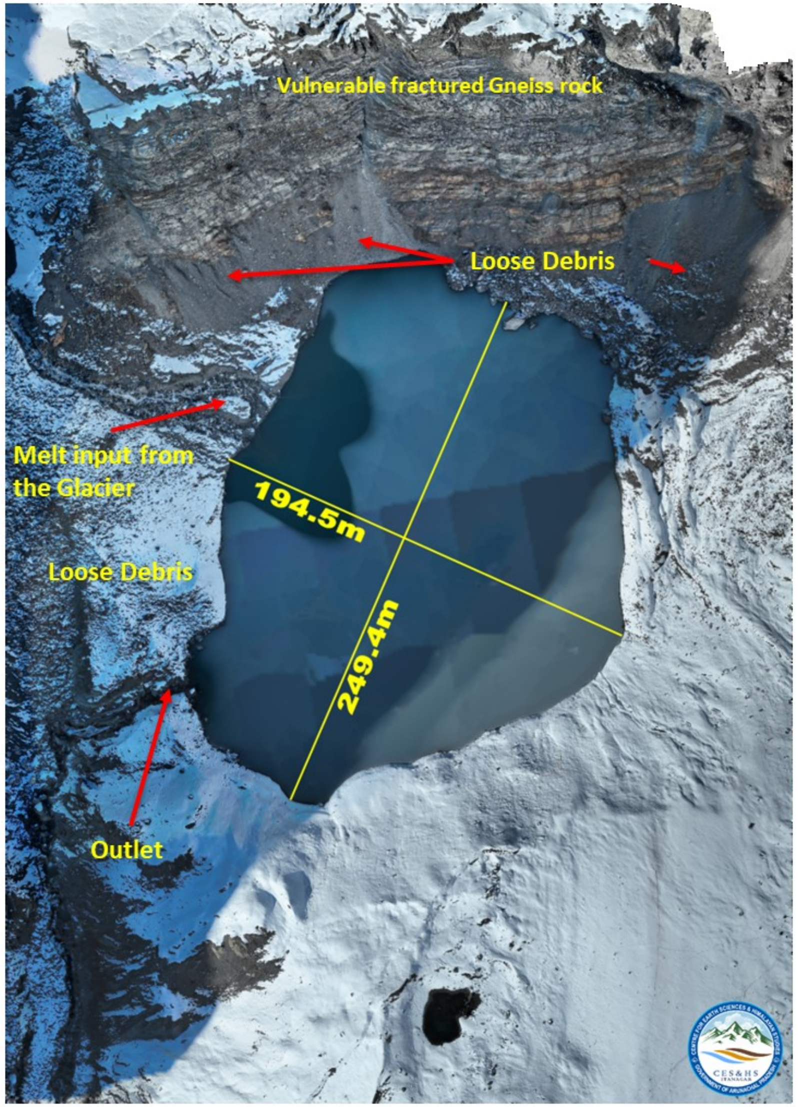
NRSC details

Glacial Lake Details	
ID	383A0514671
River System	Brahmaputra
Basin	Manas
Sub Basin	Dangme Chu
Area	3.899 ha
Latitude	27.78
Longitude	92.35
Elevation	4711 m
Glacial lake type	E(o): Other Glacial Erosion Lake

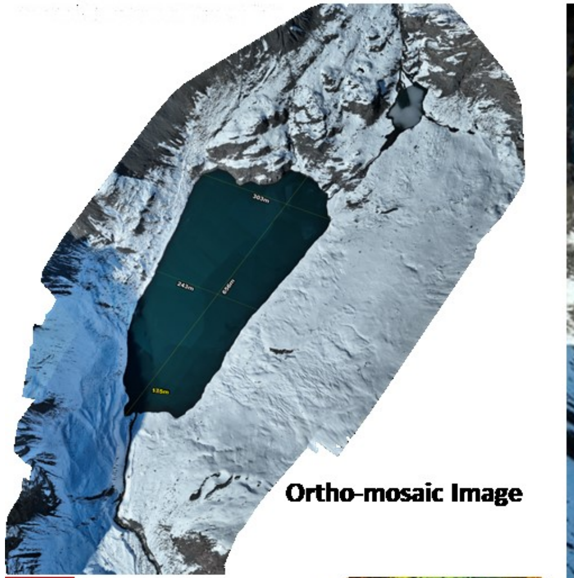
DIGITAL SURFACE MODEL OF RANI LAKE

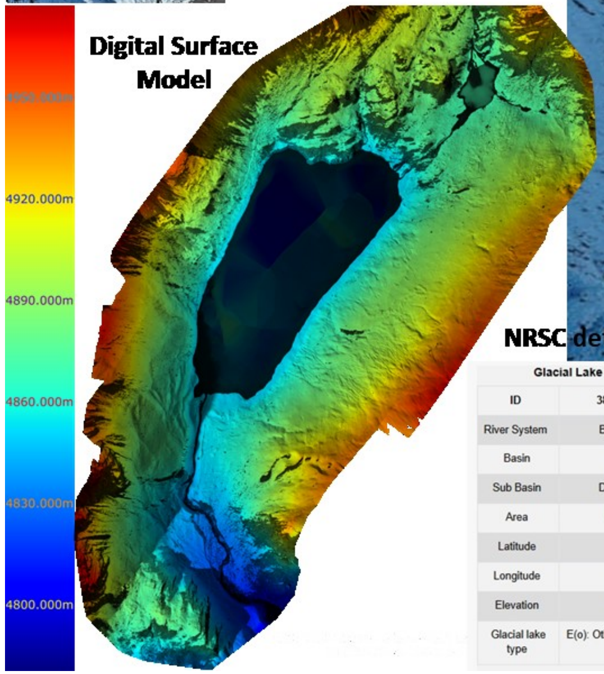


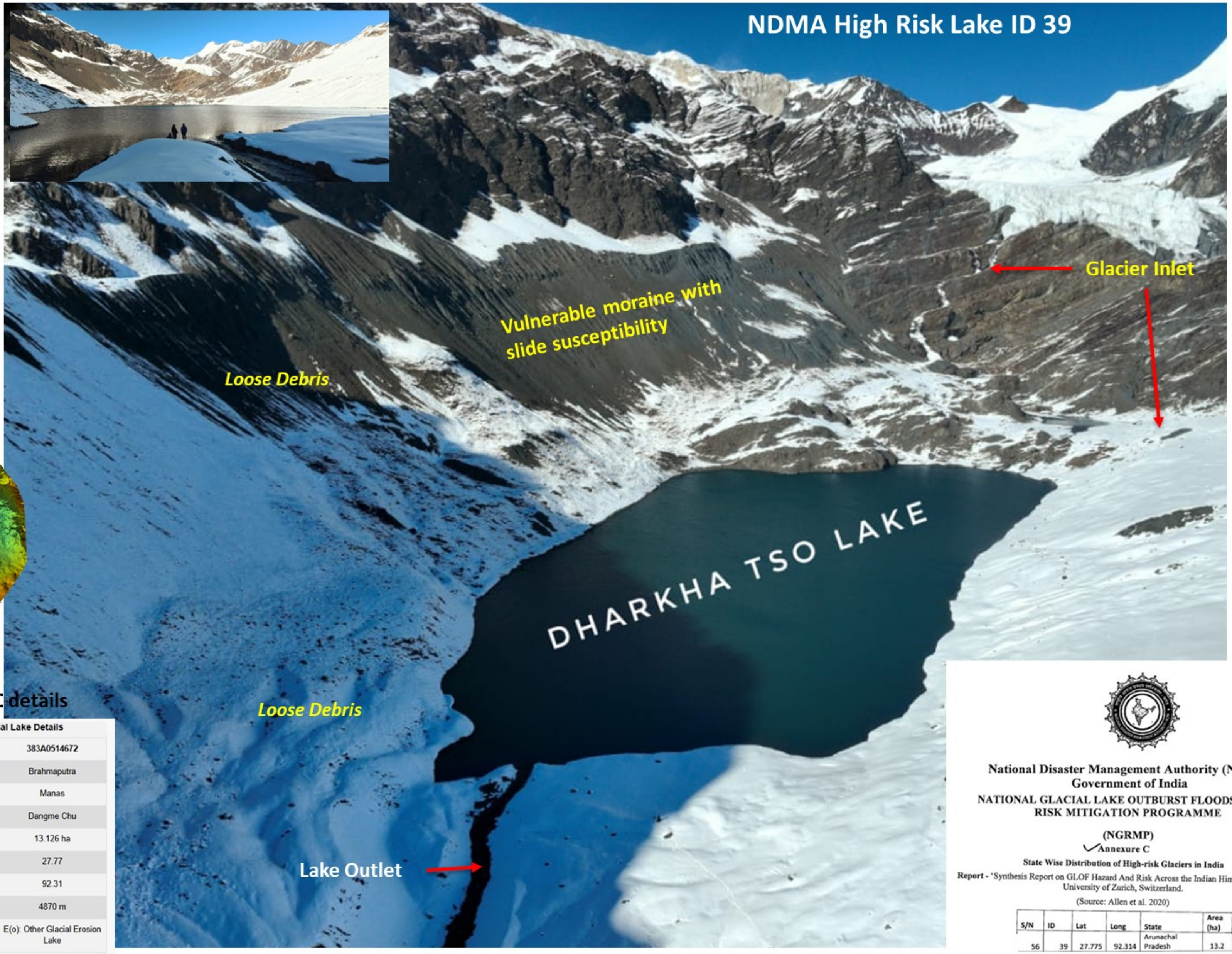
4th KHANGRI GLACIER EXPEDITION 2025
ORTHOMOSAIC IMAGE OF RANI LAKE WITH DIMENSION



Survey of High-Risk Lakes







NRSC details

Glacial Lake Details	
ID	383A0514672
River System	Brahmaputra
Basin	Manas
Sub Basin	Dangme Chu
Area	13.126 ha
Latitude	27.77
Longitude	92.31
Elevation	4870 m
Glacial lake type	E(o): Other Glacial Erosion Lake

National Disaster Management Authority (NDMA)
Government of India
NATIONAL GLACIAL LAKE OUTBURST FLOODS (GLOF) RISK MITIGATION PROGRAMME

(NGRMP)

Annexure C

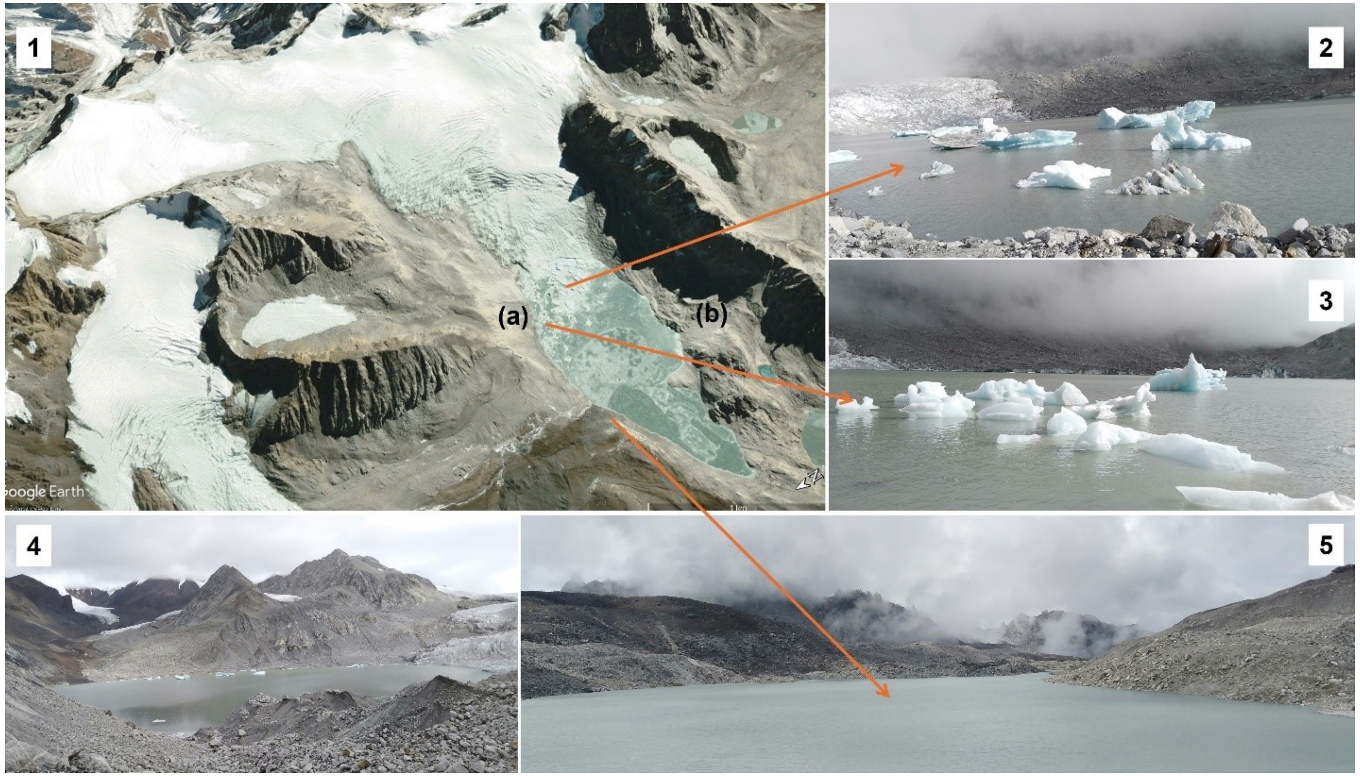
State Wise Distribution of High-risk Glaciers in India

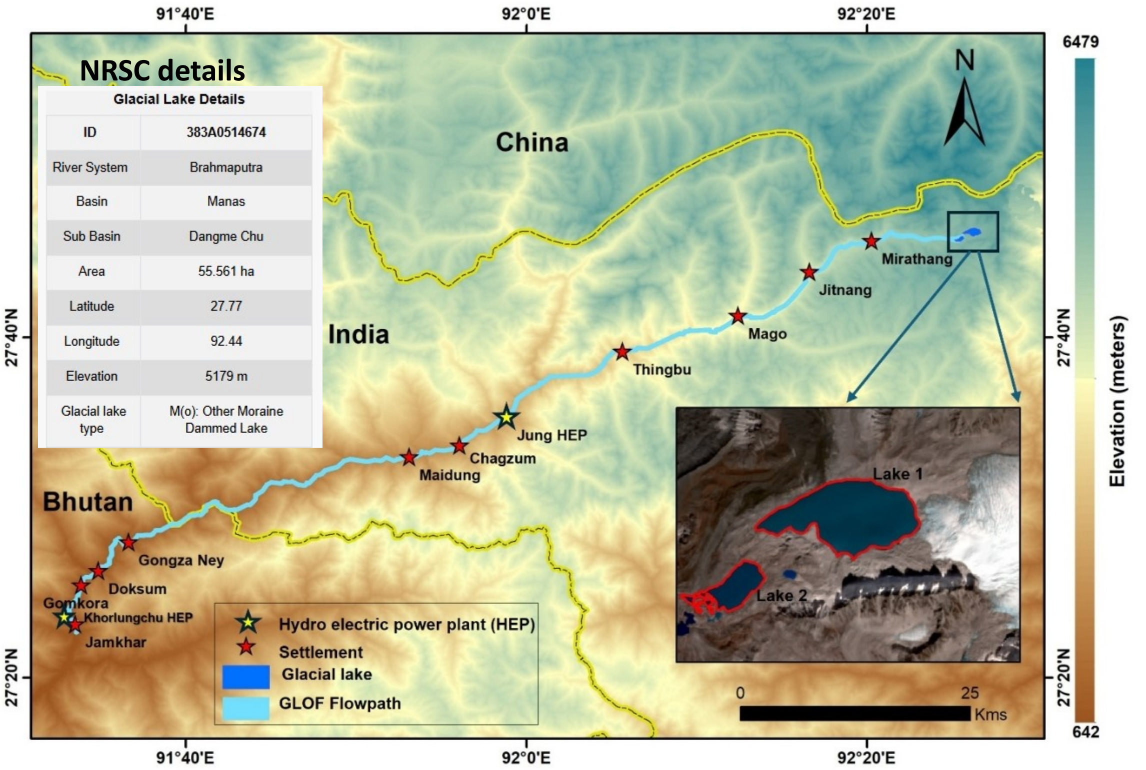
Report - 'Synthesis Report on GLOF Hazard And Risk Across the Indian Himalayan Region', University of Zurich, Switzerland.

(Source: Allen et al. 2020)

S/N	ID	Lat	Long	State	Area (ha)
56	39	27.775	92.314	Arunachal Pradesh	13.2

Transboundary glacial lake Tsenapho (category B by NDMA) leading to transboundary threat





- The study focused on a high-risk glacial lake called Tsenapho lake cluster and a smaller adjacent erosion lake, evaluating their evolution, expansion scenarios, and potential GLOF impacts.
- From 1989 to 2023, the main glacier retreated by 160 meters and the lake expanded by 100 meters.
- GLOF modelling using HEC-RAS indicated peak flood magnitudes of 12,000 m^3/sec, threatening villages in India and Bhutan (Mago, Thingbu, Chagzum, Mirathang, Jithang, Gongza Ney, Doksum, Gomkora) and two hydropower projects including Thingbu Hydel and Jung HEP.
- Accelerated glacier retreat in the Mago Chu basin has led to rapid glacial lake formation, substantially increasing downstream risk of GLOF

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Transboundary GLOF threat

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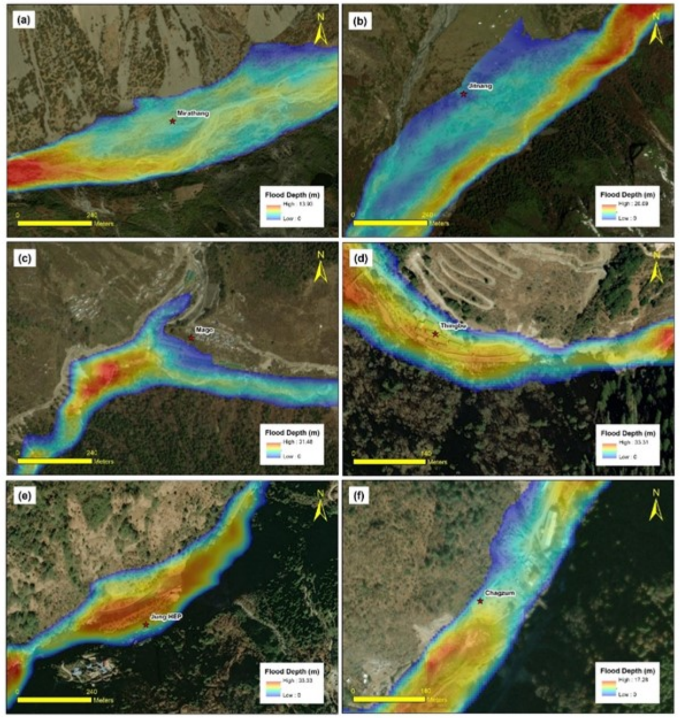
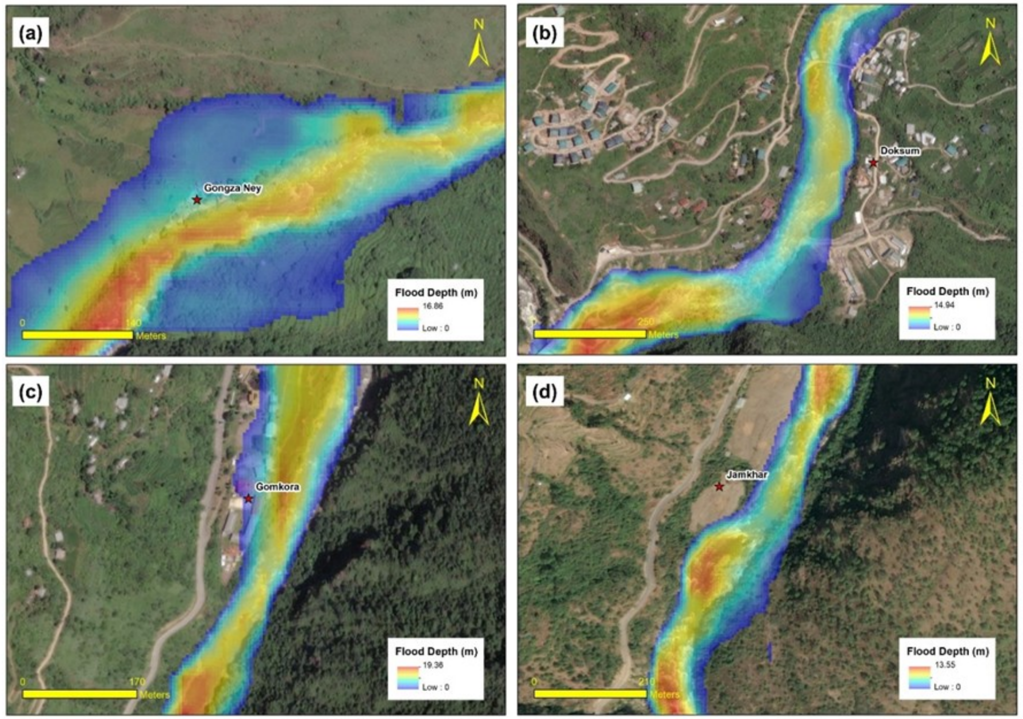
- Flood waves from lake breaches can reach downstream areas within hours, leaving minimal time for evacuation and causing high risk to settlements, roads, bridges, and socio-economic stability.
- Pro-glacial and moraine-dammed lakes show particularly rapid expansion and hazard potential in the study area.



Flood depth map depicting downstream locations of India (a) Mirathang (NIMAS basecamp) (b) Jitnang (c) Mago (d) Thingbu (e) Jung HEP (f) Chagzum, under inundation in case of 100% breaching of present lakes. background imagery: ESRI ArcMap)

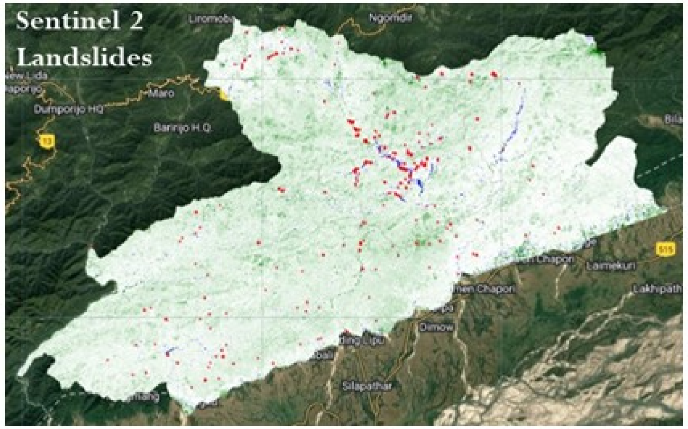


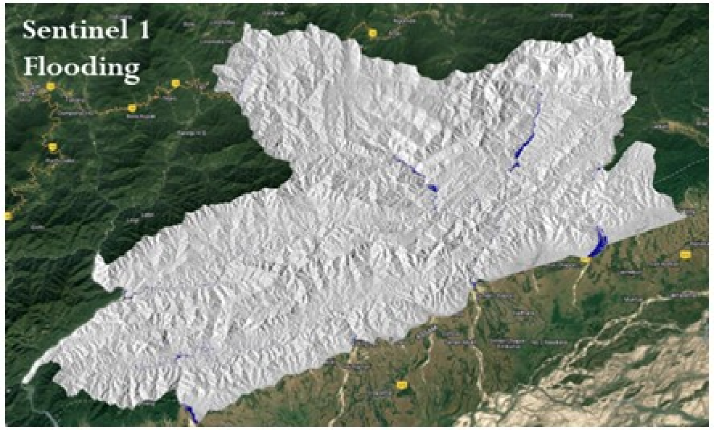
Flood depth map depicting downstream locations of Bhutan (a) Gongza Ney (b) Doksum (c) Gomkora (d) Jamkhar, under inundation in case of 100% breaching of present lakes. background imagery: ESRI ArcMap)

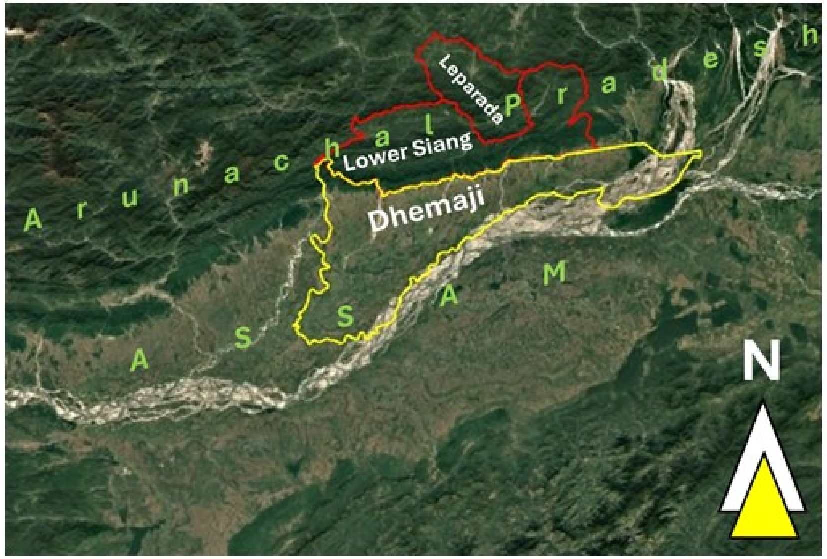
Extreme Climatic Event: Case Study

September 17th & 18th 2020

Upstream flash flood, debris flow and landslides in Leparada & Lower Siang

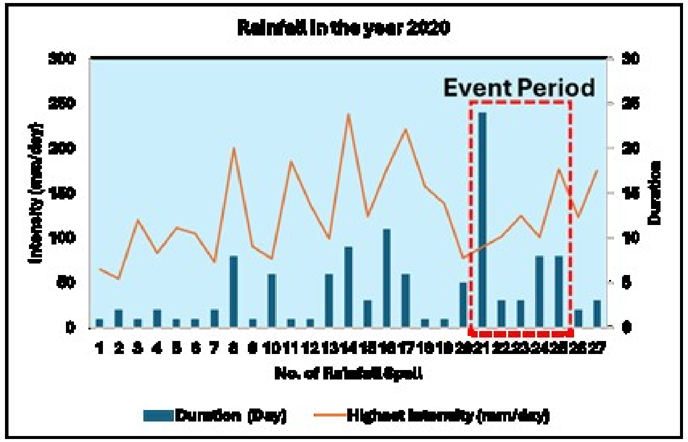




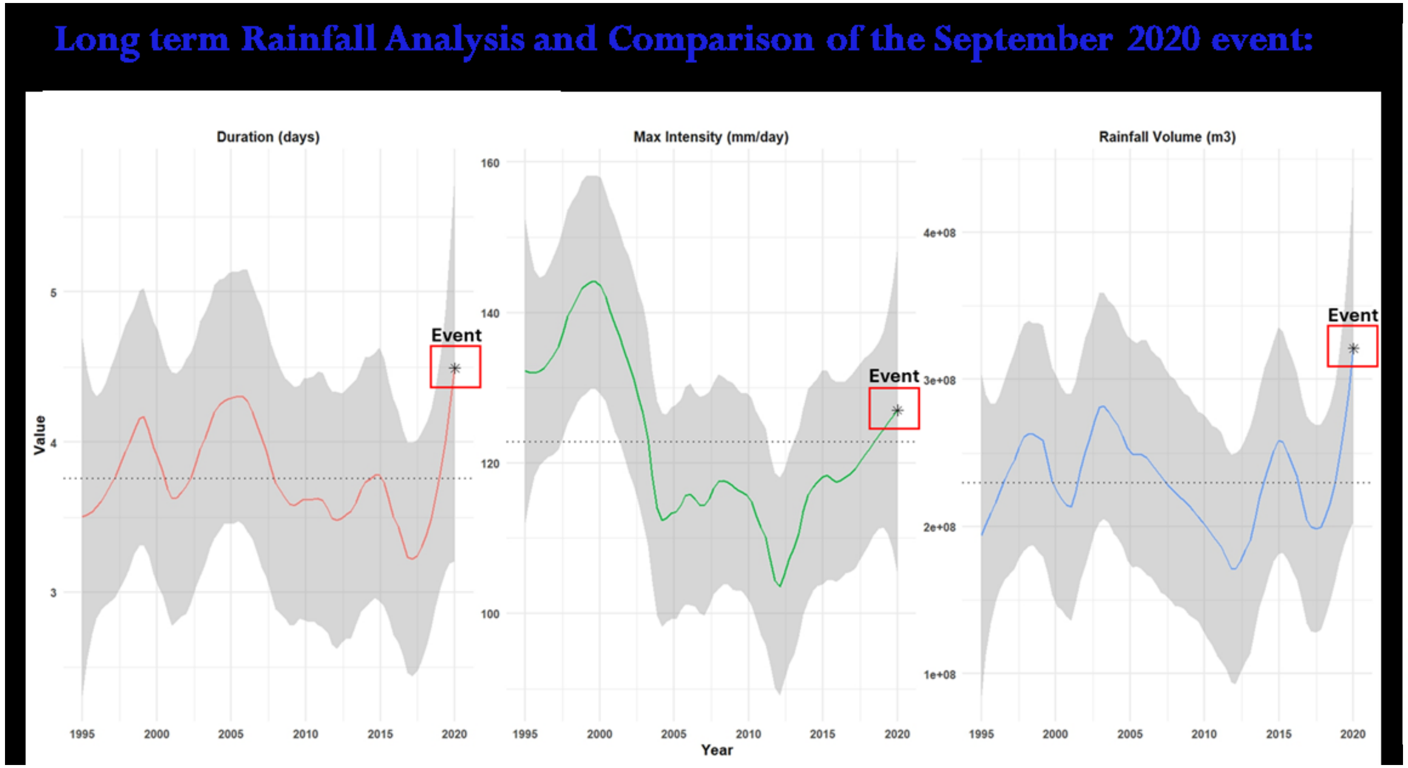


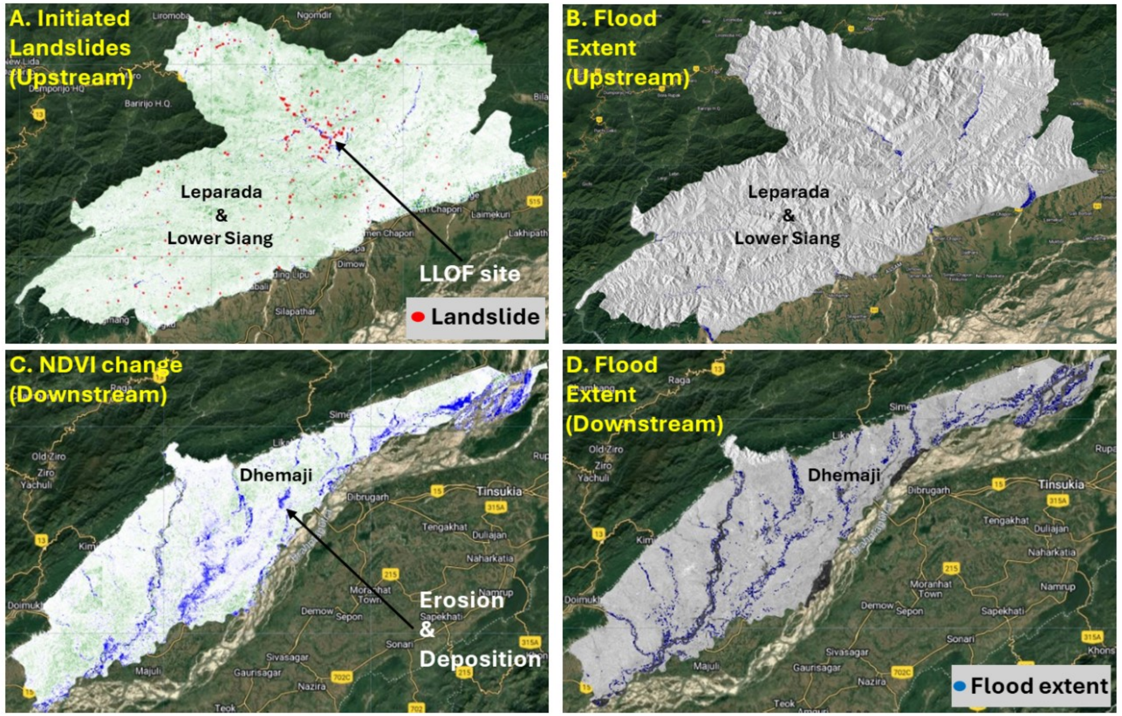
Upstream (Leparada & Lower Siang): 2678 sq. km
Downstream (Dhamaji): 3237 sq. km

The event triggered landslides and debris flows, forming a temporary landslide dam, and within 3–4 hours, houses, bridges, and infrastructure were destroyed.



Extreme Climatic Event: Case Study





- Approximately 160 landslide scars were identified, along with flooded areas of 9.7 sq. km (upstream) and 100 sq. km (downstream).
- The September 2020 Leparada and Dhemaji cascade demonstrates rapid upstream to downstream coupling, where slope failures, temporary damming, and sediment pulses intensified downstream inundation and flood volume.
- Rainfall in the Eastern Himalaya is shifting toward high-intensity, short-duration storms, with peak daily intensities rising with modest increases in spell length or frequency.

Extreme Climatic Event: Case Study

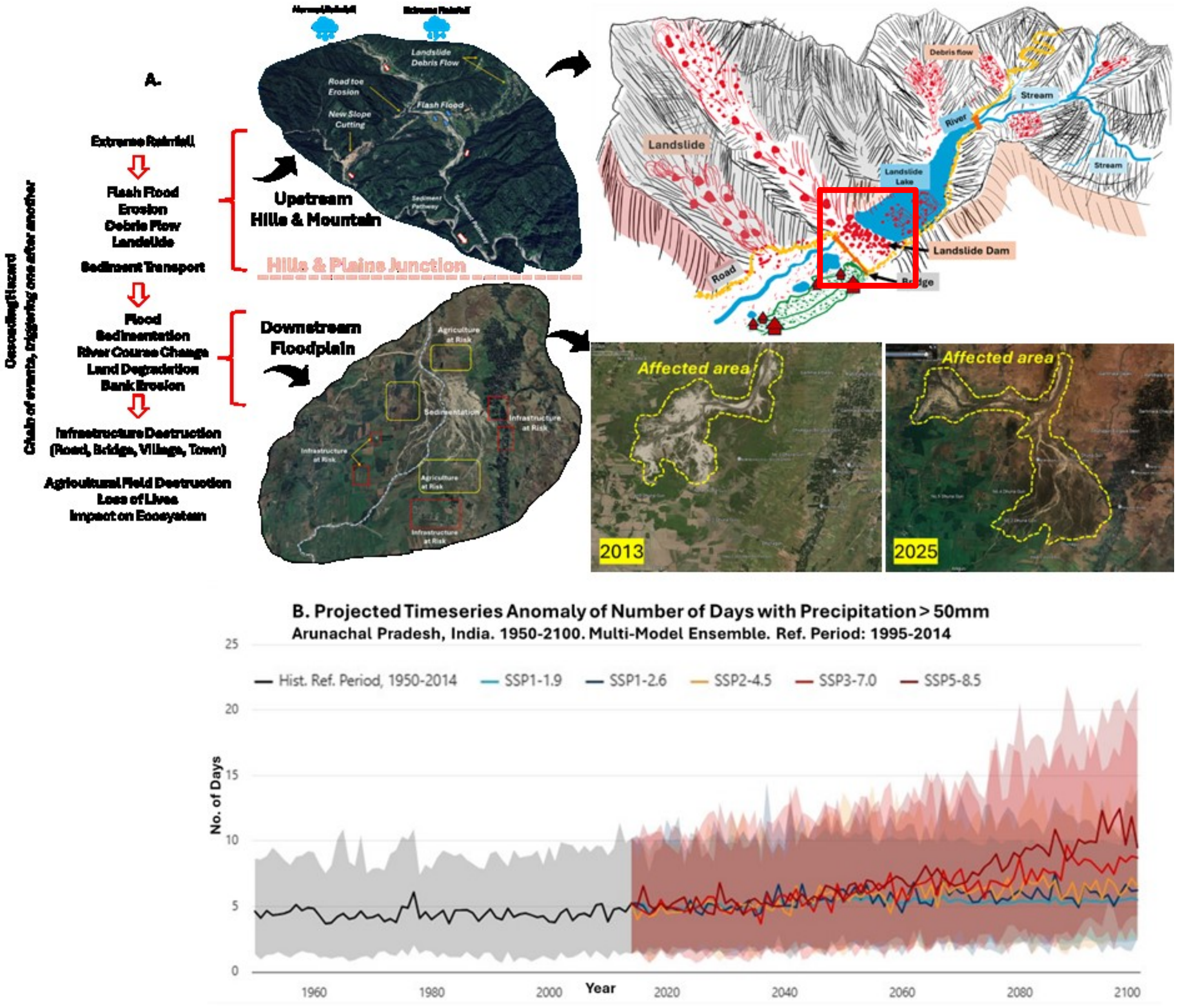


Figure: *Cascading hazard processes and projected future hydroclimatic stress in the Arunachal Pradesh and Assam corridor, (A) Conceptual representation of the compound cascade triggered by the 17th and 18th September 2020 extreme rainfall event. Intense rainfall generated rapid hillslope erosion, widespread landslides, and debris flows in the upstream terrain, including the formation and subsequent breach of a landslide-dammed lake. The resulting sediment-laden surge propagated into the downstream floodplains, driving channel aggradation, river course adjustments, extensive siltation, bank erosion, infrastructure damage, agricultural losses, and ecosystem disruption. These geomorphic responses not only characterize the 2020 event but also illustrate recurrent annual landscape reorganization that is progressively elevating regional hazard risk, (B) Projected time-series anomalies of the number of days with precipitation greater than 50 mm for the study area in Arunachal Pradesh, derived from the World Bank Climate Change Knowledge Portal (CCKP) under multiple SSP scenarios. All scenarios show a consistent increase in the frequency of high-rainfall days through the 21st century, indicating a likely intensification of extreme rainfall and associated compound cascade hazards in the region.*

CESHS Field Instrumentation

Cryosphere & Climate issues transcend local boundaries and require regional solutions.

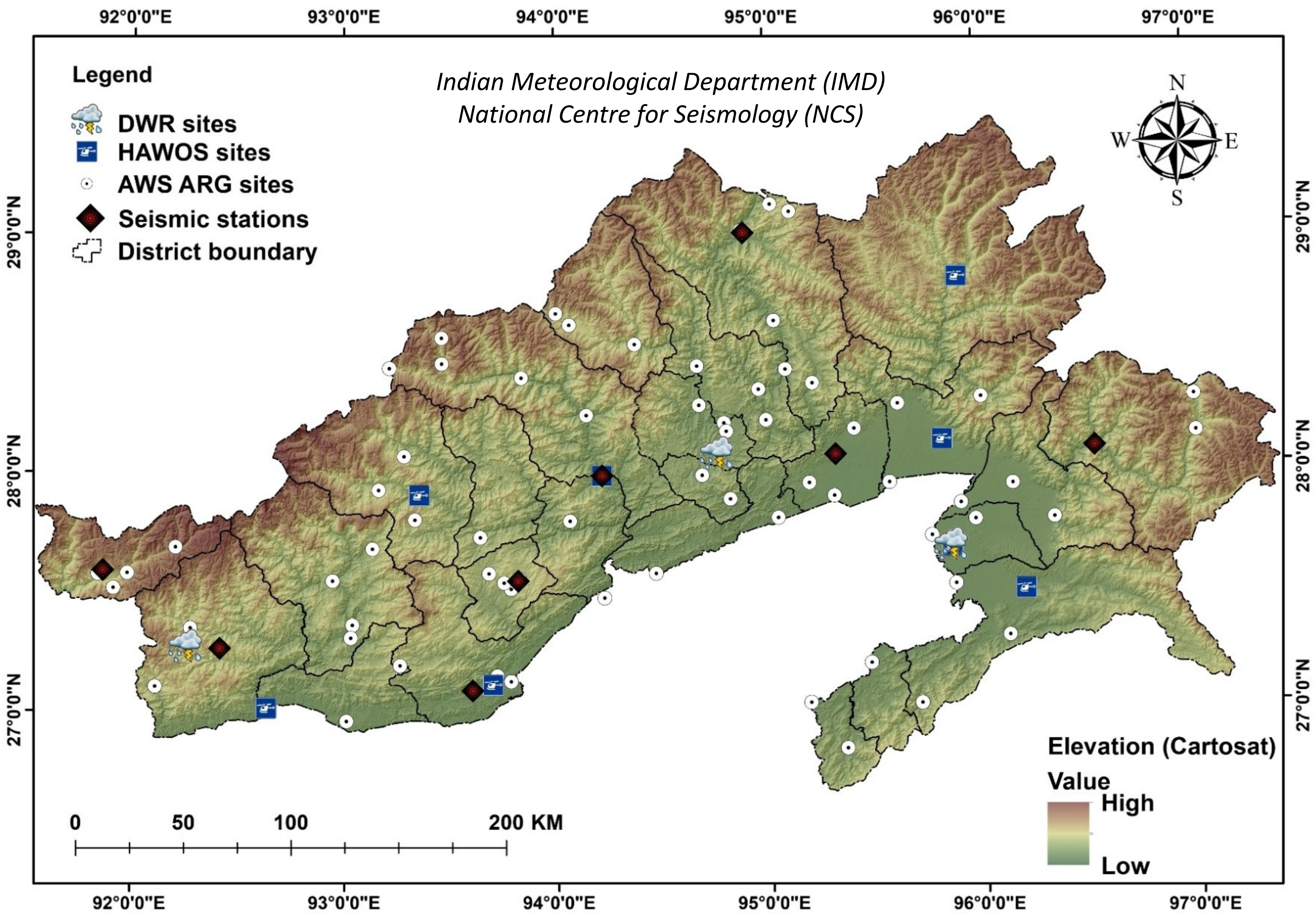
↓

CESHS has systematically deployed a comprehensive monitoring network across Arunachal Pradesh through institutional collaboration with India Meteorological Department (IMD) and the National Centre for Seismology (NCS).

↓

CESHS has installed,

- 3 Doppler Weather Radar (DWR) sites
- 8 Heliport Automatic Weather Observation Systems (HAWOS)
- More than 80 Automatic Weather Stations (AWS) and Automatic Rain Gauges (ARG)
- 8 seismic monitoring stations



Way forward & Conclusions

• Rapid Cryospheric change is now an observed reality in the Eastern Himalaya, with rapid glacier mass loss, thinning, and retreat altering seasonal runoff, flow variability, and sediment dynamics in the Brahmaputra headwaters.

• Rapid growth of proglacial and supraglacial lakes is significantly increasing GLOF risk, especially in moraine-dammed, tectonically active, and climatically sensitive terrain, threatening downstream dams, hydropower projects, and transboundary infrastructure.

• Cascade hazards driven by extreme rainfall are intensifying, linking landslides, debris flows, river damming, and downstream flooding through strong upstream–downstream coupling that must be integrated into dam safety and hydropower planning.

• Model-based assessments show that potential GLOF peak discharges and sediment surges can exceed current design assumptions, highlighting the need for climate-informed design standards, spillway re-evaluation, and proactive sediment management.

• Hazards exhibit a dual hydro-meteorological trigger, where short-duration high-intensity rainfall initiates hillslope failures, while multi-day rainfall accumulation controls downstream flooding, reservoir siltation, and channel instability.

• Dense, multi-parameter monitoring networks are critical for climate-resilient infrastructure, enabling real-time hazard tracking, early warning systems, and informed operational decision-making for dams and hydropower projects.

• Integrated source-to-sink frameworks combining cryosphere science, extreme event analysis, and hazard modelling are essential.

Way forward & Conclusions

• Effective climate resilience requires institutionalised collaboration among scientific agencies, dam owners, hydropower developers, and regulators to translate science into operational protocols and adaptive management.

• CESHS provides a regional scientific backbone for climate-resilient hydropower development, supporting pre-project investigations, continuous risk monitoring, post-event assessments, and targeted remediation.

• Sustainable hydropower development in the Eastern Himalaya demands embedding climate intelligence into policy, planning, and operations, ensuring long-term infrastructure safety and downstream risk reduction.

Thank You

Collaborators

Thamban Meloth
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Aditi Bhadra
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Hago Nabam