Susceptibility Assessment of different regions related to the Glacier Hazards

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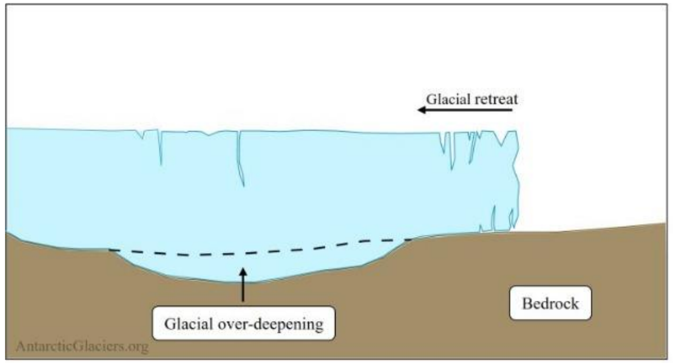
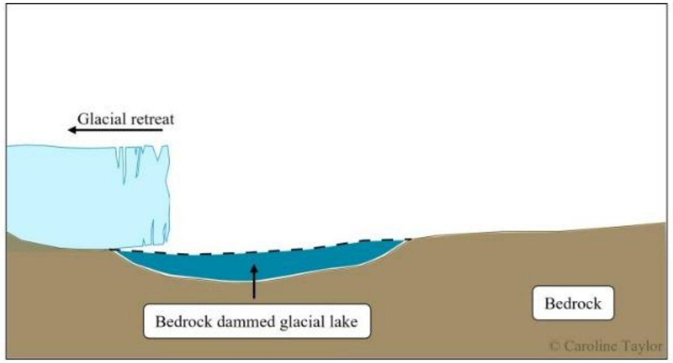
Glacier National park, Argentina

Introduction

- **Glacier** – It is large, long-lasting mass of ice found on the land that moves because of gravity.
- **Glacier Hazards** - They Glacial lake outburst floods (GLOFs), ice avalanches, and glacier surges. These hazards can threaten people, infrastructure, and the environment.
- **Glacier Lakes -** During the last few decades, accelerated ice mass loss and Glacier retreat has resulted not only the expansion of existing glacial lakes but also the formation of new glacial lakes . As a result, glacial lakes are now found across all glaciated regions.

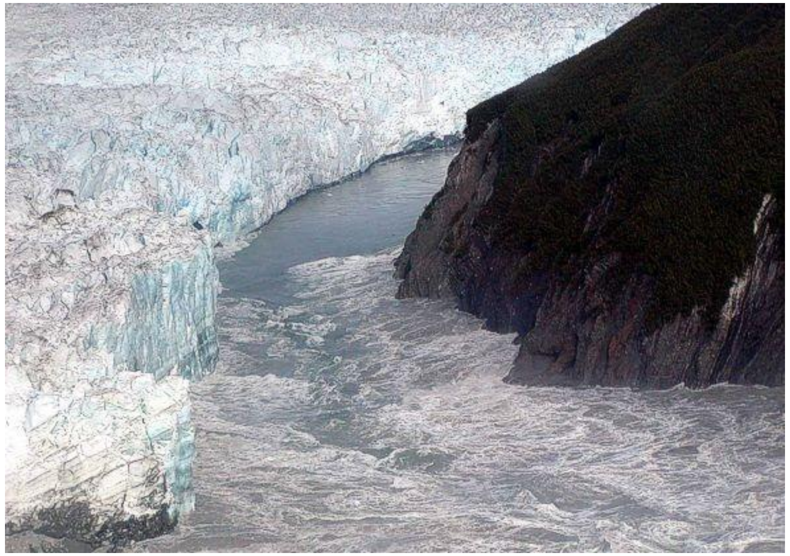




- A **proglacial lake** is a body of water that forms in front of a glacier due to melting ice. These lakes are typically dammed by moraine, ice, or bedrock

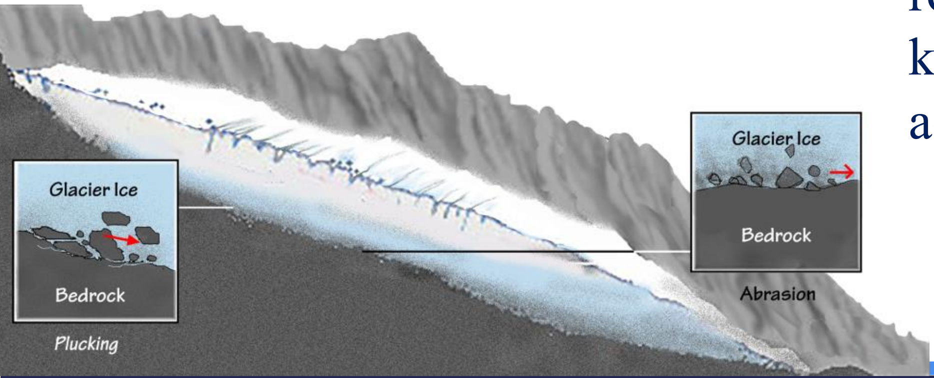
➢A **glacial lake outburst flood** (GLOF) is a release of meltwater from a moraine- or ice-dam glacial lake due to dam failure GLOFs often result in catastrophic flooding downstream, with major geomorphic and socioeconomic impacts.

➢**Glacial debris** refers to the rock debris that is eroded, plucked up, and entrained in the flowing ice of a glacier as it moves down mountainsides.



GLOF, Hubbard Glacier, Alaska, 2002

➢ **Moraines** As glaciers advance and retreat, they result in transportation of rock debris, depositing it in ridges known as moraines, which mainly act as natural dams



Study Area – 1 (Gangotri Glacier)

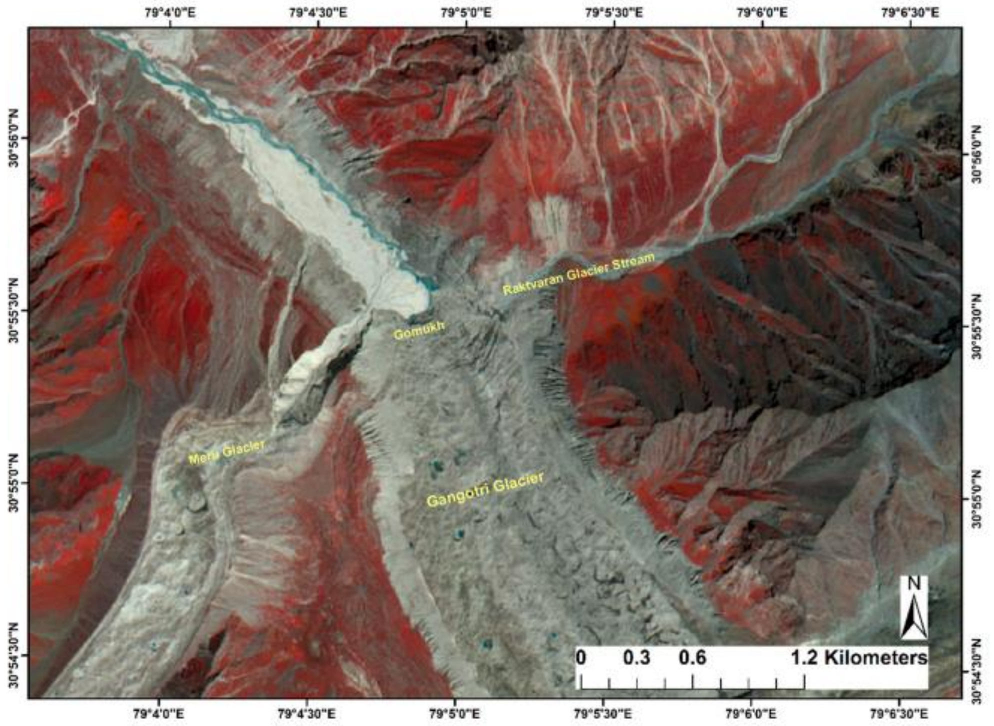


Fig 1: Lower ablation part of Gangotri Glacier as seen in the LISS IV image of ISRO's Resourcesat -2 satelite (20 September 2017)

Source: Thakur, P,K., Pandey & Chauhan, P (2023), Assessment of dynamics frontal of part of Gangotri glacier, India, from 2017 to 2021 using remote sensing data, Journal of Indian society of Remote Sensing, 51(4), 691-698.

- **Location:** Gangotri Glacier, Uttarkashi District, Uttarakhand, India (30°55′26.88″N, 79°40′53.20″E).
- **Elevation:** 4100 – 7000 masl.
- **Size:** Length: 30 km, Width: 0.5 m to 1.75 km, Area: 122 km².
- **Tributaries:** Raktvarn (15.90 km), Chaturangi (22.45 km), Kriti (11.05 km), and 18 minor glaciers.

Study Area – 2 (Shisper and Mochowar glaciers)

- Shisper and Mochowar glaciers are part of Hassanabad glacier system.
- Located in Western Karakoram ranges (36.35-36.48ºN, 74.57-74.61ºE).
- Watershed area drained by both glaciers 359km^2.
- The melt water flows to Hunza river.
- The region has an annual temperature of 11°C and precipitation of 125mm.

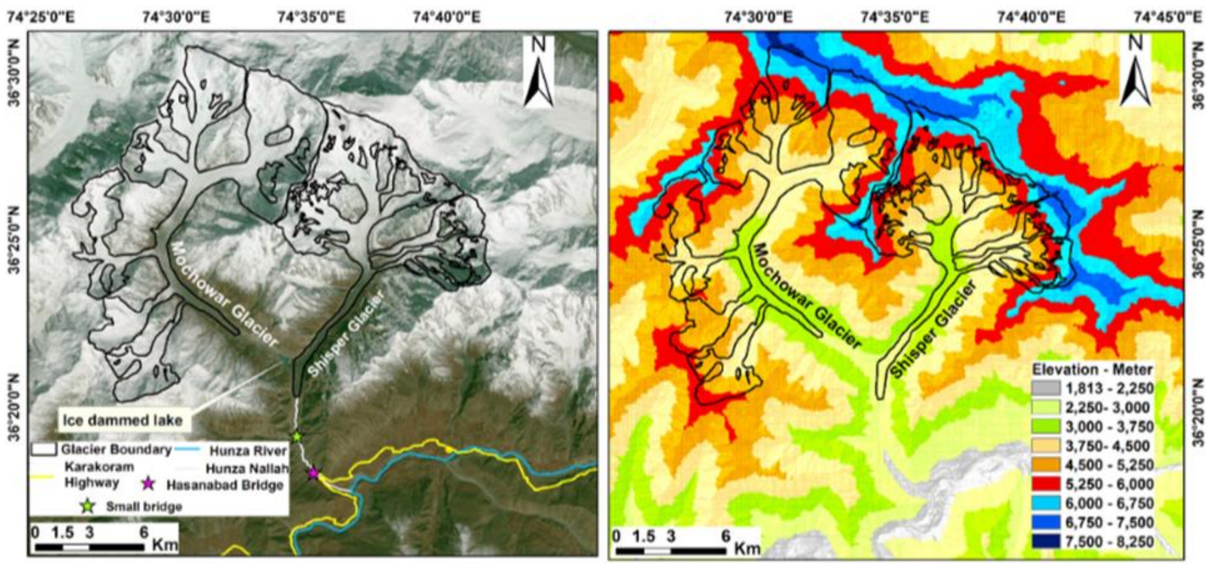


Fig 2: Topography of Shisper and Mochowar glacier system.
Source: Singh H et. Al (2023)

Study Area – 3 (Yigong Tsangpo Basin)

- Yigong Tsangpo basin is consist of parts of three counties which are Jiali, Bainba, and Bomi.
- It is located in the southeastern Tibetan plateau (Fig.3).
- The basin area is 13,533 km^2 and extended up to 286 km).

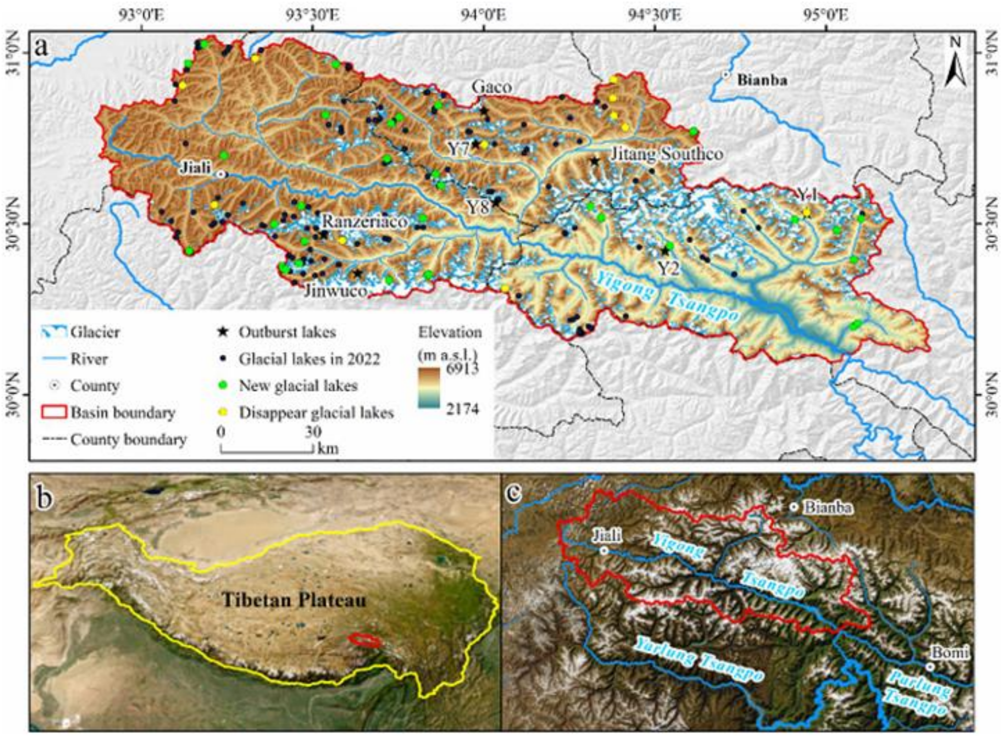


Fig 3: Overview map of study area (a) distribution of glacial lakes; (b) location of the study area; and (c) surrounding water systems (base map from World Imagery),
Source: Ziyang et al. 2024

Study Area – 4 (Qinghai – Tibet Plateau)

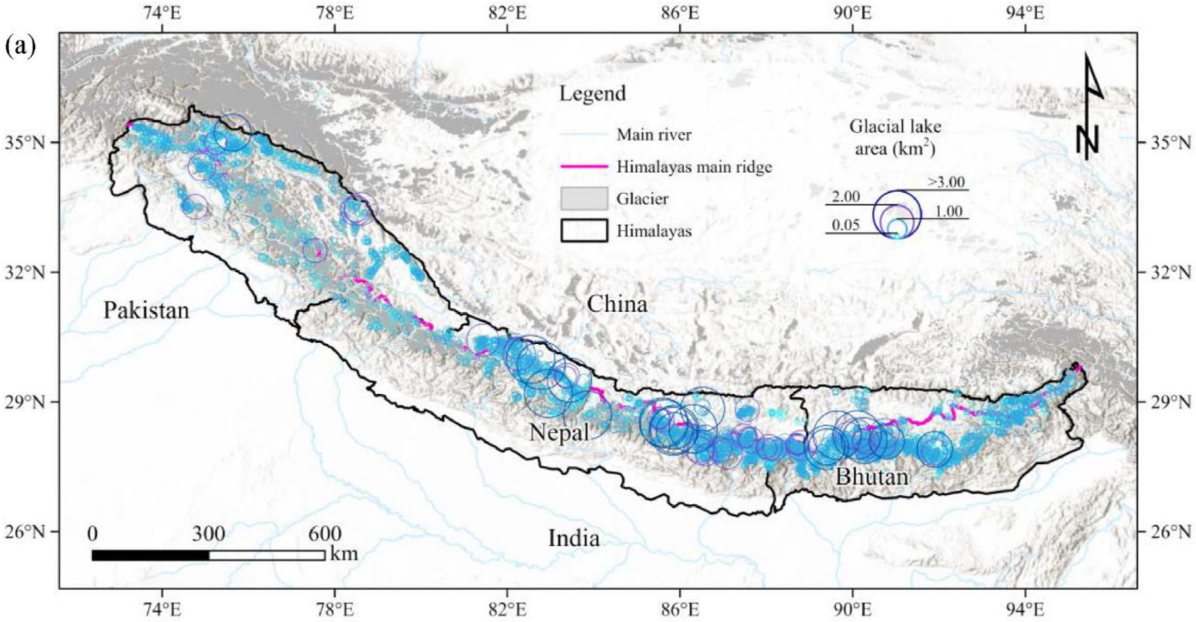


Fig 4: Topography of study area in Himalayan region on the southern margin of the Qinghai-Tibet Plateau

Source: ZHOU B. et al. / Advances in Climate Change Research 15 (2024) 500e514

- Latitude - 26.35° – 35.85 ° N, Longitude - 72.77 ° – 95.43 ° E
- Lies in the Southern margin of Himalayas has various tectonic fault zones in the region from south to north.
- Area – 662,200 km².
- Himalayas - 20,436 glaciers (~19,900 km²) in 2015.
- Study Area - 8,024 glacial lakes (~635 km²) in 2015.
- This area experiences high precipitation, has steep terrain, loose moraine deposits, abundant glaciers and glacial lakes.
- Leads to the GLODF's

Methodology 1 - Thakur K.P et. al

Data Collection

1)Multi-sensor remote sensing data acquisition:

2)Sentinel-2 MSI (Medium Resolution)

3)Landsat-8 OLI (High Resolution)

4)IRS LISS-IV (Very High Resolution)

Data Preprocessing

1)Image distortion correction

2) Image enhancement and alignment

3) GIS-based processing

Snout Position Monitoring

1)Manual mapping through visual interpretation

2)Use of FCC (False Color Composite) satellite images.

Surface Velocity Measurement

1)Feature tracking using Sentinel-2 MSI images

2)Application of COSI-CORR (Co-Registration of Optically Sensed Images and Correlation) for phase-based correlation

Methodology 2 - Singh H. et al.

Glacier surface velocity

- Sentinel-2 image (2016 -2022)
- GIV Tool.

Enhancement and correction of satellite images

Divide image into small windows.

Compare displacement between 2 images.

Glacier ice thickness and overdeepening site identification

- DEM
- Glacier surface velocity
- Glacier boundary or flow line (RGI)
- HIGHTEM tool

Shallow ice Approximation

- Apply Glen's flow law:

$$\acute{\varepsilon} = A\tau^{n}$$

- Glacier thickness

$$H = \sqrt[4]{\frac{1.5U^{S}}{Af^{3}(\rho g \mathrm{Sin}\alpha)^{3}}}$$

- Basal shear

$$\tau_{b} = f\rho g H \mathrm{Sin}\alpha$$

Methodology 2 - Singh H. et al.

Estimation of ice dammed and future lake volume

- NDWI of Sentinel-2 image (2016 -2022)

$V= 0.104A_L^{1.42}$

Flood modelling

- DEM
- River cross section
- HEC-RAS tool
- Planet lab imagery

2D – hydrodynamic modelling simulation - 22nd/May/2022

Validation of post event morphological changes of stream.

Glacial lake outburst flood susceptibility

- 10 critical factors selection based on previous GLOFs.
- AHP

$W_s = \sum C_i \times W_i$

For matrix consistency:

$CR = \frac{CI}{RI} < 0.1$

Methodology 3 - Ziyang et al.

Data collection and MDL identification:

Landsat and ALOS DEM data → Image preprocessing → Automated extraction → Preliminary verification → Final verification and modification → Calculating area error → Glacial lake inventory

Landsat and ALOS DEM data
- Data collection from 1990 to 2022
- 24 images from different area

Image preprocessing
- Radiometric calibration
- Atmospheric correction
- Image fusion
- Mosaicking and
- Clipping.

Automated extraction
- Ratio image calculation in NDVI
- By NDWI and NDSI identified the boundaries of Glacier lakes
- Determine suitable threshold to binarize the images
- Convert binarized raster data into vector files and imported into ArcGIS

Preliminary verification
- Remove all the polygons and correct glacier position
- Verify the results in ArcGIS by visual inspection

Final verification and modification
- Used world imagery and Google earth
- Creating 10km buffer zone between parent glacier to lake

Calculating area error
- Image resolution and geometric correction
- Calculation of area error

Glacial lake inventory

Formulas used:

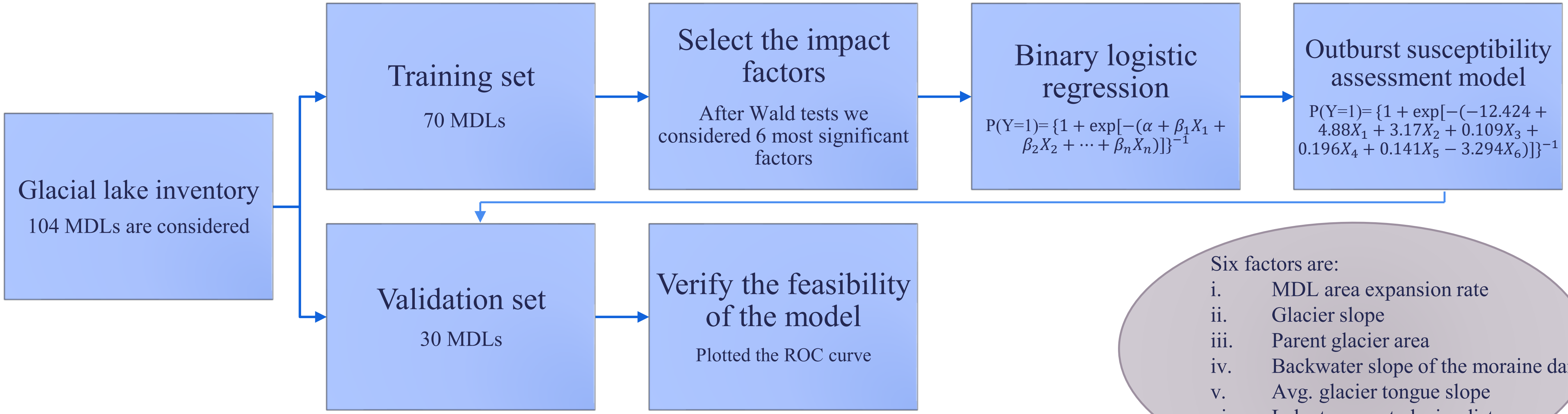
$$\mathrm{NDWI} = \frac{B_{NIR} - B_{BLUE}}{B_{NIR} + B_{BLUE}}$$

$$\mathrm{NDSI} = \frac{B_{NIR} - B_{BLUE}}{B_{NIR} + B_{BLUE}}$$

$$\mathrm{Error} = \frac{C}{G} \times \frac{G^2}{2} \times 0.6872$$

$$R = \frac{\mathrm{Error}}{A} \times 100\%$$

Methodology 3 - Ziyang et al.



Six factors are:

i. MDL area expansion rate
ii. Glacier slope
iii. Parent glacier area
iv. Backwater slope of the moraine dam
v. Avg. glacier tongue slope
vi. Lake to parent glacier distance

Methodology 4 - ZHOU B. et al.

Data Sources

Data Sources:
•Glacial Lake Data (Satellite Imagery, GIS)
•Topographic Data (DEM – 30m resolution)
•Climate Data (Temperature, Precipitation)
•Hydrology Data (Watershed Area, Connectivity Index)
Preprocessing:
✓ Catchment-Based Mapping (1,435 catchments analysed) Area of 1.07 to 360.30 km2.

Machine Learning Model Training

Algorithms Used:
- ➢ Support Vector Classification (SVC)
- ➢ Random Forest (RF)
- ➢ Gradient Tree Boosting (GTB)

Optimization Method:
Whale Optimization Algorithm **(WOA)** – fine-tunes ML parameters for better accuracy
Model Training:
✓ 70% Training Data | 30% Test Data
✓ Cross-validation applied to prevent overfitting

Model Evaluation & Selection

Performance Metrics:
•ROC-AUC Score (Model Classification Ability)
•Accuracy (ACC) (Correct Predictions %)
•MSE & RMSE (Error Measurement)
Best Model Identified:
WOA-SVC – Achieved highest prediction accuracy

Susceptibility Mapping & Analysis

GLODF Risk Zones Identified:
• High & Very High Risk (Mostly in Eastern & Central Himalayas)
•China-Nepal Border Identified as a Hotspot
•**128** Transboundary Threat Catchments (CPTT) Identified
Key Contributing Factors: (23 VH & 29 H)
✓ Topographic Potential (39.96%) – Most critical factor
✓ Potential Flood Volume & Glacial Lake Volume – Key triggers for GLODFs

Support Vector Machine (SVM)

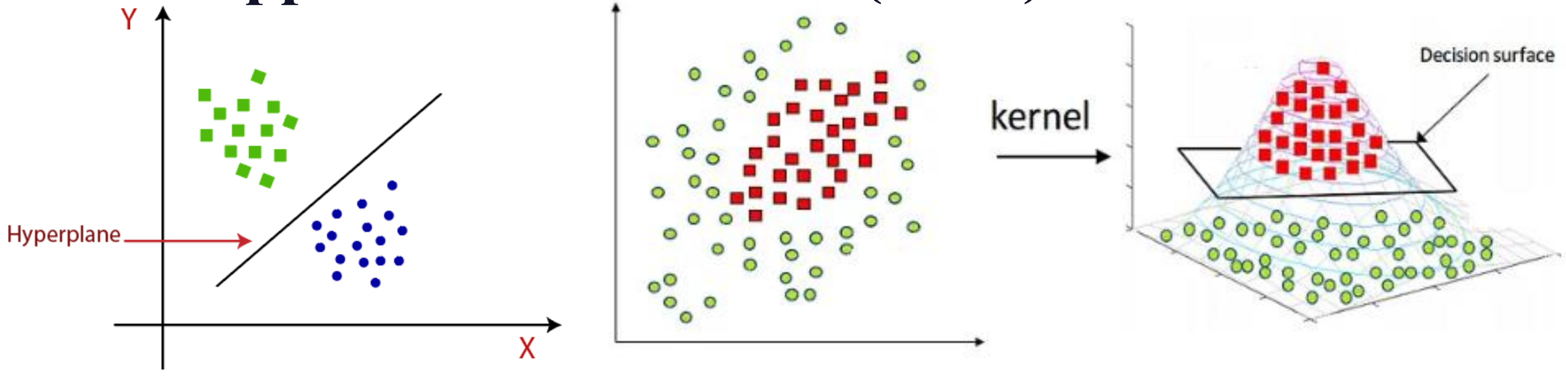


Fig 5: Linear vs Non linear (kernel) in SVC

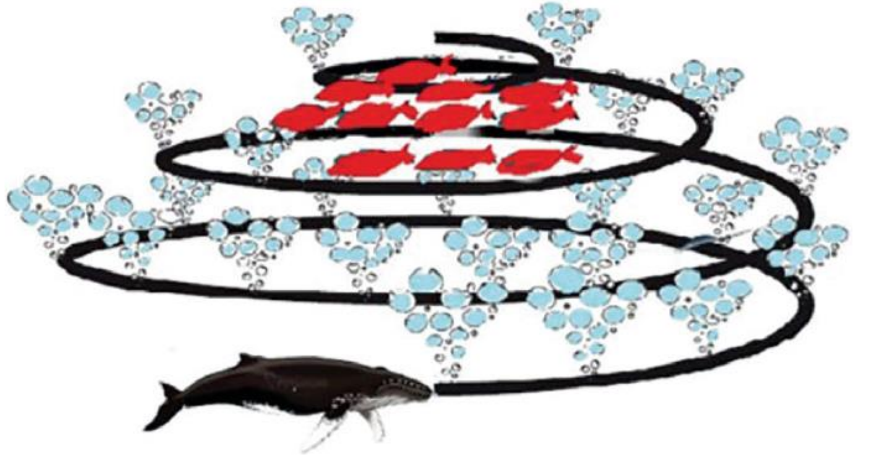


Fig 6: Humpback whale searching the prey with the bubble net in WOA

Random Forest

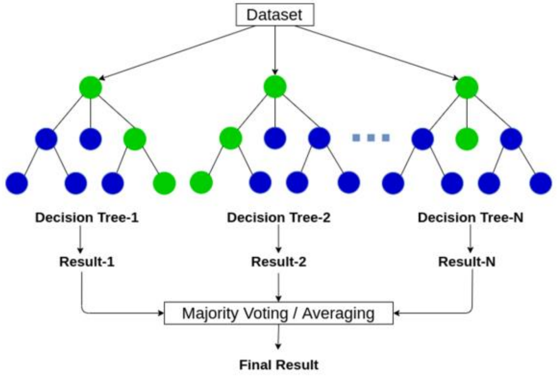


Fig 7: Random forest Representation Diagram

Gradient Tree Boosting (GTB)

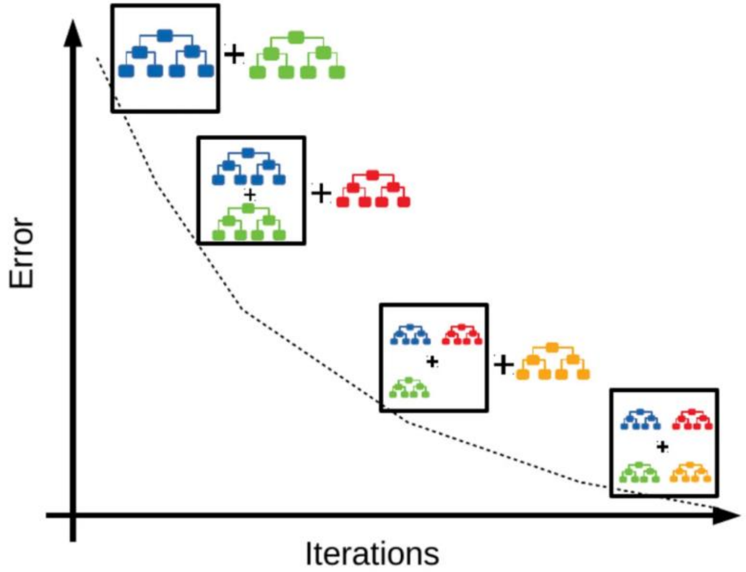


Fig 8: Graph representing the errors & iterations of GTB

Results 1 - Thakur K.P et. al

2017

- Total debris flow covered ~0.4 km².

2018

- Formation of two small pro-glacial lakes:
  Left side: ~0.002 km² Right side: ~0.0034 km²

2019

- Formation of a supra-glacial lake (~0.0086 km²) on the glacier surface.

2020

- Melting of the 60-meter ice bridge.
- Merging of the supra- and pro-glacial lakes

2021

- Direct flow of meltwater from Raktvarn Glacier to Gomukh Glacier.
- Front part of the glacier lost ~0.8 km² (2017-2021).

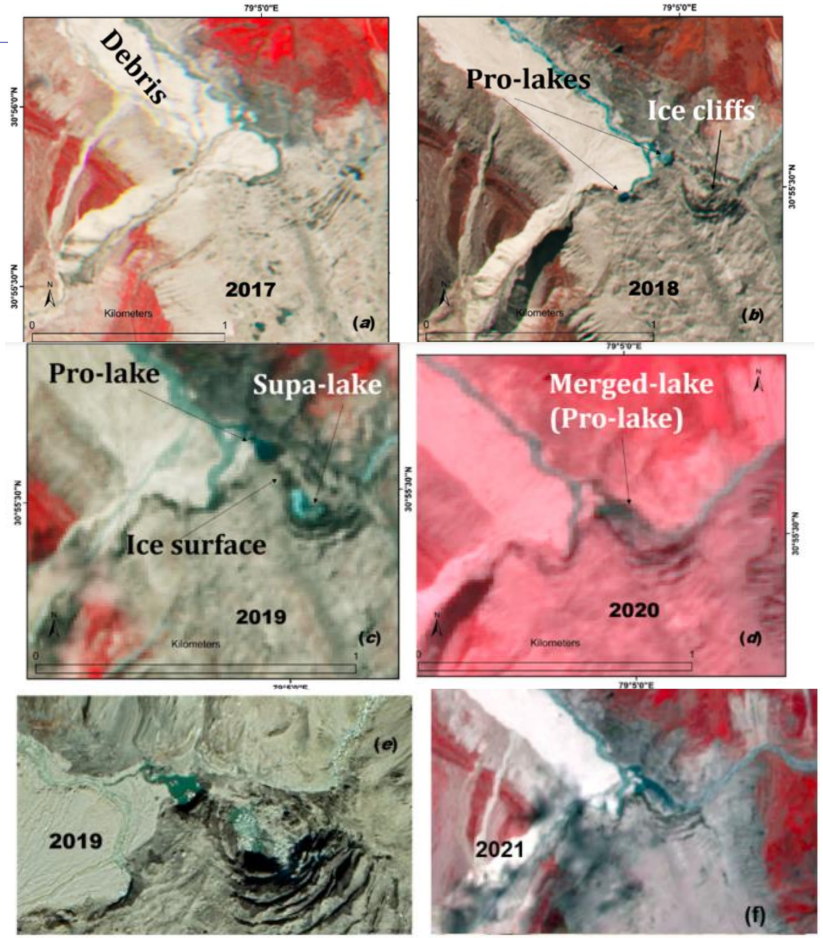


Fig 9:IRS LISS-IV image showing snout condition from 2017-21 Thakur, P.K., Pandey & Chauhan, P (2023)

Results 1 - Thakur K.P et. al

Surface Velocity Changes of Gangotri Glacier:

2013-2014 (Sentinel-2 MSI Data)

- Glacier velocity (0-150 m): ~8 m/year, (150 m - 3 km) ~18.32 m/year,(3 km - 6 km)~27.56 m/year

2013-2014 (Landsat OLI Data)

- Mean glacier velocity: ~7.17 m/year (higher range)

2015

- Glacier velocity (214 m): ~24.52 m/year (3.18 km - 6.36 km): ~32.89 m/year

2018-2019 (Sentinel-2 MSI Data)

- Mean glacier velocity (0-150 m): ~8 m/year

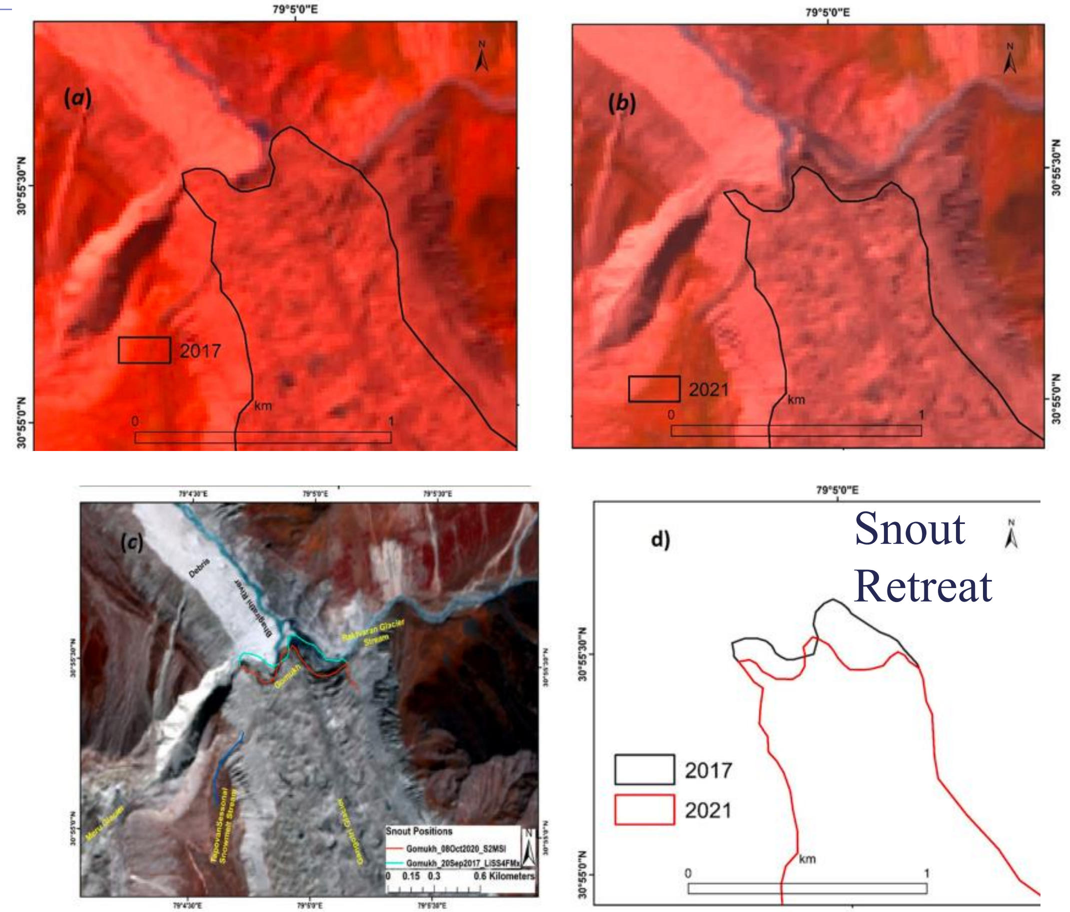


Fig 10: Relative positions of Gomukh snout during 2017 and 2021 time period. Thakur, P.K., Pandey & Chauhan, P (2023)

Result 2 - Singh H., et al.

- Evolution of Shisper ice-dammed lake: The Shisper lake bifurcated which led to one part blocking water flow in Mochowar glacier and other part continued to flow downstream.

- Glacier velocity:

Ablation zone: Melt velocity 12.02 m/year and maximum velocity 111.42 m/year.

Accumulation zone: Melt velocity 1.91 m/year and maximum velocity 62.88 m/year

- Ice thickness and lake formation at Mochowar glacier: Maximum glacier thickness 409.31 m

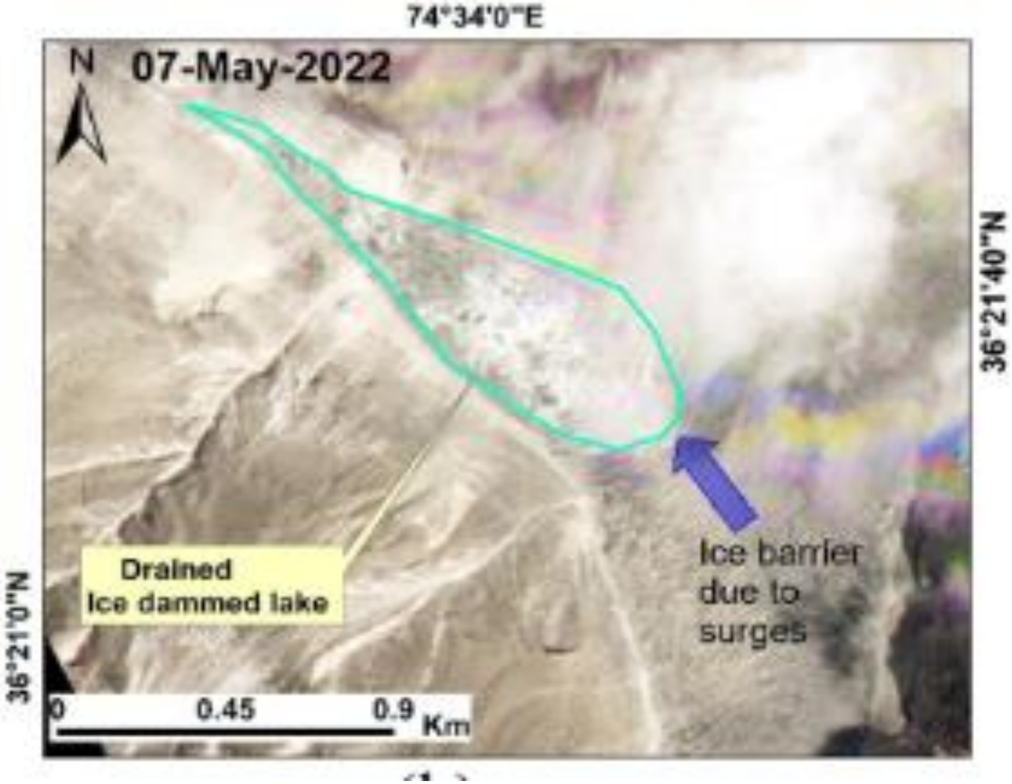


Fig 11: Ice dammed lake formed due to Shisper lake surge
Source: Singh H et. Al (2023)

Result 2 - Singh H. et al.

- Potential lake in Mochowar terminus has Length 1.2 km, Area 0.22 km2, Maximum depth 146.77 m^2 and Volume 3.9 MCM.
- GLOF simulation for Shisper lake: Modelled for May 2022 at 7:00 am Peak flow 1505 m3/s. Flood travelled 8.7 km in 28 min.
- Investigation of stream morphological changes: For May 2022 GLOF event, there was 4 times increased in surface area and stream width (15.43 m to 62.08 m) .
- GLOF Susceptibility Potential Mochowar lake 0.76
- GLOF Susceptibility Shisper ice dammed lake 0.94.

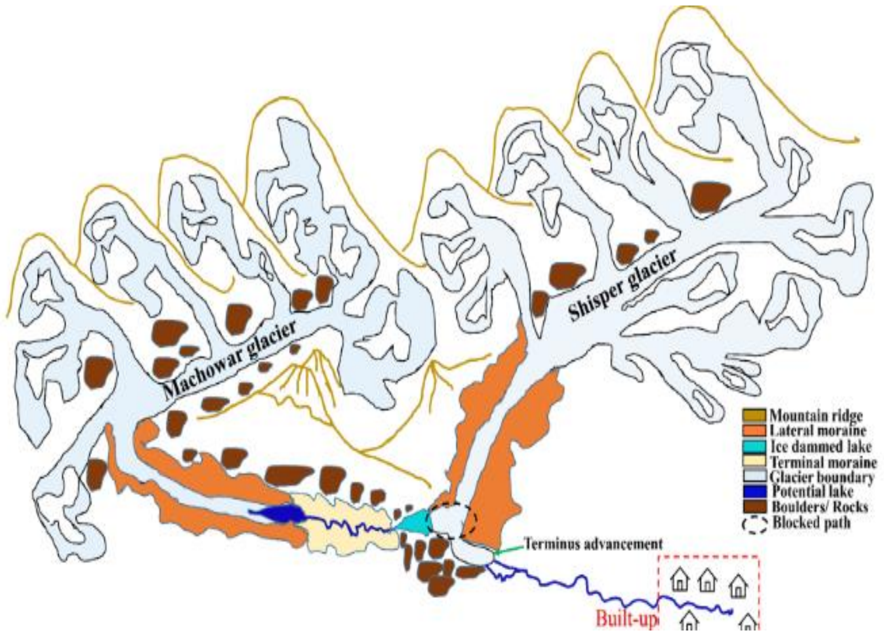


Fig 12: Present and future scenario of Shisper and Mochowar glacial system
Source: Singh H et. Al (2023)

Results 3 - Ziyang et al.

Verify the feasibility of the model

Plotted the ROC curve

Outburst susceptibility assessment model

$P(Y=1)= \{1 + \exp[-(-12.424 + 4.88X_1 + 3.17X_2 + 0.109X_3 + 0.196X_4 + 0.141X_5 - 3.294X_6)]\}^{-1}$

The results of the outburst susceptibility of MDLs

1. We detected the increment of the glacier lakes number as well as total area covered at the rate of 0.78 lakes per year and 0.24km^2 per year respectively.
2. On the opposite glacier number and area covered decreased at the rate of 2.55 per year and 12.83 km^2 per year respectively. Especially in the lakes like Jionglaco (191.49%) and Dongguanlaco (172.15%).
3. In the Yigong Tsangpo Basin we found 11high-risk Mdls, 21medium-risk MDLs and 72 low-risk MDLs are present. The high risk MDLs are mainly distributed in western side of the basin at the elevation between 4000m to 5000m.

Results 3 - Ziyang et al.

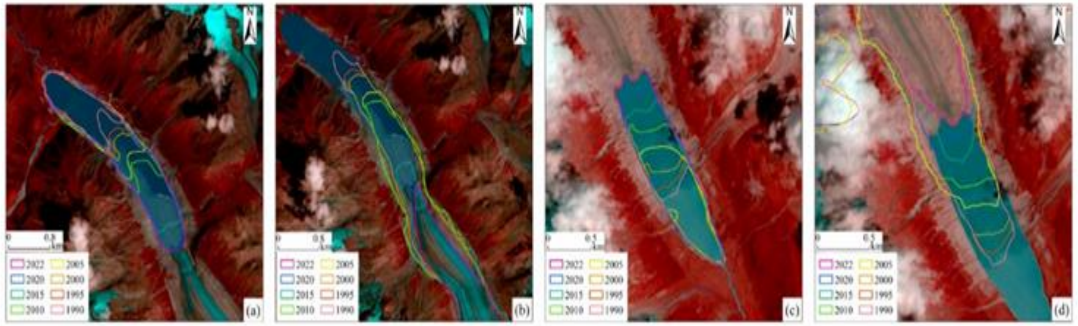


Fig. 13: Change process of typical glacial lakes and the tongues of their parent glaciers. (a) Jionglaco; (b) tongue of the Jionglaco parent glacier; (c) Dongguanlaco; (d) tongue of the Dongguanlaco parent glacier, Ziyang et al. 2024

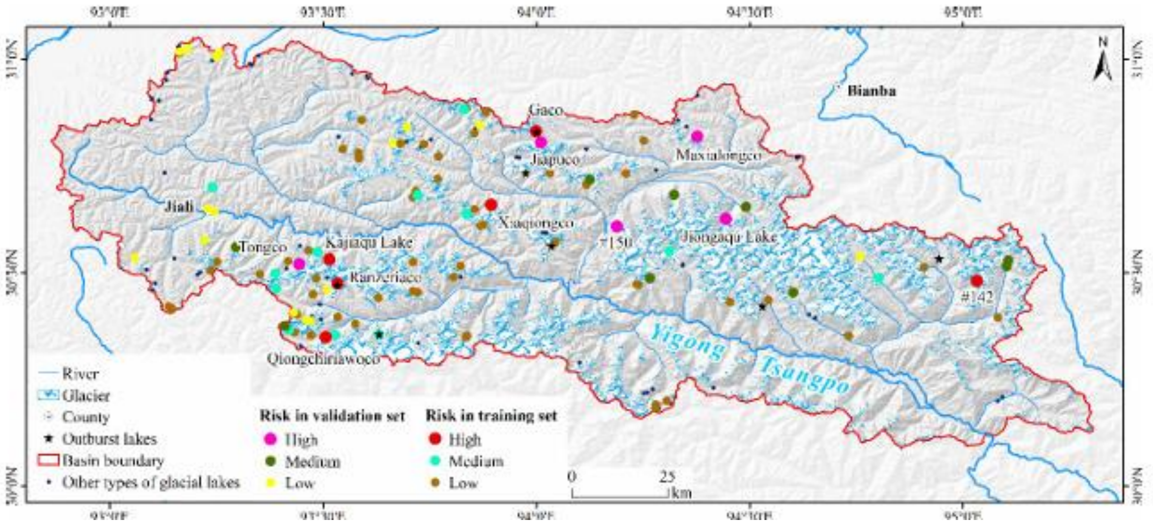


Fig 14: Risk levels of MDLs in the Yigong Tsangpo Basin, Ziyang et al. 2024

Results 4 - ZHOU B. et al.

Key Findings from GLODF Susceptibility Analysis

Best Performing Model:

- WOA-SVC achieved the highest prediction accuracy, outperforming RF and GTB.

High-Risk GLODF Zones Identified:

• High & Very High Susceptibility Areas are concentrated in the Eastern & Central Himalayas.

• China-Nepal Border is the most critical transboundary hotspot for GLODF threats.

• **128** Catchments Identified with Potential Transboundary Threat (CPTT) – with **23** Very High Susceptible and **29** High Susceptible.

•**34** % of the Overall region is identified as the Susceptible (Very High and High)

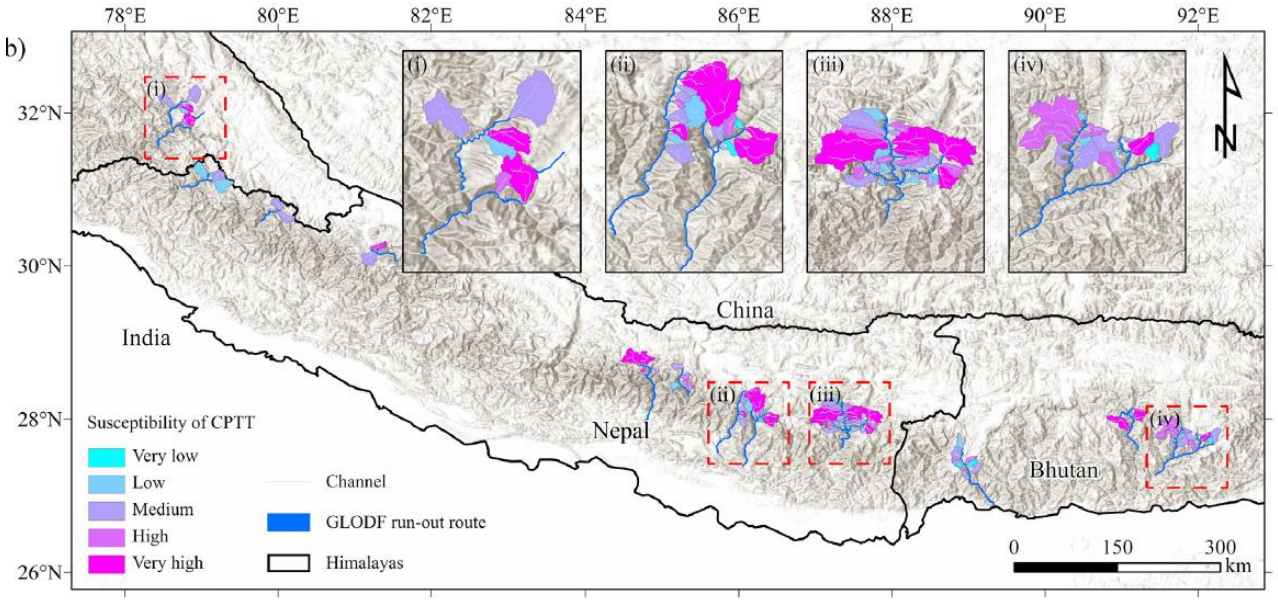


Fig 15: Susceptibility of catchments with the potential transboundary threat in the Himalayas

Source: ZHOU B. et al. / Advances in Climate Change Research 15 (2024) 500e514

Results 4 - ZHOU B. et al.

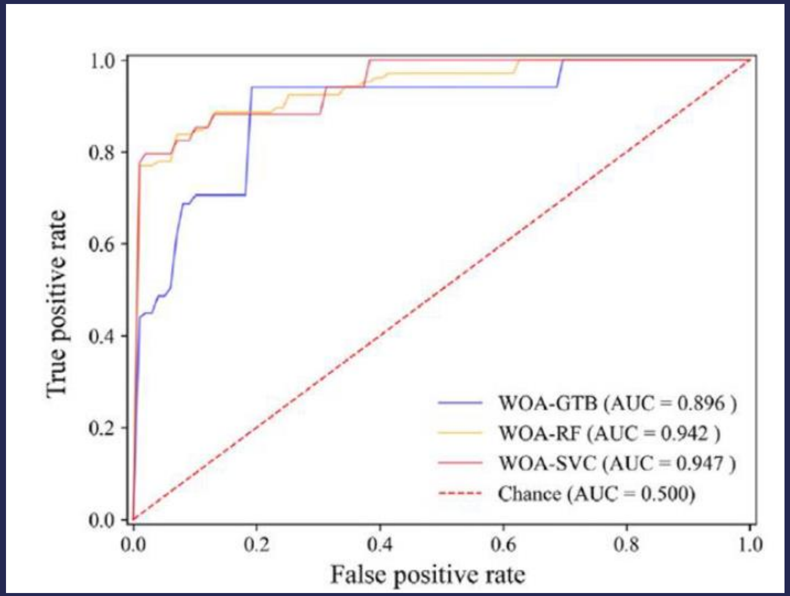


Fig 16: ROC curve of three models

Model Validation & Accuracy Metrics:

- AUC Scores: WOA-SVC > RF > GTB
- High reliability confirmed by ROC-AUC analysis

Factor	Impact on GLODF	Influence percentage (%)
Topographic Potential	Steeper slopes mean higher risk. More critical factor.	39.96
Potential Flood Volume	Bigger lakes mean more damage	11.76
Annual mean Temperature	Increase in Global warming meltwater and making GLODF's more common.	~ 10
Excess Volume	Loose rocks in the flood path make the flow worse.	7.39
Glacier lake volume	Change in the volume leads, increase in the flow rate.	6.30
Propagation probability index	How fat the debris will travel	5.28
Connectivity Index	How easily the debris flows	5.14

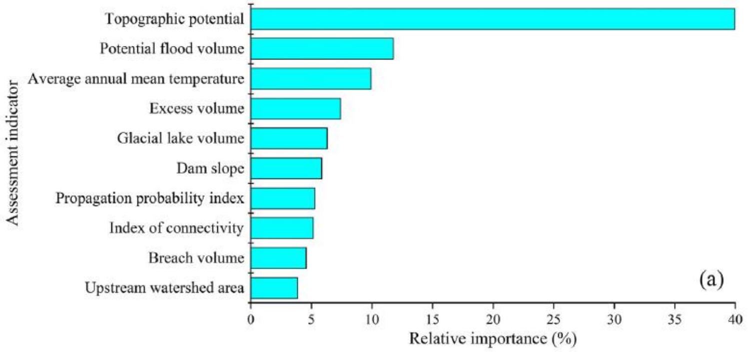


Fig 17: Relative importance and distribution of assessment indicators

Conclusion

- The assessment confirms an increasing susceptibility to glacier outbursts in the Himalayan region.
- High-risk levels indicate a strong possibility of future glacier floods affecting downstream villages.
- These findings highlight the urgent need for proactive risk mitigation strategies.
- Authorities must implement appropriate measures to reduce potential hazards and protect vulnerable communities.
- Continued monitoring and adaptation strategies are essential for long-term resilience against glacier-related disasters.

Practical Implications:

✓ Early warning systems for Disaster management

✓ Guides policymakers in transboundary hazard mitigation

References

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