



1 **Glacial Lake Outburst Flood Hazard Assessment in the Upper Indus Basin, Ladakh**
2 **Himalaya Using Remote Sensing and Hydrodynamic Modeling**

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6 **Abstract**

7 The Indian Himalayan Region (IHR), often called the “Third Pole,” contains the largest
8 concentration of glaciers and perennial snow outside the polar regions and is highly sensitive
9 to climate change. Rapid glacier retreat has accelerated the formation and expansion of glacial
10 lakes, increasing the likelihood of Glacial Lake Outburst Floods (GLOFs). This study presents
11 a multi-site GLOF hazard assessment of four glacier-fed lakes associated with the Gya, Raru,
12 and Panikhar glaciers in the Upper Indus Basin, Ladakh. Spatio-temporal lake-area changes
13 were mapped using Sentinel-2 imagery and geographic information system (GIS) techniques,
14 while lake depth and volume were estimated using empirical relationships supported by digital
15 elevation model analysis. Dam-break simulations using the Hydrologic Engineering Center’s
16 River Analysis System (HEC-RAS) were conducted for 25%, 50%, 75%, and 100% lake-
17 volume release scenarios for the Gya, Raru, and Panikhar lakes. Simulation outputs provided
18 peak discharge, flow velocity, flood depth, and inundation extent. Results show that worst-case
19 scenarios could affect downstream infrastructure such as bridges and roads, whereas the
20 Rumbak lake poses limited hazard potential because of its low volume and natural moraine
21 buffering. The hazard maps developed in this study support risk prioritization, early-warning
22 planning, and climate-resilient disaster management in the Indian Himalaya.

23 **Keywords:** GLOF, IHR, Sentinel-2, HEC-RAS, dam-break modeling, flood inundation
24 mapping.



25 **1. Introduction**

26 Mountain glaciers worldwide are retreating rapidly due to climate warming, causing major
27 geomorphic and hydrological changes in high-altitude regions. One significant consequence of
28 glacier recession is the formation and expansion of glacial lakes behind unstable moraine or
29 ice dams (Zemp et al., 2009; Bolch et al., 2012; Nie et al., 2017). These lakes can store large
30 volumes of meltwater and may suddenly release catastrophic Glacial Lake Outburst Floods
31 (GLOFs), among the most destructive hazards in mountain environments.

32 A GLOF occurs when a moraine- or ice-dammed lake breaches due to structural instability or
33 external triggers, releasing large volumes of water, sediment, and debris (Richardson &
34 Reynolds, 2000; Emmer & Vilimek, 2013). Such floods propagate rapidly through steep and
35 confined valleys, generating high flow velocities and extreme peak discharges capable of
36 destroying infrastructure, agricultural land, and settlements. Triggers include glacier calving
37 (Zhang et al., 2020), snow or ice avalanches (Schaub et al., 2016), landslides, intense rainfall
38 or cloudburst events (Bhambri et al., 2016), permafrost degradation, and seismic activity
39 (Kargel et al., 2016). In some cases, flood waves can travel over 100 km downstream,
40 impacting communities far from the source.

41 Globally, nearly 15 million people are exposed to potential GLOF hazards, with the highest
42 vulnerability in the Himalayan and Andean regions (Taylor et al., 2023). The steep topography
43 and fragile moraine dams of the Himalaya intensify downstream impacts (Mool, 1995;
44 Reynolds, 1998; Worni et al., 2013). Recent disasters, including the Chorabari Lake outburst
45 during the 2013 Kedarnath catastrophe and the 2023 South Lhonak Lake GLOF in Sikkim,
46 highlight the urgent need for systematic hazard assessment and monitoring.

47 The Indian Himalayan Region (IHR), often called the “Third Pole,” contains the largest
48 concentration of glaciers outside the polar regions. These glaciers feed major river systems



49 such as the Indus, Ganga, and Brahmaputra, sustaining millions downstream. However,
50 accelerated glacier retreat has led to rapid growth in glacial lakes across High Mountain Asia,
51 particularly in Nepal, Bhutan, Tibet, and northern India (Bolch et al., 2012; Veh et al., 2020;
52 Bajracharya et al., 2007; Emmer et al., 2020; Ashraf et al., 2021). Studies in the Upper Indus
53 and Jhelum basins have identified several high-risk lakes (Gupta et al., 2021; Ahmed et al.,
54 2022).

55 In Ladakh, located in the Trans-Himalayan region, numerous moraine-dammed lakes have
56 formed due to glacier retreat. Although glacier retreat rates are comparatively slower than in
57 the eastern Himalaya, ongoing warming and precipitation variability are likely to increase
58 future GLOF risk. Previous studies have investigated individual lakes, such as the
59 reconstruction of the 2014 Gya GLOF (Majeed et al., 2021) and hazard assessments in the
60 Zaskar Valley (Mir et al., 2018). These studies demonstrate the importance of integrating
61 remote sensing and hydrodynamic modeling (Sattar et al., 2019; Ahmed et al., 2023; Rawat et
62 al., 2023).

63 Despite increasing research, significant knowledge gaps remain in the western Himalaya,
64 where many lakes are remote and lack field data. Remote sensing from Sentinel-2, Landsat-8,
65 and Landsat-9 enables mapping of lake extent and glacier retreat, while digital elevation
66 models support volume estimation and terrain analysis. Hydrodynamic models such as HEC-
67 RAS simulate dam-break scenarios to estimate peak discharge, flow depth, velocity, and
68 inundation extent. Scenario-based simulations are essential for disaster risk reduction and
69 infrastructure planning.

70 Given accelerating glacier retreat and extreme weather events, comprehensive multi-lake
71 hazard assessments integrating remote sensing and hydrodynamic modeling are urgently
72 needed in Ladakh to support climate-resilient development and GLOF risk mitigation.

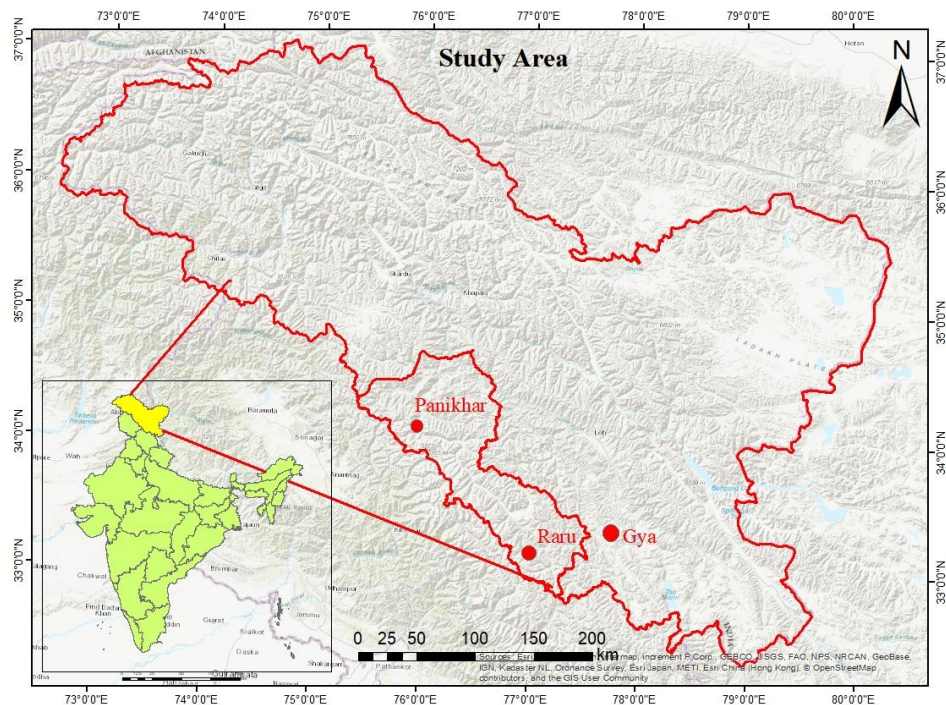


73 2. Study Area

74 The study area is located in Ladakh, in the northwestern Trans-Himalaya of the Indian
75 Himalayan Region, and includes three glacier-fed lake systems associated with the Gya, Raru,
76 and Panikhar glaciers in the upper Indus Basin. The region lies between 33°–35° N and 75°–
77 78° E, with Gya in Leh district and Panikhar and Raru in Kargil district. Ladakh is a high-
78 altitude cold desert ranging from ~3700 m to >6400 m a.s.l., bounded by the Zaskar, Ladakh,
79 and Karakoram ranges and shaped by active glacial and geomorphic processes (Raina & Koul,
80 2011).

81 Gya village (~4010 m) lies near Taglang La along the historic Leh–Manali route, where a
82 glacier-fed valley and retreating Gya Glacier raise GLOF concerns (Schmidt & Nüsser, 2012;
83 Gazetteer of Kashmir and Ladakh). The second site, Panikhar (~4062 m), is located in the Suru
84 catchment above Panikhar and Pranti villages, ~15 km from Parkachik Glacier, with potential
85 downstream GLOF exposure. The Raru lake (~4563 m) in the Tsarap catchment shows a steep
86 23-km downstream gradient indicating high flow energy.

87 According to Office of the Registrar General & Census Commissioner, India (Census
88 2011/2021; <http://censusindia.gov.in/>), the study villages have small high-altitude populations:
89 Gya – 658 people (140 houses), Panikhar & Pranti – 843 people (124 houses), Raru – 329
90 people (60 houses). These glacier-fed systems and settlements highlight the region's
91 vulnerability to glacial hazards and climate-driven hydrological change.



92
93 Fig. 1 Location of the GLOF study sites (Gya, Panikhar and Raru) in Ladakh. Credit: Basemap:
94 Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS
95 User Community (ArcGIS World Topographic Map); administrative boundaries: Survey of
96 India.

97 **3. Data Set Used**

98 This study employed multispectral imagery from Sentinel-2 (10 m spatial resolution) of the
99 European Space Agency to delineate glacial lakes and their associated glaciers and to quantify
100 lake-area changes for the period 2018–2025 in selected glacier basins of Ladakh. Extracted
101 lake boundaries were validated and refined using high-resolution historical imagery available
102 in Google Earth Pro. Topographic information was derived from the ALOS PALSAR DEM,
103 where ALOS PALSAR stands for Advanced Land Observing Satellite – Phased Array type L-
104 band Synthetic Aperture Radar, provided by Alaska Satellite Facility. This DEM was used to
105 generate elevation, slope, flow direction, and channel geometry required for hydrodynamic
106 simulations. Dam-break and flood-routing simulations for multiple breach scenarios were



107 carried out using HEC-RAS developed by the US Army Corps of Engineers to estimate peak
108 discharge, flow velocity, flood depth, and downstream inundation extent. The integration of
109 satellite imagery, high-resolution DEM data, and hydrodynamic modeling provided a reliable
110 dataset framework for assessing Glacial Lake Outburst Flood hazards in the Indian Himalayan
111 Region.

	Data	Year	No.of Bands	Spatial Resolution	Source	Purpose
1	Sentinal-2	2024	13	10m	Copernicus https://browser.dataspace.copernicus.eu	Lake mapping
2	ALOS-PALSAR		1	12.5m	ASF Data Search	Hydrodynamic Modeling
3	Google Earth Pro	2022		0.5-30m	Google Earth pro	LU/LC Mapping

112 Table.1. Datasets used in the Study

113 **4. Methods**

114 Glacial lake boundaries in this study were delineated manually using multispectral imagery
115 from Sentinel-2 provided by the European Space Agency. Lake mapping was carried out for
116 the period 2018–2025 using images acquired during the September post-monsoon season,
117 when cloud cover is minimal and lake-water contrast with surrounding snow, ice, and debris is
118 highest. This seasonal selection improved the accuracy of lake-boundary interpretation in the
119 high-altitude terrain of Ladakh. The outlines of glacial lakes were digitized manually to avoid
120 classification errors commonly associated with automated indices in areas affected by debris
121 cover, shadows, seasonal snow, or partially frozen water surfaces. High-resolution reference
122 imagery from Google Earth Pro was used to verify lake boundaries and ensure consistency
123 across years. This approach enabled reliable estimation of recent glacial lake area changes in
124 the selected glacier basins while minimizing mapping uncertainties in complex Himalayan
125 terrain.

126



127 **4.1 Estimation of Glacial Lake Depth, Volume, and Peak Discharge**

128 The depth, storage volume, and potential peak discharge of a glacial lake are key parameters
129 for assessing the magnitude of possible Glacial Lake Outburst Flood (GLOF) hazards. Because
130 direct field measurements in the remote and high-altitude glacier basins of Ladakh within the
131 Indian Himalayan Region are logistically challenging and resource intensive, glacial lake depth
132 and volume were estimated using widely accepted empirical relationships derived from lake
133 area and basin geometry. Such empirical approaches have been widely applied in Himalayan
134 studies, including those by Evans (1986), Huggel et al. (2002), Wang et al. (2011), Fujita et al.
135 (2013), Emmer and Vilímek (2013), Patel et al. (2017), and Qi et al. (2022).

136 In this study, glacial lake areas extracted from Sentinel-2 imagery were used as input for these
137 empirical equations to estimate lake depth, volume, and potential peak discharge. To reduce
138 uncertainty associated with individual equations, lake volumes were calculated using multiple
139 formulas, and the final value for each lake was obtained by averaging the results. Among the
140 tested relations, the equations proposed by Qi et al. (2022) provided estimates closest to the
141 overall mean and were therefore considered most representative for lakes larger than 0.1 km²
142 in the study area, as these equations incorporate both lake surface area and basin geometry for
143 improved accuracy.

144 The derived lake volumes were subsequently used as input parameters in dam-break
145 simulations performed using HEC-RAS developed by the US Army Corps of Engineers to
146 estimate peak discharge and downstream flood characteristics under different breach scenarios.

147 For lakes larger than 0.1 km² $V = 40.671 \cdot A^{0.184} - 3.218 \cdot A$ mxw mxl

148 For lakes smaller than 0.1 km² $V = 557.42 \cdot A^{0.455} - 0.2005 \cdot A$ mxw mxl

149



150

Empirical Equation	Parameter Calculated	Reference
$D = 0.104 \times A^{0.42}$	Lake Depth	Huggel et al. (2002)
$D_m = 55 \times A^{0.25}$	Lake Depth	Fujita et al. (2013)
$D_m = 4 \times 10^{-5} \times A^{5.0564}$	Lake Depth	Patel et al. (2017)
$V = 0.104 \times A^{1.42}$	Lake Volume	Huggel et al. (2002)
$V = 0.035 \times A^{1.5}$	Lake Volume	Evans (1986)
$V = 0.0578 \times A^{1.4683}$	Lake Volume	(Liu et al., 2020)
$V = 40.67 \frac{mxw}{mxl} - 3.218$	Lake Volume	
$V = 557.42.455 + 0.2005 \frac{mxw}{mxl}$	Lake Volume	Qi et al. (2022)
$V = A \times D_m$	Lake Volume	Patel et al. (2017)
$V = 0.104 \times A^{1.42}$	Lake Volume	Cook & Quincey (2015)
$V = 0.042 \times A^{1.59}$	Lake Volume	Lamsal (2014)
$V = 0.035 \times A^{1.5}$	Lake Volume	Sakai (2012)
$Q_{max} = 0.00077 \times V^{1.017}$	Peak discharge	Huggel et al. (2002)
$Q_{max} = 0.72 \times V^{0.53}$	Peak discharge	Evans (1986)
$Q_{max} = 75 \times V^{0.67}$	Peak discharge	Clague & Mathews (1973)
$Q_{max} = 0.045 \times V^{0.66}$	Peak discharge	Costa & Schuster (1988)
$Q_{max} = 0.72 \times V^{0.53}$	Peak discharge	Vuichard & Zimmermann (1987)

151 Table.2. Empirical equations used for depth and volume calculations.

152 4.2 Model Input and Setup

153 Hydrodynamic simulations in HEC-RAS require a high-quality Digital Elevation Model
 154 (DEM) to represent terrain characteristics across the study area. In this research, the DEM
 155 provided the base surface for defining the hydraulic domain extending from the glacial lake
 156 outlet to downstream vulnerable settlements within Ladakh. The terrain data were used to
 157 generate a two-dimensional computational flow area, where the river channel and floodplain
 158 were discretized into a mesh of uniform grid cells.

159 Each cell in the computational mesh was assigned essential hydraulic parameters, including
 160 elevation values derived from the DEM and Manning's roughness coefficient (n), which
 161 represents surface resistance to flow based on land-cover conditions. For terrain representation,
 162 the ALOS PALSAR DEM developed by Japan Aerospace Exploration Agency and distributed



163 by the Alaska Satellite Facility was used because of its relatively high spatial resolution and
164 suitability for mountainous terrain. This DEM enabled accurate extraction of channel profiles,
165 slope gradients, and floodplain geometry, which are critical inputs for realistic dam-break and
166 flood-routing simulations in the upper Indian Himalayan Region.

167 **4.3 Model Outputs and Analysis**

168 The two-dimensional simulations performed using HEC-RAS produced spatially distributed
169 results such as flood-depth maps, flow-velocity patterns, and inundation extents across the
170 downstream valleys. These outputs were analyzed along the flow path from each glacial lake
171 to downstream settlements in Ladakh to understand flood-wave propagation under overtopping
172 breach scenarios. The modeled depth and velocity distributions helped identify zones of severe
173 hydraulic impact, while inundation maps highlighted infrastructure, transport routes, and
174 habitation areas likely to be affected.

175 By combining high-resolution terrain information, hydraulic parameters, and breach
176 characteristics, the simulations provided a detailed representation of possible flood behaviour
177 in glacier-fed basins of the Indian Himalayan Region. These model outputs offer valuable
178 guidance for hazard zonation, early-warning planning, and disaster-risk reduction strategies in
179 areas vulnerable to Glacial Lake Outburst Flood events.

180 **4.4 GLOF Modelling**

181 The two-dimensional (2D) GLOF simulations for the selected glacial lakes were performed
182 using HEC-RAS 2D (Version 6.7beta5) to model overtopping breach scenarios, one of the most
183 critical mechanisms responsible for Glacial Lake Outburst Floods. The modelling aimed to
184 evaluate potential downstream flood impacts and to quantify flood extent, depth, and flow
185 velocity affecting valley systems and infrastructure. HEC-RAS 2D has been widely applied in



186 high-mountain environments due to its capability to represent complex terrain and simulate
187 hydrodynamic flow.

188 All three investigated lakes—Gya, Panikhar, and Raru—are moraine-dammed proglacial lakes,
189 though they differ significantly in morphometry and topographic setting. The Gya Lake has an
190 area of 0.062 km² at an elevation of 5,399 m, located 89 m from its parent glacier (0.846 km²)
191 with an average glacier slope of 31.3° and a 12° slope between the glacier and lake. The
192 Panikhar lake (0.589 km²; 4,120 m) is situated 303.65 m from a 4.30 km² glacier with a 33.3°
193 average slope. The Raru lake (0.542 km²; 4,489 m) is associated with a 21.71 km² glacier
194 exhibiting a steep 48° slope. These morphometric and topographic characteristics were
195 incorporated into the hydrodynamic simulations to assess relative GLOF hazard potential
196 across the study sites.

197

198 **5. Results**

199 **5.1 Temporal Changes in Glacial Lake Area**

200 The temporal analysis of three glacier-fed lakes in Ladakh between 2018 and 2025 reveals
201 contrasting patterns of lake evolution influenced by glacier dynamics, meltwater supply, and
202 geomorphic processes. Panikhar glacial lake shows a consistent and significant increase in area,
203 expanding from 0.3715 km² in 2018 to 0.5897 km² in 2025, indicating enhanced glacier melt
204 and sustained water accumulation. This steady growth suggests increasing hydrostatic pressure
205 on the moraine dam and a rising potential for glacial lake outburst flood (GLOF) hazard.

206 In contrast, Raru glacial lake shows a slow decreasing trend overall, reducing from 0.5754 km²
207 in 2018 to 0.5417 km² in 2025, suggesting reduced meltwater inflow, lake drainage, or
208 geomorphological adjustments within the basin.



209 Gya glacial lake displays a different pattern, with rapid expansion between 2018 and 2021
210 followed by stabilization and decline after 2023, reaching 0.062 km² in 2025. Such fluctuations
211 may be linked to partial drainage events, moraine dam seepage, or reduced glacier melt
212 contribution. Overall, the multi-lake analysis highlights spatial variability in glacial lake
213 behaviour across Ladakh. While Panikhar lake shows continuous expansion and increasing
214 hazard potential, Gya and Raru lakes exhibit declining or fluctuating trends, emphasizing the
215 importance of lake-specific monitoring for accurate GLOF risk assessment and disaster
216 management planning.

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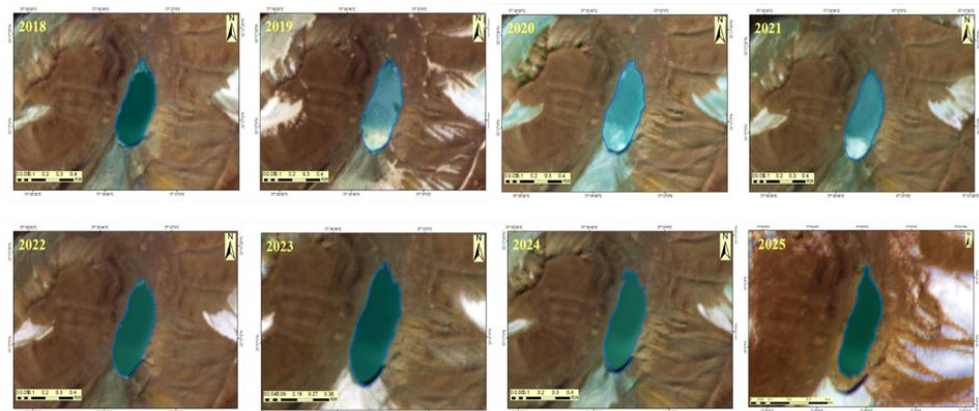
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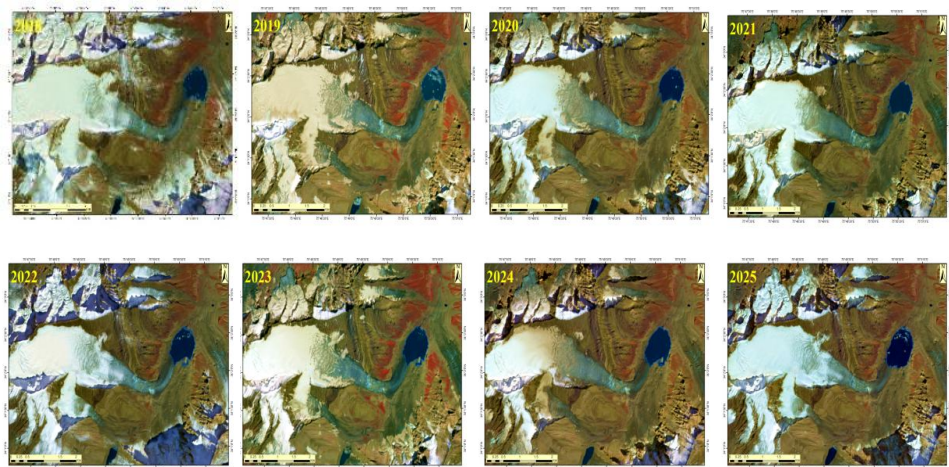


Year	Gya Lake (km ²)	Raru Lake (km ²)	Panikhar Lake (km ²) 223
2018	0.010	0.575424	0.371533 224
2019	0.113	0.559345	0.397993 225
2020	0.114	0.566803	0.413114 226
2021	0.116	0.555156	0.422482 227
2022	0.116	0.551016	0.493914 228
2023	0.108	0.543982	0.512483 229
2024	0.108	0.545378	0.527223 230
2025	0.062	0.541736	0.589737 231

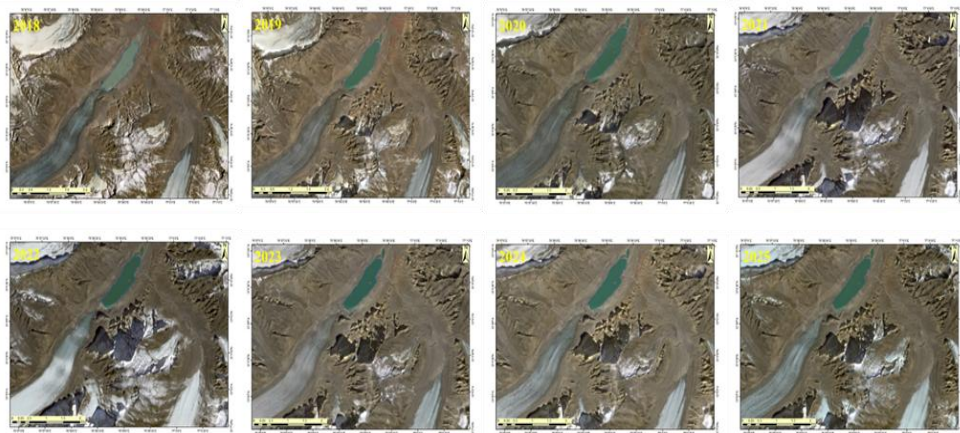
232 Table .3. Temporal variation in area of four glacial lakes (2018–2025)



233
234 Fig. 2. Area change of Gya lake from 2018 to 2025 shown on Sentinel-2 images acquired in
235 September of each year (panel labels indicate the year). Credit: Contains modified Copernicus
236 Sentinel data (2018–2025).



237
238 Fig. 3. Area change of Panikhar lake from 2018 to 2025 shown on Sentinel-2 images acquired
239 in September of each year (panel labels indicate the year). Credit: Contains modified
240 Copernicus Sentinel data (2018–2025).



241
242 Fig. 4. Area change of Raru lake from 2018 to 2025 shown on Sentinel-2 images acquired in
243 September of each year (panel labels indicate the year). Credit: Contains modified Copernicus
244 Sentinel data (2018–2025).

245 **5.2 Glacial Lake Depth, Volume and Peak Discharge Estimation**

246 Glacial lake depth and storage volume were estimated using multiple empirical regression
247 equations commonly applied in GLOF studies, and averaged values were adopted to minimize



248 regional bias following Martin Emmer (2018). The analysis was carried out for three glacier-
249 fed lakes located in Ladakh.

250 For Gya glacial lake, the estimated mean lake depth was 11.32 m, with an average storage
251 volume of $0.724 \times 10^6 \text{ m}^3$. For Panikhar glacial lake, significantly higher values were obtained,
252 with a mean depth of 32.54 m and an average volume of $19.188 \times 10^6 \text{ m}^3$, indicating substantial
253 meltwater accumulation. Raru glacial lake exhibited a mean depth of 31.52 m and an average
254 volume of $17.007 \times 10^6 \text{ m}^3$, while Rumbak glacial lake showed comparatively smaller
255 dimensions, with a mean depth of 5.12 m and an average volume of $0.046 \times 10^6 \text{ m}^3$.

256 Among the tested relations, equations proposed by Koji Fujita et al. (2013) yielded relatively
257 higher depth estimates, whereas volume estimates from Qi Xinyu et al. (2022) were closest to
258 the overall mean values. Other applied empirical relationships included those developed by
259 Christian Huggel et al. (2002), Stephen G. Evans (1986), Jin Liu (2020), Nitin Patel et al.
260 (2017), Samuel Cook and Duncan Quincey (2015), Dawa Lamsal et al. (2014), and Atsushi
261 Sakai et al. (2012).

262 Peak discharge was estimated using empirical relations from Christian Huggel et al. (2002),
263 Stephen G. Evans (1986), John J. Clague and William H. Mathews (1973), John E. Costa and
264 Robert L. Schuster (1998), and Dominique Vuichard and Michael Zimmermann (1987). The
265 averaged peak discharge values were $354.6 \text{ m}^3 \text{ s}^{-1}$ for Gya lake, $5237.5 \text{ m}^3 \text{ s}^{-1}$ for Panikhar
266 lake, $4716.3 \text{ m}^3 \text{ s}^{-1}$ for Raru lake, and $56.4 \text{ m}^3 \text{ s}^{-1}$ for Rumbak lake. These values were used as
267 input parameters in dam-break simulations using HEC-RAS to assess downstream flood
268 hazards in glacier-fed basins of Ladakh.

269 Overall, the results indicate that Panikhar and Raru lakes possess substantially larger storage
270 volumes and peak discharge potential compared to Gya and Rumbak lakes, suggesting higher



271 GLOF hazard susceptibility and the need for continuous monitoring and risk mitigation
272 planning.

Emp. Equation	Depth (m)	Volume (M m3)	Peak Discharge (m3/s)
Huggel(2000)[Global]	10.85 m	0.698	700.9m ³ /s
Fujita(2013)	27.66m	-	-
Evans(1986)[Global]	-	0.566	918.1m ³ /s
Liu (2020)[Himalaya]	-	0.658	-
Qi (2022) [General]	-	0.672	-
Patel (2017)[India]	7.61m	0.487	-
Cook & Quincey (2015) [Sikkim]	-	1.278	-
Lamsal (2014) [Nepal]	-	0.658	-
Sakai (2012) [Himalaya]	-	0.776	-
Clague & Mathews (1973)	-	-	60.4 m ³ /s
Costa & Schuster (1998)	-	-	91.9 m ³ /s
Vuichard & Zimmermann (1987)	-	-	1.8 m ³ /s
Average	11.32m	0.724	354.6 m ³ /s

273 Table.4. Gya volume depth and peak discharge

274



Emp. Equation	Depth (m)	Volume (106 m ³)	Peak Discharge (m ³ /s)
Huggel(2000)[Global]	27.59 m	16.269	19648.3m ³ /s
Fujita(2013)	48.20 m	-	-
Evans(1986)[Global]	-	15.851	5216.0 m ³ /s
Liu (2020)[Himalaya]	-	17.179	-
Qi (2022) [General]	-	19.790	-
Patel (2017)[India]	28.65 m	16.896	-
Cook & Quincey (2015) [Sikkim]	-	25.638	-
Lamsal (2014) [Nepal]	-	20.140	-
Sakai (2012) [Himalaya]	-	21.738	-
Clague & Mathews (1973)	-	-	542.9
Costa & Schuster (1998)	-	-	748.5
Vuichard & Zimmermann (1987)	-	-	31.0
Average	32.54m	19.188	5237.5 m ³ /s

275 Table.5. Panikhar volume depth and peak discharge

Emp. Equation	Depth (m)	Volume (M m ³)	Peak Discharge (m ³ /s)
Huggel(2000)[Global]	26.62 m	14.422	17452.2m ³ /s
Fujita(2013)	47.19m	-	-
Evans(1986)[Global]	-	13.956	4903.5m ³ /s
Liu (2020)[Himalaya]	-	15.165	-
Patel (2017)[India]	26.73m	14.480	-
Cook & Quincey (2015) [Sikkim]	-	22.862	-
Lamsal (2014) [Nepal]	-	17.672	-
Sakai (2012) [Himalaya]	-	19.139	-
Clague & Mathews (1973)	-	-	502.1m ³ /s
Costa & Schuster (1998)	-	-	694.7m ³ /s
Vuichard & Zimmermann (1987)	-	-	28.8m ³ /s
Average	31.52m	17.077	4716.3m ³ /s

276 Table.6. Raru volume depth and peak discharge

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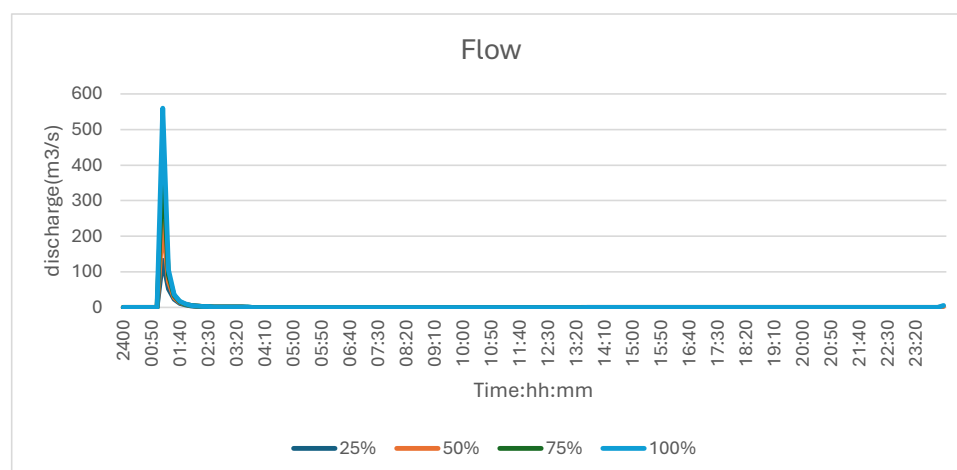
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279 5.3 Gya

280 **Dam-break simulations using HEC-RAS were conducted for the Gya glacial lake in**
 281 **Ladakh to evaluate downstream flood behaviour.**

282 For the 50% lake-volume release, the peak discharge at the breach was 239.68 m³/s, with a
 283 mean channel discharge of 2.63 m³/s and mean flood depth of 0.27 m. The routed hydrograph
 284 indicated a slow flood wave with no significant downstream inundation or expected damage
 285 infrastructure.



286

287 Fig.5.Breach hydrographs depicting peak discharge at the breach in overtopping failures 25%,
 288 50%75%&100% volume of the Gya lake.

289 Under the 100% release (worst-case scenario), the peak discharge increased to 559.9 m³/s, and
 290 the flood wave reached Gya village in about 1 hour 10 minutes, affecting an estimated 1.01
 291 km² area with a mean flood depth of 0.77 m. Flood intensity varied along the channel depending
 292 on local terrain and valley confinement.

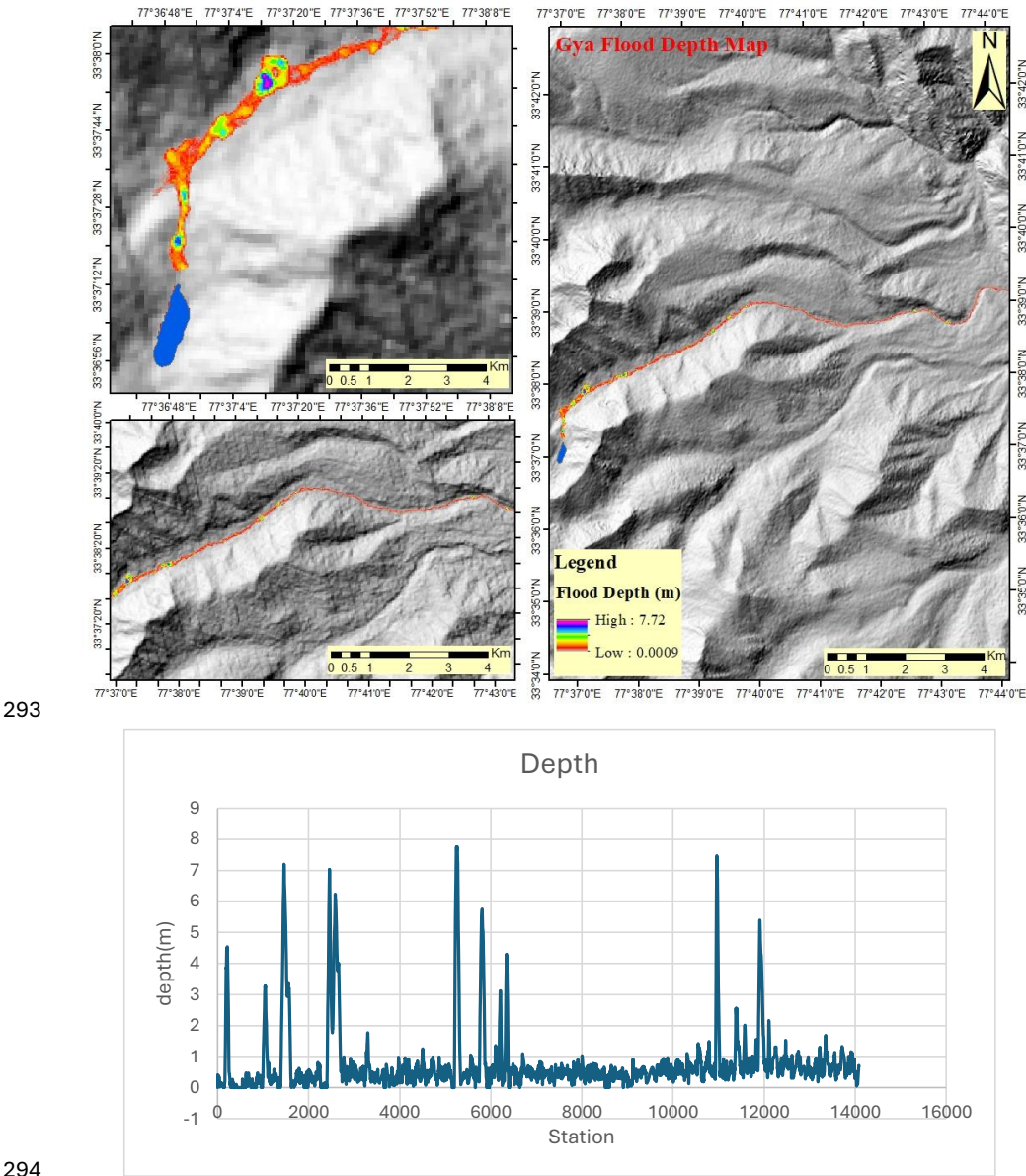
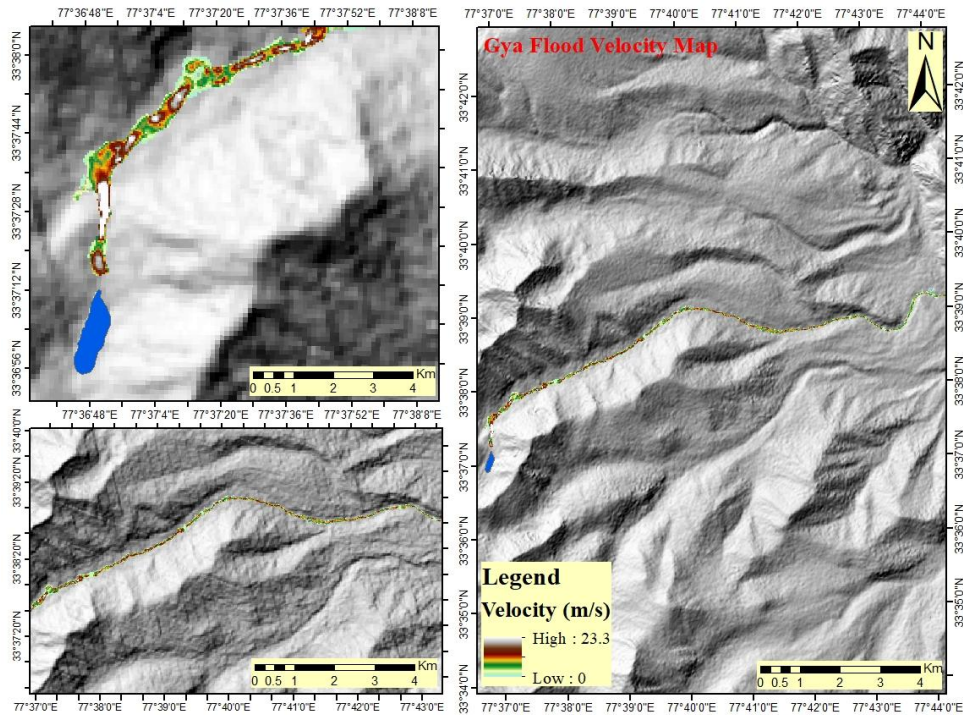


Fig.6. Flood depth along the downstream flow channel of Gya lake for the 50 % volume release scenario: depth map (top) and depth profile along the channel (bottom). Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from ALOS PALSAR

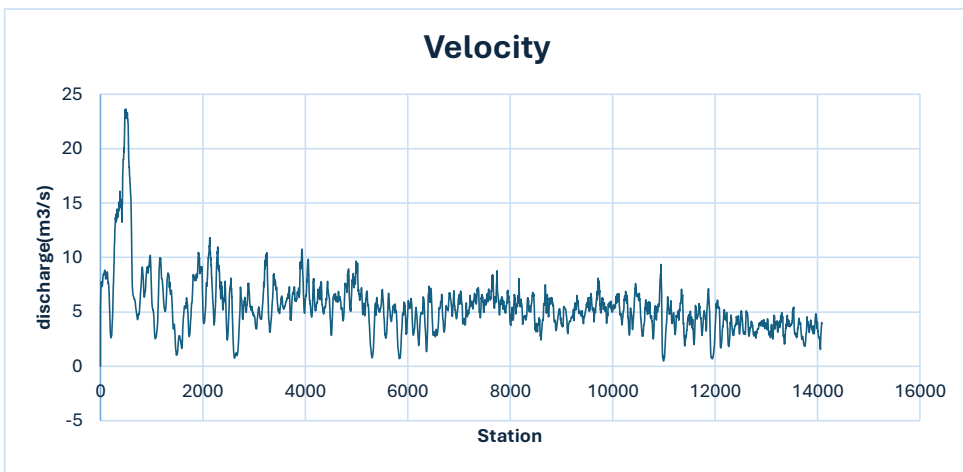


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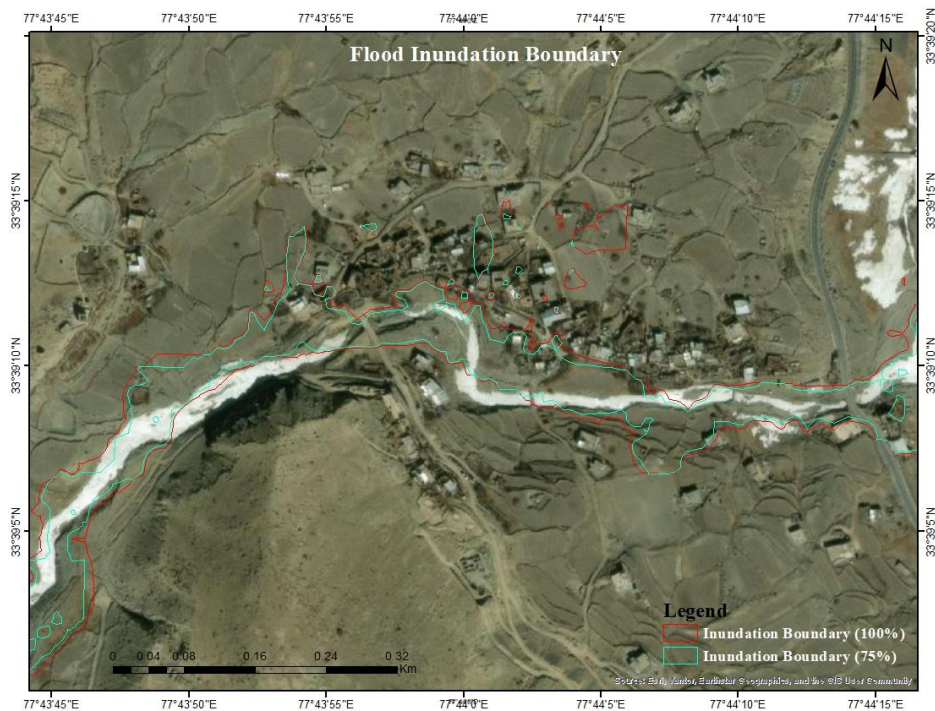


300

301 Fig.7. Flood velocity along the downstream flow channel of Gya lake for the 50 % volume release
302 scenario: velocity map (top) and velocity profile along the channel (bottom). Credit: Flood simulation
303 by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from ALOS PALSAR
304 DEM © JAXA/METI, distributed by ASF DAAC



305 **.Inundation Boundary of Breach Scenario**



306 Fig.8. Inundation extent downstream of Gya lake, near Gya village, for the 75 % and 100 % volume
307 release scenarios. Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-
308 HEC); basemap: Esri, Maxar, Earthstar Geographics, and the GIS User Community (ArcGIS World
309 Imagery).

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Breach	Total Flow	Inundation	
20%	132.6	0.19 km ²	313
50%	239.68	0.42 km ²	314
75%	366.38	0.87 km ²	315
100%	559.9	1.01 km ²	316

Table.7. Inundation Area Gya

100%	559.9	1.01 km ²	318
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320

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Name	Area
Agriculture Field	1.0 ha
Built -up	0.19 ha
Fallow Land	0.22 ha
Road	0.03 ha

Table.8. Area under Vulnerability Zone

Under the worst-case (100% drainage) breach scenario of GYA Lake simulated in HEC-RAS, the flood wave shows spatially variable impacts on downstream infrastructure. Settlement 1 experiences minor flooding (mean depth 0.02 m; max 0.35 m; velocity 1.53 m/s), whereas Settlement 2 shows higher hazard (mean 0.21 m; max 1.13 m; velocity 2.27 m/s). Bridge sites display strong hydraulic variability, with Bridge 1 recording the highest flow velocity (4.58 m/s), Bridge 2 showing minor inundation, and Bridge 3 moderate flow concentration. These variations are mainly controlled by local channel slope, valley confinement, and geometry, as summarized in Table 8 for downstream locations of GYA Lake.

Location	Mean Depth	Max Depth	Peak Discharge(m/s
Settlement 1	0.02	0.35	1.53
Bridge1	0.03	0.75	4.58
Settlement 2	0.21	1.13	2.27
Bridge 2	0.006	0.37	0.65
Bridge 3	0.03	0.05	4.36

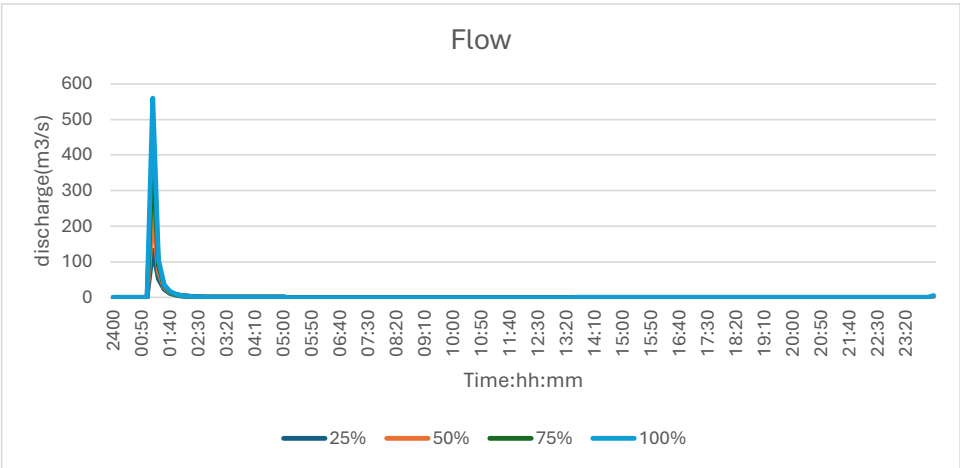
Table.9. Flood parameters at various locations of the flow path downstream of Gya Lake for the worst-case scenario i.e. 100% water release.

5.4 Panikhar

For the 50% lake-volume release scenario, the peak discharge at the breach of the Panikhar glacial lake was estimated to be 6577.21 m³/s, with a mean channel discharge of 109.03 m³/s



338 and a maximum flood depth of 5.16 m. The routed hydrograph indicates that the flood wave
339 would reach Panikhar village approximately 50 minutes after the breach, inundating an
340 estimated 4.12 km² area along the valley. Floodwaters are expected to affect downstream
341 bridges, roads, and residential areas under this partial-drainage condition.

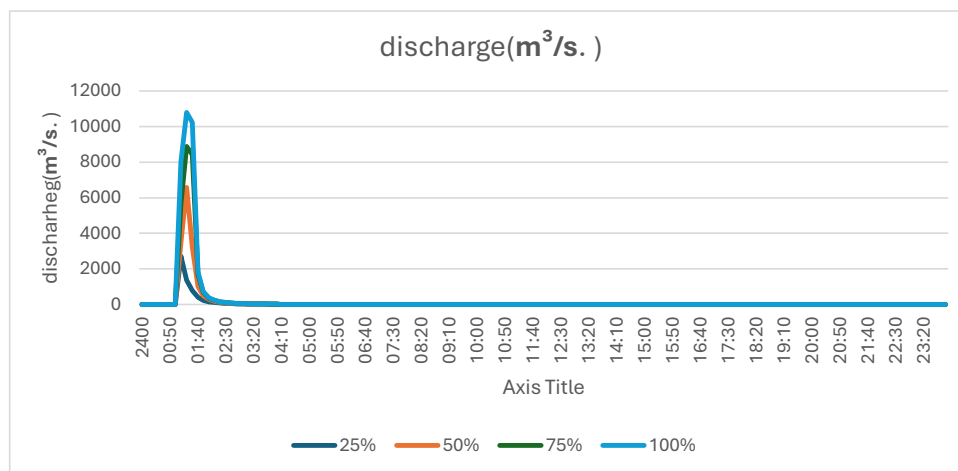


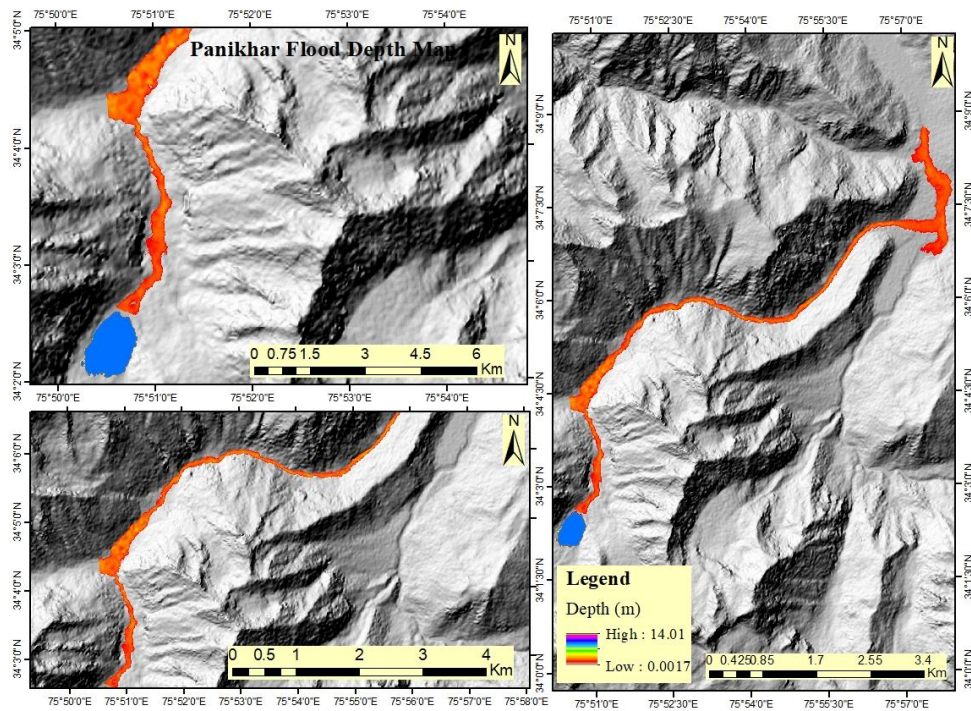
342
343 *Fig.9.Breach hydrographs depicting peak discharge at the breach in overtopping failures 25%,*
344 *50%75%&100% volume of the lake.*
345 Under the 100% lake-volume release (worst-case scenario), the peak discharge increased to
346 10793.89 m³/s, and the flood wave reached Panikhar village in about 40 minutes, affecting
347 approximately 4.69 km² of valley area. The mean channel discharge and mean flood depth were
348 estimated as 226.6 m³/s and 6.43 m, respectively. Flood depth and velocity varied spatially
349 along the flow path due to local terrain, valley confinement, and hydraulic constrictions, with



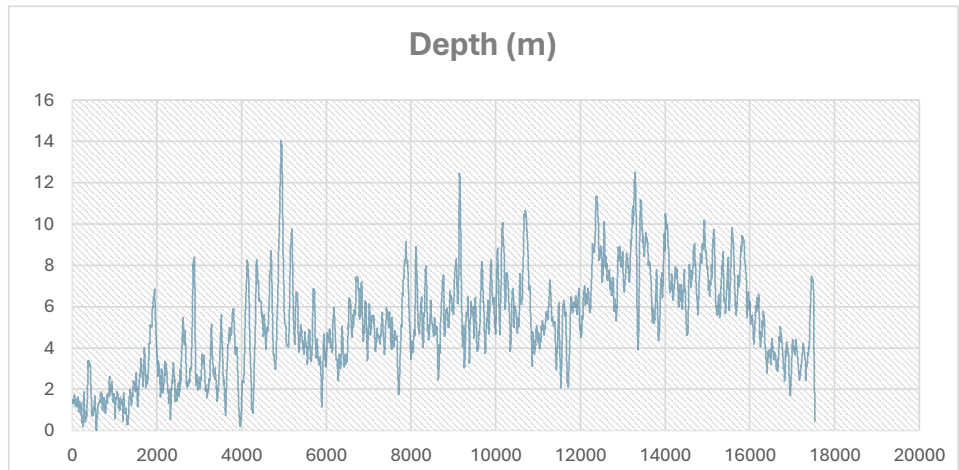
350 higher flow concentration observed near bridge crossings and reduced intensity toward

351 downstream reaches.





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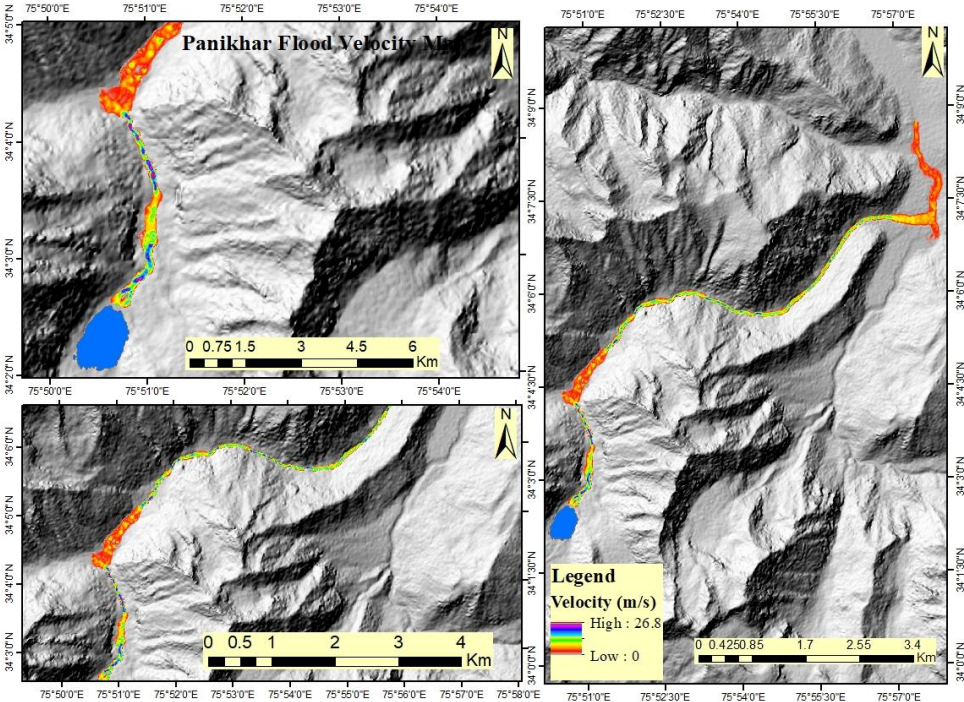
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354 Fig.10. Flood depth along the downstream flow channel of Panikhar lake for the 50 % volume release
355 scenario: depth map (top) and depth profile along the channel (bottom). Credit: Flood simulation by
356 the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from ALOS PALSAR

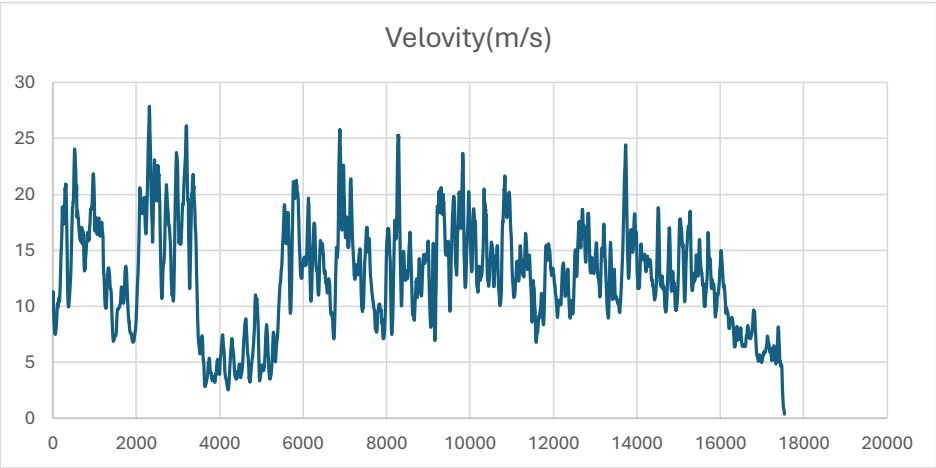


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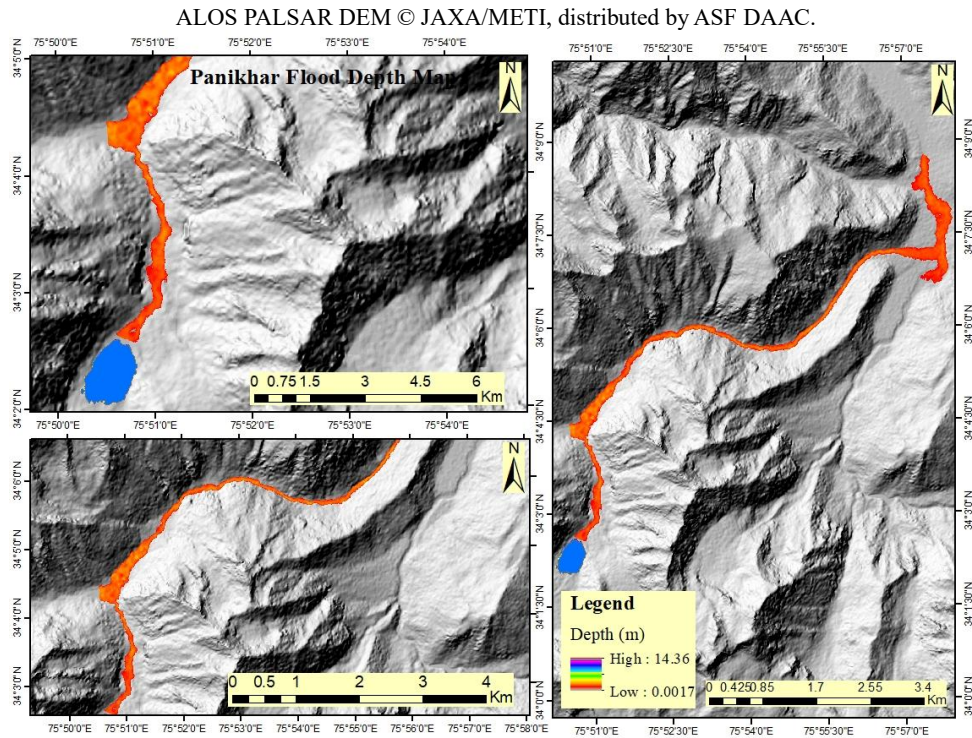


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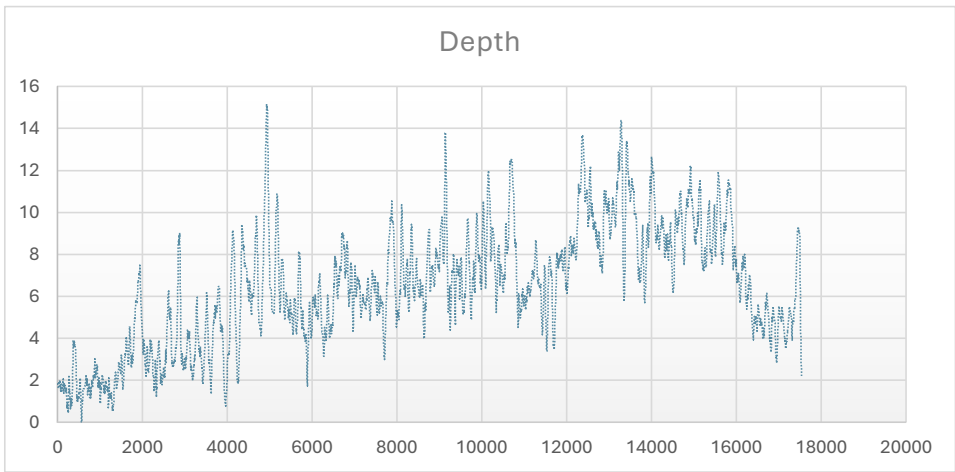
360 **Fig.11.** Flood velocity along the downstream flow channel of Panikhar lake for the 50 % volume
361 release scenario: velocity map (top) and velocity profile along the channel (bottom). Credit: Flood
362 simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from



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Fig.12. Flood depth along the downstream flow channel of Panikhar lake for the 100 % volume release scenario (worst case): depth map (top) and depth profile along the channel (bottom). Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived

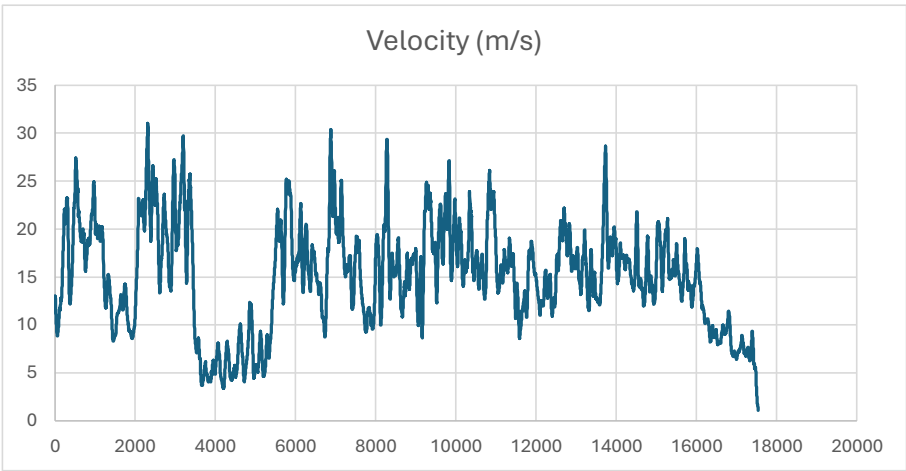
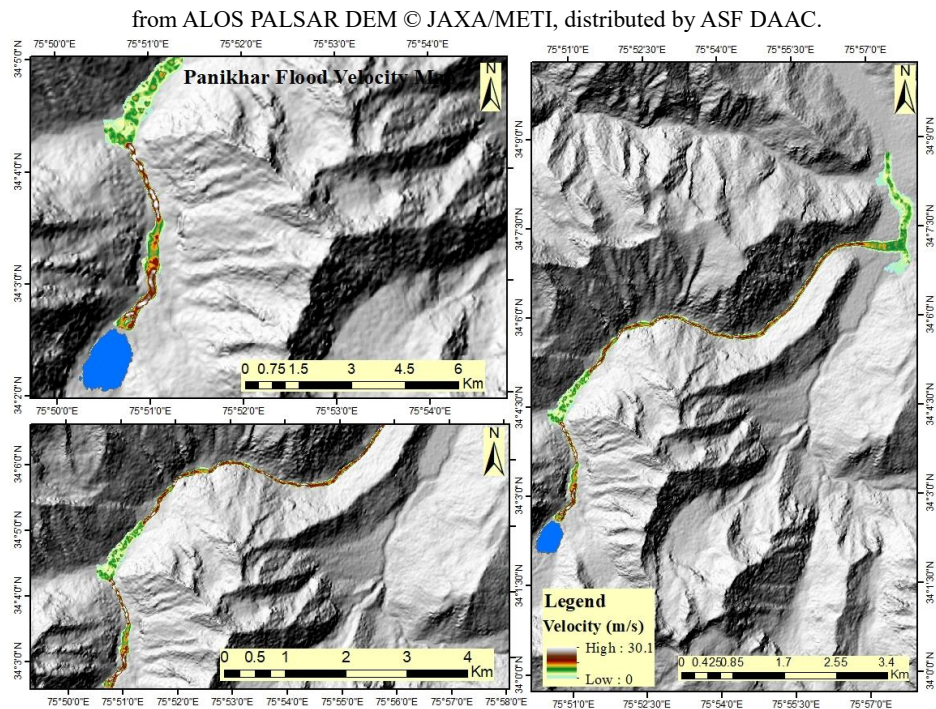
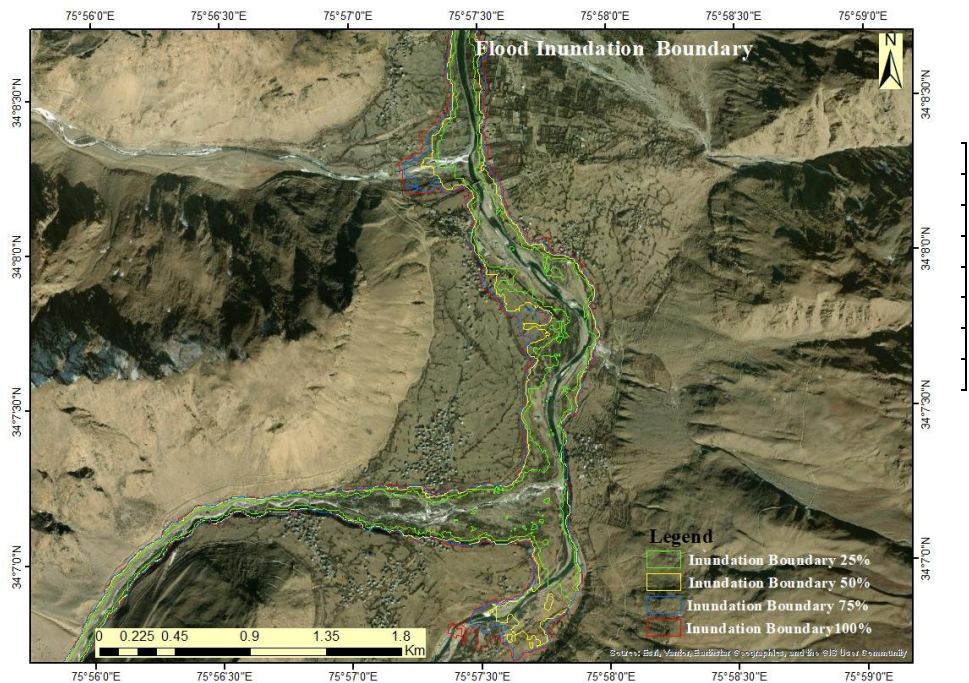


Fig.13. Flood velocity along the downstream flow channel of Panikhar lake for the 100 % volume release scenario (worst case): velocity map (top) and velocity profile along the channel (bottom). Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from ALOS PALSAR DEM © JAXA/METI, distributed by ASF DAAC.



379 **Inundation Boundary of Breach Scenario**



380 Fig.14. Inundation extent downstream of Panikhar lake for the 25 %, 50 %, 75 % and 100 % volume
381 release scenarios.Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-
382 HEC); basemap: Esri, Maxar, Earthstar Geographics, and the GIS User Community (ArcGIS World
383 Imagery).

Breach	Total Flow	Inundation km2
25%	2718.19	3.16km2
50%	6577.21	4.12km2
75%	8881.91	4.48km2
100%	10793.89	4.69km2

384 *Table.10. Inundation Area Panikhar*

Location	Mean Depth	Max Depth	Peak Velocity(m/s)
Bridge 1	0.71	10.7	16.8
Bridge 2	0.38	6.09	7.2
Settlement	0.01	1.16	4.18

385 *Table.11. Flood parameters at various locations of the flow path downstream of Panikhar lake for the*
386 *worst-case scenario i.e.100% water release.*

387 Under the worst-case (100% drainage) breach scenario of Panikhar Lake simulated in HEC-
388 RAS, the flood wave exhibits pronounced spatial variability along the downstream reach. The
389 downstream settlement experiences relatively minor inundation (mean depth 0.01 m;



390 maximum depth 1.16 m; peak discharge $4.18 \text{ m}^3 \text{ s}^{-1}$), indicating comparatively lower hazard
391 intensity. In contrast, Bridge 1 records the most severe hydraulic conditions (mean depth 0.71
392 m; maximum depth 10.7 m; peak discharge $16.8 \text{ m}^3 \text{ s}^{-1}$), reflecting strong flow concentration

Name	Area
Agriculture Field	0.44 ha
Plantation	13.31 ha
Bridge	3
Road	0.38 km

393 *Table.12. Area under Vulnerability Zone*

394 and channel constriction effects at the crossing. Bridge 2 shows moderate flooding (mean depth
395 0.38 m; maximum depth 6.09 m; peak discharge $7.2 \text{ m}^3 \text{ s}^{-1}$), suggesting localized hydraulic
396 amplification.

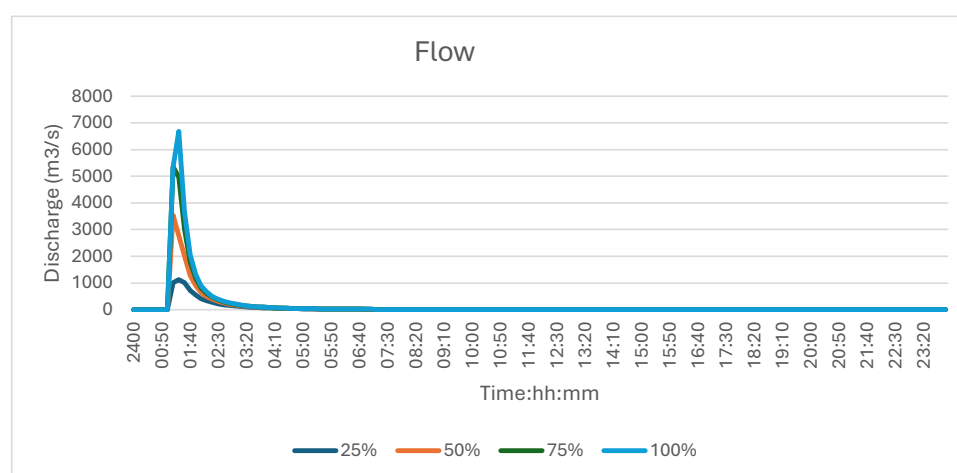
397 The spatial variation in flood depth and flow intensity is primarily governed by local channel
398 geometry, longitudinal slope, and valley confinement, which control flow acceleration, energy
399 concentration, and downstream flood propagation patterns. These results are summarized in
400 Table 12 for key downstream locations of Panikhar Lake.

401 **5.5 Raru**

402 For the 50% lake-volume release scenario of Raru Lake modeled in HEC-RAS, the peak
403 discharge at the breach was estimated at $143205 \text{ m}^3 \text{ s}^{-1}$. The routed flood wave travelled about
404 22 km and reached the downstream area after nearly 30 min. The mean channel discharge was
405 $4257.1 \text{ m}^3 \text{ s}^{-1}$, with an average flood depth of 25.09 m, affecting roughly 7.92 km^2 of the valley
406 floor. A breach width of 57 m played an important role in controlling the outflow magnitude,



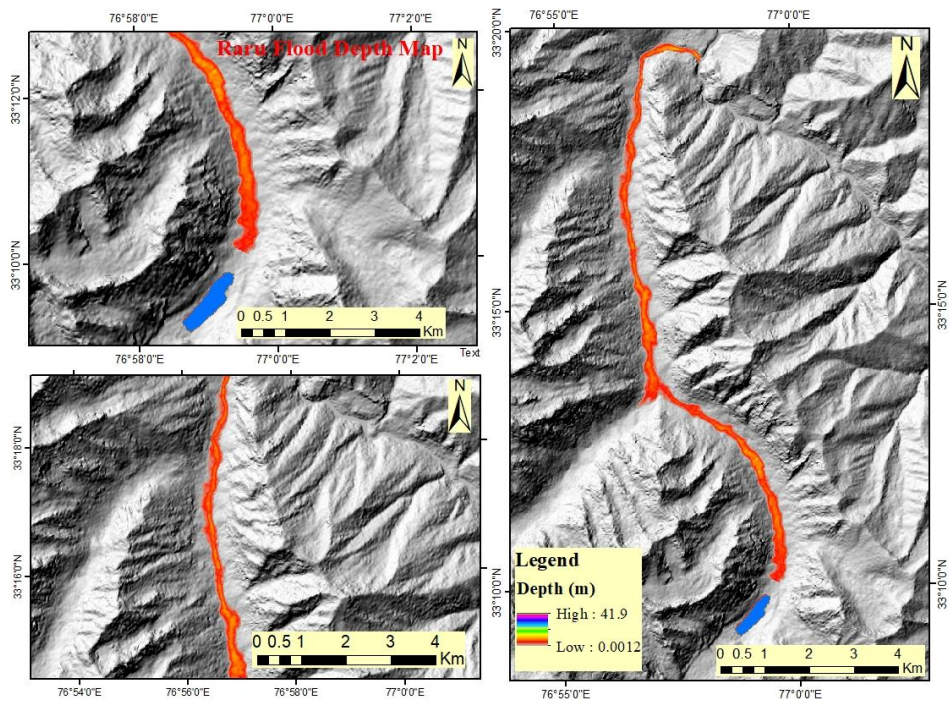
407 and the results indicate moderate risk to downstream bridges, roads, and nearby settlements.



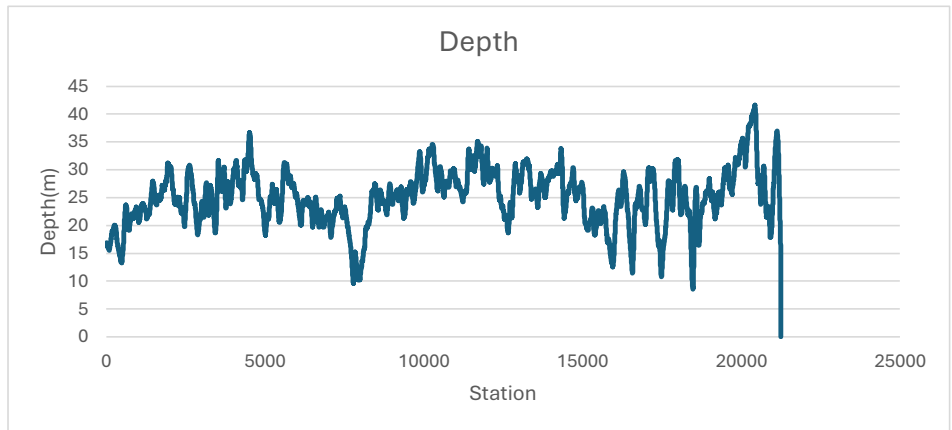
408

409 *Fig.15.Breach hydrographs depicting peak discharge at the breach in overtopping failures 25% 50%*
410 *75%&100% volume of the lake (worst case scenario).*

411 Under the 100% release (worst-case) scenario, the peak discharge increased to $417.56 \text{ m}^3 \text{ s}^{-1}$,
412 and the flood wave reached the downstream area in about 3 hours. The inundation extent
413 expanded to nearly 2.18 km^2 , while the mean discharge and mean flood depth along the flow
414 channel were $155.23 \text{ m}^3 \text{ s}^{-1}$ and 1.61 m , respectively. The 43 m breach width influenced the
415 release intensity, and flood depth and velocity gradually decreased downstream due to channel
416 widening and reduced slope, showing the strong control of local terrain on flood behaviour.

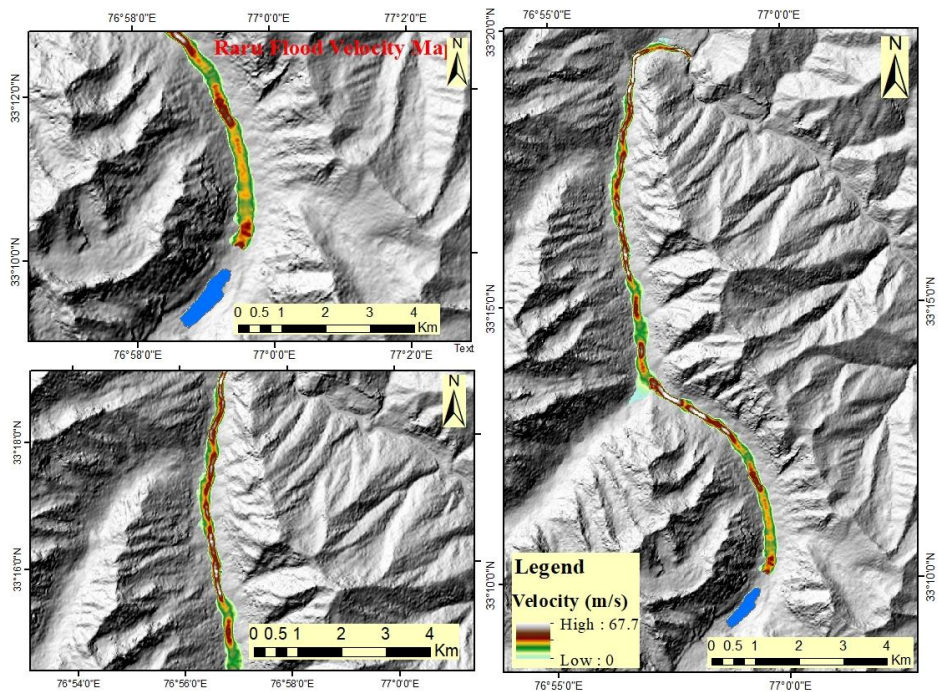


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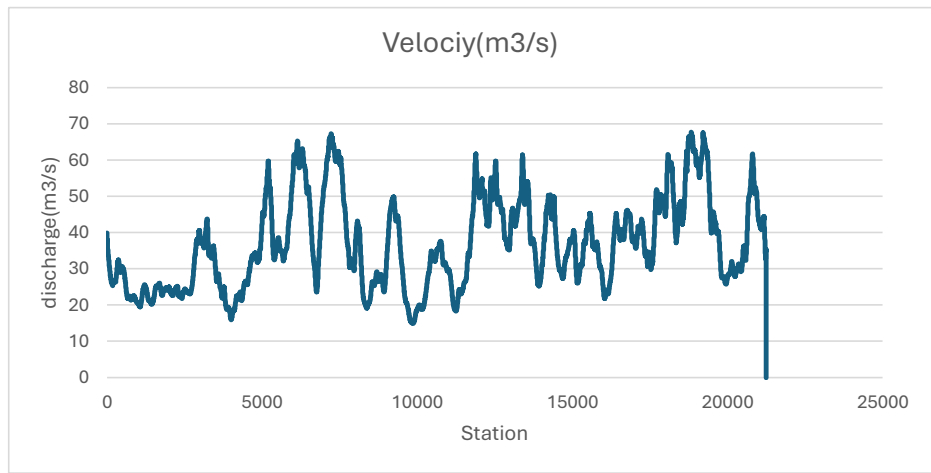


418

419 Fig.16. Flood depth along the downstream flow channel of Raru lake for the 50 % volume release
420 scenario: depth map (top) and depth profile along the channel (bottom). Credit: Flood simulation by
421 the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from ALOS PALSAR DEM
422 © JAXA/METI, distributed by ASF DAAC.



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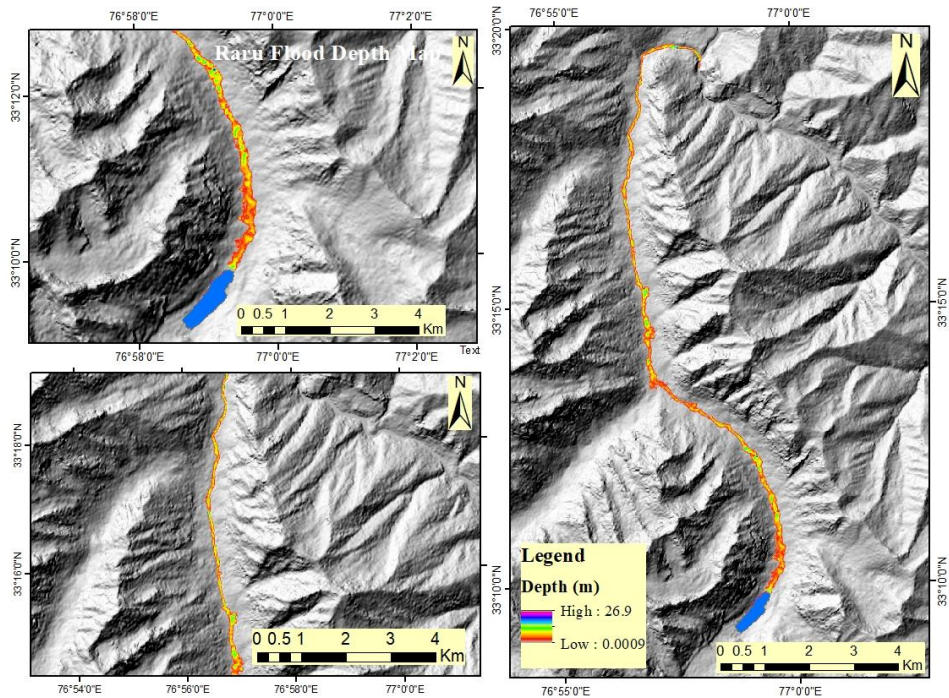


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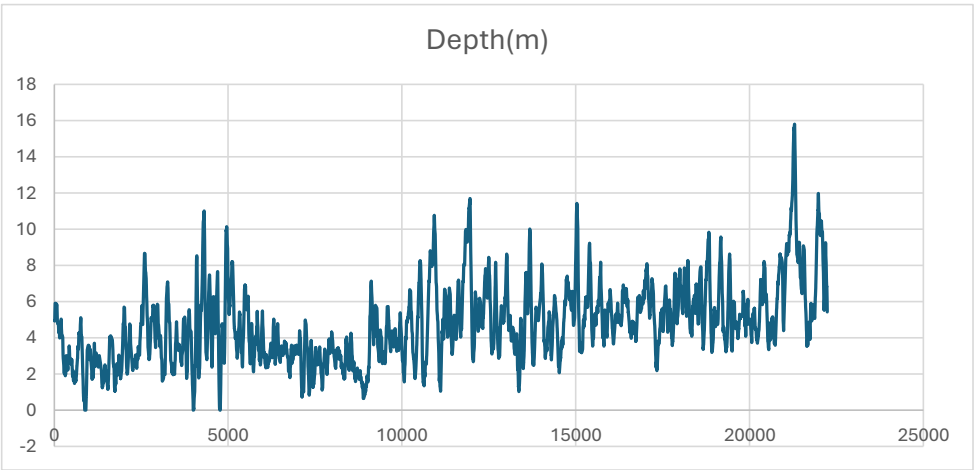
425 Fig.17. Flood velocity along the downstream flow channel of Raru lake for the 50 % volume release
426 scenario: velocity map (top) and velocity profile along the channel (bottom). Credit: Flood simulation
427 by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from ALOS



428 PALSAR DEM © JAXA/METI, distributed by ASF DAAC.



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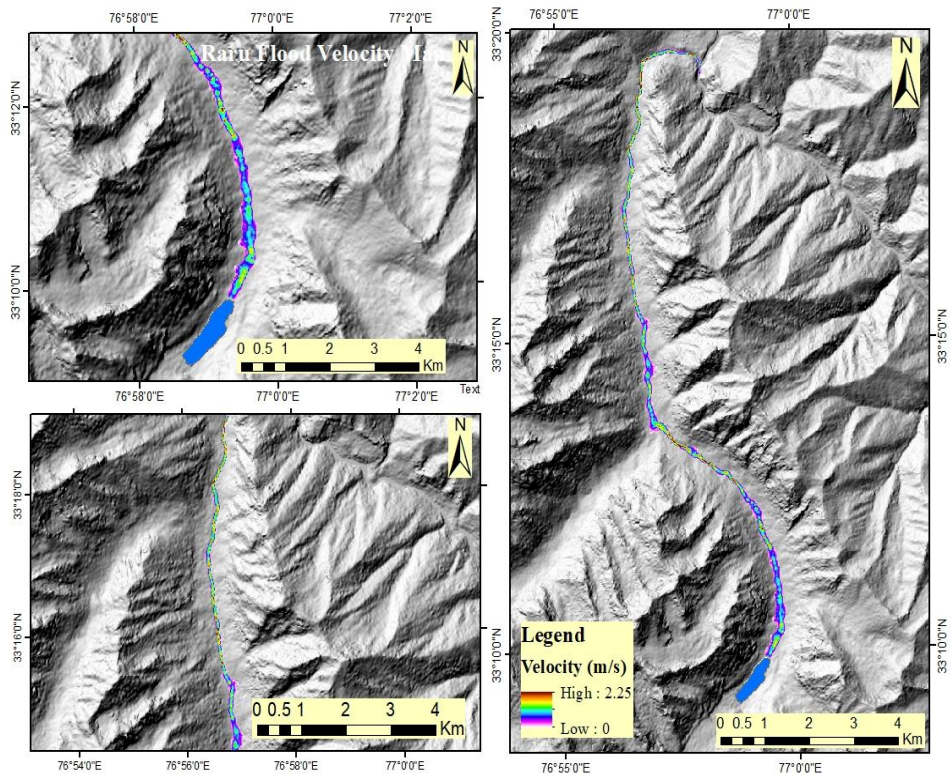


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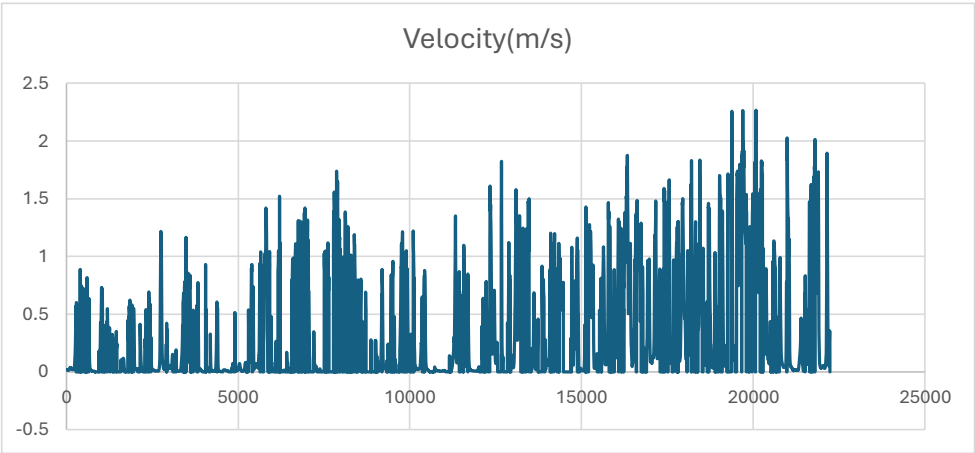
431 Fig.18. Flood depth along the downstream flow channel of Raru lake for the 100 % volume release
432 scenario (worst case): depth map (top) and depth profile along the channel (bottom). Credit: Flood
433 simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from



ALOS PALSAR DEM © JAXA/METI, distributed by ASF DAAC.



435



436

437 Fig.19. Flood velocity along the downstream flow channel of Raru lake for the 100 % volume
438 release scenario (worst case): velocity map (top) and velocity profile along the channel (bottom).
439 Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade
440 derived from ALOS PALSAR DEM © JAXA/METI, distributed by ASF DAAC.



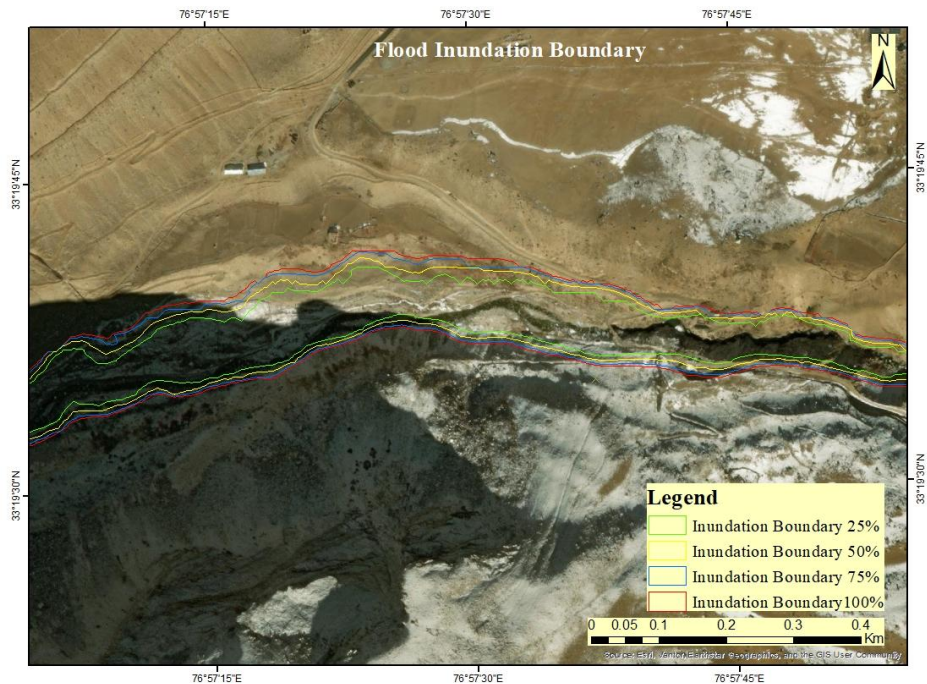
Under the worst-case (100% drainage) breach scenario of Raru Lake simulated in HEC-RAS, the flood wave remains largely confined to the river channel but poses a notable risk to **lin****Fig.19.** Flood velocity along the downstream flow channel of Raru lake for the 100 % volume release scenario (worst case): velocity map (top) and velocity profile along the channel (bottom). Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC); hillshade derived from ALOS PALSAR DEM © JAXA/METI, distributed by ASF DAAC.infrastructure such as bridges and roads, while the downstream settlement located on elevated terrain remains unaffected. Flood assessment at key locations shows that Bridge 1 experiences the highest impact, with a mean flood depth of 7.04 m, a maximum depth of 14.85 m, and a peak discharge of $3.03 \text{ m}^3 \text{ s}^{-1}$, indicating localized but potentially damaging flow concentration. The spatial variation in flood intensity along the downstream reach is mainly controlled by channel geometry, valley confinement, and longitudinal slope conditions.

Location	Mean Depth	Max Depth	Peak Discharge
Bridge	7.04	14.85	3.03

Table.13. Flood parameters at various locations of the flow path downstream of Raru lake for the worst-case scenario i.e.100% water release.

Breach	Total Flow	Inundation km2
25%	1126.36	2.77 km2
50%	3539.25	3.37km2
75%	5359.73	3.84 km2
100%	6682.77	4.02km2

Table.14. Inundation Area Raru



458
459 *Fig. 20. Inundation extent downstream of Raru lake for the 25 %, 50 %, 75 % and 100 % volume release*
460 *scenarios. Credit: Flood simulation by the authors using HEC-RAS 2D (v6.7beta5, USACE-HEC);*
461 *basemap: Esri, Maxar, Earthstar Geographics, and the GIS User Community (ArcGIS World Imagery).*

462 **6. Conclusions**

463 A comparative analysis of the four glacier-fed lake systems—Panikhar, Raru and Gya, —in the
464 upper Indus Basin of Ladakh reveals notable differences in both flood magnitude and
465 downstream risk. Among the three, Panikhar shows the highest potential hazard in terms of
466 lake volume and modeled peak discharge. The simulated hydrographs indicate stronger flow
467 propagation, particularly along the Raru channel, suggesting that Panikhar lake outburst could
468 generate more intense hydraulic conditions compared to the other sites.

469 Despite this high modeled discharge along the Raru flow path, the absence of settlements in
470 the immediate floodplain and the elevated position of nearby habitations relative to the river
471 significantly reduce potential downstream damage. Thus, while the hydraulic hazard is



472 comparatively high, the actual risk to population and infrastructure remains limited due to low
473 exposure.

474 In contrast, the Gya lake system presents moderate hazard conditions. Most simulated breach
475 scenarios show minimal downstream impact; however, in extreme cases—especially when up
476 to 75% of the lake volume is released—the flood wave may reach nearby settlements.
477 Therefore, Gya can be considered a site where risk is conditional and primarily dependent on
478 worst-case scenarios.

479 Overall, the comparative study highlights that Panikhar has the highest flood hazard, Gya
480 shows risk only under extreme scenarios, Raru experiences high discharge but minimal
481 exposure due to settlement location. These findings emphasize that GLOF danger is controlled
482 not only by lake size and discharge but also by settlement distribution, channel morphology,
483 and climatic variability, underscoring the need for site-specific monitoring and risk
484 management strategies in Ladakh.

485 **Data availability**

486 The Sentinel-2 imagery used in this study is freely available from the Copernicus Data Space
487 Ecosystem (<https://browser.dataspace.copernicus.eu>), and the ALOS PALSAR digital
488 elevation model is freely available from the Alaska Satellite Facility (ASF Data Search).

489 **Author contribution**

490 JA conceptualised the study, collected and processed the data, performed the GIS analysis and
491 the HEC-RAS dam-break modelling, and wrote the manuscript.

492 **Competing interests**

493 No

494 **Acknowledgements**



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