GLOF DISASTER RISK REDUCTION IN SIKKIM

Innovations In Science, Policy And Practice



Wake up Call for the Nation

South Lhonak Glacial Flood 2023 catastrophe

Rs in crores

No.	Item	Amount	Source
1	Sikkim Urja 1200 MW Dam	14,000	PDNA
2	NHPC Four Dams (one year)	1,838	NHPC
3	State infrastructure	1,480	PDNA
4	Defence infrastructure	550	
5	Border Roads	380	BRO
6	Forests	168	PDNA
7	Tourism economy (one year)	139	Tourism Dept
	Total	**18,555**	

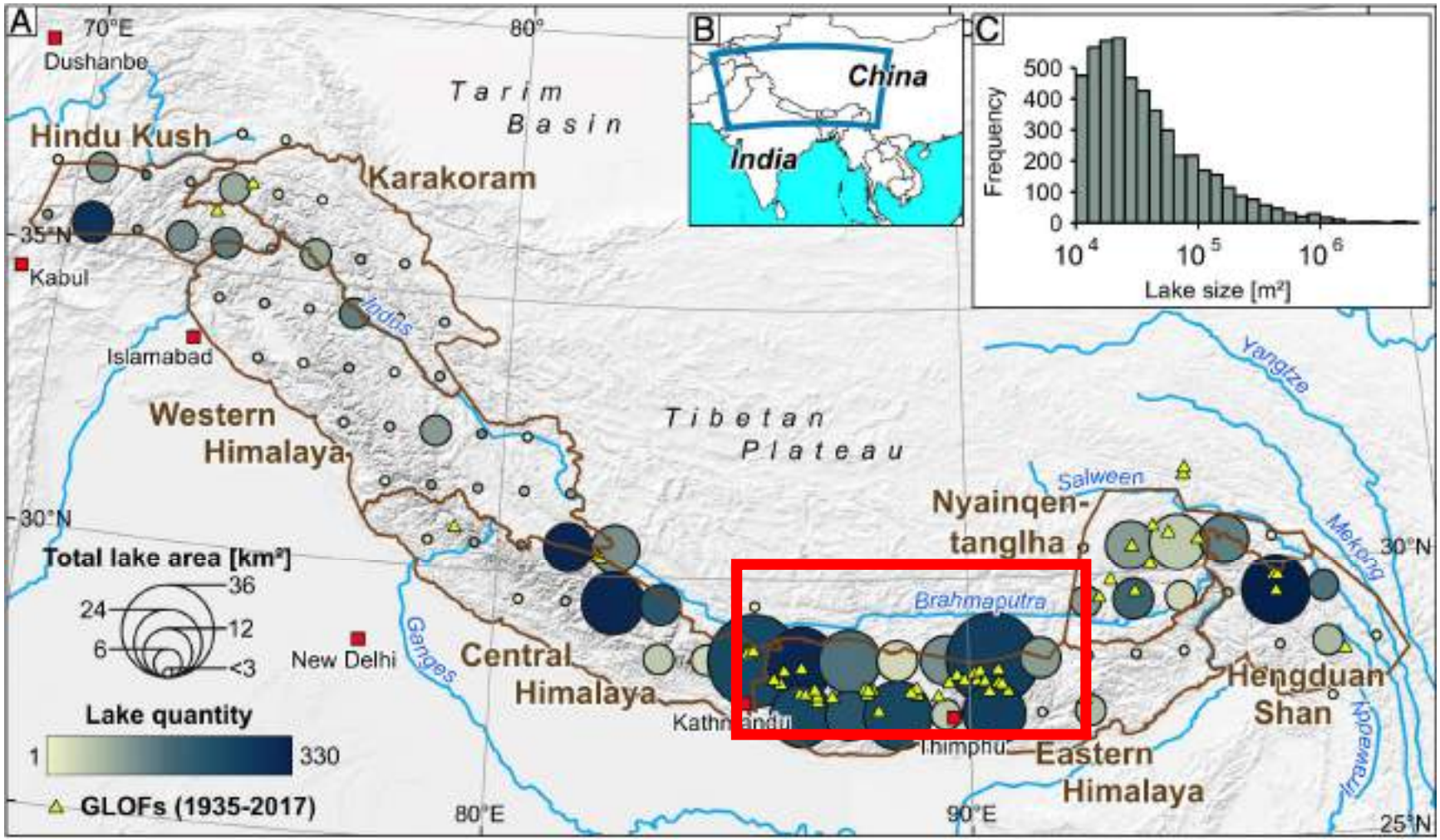
GLOF: Ticking Timebomb in the Himalayas

- Accelerating Climate Change and retreating glaciers are leaving behind growing lakes
- There are 28,043 mapped glacial lakes (≥ 0.25 ha) across the Himalayas of which 733 are located in Sikkim (Rao et al., 2023)
- Tremendous altitude differential (2-3km) between the lakes and habitations results in debris-laden floods.
- In the Himalayas, 54% of all GLOFs with known triggers, were triggered by avalanches, rock falls, and landslides impacting the lake.

GLOF Hotspot – Eastern Himalaya

- The Eastern Himalayas are a hotspot of GLOF hazard, which is 3 times higher than in any other Himalayan region. This is due to the region currently having the largest lakes and experiencing the highest GLOF activity over the past three decades (Veh et al., 2019).
- EWS is critical to save human lives, but is not sufficient.
- Main challenge is to safeguard mountain infrastructure (roads, bridges, dams, habitations etc…), which is costly and time taking to rebuild
- Unlike other disasters, such as earthquakes, cyclones, cloudbursts, landslides, etc, GLOF disasters can be prevented.
- Also, a big challenge to defense preparedness, as most of these lakes are in border areas, which can get cut off for years

GLOF Hotspot: Eastern Himalaya



Source: Veh et al. 2019

Government Vision and Policy

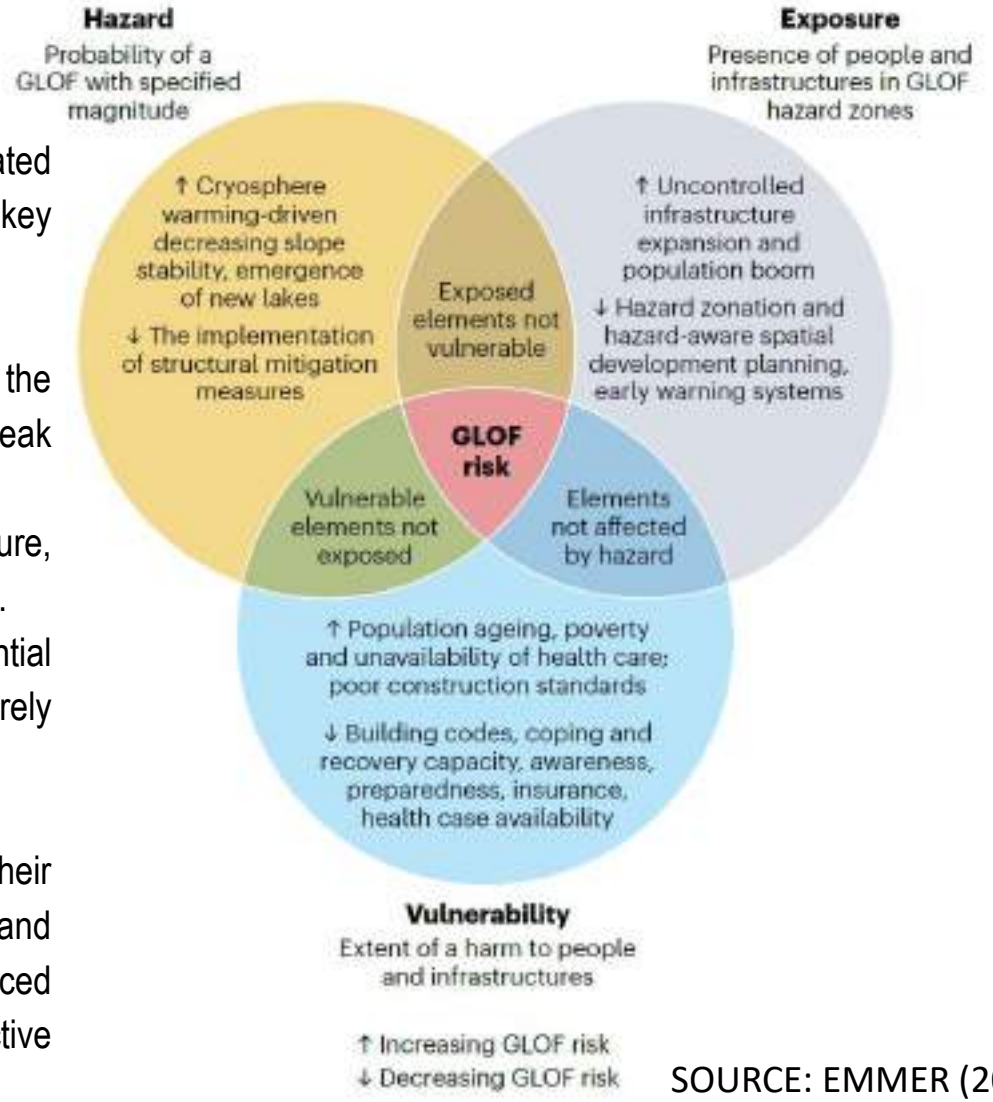
- Safeguard Sikkim from future GLOF events
- Imperative to protect mountain infrastructure such as highways, dams, bridges, habitations, defense assets from future GLOFs
- Urgency to develop GLOF mitigation proposals
- Whole of Government approach through High Level Steering Committee and Multi-disciplinary Task Force was notified
- Business rules were amended to designate S&T department as the nodal department for GLOF
- Special engineering section was established for designing structural measures for GLOF mitigation

GLOF DRR

A well-established framework for understanding the risks associated with natural hazards, including GLOFs, is built on three key components—**hazard, exposure, and vulnerability**.

The **hazard component** defines the probability and magnitude of the event, such as the likelihood of a GLOF occurring with a specific peak discharge or water volume release.
The **exposure component** accounts for the infrastructure, settlements, and populations situated within the flood's impact zone.
The **vulnerability component** determines the extent of potential damage—whether infrastructure will be partially affected or entirely destroyed, and the number of people at risk of injury or loss of life.

These three factors do not contribute equally to risk; instead, their influence shifts depending on local topography, climatic conditions, and human interventions. As highlighted in Emmer (2024), a nuanced understanding of these interactions is essential for designing effective GLOF mitigation strategies.



SOURCE: EMMER (2024)

GLOF Disaster Risk Reduction

The GLOF disaster risk reduction involves addressing the **three** components of hazard: exposure and vulnerability (Table).

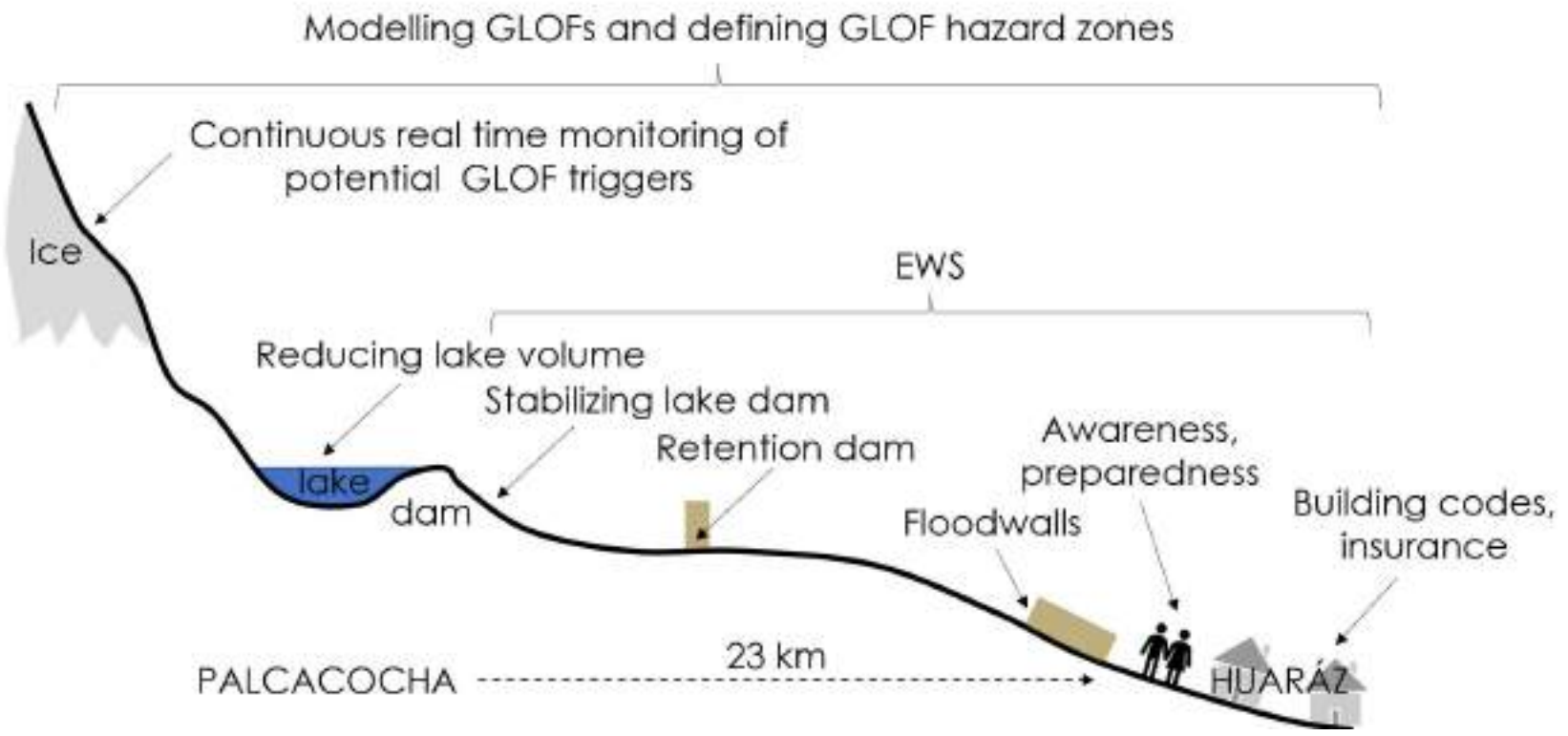
Reducing hazard will involve lowering the lake water level through structural measures such as open cuts, artificial dams, tunnels, and pumping and non-structural measures such as siphoning and pumping. It also involves the construction of floodwalls to prevent the flood from rushing into built-up areas.

Reducing exposure will involve the development of hazard maps, restricting new constructions in the hazard zones, relocating critical infrastructure from the hazard zones, and creating an early warning system to reduce the exposure of people in the hazard zones.

Vulnerability reduction will entail insurance cover for the assets in the hazard zones and developing preparedness and evacuation planning of the people in the hazard zones.

SOURCE: EMMER (2024)

GLOF DRR – Possible Interventions



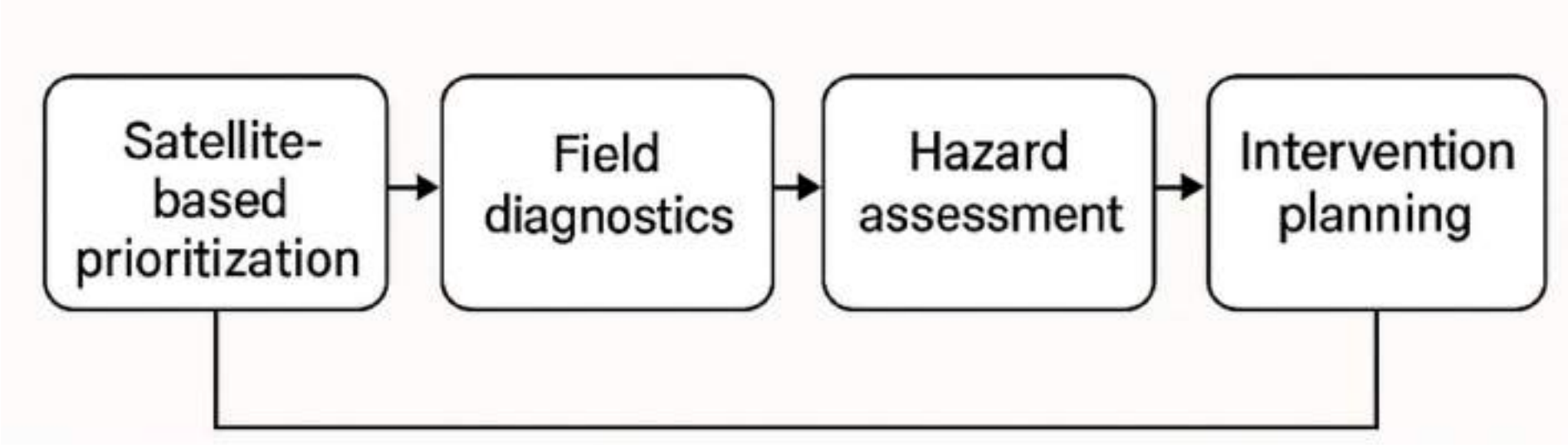
SOURCE: EMMER (2024)

GLOF Disaster Risk Reduction

	Measure	Implementation	Purpose
hazard	Open cuts	Lake dam	Lake level lowering, volume reduction, prevents outflow incision
	Artificial dams	Lake dam	Increased freeboard, dam reinforcement, prevents dam overtopping
	Tunnels	Lake dam	(Regulable) lake level lowering, volume reduction, hydropower
	Retention dams	Downstream	Potential flood retention + hydropower, recreation, water storage (multipurpose)
	Floodwalls	Downstream	Prevent the flood from rushing into built-up areas
exposure	Hazard maps	Spatial planning	Restrict new constructions in GLOF hazard zones
	Relocation	GLOF hazard zones	Removal of critical infrastructure from GLOF hazard zones
	Early warning system	GLOF hazard zones	Exposure reduction of people in GLOF hazard zones
vulnerability	Building codes	GLOF hazard zones	Appropriate design and quality standards of buildings in GLOF hazard zones
	Insurance	Assets in hazard zones	Coverage of the disater-associated costs and faster recovery
	Awareness and preparedness	People in hazard zones	Perception of a risk and readiness to take an appropriate actions in case of a GLOF and after
	GLOF-aware critical infrastructure	Spatial planning	Well-designed evacuation routes with sufficient capacity, availability of a health care

SOURCE: EMMER (2024)

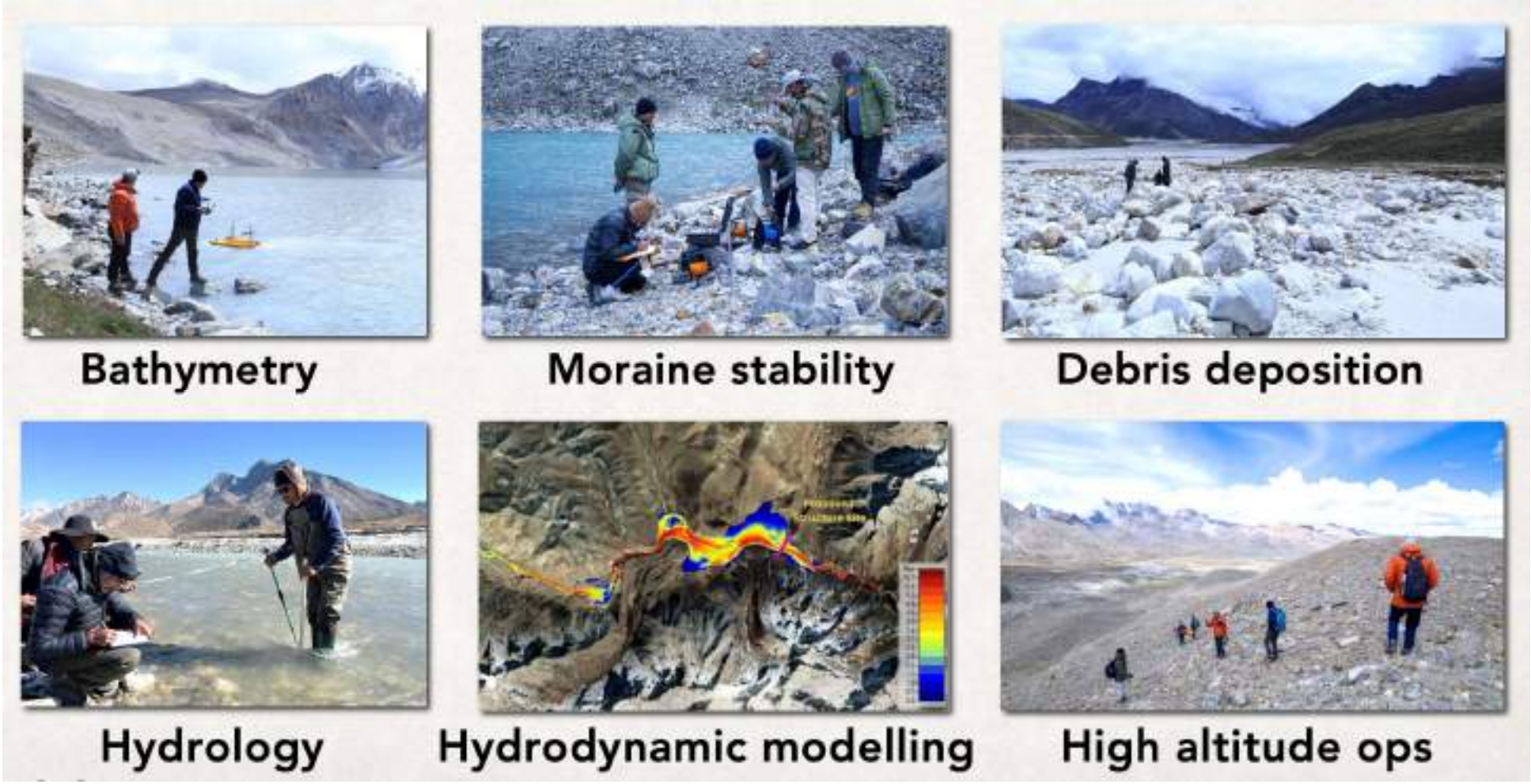
Sikkim 4-Step Mitigation Framework



Step 1
Satellite Based Prioritization



Step 2: Field diagnostics



Step 02: Field Diagnostics

Morphometry

Lake Characteristics	Tikip Lake	Shako Chho	Lachung Khangse	Lha Chho	Lachen Khangse	Khangchung Chho	Changsang lake	South Lhonak Lake
Lake area (km^2)	0.36	0.58	0.26	0.26	0.69	1.83	0.85	1.50
Lake length (km)	1.50	1.41	0.86	0.85	1.69	3.20	1.79	2.58
Type of dam	Moraine-dam	Moraine-dam	Moraine-dam	Moraine-dam	Moraine-dam	Moraine-dam	Moraine-dam	Moraine-dam
Dam width to height ratio	4.3	0.52	0.105	0.22	0.005	0.05	0.09	0.12
Freeboard	7	20	1	27	8	1	3	0
Active snow avalanche site	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Lake level (masl)	4847	4962	5008	5064	5155	5315	5411	5200
Natural outlet	No	No	Yes	No	No	Yes	Yes	Yes
Lake orientation	NW- SE	NE-SW	NW- SE	W-E	SW-NE	NW-SE	W-E	W-E
Contact with parent glacier	No	Yes	No	No	Yes	Yes	Yes	Yes
Measured volume (million m^3)	10	27.5	1.59	10	33.73	106.28	43.11	*65.81
Ice Calving in lake	No	Moderate	No	No	No	Substantial	Substantial	Substantial

**Lake bathymetric information adopted from Sharma et al 2018.*

Step 02: Field Diagnostics
Hydrometeorology

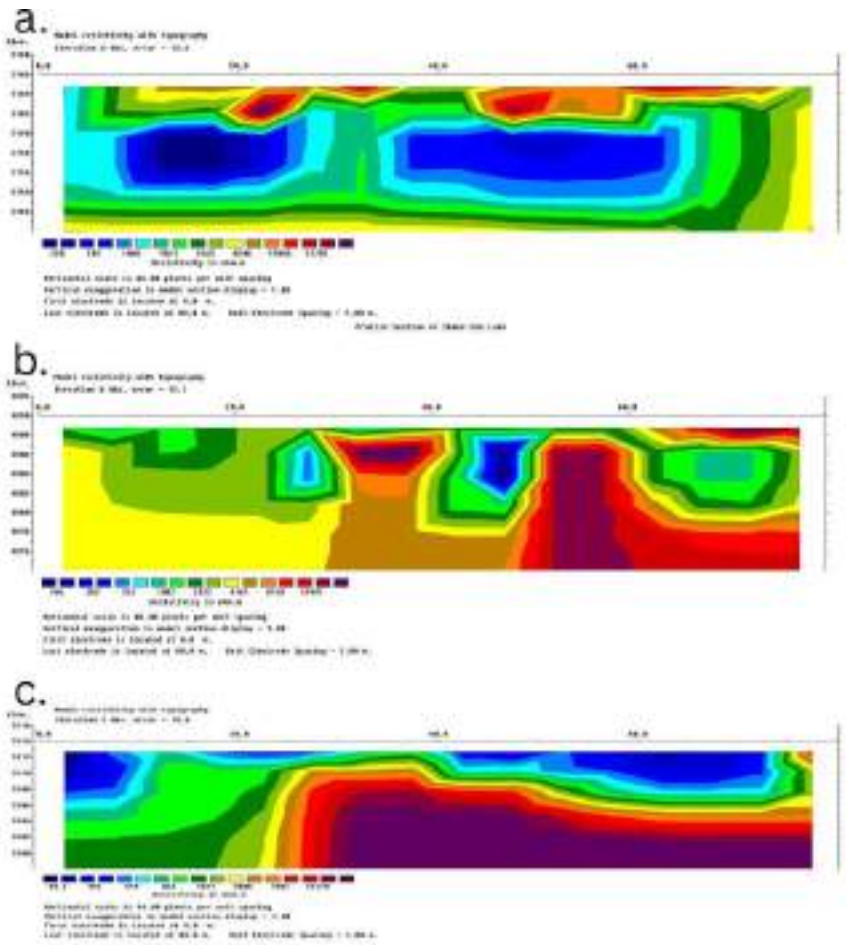




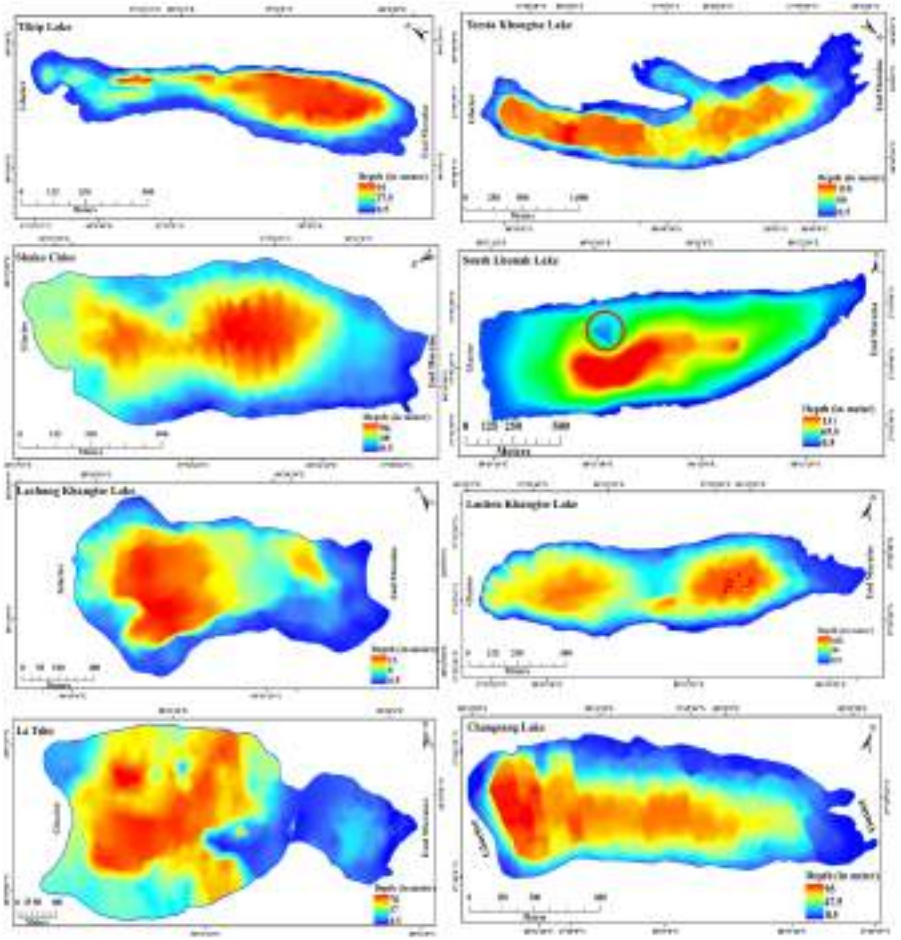
AWS, Monitoring Stations, Lake water level monitoring

Step 3: Hazard assessment

Geophysical



Bathymetry



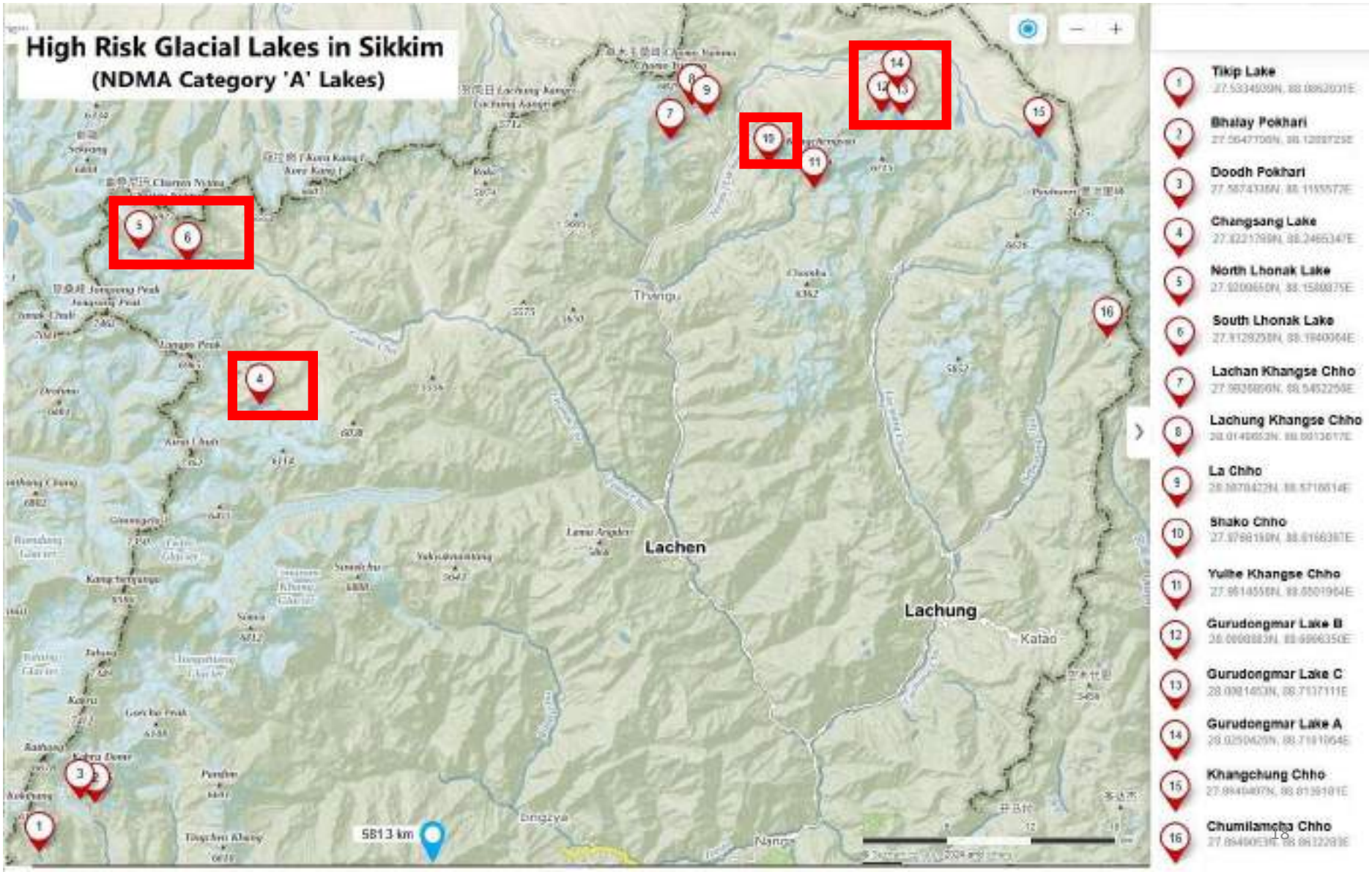
KEY FINDINGS & RECOMMENDATIONS FROM CFBHA

FOR GLOF HAZARD AND MITIGATION PLANNING

LAKE	KEY INSIGHT	HAZARD IMPLICATION	RECOMMENDED ACTION
Tikip Lake 	Shallow lake depth near the potential mass movement zone; no lake outlet	Low likelihood of large impulse waves	Monitor terminal moraine and mass movement zone with real-time deformation camera and InSAR
Shako Chho 	Subsurface seepage in terminal moraine; no lake outlet; sufficient solar radiation	Moraine weakening due to freeze–thaw; suitable for lake lowering	Install piezometers, pressure probes; Monitor moraines with InSAR, and real-time deformation camera; Solar-based pumping system
Lachung Khangtse 	Shallow lake; no PAS	Low Hazard and low outburst potential	No immediate intervention required
La Chho 	No lake outlet; high freeboard	Possible moraine degradation	Monitor terminal moraine and mass movement zone with real-time deformation camera and InSAR
Lachen Khangtse 	Ice-cored terminal moraine; no lake outlet	Risk of dam instability due to ice-core melt	Install piezometers, pressure probes; monitor moraines with real-time deformation camera and InSAR
Khangchung Chho 	Deep basin near active calving front; push moraine	High impulse wave potential; relatively stable dam	Monitor lake level through pressure probes; monitor calving front of the glacier and PAS with a real-time deformation camera and InSAR
Changsang Lake 	Deep basin near active calving front	Calving-induced high impulse wave potential	Monitor glacier's calving front and PAS with real-time deformation camera and InSAR
Bhalay Pokhari 	Lake outlet present; lower volume; steep headwalls having PAS	Limited potential expansion; localized impulse wave risk	Monitor PAS and hanging glacier with InSAR
Yulhe Khangtse 	Lake outlet and PAS present; mid basin maximum depth	Moderate impulse wave potential	Monitor PAS and hanging glacier with InSAR

Step-4: Intervention planning

Most Dangerous Lakes





Shako Chho Lake

- Its size is 143 acres and stores 27 mcm water.
- Does not have a natural open outlet and hence the outflow is seeping through the 70m high terminal moraine.
- Flows directly into Thangu habitation and army establishments just 15 km downstream.



Solar-powered lake lowering

- Lake environ is fragile and hence invasive methods are not advisable.
- Solar-powered lake lowering DPR has been prepared for funding from NGRMP.
- DPR has been technically approved and financial sanction from NDMA is awaited.



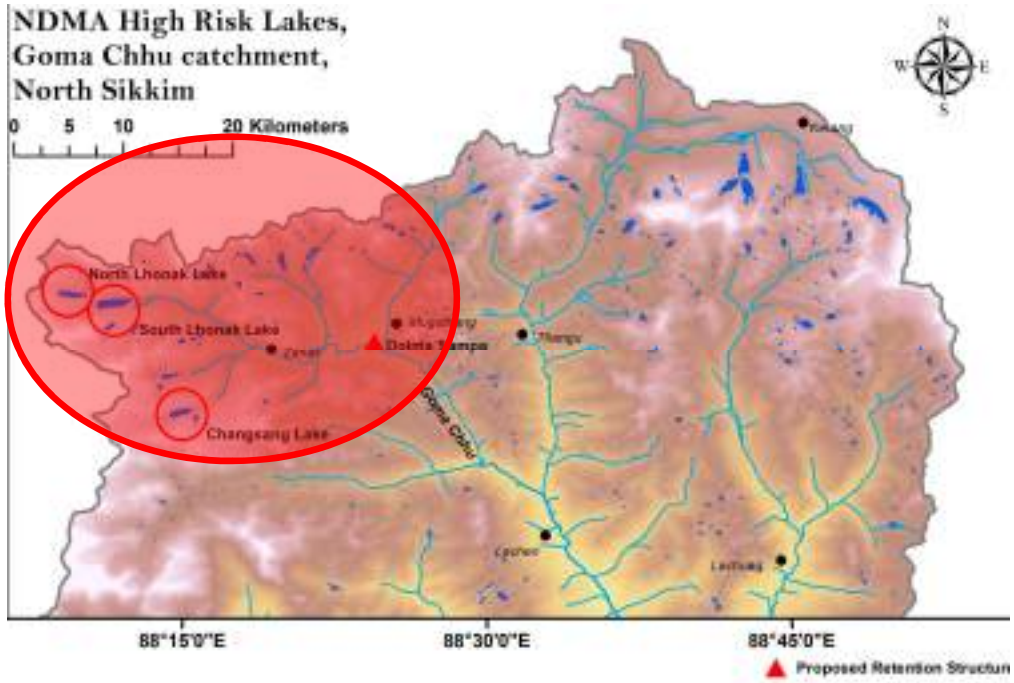
Changsang lake

- Formed in the 1990s, it has grown to about 210 acres and stores 43 mcm of water.
- As a glacier-terminating lake, its volume is projected to increase further.
- The terminal moraine is made up of ice and rock, making it unstable.

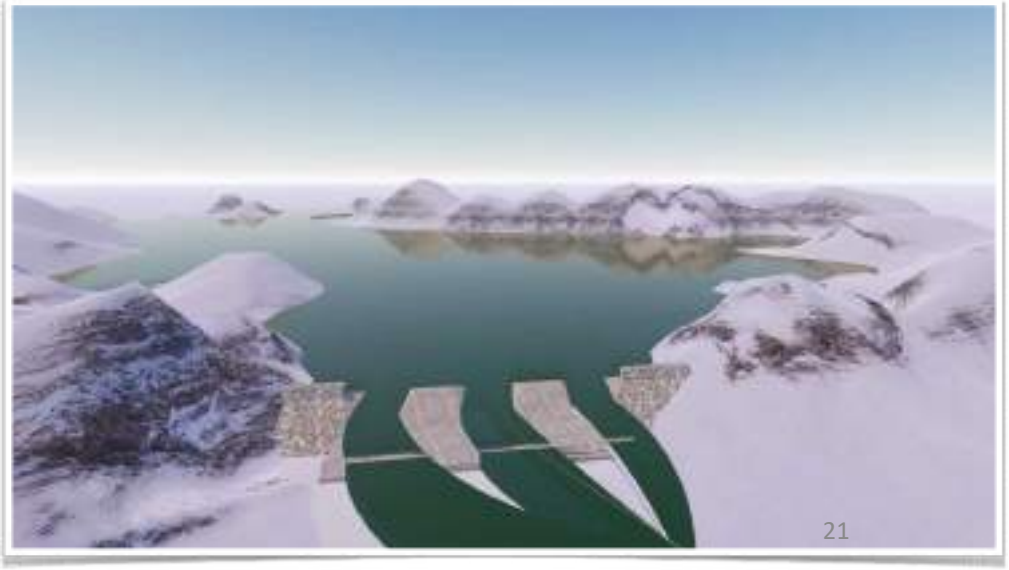


Lhonak Lake Complex

- This lake discharged 40 mcm of debris-laden flood during Oct 2023 due to a massive landslide from the left lateral moraine
- It is coupled with North Lhonak lake and North Lhonak glacier. Total volume of water is 107 mcm - South Lhonak (65 mcm) and North Lhonak lake (42 mcm)







Retention Structure in Lhonak

- The valley's unique geometry caused dramatic flood deceleration and extensive debris deposition 25 km downstream.
- This insight presents possibility for designing a retention structure at Dolma Sampa to safeguard against 183 lakes to delay and attenuate downstream flood peaks.



Gurudongmar Lake Complex

- It is the most sacred, wish fulfilling lake.
- It has a total volume of 178 mcm and comprises three lakes.
- Gurudongmar East (C), is a young lake formed in 1990s and has expanded to 299 acres over past few decades and holding 65 mcm of water.



Integrating resilience with reverence

(Concept Stage)

- A moraine plug safety wall can help contain the GLOF displacement waves within the lake.
- Regulated outflow through reinforced drainage pipes and paved spillway.
- 108 prayer wheel corridor and 108 cascading dharas can enhance the spiritual experience.

Gurudongmar Lake Complex

Proof of concept: Construction of moraine plug safety wall was a standard practice adopted by Peruvian engineers in the Andes in the 1970s (USAID 2014). This safety wall is backed by an impervious core and internal filter layers to prevent piping and erosion.

