BEFORE THE NATIONAL GREEN TRIBUNAL
EASTERN ZONE BENCH AT KOLKATA
ORIGINAL APPLICATION NO. 171/ 2023

IN THE MATTER OF:-

IN RE.: NEWS ITEM APPEARED IN EAST MOJO ON 05.10.2023 TITLED "SIKKIM: HERE'S WHY THE CHUNGTHANG HYDRO-DAM BREACH IS A BIG DEAL" .... APPLICANT

Versus

THE STATE OF SIKKIM & ORS. …. RESPONDENTS

INDEX

Through

(SAMEER ABHYANKAR)
ADVOCATE FOR RESPONDENT NO. 1
(STATE OF SIKKIM)
D-247, LGF, DEFENCE COLONY,
NEW DELHI-110024
Email: contactadvsa@gmail.com
M-995332839

PLACE: NEW DELHI
Dated:28.02.2026

BEFORE THE NATIONAL GREEN TRIBUNAL
EASTERN ZONE BENCH AT KOLKATA
ORIGINAL APPLICATION NO. 171/ 2023

IN THE MATTER OF:-

IN RE.: NEWS ITEM APPEARED IN EAST MOJO ON 05.10.2023 TITLED "SIKKIM: HERE'S WHY THE CHUNGTHANG HYDRO-DAM BREACH IS A BIG DEAL"

.... APPLICANT

Versus

THE STATE OF SIKKIM & ORS. .... RESPONDENTS

ADDITIONAL AFFIDAVIT ON BEHALF OF THE RESPONDENT NO. 1 (THE STATE OF SIKKIM)

I, Ashwani Kumar Chand, I.P.S., Principal Resident Commissioner, Government of Sikkim, Sikkim House, 12, Panchsheel Marg, Chanakyapuri, New Delhi, do hereby solemnly affirm and most humbly and respectfully submit that:

1. I am the Principal Resident Commissioner of the State Government of Sikkim, and as such am competent to depose to the contents of this Affidavit. I have gone through the contents of the Petition and have understood its contents.

2. I am authorized to swear the present affidavit based on the instructions received from the Home Department, Government of Sikkim, the Relief Commissioner-cum-Secretary, Land Revenue & Disaster Management Department, Government of Sikkim and the PCE-cum-Secretary, Energy & Power Department, Government of Sikkim.

3. The present affidavit is being filed on behalf of the State of Sikkim in response to the *suo moto* notice issued by this Hon'ble Tribunal on

NOTARY PUBLIC
HARPAL SINGH
ADVOCATE
NCT DELHI
Regd. No.: 19710/2020
GOVT. OF INDIA

20.10.2023 on the basis of the newspaper item published in "East Mojo" dated 05.10.2023 titled "*Sikkim: here's why the Chungthang Hydro-dam breach is a BIG DEAL*".

4. That State of Sikkim vide affidavit dated 05.04.2024, taken on record vide order dated 08.04.2024, apprised this Hon'ble Tribunal of the developments that unfolded following the breach of the Chungthang Hydro-Dam, along with the precautionary and remedial measures undertaken by the State of Sikkim to ensure the safety of the dam and other water bodies in the State. The said affidavit also contained a brief synopsis outlining the cause of the incident, attributing the same primarily to a cloudburst.

5. That the present additional affidavit is being filed in compliance with the order dated 13.01.2026, whereby this Hon'ble Tribunal was pleased to grant six weeks' time, upon our request, to place on record additional information regarding the working and functioning of all dams situated on the Teesta River within the State of Sikkim.

6. I say that the present affidavit is being filed to place on record information on the following aspects arising subsequent to the incident:

   A. Constitution of the Technical Committee and meetings held after February 2024
   B. Remedial measures undertaken by the State to mitigate and prevent adverse effects of any future natural disaster
   C. The full extent of damages arising out of the Chungthang Breach incident and Glacial Lake Outburst Flood (GLOF), 2023; and
   D. The present status of Teesta Stage–III and other dams in the State of Sikkim, including the functional capacity at which they are presently operating.

NOTARY PUBLIC HARPAL SINGH ADVOCATE NCT DELHI Regd. No.: 19710/2020 GOVT. OF INDIA

A. CONSTITUTION OF THE TECHNICAL COMMITTEE AND MEETINGS HELD AFTER FEBRUARY 2024

7. As stated in the affidavit dated 05.04.2024, a High-Level Technical Committee **(HTC)** was constituted vide Cabinet decision dated 17.10.2023, in consultation with the National Disaster Management Authority **(NDMA),** to examine the causes of the Teesta Stage–III Dam breach and recommend further measures. Consequent meetings and deliberations were undertaken beginning 30.10.2023, with continued consultations through November and December 2023, and culminating in discussions held from 11.01.2024 to 19.01.2024 during the 4th meeting of the Committee on Disaster Risk Reduction **(CoDRR).**

8. It is pertinent to mention herein that the earlier High-Technical Committee (HTC) has since been upgraded, and a technical committee has been formed by Government of Sikkim under the chairmanship of Dr. Akhelesh Gupta, eminent Scientist to study and guide the state government to mitigate risk of glacier hazard in Sikkim.

   Copy of notification bearing no. 73/Home/2024 dated 11.09.2024 constituting Sikkim Commission on Glacial Hazards is marked and annexed hereto as ANNEXURE - R1

9. The Science and Technology Department **(DST)** has been engaged in systematic studies of glacial lakes, including South Lhonak Lake, since 2010. Based on its long-term involvement and technical expertise, the Government of Sikkim formally designated DST as the nodal department for GLOF studies and mitigation in the state.

   Copy of Notification bearing no. 10/Home/2025 dated 07.02.2025 Designating Science and Technology Department as nodal

department for glacial risk mitigation is marked and annexed hereto as ANNEXURE R-2.

10. Given that glacial hazards involve complex geological, hydrological, engineering, and social dimensions, effective mitigation cannot be addressed by a single department. Glacial lakes are often dammed by weak moraine material composed of loose boulders and sediments, making them highly vulnerable to sudden failure. Accordingly, a High-Level Steering Committee was constituted to guide policy and strategic decisions, supported by a Multi-disciplinary Task Force responsible for field-level implementation. Till date, six meetings of the Multi-disciplinary Task Force have been conducted to review and guide mitigation activities.

Copy of Notification bearing no. 72/Home/2024 dated 11.09.2024 constituting a High-Level steering committee (HLSC) and a multi-disciplinary task force (MTF) is marked and annexed hereto as ANNEXURE R-3.

11. At the National Level, the National Disaster Management Authority (NDMA) has established a Technical Advisory Committee (TAC) and a Committee on Disaster Risk Reduction (CoDRR) specifically to oversee the implementation of the National Glacial Lake Outburst Flood (GLOF) Risk Mitigation Programme (NGRMP). Key Details of the TAC for GLOF

   a) **Purpose**: The TAC is responsible for providing technical guidance, monitoring project implementation, and appraising GLOF mitigation projects from both technical and social perspectives. The committee is chaired by a senior official or a designated expert in the field.

NOTARY PUBLIC
HARPAL SINGH
ADVOCATE
NCT DELHI
Regd. No.: 19710/2020
GOVT. OF INDIA

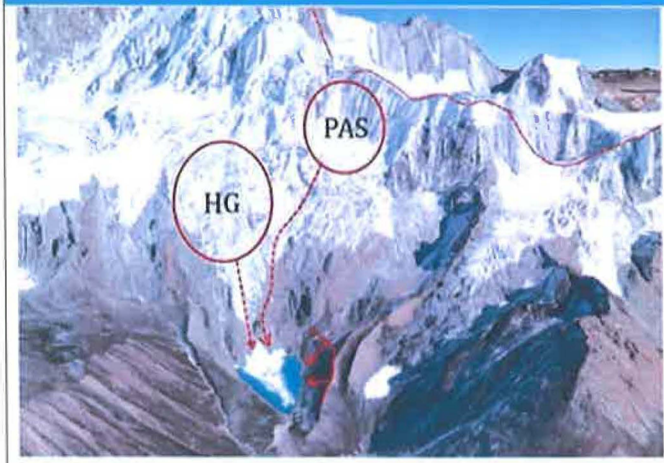
b) **Composition:** It includes representatives from inter-disciplinary expert groups, central ministries (Home Affairs, Jal Shakti, Science & Technology), and scientific institutions such as the Wadia Institute of Himalayan Geology (WIHG).

c) **Current Focus:** Monitoring 190 high-risk glacial lakes identified in the Himalayan region; Coordinating field expeditions for bathymetric surveys and structural stability assessments; Overseeing the installation of Early Warning Systems (EWS) and Automatic Weather Stations (AWS).

d) **Lab based preliminary hazard assessment of high-risk lakes:** The National Disaster Management Authority (NDMA) has identified 40 high-risk glacial lakes in Sikkim, out of which 16 are classified as very high risk, 2 as moderate risk, and the remaining as relatively lower risk. A preliminary hazard assessment of 16 high risk were undertaken through laboratory-based analysis using Remote Sensing and GIS platform. The assessment covered all 16 identified high-risk glacial lakes in Sikkim

Tenchungkha Lake

High risk lake No 16



NDMA ID: NDMA106
Coordinates: 27°51'52.038"N 88°51'44.627"E

Hazard Assessment

- Elevation: 4800 m, Area: 14 Ha, Volume: 5 million m³
- Steep gradient from head wall possessing threat of falling hanging glacier(HG)/ice cliff (IC) and presence of potential avalanche site (PAS)
- Unstable lateral moraine prone to slope failures
- Natural outlet exists; stable moraine dam

Figure 1: Hazard assessment of the Tenchungkha Lake

High Risk Glacial lakes in Sikkim

Sl. No	Lakes	Latitude	Longitude	Elevation (meter)	Area (Ha) 2022	Volume (million m³) 2022	Hazard Assessment
1	Tikip Lake	27°31'57.30"N	88° 5'10.89"E	4884	36	16	Risk of landslides, ice falls and avalanches, limited moraine dam height and low free board, no natural outlet exists
2	Bhaley Pokhari	27°33'47.764"N	88°7'25.656"E	4740	12	4	Located above the fragile lateral moraine of East Rathong Glacier risk of ice fall and avalanches, natural outlet exists
3	Doodh Pokhari	27°33'57.435"N	88°7'0.372"E	4780	3	0.5	Located above lateral moraine of Rathong Glacier, overflowing into the East Rathong lake, fragile lateral moraines
4	Changsang Lake	27°49'10.47"N	88°14'50.46"E	5431	85	43	Glacier tongue and lake is in direct contact, Risk of Avalanche and Hanging Glacier, unstable lateral moraine, high lake volume, no natural outlet exists
5	North Lhonak Lake	27°55'12.27"N	88° 9'26.44"E	5470	83	42	High lake volume, risk of snow avalanches, natural outlet exists.
6	South Lhonak Lake	27°54'45.38"N	88°11'36.60"E	5210	150	*84	High lake volume, expanding lake area, Unstable lateral moraine prone to slope failures, melt water from above draining into it, lake in contact with parent glacier, excessive calving, natural outlet exists
7	Lachen Khangtse Lake	27°58'32.70"N	88°32'44.12"E	5212	69	34	Moderate lake volume, Hanging glacier exists at steep head wall, limited freeboard, no natural outlet exists; vulnerable moraine dam
8	Lachung Khangtse Lake	28° 0'52.90"N	88°33'39.66"E	5090	26	11	Risk of avalanche and ice fall from hanging glacier, Unstable moraine dam and no natural outlet exists
9	La Chho	28° 0'25.08"N	88°34'18.91"E	5030	26	11	Compounded risk from Lachung Khangtse Chho in case of avalanche and ice falls, Natural outlet exists
10	Shako Chho	27°58'31.73"N	88°38'59.51"E	4990	58	27	Steep downhill gradient from head wall of glacier possessing threat of ice fall and avalanches, high lake volume, low freeboard, no natural outlet exists; vulnerable moraine dam
11	Yulhe Khangtse Lake	27°57'39.51"N	88°38'0.35"E	4992	19	7	Risk of ice fall and avalanches, expanding lake, natural outlet exists
12	Gurdongmar Lake B	28° 0'18.84"N	88°42'49.96"E	5225	101	53	High lake volume, Unstable lateral moraine, unstable moraine dam, risk from hanging glaciers in the headwall, no natural outlet exists; vulnerable moraine dam
13	Gurdongmar Lake C	28° 0'29.23"N	88°41'54.11"E	5254	121	65	High lake volume, expanding lake, risk of avalanches, Glacier tongue and lake is in direct contact, no natural outlet exists, vulnerable moraine dam
14	Gurdongmar Lake A	28° 1'31.42"N	88°42'38.89"E	5184	113	60	Compounded impact consisting of landslides, ice falls and avalanches from B and C lakes may trigger Glacial floods, Natural outlet exists
15	Khangchung Chho	27°59'20.00"N	88°48'9.89"E	5320	183	106	Very High lake volume, expanding lake, Glacier tongue and lake is in direct contact, risk of ice fall and avalanches, low freeboard, Natural outlet exists
16	Tenchungkha Lake	27°51'52.038"N	88°51'44.827"E	4800	14	5	Risk of ice fall and avalanches from steep headwall, unstable lateral moraine, natural outlet exists

*Present volume

Table 2: Hazard assessment of 16 high risk lakes in Sikkim

12. That a comprehensive field-based hazard and risk assessment involving DST, the Mines, Minerals and Geology Department, Sikkim University, Central Water Commission (CWC), and other expert agencies. 16 very high-risk lakes are prioritized and organized multiple field expeditions involving multidisciplinary teams. These expeditions undertake:

   a) Bathymetric surveys: Bathymetric survey completed for the following 9 lakes: Shako Chho, Lachen Khangtse, Lachung Khangsey, La Chho, Khangchung Chho, Tikip Lake, Bhalay Pokhari, Changsang, Yuley Khangsey

   b) Geophysical investigations: Electrical Resistivity Tomography (ERT) study completed for the following 7 Lakes: Chumilancha, Shako Chho, Lachen Khangsey, Khangchung Chho, Tikip Lake, Dood Pokhari, Bhalay Pokhari.

   c) Comprehensive hazard assessments: Compressive Hazard Assessment of 10 High Risk Glacial Lakes is completed.

   d) Water discharge measurements: Discharge Measurement completed for the following site: Dolma Sampa area, Khangchung Chho, Chumilancha, Tikip Lake

   e) High-resolution areal surveys using drones: 3-D terrain mapping of the Dolma Sampa area in Lhonak valley and Sora funnel area

NOTARY PUBLIC HARPAL SINGH ADVOCATE NCT DELHI Regd. No.: 19710/2020 GOVT. OF INDIA

in Gurudongmar valley is completed using drone. LIDER sensor used for high resolution topography survey.

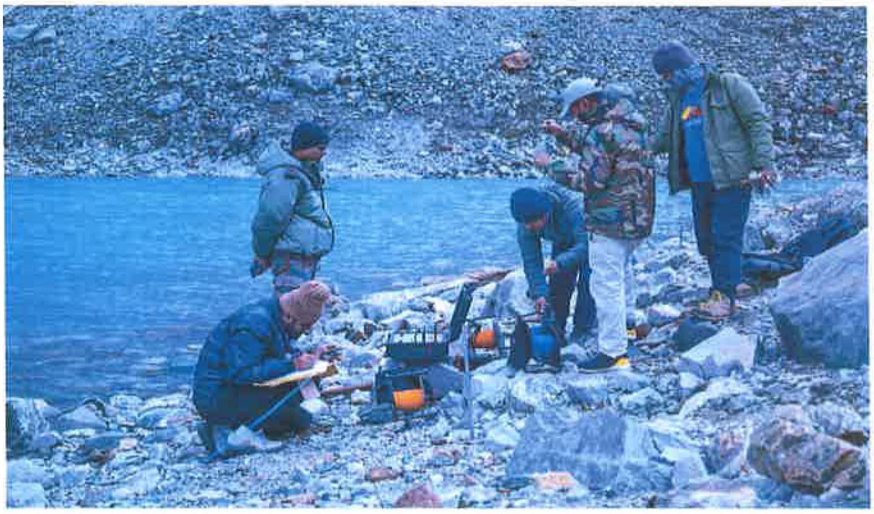


Figure 2: Geophysical Survey of the moraines using Electrical Resistivity Tomography Machine

Figure 3: Bathymetry survey for volume estimation of the lake

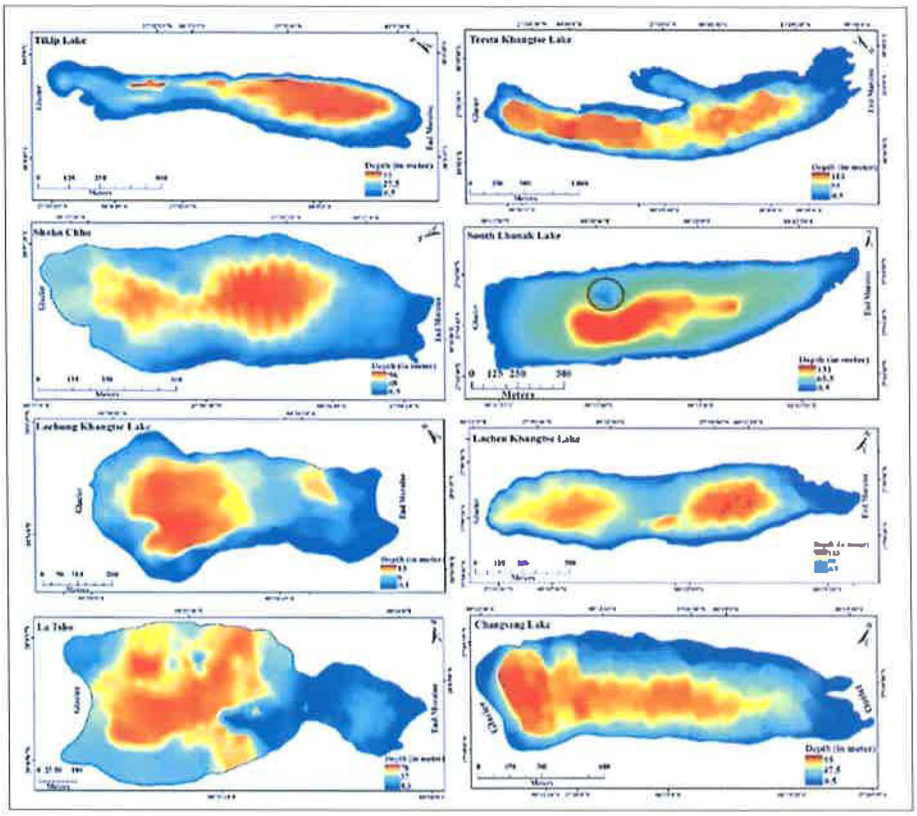


Figure 4: Bathymetric profile of the high-risk lakes

13. That a multi-disciplinary study team has conducted detailed field-based as well as lab-based study for construction of a flood retention structure at Dolma Sampa Hydrodynamic modeling of Dolma Sampa valley carried out for GLOF risk assessment apart from field-based studies. Project feasibility report has been prepared and submitted to NDMA. NDMA has approved the PPR and submitted to the Ministry of Jal Shakti for further process.

14. Although the proposed structure involves substantial investment, it is expected to mitigate GLOF risks over a catchment exceeding 400 km². The rapidly expanding Changsang Lake, now exceeding 90 hectares, along with other growing glacial lakes in the same catchment, further underscores the importance of this intervention. Taking the initiatives

NOTARY PUBLIC HARPAL SINGH ADVOCATE NCT DELHI Regd. No.: 19710/2020 GOVT. OF INDIA

further, the Ministry of Jal Shakti has further entrusted Central Water Commission for preparation of DPR of the said retention structure.

Copy of Letter of Ministry of Jal Shakti to Central Water Commission (CWC) for preparation of DPR for construction of retention structure at Dolma Sampa is marked and annexed hereto as ANNEXURE R-4.

Figure 5: Discharge measurement of the streams

Figure 6: Areal survey using drone

NOTARY PUBLIC
HARPAL SINGH
ADVOCATE
NCT DELHI
Regd. No.: 19710/2020
GOVT. OF INDIA

15. **Proposal for siphoning of Shako Chho Lake for decreasing the water level using solar power:** Shako Chho, a high-risk glacial lake located in North Sikkim, covers an area of approximately 58 hectares with a maximum depth of about 96 m and lacks a natural outlet. In view of its vulnerability, mitigation measures were proposed for the lake. However, geophysical investigations carried out by the Mines and Geology Department advised against any form of physical intervention on the moraine dam.

16. Considering the lake's risk profile and the advisory of the Mines and Geology Department, siphoning has been identified as the safest method for controlled release of lake water, using solar power. A Project Prefeasibility Report (PPR) dated March, 2025 for the proposed intervention has been prepared and submitted to NDMA for funding under the NGRMP Project. This proposal is conceived as a pilot initiative for lake level lowering, and upon successful implementation, the approach can be replicated in other Himalayan regions. **Copy of a Project Prefeasibility Report (PPR) for the proposed intervention prepared and submitted to NDMA for funding under the NGRMP Project is annexed hereto as ANNEXURE R-5**

17. **Proposal of building a Moraine Plug Safety Wall at Gurudongmar Lake-Integrating Resilience with Reverence:** A Sacred Disaster Resilient Engineering the Gurudongmar Lake Complex has a total volume of 178 mcm and comprises three lakes A, B and C which have been categorized from the GLOF risk perspective as high-risk category A lakes by NDMA. Gurudongmar East (C), which lies upstream of the main lake, is a young lake formed in the 1990s and has shown significant expansion by attaining 65 mcm over the past few decades, increasing the risk of potential GLOF. As a glacier-terminating lake, its volume is projected to increase further.

18. As direct interventions within the lakes are restricted due to scared nature of the lake, it has been proposed to strengthen and stabilize the outlet of the main Gurudongmar Lake by building Moraine Plug Safety Wall with Spiritual and Tourism Integration. It has been planned to transform this climate adaptation infrastructure into a cultural pilgrimage experience. Spiritual architectural and symbolic elements are integrated into the outer design. This measure is intended to retain floodwaters in the event of sudden inflows and reduce downstream flood intensity, while also supporting tourism-related infrastructure. This is still in the concept phase and needs more expert advice.

Figure 7: Proposed mitigation measures at Gurudongmar Lake

19. All mitigation and assessment activities are undertaken under the guidance of the High-Level Steering Committee and coordinated through the Task Force. Field operations in high-altitude Himalayan terrain are extremely challenging due to harsh climatic conditions, low oxygen levels, high wind velocities, limited road connectivity, and a very short working season. Winter snowfall severely restricts access, while frequent landslides and heavy monsoon rains hamper summer

NOTARY PUBLIC HARPAL SINGH ADVOCATE NCT DELHI Regd. No.: 19710/2020 GOVT. OF INDIA

operations. Despite these constraints, the Science and Technology Department in collaboration with local, national and international organisations continues to play a critical role in strengthening Sikkim's resilience against glacial hazards through scientific assessment, inter-agency coordination, and innovative mitigation strategies.

B. REMEDIAL MEASURES UNDERTAKEN BY THE STATE TO MITIGATE AND PREVENT ADVERSE EFFECTS OF ANY FUTURE NATURAL DISASTER

20. In the aftermath of the flash floods in 2023, the State has taken proactive measures to enhance preparedness and resilience against potential GLOF events. Sikkim State Disaster Management Authority (SSDMA) along with District Disaster Management Authority (DDMA) and local authorities initiated a two-pronged approach involving awareness campaigns and participatory rural appraisals. (PRAs), with the ultimate goal of developing comprehensive evacuation maps for vulnerable settlements. The programme was undertaken from 17th to 29th May, 2024. The programme interventions included the following:

a) **Awareness Campaigns:** SSDMA along with DDMAs embarked on a widespread awareness campaign, reaching out to communities. The key objectives were to educate residents about the risks associated with GLOF, the importance of timely evacuation and the role of early warning systems. Public meetings were organized in community centres, schools and other gathering places. These meetings served as platforms for SSDMA experts to provide detailed explanations, demonstrations and engage in open discussion with residents. SSDMA developed a series of informative Audio – Visual materials- posters and pictorial booklets tailored to local languages and cultural contexts. These materials were widely distributed and played on local radio channels ensuring widespread dissemination of awareness messages.

b) **Participatory Rural Appraisals (PRAs):** Building upon the awareness campaigns, SSDMA facilitated Participatory Rural Appraisals in vulnerable communities residing along the Teesta River basin. These PRAs aimed to actively involve residents in the process of identifying hazards, mapping resources and developing connect specific evacuation plans.

- **Community Mapping**: Residents guided by SSDMA and DDMA officials along with local authorities and utilizing local knowledge mapped their settlements highlighting potential hazard zones, safe areas and existing infrastructure.
- **Resource Identification**: Residents identified available resources within their communities, such as emergency shelters, healthcare facilities and transportation options, which could be utilized during evacuation efforts.
- **Focus Group Discussions:** FGDs were held with various community stakeholders, including elders, women's groups and local leaders to ensure diverse perspectives were incorporated into the evacuation plans.

c) **Evacuation Map Development:** The information gathered through the PRAs served as the foundation for developing comprehensive evacuation maps for each vulnerable community. These maps delineated safe evacuation routes, designated assembly points, and temporary shelters, taking into account the unique topography, accessibility and available resources of each region.

d) **Implementation of National GLOF Risk Mitigation Programme (NGRMP) in Sikkim:** The National GLOF Risk Mitigation Programme (NGRMP) is a centrally sponsored scheme being implemented in the State of Sikkim in coordination with the National Disaster Management Authority (NDMA), with an approved outlay of ₹40 crore, aimed at reducing risks associated with Glacial Lake Outburst Floods (GLOFs) through scientific assessment, monitoring, mitigation, and community preparedness. The programme comprises four key components, namely hazard and risk assessment through preparation of an updated glacial lake inventory and classification of lakes based on risk to downstream communities and critical infrastructure; establishment of monitoring and Early Warning Systems (EWS) using remote sensing tools, seismometers, water-level sensors, high-resolution cameras, and trigger-based systems; implementation of site-specific mitigation measures such as reinforcement of moraine dams and controlled lake drainage; and community awareness and capacity building.

In this regard, the High-Level Steering Committee (HLSC) and Multi-Disciplinary Task Force (MTF) were constituted in November 2024, the Department of Science & Technology has completed procurement of approved scientific and monitoring equipment under the first instalment, and scientific expeditions and baseline studies of identified glacial lakes have been completed. The State is presently awaiting release of the second instalment to initiate installation, integration, and commissioning of the Early Warning System in identified GLOF-prone locations.

NOTARY PUBLIC
HARPAL SINGH
ADVOCATE
NCT DELHI
Regd. No.: 19710/2020
GOVT. OF INDIA

e) A State Level Day and night Mock Exercise was conducted in 17th November 2025 in coordination with NDMA with the objective to gauge the level of preparedness of the State and District Authorities. The exercise was earthquake triggered GLOF.

f) Participatory Rural Appraisals (PRAs) and community awareness campaigns are planned to be conducted in seven locations in Mangan District along the Teesta River basin, namely Thangu, Lachen, Lachung, Zema, Chungthang, and Munshithang, in last week of January 2026, with the objective of strengthening community preparedness and risk awareness in GLOF-prone areas.

C. THE FULL EXTENT OF DAMAGES ARISING OUT OF THE CHUNGTHANG BREACH INCIDENT AND GLOF, 2023

21. **Post Disaster Needs Assessment (PDNA):** The Post Disaster Needs Assessment (PDNA) for the Sikkim Flash Floods, 2023 was conducted by the Sikkim State Disaster Management Authority in coordination with the National Disaster Management Authority between 7–11 December 2023. The assessment followed a multi-stakeholder, state-level approach involving government departments, scientific institutions, and international agencies including UNICEF, Coalition for Disaster Resilient Infrastructure, Border Roads Organisation, and World Food Programme. Conducted in phases comprising data collection and field assessments by external and state sectoral experts, the PDNA aimed to systematically assess the scale of damage, losses, and recovery requirements across social, productive, infrastructure, and cross-cutting sectors.

22. **Overview of Impact and Major Damages:** The flash floods caused extensive human, social, and physical impacts across multiple districts of Sikkim. A large population was affected, with significant loss of life, injuries, displacement, and evacuation. Numerous villages were impacted, relief camps were established and later closed, and vulnerable groups experienced psychological and social distress. Housing was one of the worst affected sectors, with substantial destruction and partial damage to both pucca and kutcha houses, leading to temporary homelessness and long-term rehabilitation needs. Livelihoods were severely disrupted due to large-scale livestock losses and damage to commercial establishments. Public infrastructure, particularly bridges, roads, water supply, and sanitation systems, sustained serious damage, impairing connectivity and access to essential services.

23. **Sector-wise Damage and Loss Assessment:** The PDNA undertook a comprehensive sector-wise evaluation covering social, productive, infrastructure, and cross-cutting sectors. The social sector, including housing, health, education, and community infrastructure, recorded the highest direct damages. The productive sector reflected significant livelihood losses, particularly in tourism, animal husbandry, livestock, and fisheries. Infrastructure damage primarily affected transport networks and drinking water and sanitation systems. The cross-cutting sector, including environment, forests, and disaster risk reduction, highlighted the need for long-term ecological restoration and resilience-building measures. Recovery and reconstruction needs were assessed not merely to restore pre-disaster conditions but to strengthen structural and institutional resilience.

24. **Aggregate Impact:** The disaster resulted in substantial aggregate damages and losses amounting to over ₹1,480 crore, with total recovery and reconstruction requirements estimated at approximately ₹2,192 crore. The higher recovery requirement reflects the emphasis on resilient rebuilding, livelihood restoration, environmental rehabilitation, and strengthening disaster preparedness mechanisms. The findings underscore the need for a coordinated, multi-sectoral recovery strategy aimed at sustainable and climate-resilient reconstruction across the State.

Copy of a detailed Report on the Full Extent of Damages pertaining to GLOF 2023 is marked and annexed hereto as ANNEXURE R-6

D. **THE PRESENT STATUS OF TEESTA STAGE–III AND OTHER DAMS IN THE STATE OF SIKKIM, INCLUDING THE FUNCTIONAL CAPACITY AT WHICH THEY ARE PRESENTLY OPERATING.**

25. In view of the aforesaid incident, it is necessary to place on record a concise yet comprehensive account of all hydro-electric power plants presently functioning in the State of Sikkim, specifying their installed and operational capacity, location and river basin, where applicable, the current stage of construction along with the estimated timeline for completion as mentioned below: -

SL. NO	NAME OF HYDRO ELECTRIC POWERPLANTS (HEP)	POWER CAPACITY (MEGAWATT)	CURRENT RUNNING STATUS	STORAGE CAPACITY
1.	RONGNICHU	113 MW	Run of the River OPERATIONAL	1,25,000 Cubic metres (equivalent to 1:30 hrs at full load operation

NOTARY PUBLIC HARPAL SINGH ADVOCATE NCT DELHI Regd. No.: 19710/2020 GOVT. OF INDIA

2.	TEESTA III	1200 MW	Under restoration & first phase of wet commissioning is expected by 31st MAY 2026 through coffer dam	No live storage would be available in the first phase, because plants would be running through coffer dam. Therefore, units will be operated on Run of River (RoR) basis.
3.	DIKCHU	96 MW	Operational (RoR)	3,30,000 Cubic meter equivalent to 3.5 hours running of full capacity.
4.	CHUZACHEN	110 MW	Plant shut down. Operation may commence from 16th FEB 2026(RoR)	4,88,000 Cubic Meter equivalent to 2.5 hours of full capacity.
5.	JORETHANG	96 MW	Operational (barrage)	0.45 million cubic meters
6.	TASHIDING	97 MW	Operational (Barrage)	0.075 million cubic meters
7.	TEESTA VI	500 MW	Under Construction (RoR)	Gross Storage at FRL is 3.18 M Cum. EXPECTED COMPLETION DATE SEP 2029
8.	RANGIT III	60 MW	Operational (RoR)	Dead Storage capacity: 0.0239 M Cum Live storage capacity: 0.8202 M cum Gross Storage capacity: - 0.8441 M Cum
9.	TEESTA V	510 MW	Under restoration (Barrage))	EXPECTED COMPLETION END OF FY 2025-26
10.	RANGIT IV	120 MW	Under Construction (RoR)	Dead Storage capacity: 0.59 M Cum

NOTARY PUBLIC
HARPAL SINGH
ADVOCATE
NCT DELHI
Regd. No. 19710/2020
GOVT. OF INDIA

				Live storage capacity: 1.22 M cum Gross Storage capacity: - 1.81 M Cum

26. I say that the present affidavit is true to the best of my knowledge and information received from the Answering Respondent and nothing material has been concealed therefrom. The annexures are true copies of their respective originals.

DEPONENT
Ashwani Kumar Chand, IPS
Principal Resident Commissioner
Government of Sikkim
Sikkim House, 12, Panchsheel Marg,
Chanakyapuri, New Delhi-110 021

VERIFICATION:

28 FEB 2026

I Identify the deponent who has Signed / Put T.I. in my presence
D5537/2023

Verified at Gangtok, Sikkim on the ___ day of February 2026 that the contents of the above said affidavit are true and correct to the best of my knowledge and belief. Nothing material has been concealed therefrom.

NOTARY PUBLIC
HARPAL SINGH
ADVOCATE
NCT DELHI
Regd. No.: 19710/2020
GOVT. OF INDIA

ATTESTED
NOTARY PUBLIC
GOVT OF INDIA

28 FEB 2026

DEPONENT
Ashwani Kumar Chand, IPS
Principal Resident Commissioner
Government of Sikkim
Sikkim House, 12, Panchsheel Marg,
Chanakyapuri, New Delhi-110 021

GOVERNMENT OF SIKKIM
HOME DEPARTMENT
GANGTOK

No. 73/Home/2024

Dated: 11/09/2024

NOTIFICATION

Whereas, the State Government has deemed it expedient to constitute the "Sikkim Commission on Glacial Hazards" to address future glacial threats in the State;

And whereas, the State of Sikkim witnessed a massive Glacial Lake Outburst Flood (GLOF) on 3rd and 4th of October, 2023, which had caused widespread damage along the river Teesta. The accelerated rate of melting glaciers influenced by climate change has resulted in the formation of a large number of glacial lakes and many that are in the process of being formed. This has created an immense threat of glacial hazards in the State;

Now therefore, in order to address and mitigate future glacial threats in the State and in supersession of Notification No. 38/Home/2024 dated 20/04/2024, the State Government is hereby pleased to constitute the "Sikkim Commission on Glacial Hazards" comprising the following members, namely :-

1. Composition of Sikkim Commission on Glacial Hazards :-

Sl. No.	Name and designation	Proposed as
1.	Dr. Akhilesh Gupta, Former Senior Adviser & Head, Policy Coordination & Programme Management, Department of Science and Technology, Government of India	Chairman
2.	Professor (Dr.) Mahendra P. Lama, Former Economic Advisor to the Government of Sikkim	Member
3.	Prof. A. Ramsoo, Vice Chancellor, Islamic University of Science and Technology, Awantipore, Jammu and Kashmir, India	Member
4.	Dr. Rajesh Kumar, Professor & Dean, School of Earth Science, Department of Environmental Science, Central University of Rajasthan	Member
5.	Dr. Piyush Gourav, Sr. Consultant (GLOF and Urban Flood), National Disaster Management Authority	Member
6.	Dr. Ashim Sattar, Assistant Professor, School of Earth, Ocean & Climate Sciences, Indian Institute of Technology Bhuwaneshwar, Orissa	Member
7.	Dr. Kalachand Sain, Director, Wadia Institute of Himalayan Geology, Dehradun	Member
8.	Dr Anil Kumar Gupta, Professor & Head Environment and Climate Disaster Risk Management, International Cooperation, Director of Projects & Center of Excellence, National Institute of Disaster Management, New Delhi	Member
9.	Principal Chief Conservator of Forest-cum-Secretary, Forest and Environment Department, Government of Sikkim	Member

10.	Secretary, Land Revenue and Disaster Management Department, Government of Sikkim	Member
11.	Secretary, Mines and Geology Department, Government of Sikkim.	Member
12.	Principal Chief Engineer-cum-Secretary, Water Resources Department, Government of Sikkim	Member
13.	Secretary, Science and Technology Department, Government of Sikkim	Member Secretary

2. Terms of Reference:

The terms of reference shall be as under:

(1) (a) to review the current status of glacier and glacier lakes in Sikkim, to establish the link of climate change and global warming to glacier melt in Sikkim;
(b) to identify the vulnerable glacial lakes in Sikkim in terms of glacial hazard;
(c) to suggest the site specific best technical measures to minimize the glacial threat in the identified glacial lakes;
(d) to suggest the special care of measures to follow during the mitigation measures especially during the engineering interventions at the lake and in the downstream areas;
(e) to suggest the roles and responsibilities of the different stakeholders in terms of glacial hazards. If required, to suggest the formulation of specific task force to take up mitigation measures in the field level;
(f) to provide policy prescriptions on a cross sectoral basis and inter disciplinary issues to the Government of Sikkim. These are essential to enhance the efficacy of operationalization of both the technical and scientific recommendation and also to assess and mobilize the institutional or resources support;
(g) to suggest the State Government to tap national and international climate fund towards glacial threat mitigation measures as well as other climate hazards in Sikkim;
(h) to suggest action required on human resources generation or capacity building towards the study and management of glacial threat and associated threats;
(i) to review and monitor the progress made towards minimizing the glacial threat in the State;
(j) to suggest any other specific measures to minimize the glacial threat in Sikkim.

2) The Committee may, as and when required also consult leading experts or organizations.

. **Other Conditions :-**

(a) The Chairman may co-opt any person for 1(one) or number of meetings to obtain the required technical and inter-disciplinary inputs for the benefit of the State.
(b) The Committee shall submit its report within 1(one) year of the first meeting of the Committee or latest by February 2025.
(c) The members of the Committee will be given the facilities and entitlements of the Departmental Guest.
(d) The Committee will be assisted by the relevant officials or Departments in their various field studies or observations in Sikkim.

By order and in the name of the Governor.

HOME DEPARTMENT GOVT. OF SIKKIM, GANGTOK

Sd/-
(V.B. Pathak, IAS)
Chief Secretary
Government of Sikkim
File No. 2024/Loose/

Aryanshrivastava
-//TRUE COPY//-

ANNEXURE R-21062

GOVERNMENT OF SIKKIM
HOME DEPARTMENT
GANGTOK

No: 10 /Home/2025 **Dated: 07 /02/2025**

NOTIFICATION

Whereas, the State Government has deemed it expedient to designate the Department of Science and Technology to address the growing threats posed by Glacial Lake Outburst Floods (GLOF) and the increasing need for effective risk mitigation strategies in the State of Sikkim;

And whereas, the Department of Science and Technology, with its extensive expertise and long experience in wetland inventory, glacial studies, glacial hazard assessment and collaborative initiatives, is equipped to lead Sikkim's efforts in addressing Glacial Lake Outburst Flood related risks;

And whereas, the Department of Science and Technology has demonstrated capacity in, conducting specialized field-based studies such as glacial lake monitoring, lake bathymetric assessment, hydrological assessment, and hazard assessments, implementing advanced technologies such as remote sensing and Geographic Information System for high-risk lake analysis, designing structural measures for glacial risk mitigation, and collaboration with international agencies, national institutions, central agencies and other stakeholders;

Now therefore, with a view to achieve the above objectives, the State Government hereby designates the Department of Science and Technology, Government of Sikkim, as the Nodal Department for Glacial Risk Mitigation, with immediate effect.

2. **Terms of Reference :-** As the Nodal Department, the Department of Science and Technology shall conduct ;

(a) Glacial hazard assessments, vulnerability mapping, mitigation planning, lead research and innovation;
(b) Prepare policy recommendations, coordinate with related national agencies and institutions;
(c) Prepare proposals, secure funding and execute glacial risk mitigation projects.

3. All Government departments, authorities, agencies, and stakeholders involved in disaster management, infrastructure planning, and environmental conservation shall fully cooperate with and support the Department of Science and Technology in fulfilling its responsibilities as the Nodal Department.

By order and in the name of the Governor.

HOME DEPARTMENT * GOVT OF SIKKIM GANGTOK

(R. Telang) IAS
Chief Secretary
Government of Sikkim
File No.: 999/DST/2024

Aryanshrivastava
-//TRUE COPY//-

GOVERNMENT OF SIKKIM
HOME DEPARTMENT
GANGTOK

No. 72/Home/2024 **Dated: 11/09/2024**

NOTIFICATION

Whereas, the State Government has deemed it expedient to constitute a High-Level Steering Committee (HLSC) and a Multi-disciplinary Task Force (MTF) to address the threat of glacial lake outburst floods (GLOFs) in the State,

And whereas, as per the report of National Disaster Management Authority (NDMA), Sikkim has 40 (forty) high-risk glacial lakes;

And whereas, mitigating GLOFs is a complex task of inter-disciplinary nature, which involves remote location, high altitude, complex topography and extreme cold weather;

Now therefore, with a view to achieve the above objective, the State Government is hereby pleased to constitute a High-Level Steering Committee (HLSC) and a Multi-disciplinary Task Force (MTF) comprising the following members, namely :-

1. Composition of High-Level Steering Committee (HLSC)

1	Chief Secretary	Chairman
2	Director General of Police, Police Headquarters	Member
3	Principal Chief Conservator of Forest-cum-Secretary, Forest and Environment Department	Member
4	Relief Commissioner-cum-Secretary, Land Revenue and Disaster Management Department	Member
5	Secretary, Planning and Development Department	Member
6	Secretary, Finance Department	Member
7	Principal Chief Engineer-cum-Secretary, Water Resources Department	Member
8	Secretary, Mines and Geology Department	Member
9	Secretary, Science and Technology Department	Member Secretary

(I) Terms of Reference of HLSC :-

(a) to coordinate with defense establishments, paramilitary forces and Central Government agencies to provide support;
(b) to consult and partner with leading experts and organizations in this field;
(c) to evaluate various mitigation options and approve the glacial flood mitigation plans;
(d) to suggest possible funding sources to fund the glacial flood mitigation plans;
(e) to review and evaluate the progress made towards glacial flood mitigation;
(f) to invite subject experts, academicians and others as required while convening its meetings;
(g) to take up capacity building of the officials involved in field studies and mitigation;

(h) to clarify and assign roles and responsibilities to various departments and agencies and resolve inter-sectoral and coordination issues;
(i) to co-opt any other Head of Department as a member of the High Level Steering Committee as deemed necessary;
(j) the Terms of Reference may be expanded by the committee itself, as required;
(k) the High Level Steering Committee shall meet at least once in six months and if required, more frequently.

2. Composition of Multi-disciplinary Task Force (MTF)

1	Secretary, Science and Technology Department	Chairman
2	Additional Principal Chief Conservator of Forest, Forest and Environment Department	Member
3	Inspector General of Police, Home Guards & Civil Defence, Police Headquarters	Member
4	Principal Director, Science and Technology Department	Member
5	Principal Chief Engineer, Water Resources Department	Member
6	Principal Director, Mines and Geology Department	Member
7	Director, Geological Survey of India, Gangtok, Sikkim, Government of Sikkim	Member
8	Prof. Vikram Gupta, Geology Department, Sikkim University	Member
9	Superintendent Engineer, Central Water Commission, Gangtok, Government of Sikkim	Member
10	Director, Sikkim State Disaster Management Authority	Member Secretary

(I) Terms of Reference of MTF

(a) to contribute to the expeditions to the high-risk glacial lakes for hazard assessment and mitigation;
(b) to prepare glacial flood mitigation plans for the high-risk glacial lakes;
(c) to prepare the cost estimates and develop the Detailed Project Report for mitigation;
(d) to implement these mitigation plans under the direction of the High Level Steering Committee:
(e) to consult leading experts and organizations in this field;
(f) to invite subject experts, academicians, department officials and others as and when required while convening its meetings;
(g) to regularly update the High Level Steering Committee on progress made and future plans;
(h) to take up any other task as assigned by the High Level Steering Committee;
(i) to monitor, document and disseminate the progress made;
(j) the Multi-disciplinary Task Force shall meet at least once a month and, if required, more frequently.

By order and in the name of the Governor.

Sd/-
(V. B. Pathak, IAS)
Chief Secretary
Government of Sikkim
File No. 999/DST/2024

Copy for information to:
1. All concerned above;
2. The Pr. Secretary to Hon'ble, Chief Minister, CMO;
3. The Secretary to Hon'ble Governor, Raj Bhawan:

Aryanshrivastava
-//TRUE COPY//-

ANNEXURE R-4

eF.no. R-20012/2/2025-Pen Riv Section-MOWR
Government of India
Ministry of Jal Shakti
Dept. of Water Resources, RD& GR
(Peninsular Rivers Division)

Room No.242 B, C-Wing
Krishi Bhawan, New Delhi
Dated: 01-01-2026

To,

The Chairman
Central Water Commission
R.K.Puram, New Delhi-110066

Subject: - Support to Government of Sikkim for the preparation of PFR/ DPR for the construction of Retention Structure in Lhonak Valley for GLOF Risk Mitigation -Regd.

Sir,

I am directed to refer to the letter dated 12.08.2025 from the Chief Secretary, Government of Sikkim, addressed to the Secretary, DoWR, RD&GR, requesting technical and financial support for preparation of the Pre-Feasibility Report (PFR) and Detailed Project Report (DPR) for mitigation measures related to GLOF risk in the South Lhonak Valley, Sikkim. In order to expedite this critical initiative, the Government of Sikkim has sought the Ministry's support in the following areas:

i. **Constitution of a Working Group-** comprising relevant central agencies, technical institutions and domain experts to guide the preparation of the PFR/DPR
ii. **Technical & Financial Assistance: -** for engaging and funding appropriate technical institutions and experts to undertake the preparation of the PFR/DPR
iii. **Participation in Field Expedition: -** Requested for participation of relevant central agencies/institutes in the field expedition to study the glacial lakes from 20th August to 10th September 2025.

Secretary, DoWR, RD&GR, vide letter dated 27.08.2025, reaffirmed the commitment to supporting the Government of Sikkim's initiative and conveyed that the Department stands ready to extend all requisite assistance for the constitution of a dedicated Working Group and for providing specialized technical expertise, thereby strengthening collaborative efforts to advance GLOF risk reduction measures in the region.

Subsequent to this, the Government of Sikkim's Project Preliminary Report (PPR) for construction of a Retention Structure in the Lhonak Valley under the GLOF Risk Mitigation initiative was forwarded to the Central Water Commission for comments. CWC provided its observations on the proposal, which were duly conveyed to the Government of Sikkim. Furthermore, during the follow-up meeting held under the chairmanship of the Joint Secretary (RD&PP) on 1st October 2025, and at the request of the Government of Sikkim, it was agreed that the DoWR, RD&GR would extend support to Sikkim for implementation of the GLOF mitigation initiatives.

2. Funding support for preparation of PFR and DPR for the proposed works has been deliberated under various schemes of the DoWR, RD&GR. Accordingly, it was decided that funding support for preparation of the PFR and DPR for the proposed Retention Structure in the Lhonak Valley, under the GLOF Risk Mitigation initiative in Sikkim, would be explored through the Investigation of Water Resources Development (IWRD) Scheme of the Ministry, in coordination with the CWC.

In this regard, it is requested that the CWC may extend full technical support to the Government of Sikkim in the preparation of the PFR and DPR for the said project, through its Investigation Division at Faridabad or the Sikkim Office, as deemed appropriate. Further, efforts may be undertaken to include this investigation work under the IWRD Scheme for funding support.

3. Regarding the Government of Sikkim's request for constitution of a Working Group to guide the preparation of the Preliminary Feasibility Report (PFR) and Detailed Project Report (DPR), the following composition is proposed for the said Working Group:

1. Chief Engineer, Design (E&NE), CWC: Chairman
2. Representative of Govt. of Sikkim (DST Department at the level of Secretary)
3. Chief Engineer, YBO, CWC/Chief Engineer (TBO), CWC
4. Chief Engineer (P&D), CWC
5. Chief Engineer, HSO, CWC
6. Chief Engineer, DSO, CWC
7. Director, GSI, Kolkata Office
8. Representative of CSMRS, CWPRS & NIH
9. Representative from DoWR, RD&GR

Secretariat function of the said Committee will be provided by the CWC (CWC's Design Unit).

4. Accordingly, I have been directed to request CWC to assist Government of Sikkim for preparation of PFR / DPR for GLOF Risk Mitigation in Lhonak Valley, Sikkim on priority basis.

5. This issues with the approval of the Secretary, DoWR, RD& GR.

Yours sincerely,

01/01/2026

(Manoj Kumar)
Sr. Joint Commissioner (PR)
Tel-011-23388020
Email- cadwmcentral-mowr@nic.in

Copy to:

1. Shri Sandeep Thambe, Principal Secretary, Science and Technology, Government of Sikkim
2. PPS to Secretary (WR, RD & GR), Department of Water Resources, River Development & Ganga Rejuvenation
3. PPS to JS (RD & PP), Department of Water Resources, River Development & Ganga Rejuvenation

GLOF Risk Mitigation in Lhonak Valley, Sikkim

Project Pre-Feasibility Report

March 2025

Department of Science and Technology
Government of Sikkim

GLOF Risk Mitigation in Lhonak Valley, Sikkim

Project Pre-Feasibility Report

March 2025

Department of Science and Technology
Government of Sikkim

Executive Summary

Project Title: GLOF Risk Mitigation in Lhonak Valley, Sikkim

Project area: Sikkim state

Broad area: Disaster risk reduction (DRR)

Implementing Agency: Department of Science and Technology, Vigyan Bhawan, Deorali, Gangtok, Sikkim, 737102

Total Project Cost: Varies between Rs 760 crore to Rs 1,750 crore excluding taxes

Project site: Lhonak Valley, Chungthang subdivision, Mangan district, Sikkim

Total Duration: 5 years

Project Summary:

The proposal for "GLOF Risk Mitigation in Lhonak Valley, Sikkim" has been developed in response to the catastrophic 2023 South Lhonak Glacial flood, which inflicted irreversible damage on infrastructure, the economy, and defense preparedness. The disaster set Sikkim's development back by a decade, severely impacting transport, tourism, and local communities. This five-year initiative aims to protect critical mountain infrastructure from future Glacial Lake Outburst Floods (GLOFs) through structural mitigation measures, making it India's first-ever structural intervention for GLOF risk reduction. The project will focus on the Lhonak Valley, which houses 3 of the 16 Category A high-risk lakes and a total of 183 glacial lakes and poses the greatest threat. The primary objective is to safeguard roads, bridges, hydropower projects, defense installations, towns, and villages from future GLOFs by implementing a watershed-level retention structure designed to regulate flood peaks.

A three-pronged methodology was adopted to develop this proposal: conducting a global review of GLOF risk mitigation measures, undertaking field and laboratory-based studies, and engaging stakeholders. The study analysed international best practices in GLOF hazard management, performed hydrodynamic modeling, debris deposition analysis, and stream power assessments, and engaged with key stakeholders, including the National Disaster Management Authority (NDMA), government agencies, and local communities to ensure project feasibility.

The key findings from the study highlight that the 2023 South Lhonak glacial flood deviated from conventional models, exhibiting alternating episodes of erosion and deposition due to variations in valley morphometry and slope. This complexity necessitated a comprehensive approach to risk mitigation. Through detailed assessments, the study identified Dolma Sampa (Chainage 26 and 27) as the most suitable site for flood attenuation structures. The proposal evaluates three concepts for retention structures, ranging from 20 to 30 meters in height, with estimated costs between Rs 760 crore and Rs 1,750 crore. The final design will be determined through expert consultations, ensuring optimal feasibility and effectiveness. The cost-benefit analysis underscores the necessity of intervention, with the damage caused by the 2023 flood amounting to Rs 18,555 crore. This highlights the economic viability of the proposed mitigation measures compared to potential future losses. The project also acknowledges significant challenges, including high-altitude construction constraints, climate variability, and engineering limitations.

Combining advanced scientific modeling, infrastructure protection, and community engagement, this initiative represents a pioneering effort in GLOF risk mitigation in the Himalayan region. Its successful implementation will serve as a national model for climate resilience and disaster risk reduction in vulnerable mountain areas. The proposed measures

will safeguard critical infrastructure and livelihoods and strengthen adaptive capacity in the face of climate-induced glacial hazards. As a first-of-its-kind project in India, this initiative is expected to set a precedent for proactive disaster mitigation strategies across other glacial regions, ensuring long-term sustainability and resilience for Sikkim and beyond.

This proposal aims to kickstart the process of developing a DPR by involving premier national institutes and subject experts with proven expertise in this domain to refine the designs and strategies. Mitigating GLOF should be given national importance as most of the country's glacial lakes lie in border areas and can potentially wipe out infrastructure involving national security. Therefore, the nation's best brains must join hands and devise an effective solution with climate change and the possibility of increased frequency and intensity of GLOF events.

Report layout:

The PPR comprises a total of 10 chapters:

- **Chapter 1**: Reviews glacial floods, the parameters used to assess the vulnerability of glacial lakes, and their vulnerability classification. NDMA has identified 40 high-risk glacial lakes in Sikkim, of which 16 are in category A.
- **Chapter 2**: Documents the impact of the Lhonak 2023 glacial flood, highlighting the unanticipated and irreversible damages. Protecting mountain infrastructures such as roads, bridges, hydropower projects, defense establishments, and villages is the key challenge, given the high costs and time required for reconstruction.
- **Chapter 3**: Outlines the 3-pronged methodology adopted which includes i) global review of GLOF risk mitigation measures, ii) extensive field and lab-based studies, and iii) stakeholder consultations.
- **Chapter 4**: Compares the two global GLOF mitigation approaches namely lake water level lowering and watershed level retention structure, emphasizing why implementing lake-level lowering methods is challenging in the Lhonak Valley.
- **Chapter 5**: Presents a reimagined view of GLOF propagation, supported by debris deposition studies, hydrodynamic modeling, and stream power assessments. The traditional understanding of GLOF propagation is that in the initial stage, the surge of water from the lake carries massive amounts of debris, including rocks, sediment, and ice. As this torrent of water flows downhill, it gains momentum and volume, incorporating more material from the valley walls and river-bed, amplifying the glacial flood's power. The cascading floodwater grows larger and more forceful as tributaries and landslides contribute additional water and debris to the flow. Entire sections of valley slopes may collapse into the torrent, further intensifying the flood. By the time the GLOF reaches downstream areas, it has transformed into a massive and chaotic flood wave capable of sweeping away bridges, roads, and settlements. Eventually, the flood dissipates as the energy diminishes when it reaches the foothills, where the river section widens and the gradient becomes gentle. The field studies found that the propagation pattern of the Lhonak glacial flood did not follow this conventional pattern in the upper reaches (first 30 km) as the geometry of the Lhonak valley varies a lot, having both narrow and broad sections. The flood gained momentum in the narrow sections and dissipated in the broad valleys. Hence, contrary to the conventional understanding of "erosion in upper reaches and deposition in lower reaches", the unique geometry of the Lhonak valley in the upper stretches caused alternating episodes of erosion and deposition episodes. Erosion was most pronounced at the South Lhonak terminal moraine, Dzanak, and Lungma funnel,

while deposition occurred at broader, gentler gradient sections such as Chirap, Khora Chu confluence, and Dolma Sampa.

The hydrodynamic modeling of the river stretch from South Lhonak Lake to Chungthang indicates that the maximum flood depth at Chainage 26 is lower compared to Chainage 27. The maximum discharge, which reaches approximately 12,000 m^3/s, decreases to about 8,000 m^3/s at Chainage 26, resulting in a flood attenuation of around 4,000 m^3/s in Dolma Sampa. Additionally, the unit stream power assessment at Chainage 26 supports the hydrodynamic modeling, suggesting that Chainage 26 is the potential site for constructing a retention structure to mitigate GLOF.

- **Chapter 6**: This proposal evaluates three concepts (Concept structures 1, 2, and 3) of the watershed-level Retention structure in two potential sites (Location 1 and 2) with different structure heights (20 meters to 30 meters) and an estimated cost ranging from Rs 760 to 1750 crore + taxes. The final design and cost of the proposed structure will be decided based on expert advice from dam engineers and dam designers.
- **Chapter 7**: A social benefit-cost analysis illustrates that while the South Lhonak glacial flood caused damages worth Rs 18,555 crore, the proposed retention structure costs only a fraction of this amount. Additionally, the project's strategic value for border area development and defense preparedness far outweighs the financial costs. The benefits and opportunities to the local community with the proposed structure are also described.
- **Chapter 8**: Addresses the risks and uncertainties inherent to implementing this pioneering initiative in a high-altitude, harsh climate.
- **Chapter 9**: Provides a bibliography of research papers and the reports reviewed for this proposal.
- **Chapter 10**: Contains annexures that include Notification of Government of Sikkim regarding the formation of High Level Steering Committee (HLSC) and Multi-disciplinary Task Force (MTF). The chapter also contains the Minutes of Meeting of Multi-disciplinary Task Force (MTF) on 20 February 2025.

Table of Contents

1. Background

1.1 Introduction

Sikkim is a small, mountainous, landlocked state in the eastern Himalayas. The state is strategically located between Nepal in the west, China in the north, and Bhutan in the east. It covers a total area of 7096 square kilometers, of which about 900 square kilometers is covered by glaciers (Worni et al. 2013). It is India's least populous state and also the second-smallest after Goa. Located in the north-east, Sikkim reported a population of 6,10,577 in 2011. The state is rich in biodiversity and natural resources, characterized by its vast floral and faunal wealth, abundant water resources, streams, rivers, glaciers, and abundant forest cover. The state has ten mountain peaks above 7,000 meters, 84 glaciers, and 320 glacial lakes. Mount Khangchendzonga (8,586 meters), the world's third-highest mountain peak revered as a guardian deity, is situated on the border between Sikkim and Nepal. It is not easy to come across vast, flat land areas. Rocky and steep slopes make agriculture, transportation, and communication difficult. The state is characterized by a fragile landscape where the impacts of disasters are amplified several times. It is the highest and steepest landscape in the country, with weak geology comprising low-grade metamorphic rocks, steep slopes, and rugged terrain. Also, the state receives torrential monsoon rainfall of 300 cm annually. The state is also a multi-hazard hotspot where natural hazards often cascade where one hazard triggers or exacerbates another, leading to compounded or simultaneous impacts. The cascading natural hazards include a combination of earthquakes, landslides, flash floods, and GLOFs.

1.2 Glacial hazards

The disappearance of mountain glaciers and the expansion of glacial lakes are amongst the most recognizable and dynamic impacts of climate warming in the Himalayan environment. A remote sensing satellite study conducted by NRSC, ISRO in April 2024 reports significant expansion in 676 glacial lakes between 1984 and 2023 across the Indus, Ganga, and Brahmaputra River basins, highlighting the growing risk of Glacial Lake Outburst Floods (GLOFs) in the Indian Himalayas. Notably, 601 lakes (89%) have expanded more than twice their original size, 10 lakes have grown by 1.5 to 2 times, and 65 lakes have increased by 1.5 times. According to the Assessment by the National Disaster Management Authority (NDMA), Ministry of Home, Government of India, there are 189 high-risk glacial lakes in India, 40 of which are in Sikkim alone. There are 320 glacial lakes in the state, some of which are expected to expand and turn high-risk in the future. Also, new glacial lakes might form as more glaciers retreat.

The rapid melting of glaciers and the expansion of proglacial lakes from 2018 to 2022 has led to an exponential increase in Glacial Lake Outburst Flood (GLOF) incidents. Particularly susceptible regions include Afghanistan (Panjshir, 12th July 2024), India

(South Lhonak Lake, October 2023, and Sangmya Meghu Lake, August 2024), Nepal (Birendra Glacial Lake, April 2024), Bhutan (Thorthormi Tsho, June 2019), Pakistan (Thame, August 2024), China (June 2020), placing over 6,353 km² area at risk. GLOF events have also occurred in other mountainous regions globally. In Peru, the outburst from Lake Palcacocha on 13th December 1941 flooded Huaraz, claiming 1,800 to 6,000 lives. In Switzerland, the Giétro Glacier ice dam burst on 16 September 1818, causing major flooding from Lake Mauvoisin. These events demonstrate the global nature of GLOF risks, underscoring the urgent need for international collaboration in mitigation efforts.

In Sikkim state as well, due to accelerated climate change, glacial lakes are rapidly growing in number and area as a direct consequence of glacier recession. In combination with the altered stability of surrounding rock and ice walls, the potential threat from Glacial Lake Outburst Foods (GLOFs) is thus increasing over time. These floods can be catastrophic and threaten lives, property, critical infrastructure, and the environment. On the 4th of October, 2023, a similar triple disaster hit the Himalayan state of Sikkim, India. A massive landslide in South Lhonak Lake in North Sikkim triggered a glacial flood, which destroyed the 1,200 MW Hydroelectric dam. This multi-hazard disaster in the Teesta basin caused severe disruptions across multiple lifeline sectors such as transport, energy, industry, social infrastructure, etc., effectively crippling the state and resulting in heavy losses of life and property. The total losses are estimated at Rs. 25,000 crores, nearly 60 percent of the GSDP of the State during 2022-23. Some of the impacts appear irreversible, such as the drastic change in the morphometry of the Teesta River basin. The debris deposition has caused the river bed level to rise by 7-8 m, thus making it more prone to floods. A dangerous outcome of climate change-induced glacier retreat, this catastrophe exemplifies how disaster risks compound and cascade in the fragile mountainous context of the Himalayas. The state is yet to recover from the catastrophic glacial flood event in October 2023 from the South Lhonak Glacial Lake, as it has crippled the road infrastructure, hydropower development, and the tourism economy.

These glacial lakes are located in remote, high-altitude areas with complex topography and a frigid climate. They are difficult to access and are not serviced by cellular mobile networks. However, unlike other disasters, such as earthquakes, cyclones, cloudbursts, and landslides, GLOF disasters can be prevented. The changing climate is expected to exacerbate the adverse impacts due to the increasing severity and frequency of hydrometeorological hazards. The state faces significant risks to human life, infrastructure, and the environment from GLOFs. Also, with infrastructure and defence establishments expanding higher into alpine areas and river valleys seeing rapid infrastructure development, there is a clear need to manage glacial-related hazards such as GLOFs through comprehensive risk reduction strategies.

1.3 Parameters impacting susceptibility of glacial lakes

According to Hazra and Krishna (2022), apart from the expanding glacial lakes, various topographic factors play an important role in their susceptibility to glacial lake outburst flood (GLOF). Sikkim has a hilly terrain, and some glacial lakes are located in highly avalanche-prone zones. It is triggered by various events such as ice avalanches, hanging glaciers, landslides, extreme rainfall, earthquakes, or a combination of multiple factors. Over 54% of GLOFs are triggered by mass movements such as avalanches, rock falls, and landslides (such as in Sikkim in 2023), while 18% are due to intense rainfall events. A recent study by Reddy et al. (2025) estimated that 11.50 million cubic meters (MCM) of debris entered the South Lhonak lake, reducing water volume by 43.21 MCM, with a total estimated flood of 54.71 MCM on the night of Oct 3rd, 2023. Further, Sattar et al (2025) reported that South Lhonak Lake is still highly susceptible to future GLOF events and there is the possibility of repeat triggers from northern lateral moraine failures due to highly deformation zones. This points to a need for better precipitation forecasting at high altitudes and mapping an increasingly unstable cryosphere. (ICIMOD 2023) as many of the glacial floods are results of cascading triggers causing devastation downstream.

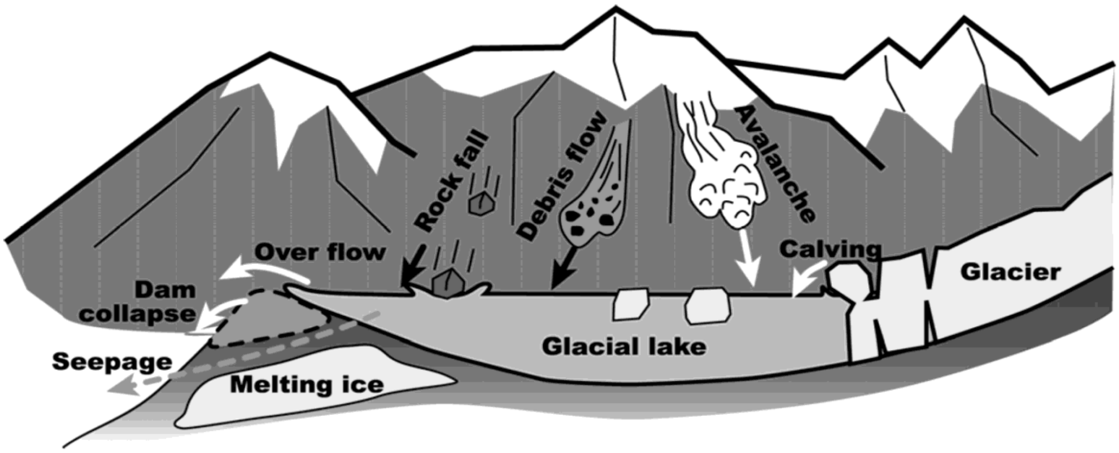


Figure1.1: Triggers for GLOF (Source Fujita et al. 2012)

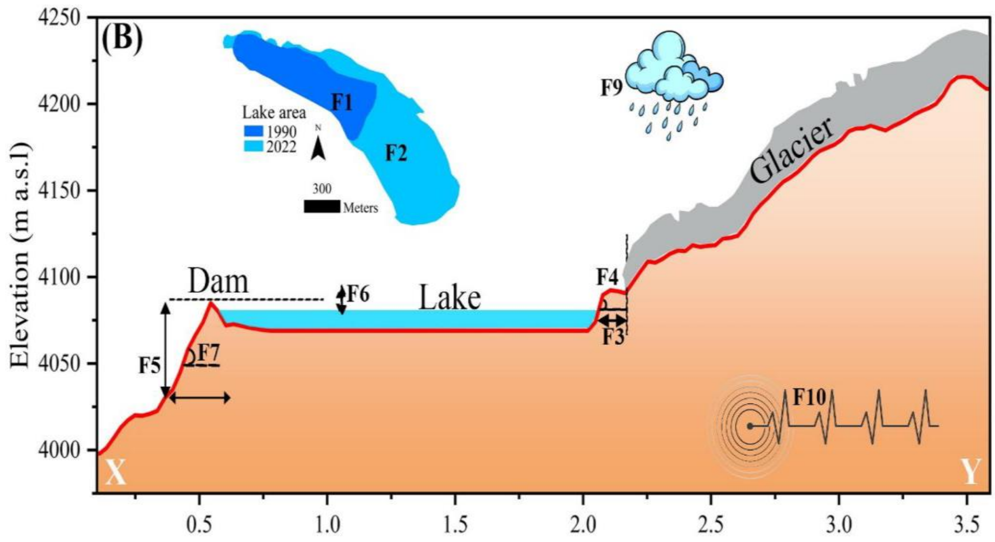


Figure1.2: Parameters to be considered for GLOF hazard assessment (Source: Das et al. 2024)

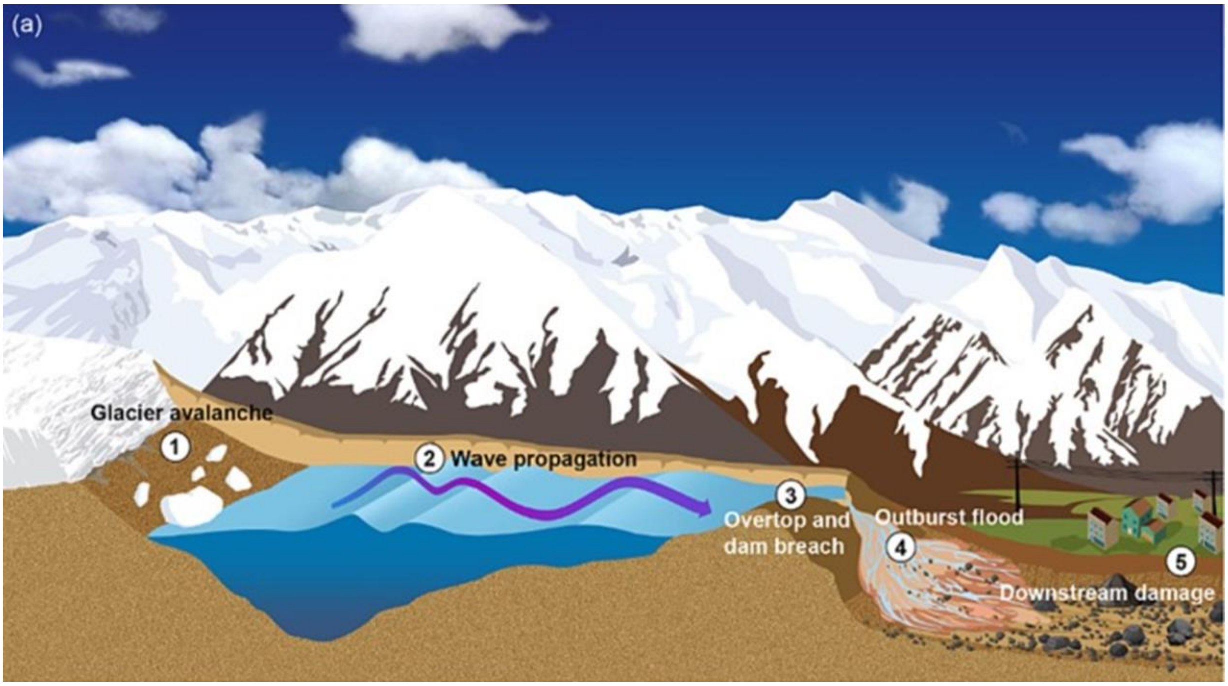


Figure1.3: Glacier avalanche can trigger GLOFs with the displacement wave overtopping the dam and causing a breach (Source Peng et al. 2023)

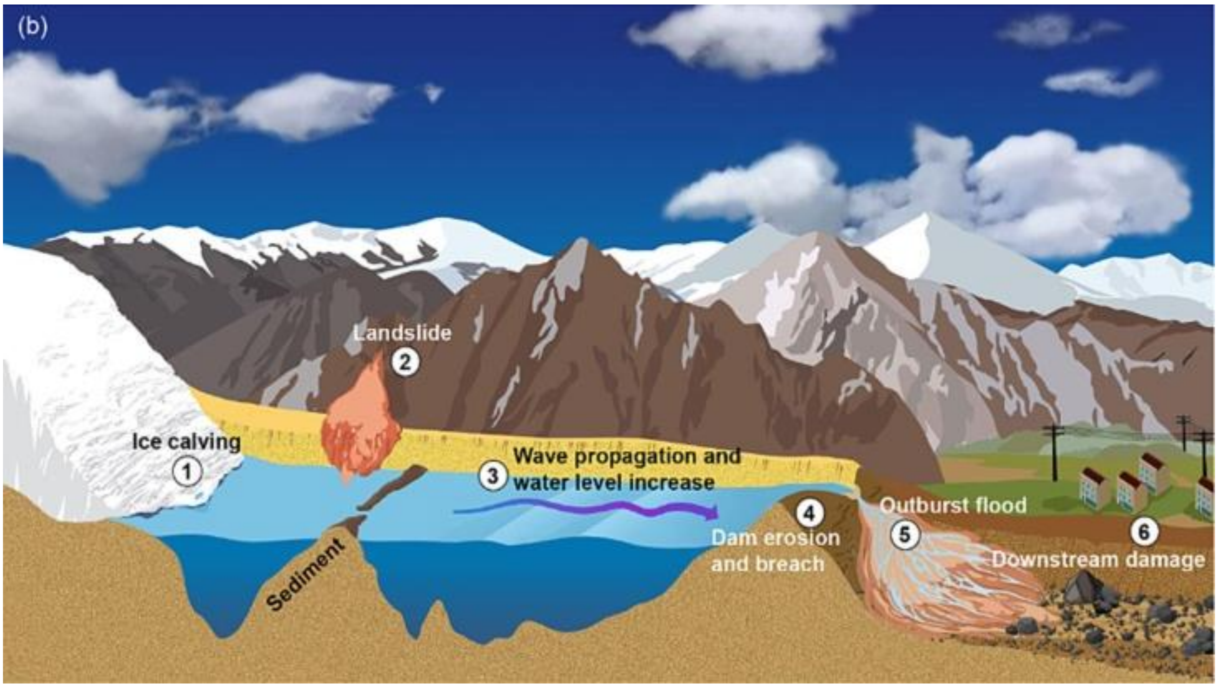


Figure 1.4: Landslides originating from the lateral moraines can also trigger GLOFs (Source Peng et al. 2023)

1.4 Vulnerable glacier lakes in Sikkim

GLOF risks in Sikkim, located in the Eastern Himalayas, are a significant concern due to the region's rapidly changing climate, glacial retreat, and the potential for catastrophic flooding from glacial lakes. Based on existing scientific assessments, NDMA has identified 40 high-risk glacial lakes in Sikkim based on the hazards and risks they pose downstream under A, B, C, and Unclassified (UC) categories. Of these, 16 are A-category, 2 are in B-category, 13 are in C-category and 9 are unclassified.

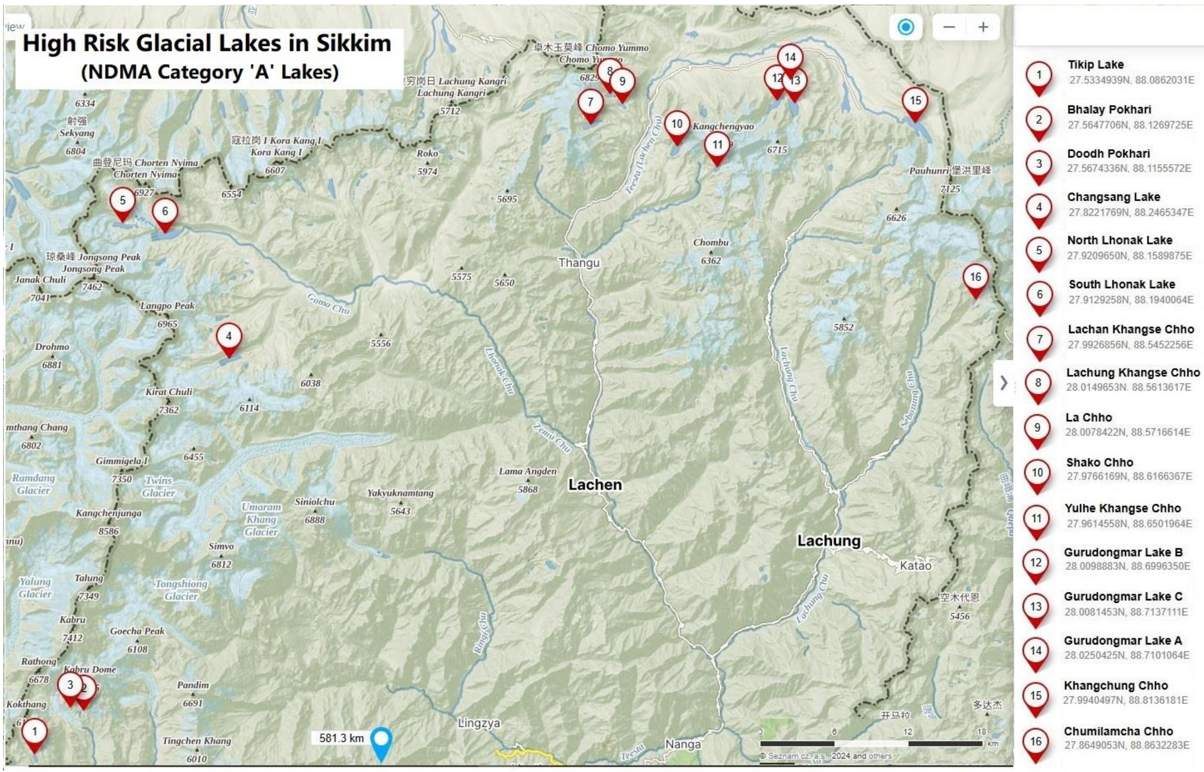


Figure 1.5. NDMA has identified 16 high-risk glacial lakes (Category A) in Sikkim

A preliminary hazard assessment of these 16 A-category high-risk glacial lakes was carried out using high-resolution remote sensing images, which are provided in Table 1. This assessment shows that these lakes are located in two of Sikkim's six districts: 3 in Gyalshing district and 13 in Mangan district. Also, 12 of these 16 lakes are concentrated in the Lachen Chu watershed, a potential GLOF hotspot. These lakes are located at an elevation range of 4740-5470 masl (mean 5100 m), and their size ranges from 2 ha to 183 ha (mean 69 ha). The volume of water in these lakes ranges from 0.5 to 106 mcm (mean 32 mcm). Among these 16 lakes, ten glacial lakes do not have a clear-cut surface outlet; therefore, their moraine dam remains vulnerable. The potential hazard of avalanches and ice fall from hanging glaciers is recorded in 14 of these lakes. Also, the potential hazard arising from an unstable slope or moraine failure was observed in South Lhonak, Changsang, and Gurudongmar lakes. Limited freeboard was observed in 4 lakes: Tikip Lake, Lachen Khangse, Shako Chho, and Khangchung Chho. Besides, excessive ice calving was recorded in South Lhonak Lake and Khangchung Chho. Overall, the South Lhonak Lake, Gurudongmar B, Khangchung Chho, Changsang Lake, Gurudongmar C and Shako Chho are categorized as high-hazard and high-risk glacial lakes as the first five lakes are expanding rapidly due to the melting of their parent glaciers. Shako Chho has habitations and Army establishments just 15 km downstream, posing a high risk.

Table 1.1: Preliminary hazard assessment of the 16 very high risk lakes

Sl. No	Lakes	Elevation (meter)	Volume (mcm) 2022	Preliminary Hazard Assessment
1	Tikip Lake	4884	16	Risk of landslides, ice falls and avalanches, limited moraine dam height, and low freeboard, no natural outlet exists
2	Bhalay Pokhari	4740	4	Located above the fragile lateral moraine of East Rathong Glacier risk of ice fall and avalanches, natural outlet exists
3	Doodh Pokhari	4780	0.5	Located above the lateral moraine of Rathong Glacier, overflowing into the East Rathong Lake, fragile lateral moraines
4	Changsang Lake	5431	43	Glacier tongue and lake are in direct contact, Risk of avalanche and hanging Glacier, unstable lateral moraine, high lake volume, Natural outlet exists
5	North Lhonak Lake	5470	42	High lake volume, risk of snow avalanches, natural outlet exists,
6	South Lhonak Lake	5210	84*	High lake volume, expanding lake area, Unstable lateral moraine prone to slope failures, meltwater from above draining into it, lake in contact with parent glacier, excessive calving, natural outlet exists
7	Lachen Khangse Lake	5212	34	Moderate lake volume, Hanging glacier exists at the steep headwall, limited freeboard, no natural outlet exists; vulnerable moraine dam
8	La Chho	5090	11	Risk of avalanche and ice fall from hanging glacier, Unstable moraine dam and no natural outlet exists
9	Lachung Khangse Lake	5030	11	Compounded risk from La Chho in case of avalanche and ice falls, Natural outlet exists
10	Shako Chho	4990	27	Steep downhill gradient from headwall of glacier possessing

				threat of Ice fall and avalanches, high lake volume, low freeboard, no natural outlet exists; vulnerable moraine dam
11	Yulhe Khangse Lake	4992	7	Risk of ice fall and avalanches, expanding lake, natural outlet exists
12	Gurdongmar Lake B	5225	53	High lake volume, Unstable lateral moraine, unstable moraine dam, risk from hanging glaciers in the headwall, no natural outlet exists; vulnerable moraine dam
13	Gurdongmar Lake C	5254	65	High lake volume, expanding lake, risk of avalanches, Glacier tongue and lake is in direct contact, no natural outlet exists, vulnerable moraine dam
14	Gurdongmar Lake A	5164	60	Compounded impact consisting of landslides, ice falls and avalanches from B and C lakes may trigger Glacial floods, Natural outlet exists
15	Khangchung Chho	5320	106	Very High Lake volume, expanding lake, Glacier tongue and lake is in direct contact risk of ice fall and avalanches, low freeboard, Natural outlet exists
16	Chumilamcha Chho	4800	5	Risk of Ice fall and avalanches from steep headwall, unstable lateral moraine, natural outlet exists

2. Problem statement and objective

2.1 Impact of South Lhonak glacial flood

On the night of October 3rd, 2023, the moraine-dammed South Lhonak Lake in Sikkim suddenly discharged a substantial volume of water, resulting in a glacial flood. So, what were the consequences and lessons from this glacial flood event? While one would expect that the roads, bridges, hydel projects, and infrastructure along the river would be severely impacted, there were a few unexpected and irreversible consequences as well.

- **Impact of the hydropower sector**

The 1200 MW Teesta Stage III, Sikkim Urja HEP at Chungthang was breached. The state government constructed this dam with an investment of Rs 14,000 crore. The impact on the other HEPs regarding the estimated material damage and business interruption (BI) loss is estimated at Rs 1,838 crore.

Table 2.1: Details of losses due to Floods in Teesta Basin in Oct 2023 (losses assessed till 30th Sept 2024)

SL no	**Project/ Power Station**	**Rise in River bed level (Approx)**	**Estimated Material Damage (Rs. in Cr)**	**Estimated BI Loss (Rs. in Cr)**	**Total Loss (Rs. in Cr)**
1	TLDP-IV PS	~ 7.44 mtrs	10.75	0	10.75
2	TLDP -III PS	~ 7.29 mtrs	88.09	266.46	354.55
3	Teesta-VI HE Project	~2.00 mtrs	397.00	0	397.00
4	Teesta -V PS	~ 6.00 mtrs	538.7	537.27	1075.97
	Total		**1034.54**	**803.73**	**1838.27**

Aryanshrivastava
-//TRUE COPY//-

Figure 2.1: The 1200 MW Teesta Stage III, Sikkim Urja HEP at Chungthang built at Rs 14,000 crore was breached

Figure 2.2: The NH-10, which is the lifeline of Sikkim faced repeated closures during 2024 severely impacting the transport, tourism, economy and defence preparedness

- **National highway has become vulnerable, several bridges washed away**

Along with significant damage to the National Highway NH 10, 33 bridges were also washed away. Many border areas, such as Chungthang, Lachen, Thangu, Lachung, etc., were cut off for more than 11 months. As a result, the NH 10, which is Sikkim's lifeline, was badly damaged and frequently closed down for repairs during the 2024 monsoons. This severely impacted the state's economy, tourist footfall, and defence preparedness. Also, the NH between Gangtok and Mangan was damaged in Toong Naga, and as the whole mountainside is sliding down, it has yet to be fully functional for more than a year after the 2023 glacial flood. As a result, during the monsoon season, the plateau region, which has strategic importance, was cut off due to disrupted road connectivity.

- **Raising of the Teesta River bed in downstream locations**

The glacial flood has brought about significant morphometric changes in the Teesta River. The river bed has risen by an average of 7-8 meters due to the accumulation of debris and silt from the flood, resulting in a flattened, more expansive river profile than the typical V-shaped valley (Figure). This change has critical implications in increasing flooding risk, submergence of infrastructure, and environmental impact. With the river bed elevated, the Teesta now has reduced capacity to channel water. This poses a heightened risk of flooding during the monsoon season, as the flattened valley has less room to contain heavy rainwater flows. The altered profile could lead to frequent and severe inundation along the riverbanks. The National Highway (NH10) running along the Teesta River has become prone to submergence and subsidence, and this issue is likely to recur and worsen during monsoons due to the raised river bed. Flooding of the NH10 has disrupted transportation, created a deterrence for tourists, and hence severely impacted the economy of the state.

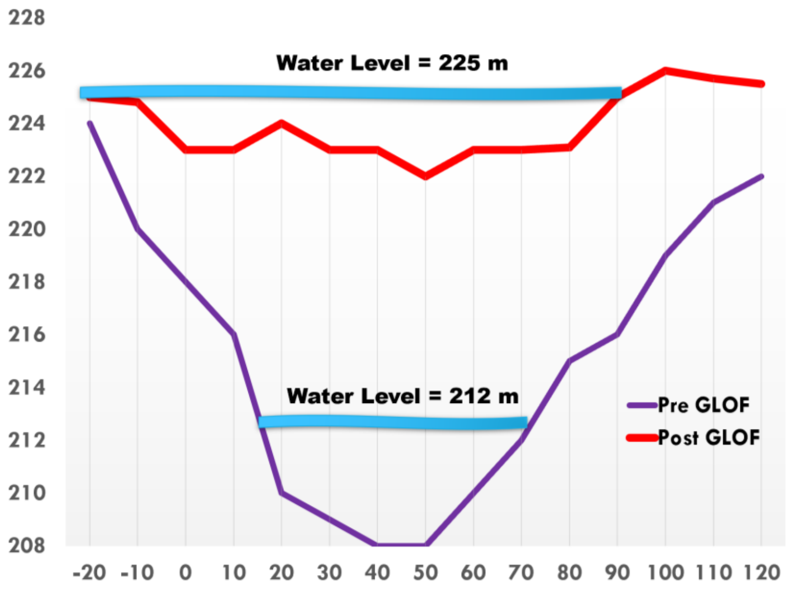


Figure 2.3: Downstream debris deposition by the glacial flood at Melli has raised the river bed of the Teesta by several meters, causing frequent inundation (Source: Central Water Commission)

Aryanshrivastava
-//TRUE COPY//-

- **Slope movement and valley subsidence at Toong Naga village**

The flash flood caused significant damage to the Toong Naga gram panchayat, necessitating the entire village's relocation due to the damage's severity. Several buildings and houses were completely damaged due to the subsidence of valley and slope failures, out of which 155 households have been mandated for relocation (PDNA, 2023). Flash floods in V-shaped valleys often bring substantial amounts of water that can significantly increase the river's erosive power. The unique geomorphology and slope composition of the area between Chungthang and Mangan have contributed to the extent of the damage. The right bank of the Teesta River is composed of stable in-situ Gneiss rock, but the left bank, where the village is situated, consists of loosely compacted soil mixed with boulders. The flash flood's erosive power was focused on this left bank, causing significant toe erosion and destabilizing the slope, resulting in valley subsistence. This instability has led to sinking and subsidence, making the area highly vulnerable to further landslides and erosion. The ensuring slope movement and valley subsidence have caused substantial structural damage in the area. Several reinforced concrete (R.C.C.) buildings have developed cracks as the slope shifts toward the river, threatening their structural integrity. This indicates that the entire slope is undergoing mobilization, putting all structures at risk. This incident highlights the susceptibility of habitations located even far away from the glacial lake breach site due to their inherent geological vulnerabilities exacerbated by the severe scouring impact of the flood.

Figure 2.4: The left bank of the Teesta River below Toong Naga Gram Panchayat consists of loosely compacted soil mixed with boulders. Hence, the glacial flood caused significant toe erosion, resulting in slope destabilizing and valley subsistence, necessitating the relocation of the entire village. Source: Mines and Geology Department (2023)

Aryanshrivastava
-//TRUE COPY//-

- **Restoring connectivity in fragile terrain is a herculean task**

Reconstructing roads and bridges after a glacial flood of this magnitude poses formidable challenges due to the extensive damage along the entire stretch of the national highway that runs along the Teesta River. The floodwaters destroyed surface infrastructure and completely wiped out the road's foundational structure in many areas. This situation requires new road alignments, as several sections of the valley side have subsided, making reconstruction on the original route infeasible. These subsidence issues and the unstable terrain severely complicate restoring connectivity quickly. Building along the original alignment may be impossible in certain areas, necessitating alternative routes or more complex engineering solutions. The scale of damage underscores the need for thorough geotechnical surveys and potentially innovative, resilient design approaches to ensure long-term stability and safety in a region prone to such extreme natural events. Also, restoring connectivity will require extensive resources, time, and collaborative efforts from geologists, engineers, and the local communities. Reconstruction must also integrate adaptive measures for future disasters, such as reinforced structures, slope stabilization, and early warning infrastructure along critical roadways. These factors delayed the restoration of connectivity to remote areas, taking nearly 12 months to re-establish access to Lachen village. The main route from Mangan to Chungthang traverses the highly unstable Toong Naga area and remains inoperative due to ongoing subsidence and slope instability. Consequently, communication and limited access to Chungthang are being maintained via an alternative route along the right bank of the Teesta River, using the narrow and precarious Dikchu-Phidang-Sangkalang-Shipgyer road. This alternative route poses significant logistical challenges due to its limited capacity and rugged terrain that hampers the efficient transport of essential supplies, slowing the recovery process.

- **Assessment of the ecological impact on riparian ecosystem**

In the Post Disaster Needs Assessment (2023) compiled by the SSDMA, the Forest and Environment Department, Government of Sikkim, estimated the damage and loss incurred to the forests and vegetation along the Teesta River due to the glacial flood of Oct 2023. This loss was calculated by determining the impact area using pre- and post-disaster maps/satellite imagery and inputs from physical records and ground truth verification exercises. This damage to forests was assessed using remote sensing and Net Present Value for various forest types and density classes (Figure Table). This valuation method is used while processing the diversion of forest land for non-forestry purposes as per the Forest Conservation Act 1980. The details for calculating the Net Present Value of the forest land have been notified by the Ministry of Environment, Forest and Climate Change File No. 5- 3/ 2011- FC (Volume 1) Dated 6-1-2022 and is in alignment with the Forest Conservation Act and Guidelines.

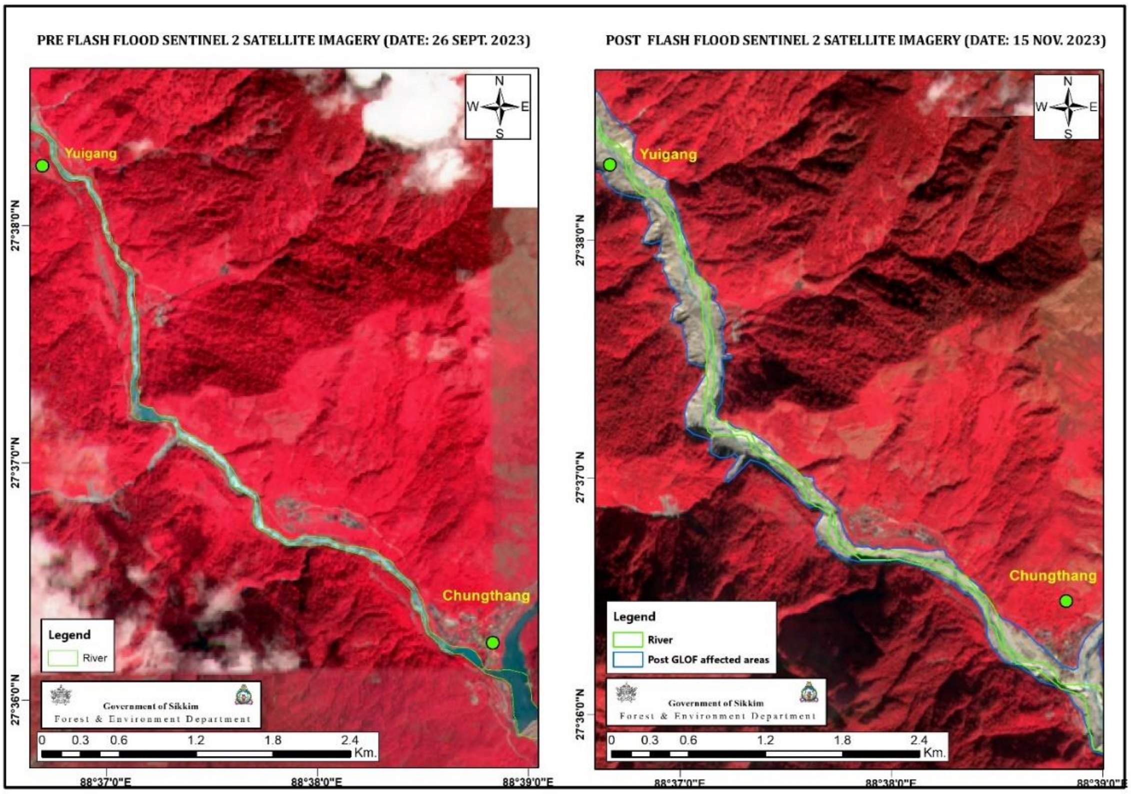


Figure 2.5: Satellite imagery depicting the riverbank between Yuigang and Chungthang mapping the pre- and post-disaster scenario. The imagery depicts the extent of flooding and damage caused along the course of the river Teesta.

Table 2.2: Damage to forests assessed as per the Net Present Value methodology

Amount in Lakhs

Forest category	Affected area above 2400 m (HA)	Affected area below 2400 m (LA)	NPV Rates (LA)	NPV Rates (HA)	Losses calculated as per NPV (HA)	Losses calculated as per NPV (LA)
Very dense forest	85.64	105.32	14,36,670	5,16,230	1,298	1,513
Moderately dense	126.99	318.26	12,92,850	13,72,410	1,743	4,115
Open forest	65.43	126.29	10,05,210	10,69,470	700	1,269
Scrub	33.47	1.12				-
Non-forest	121.80	256.91				
Alpine scrub	577.68	0		10,69,470	6,178	-
Total affected vegetation	**1011.02**	**807.90**		**Total**	**9,919**	**6,897**
Grand Total		**1818.92**				**16,816**

Aryanshrivastava
-//TRUE COPY//-

According to this assessment, the glacial flood impacted 1,819 ha of riverine forests, which were assessed at Rs 168.16 Crore using the Net Present Value (NPV) methodology.

- **Altered vulnerability profile of the Teesta valley**

The glacial flood has fundamentally transformed the vulnerability profile of the region, with both the upper and lower reaches experiencing distinct, lasting impacts. In the upper reaches, the glacial flood caused complete devastation of infrastructure such as roads, bridges, and dams, leaving no structures intact in its path. The floodwaters scoured the river valley extensively, stripping away all vegetation and exposing the bedrock, leading to significant environmental degradation. Furthermore, severe toe erosion along the vulnerable valley sides has caused slope destabilization and valley subsidence specially along the left bank, posing long-term stability risks. The lower reaches, while spared from the immediate high-energy impact of the flood, experienced extensive deposition of slush and silt, raising the river bed by an estimated 7-8 meters. This bed elevation has altered the river's morphometry, significantly reducing its capacity to channel water and increasing its susceptibility to overflow during future floods. The risk of inundation now threatens nearby infrastructure and communities, making the lower reaches especially vulnerable to monsoon flooding and associated damage. While the upstream areas have already faced the full brunt of the damage, leaving limited opportunities for further loss, the downstream areas have become increasingly vulnerable to future flooding. This shift calls for urgent adaptation measures, including infrastructure reinforcement, slope stabilization, and riverbed management to mitigate further risks. The transformed vulnerability profile of the Teesta Valley requires an integrated approach to disaster risk management that considers both immediate and long-term impacts on the region's communities, infrastructure, and environment.

Figure 2.6: Debris deposition in the downstream border towns has increased their vulnerability to future flood events

- **National security and preparedness of defence forces**

Poor road connectivity, limited land available for expansion, and the harsh terrain have already been plaguing the defense establishments in the Mangan district. The glacial flood resulted in significant loss to vital roads, dams, bridges, arms and ammunition, and infrastructure for defense establishments. The ITBP camp at Dzanak has been rendered non-operational due to the flood. The ammunition depot at Munshitang has been severely damaged, and a significant part of the facility swept away. The 272 Army Supply Corps and 214 Field Workshop in Chungthang were also damaged. North of the Lhonak valley, the Chinese have developed a network of roads, helipads, etc., close to the LAC, allowing quick mobilization in the event of an exigency. However, the roads on our side have been damaged due to the South Lhonak flood of Oct 2023. Though repair works are ongoing, progress is slow, directly impacting the preparedness of the defense forces.

Figure 2.7: The ammunition depot at Munshitang was swept away

2.2 How to safeguard mountain infrastructure?

In mountainous areas, essential infrastructure such as roads, bridges, and power plants are often concentrated along river valleys, making them especially susceptible to flooding and debris flows triggered by GLOFs. Mountain infrastructure, particularly in regions prone to GLOFs, faces unique vulnerabilities that require proactive measures. Early Warning Systems (EWS) are invaluable for saving lives during such disasters, but protecting critical infrastructure remains a pressing concern.

Rebuilding damaged infrastructure in this remote and challenging terrain is costly and time-intensive, further underscoring the importance of safeguarding these assets. Protecting mountain infrastructure, both public and private from GLOFs is the main problem that this proposal aims to address.

2.3 Objectives of the proposal

The main objective of the proposal is to safeguard mountain infrastructure from future glacial flood events in the Lhonak Valley. It aims to demonstrate glacial flood risk mitigation in the Lhonak Valley by taking structural mitigation measures. A retention structure innovation is proposed to tackle this challenge.

2.4 Mitigation is super challenging

Several issues make the implementation of GLOF mitigation works challenging:

- **Environmental issues**: Lakes are often located in protected natural areas/national parks, and any human interventions may damage fragile geo- and eco-systems.
- **Technological issues**: Lakes are often located in remote mountain areas without electricity and access to heavy machinery.
- **Economical issues**: Complex GLOF risk mitigation projects involving dam remediations and/or construction of retention dams in harsh mountain environments are expensive.
- **Societal issues**: Any measure that does not have the support from local communities is doomed to failure.
- **Political issues/governance**: Authorities in charge of DRR need to recognize and prioritize GLOF risk, and funding mechanisms need to be established.

2.5 Provides a unique opportunity

The glacial hazard mitigation addresses an urgent environmental challenge and sets the stage for pioneering, ground-breaking efforts that will serve as a national benchmark. This initiative has the opportunity to be the first comprehensive initiative of its kind in India, integrating advanced scientific methods with localized strategies tailored to the unique glacial risks in Sikkim. By proactively safeguarding the state from potential glacial hazards, the project aims to protect human lives, infrastructure, and delicate ecosystems, creating a model for climate resilience and environmental stewardship. Beyond immediate safety and environmental benefits, the project contributes meaningfully to national interests. The project enhances national security by ensuring the security of defence installations in sensitive areas, reinforcing Sikkim’s strategic role within India’s borders. Furthermore, the success of this ambitious project could earn Sikkim recognition from the Government of India as a high-performing, innovative state. This achievement would elevate Sikkim's status within the country and establish it as a global leader in glacial flood mitigation. It would set a precedent for other regions vulnerable to glacial hazards worldwide. This initiative can potentially strengthen regional resilience and national security while positioning Sikkim as a forward-thinking and climate-resilient state.

3. Project development process

As per the NDMA Guidelines on GLOF Management, 2020, the states need to take up detailed hazard assessments. This will comprise baseline studies to assess the geomorphology, glacial lake hazard, lake volume, geophysical studies of the moraine dam, topographical study, slope stability assessment to assess mass movement hazard, lake discharge etc. Using both primary investigations and syntheses of secondary studies, a site-specific GLOF mitigation plan needs to be developed. In this regard, the Government of Sikkim has undertaken a multi-pronged approach to glacial flood risk mitigation. Firstly, an extensive review of literature was undertaken to assess the present state of knowledge and to review the global interventions and experiences in GLOF risk mitigation. Secondly, expeditions with multi-disciplinary experts were undertaken to take up comprehensive hazard assessment studies. Thirdly, consultations were held with key stakeholders in the Government of India such as NDMA, Ministry of Jal Shakti, Central Water Commission, National Dam Safety Agency and others.

3.1 Review of scientific literature

An extensive literature review was conducted, encompassing research papers, doctoral studies, and reports focusing on various aspects of glacial floods, hazard assessment, risk mitigation, etc.

3.2 Stakeholder consultations

Various consultations were held across village, state, and national levels. On 14th September 2024, at the invitation of the Lachen Pipons, the team participated in a Dzumsa meeting at Lachen. The team briefed the people on the expedition's objectives, methodology, and initial findings and answered the community's queries. During November and December 2024, a series of interactions were also held with the senior officials of NDMA, the Ministry of Jal Shakti, and the National Dam Safety Agency. This proposal was also presented during the NDMA National GLOF Workshop on 11th and 12th November 2024 in New Delhi. Subsequently, NDMA organized a consultation workshop on 23rd December with various ministries and agencies of GoI, where this proposal was presented and discussed threadbare. On 2nd Jan, 2025 the proposal was also presented at CWPRS Pune.

Figure 3.1: Meeting with the local community of Lachen village held on 14th Sept, 2024

Figure 3.2: Presentation of Sikkim Strategy on GLOF risk mitigation in the NDMA National GLOF workshop held on 11-12, November 2024

Aryanshrivastava

-//TRUE COPY//-

Figure 3.3: Presentation of the PPR on GLOF risk reduction in Lhonak valley in the meeting held at NDA on 23rd December 2024

Figure 3.4: Presentation of the PPR on GLOF risk reduction in Lhonak Valley at CWPRS Pune on 2nd Jan 2025

3.3 Comprehensive field studies

A multi-disciplinary team comprising glaciologists, geologists, hydrologists, ecologists, disaster experts, engineers, and others undertook comprehensive field studies of the high-risk glacier lakes. Bathymetric investigations, moraine dam stability, mass movement risks, and hydrological discharge assessment were undertaken in the high-risk lakes. At Dolma Sampa in Lhonak Valley, subsurface geophysical investigations, discharge assessment of Goma Chu, debris deposition analysis, and flood-level measurements were undertaken. The studies will help refine glacial flood modeling, provide insights into subsurface geology, and inform the design of retention structures

Aryanshrivastava
-//TRUE COPY//-

to mitigate potential GLOFs. Also, Automatic Weather and Water Level Monitoring stations (AWWS) were installed at Shako Chho and South Lhonak Lake with support from the Swiss Development Corporation (SDC) and NDMA. These monitoring stations have started providing daily weather data, water level data, and photographs, and also have a built-in alert system in case of sudden water level changes.

Figure 3.5: Comprehensive field studies undertaken by a multi-disciplinary team

Figure 3.6: Sub-surface geology at Dolma Sampa being assessed using Electrical Resistivity Tomography (ERT) by geologists

Figure 3.7: Hydrological discharge assessment of Goma chu using Current meter

Figure 3.8: Debris deposition pattern study at Dolma Sampa by geologists

Figure 3.9: Measuring 2023 glacial flood level using DGPS in Dolma Sampa

4. Review of glacial flood risk mitigation measures

The GLOF risk mitigation measures fall under three broad components: hazard, exposure, and vulnerability (Table 4.1). This proposal focuses on the GLOF risk mitigation measures, which fall under three broad categories: lake level lowering (such as open cuts, artificial dams, and tunnels), retention dams (watershed level), and floodwalls.

Table 4.1: An overview of GLOF risk mitigation measures (Source: Emmer 2024)

	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

The typical locations for the various GLOF risk mitigation measures along the river valley are indicated in Figure 4.1 below.

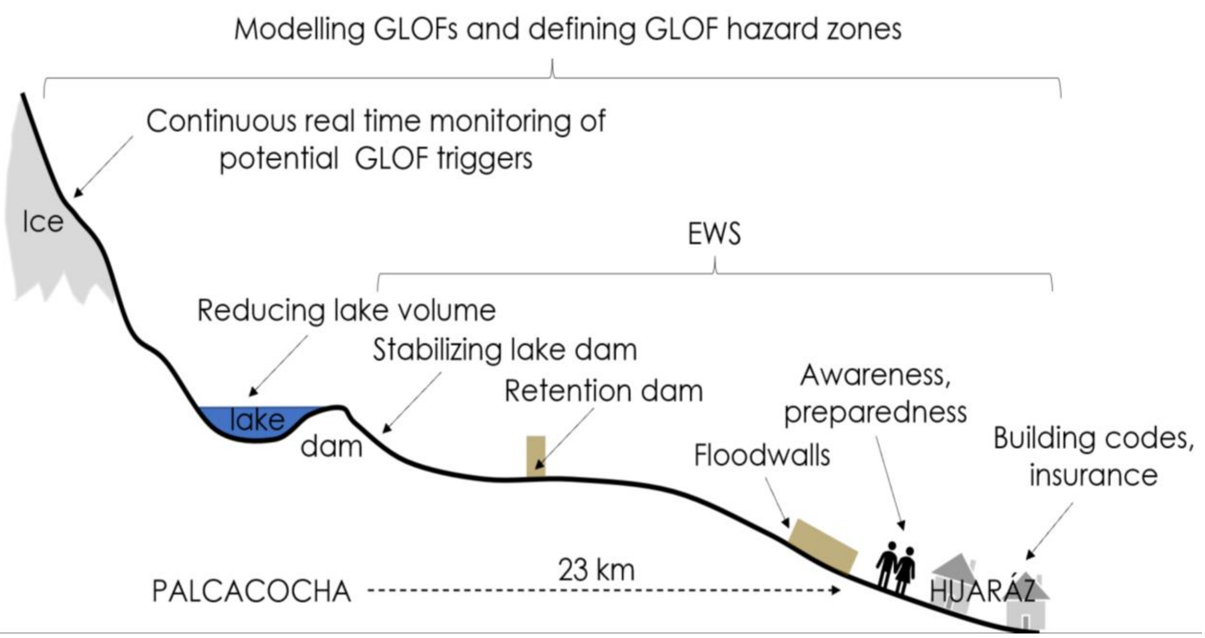


Figure 4.1: Location of the GLOF risk mitigation measures along the river valley (Source: Emmer 2024)

4.1 Lake level lowering

Although the specific triggers for GLOFs may vary, the most important mitigation measure for reducing GLOF risk is reducing the water volume in the lake. This reduction can significantly decrease susceptibility to GLOFs by lowering the hydraulic gradient and hydrostatic pressure head. If a GLOF event were to occur, the magnitude of the flood would be significantly reduced (Reynolds 1998, Haeberli et al. 2017, NDMA 2020). In addition, a larger retention space can be achieved by reducing the volume of water in the lake. Therefore, displacement waves generated by slope movement, avalanches, or flood waves will not reach heights sufficient to overtop the dam crest (Hrebrina et al. 2023). However, the feasibility of this intervention will depend on site-specific aspects such as whether the terrain is accessible for heavy machinery, concerns regarding heavy equipment toppling over on the steep slopes surrounding the lake, and the extreme logistic complexity due to the high elevations and harsh working conditions (NASA 2009). Also, local acceptability of this intervention is essential as invasive techniques such as breaching, tunnelling, artificial spillway, moraine cut dam, etc., may hurt the local beliefs since many of these lakes are considered sacred by the local communities.

Six options are available for lowering the lake level: siphoning, pumping, controlled breaching, artificial spillway, moraine open cut with the artificial dam, and tunnelling (USAID 2014).

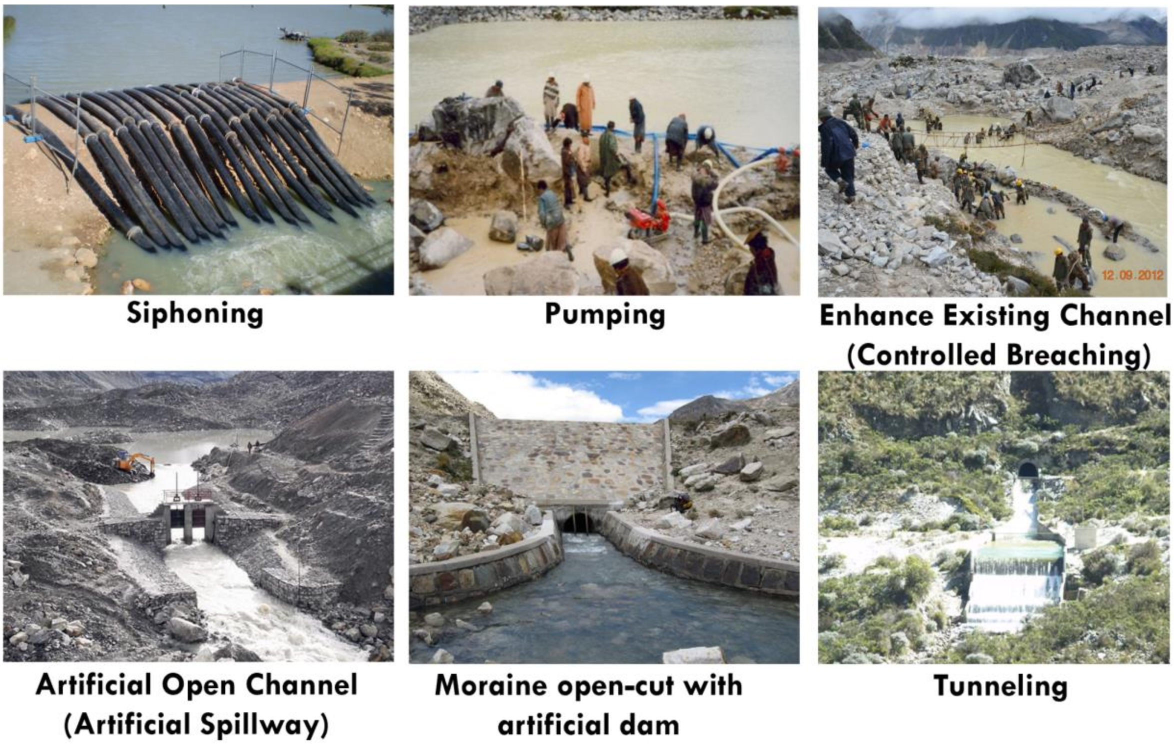


Figure 4.2: Options available for lake-level lowering of glacial lakes

These six options are analysed in detail below:

- **Siphoning** is a non-invasive and low-risk option. However, it offers a low discharge rate and requires regular maintenance due to breakdowns. It is considered a temporary solution as workability and maintenance are issues. This option was tried out in three other instances, namely, Thorthormi Tsho (2009) in Bhutan, Tsho Rolpa (1995) in Nepal, and South Lhonak (2018) in Sikkim, and it did not provide the desired results.
- **Pumping** had limited impact and was expensive due to fuel transportation costs. This option was tried out in Bhutan in Raphstreng Tsho (1996) and Thorthormi Tsho (2009) and was abandoned as it had minimal impact and fuel transport costs were prohibitive. The feasibility of using solar pumps instead of diesel pumps can be explored.
- **Controlled breaching** can lower the lake level by widening and deepening the natural outlet by 3-5 m. This approach was adopted in Bhutan at Raphstreng Tsho (1996) and Thorthormi Tsho (2009). Due to a lack of road access and local sentiments, this approach was carried out manually without heavy machinery and was expensive. This approach is not feasible in lakes with steep and fragile lateral and terminal moraine walls, as there is a risk of the moraine walls collapsing during the breaching.
- **Artificial spillway** by cutting through the moraine dam to create a new drainage channel with gate can lower the lake level by upto 3-5 m. This approach was adopted in Nepal at Imja Tsho and Tsho Rolpa (1995). In lakes where the lateral and terminal moraine walls are steep and fragile, this approach is not feasible as there is a risk of the moraine walls collapsing during the spillway construction.
- **Moraine open-cut with artificial dam** approach has been widely used in Peru. It involves cutting the downstream face of the moraine into a V-shape and gradually lowering the water level. After the opening has been cut, a reinforced concrete pipe is installed to maintain the reduced lake level. An earth dam with a stone façade is built over the pipes, restoring much of the original V-shaped cut in the moraine. This creates a freeboard to contain future wave surges created by ice avalanches falling into the lake. This approach is not feasible in locations with steep and fragile lateral and terminal moraine walls. Hence, there is a risk of the moraine walls collapsing during the open cut.
- **Tunnelling** approach involves drilling drainage tunnels into glacial lakes with natural rock dams. This option would involve drilling through the lateral moraine using a horizontal boring machine to lower the lake water level. However, if the lateral moraine is too fragile and steep it runs the risk of collapsing due to the vibrations during drilling.

4.2 Review of global experiences in lake level lowering

Siphoning is a non-invasive and low-risk option. However, it offers a low discharge rate and requires regular maintenance due to breakdowns. Looked upon as a temporary solution as workability and maintenance is an issue. Pumping had a limited impact and was expensive due to the transportation costs of fuel. Enhancing existing channel (controlled breaching): Widening and deepening of natural outlet can lower the lake level by 3-5 m. This approach was adopted in Bhutan. Artificial open channel (artificial spillway): Cutting through the moraine dam to create a new drainage channel with a gate can lower the lake level by 3-5 m. This approach was adopted in Nepal. In Bhutan, the field operations were carried out manually by labor and were time-consuming and expensive. In Nepal, the operation was done jointly with the Nepalese Army using heavy machinery and labour. Men, machines, and equipment were flown in by helicopter.

Table 4.2: Review of global experiences in lake level lowering using different mitigation options

Mitigation strategy	Country	Lake	Learnings
Siphoning	Bhutan	Thorthormi Tsho, 2009	• Siphoning was ruled out as limited discharge, workability of siphons and considered as a temporary measure
	Nepal	Tsho Rolpa, 1995	• Siphoning became non-functional in 2 years. No noticeable impact, maintenance issues
	Sikkim	South Lhonak 2018	• Siphoning became non-functional in 2 years, maintenance issues
Pumping	Bhutan	Raphstreng Tsho, 1996	• Pumping had minimal impact and also fuel transport costs were prohibitive
	Bhutan	Thorthormi Tsho, 2009	• Pumping was ruled out as 800 cum/hr required, which needs heavy equipment. Pumps did not work properly and very high fuel costs
Controlled breaching	Bhutan	Raphstreng Tsho, 1996	• The channel was manually widened and deepened using basic tools. It was 78.5m long and 36m wide and constructed at lake outlet. Water level was lowered by 4m.
	Bhutan	Thorthormi Tsho, 2009	• Natural outlet was widened and deepened. It was 192 m long and 15m wide. Lowering lake level by 5m • Labour intensive and very expensive
Artificial spillway	Nepal	Imja Tsho,	• New, artificial drainage channel 45m long, 3m wide, 3m deep and gate
	Nepal	Tsho Rolpa, 1995	• New, artificial channel 70m long, 4.2m wide, 3m deep and gate constructed • Support of army, heli-transportation • Heavy machinery and porters used

			• Lowering of lake level by 3m
Moraine open-cut with artificial dam	Peru		This was the standard practice adopted by Peruvian engineers: • Cutting the downstream face of the moraine into a V-shape • The cutting process gradually lowers the water level. • After the opening has been cut, a reinforced concrete pipe is installed to maintain the reduced lake level. • An earth dam with a stone façade is built over the pipes, restoring much of the original V-shaped cut in the moraine. • This creates a freeboard, to contain future wave surges created by ice avalanches falling into the lake
Tunnelling			• Drainage tunnels can be drilled into glacial lakes with natural rock dams and, in some cases, lakes with loose moraine dams.

4.3 Watershed-level retention structure

Retention structures assist in reducing the downstream impact of sudden flood surges caused by the failure of glacial lake dams. These structures are engineered to hold back, control, or divert floodwaters. At times, the terrain of the glaciated valleys is amenable to the construction of retention structures that help to contain the impact of the GLOF and then release the flood waters in a controlled manner to reduce downstream implications.

4.4 Comparative analysis of the approaches

The next decision is when to adopt lake-based and when to go for watershed-based GLOF mitigation. The following guidance can be considered for this decision-making:

- **Risk profile of the lake**: If the lake is considered highly unstable and likely to breach soon, lake lowering may be the priority. Retention structures are better suited for more stable lakes or where downstream protection is the primary concern.

- **Technological challenges**: The primary concern in lake level lowering using pumping is the lack of grid-based electricity, lack of road access, and the limited capacity of conventional pumping technology. Hence, lake level lowering is feasible only for small lakes, where pumping can lower the lake level by around 4-5 meters. After lowering the lake water level, the lake's natural outlet has to be deepened by the corresponding amount to maintain this reduced water level. Otherwise, the lake will soon start refilling and regaining its original level.

- **Geographic and environmental factors**: If the glacial lake is in a highly sensitive ecosystem or inaccessible area, lake lowering can be a more practical approach. If the surrounding landscape allows for it, and the long-term protection of the downstream regions is critical, retention structures offer better protection.
- **Budget and resource availability**: Lake lowering is often more affordable and quicker to implement with limited budgets. However, if the necessary resources are available, retention structures provide comprehensive, long-term flood mitigation. While the upfront investment for retention structures is much more, they offer multi-lake mitigation in a one-shot operation.

Lake lowering is ideal for addressing the immediate risks of smaller lakes and provides short-term or temporary solutions. Retention structures are preferable when long-term protection, large-scale flood control, and downstream impact management are required.

4.5 Why Lake level lowering is challenging at Lhonak?

The three biggest high-risk lakes in Lhonak Valley - South Lhonak, North Lhonak, and Changsang, are massive, with more than 40 million cubic meters (MCM) of water each, and have a natural outlet. Lowering the water levels of glacial lakes to mitigate the risk of GLOFs presents numerous challenges due to the unique characteristics of these environments. Terminal moraines, which act as natural dams for these lakes, are inherently fragile and often contain dead ice, making them unstable and prone to collapse under stress. This fragility complicates any intervention efforts, especially those involving the use of machinery. Accessing these remote lakes is another significant hurdle, as they are often located in high-altitude regions with steep and rugged terrain. Deploying heavy machinery is logistically challenging and poses risks of toppling over the precarious slopes surrounding these lakes. The harsh climatic conditions and thin air at high elevations further add to the logistical complexity, requiring meticulous planning and specialized equipment to ensure workers' safety and the intervention's success. The lack of road access precludes the use of heavy machinery, so engineering measures to lower the lake level are not feasible.

Moreover, these glacial lakes are enormous in size, holding over 40 million cubic meters (MCM) of water each, making lowering water levels a technological challenge. Even after successful interventions, these lakes refill over time due to continuous glacier melt and precipitation, necessitating repeated efforts to maintain reduced levels. This cyclical nature of the problem increases the long-term costs and logistical demands. Finally, the local community’s acceptance of such interventions is critical.

5. Reimagining glacial flood propagation

5.1 Conventional understanding of GLOF propagation

How do glacial floods propagate along the river valley? Conventionally, GLOF propagation is visualized as a high-velocity torrent carrying debris, sediment, and boulders. When a glacial lake bursts, the sudden outflow of water rapidly erodes the valley as it cascades downstream. The initial surge of water from the lake carries massive amounts of debris, including rocks, sediment, and ice. As this torrent of water flows downhill, it gains momentum and volume, incorporating more material from the valley walls and riverbed. This erosion process not only deepens and widens the flood channel but also amplifies the flood's destructive power. The cascading floodwater grows larger and more forceful as tributaries and landslides contribute additional water and debris to the flow. Entire sections of valley slopes may collapse into the torrent, further intensifying the flood. By the time the GLOF reaches downstream areas, it has transformed into a massive and chaotic flood wave capable of sweeping away bridges, roads, and settlements. Eventually, the flood dissipates as it enters gentler terrain on reaching the foothills or merging with the larger rivers. This results in massive erosion upstream and debris deposition downstream, leaving a scarred landscape and affecting communities.

A multidisciplinary team undertook expeditions to the Lhonak Valley in October and December 2024 to uncover whether the propagation of the 2023 glacial flood aligned with the conventional understanding. Three studies were undertaken to collect evidence: i) hydrodynamic modeling, ii) assessing stream power during GLOF, and iii) debris deposition pattern.

5.2 Hydrodynamic modeling

The Hydrologic Engineering Center-River Analysis System (HEC-RAS ver. 6.6) was used for hydrodynamic modeling to reconstruct the glacial floods in Lhonak Valley. This open-source software is widely used for one- and two-dimensional (1D and 2D) dam breach modeling and downstream routing of the estimated breach discharge/hydrograph.

5.2.1 Objectives

1. To reconstruct the flood depth, velocity, and discharge along the Goma Chu in the Lhonak Valley
2. To identify the suitable location for the construction of a retention structure in the Lhonak Valley from the hydrodynamic model output

5.2.2 Methodology

Root mean square error (RMSE) was computed using the elevation of the sixteen DGPS points and the corresponding elevation of HMA DEM dated July 16, 2017 (Eq.1).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{Obs} - X_{Sim})^2}{n}} \text{ .... (1)}$$

Where X_{obs}= DGPS point elevation, X_{sim}= HMA DEM elevation and n= no. of observation.

The computed RMSE between the DGPS point and corresponding HMA DEM elevation is only 1.57 m with a coefficient of determination of 0.97 (Figure 5.1). Thus, these statistics indicate that the HMA DEM is appropriate for performing hydrodynamic modeling.

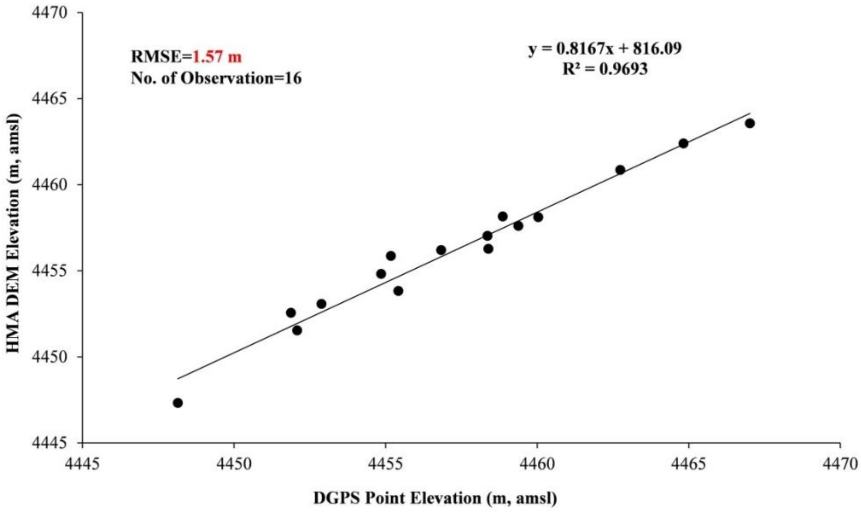


Figure 5.1: Association between DGP points and HMA DEM elevations

Average breach width and breach formation time were computed using Eq. 2 and 3, respectively (Froehlich, 1995a).

$$B_{ave} = 0.1803\ K_o V_w^{0.32} h_b^{0.19} \text{ .... (2)}$$

$$T_f = 0.00254\ V_w^{0.53} h_b^{-0.90} \text{ .... (3)}$$

Where B_{ave}= average breach width (m), K_o= constant (1.4 for overtopping failures and 1.0 for piping), T_f =breach formation time (h), V_w = reservoir volume above breach invert at time of failure (m^3), h_b= height of the final breach (m). According to Froehlich, average side slopes should be 1.4H: 1V for overtopping failures.

Height (amplitude) of impulse wave was estimated using Sentinel 2 satellite image of pre- and post- glacial outburst flood (GLOF) and 5 m interval contour derived from the HMA DEM. The peak discharge of the breach flow was computed using Eq. 4 (Froehlich, 1995b).

$$Q = 0.607\ V_w^{0.295}\ h_w^{1.24} \text{ .... (4)}$$

Where h_w=depth of water above breach invert at time of failure

The statistics and computational methods from steps 2 to 3 are summarized in Table 5.1.

Table 5.1: Impulse wave height, breach parameters and estimated peak discharge

Description of Parameters	Computed Values	Computational methods
Impulse wave height (m)*	22	HMA DEM and Post-GLOF Sentinel 2 image-based analysis. (5192m-5170m)=22. The maximum elevation of the deformation in the end moraine is 5192 m, amsl. The elevation of the pre-GLOF lake level is 5170m, amsl (Figure 5.2).
Volume of water above breach invert (m^3)	3,93,07,960	Pre-GLOF lake shoreline (5170) and average lowering of lake (24m). (5170m-24m)=5146m. Elevation of breach invert is 5146m, amsl.
Height of the final breach (m)	45	Elevation of breach initiation is 5191 m, amsl. Elevation of breach invert is 5146m, amsl. Height of the final breach=(5191m-5146m)=45m
Left side slope	1.4	Froehlich (1995a)
Right side slope	1.4	Froehlich (1995a)
Average breach width (m)	140	**Eq. 2**
Breach bottom width (m)	77	HEC-RAS parameter calculator
Breach formation time (h)	0.88	**Eq. 3**
Depth of water above breach invert at time of failure (m)	46	Overtopping Moraine Dam Failure. Depth of Water=(5192m-5146m)=46m
Peak discharge (m^3s^{-1})	12,173	**Eq. 4**

Assessed using Sentinel 2 MSI image (Oct. 06, 2023) and HMA DEM (July 16, 2017)

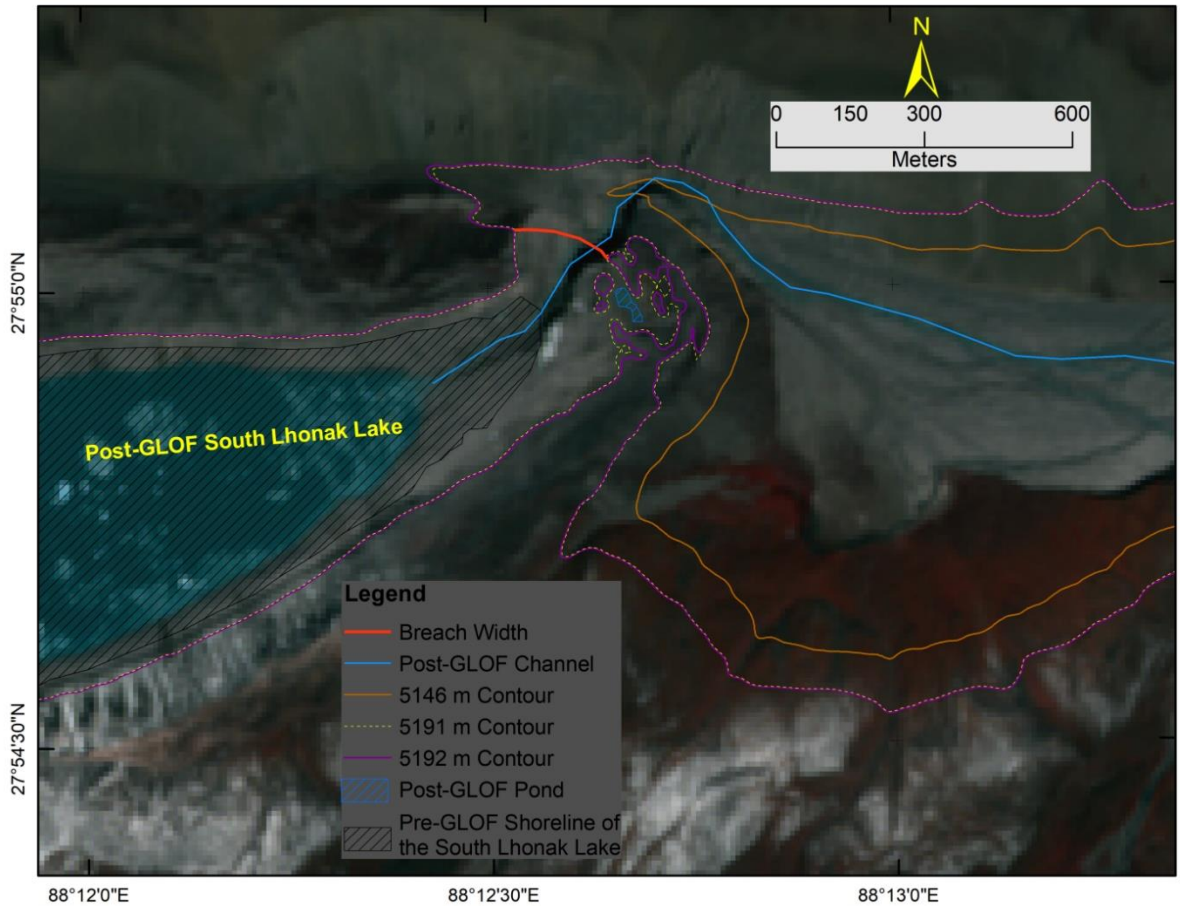


Figure 5.2: Determination of the maximum elevation of the impulse wave using HMA DEM-derived contours and post-GLOF sentinel 2 image (Oct.06, 2023)

The spatial distribution of different land cover classes is given in Figure 5.3. Land cover-based Manning's N values are listed in Table 5.2. A triangular hydrograph was constructed and peak flow was set at an ordinate of 26 mins which is almost the mid-point of the breach formation time (0.88 h or 52.8 mins) (Figure 5.4) (e.g., Froehlich, 1995b). Further, this hydrography was used as the upstream boundary, and normal depth i.e., bed slope of 0.026 m/m was selected as the downstream boundary condition for hydrodynamic modeling using HEC-RAS 6.6.

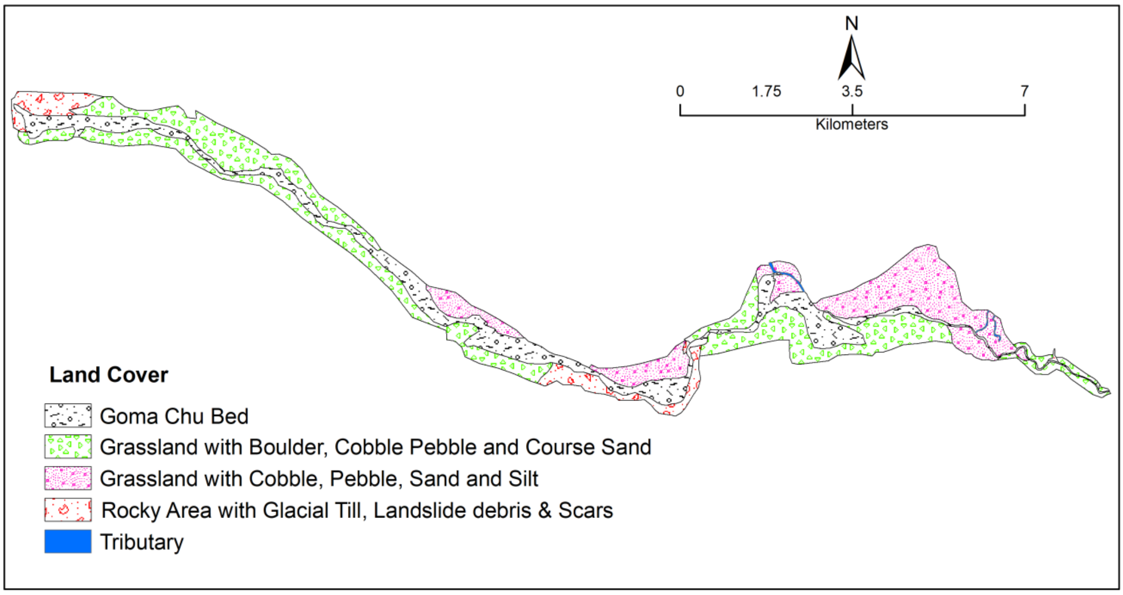


Figure 5.3: Land cover classes of the Goma Chu valley

Table 5.2: Manning's N values for different land cover classes

Land Cover Class	Manning's N Values (s $m^{-1/3}$)
Goma Chu Bed	0.04
Grassland with Boulder Cobble, Pebble, and Course Sand	0.03
Grassland with Cobble, Pebble, Sand and Silt	0.023
Rocky Area with Glacial Till, Landslide Debris and Scars	0.03
Tributary	0.025

Source:https://rashms.com/wp-content/uploads/2021/01/Mannings-n-values-NLCD-NRCS.pdf

The Shallow Water Equation (SWE) was applied to simulate the breach hydrograph along a 30 km stretch downstream of South Lhonak Lake. The estimated average flow velocity between the end moraine of the South Lhonak Glacier and Chungthang town is 9.86 m/s, with the distance between the moraine and Chungthang measuring 71,000 m. The GLOF event originated at 10:30 PM on October 3, 2023, and reached Chungthang in just 2 hours (7,200 seconds), arriving at 12:30 AM on October 4, 2024 (Gupta, 2023; East Mojo, 2023). The average velocity was calculated by dividing the distance by the time. The mesh size used in the simulation was 40 m x 40 m, and the computational time interval was determined by dividing the mesh size by the average velocity (40/9.86 = 4.05 s) (Figure 5.5 and 5.6).

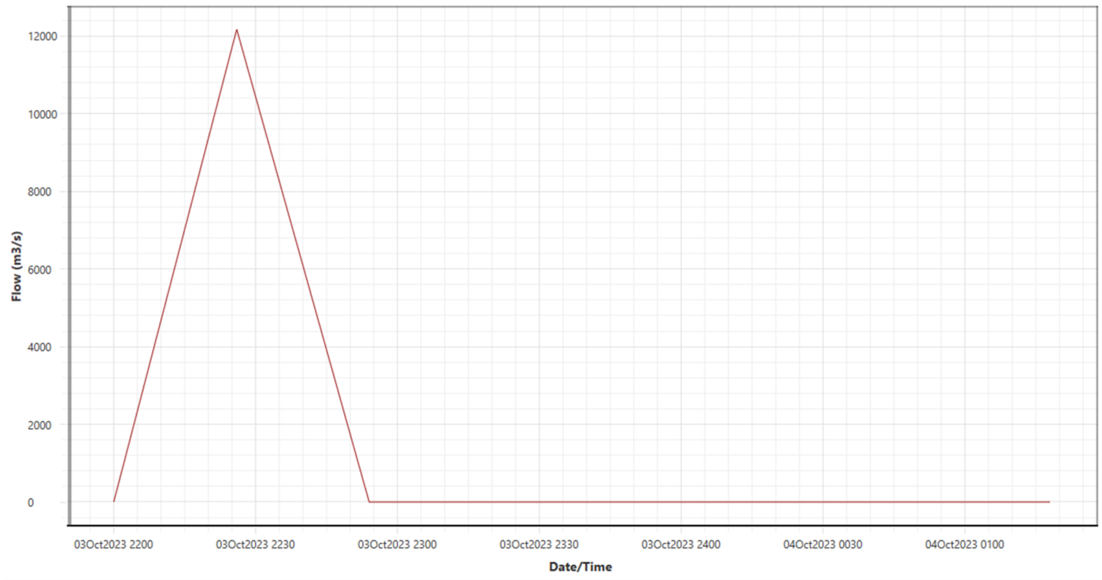


Figure 5.4: Inflow breach hydrograph selected as upstream boundary condition

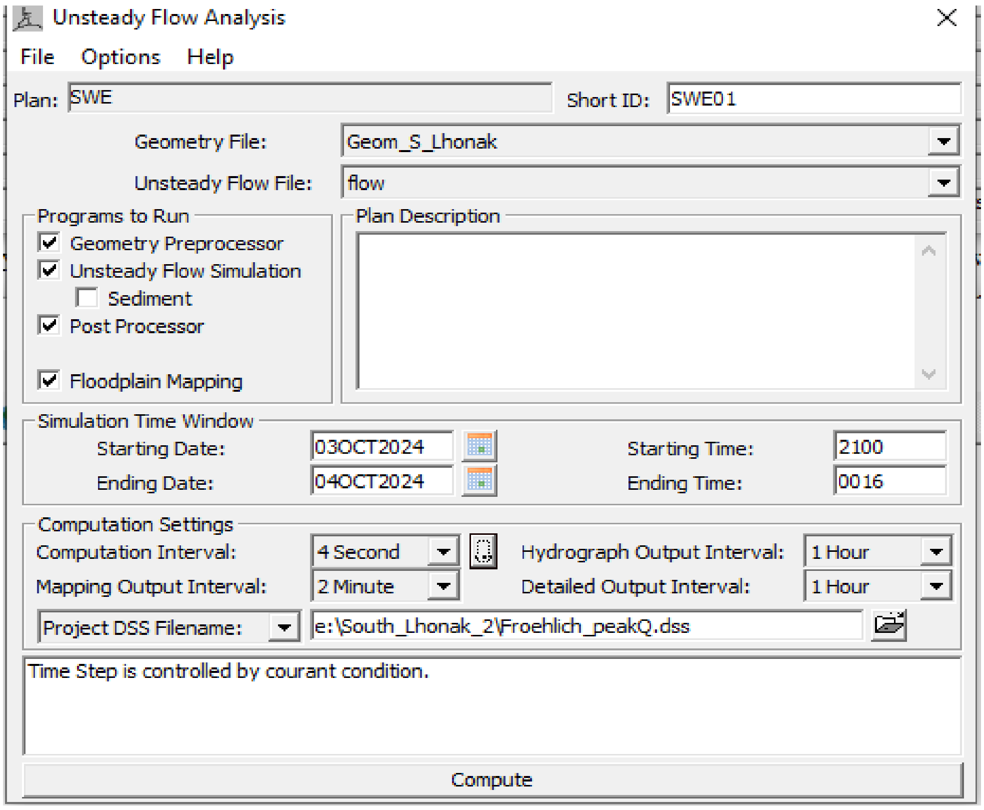


Figure 5.5 Computational time interval window of HEC-RAS 6.6.

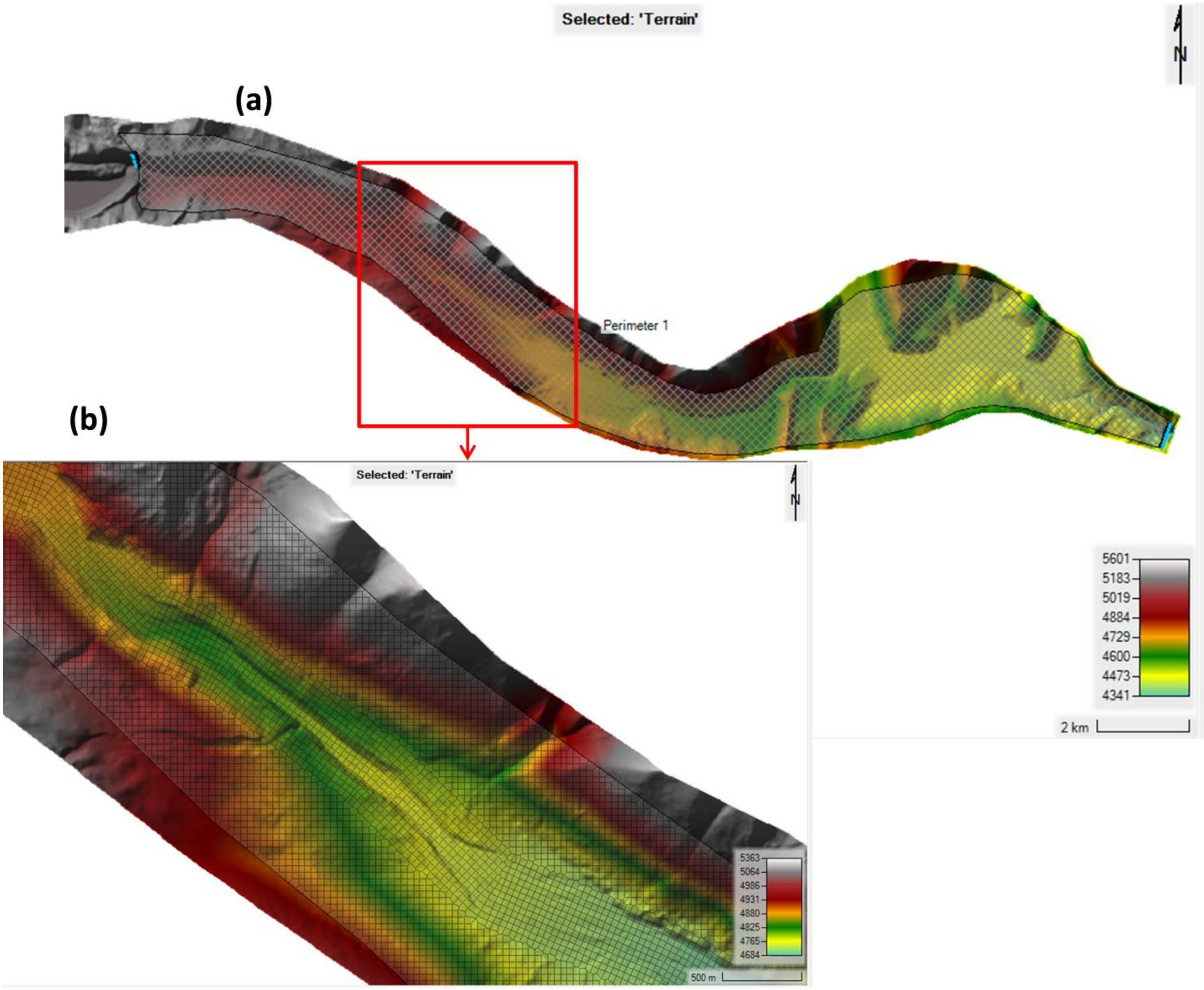


Figure 5.6: a) 2D mesh and b) all cells of the valley floor are aligned in the direction of flow.

Model performance index (MPI) was computed to check the level of agreement between simulated and satellite image-based delineation of flood extent almost 30 km downstream of the end moraine of the south Lhonak glacier (Eq. 5) (Pilotti et al.,2020).

$$MPI = \frac{Simulated \cap Observed\ flooded\ area}{Simulated \cup Observed\ flooded\ area} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5)$$

MPI values range from 0 (no overlap) to 1 (complete overlap).

Post-GLOF Sentinel 2 image (October 06, 2023) were used to map the flooded area with help of keys of visual image interpretation.

5.2.3 Observations

- The hydrodynamic modeling was conducted along a 30 km stretch downstream of South Lhonak Lake, from chainage 1 km to 30 km, to reconstruct the flood events in the valley. The simulated maximum flood depth across the entire area ranges from 0.00097 m to 23 m above ground level, with an average depth of 4 m. At the PRS1 site, the maximum flood depth varies from 0.15 m to 7.81 m, with an average maximum depth of 4.26 ± 2.3 m. Similarly, at the PRS2, the maximum flood depth varies from 0.25 m to 14.57 m, with an average maximum depth of 5.45 ± 4.57 m.
- The simulated maximum velocity ranges from 0.0043 m/s to 24.63 m/s, with an average velocity of 7 m/s. At the PRS1, the maximum velocity varies between 2.98 m/s and 8.9 m/s, with an average maximum velocity of 7 m/s. Similarly, at PRS2, the maximum velocity varies between 1.17 m/s and 9.37 m/s, with an average maximum velocity of 5.35 m/s.
- The simulated peak discharge ranges from 8,100 m^3/s to 12,173 m^3/s along the stretch of 1 km to 30 km. The model calculated a peak discharge of 8,737 m^3/s at the PRS1. Similarly, at PRS2, a peak discharge of 8627 m^3/s was computed in GLOF reconstruction.

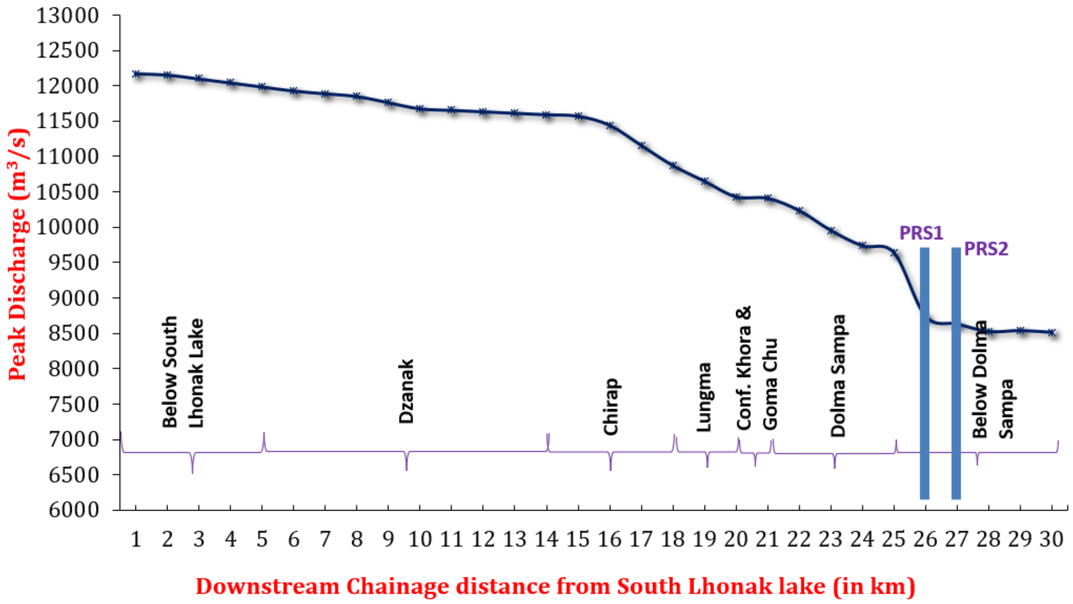


Figure 5.7: Peak discharge computed from hydrodynamic modeling along the Goma Chu. PRS is the Proposed Retention Structure

- The total flooded area simulated by the hydrodynamic modeling (HEC-RAS 6.6) is 9.5 km^2, while the satellite image-based flooded area is 9.56 km^2. The computed MPI is 0.85, indicating a strong agreement between the simulated and satellite image-derived flood extents.

- The vertical accuracy of the HMA DEM used in this assessment is statistically significant, based on geographical coordinates obtained from a field-based DGPS survey of the area. The assessment is conducted at a 95% confidence level.

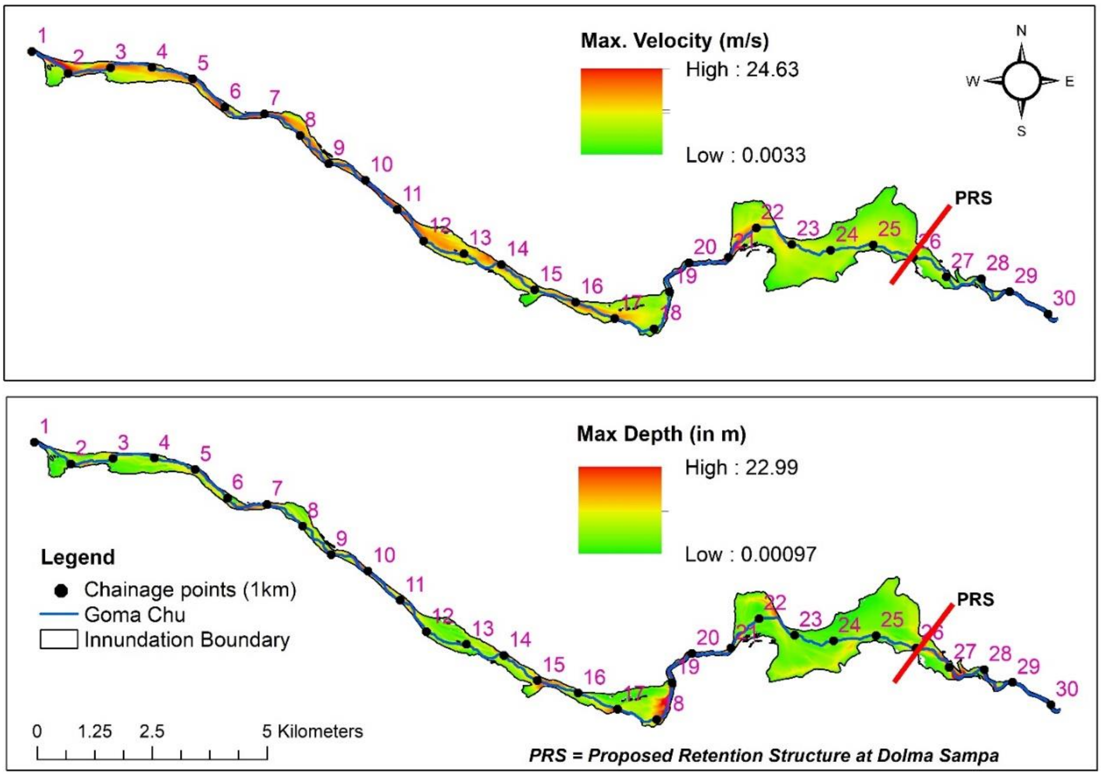


Figure 5.8: Modelled maximum depth and velocity from the hydrodynamic modeling during GLOF

5.3 Stream power assessment (GLOF)

The term stream power is associated with the general concept of flowing water possessing the properties of mechanical power (Rhoades 1987). It refers to the time rate of potential energy expenditure, i.e., the conversion of potential energy to kinetic energy that is dissipated in overcoming internal and boundary friction, transporting sediment, and eroding the channel perimeter as water travels downslope in a channel (Rhoades 1987).

5.3.1 Objectives

- To compute the unit stream power along the Goma Chu in the Lhonak Valley
- To identify the minimum unit stream power during GLOF for suitable positioning of the retention structure in the valley

5.3.2 Methods

Stream power is a product of stream slope, discharge, and weight of water that influence sediment transport (Rhoads, 1987; Gartner, 2016). It is given by the following equation:

Aryanshrivastava

-//TRUE COPY//-

Ω = yQS ……………………………………………….(Bagnold, 1966)

Where Ω is total stream power per unit length of the channel (Wm^{-1}), y is the specific weight of water (9800 Nm^{-3}), Q is discharge (m^3/s), and S is the energy slope (m/m) of the flow within a given reach. The discharge (Q) has been computed from the output of hydrodynamic modeling in HECRAS 6.6.

Unit stream power is a measurement of the rate of energy expenditure per unit area of a river channel width (Rhoads, 1987).

$$\text{Unit Stream Power for GLOF(Watts}/m^2) = \frac{\text{Total Stream power (watts/m)}}{\text{Flood extent width (m)}}$$

The Flood extend width has been computed from the output of hydrodynamic modeling in HECRAS 6.6.

5.3.3 Observations

- The downstream distribution of total and unit stream power shows a non-linear variation or trend. Unit stream power during the GLOF event is taken as a proxy for sediment transport in the Goma Chu.
- In the Goma Chu, the unit stream power for GLOF ranges from a minimum of 976 to a maximum of 100183 watts/m^2. It is observed that stream power does not follow a uniform pattern in the valley as it increases with erosion and decreases with deposition in the valley.
- Substantial deposition of sediments is observed when the unit stream power for GLOF ranges between 967 and 6601 watts/ m^2.
- It is observed that when the GLOF width (Flood extent width) is more than 400 m, the unit stream power decreases sharply, denoting debris deposition in the channel belt.
- The unit stream power decreases sharply from Chainage 22 due to the gentle slope and maximum inundation width, which provide extended flood reach and have supported fine sand deposition.
- The reconstructed flood extent width in the Goma Chu ranges from 66 to 1229 m. The maximum flood extent in the PRS1 and PRS2 were 382 and 304 m respectively.
- The Channel slope in the Lhonak Valley ranges from 0.01 to 0.065 m/m. In the PRS1 in the Dolma Sampa, the channel slope is found to be minimum amounting to 0.010 m/m representing the appropriate site to construct the retention structure. Whereas, the Channel Slope in PRS2 was 0.011m/m.
- The analysis shows that the unit stream power is directly proportional to the channel slope and inversely proportional to the flood inundation width.

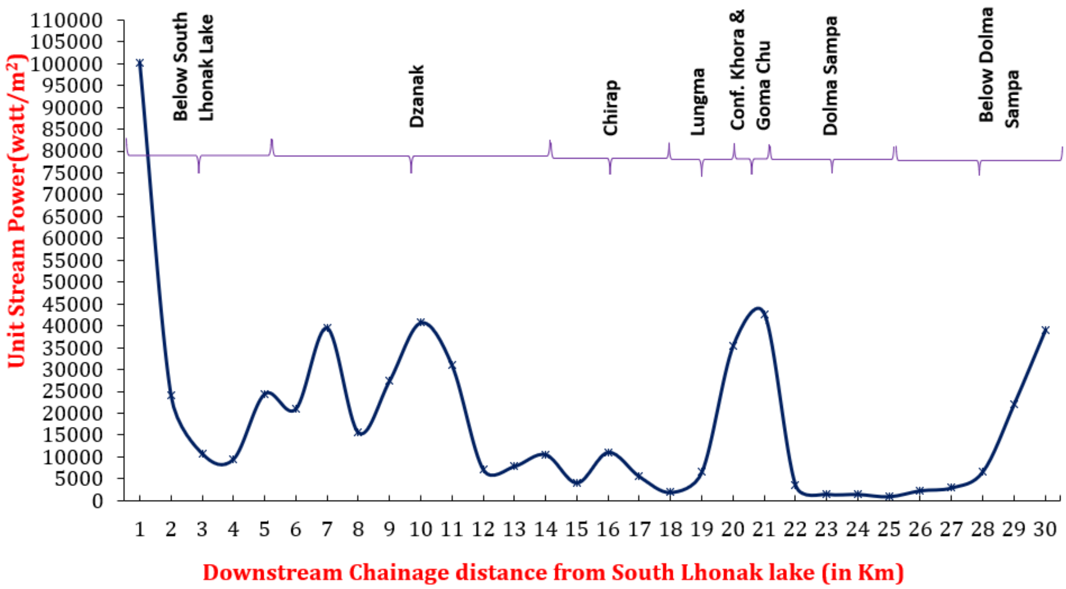


Figure 5.9: Unit Stream power of GLOF in the different sections along the Goma Chu

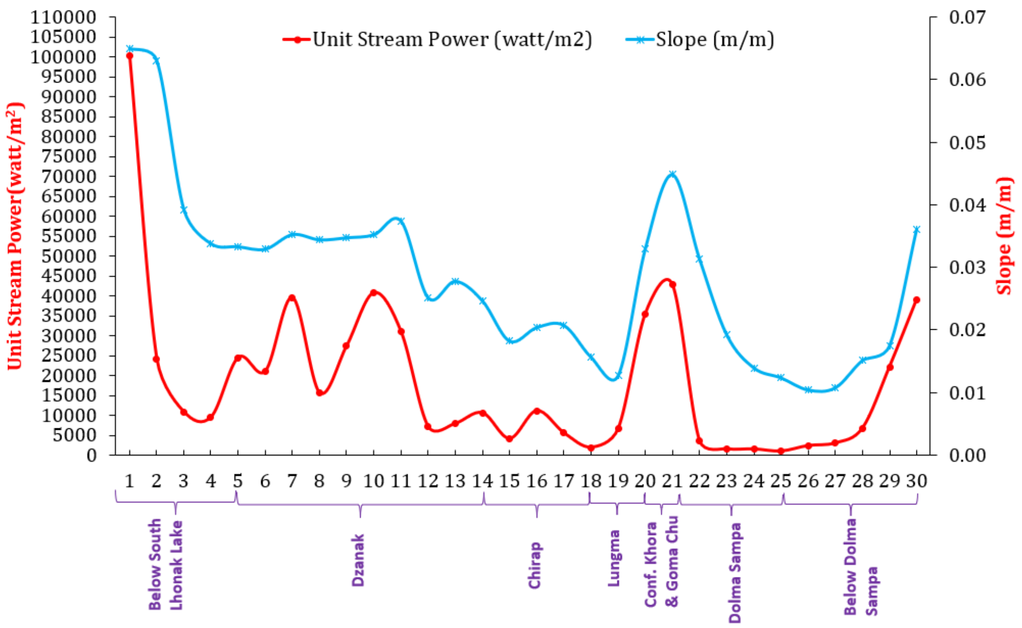


Figure 5.10: Unit Stream Power *vs* Slope Gradient along the Goma Chu

Aryanshrivastava
-//TRUE COPY//-

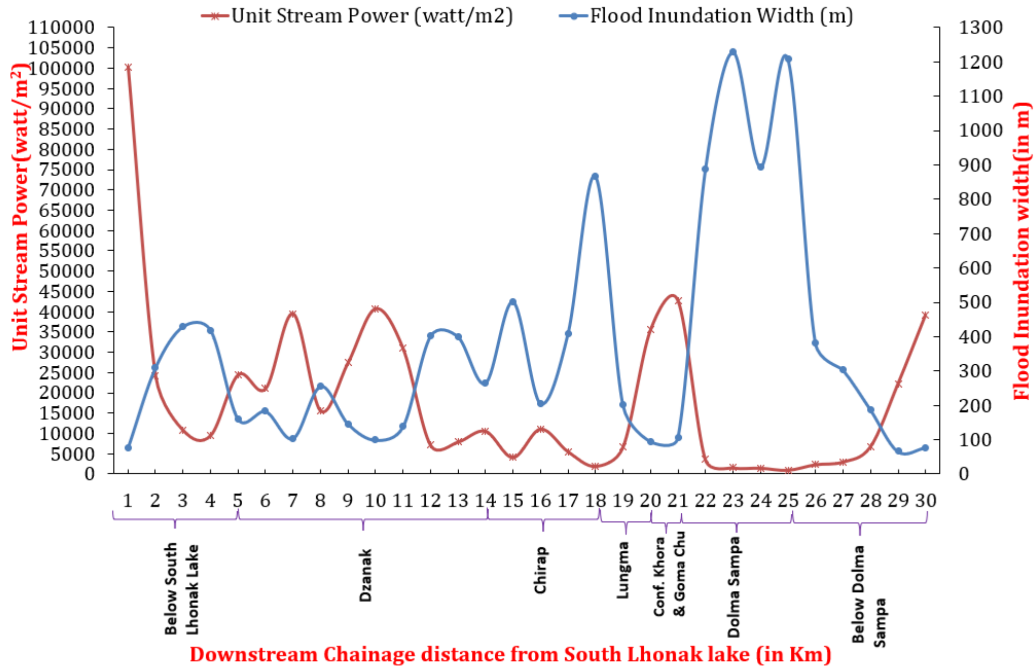


Fig 5.11: Unit stream power vs flood inundation width along the Goma Chu

Table 5.3: Comparative River hydro-morphometric characteristics for identification of suitable locations of Retention structure based on hydrodynamic modeling and stream power assessment

		Downstream Chainage (km) from Lake outlet			
River hydro-morphometric characteristics	**1**	**25**	**26 (PRS1)**	**27 (PRS2)**	**28**
Flood Inundation width (m)	77.4	1208	382	304	188
Max. Velocity (m/s)	19.30	7.65	8.58	9.37	8.46
Maximum flood Depth (m)	16.98	4.59	7.81	14.57	22.24
Maximum Discharge (m^3/s)	12173	9638	8737	8627	8520
Slope (m/m)	0.065	0.012	0.010	0.011	0.015
Unit Stream power (Watts/ m^2)	100183	967	2337	2996	6725

5.4 Debris deposition pattern

The Lhonak valley from the South Lhonak lake outlet to Chungthang can be divided based on its topography into seven sections: 1. South Lhonak outlet to Dzanak (0-5 km), 2. Dzanak to Chirap (5-14 km), 3. Chirap (14-18 km), 4. Lungma (18-20 km), 5. Khora-Goma chu confluence (20-21 km), and 6. Dolma Sampa (21-25 km) and the 7. Stretch from Langbuk downstream beyond 25 km).

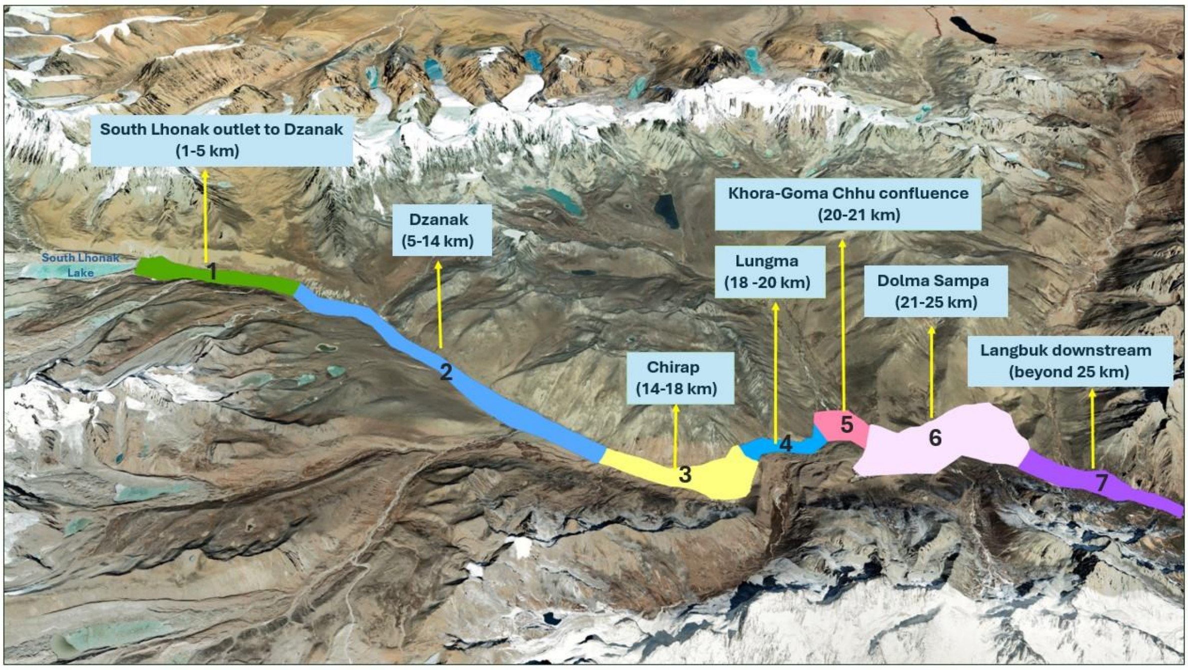


Figure 5.12: The different sections of Goma Chu based on topography

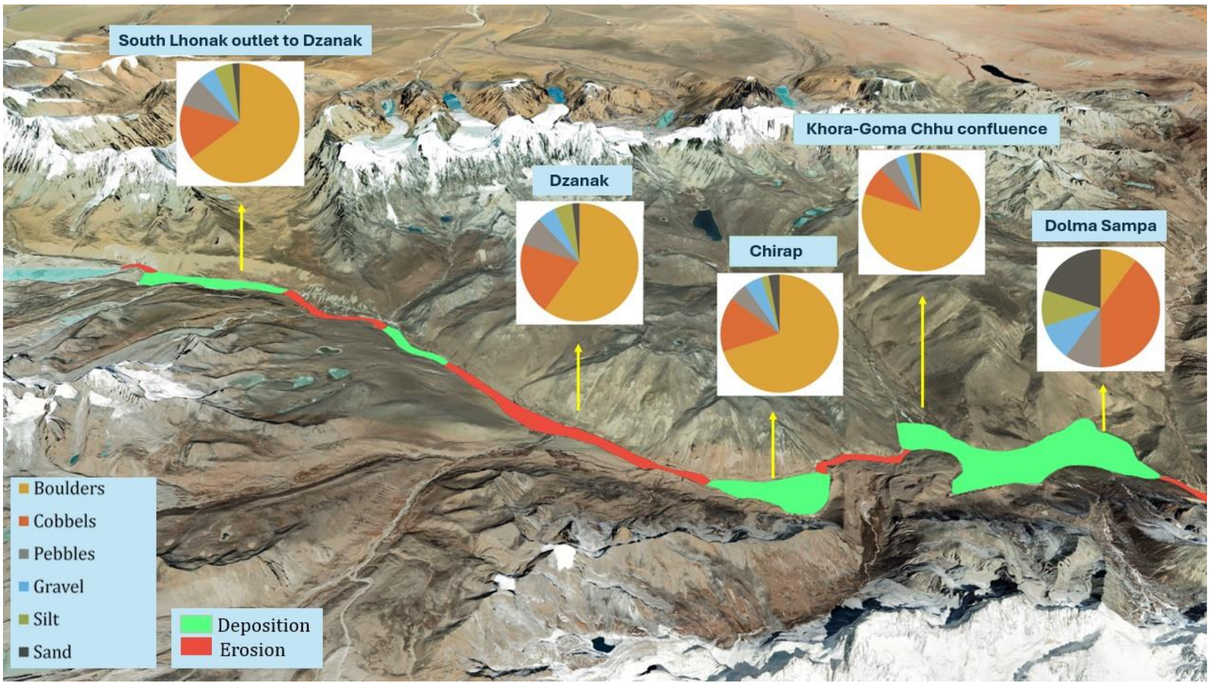


Figure 5.13: Glacial flood-induced deposition and erosion in different stretches of Goma Chu (after field survey 2024)

Section 1: Below South Lhonak lake

- Wide U-shaped valley with a maximum width of approximately 560 meters and minimum width of approximately 270 meters.
- High slope gradient (>35°) along the terminal moraine followed by a U-shaped valley with a gentle slope (<5°) gradient towards the downstream area.
- It falls under the Greater Himalayan sequence, comprising a high-grade metamorphic rock sequence represented by augen gneiss, migmatites, and their variants.
- Flood deposits comprise 70% boulders and 15% cobbles, 10% pebbles, 3% gravel, 1% sand, and 1% silty materials.

Figure 5.14: Flood plain below South Lhonak lake showing U-shaped Valley

Section 2: Dzanak to Chirap

- U-shaped valley with gentle slope gradient (<5°) with a maximum width of approximately 350 m and a minimum width of 180 meters.
- The area falls under the Greater Himalayan sequence with a high-grade metamorphic rock sequence.
- Maximum deposits comprising boulders in the middle portion of the valley followed by less dense and lighter materials such as cobbles, pebbles, gravels, silt, and sandy materials on the outer portion of the valley.

Figure 5.15: U-shaped Valley of Dzanak showing valley erosion due to recent glacial flood

Section 3: Chirap

- This is the first speed breaker for the glacial flood, as the valley widens out and the river takes a S-shaped turn.
- Bed rock exists towards the left bank, whereas loosely compacted stratified old river terrace deposits towards the right bank slope of Goma chu in this area.
- Massive erosion due to the toe cutting by the recent GLOF event resulting in vertical unstable slopes towards the right bank between 20 m to 30 meters high.
- A high density of transported boulders is found in the middle portion of the valley, and lighter materials such as cobbles, pebbles, gravels, and silt towards the outer portion.

Figure 5.16: At Chirap, the Goma chu river takes a 'S' shaped turn and the valley also widens out before again narrowing as it enters Lungma funnel

Figure 5.17: Large-scale deposition of debris in Chirap, as the valley widens out, slowing down the flood waters as the river takes a S-shaped turn

Section 4: Lungma funnel

- It is a narrow valley with a width of 80m and a length of about 2 km.
- Due to its narrow width and curvy structure, the erosional process is prominent.
- Massive erosion due to the toe cutting by the recent GLOF event resulting in vertical unstable slopes towards the right bank between 20 to 30 meters high.
- Bed rock exists towards the left bank, whereas loosely compacted stratified old river terrace deposits towards the right bank slope of Goma chu in this area.

Figure 5.18: At Lungma, the valley narrows down, resulting in large-scale erosion of the right bank

Section 5: Confluence with Khora chu

- U-shaped valley approximately 400 meters wide with a gentle slope gradient (<5°) where the Khora Chu and Goma Chu meet.
- Maximum deposition of boulders (80%) from GLOF towards the convex side of the valley followed by less denser/finer materials towards the inner portion of the concave portion.
- The Goma Chu was diverted towards the right bank due to a rise in the river bed caused by the deposition of flood materials towards the left bank.

Figure 5.19: At the confluence of Goma chu and Khora chu the river valley again widens out and the river again takes another 90 degrees turn resulting in large scale boulder deposition at the mouth of Khora chu

Figure 5.20: Large-scale boulder deposition at the mouth of Khora chu

Section 6: Dolma Sampa valley

- Wide U-shaped valley approximately 1 km wide with gentle slope gradient.
- The Goma Chu River bifurcates into two streams in the valley, which join on the down slope, approximately 150 m from the helipad area.
- High boulder density in the vicinity of the Goma Chu followed by lesser dense finer materials at the edges.
- High-grade gneiss and its variants is exposed along the ridge towards the north direction of the Helipad area trending along NW-SE direction.
- Dip of foliation S40°W to S70°W with dip amount of 15° to 25° SW with slope facet towards S30°W.
- Due to the wide valley, deposition and erosion have occurred towards the right bank slope and the middle portion of the old river terrace has not been affected by the recent flood event.

Figure 5.21: Dolma Sampa area has a gentle gradient. It is about 1 km wide and 3 km long and is possibly the flattest terrain available in the northern part of the state

Figure 5.22: The 2023 glacial flood debris deposition pattern in Dolma Sampa, with the boulders getting deposited in the upper reaches and smaller-sized sediments in the middle and lower reaches

Figure 5.23: The 2023 glacial flood debris deposition pattern in the lower reaches of Dolma Sampa, with mostly small-sized sediments comprising of pebbles and sand deposited along the left bank

Figure 5.24: The 2023 glacial flood debris deposition pattern in the lower reaches of Dolma Sampa shows a high density of sediments in the vicinity of the Goma Chu stream, followed by less dense/finer materials at the edges.

Figure 5.25: The 2023 glacial flood debris deposition pattern in the lower reaches of Dolma Sampa, with mostly small-sized sediments comprising of pebbles and sand deposited at the valley edges especially along the left bank

Figure 5.26: A bird's eye view of the Dolma Sampa, where the retention structure is proposed

5.5 Reimagining Glacial Flood Propagation

A significant finding was that the flood slowed dramatically through the widened valley sections at Chirap, Khora Chu confluence, and Dolma Sampa. This natural dissipation of force caused debris deposition, reducing the flood's destructive impact downstream. The flood picked up momentum only below Dolma Sampa, and debris caused widespread devastation downstream. When the floodwaters enter this wide valley, the terrain opens up, allowing the floodwaters to spread laterally. The sudden increase in width reduces the confinement of the flow. Due to the gentle gradient and broader area, the water velocity decreases. The gradient, or slope of the valley, plays a significant role in slowing the flow down. The energy of the floodwaters dissipates as the force driving the flow is reduced. Under the influence of this terrain, the peak discharge of the flood gets attenuated, and its duration is prolonged. As the velocity decreases, the turbulent nature of the flood may gradually transition to a more laminar (smoother) flow. With reduced energy, the floodwaters lose their capacity to carry larger debris and sediment, which start settling. Larger materials like boulders, rocks, and coarse sediment are deposited first. Over time, finer sediment (sand, silt, clay) is deposited as the flood continues to slow.

Table 5.4: Debris deposition pattern in the upper reaches of Lhonak valley

Parameter	Conventional GLOF Visualization	Lhonak GLOF pattern
Debris deposition pattern	Erosion in the upper reaches followed by deposition in the foothills	Multiple episodes of erosion and deposition pattern, especially in the upper reaches
Valley geometry	Steep narrow valley	Widely varying cross-section ranging from narrow valleys to vast, gently sloping plains (80m to 1200 m). Slope also varies from 0.01 to 0.06 m/m.
Destructive force	Cascades down and gains momentum before dissipating on reaching the foothills	Fluctuating momentum in the upper reaches, and gains momentum on entering the river gorge before dissipating in the lower reaches
Risk reduction	Cannot be tamed	The possibility to tame in the upper reaches is there, but feasibility needs to be assessed.

Multiple episodes of erosion and deposition patterns were observed, starting from below South Lhonak Lake to the lower reaches of Dolma Sampa Valley. The erosion of slope materials was observed along the banks of Goma Chu up to about 30 meters high at narrow valleys such as the Lungma and Zanak valley portions. The deposition of the flash flood materials was observed in wide valleys such as Chirap Valley, the confluence of Kora Chu/Goma Chu, and Dolma Sampa. The maximum deposition of flood materials occurred at the convex turns of the Goma chu river, followed by erosion of the banks by the flood waters.

6 Proposed strategy and design of the GLOF Kavach

Sikkim, being a part of the eastern Himalayas, is highly vulnerable to Glacial Lake Outburst Flood (GLOF) due to the increasing formation and expansion of moraine-dammed lakes caused by glacial retreat. With a focus on prevention, a strategy that blends engineering solutions, monitoring, and community-based approaches is essential.

6.1. Engineering Mitigation Options and Rationale

A. Engineering Mitigation at Lake level:

- Controlled drainage using siphon or pump systems, or spillways by constructing reinforced outlets to lower water levels without destabilizing the moraine dam. It reduces water pressure and increases freeboard which helps to prevent sudden dam bursts.
- Strengthening of Moraine Dams by using reinforcement to stabilize loose materials. Geotextiles or riprap can also be employed for added strength. This reduces the risk of sudden breaches in the moraine structure due to external forces.
- Controlled breaching of the moraine dam to reduce water pressure on the dam, regulating the flow and volume of downstream water.

Table 6.1. Different GLOF mitigation methods, their suitability and limitations

Method	Best Suited For	Limitations
Siphon/pump System	Small lakes; temporary or emergency risk reduction	Ineffective for large lakes or high-water volumes.
Constructing Spillways	Large lakes needing permanent risk mitigation.	Expensive, challenging to construct in remote and ecologically fragile areas
Strengthening Moraine	Long-te1rm stability of critical moraine dams.	Costly, labour-intensive, and time-consuming.
Controlled Breaching	Immediate risk reduction in emergencies; high-risk lakes.,	Risky and environmentally disruptive if not carefully managed.

The above mitigation measures have been adopted in various parts of the world. However, its success rate is yet to be fully ascertained as there is no standard yardstick to measure the extent of mitigation achieved.

Further, the above mitigation measures target to mitigate risk from lakes individually. This approach necessitates the categorization of high-risk lakes based on parameters defined by experts. However, due to the inherent complexity and variability of Glacial Lake outburst events, predicting such occurrences with certainty remains a significant challenge.

In addition, the location of Glacial lakes in extreme terrain, harsh climatic conditions, limited infrastructure, sparse data, and inaccessibility pose significant challenges to undertake such engineering measures. The dynamic nature of the glacial system combined with the increasing frequency of extreme weather events necessitates a more comprehensive approach.

B. Engineering Mitigation at Watershed level:

The mitigation measures at Lake Level address current risks associated with high-risk glacial lakes, they are not future-proof due to the dynamic and evolving nature of climate change. Accelerating glacial retreat may lead to the formation of new lakes, changes in lake dynamics, and the emergence of unforeseen threats. The increasing unpredictability of extreme weather events, seismic activity, and changes in hydrology further complicate long-term risk management. These measures primarily serve as short-term solution and may be recurring in nature. While they reduce the likelihood of catastrophic events in the near term, they do not offer a permanent solution to the growing threats posed by climate change.

Mitigating **Glacial Lake Outburst Floods (GLOFs)** at the **watershed level** involves addressing the entire hydrological system that is influenced by glacial lakes, their tributaries, and the surrounding environment. The watershed level approach recognizes the interconnectedness of glaciers, glacial lakes, moraine dams, downstream communities, and focuses on managing risks at a broader scale to reduce the impact of GLOFs. This comprehensive approach integrates structural, non-structural, and ecosystem-based measures to ensure long-term flood prevention and resilience.

The Engineering interventions at the watershed level are as follows:

1. Flood Protection Infrastructure

Once a GLOF occurs, the water can cause catastrophic downstream flooding. Engineering measures downstream of glacial lakes are essential to protect infrastructure and communities.

a. Flood Barriers and Levees:

- **Levees**: Earth embankments can be constructed along riverbanks or floodplains to redirect water away from communities and critical infrastructure. Levees are designed to withstand the force of the GLOF water, and their height can be determined based on the estimated floodwater levels.
- **Floodwalls**: In more urbanized areas, **concrete or steel floodwalls** can be constructed to protect infrastructure such as roads, bridges, and power stations from GLOF water.
- **Dikes and Dams**: In addition to levees, larger-scale **dams or dikes** can be built to capture and divert floodwaters before they reach populated areas. These structures can act as barriers to slow down or block the flow of water, storing it safely in reservoirs or diverting it to lower-risk areas.

b. Diversion Channels and Sediment Traps:

- **Diversion Channels**: Engineered channels or canals can be built to reroute floodwaters away from high-risk areas. These channels can direct water into safe zones, often through tunnels or open ditches.
- **Sediment Traps and Basins**: In addition to managing water, GLOFs can carry large amounts of debris and sediment. **Sediment traps** or **sedimentation basins** can be constructed downstream to capture and store sediment, preventing it from clogging rivers and watercourses and reducing the potential for secondary flooding or landslides.

c. Floodplain Zoning and Engineering Design:

- **High-risk Zoning**: For floodplains downstream from glaciers and glacial lakes, **zoning regulations** can be put in place to prevent the construction of critical infrastructure (e.g., homes, schools, hospitals) in high-risk flood zones. Where construction is necessary, buildings can be elevated, and foundations reinforced to withstand flooding.
- **Engineered Bridges and Roads**: Infrastructure like bridges and roads in flood-prone areas can be designed with **high water clearance**, reinforced to prevent washouts during flooding events, and built with **erosion-resistant materials**.

2. Hydrological and Hydraulic Modelling

a. Flood Modelling and Risk Mapping:

Before implementing engineering solutions, comprehensive hydrological and hydraulic models must be developed to simulate GLOF events. These models can help assess:

- The **volume of water** likely to be released in the event of a GLOF.
- The **flow dynamics** of the floodwater as it moves downstream.
- The **flooding extent** in various parts of the watershed, including impacts on infrastructure, agriculture, and communities.
- **Risk maps** can then be created to guide decision-makers in prioritizing mitigation actions.

b. Monitoring and Adaptive Management:

Engineering mitigation measures should be integrated into an adaptive management framework that incorporates regular **monitoring of glacier and lake dynamics** and ongoing **hydrological modelling** to reassess flood risk. Remote sensing, in-situ sensors, and ground surveys are essential to ensure that engineering interventions remain effective as conditions evolve.

3. Dam Construction and Modification

In some cases, large-scale dams may be necessary to control water flow from glacial lakes or mitigate the impacts of a GLOF.

a. Artificial Dams/Retention structures:

- In areas where moraine dams are deemed too unstable to reinforce effectively, **artificial dams/retention structures** can be constructed in downstream areas to control the flow of water and provide storage capacity for floodwaters. These dams are designed with flood routing systems to control peak water levels and prevent downstream flooding.

b. Dam Modification (for Existing Dams):

- **Raising Dam Height**: Existing dams in the watershed may need to be raised in height to accommodate larger flood volumes that could result from GLOF events.
- **Spillway Design**: Spillways are critical in managing the release of water during a flood event. Dams may require the installation of larger spillways or floodgates to safely release water during peak flow conditions.

4. Sediment and Debris Management

During a GLOF, large amounts of debris and sediment are often released, which can cause landslides, block waterways, and damage infrastructure. Engineering solutions to manage these materials are important.

a. Sediment and Debris Basins:

- **Sediment Basins**: Constructing **sediment detention basins** near glacial lakes can help trap and settle large amounts of debris before they move downstream, thus preventing infrastructure clogging and reducing the force of floodwaters.
- **Debris Flow Channels**: Engineering **debris flow channels** may be used to direct loose materials (e.g., rocks, ice, and sediment) away from populated areas and infrastructure. These channels are designed to safely direct debris flows into natural sediment deposits or controlled areas where they cause minimal damage.

5. Community Infrastructure and Resilience

Engineering strategies can also enhance the resilience of community infrastructure:

- **Elevated Infrastructure**: Buildings, roads, and bridges in flood-prone areas can be **elevated** above expected flood levels to minimize damage.
- **Flood-Resistant Building Techniques**: Infrastructure such as bridges and roads should be designed to withstand GLOF-induced floods, using **flexible materials** that can accommodate water flow or **reinforced materials** to prevent erosion and collapse.

While engineering solutions are essential for GLOF mitigation, they should be integrated into a broader **watershed management approach** that includes environmental, socio-economic, and regulatory measures. Effective GLOF mitigation at the watershed level requires continuous monitoring, community involvement, and collaboration between engineers, scientists, and local authorities. The engineering interventions should complement other measures like **early warning systems**, **disaster preparedness plans**, and **climate change adaptation strategies** to provide holistic and sustainable solutions for GLOF risk reduction.

As discussed above**, Retention structures** for Glacial Lake Outburst Flood (GLOF) mitigation is one of the engineering solutions aimed to manage, store, and redirect floodwaters in case of a moraine dam failure or rapid glacial lake outburst. These structures are intended to reduce the immediate impact of GLOFs on downstream areas, protect infrastructure and communities, and provide a buffer against catastrophic flooding. Retention structures work by capturing excess water, slowing down its flow, and allowing for a controlled release.

Further, the said structural intervention is usually located at valley level which is more favourable as compared to lake level intervention in terms of terrain, climatic condition, available infrastructure and accessibility. The location also ensures mitigation of multiple lakes located within its upper catchment area.

Retention structure at watershed level seems to be one of the more rationale and long-term solution to mitigate the impact of GLOF at a much broader level.

6.2. Dolma Sampa Retention Structure

The possibility of having a retention structure at Dolma Sampa is being actively explored by a multi-disciplinary team under the aegis of the Department of Science & Technology, Government of Sikkim. Numerous field expeditions have already been undertaken and field data have been collected and further expeditions are been planned.

Figure 6.1 Topography of Dolma Sampa

Dolma Sampa is positioned between Khora Chu Valley and Naku chu valley. There are two valleys in the area, the Goma valley through which Goma Chu flows and the Naku Valley through which Naku chu flows. The Goma valley spans approximately 3 kilometres in length and 1 kilometre in width, and the Naku Valley spans approximately 1 kilometre in length and 1/2 kilometre in width, both have a very mild bed slope.

From various reviews of the literature available on the South Lhonak GLOF event, and the numerous field verifications and Hydrodynamic Model studies conducted by the Department; it is clear that the Goma Valley played a very crucial role in the natural flood attenuation of the South Lhonak GLOF event. This location of the valley is about 22 kilometres downstream from South Lhonak Lake. The Goma Chu after taking a S-turn fans out to the Goma Valley for a width of 1 KM and length of 3 KM with a very minimal bed slope. Shortly thereafter, after about a Kilometre downstream, the river course takes a steep gradient with a narrow width.

The Hydrodynamic Model studies undertaken by the Department clearly shows that a very significant flood peak attenuation happened in the Dolma Sampa valley. The initial flood peak of 12000 to 12500 cumecs *(Refer to Chapter 5)* was attenuated to about 8500 to 9000 cumecs which is to the tune of about 40% attenuation. This is a very significant level of attenuation in such a short distance. It indicates that had this not happened the devastation downstream would have been to a much higher degree as the slope is towards the steeper side and the river valley much narrower thereafter. Therefore, the selected locations are already natural retention areas and a retention structure to further augment the retention capacity is most suitable in the Dolma Sampa Valley.

Table 6.2. River Hydro-morphometric characteristics in the proposed site for the retention structure

	Downstream Chainage (km) from Lake outlet				
River hydro-morphometric characteristics	**1**	**25**	**26 (PRS1)**	**27 (PRS2)**	**28**
Flood Inundation width (m)	77.4	1208	382	304	188
Max. Velocity (m/s)	19.30	7.65	8.58	9.37	8.46
Maximum flood Depth (m)	16.98	4.59	7.81	14.57	22.24
Maximum Discharge (m^3/s)	12173	9638	8737	8627	8520
Unit Stream power (Watts/ m^2)	100183	967	2337	2996	6725

(Refer to Chapter 5)

The Department of Mines & Geology undertook a post-GLOF debris deposition pattern study. This shows that higher-order debris like boulders and stones were found in the upper reaches of the valley and finer materials like coarse sand and silt were found towards the end of the valley. This debris deposition pattern indicates that the velocity of flow of the flood was greatly reduced in the valley. This further reinforces the justification for the location of the structure in the valley. *(Refer Figure 5.13)*

Further, the ERT studies carried out by the Mines & Geology Department indicates the absence of any dead Ice and Permafrost along the proposed axis of the structure at Goma Valley. However, this is subject to further detailed investigations in the proposed locations.

The Department has also carried out a study of Unit Stream Power (GLOF) in Goma Chhu. This indicates the amount of energy the water in a river or stream is exerting on the sides and bottom of the river along its flow path. It is seen that the Unit Stream Power is lowest from a distance of 22 to 28 Km from the South Lhonak Lake. The proposed locations of the Retention Structure are within this stretch. This also clearly indicates that there will be the least impact of the flood on the retention structure at this location. *(Refer Figure 5.9 & 5.10)*

From the above-mentioned facts, it seems justified to conclude that a retention structure at Dolma Sampa will cater to mitigate the impact of GLOF from the existing numerous lakes as well as lakes that may be formed in the future. This will do away the necessity for individual lake level intervention and seems to be the most viable measure.

Two alternate sites in Dolma Sampa, Option-1 at Goma valley and Option-2 about a Kilometre downstream, have been identified for the location of the retention structure.

Figure 6.2. Location of two alternate sites in Dolma Sampa, Option-1 at Goma valley and Option-2 about a Kilometre downstream

Table 6.3 The basic data of the two alternative sites.

Sl. No.	Particulars	Option - 1	Option - 2

1	Location	At Goma Valley in Dolma Sampa, positioned between the confluence of Goma Chu and Kora Chu and Langbuk Rock (Chainage 26)	One Kilometre downstream of Option-1, positioned between the confluence of Goma Chu and Kora Chu and the confluence of Goma Chu and Naku Chu (Chainage 27)
2	Location of Retention Structure Axis	27°52’36”N and 88°24’22”E	27°52’14.34”N and 88°24’58.70”E
3	Valley Length	3 Kms	Goma Valley - 3 Kms Naku Valley - 1 Kms
4	Valley Average Width	1 Km	Goma Valley - 1 Km Naku Valley – 1/2 Kms
5	Valley Average Slope	1 in 85	Goma Valley - 1 in 90 Naku Valley – 1 in 35
6	Number of lakes it caters to	138	183
7	Unit Stream Power	2337	2996

The final location is subject to further detailed investigations, analysis, design as well as Techno-economical studies by the experts.

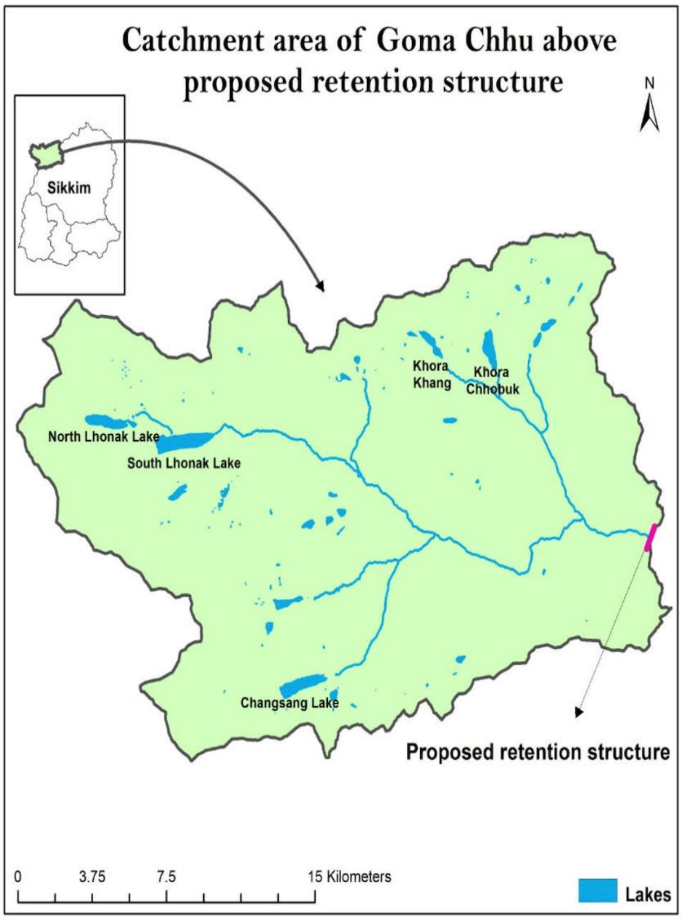
6.3. Option - 1 (Chainage 26)

This site offers highly favourable topography for the planned infrastructure. Additionally, the upstream watercourse features a S-shaped bend, which serves as a natural speed reduction feature, taking the first major impact of high-risk scenarios involving glacial lakes such as North Lhonak, South Lhonak and Changsang Lakes. This valley has a maximum retention capacity of about 400 MCM.

There are a total of 138 lakes that have a flow path that passes through Goma Chu Valley. Most of these lakes are currently not classified as high-risk lakes; however, due to the dynamic effects of climate change, they may present a significant threat in the near future. In addition, the said valley is well connected with the rest of the state via road network which makes the valley and site more feasible.

Figure 6.3: Proposed Axis for the Retention Structure at Location-1 in Dolma Sampa

Figure 6.4: Visualization of Maximum retention capacity of the valley for option 1



Total Catchment area	393 Sqkm
Total No Of Lakes	138
Lakes aboce 1 Hectares	56

Sl. No	Name Of Lakes/ Unnamed Lakes	Area (Ha)	Volume (MCM)
1	South Lhonak Lake	141	78.11
2	Changsang Lake	93	34.8
3	North Lhonak Lake	79	41.67
4	Khora Chhobuk	60	28.36
5	Khora Khang	34	15.38
6	East Langpo Lake	31	-
7	Green Lake	23	-
8	Khora Chyamnak	18	-
9	Unnamed Lake	14	-
10	Unnamed Lake	12	-
11	Unnamed Lake	12	-
12	Unnamed Lake	12	-
13	Unnamed Lake	10	-
14	Unnamed Lake	10	-
15	Unnamed Lake	8	-
16	Green Lake	8	-
17	Unnamed Lake	8	-
18	Unnamed Lake	8	-
19	Unnamed Lake	6	-
20	Unnamed Lake	6	-

Figure 6.5. Goma Chhu Watershed catering 138 glacial lakes

6.4. Option -2 (Chainage 27)

The second proposed site is located 1 km downstream of the location of Option-1. Downstream to this location, the flow path takes a steep gradient through a narrow gorge. The proposed axis lies at the confluence point of the Goma Chu and Naku Chu. The reservoir area of the proposed retention structure spreads into both the Goma Valley and the Naku Valley. In this location, the possible height of the structure and the retention capacity is immensely high.

The major advantage of this location is that in addition to the advantages offered by Option-1, this will also cater to the glacial lakes within the Naku watershed. The Naku watershed has an additional 45 lakes that have a flow path that passes through this location.

Figure 6.6 Proposed Axis for the Retention Structure at Location-2 in Dolma Sampa

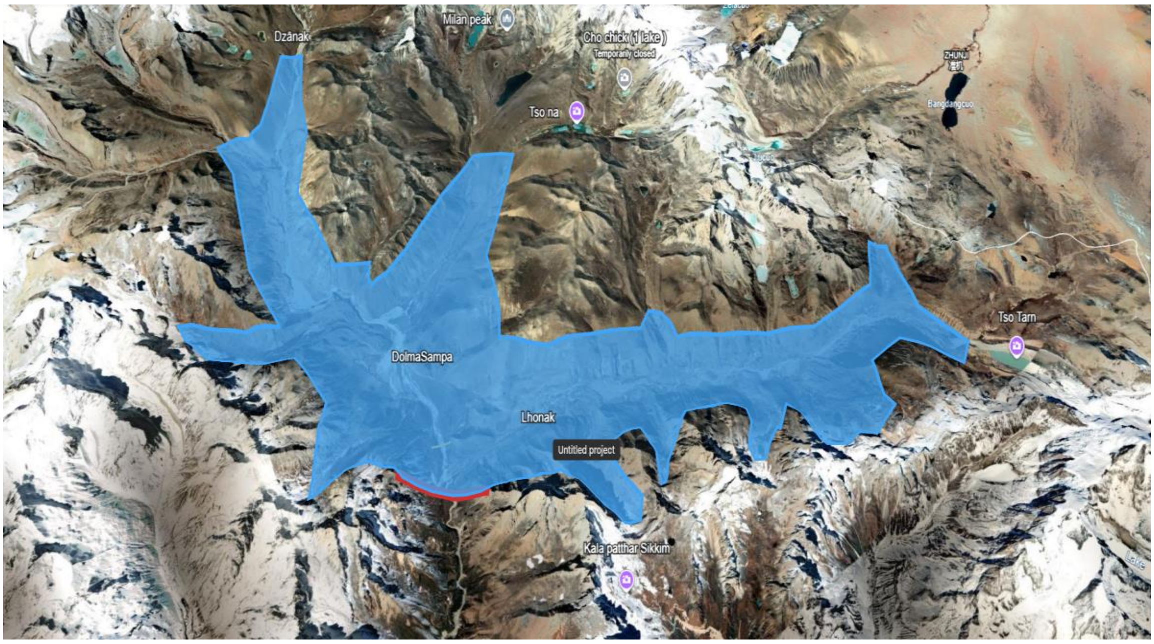
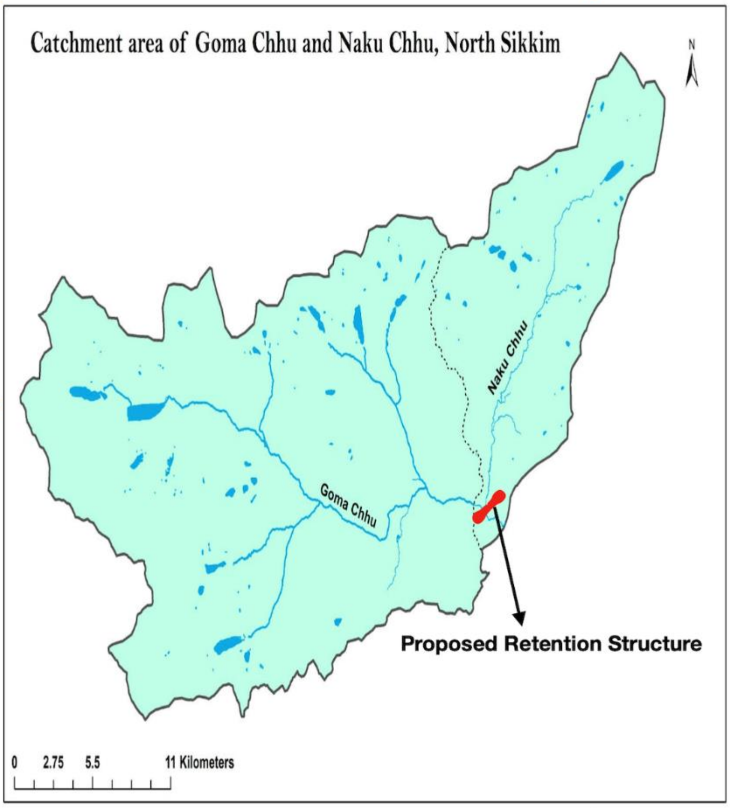


Figure 6.7 Visualization of Maximum retention capacity of the valley for option 2



Total Catchment area	498 Sqkm
Total No Of Lakes	183
Lakes aboce 1 Hectares	56

Sl. No	Name Of Lakes/ Unnamed Lakes	Area (Ha)	Volume (MCM)
1	South Lhonak Lake	141	78.11
2	Changsang Lake	93	34.8
3	North Lhonak Lake	79	41.67
4	Khora Chhobuk	60	28.36
5	Khora Khang	34	15.38
6	East Langpo Lake	31	-
7	Green Lake	23	-
8	Khora Chyamnak	18	-
9	Unnamed Lake	14	-
10	Unnamed Lake	12	-
11	Unnamed Lake	12	-
12	Unnamed Lake	12	-
13	Unnamed Lake	10	-
14	Unnamed Lake	10	-
15	Unnamed Lake	8	-
16	Green Lake	8	-
17	Unnamed Lake	8	-
18	Unnamed Lake	8	-
19	Unnamed Lake	6	-
20	Unnamed Lake	6	-

Figure 6.8 Goma Chhu and Naku Chhu watershed catering 183 glacial lakes

6.4. Conceptualization of the Retention Structure at Dolma Sampa

Flood mitigation retention structures store all or a portion of the flood waters in the reservoir, particularly during peak floods, and then release the water slowly. Typically, the principal use of such structures is to store a portion of the flood volume, to delay and attenuate flood peaks downstream.

The design of a retention structure for mitigating GLOF is a complex process and is a highly multi-disciplinary subject. The location of the structure at a very high altitude, harsh climatic conditions and limited data poses numerous engineering challenges in every stage.

Further, as these structures will have to tackle uncertain flood volume, very high debris and sediment load, higher impact forces, harsh climatic conditions and in addition, be able to function as a more self-reliant system as compared to the conventional dam, the design demands a much higher level of innovative engineering.

However, basic conceptualization considering the limited study and data available has been attempted which is subject to further adaptation of more complex parameters, design and expertise.

6.6. The Design principles of the Retention Structure should be as follows:

i. The structure should be able to withstand the impact of the GLOF.

ii. The structure should be able to withstand high Seismic forces.

iii. The structure should be able to withhold design volume of water for the designated time frame.

iv. The structure should be able to automatically release the design volume of water without human intervention and loss of time.

v. The structure should not disrupt the normal flow regime of the river.

vi. The structure should be able to cater to the debris and sediment load of the flood water.

vii. The structure should be able to withstand overtopping in case of flood event more than the design flood.

viii. The structure should be technically and financially feasible.

ix. The structure should require minimal monitoring and maintenance.

x. The Structure in the future, should be able to be converted to a reservoir at low cost and over a short period of time, if necessary.

6.7. Basic Considerations:

Sl.No	Particulars	Option-1	Option-2
1	Maximum Possible Retention Capacity	400 MCM	More than 20000 MCM
2	Maximum Possible Structure Height	90 meters	More than 300 mts
3	ERT result along the proposed Axis	No dead ice and permafrost present upto 16 mts depth	To be carried out
4	Proposed retention height	To be optimized	To be optimized
5	Volume proposed to be retained	To be determined after optimization of worst-case GLOF scenario.	To be determined after optimization of worst-case GLOF scenario.

6	Safe Discharge proposed to be released downstream	To be determined after further studies.	To be determined after further studies.

The feasibility of constructing a Retention Structure along the proposed locations is supported by the data presented above. However, further detailed analysis and validation are recommended to confirm its suitability. The data above indicates the following.

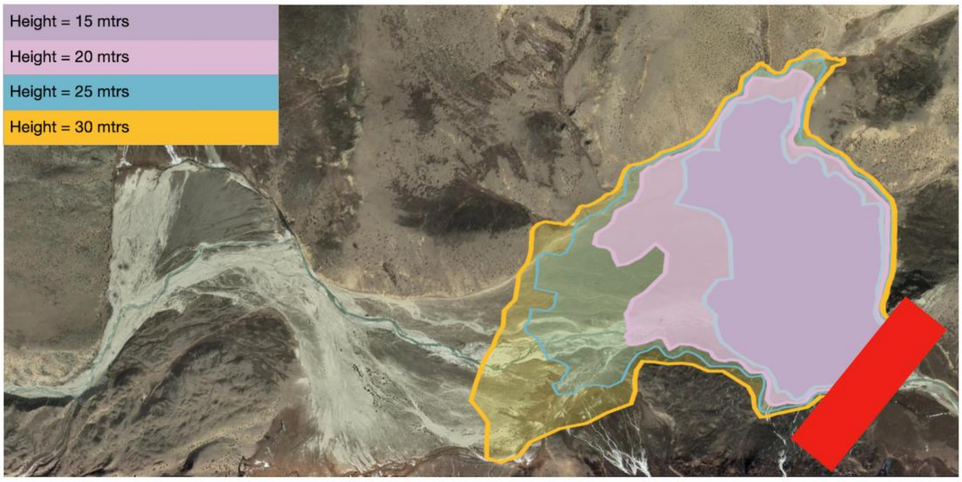
- The proposed valleys/basins have more than enough retention capacity to cater to the demand of GLOF event upstream.
- The debris deposition pattern and the modelled flood flow velocity supports the hypothesis that the flow velocity of the flood drastically reduced at the said valley. However, this needs to be validated further by more complex modelling studies.
- The ERT result shows bed rock at a depth of 16 mts for Option-1. It also shows the absence of permafrost and dead ice at the proposed site. This indicates the suitability of having a retention structure at the said site. However, further detailed geological investigation needs to be carried out.

The observed Highest Flood Marks, the capacity of the basin, and the possibility of high structure fulfil the target design requirements of the proposal. However, detailed modelling studies need to be carried out to validate the same and to study the effects of the same in the downstream stretch of the water way.

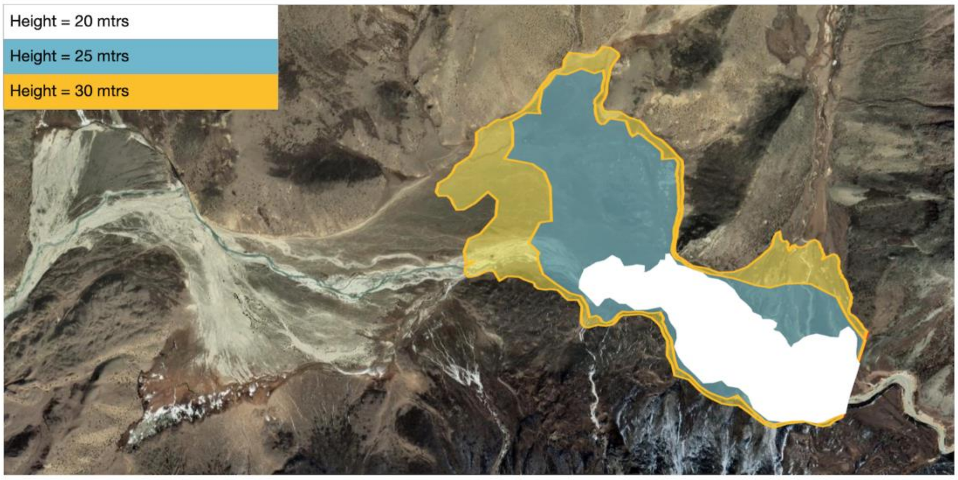
The South Lhonak Lake is the largest lake within the Goma Chu Catchment. It was observed that in the GLOF event of South Lhonak Lake on 3rd October 2024, the breach was to the tune of about 40% resulting in the release of about 40 MCM of flood water.

However, as the Glacial lakes are highly dynamic in nature, the future volume may vary greatly and is subject to further in-depth studies, analysis and optimization, based on which the structure may be designed. Further, the debris and sedimentation flow volume should also be taken into consideration after detailed studies and analysis.

A different retention scenario has been worked out using the Google Earth Engine for indicative purposes. The retention capacity and reservoir area with respect to the different heights of Retention Structures are as follows.



Sl.No	Length of the Structure axix (m)	Elevation of the bed level at structure axis	Elevation of the Top of Structure	Reservior Depth (m)	Reservior Area (Sqkm)	Total Volume (MCM)
1	410	4475	4490	15	1.04	14.60
2	440	4475	4495	20	1.56	29.90
3	460	4475	4500	25	2.06	50.00
4	570	4475	4505	30	2.61	76.30



Sl.No	Length of the Structure axix (m)	Elevation of the bed level at structure axis	Elevation of the Top of Structure	Reservior Depth (m)	Reservior Area (Sqkm)	Total Volume (MCM)
1	320	4460	4480	20	0.73	13.30
2	470	4460	4485	25	1.56	37.50
3	550	4460	4490	30	2.06	59.80

6.8. GLOF Kavach – 1

The 1st GLOF Kavach as shown in Figure 6.9, has been conceived taking into consideration the following:

- Use of local material such as boulders and stones, mostly available locally.

- Flow through using multiple pipes to cater to normal flow as well controlled discharge during flood events.
- Gabion core with Concrete lining to withstand the impact of debris and enhance the overtopping capacity.
- Upstream and downstream aprons have been provided in concrete to prevent heel and toe scouring

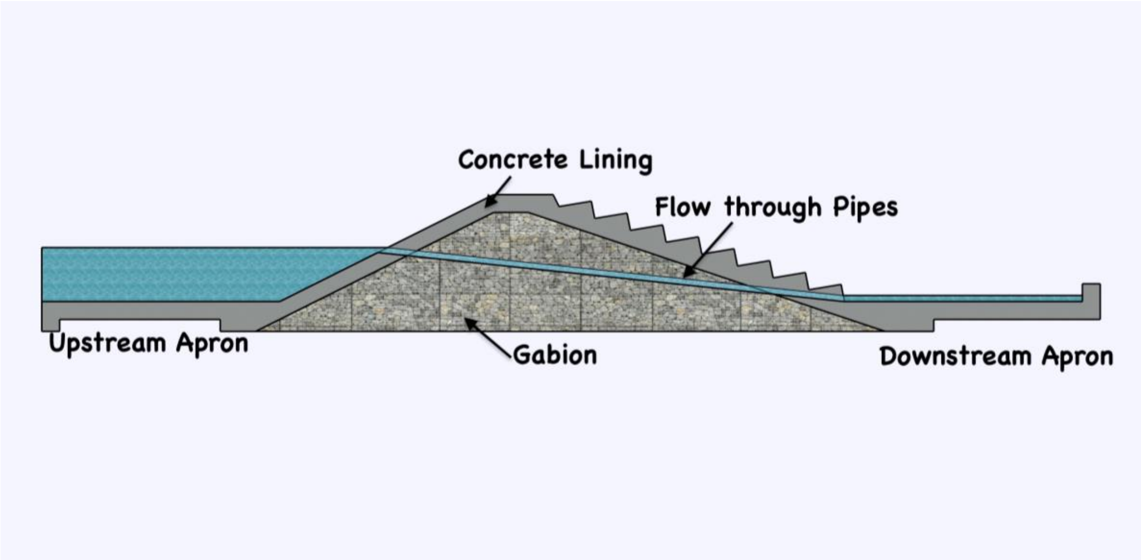


Figure 6.9: Cross-sectional view of GLOF Kavach 1

However, this concept raises some challenges as listed below:

- Financial implication due to the use of concrete lining throughout the length of the structure.
- Technical challenge of taking pipes through rockfill structure without leakages, overburden weight above the pipes.
- Choking of pipes due to siltation during flood events leading to major design failure as a flow-through structure. Further, the pipes are prone to the effects of corrosion, wear and tear.
- Challenges in maintaining the normal flow regime of the river flow during non-flood time, due to the pipes being raised from the ground level to maintain hydraulic head, if necessary.
- There is no scope of partial failure of the structure in any possible scenarios.

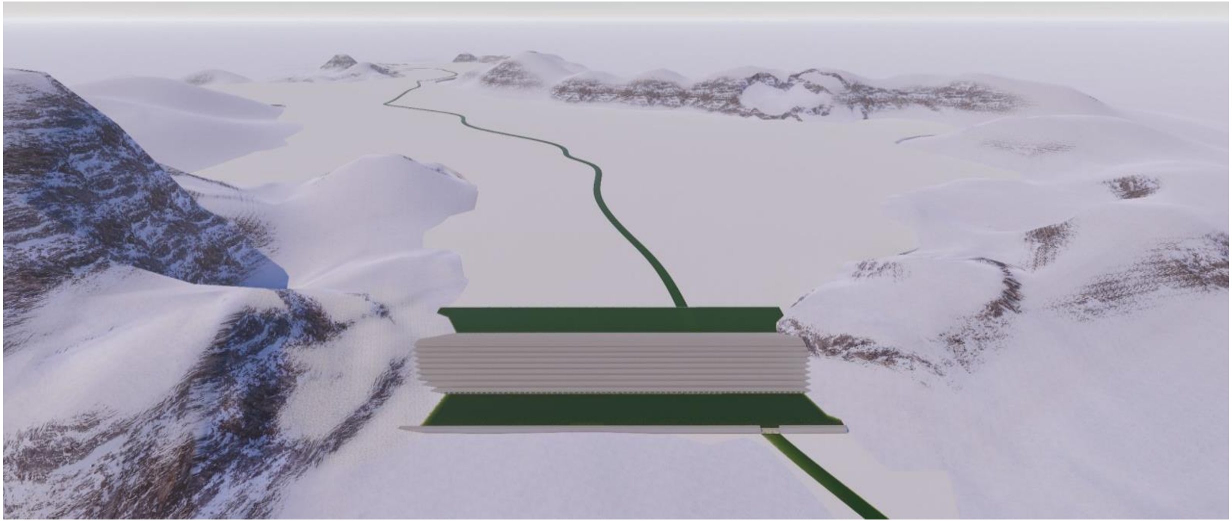


Figure 6.10: Representative pictures of GLOF Kavach -1 of Retention Structure at Dolma Sampa during Normal flow regime

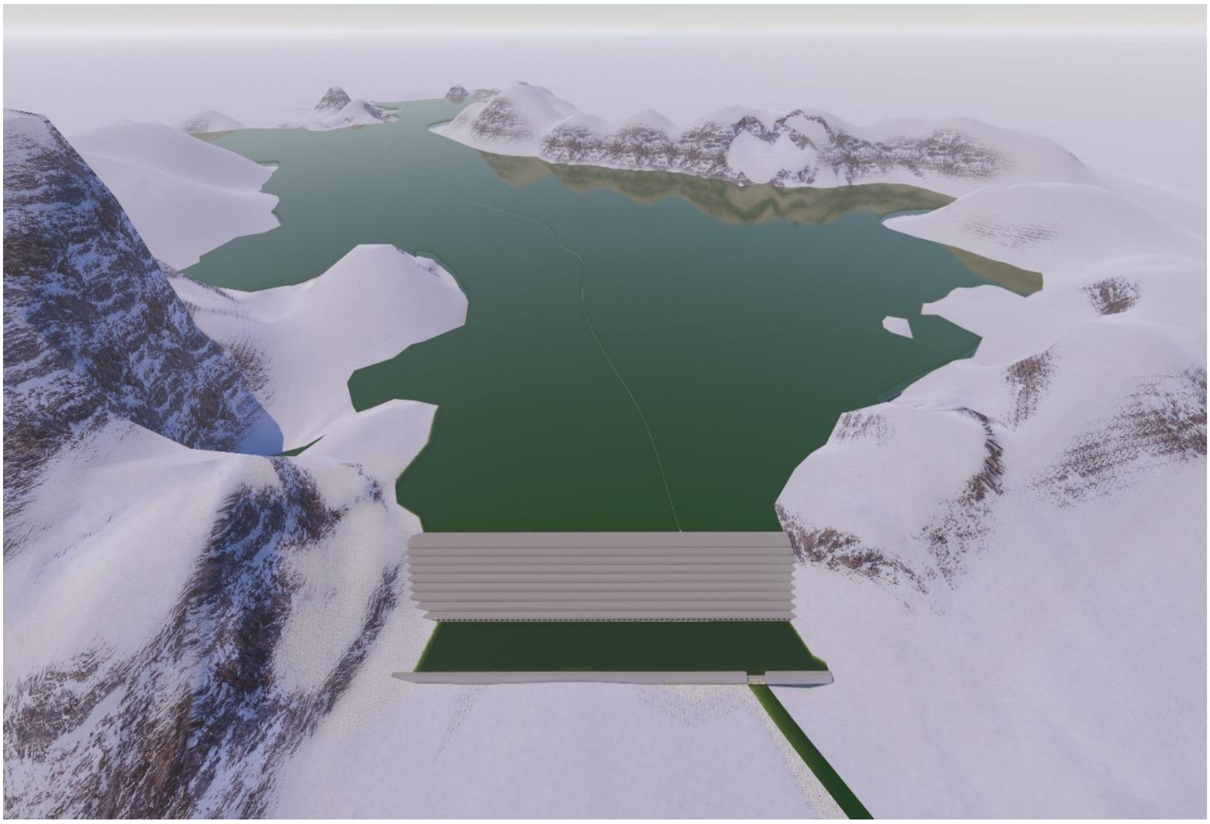


Figure 6.11: Representative pictures of GLOF Kavach -1 of Retention Structure at Dolma Sampa during GLOF event

6.9. GLOF Kavach -2

To overcome the above-mentioned challenges, some modifications in the GLOF Kavach -1 was incorporated and the GLOF Kavach -2 was worked out.

The justifications for the same are as follows:

- The use of flow through pipes has been replaced by Triangular notche. This will maintain the natural flow through regime of the river as well as eradicate the possibility of any choking due to debris and silt. Further, this resolves the issue of taking pipes through the rockfill structure without leakages, overburden weight above it.
- The Rectangular notche will act as isolation joints segregating the structure into parts, ensuring only partial failure during unprecedented flooding.
- The end segments have been raised and the overtopping is allowed only through the middle segments to reduce the volume of concrete lining. This will also allow additional flood water to flow through only these segments in case the discharge exceeds the design discharge.

The GLOF Kavach -2, resolves almost all the issues raised in the GLOF Kavach -1. However, this concept also has some challenges as enlisted below:

- The size of the notch may have to be restricted for small release if required by flood modelling and optimization. This may not be possible if the outflow discharge required is too small

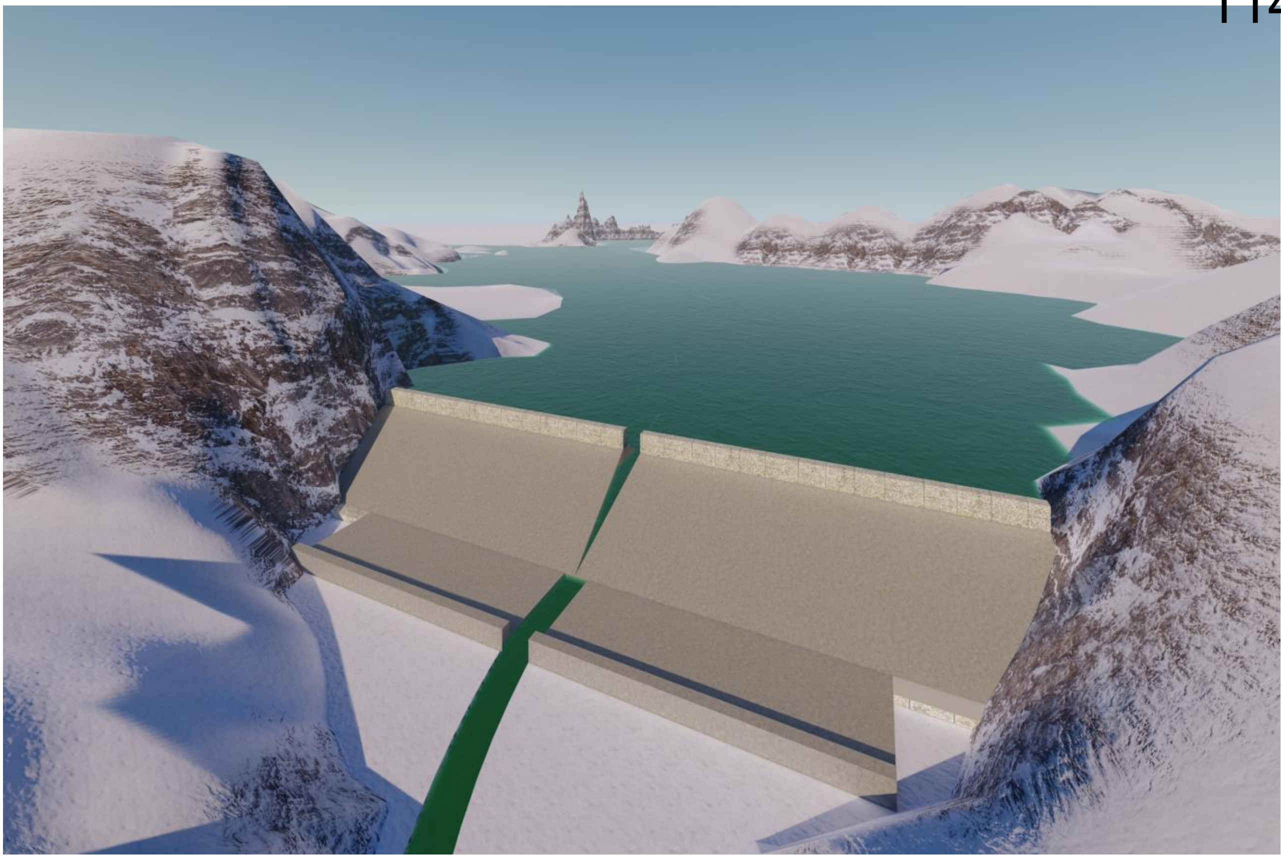


Figure 6.14: Representative pictures of GLOF Kavach-2 of Retention Structure at Dolma Sampa during Normal flow regime

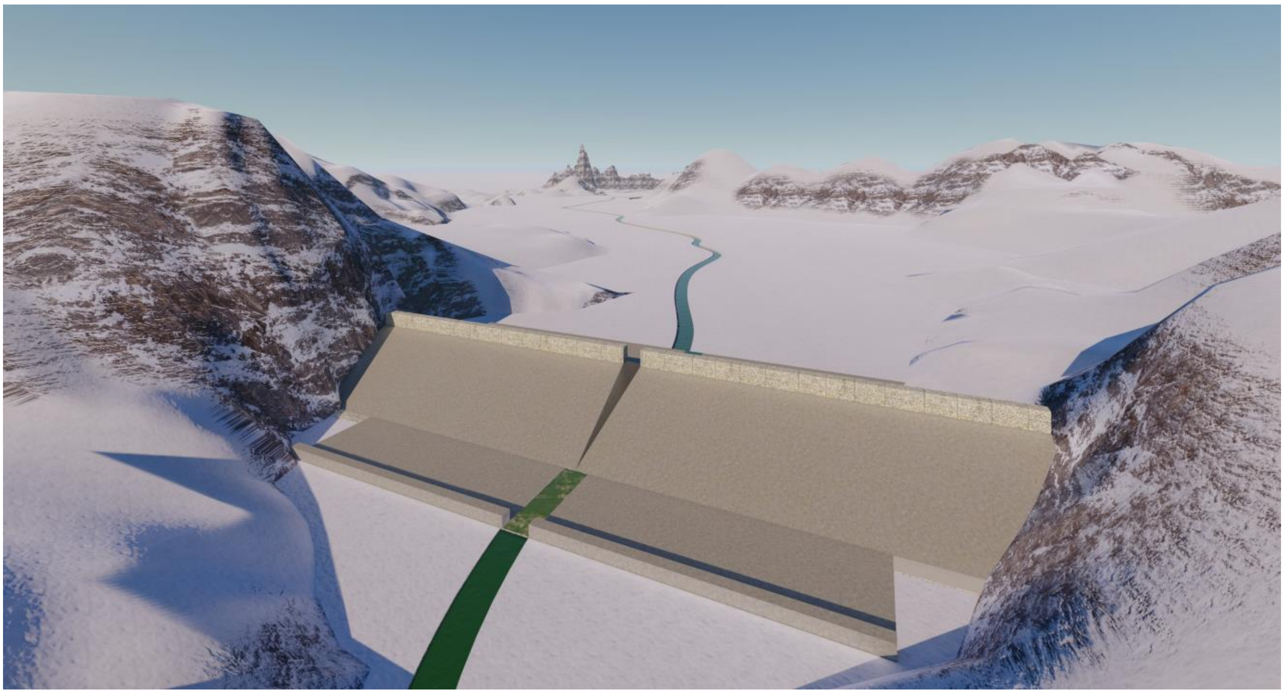


Figure 6.15: Representative pictures of GLOF Kavach-2 of Retention Structure at Dolma Sampa during Normal flow regime

6.10. GLOF Kavach-3

To overcome all the challenges raised above by the two designs, further modifications are deemed to be necessary as small flow demands opening in the structure itself which is only possible in concrete structures.

- The Gabion Core of GLOF Kavach -1 is proposed to be replaced by using Preplaced Aggregate Concrete.
- This will facilitate the halving of opening in the structure using pipes at river bed level to allow normal flow as well as design discharge during flood event.
- This will also allow the overtopping of the dam in case of extreme events if necessary. The structure will have to be designed for the same.
- Construction joint/failure joint to be provided to facilitate segment failure.
- A single large pipe instead of multiple pipes has been proposed to avoid choking of the pipe due to sediment.

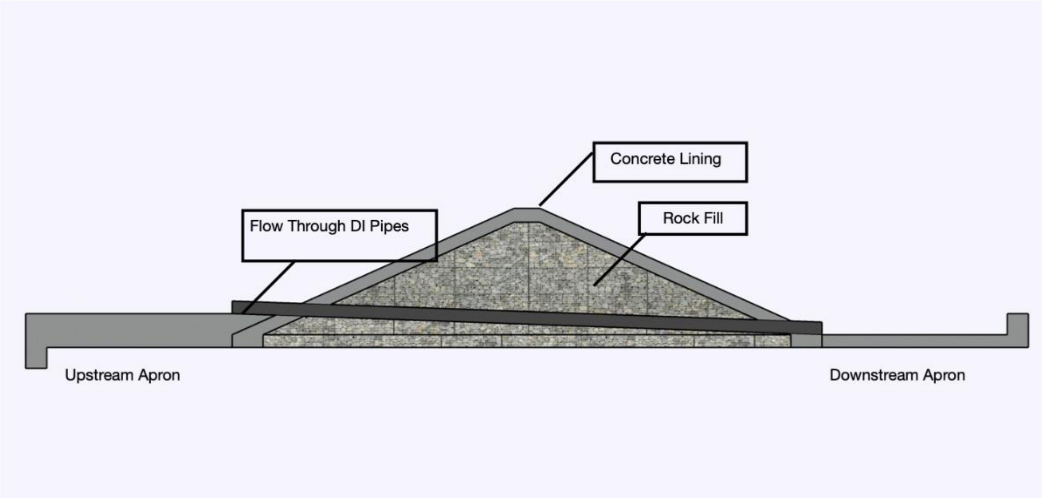


Figure 6.16: Cross section Of GLOF Kavach 3

However, this concept also raises some challenges as enlisted below:

- Transportation of pipes to the site is a big challenge.
- Huge amount of concrete has to be used at a very high altitude.

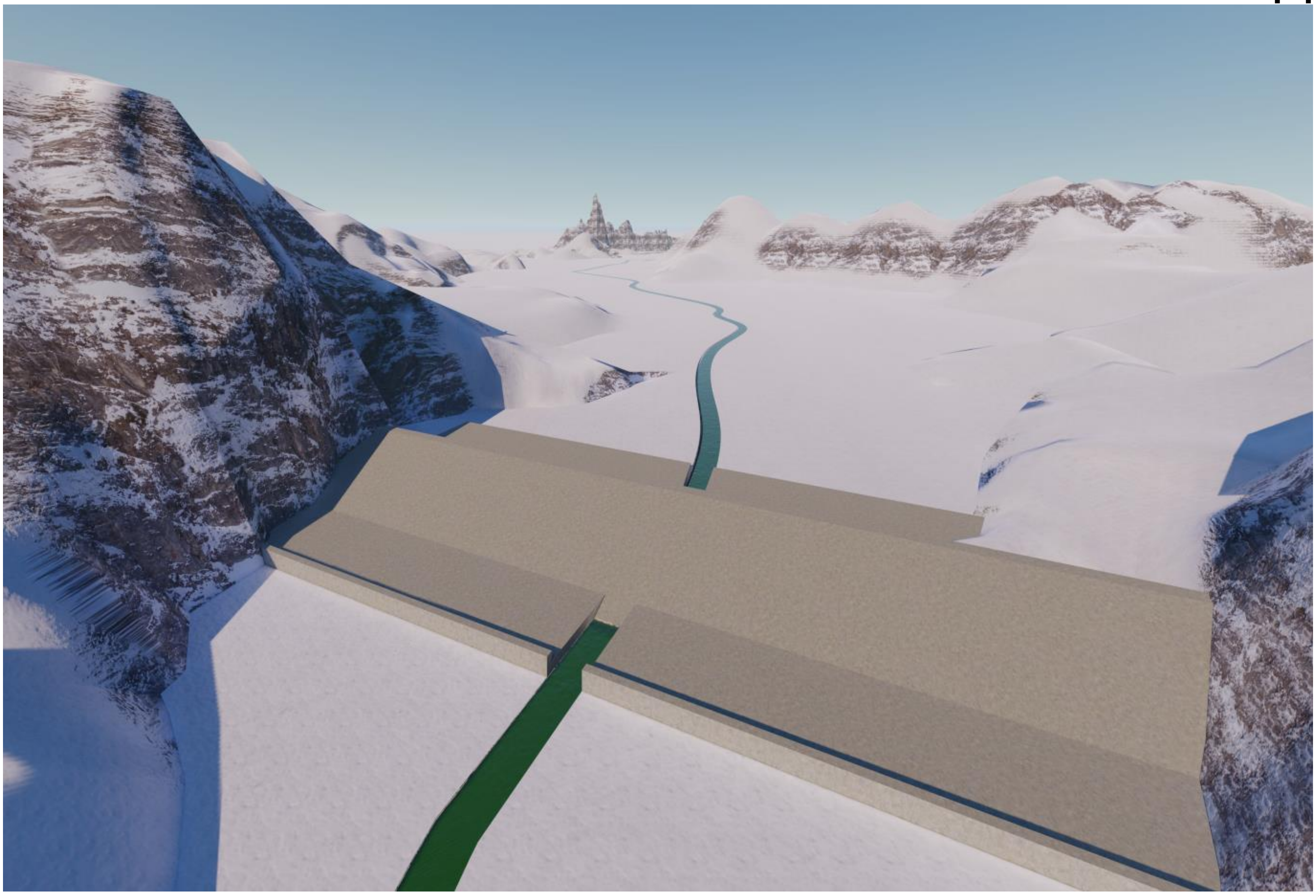


Figure 6.17: Representative pictures of GLOF Kavach-3 of Retention Structure at Dolma Sampa during normal flow

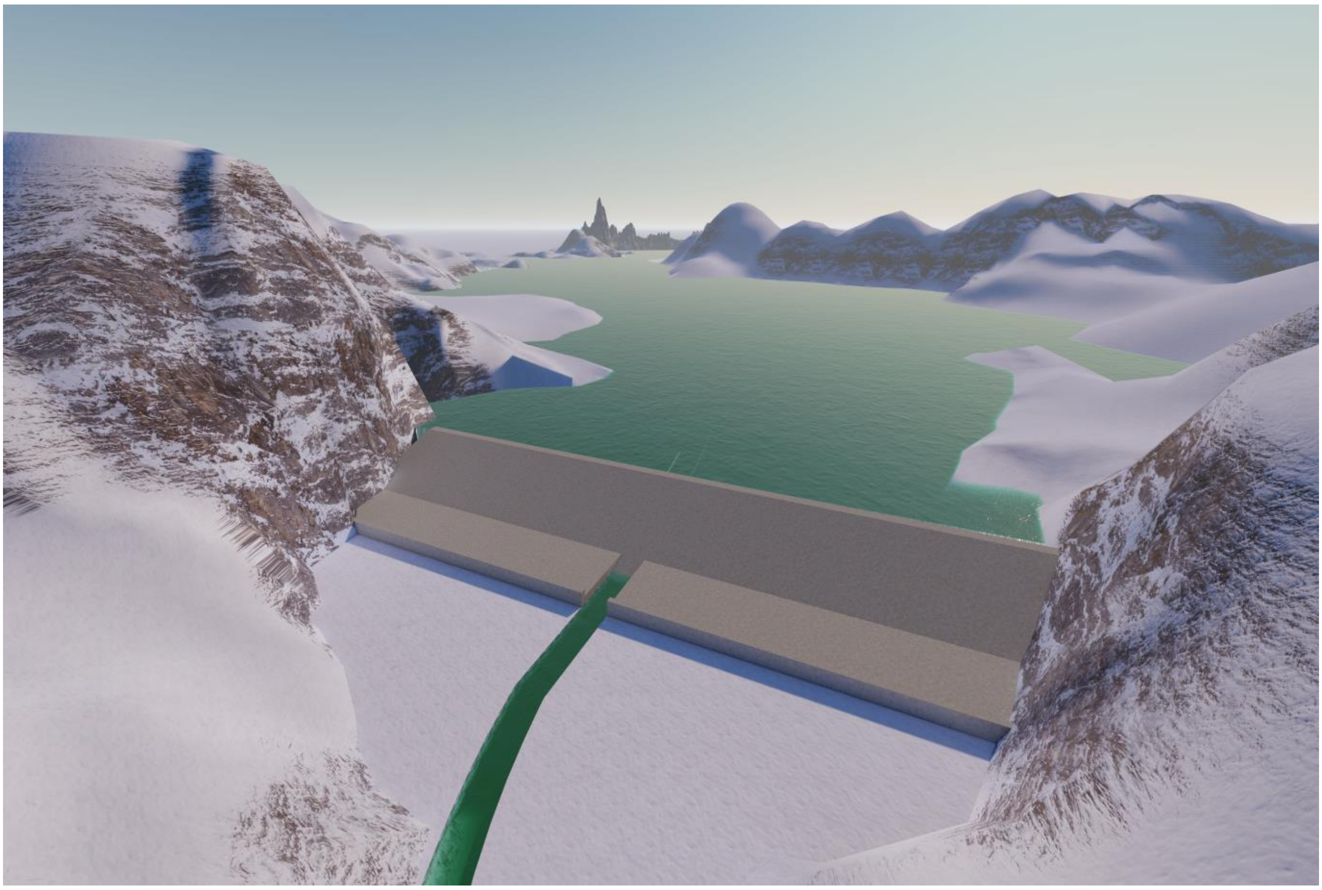


Figure 6.18: Representative pictures of GLOF Kavach-3 of Retention Structure at Dolma Sampa during GLOF

It may be noted that the above concept structures are concepts that may be possible to be further explored. These are subject to further detailed design, modifications, and refinements by competent experts and as per the standard industry practices.

The actual engineering design can only be undertaken after further vigorous investigations and the involvement of subject experts.

The following are some of the many studies and investigations that will have to be undertaken:

- Further Hydrometeorological and lake volume studies.
- Determination of future lake volumes and possible GLOF volumes.
- Determination of optimum retention volume.
- Determination of optimum release discharge.
- Hydrodynamic modeling of the future flood volume of the worst-case scenario.
- Downstream flood inundation studies.
- Detailed geological investigations, especially along the Retention Structure axis.
- Detailed river and valley morphological studies.
- Detailed Techno-economic studies.

It may be noted that the intend to attempt to show that a Retention Structure is not only possible in the proposed locations, but may be the only viable solution to mitigate the risk of future GLOF events in a broader scale. If successful, this mitigation strategy can be replicated not only in Sikkim but throughout the Himalayan belt as well as in other parts of the world.

However, the competent subject experts, as well as the country's institutions, need to come together to devise a viable design of the Retention Structure that not only absorbs the GLOF but is also feasible to construct, operate, and maintain at such a high altitude.

6.11. Implementation Strategy

Implementing a project in high-altitude regions, such as glacial lake mitigation, presents unique challenges due to the extreme terrain, harsh climatic conditions, and logistical constraints. The plan focuses on a phased approach combining careful planning, robust engineering, and community engagement to ensure safe and effective execution. This outlines the detailed steps, resource allocation, and strategies to overcome the challenges posed by the high-altitude environment.

6.12. Phased Approach to Implementation

6.12.1 Phase 1: Pre-Implementation Planning

This phase involves detailed surveys, risk assessment, and preparation to set a strong foundation for the project.

- Risk Identification: Prioritize high-risk lakes using geospatial data, field surveys, and remote sensing technologies.
- Site Assessment: Conduct thorough site evaluations, including site stability, water volume, and downstream vulnerability.
- Environmental and Social Impact Assessment (ESIA): Assess potential impacts on the ecosystem and communities to minimize negative consequences.
- Logistics Planning: Identify accessible routes for transporting materials and equipment. Set up temporary base camps equipped with high-altitude medical support and essential supplies.

6.12.2. Phase 2: Mobilization of Resources

- Material and Equipment Transport: Use helicopters, pack animals, or high-altitude vehicles to transport lightweight and modular equipment to the site.
- Workforce Deployment: Employ trained personnel with high-altitude experience, supported by local workers familiar with the terrain. Conduct acclimatization programs to prepare the workforce for altitude-related challenges.

6.12.3 Phase 3: Construction and Execution

The construction phase focuses on implementing mitigation measures based on site-specific requirements. In doing so it becomes very important to focus on the safety of the workers.

- Safety Protocols: Implement stringent safety measures to address potential hazards such as avalanches, landslides, and extreme weather. Maintain communication links with downstream communities and emergency response teams.

6.12.4 Phase 4: Testing and Commissioning

- System Testing: Test the systems under controlled conditions to ensure functionality and stability.
- Inspection and Certification: Conduct a final inspection of all structures and certify them for operational safety.

6.12.5 Phase 5: Post-Implementation Monitoring and Maintenance

- Routine Monitoring: Install sensors and remote monitoring equipment to track water levels, dam stability, and environmental conditions.
- Periodic Assessment: Schedule regular site visits to evaluate the performance of implemented measures and address emerging issues.

6.13. High-Altitude Challenges

6.3.1. Harsh Climate

- Plan work schedules to avoid peak winter months and high precipitation periods.
- Use weather-resistant materials and ensure that all equipment is functional in sub-zero temperatures.

6.13.1 Workforce Health and Safety

- Provide high-altitude training, medical support, and adequate rest periods to prevent altitude sickness.
- Equip teams with communication devices and GPS trackers for enhanced safety.

This implementation plan combines meticulous preparation, adaptive engineering, and efficient resource management to address the unique challenges of high-altitude operations. By adopting a phased approach and leveraging local expertise, the project aims to deliver effective and sustainable solutions to mitigate the risks posed by glacial lake outburst floods.

6.14. Indicative Cost of Project

GLOF KAVACH - 1								
SL NO	PARTICULARS	HEIGHT (in mtrs)	LOCATION 1			LOCATION 2		
			RETENTION CAPACITY (in MCM)	LENGTH (in mtrs)	AMOUNT (₹ IN CRORE)	RETENTION CAPACITY (in MCM)	LENGTH (in mtrs)	AMOUNT (₹ IN CRORE)
1	FLOW THROUGH RETENTION STRUCTURE - OPTION -1	20	29.9	440	₹ 1180.00	13.3	320	₹ 860.00
		25	50	460	₹ 1350.00	37.5	470	₹ 1380.00
		30	76.3	570	₹ 1820.00	59.8	550	₹ 1750.00

GLOF KAVACH - 2								
SL NO	PARTICULARS	HEIGHT (in mtrs)	LOCATION 1			LOCATION 2		
			RETENTION CAPACITY (in MCM)	LENGTH (in mtrs)	AMOUNT (₹ IN CRORE)	RETENTION CAPACITY (in MCM)	LENGTH (in mtrs)	AMOUNT (₹ IN CRORE)
1	FLOW THROUGH RETENTION STRUCTURE OPTION -2	20	29.9	440	₹ 1050.00	13.3	320	₹ 760.00
		25	50	460	₹ 1210.00	37.5	470	₹ 1230.00
		30	76.3	570	₹ 1600.00	59.8	550	₹ 1550.00

GLOF KAVACH - 3								
SL NO	PARTICULARS	HEIGHT (in mtrs)	LOCATION 1			LOCATION 2		
			RETENTION CAPACITY (in MCM)	LENGTH (in mtrs)	AMOUNT (₹ IN CRORE)	RETENTION CAPACITY (in MCM)	LENGTH (in mtrs)	AMOUNT (₹ IN CRORE)
1	FLOW THROUGH RETENTION STRUCTURE OPTION -3	20	29.9	440	₹ 1070.00	13.3	320	₹ 800.00
		25	50	460	₹ 1230.00	37.5	470	₹ 1240.00
		30	76.3	570	₹ 1500.00	59.8	550	₹ 1470.00

Apart from the quantifiable losses accounted for above, there exist unmeasurable losses that carry significant implications. These include:

1. National Security Risks: Potential threats arising from structural vulnerabilities or failure of critical infrastructure, which can jeopardize the safety and sovereignty of the region.
2. Retrofitting of Downstream Structures: Additional expenses and challenges associated with upgrading or modifying downstream structures to adapt to changes caused by the project.
3. Loss of Human Lives: The catastrophic impact of GLOF, which cannot be adequately represented in financial terms.
4. Environmental and Ecological Damage: Irreversible harm to ecosystems, loss of biodiversity, and disruption of natural water flow patterns.
5. Cultural and Social Impact: Displacement of communities, loss of heritage sites, and long-term socio-economic challenges.
6. These intangible losses highlight the need for a more comprehensive evaluation of this proposal, ensuring that decisions are not solely based on financial metrics but also consider long-term societal and environmental consequences.

These intangible losses highlight the need for a more comprehensive evaluation of this proposal, ensuring that decisions are not solely based on financial metrics but also consider long-term societal and environmental consequences.

From the above, it can be inferred that having a Retention Structure at Lhonak Valley, has a high potential of being feasible, and the idea seriously needs to be further pursued.

Mitigating GLOF is a very challenging and complex subject that is still in a very nascent phase. The Concept Design above is intended to show a path to kickstart a journey towards broad mitigation of GLOF, which otherwise will be a major hazard to the people living in the Himalayas.

6.15. A Way Forward.

This report provides a preliminary assessment of glacial lake outburst floods (GLOFs) and their associated risks. It is important to emphasize that the concepts and approaches discussed are based on initial studies conducted by engineers without prior experience designing structures to mitigate such events. Therefore, it is imperative to involve subject experts with proven expertise in this domain to refine the designs and strategies.

A comprehensive hydrological modeling effort is essential to understand the effects of a potential GLOF event fully. Such modeling would enable more accurate prediction of flood paths, velocities, and the extent of inundation, which are crucial for planning mitigation measures and emergency response strategies.

It is also worth noting that no similar project has been implemented in the country, making this endeavor both challenging and groundbreaking. The lack of precedent underscores the need for meticulous planning, robust research, and iterative design processes informed by global best practices.

Moving forward, integrating advanced technologies, such as remote sensing and predictive modelling, alongside traditional engineering methods will be key. Moreover, fostering collaboration among the best engineers, scientists, policymakers of the country, and local communities will ensure a holistic approach to effectively addressing GLOF risks.

Lastly, the mitigation of GLOF should be given national importance as most of the country's glacial lakes lie in border areas and have the potential to wipe out infrastructure involving national security. Therefore, with climate change and the possibility of increased frequency and intensity of GLOF events, the nation's best brains need to join hands and come up with an effective solution.

7 Social benefit cost analysis

7.1 Socio benefit Cost Analysis

The Social Benefit-Cost Analysis (SBCA) is a method that determines the future risk reduction benefits of a hazard mitigation project and compares those benefits to its costs. The benefits to be accrued from the project are assessed as the prevention of damage. This prevention of damage was assessed based on the damage caused by the 2023 Lhonak glacial flood. This damage was again assessed based on the Post Disaster Needs Assessment (PDNA) report of the State Government. Also, information was collated from NHPC, the Border Roads Organization, and the Tourism Department. This assessment of the damage is on the lower side as only those impacts that could be quantified and had an authentic base were covered, while others, such as damage to private property and businesses, and others, are not accounted for adequately here. Also, only short-term and direct impacts have been documented.

Table 7.1: Damage caused by the glacial flood of 2023

		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**	

Also, after the 2023 Lhonak glacial flood, the border population and defense forces faced immense difficulties due to the absence of connectivity for several months. The benefits of a GLOF risk mitigation structure regarding defense preparedness and sentiments of the border population will be priceless, outweigh the monetary expenditures involved. Hence, this project does not just cater to mitigation efforts against natural disasters but has enormous implications for the economic development of border areas and safeguarding our territorial integrity and sovereignty.

8 Risks and uncertainties

GLOF risk mitigation is challenging due to the following unique aspects of this intervention:

- **GLOF mitigation science is still evolving:** GLOF research primarily focuses on understanding the characteristics and processes that lead to GLOFs, assessing the hazards and risks associated with individual glacial lakes, modeling the entire chain of processes involved, and comprehending their impacts (Hrebrina 2023). There is a need for more systematic investigations, technical guidelines, and studies on the hydraulic dimensioning of structural measures (Hrebrina 2023). The science behind glacial flood mitigation is still evolving and has yet to reach a stage where it can fully inform policy and practice. Given the urgency of disaster mitigation, we are adopting a 'learning by doing' approach, where practical experiences will inform future policies and practices.

- **GLOF DRR is still in the early stages:** GLOF mitigation measures are being implemented for the first time in the country. Hence, there is no existing typology for classifying glacial lake hazards or a corresponding SOP for GLOF mitigation. This project aims to develop both. The maturity of science and technology to develop and implement robust solutions to glacial flood DRR is still in the early stages. This will be amongst the first GLOF DRR projects in the country to demonstrate watershed-level and lake-level approaches, to standardize these approaches. The project interventions will serve as proof of concept (POC), helping to standardize mitigation measures. Some interventions will work, others will not, but the learnings will help make future interventions more effective.

- **Challenges in deploying personnel and technology:** The remote mountain areas create harsh working conditions in high elevations. The area of operation presents unique challenges, including high elevations of 5,000 meters, extreme cold, high ultraviolet radiation, and low oxygen levels, which complicate the deployment of personnel and technological interventions. The thinner atmosphere at high altitudes makes it harder to breathe in the same amount of air. These conditions can cause altitude sickness and other health issues, requiring the technical team to exhibit both physical and mental resilience. Deploying technologies, equipment, and machinery in the challenging high-altitude setting presents challenges in cost-effectiveness, standardization, context awareness, middleware, data analytics, fault tolerance, run-time analytics, and trusted model design. The main barrier to using technology is the extreme logistical complexity due to difficult access to some glacial lakes (ADB 2014). Lake-lowering projects often occur in remote areas with steep inclines nearly impassable by large machinery. Concerns about the possibility of heavy equipment toppling over on the steep slopes surrounding the Thorthormi and Raphstreng lakes in Bhutan led to manual labor and low-tech tools in these projects (NASA 2009). A lack of a cellular network makes coordination, connectivity, real-time data sharing, and monitoring the functioning of technological interventions challenging. This restriction impacts the effectiveness of early warning systems, emergency communication, and on-ground coordination, especially in disaster-prone areas.

9 References

ADB (2014). Technologies to Support Climate Change Adaptation in Developing Asia, Asian Development Bank, Nov 2014. http://hdl.handle.net/11540/3312

Allen, S. K., Linsbauer, A., Randhawa, S. S., Huggel, C., Rana, P., & Kumari, A. (2016). Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. *Natural Hazards*, *84*, 1741-1763.

Bagnold, R. A. (1966). An approach to the sediment transport problem from general physics. United States Geological Survey Professional Paper. 422-I, 1 – 37.

Bajracharya, S. R. 2009. Glacial Lake Outburst Floods Risk Reduction Activities in Nepal. Presented at the Asia-Pacific Symposium on New Technologies for Prediction and Mitigation of Sediment Disasters. Japan Society of Erosion Control Engineering (JSECE). Tokyo. 18–19 November.

Bolch, T., Shea, J.M., Liu, S., Azam, F.M., Gao, Y., Gruber, S., Immerzeel, W., Kulkarni, A., Li, H., Tahir, A., Zhang, G., Zhang, Y., Bannerjee, A., Berthier, E., Brun, F., Kääb, A., Kraaijenbrink, P., Moholdt, G., Nicholson, L., Pepin, N. & Racoviteanu, A., (2019) Status and change of the cryosphere in the Extended Hindu Kush Himalaya Region in P Wester, A Mishra, A Mukherji & AB Shrestha (eds), *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People.* Springer: 209-255. https://doi.org/10.1007/978-3-319-92288-1_7

Das, S., Das, S., Mandal, S. T., Sharma, M. C., & Ramsankaran, R. (2024). Inventory and GLOF susceptibility of glacial lakes in Chenab basin, Western Himalaya. *Geomatics, Natural Hazards and Risk*, *15*(1), 2356216.

Department of Mines and Geology (2023). Preliminary geological observation report along the banks of Teesta riverTeesta River from Chungthang, Mangan district to IB M, Rangpo, Pakyong district post flash flood of 4th October, 2023, Department of Mines and Geology, Gangtok, Sikkim.

East Mojo (2023). Sikkim floods: Chungthang gets bamboo bridge after 5 days, hundreds rescued. https://www.youtube.com/watch?v=-wzQvsm_p9U Accessed on January 13, 2025

Emmer, A. Understanding the risk of glacial lake outburst floods in the twenty-first century. *Nat Water* **2**, 608–610 (2024).

Froehlich D.C. (1995b). Peak Outflow from Breached Embankment Dam. *Journal of Water Resources Planning and Management*, 121(1), 90-97.

Froehlich D.C. (1995b). Peak Outflow from Breached Embankment Dam. *Journal of Water Resources Planning and Management*, 121(1), 90-97.

Froehlich, David C., (1995a). Embankment Dam Breach Parameters Revisited. Water Resources Engineering, Proceedings of the 1995 ASCE Conference on Water Resources Engineering, San Antonio, Texas, August 14-18, 1995, 887-891.

Froehlich, David C., (1995a). Embankment Dam Breach Parameters Revisited. Water Resources Engineering, Proceedings of the 1995 ASCE Conference on Water Resources Engineering,San Antonio, Texas, August 14-18, 1995, 887-891.

Gouli, M. R., Hu, K., Khadka, N., & Talchabhadel, R. (2023). Hazard assessment of a pair of glacial lakes in Nepal Himalaya: unfolding combined outbursts of Upper and Lower Barun. *Geomatics, Natural Hazards and Risk*, *14*(1), 2266219.

Gupta, M.D. (2023). How an alert ITBP jawan on duty 8 km away from South Lhonak lake raised 1st flood alarm in Sikkim. The Print, October 10, 2023 06:08 PM IST. https://theprint.in/india/how-an-alert-itbp-jawan-on-duty-8-km-away-from-south-lhonak-lake-raised-1st-flood-alarm-in-sikkim/1797562/

Haeberli, W., Schaub, Y., and Huggel, C. (2017). Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. 293.

Hrebrina, J., Conevski, S., & Pummer, E. (2023). Review of Structural Mitigation Measures for Glacial Lake Outburst Floods, Proceedings of the 40th IAHR World Congress (Vienna, 2023). https://doi.org/10.3850/978-90-833476-1-5_iahr40wc-p0999-cd

ICIMOD. (2019). *Managing Glacial Lake Outburst Flood (GLOF) Risks in Bhutan.* Retrieved from ICIMOD Publications.

Lecce, S.A. (1997). Nonlinear Downstream Changes inStream Power on Wisconsin's Blue River, Annals of the Association of American Geographers, 87, 471-486.https://doi.org/10.1111/1467-8306.00064

Leslie, J. 2013. A Torrent of Consequences. World Policy Journal. 30 (2) pp. 59–69. http://www.worldpolicy.org/journal/summer2013/torrent-consequences.

National Aeronautics and Space Administration (NASA), US. 2009. Thorthormi Glacier Lake, Bhutan. NASA Earth Observatory image by Robert Simmon. 1 November. http://earthobservatory.nasa.gov/IOTD/view.php?id = 40962

National Disaster Management Authority (NDMA) (2020). National Disaster Management Authority Guidelines Management of Glacial Lake Outburst Floods (GLOFs). Government of India - Ministry of Home Affairs. https://ndma.gov.in/sites/default/files/PDF/Guidelines/Guidelines-on-Management-of-GLOFs.pdf

Nepal, S. K. 2011. Mountain Tourism and Climate Change: Implications for the Nepal Himalaya. Nepal Tourism & Development Review. 1 (1) pp. 1–14.

Phillips, J.D., 1989. Fluvial sediment storage in wetlands. Water Resources Bulletin., 25, 867-873. https://doi.org/10.1111/j.1752-1688.1989.tb05402.x

Pilotti M., Milanesi L., Bacchi V., Tomirotti M., Maranzoni A. (2020). Dam-Break WavePropagation in Alpine Valley with HEC-RAS 2D: experimental Cancano Test Case. *Journal of Hydraulic Engineering*, 146(6), 779. https://doi.org/10.1061/(asce)hy.1943-7900.0001779

Post Disaster Needs Assessment (2023). Glacial Lake Outburst Flood 2023, Compiled by the Sikkim State Disaster Management Authority, Government of Sikkim, Gangtok.

Reddy P. S., Babu A. V. S., Bhagheerath Y. V. S, Devaraj R, Rao K. H. V. Durga & Sreenivas K. (2025) GLOF in the South Lhonak Lake, India: photogrammetric analysis and estimation. *Journal of Water and Climate Change* Vol 16 No 1, 127 doi: 10.2166/wcc.2024.566

Reynolds, J. M. (1998). High-altitude glacial lake hazard assessment and mitigation: a Himalayan perspective. Geological Society, London, Engineering Geology Special Publications, 15(1), 25-34.

Rhoads, B. L. (1987). Stream power terminology. *The Professional Geographer*, *39*(2), 189-195.

Rhoads, B.L. (1987). Stream power terminology. Association of American Geographers., 39, 189-195.https://doi.org/10.1111/j.0033-0124.1987.00189.x.

Sattar A, Cook K L, Rai S K, Berthier E, Allen S, Rinzin S, Vries M V W de, Haeberli W, Kushwaha P, Shugar D H, Emmer A, Haritashya U K, Frey H, Rao P, Gurudin Kori S K, Rai P, Rajak R, Hossain F, Huggel C, Mergili M, Azam M F, Gascoin S, Carrivick J L, Bell L E, Ranjan R K, Rashid I, Kulkarni A V, Petley D, Schwanghart W, Watson C S, Islam N, Gupta M D, Lane S N, Bhat S Y (2005). The Sikkim flood of October 2023: Drivers, causes and impacts of a multihazard cascade. *Science* 10.1126/science.ads2659 (2025).

SDC (2022). Hazard and exposure mapping for outburst floods from Shako Cho and South Lhonak glacial lakes in Sikkim, India. Technical study in the frame of the project, “Strengthening Climate Change Adaptation in the Himalayas” (SCA-Himalayas) and elaborated by the project consortium with the key authors Ashim Sattar, Holger Frey and Simon Allen from the University of Zurich, Switzerland.

SDC Synthesis report on GLOF hazard and risk across the Indian Himalayan Region. Key authors: Ashim Sattar, Holger Frey and Simon Allen from the University of Zurich, Switzerland.

Sharma, R.K., Kumar, R., Pradhan, P., & Sharma, A., (2022). Climate-Induced Glacier Retreats and Associated Hazards: Need for Robust Glaciers and Glacial Lake Management Policy in Sikkim Himalaya, India. In: Rani, S., Kumar, R. (eds) Climate Change. Springer Climate. Springer, Cham. https://doi.org/10.1007/978-3-030-92782-0_8

Shean, D. (2017). High Mountain Asia 8-meter DEM Mosaics Derived from Optical Imagery. (HMA_DEM8m_MOS, Version 1). Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/KXOVQ9L172S2. [Tile-678]. Date Accessed 12-12-2024.

Shrestha, A., Aryal, D., & Bajracharya, S. R. (2020). *Transboundary cooperation for GLOF risk management in the Himalayas: Nepal’s approach.* Kathmandu: ICIMOD.

Singh, A., Anand, V., Durga Rao, K. H. V., & Chauhan, P. (2024). Unveiling the catastrophic landslide-induced flash flood in Teesta River, Sikkim: insight from South Lhonak Glacial Lake. *Landslides*, 1-19.

United Nations Framework Convention on Climate Change (UNFCCC). (2015). *The Paris Agreement.* Bonn: UNFCCC.

United Nations Office for Disaster Risk Reduction (UNDRR). (2015). *Sendai Framework for Disaster Risk Reduction 2015–2030.* Geneva: United Nations.

USAID (2014). The Glacial Lake Handbook: Reducing risk from dangerous glacial lakes in the Cordillera Blanca, Peru. Prepared by César A. Portocarrero Rodríguez and Engility Corporation.

Worni, R., Huggel, C. and Stoffel, M. (2013). Glacial lakes in the Indian Himalayas—From an areawide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. *Science of the Total Environment*, 468, pp. S71-S84.

Worni, R., Huggel, C., Clague, J. J., Schaub, Y., & Stoffel, M. (2014). Coupling glacial lake impact, dam breach, and flood processes: A modeling perspective. *Geomorphology*, *224*, 161-176.

Wyborn, C., Leith, P., Ryan, M., Montana, J., & Hutton, J. (2019). Doing Science Differently: Co-Producing Conservation Outcomes, Luc Hoffman Institute.

Yochum S.E., Sholtes J.S., Scott J.A., Bledsoe B.P. (2017). Stream power framework for predicting geomorphic change: The 2013 Colorado Front Range flood. *Geomorphology*, 292,178-192. https://doi.org/10.1016/j.geomorph.2017.03.004

Yu, Y., Li, B., Li, Y., & Jiang, W. (2024). Retrospective Analysis of Glacial Lake Outburst Flood (GLOF) Using AI Earth InSAR and Optical Images: A Case Study of South Lhonak Lake, Sikkim. *Remote Sensing*, *16*(13), 2307.

Zhang, T., Wang, W., & An, B. (2024). A massive lateral moraine collapse triggered the 2023 South Lhonak Lake outburst flood, Sikkim Himalayas. *Landslides*, 1-13.

10 Annexures

Basis of cost estimate:

- SPWD Schedule of Rates 2020 of the Government of Sikkim
- Labour rates of the Labour Department, Government of Sikkim

GOVERNMENT OF SIKKIM
HOME DEPARTMENT
GANGTOK

No. 72/Home/2024 **Dated: 11/09/2024**

NOTIFICATION

Whereas, the State Government has deemed it expedient to constitute a High-Level Steering Committee (HLSC) and a Multi-disciplinary Task Force (MTF) to address the threat of glacial lake outburst floods (GLOFs) in the State,

And whereas, as per the report of National Disaster Management Authority (NDMA), Sikkim has 40 (forty) high-risk glacial lakes;

And whereas, mitigating GLOFs is a complex task of inter-disciplinary nature, which involves remote location, high altitude, complex topography and extreme cold weather;

Now therefore, with a view to achieve the above objective, the State Government is hereby pleased to constitute a High-Level Steering Committee (HLSC) and a Multi-disciplinary Task Force (MTF) comprising the following members, namely :-

1. Composition of High-Level Steering Committee (HLSC)

1	Chief Secretary	Chairman
2	Director General of Police, Police Headquarters	Member
3	Principal Chief Conservator of Forest-cum-Secretary, Forest and Environment Department	Member
4	Relief Commissioner-cum-Secretary, Land Revenue and Disaster Management Department	Member
5	Secretary, Planning and Development Department	Member
6	Secretary, Finance Department	Member
7	Principal Chief Engineer-cum-Secretary, Water Resources Department	Member
8	Secretary, Mines and Geology Department	Member
9	Secretary, Science and Technology Department	Member Secretary

(I) Terms of Reference of HLSC :-

(a) to coordinate with defense establishments, paramilitary forces and Central Government agencies to provide support;
(b) to consult and partner with leading experts and organizations in this field;
(c) to evaluate various mitigation options and approve the glacial flood mitigation plans;
(d) to suggest possible funding sources to fund the glacial flood mitigation plans;
(e) to review and evaluate the progress made towards glacial flood mitigation;
(f) to invite subject experts, academicians and others as required while convening its meetings;
(g) to take up capacity building of the officials involved in field studies and mitigation;

(h) to clarify and assign roles and responsibilities to various departments and agencies and resolve inter-sectoral and coordination issues;
(i) to co-opt any other Head of Department as a member of the High Level Steering Committee as deemed necessary;
(j) the Terms of Reference may be expanded by the committee itself, as required;
(k) the High Level Steering Committee shall meet at least once in six months and if required, more frequently.

2. Composition of Multi-disciplinary Task Force (MTF)

1	Secretary, Science and Technology Department	Chairman
2	Additional Principal Chief Conservator of Forest, Forest and Environment Department	Member
3	Inspector General of Police, Home Guards & Civil Defence, Police Headquarters	Member
4	Principal Director, Science and Technology Department	Member
5	Principal Chief Engineer, Water Resources Department	Member
6	Principal Director, Mines and Geology Department	Member
7	Director, Geological Survey of India, Gangtok, Sikkim, Government of Sikkim	Member
8	Prof. Vikram Gupta, Geology Department, Sikkim University	Member
9	Superintendent Engineer, Central Water Commission, Gangtok, Government of Sikkim	Member
10	Director, Sikkim State Disaster Management Authority	Member Secretary

(I) Terms of Reference of MTF

(a) to contribute to the expeditions to the high-risk glacial lakes for hazard assessment and mitigation;
(b) to prepare glacial flood mitigation plans for the high-risk glacial lakes;
(c) to prepare the cost estimates and develop the Detailed Project Report for mitigation;
(d) to implement these mitigation plans under the direction of the High Level Steering Committee:
(e) to consult leading experts and organizations in this field;
(f) to invite subject experts, academicians, department officials and others as and when required while convening its meetings;
(g) to regularly update the High Level Steering Committee on progress made and future plans;
(h) to take up any other task as assigned by the High Level Steering Committee;
(i) to monitor, document and disseminate the progress made;
(j) the Multi-disciplinary Task Force shall meet at least once a month and, if required, more frequently.

By order and in the name of the Governor.

Sd/-
(V. B. Pathak, IAS)
Chief Secretary
Government of Sikkim
File No. 999/DST/2024

Copy for information to:
1. All concerned above;
2. The Pr. Secretary to Hon'ble, Chief Minister, CMO;
3. The Secretary to Hon'ble Governor, Raj Bhawan.

Aryanshrivastava
-//TRUE COPY//-

4. All the Head of Department, Government of Sikkim;
5. The Director General of Police, PHQ, Gangtok;
6. All District Collectors, Gangtok, Gyalshing, Mangan, Namchi, Pakyong and Soreng;
7. The Staff Officer to the Chief Secretary, Government of Sikkim;
8. PS to Additional Chief Secretary, Home Department, Government of Sikkim;
9. Sr. PA to Secretary, Home Department, Government of Sikkim;
10. The Asst. Director-IT, Home Department (Confdl.) – for uploading on Government website;
11. Gazette Section – for publication in the official Gazette and uploading on the e-Gazette platform;
12. File & Guard File.

HOME DEPARTMENT GOVT. OF SIKKIM

Joint Secretary-II (Confdl.)
Home Department
Government of Sikkim

MULTI–DISCIPLINARY TASK FORCE (MTF) FOR GLOF RISK MITIGATION

Minutes of the Meeting

I. A meeting was convened under the Chairmanship of Mr. Sandeep Tambe, IFS, Principal Secretary, Department of Science & Technology on 20th February, 2025 in the Conference Hall, LR&DMD, Gangtok. The meeting was attended by members of the Multi- disciplinary Task Force (MTF) viz, Secretary cum Principal Director- DST, Special Secretary cum Director- SSDMA, Special Secretary- LRDMD, Sr. SP- Home Guards & Civil Defence, Principal Chief Engineer- WRD, Principal Director- Mines & Geology (DMG), Director- GSI, Superintendent Engineer- CWC, Prof. Vikram Gupta- Sikkim University, and officials from respective departments.

II. The Director- Member Secretary-MTF, Sikkim State Disaster Management Authority (SSDMA), welcomed all members and briefed them about the recently constituted High-Level Steering Committee (HSLC) and Multi-disciplinary Task Force (MTF) constituted vide notification no. dated 72/Home/2024 dated 11/9/2024, explaining their respective Terms of Reference. He then, briefed on the meeting agenda:

1. Review the proposal for Lake management of Shako Chho by solar pumps for GLOF Risk mitigation to be funded under the National GLOF Risk Mitigation Programme (NGRMP).
2. Review the Preliminary conceptual presentation on the retention structure at Dolma Sampa in Lhonak Valley

III. Principal Secretary, DST provided an overview of the extensive work undertaken over the past five months in collaboration with various Government of India agencies. He emphasized that Sikkim is at the forefront of GLOF hazard risk mitigation in the country, noting that no other state has reached the stage of proposing structural mitigation measures. He acknowledged the complexity of the project, particularly given the emerging nature of the science, varying terrain conditions, and the significant risks involved. The economic impact of the 2023 Sikkim GLOF disaster was referenced to underscore the importance of this initiative.

Agenda I: Lake hazard management at Shako Chho by solar pumps for GLOF risk mitigation

- Mr. Ashim Basnett, ACE-DST, presented the Sikkim 4-STEP Approach for GLOF mitigation, which includes preliminary assessment, comprehensive assessment, designing mitigation measures, and executing mitigation strategies. Shako Chho was identified as one of 16 high-risk lakes in Sikkim by NDMA. It is the only one without a natural outlet and has an unstable moraine dam thorough which the water is seeping through. As highlighted by multiple studies, Shako Chho presents high risk that make intervention essential (Worni et al. 2013; SDC 2021; Dubey and Goyal 2020; NRSC 2025). The Swiss Development Corporation (SDC) study identified it as having high failure potential and that Thangu village and adjacent defence establishments would have only 8 minutes of warning time in the event of a GLOF, regardless of the flood magnitude, creating an extremely high-risk situation. The NRSC study assessed Shako Chho as vulnerable due to various key indicators including low width-to-height ratio of the end moraine, steep damming moraine composed of loose granular material and the presence of a 1000-m high mountain slope rising above the lake.

Following field studies in 2024, the Mines and Geology Department made specific recommendations, emphasizing that while intervention is necessary, it must be carefully

Director
Sikkim State Disaster Management Authority
and Revenue & Disaster Management Department
Government of Sikkim

Aryanshrivastava
-//TRUE COPY//-

controlled. They recommended using either siphoning techniques or motorized methods to decrease the lake's water volume, while strongly cautioning that any physical intervention should not disturb the area's geological equilibrium beyond the necessary lowering of water levels.

- Option analysis indicates that the structural intervention of the Moraines is very risky and not advisable. Hence, the only option of lowering of the lake level is through non structural intervention. The usage of Siphon system is not a possibility due to the head difference of the lake water level and moraine summit being more than 20 meters. The use of pump system is the only option. The nearest electricity point is at a distance of more than 20 km. Also, the head load distance for carriage of fuel is more than 2 km. As heavy pumping is required the fuel cost will be very high. Hence, the use of Solar Pumps seems to be the only option.
- The proposed solution for Shako Chho involves an innovative solar-powered pumping system. The plan aims to reduce the lake's water level in a controlled manner over a 24-month period. The project will require the adjacent land for installing the solar panels. The water pumped would be safely discharged in the Chhombo chu stream and also used for the ecological restoration of the dried up alpine lakes. The main physical parameter used to measure the performance of the project would be the volume (mcm) of water pumped out and the resultant reduction in the lake water level.
- During discussions, queries were raised, regarding the stability of moraines during pumping operations, monitoring requirements, challenges of operating at high altitude (17,000 ft), availability of solar radiation and winter complications with frozen lakes. Response of the terminal moraine to the pumping would need to be closely monitored with technical support from DMG officials. These queries were responded to satisfactorily by the technical team from DST who also highlighted that this project was venturing in an area where not much past experience is there, and in that sense it is a demonstration project where proof of concept will be ascertained.
- In terms of sustainability assessment, attempt will be made to ecologically restore the dried up lakes using the pumped water. Pumping will not involve any physical tampering of the fragile lake system. Once the target pumping is achieved, after retaining some pumps for maintenance pumping, the remaining pumps can be re-used for the lowering of other critical lakes. Hence the lake level lowering cost will be reduced. The use of solar power for pumping is a green energy solution in a very fragile ecosystem unlike the use of fossil fuel powered pumps.
- The proposal was appreciated by the members, as a necessary step to reduce the GLOF hazard of Shako Chho lake and the use of solar pumping green technology without disturbing the moraine as a safe option without causing damage to the ecology. Also, the use of solar pumping for lake level lowering of a glacial lake has not been undertaken anywhere in the country. This will be a pioneering project and if successful will demonstrate a novel technique for GLOF risk mitigation for the whole country.

Agenda II: Conceptual presentation on the retention structure at Dolma Sampa in Lhonak valley

- The proposal for "GLOF Risk Mitigation in Lhonak Valley, Sikkim" has been developed in response to the catastrophic 2023 South Lhonak glacial flood, which inflicted irreversible damage on infrastructure, the economy, and defense preparedness. The disaster set Sikkim's development back by a decade, severely impacting transport, tourism, and local communities.

Director
Sikkim State Disaster Management Authority
and Revenue & Disaster Management Deptt
Government of Sikkim

Aryanshrivastava
-//TRUE COPY//-

This initiative aims to protect critical mountain infrastructure from future Glacial Lake Outburst Floods (GLOFs) through structural mitigation measures. The project will focus on the Lhonak Valley, which houses 3 of the 16 Category A high-risk lakes and poses the greatest threat. The primary objective is to safeguard roads, bridges, hydropower projects, defense installations, towns, and villages from future GLOFs by implementing a watershed-level retention structure designed to regulate flood peaks.

- The Lhonak watershed, encompasses an area of 498 square kilometers and contains 183 lakes. This watershed has three big category- A high risk lakes namely Changsang, South Lhonak and North Lhonak. Of these both South Lhonak and Chansang are growing very fast. Also recent studies by Sattar et al. 2025 in their research published in the reputed Science journal point to the risk of future glacial floods from South Lhonak. Also, while EWS are necessary and can help to save lives, what about infrastructure? In mountains, critical infrastructure such as roads, bridges, dams etc. and habitations are along the river valley. Also, mountain infrastructure is costly and time taking to rebuild. The main challenge is to safeguard mountain infrastructure from GLOFs.

- The proposal was developed by adopting a three-pronged methodology: conducting a global review of GLOF risk mitigation measures, undertaking field and laboratory-based studies, and engaging stakeholders. The team analysed international best practices in GLOF hazard management, performed hydrodynamic modeling, debris deposition analysis, and stream power assessments, and engaged with key stakeholders, including the National Disaster Management Authority (NDMA), government agencies, and local communities to ensure project feasibility.

- The findings of the field studies carried out during 2024 were presented wherein the debris deposition pattern from the 2023 glacial flood event was studied by DMG - which pointed to the fact that unlike the conventional visualization of the glacial flood that it will result in erosion in the upper reaches and deposition in the lower reaches, in this case several episodes of erosion and deposition were observed. They hydrodynamic modelling was also carried out using HEC-RAS software and showed that the unit stream power was lowest in Dolma Sampa due to the gentle gradient and high flood inundation width thereby providing an opportunity to tame the GLOF here.

- Based on these studies, two location options were presented for the retention structure (chainage 26 and 27): the first at Goma valley near Lumbuk rock, covering 138 lakes; and a second option one km downstream, which would include Nako valley, cover an additional 45 lakes. The proposal evaluates three structural concepts were proposed for the retention structure: GLOF Kavach with pipes; GLOF Kavach with notches; GLOF Kavach with Pre-placed aggregate concrete core, ranging from 20 to 30 meters in height, with estimated costs between Rs 760 crore and Rs 1,750 crore (excluding taxes). The final design will be determined through expert consultations, ensuring optimal feasibility and effectiveness.

- The cost-benefit analysis underscores the necessity of intervention, with the damage caused by the 2023 flood amounting to Rs 18,555 crore. This highlights the economic viability of the proposed mitigation measures compared to potential future losses. The project also acknowledges significant challenges, including high-altitude construction constraints, climate variability, and engineering limitations.

Director
Sikkim State Disaster Management Authority
Revenue & Disaster Management Deptt
Government of Sikkim

- During discussions, concerns were raised about the potential risk of creating another GLOF hazard through the retention structure. An alternative suggestion was made to consider implementing water speed reducing structures along the entire belt rather than concentrating retention at a single location. Also, the potential environmental impact of such as large structure was also raised. The benefits of the retention structure were extensively discussed, highlighting its importance for protecting border populations, supporting defence forces, promoting economic development in border areas, and its implications on national security. Also, in projects of this size there will be a trade-off between the economic benefits, environmental impacts and social acceptability which are normally assessed at the highest level where these decisions are taken.

- This proposal has already been presented at NDMA in December 2024, and they have requested for submission of the PPR.

IV. **Decisions taken:** Based on detailed deliberations, the MTF approved the detailed proposal for Shako Chho lake hazard management and the concept note for the retention structure at Dolma Sampa in Lhonak Valley. The retention structure design is a conceptual proposal and the final design will be determined through expert consultations, ensuring optimal feasibility and effectiveness. These two proposals will now be placed before the High-Level Steering Committee chaired by the Chief Secretary.

The meeting concluded with Secretary, DST expressing gratitude to all participants for their valuable inputs and emphasizing the pioneering nature of the projects.

Director
Sikkim State Disaster Management Authority
Land Revenue & Disaster Management Deptt
Government of Sikkim

Aryanshrivastava
-//TRUE COPY//-

Meeting of Multi-Disciplinary Task Force

Date: 20.02.2025 **Venue: Conference hall SSDMA**

SL.NO	Name of the Participant	Designation	Mobile Number	Email Id	Signature
1	Samdeep Tambe	Ps. Secy	94740 59791	secydst@gmail	
2	D G Shrestha	Secretary-DST	9434164409		
3.	Shashwat Rai	EE-CWC	8826030308	cesid-cwc@gov.in	
4.	Prof Vikram Gupta	Professor	9411528837.	vgupta_wihg@yahoo.com	
5.	Prashant Ilamkar GSI	Director	9465472316	pilamkar@gmail.com	
6	Ashim Rasnet, DST	ACE	76025306r6	[illegible]@gmail.com	
7	T. Doden Bhutia	JE DST	9932365138	mountaincloud9177@gmail.com	

Meeting of Multi-Disciplinary Task Force

Date: 20.02.2025 **Venue: Conference hall SSDMA**

SL.NO	Name of the Participant	Designation	Mobile Number	Email Id	Signature
8.	Sajan Poudyal	A.E (DST)	6296588372		
9.	Dr. RK Sharma	ASO (DST)	9775961141	gautam84rk@yahoo.com	
10.	Dr. N.P. Sharma	SO DST	7407184204	nareshhvse@gmail.com	
11.	K.K. Luitel	Addl. Dir. (M&G)	9474482284	Keshav.luitel@gmail.com	
12.	Rajiv Subba	Pr-CE, WRD	9434137370	rjvsubba@gmail.com	
13.	[illegible] Chettri	Spl. Secty, LRD	9434143136		
14.	Phigu Bhutia	Pr. Director DMG	9933031110	phigoo@gmail.com	

(17)

Meeting of Multi-Disciplinary Task Force

Date: 20.02.2025 **Venue: Conference hall SSDMA**

SL.NO	Name of the Participant	Designation	Mobile Number	Email Id	Signature
15.	MORDENT THAPA	Sr. SP Home Guards & Civil Defence	8768780113	mordent382@outlook.com	[signature]
16	Dr D. Manjunatha	CWLW	9591387735	manjunatha502@yahoo.co.in	[signature]

50 YEARS OF STATEHOOD

SUNAULO SAMRIDDHA ANI SAMARTH SIKKIM

(1975-2025)

Aryanshrivastava

-//TRUE COPY//-

Report on the Full Extent of Damages pertaining to GLOF 2023 (Paragraph 15 of the affidavit)

The Post Disaster Needs Assessment (PDNA) for the Sikkim Flash Floods, 2023 was conducted by the Sikkim State Disaster Management Authority (SSDMA) in coordination with the National Disaster Management Authority (NDMA) during 7–11 December 2023. The assessment followed a multi-stakeholder, state-level coordination approach involving external experts, sector specialists, representatives from Government departments, scientific institutions, and international agencies including UNICEF, Coalition for Disaster Resilient Infrastructure (CDRI), Border Roads Organisation (BRO), and the World Food Programme (WFP).

The PDNA was carried out in three phases:

- **Data collection:** 18 November to 5 December 2023
- **Field assessment:** Deployment of 16 external experts and 8 state sectoral experts from 7 to 11 December 2023

The assessment aimed to systematically capture the scale and severity of damages and losses across social, productive, infrastructure, and cross-cutting sectors, and to estimate recovery and reconstruction requirements.

2. Overview of Impact and Major Damages

The flash floods had widespread and severe impacts across multiple districts of Sikkim, affecting human lives, settlements, livelihoods, public infrastructure, and critical services.

2.1 Human and Social Impact

- **Villages affected:** 100
- **Population affected:** 88,400
- **Human lives lost:** 79
- **Missing persons:** 44
- **Persons with grievous injuries:** 26 (all discharged)
- **People rescued:** 2,563
- **People evacuated:** 5,665
- **Relief camps opened:** 30 (all closed subsequently)
- **Inmates in relief camps:** 7,025

- The disaster caused significant displacement and psychological distress, particularly among vulnerable populations including women, children, elderly persons, and persons with disabilities.

2.2 Housing and Settlement Damage

Housing emerged as one of the most severely affected sectors:

- **Total damaged houses:** 2,004
    - **Fully and severely damaged pucca and kutcha houses:** 1,425
    - **Partially damaged pucca houses:** 166
    - **Partially damaged kutcha houses:** 413
- **Persons living in rented houses affected:** 5,019

The extensive damage to housing stock resulted in temporary homelessness, increased dependence on relief support, and long-term reconstruction needs.

2.3 Livelihoods and Productive Assets

- **Livestock lost (animals, poultry, and others):** 31,727
- **Shops affected:** 922

Loss of livestock and damage to commercial establishments significantly disrupted household incomes, particularly in rural and peri-urban areas dependent on agriculture, animal husbandry, tourism, and small businesses.

2.4 Infrastructure Damage

- **Bridges affected:** 33
    - **Major bridges:** 13
    - **Minor bridges:** 20

Damage to bridges, roads, drinking water systems, and sanitation infrastructure severely affected connectivity, access to essential services, and delivery of relief and response operations.

3. Sector-wise Damage and Loss Assessment

The sector-wise assessment of damages, losses, and recovery and reconstruction needs was undertaken as part of the PDNA exercise. **The consolidated table on damages, losses, and recovery & reconstruction needs is presented under the PDNA tables section.**

Table 4. Summary of Damage, Losses and R&R needs. (In crores)						
Sector	*Sub-Sector*	Damages	Losses	Damage + Losses	Recovery and Reconstruction	Recovery & Reconstruction Needs (%)
Social Total	Housing, Health, Education, Community Buildings)	594.74	36.146	630.886	719.22	32.81%
Productive Total	Tourism, Animal Husbandry, Livestock & Fisheries	49.85	306.88	356.73	312.26	14.24%
Infrastructure Total	Roads & Transport; Drinking Water & Sanitation	201.42	45.36	246.79	440.59	20.09%
Crosscutting Total	Forest & Environment; DRR	202.69	42.97	245.66	720.52	32.86%
Grand Total		**1048.7**	**431.37**	**1480.066**	**2192.59**	**100.00%**

4. Aggregate Impact

- **Total Damages:** ₹1,048.70 crore
- **Total Losses:** ₹431.37 crore
- **Total Damage and Losses:** ₹1,480.07 crore
- **Total Recovery and Reconstruction Needs:** ₹2,192.59 crore

The recovery and reconstruction requirements exceed the immediate damages and losses, reflecting the need for resilient rebuilding, livelihood restoration, environmental rehabilitation, and strengthening of disaster preparedness mechanisms.

5. Conclusion

The Sikkim Flash Floods of 2023 caused extensive human, physical, economic, and environmental damage across the State. The PDNA highlights that while housing and social infrastructure suffered the highest direct damages, long-term recovery demands significant investments in cross-cutting areas such as disaster risk reduction and environmental restoration. The findings emphasize the necessity of a coordinated, multi-sectoral recovery strategy that not only restores pre-disaster conditions but also enhances resilience to future climate-induced disasters.

Proof of service 1178

Gmail

Office of Sameer Abhyankar <contactadvsa@gmail.com>

Service for Original Application No. 171/2023/EZ In : News item appeared in East Mojo on 05.10.2023 titled “Sikkim: Here’s why the Chungthang Hydro-dam breach is a BIG DEAL” vs The State of sikkim & Ors

1 message

Office of Sameer Abhyankar <contactadvsa@gmail.com> Sat, Feb 28, 2026 at 12:24 PM
To: "cc: amritalegal" <amritalegal@gmail.com>, ashokadvhc <ashokadvhc@gmail.com>, legumjure <legumjure@gmail.com>, vidhan Vyas <vidhan.advocate@gmail.com>

Additinal Affidavit on behalf of Respondent No. 1.pdf

Dear sir,

Please find attached scanned copy of the Additional affidavit on behalf of Respondent No.1 (State Of Sikkim) in the captions Matter.

Thanks
Prince Kumar
For
Mr. Sameer Abhyankar
Standing Counsel sikkim

--
Address for Correspondence:
D-247, LGF, Defence Colony,
New Delhi 110024
Ph. +91-11-49402169