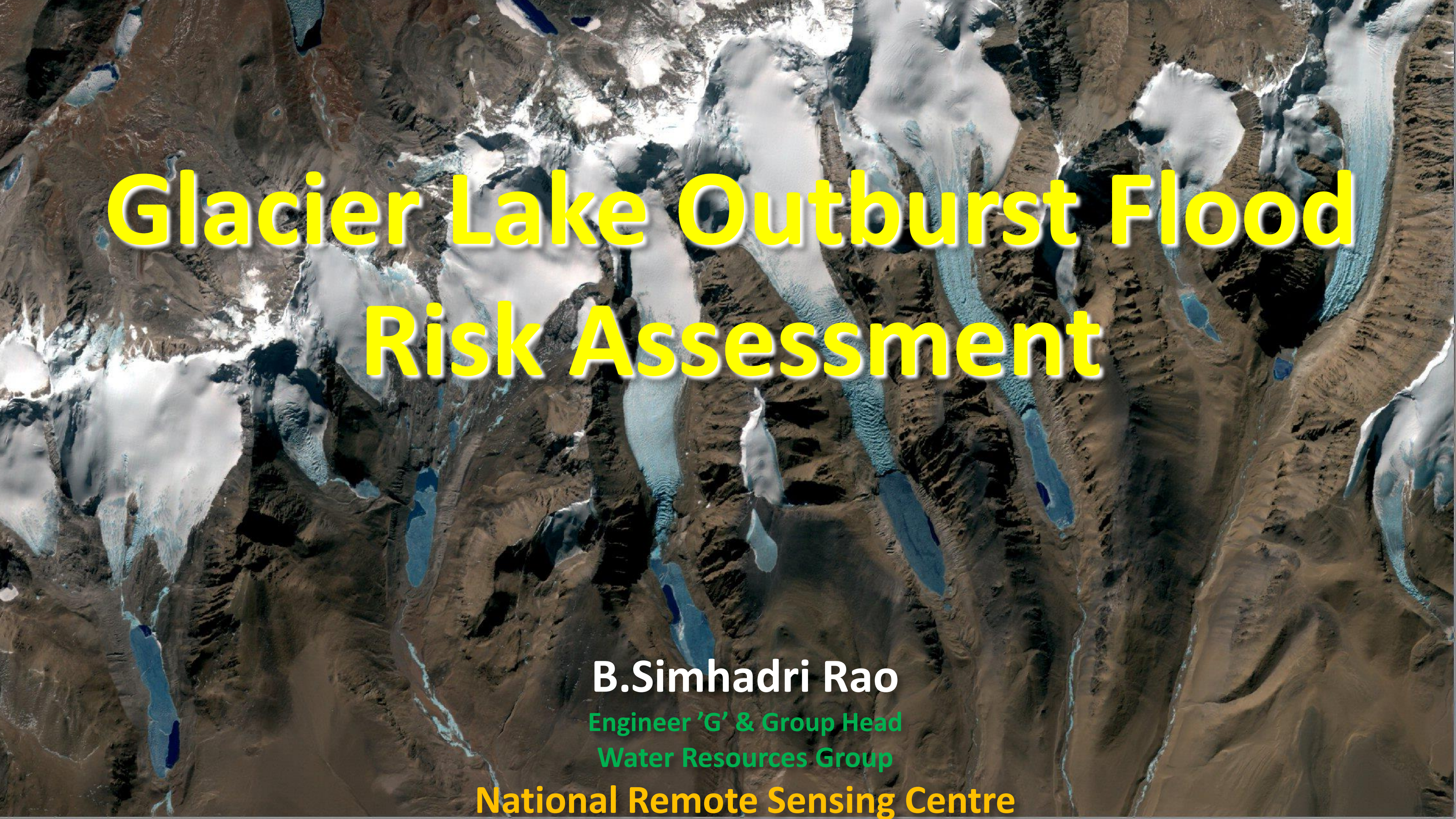


Glacier Lake Outburst Flood Risk Assessment

B.Simhadri Rao

Engineer 'G' & Group Head

Water Resources Group

National Remote Sensing Centre

Glacier Lake Outburst Flood Risk Assessment

Glacier Lake

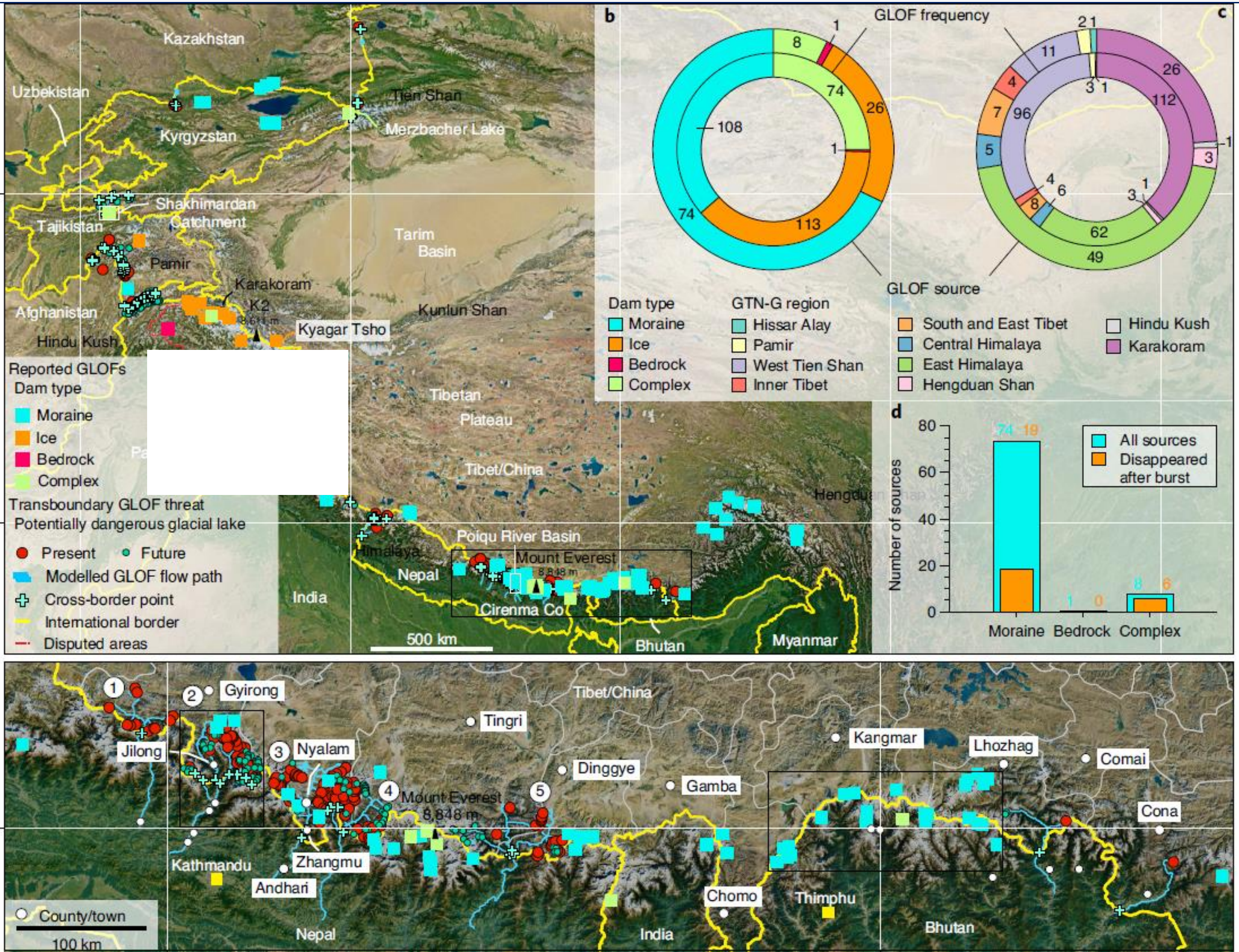
A glacier lake is defined as a water mass existing in a sufficient amount and extending with a free surface beside and/or in front of a glacier and originated by glacier activities and/or retreating processes of a glacier.

Glacier Lake Outburst Flood Risk Assessment

- Glacial lakes associated glaciers are common in high mountain areas like Himalayas
- As the glaciers recede, new glacial lakes are forming and existing glacial lakes are expanding
- At times glacial melt water stored in these glacial lakes suddenly gets released causing the flash floods called Glacial Lake Outburst Floods (GLOF)
- These flash floods create havoc to the downstream areas of the river reach affecting people and infrastructure like roads, hydropower plants, agriculture, etc.
- Many GLOF events happened in the Himalayas and increasing in trend




Glacier Lake Outburst Flood Risk Assessment



Historic GLOF events

Source: Zheng et al (2020), Increasing risk of glacial lake outburst floods from future Third Pole deglaciation

Glacier Lake Outburst Flood Risk Assessment

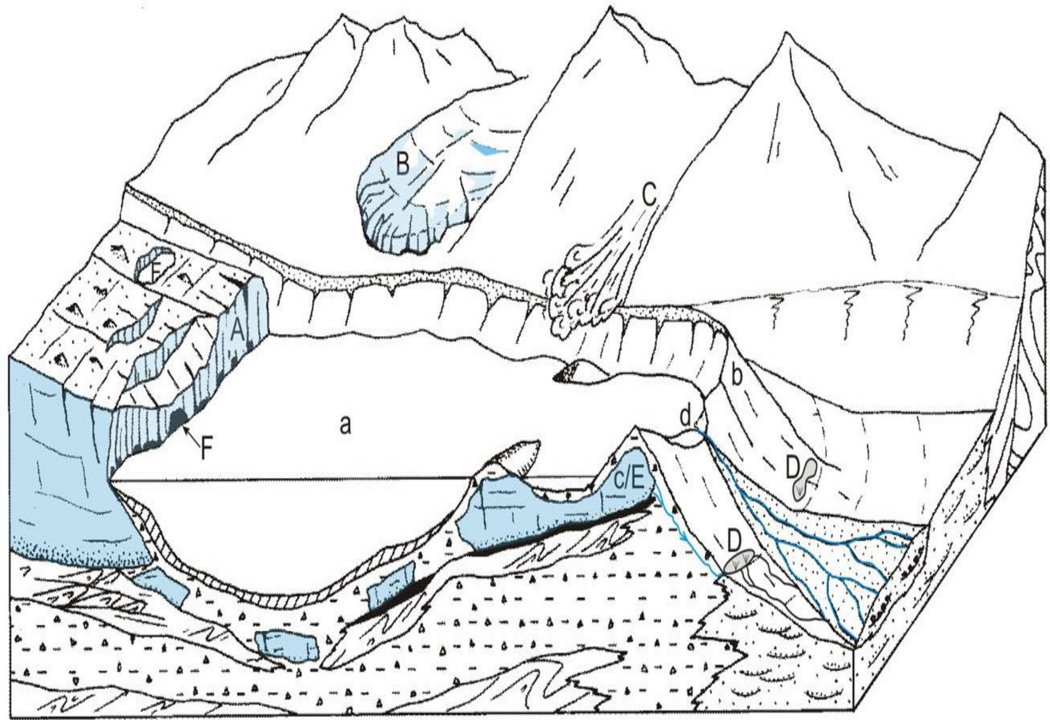
Factors contributing to GLOF of moraine-dammed glacial lake include:

a. Large lake volume
b. Narrow and high moraine dam and condition of material
c. Stagnant glacier ice within the dam and
d. Limited freeboard between the lake level and the crest of the moraine ridge.

(Source: Richardson, S.D. and J.M. Reynolds ,2000)

Potential outburst flood triggers include avalanche displacement waves from

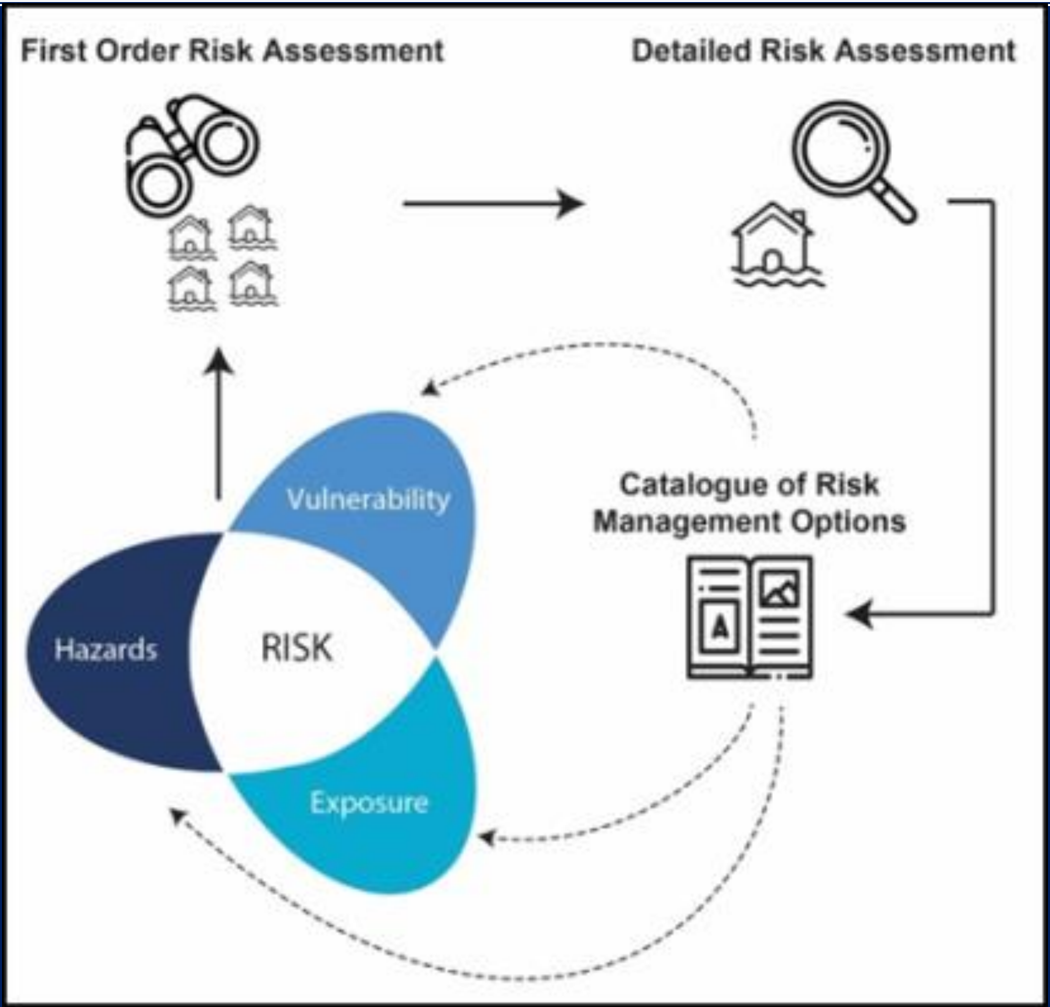
A. Calving glaciers
B. Hanging glaciers
C. Rock falls
D. Settlement and/or piping within the dam
E. Melting ice-core and
F. Catastrophic glacial drainage into the lake from subglacial or englacial channels or supraglacial lakes



External Triggering Events

- Cloud burst
- Earth quake

GLOF Risk Assessment

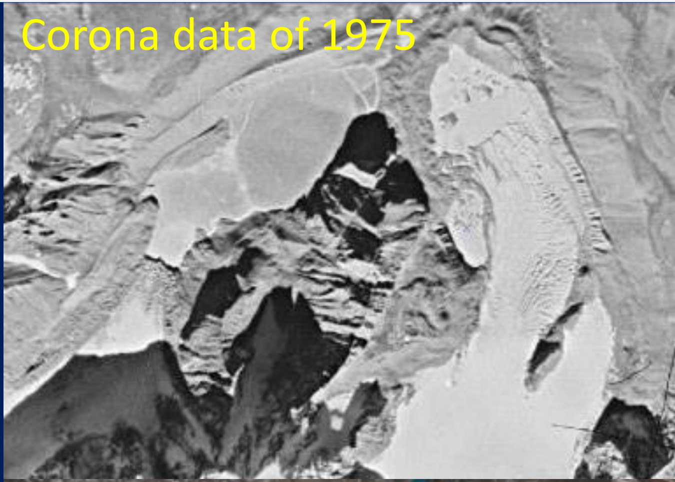


Glacier Lake Outburst Flood Risk Assessment

Glacial Lake Characteristics

Criteria for Identifying Critical Glacial Lakes

- Lake area
- Lake volume
- Lake expansion rate
- Lake depth
- Lake elevation
- Lake perimeter
- Lake width
- Changes in the lake level
- Slope between lake & settlement
- Slope between lake & glacier snout
- Steepest slope surrounding lake
- Distance between lake & glacier snout
- Distance between lake & settlement
- Interconnected lakes upstream



Glacier Lake Outburst Flood Risk Assessment

Glacier Characteristics

Criteria for Identifying Critical Glacial Lakes

- Area of the glacier
- Condition of the glacier
- Glacier advance
- Glacier shrinkage
- Debris cover on the glacier
- Buried ice in moraine
- Calving susceptibility
- Crevassed glacier snout above lake
- Icebergs breaking off glacier terminus
- Parent glacier snout steepness
- Reaction of the glacier to climate change
- Slope of lateral moraines
- Supra/englacial drainage

Glacier Lake Outburst Flood Risk Assessment

Criteria for Identifying Critical Glacial Lakes

Moraine Dam Characteristics

- Dam type
- Height of moraine
- Main rock type of moraine
- Dam freeboard
- Piping gradient
- Piping/seepage through moraine
- Steepness of moraine
- Top width of dam
- Width and height ratio of dam
- Drainage outflow / Seepage from moraines

Triggering Parameters

- Earthquake
- Landslide
- Precipitation (intense PCP events)
- Temperature (high TEMP events)

Lake surrounding conditions

- Distance from hanging glacier
- Distance to nearest settlement
- Mass movement into lake
- Rock fall/landslide susceptibility
- Slope between lake & settlement
- Snow avalanche/icefall susceptibility

Socio-economic characteristics

- Cultivated area
- Total population
- Major/minor infrastructure
- Livestock density
- Population density
- Proportion of rural population
- Disabled population
- Frequent tourist/experiment sites

Glacier Lake Outburst Flood Risk Assessment

Prioritization of Glacial Lakes

Screening:

1. Based on **Type: (Moraine, Supra, Cirque)**
   - **M(e):** End-moraine Dammed Lake
   - **M(l):** Lateral-moraine Dammed Lake
   - **M(lg):** Lateral-moraine Dammed Lake (with ice)
   - **M(o):** Other-moraine Dammed Lake
   - **I(s):** Supra-glacial Lake
   - **I(d):** Ice-dammed Lake
   - **E(c):** Cirque-erosion Lake
2. Based on **Area > 1ha**
3. Based on **Glacier Association**:
   - M(e), M(lg) – Already associated
   - M(l), M(o) – Check glacier association
   - I(s) – Closely-spaced in Valley Glacier (>2 nos. within 500m from upstream of snout)
   - E(c) – Glacier Association + Steep Hanging Glacier (> 15^{o} or > 33.3%)

Step 1: Preliminary Screening

1. Lake Type
2. Lake Area > 1 ha
3. Glacier Association
4. Contributing to WB (w/o Sett.)

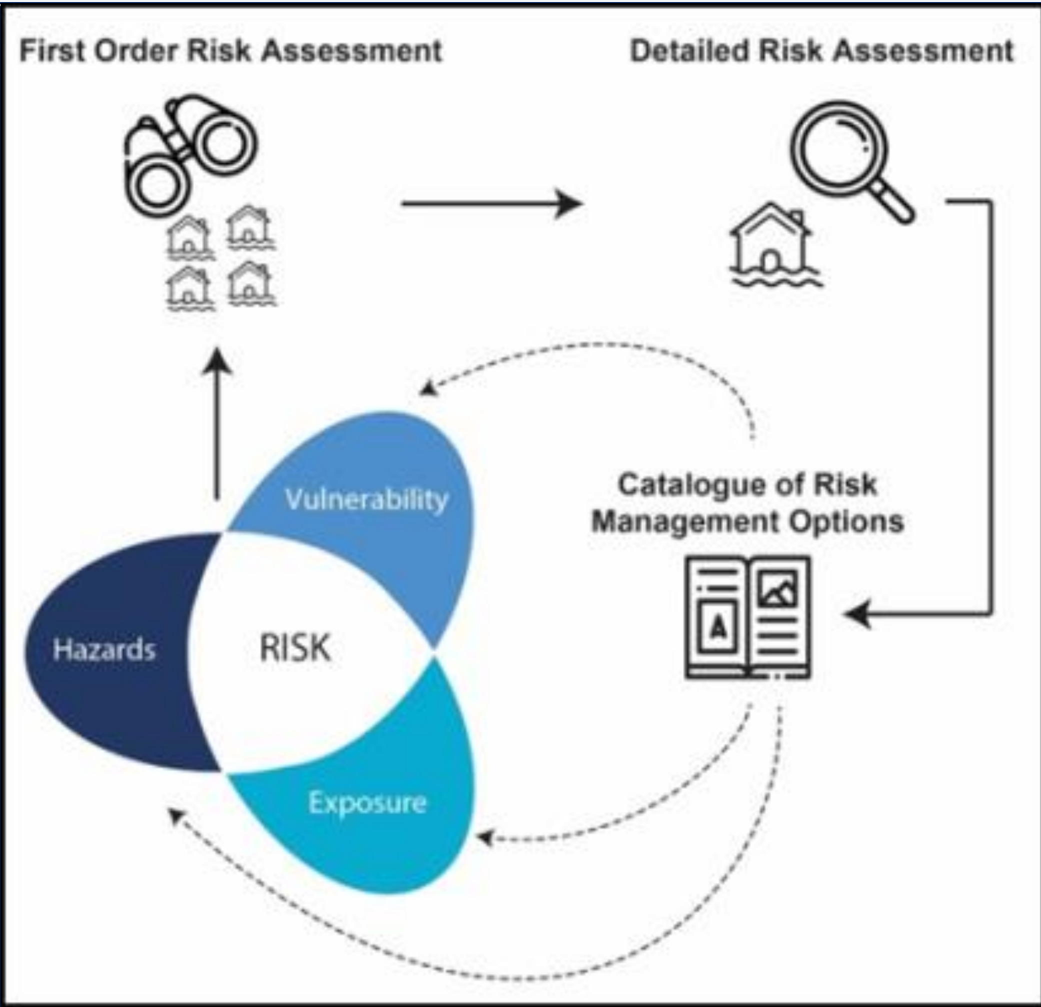
Step 2: Ranking

1. Lake Type
2. Lake Area
3. Lake distance from associated Glacier Snout
4. Slope between Glacier Snout and Lake
5. Distance of Lake from Settlement/Infrastructure
6. Slope b/w Glacial Lake and Settlement/Infrastructure

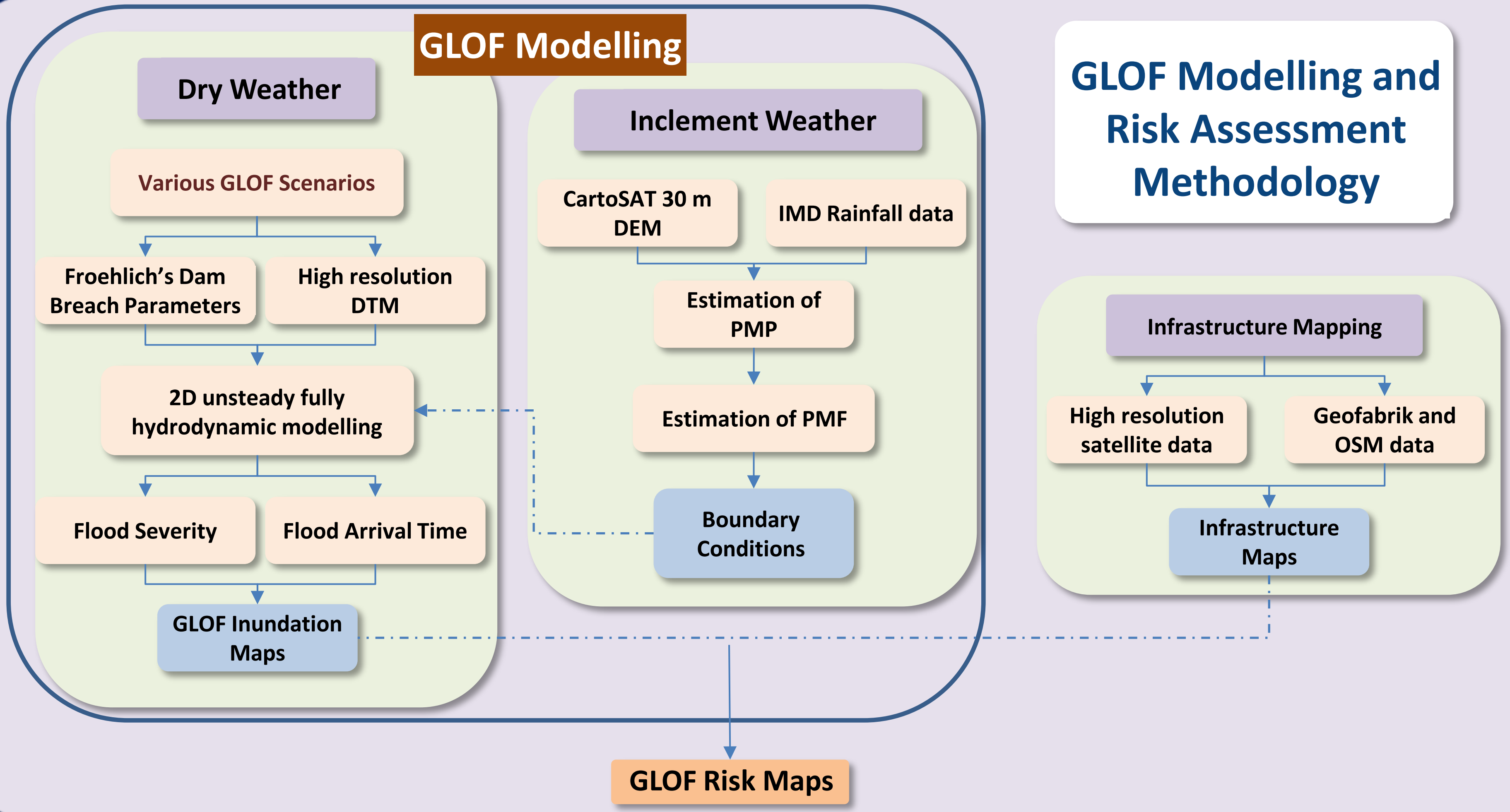
Glacier Lake Outburst Flood Risk Assessment

GLOF Risk Assessment

- GLOF simulation modelling for various scenarios
- Vulnerability assessment of settlements and infrastructure affected by GLOF
- Assessment of GLOF risk (both static and triggering events)

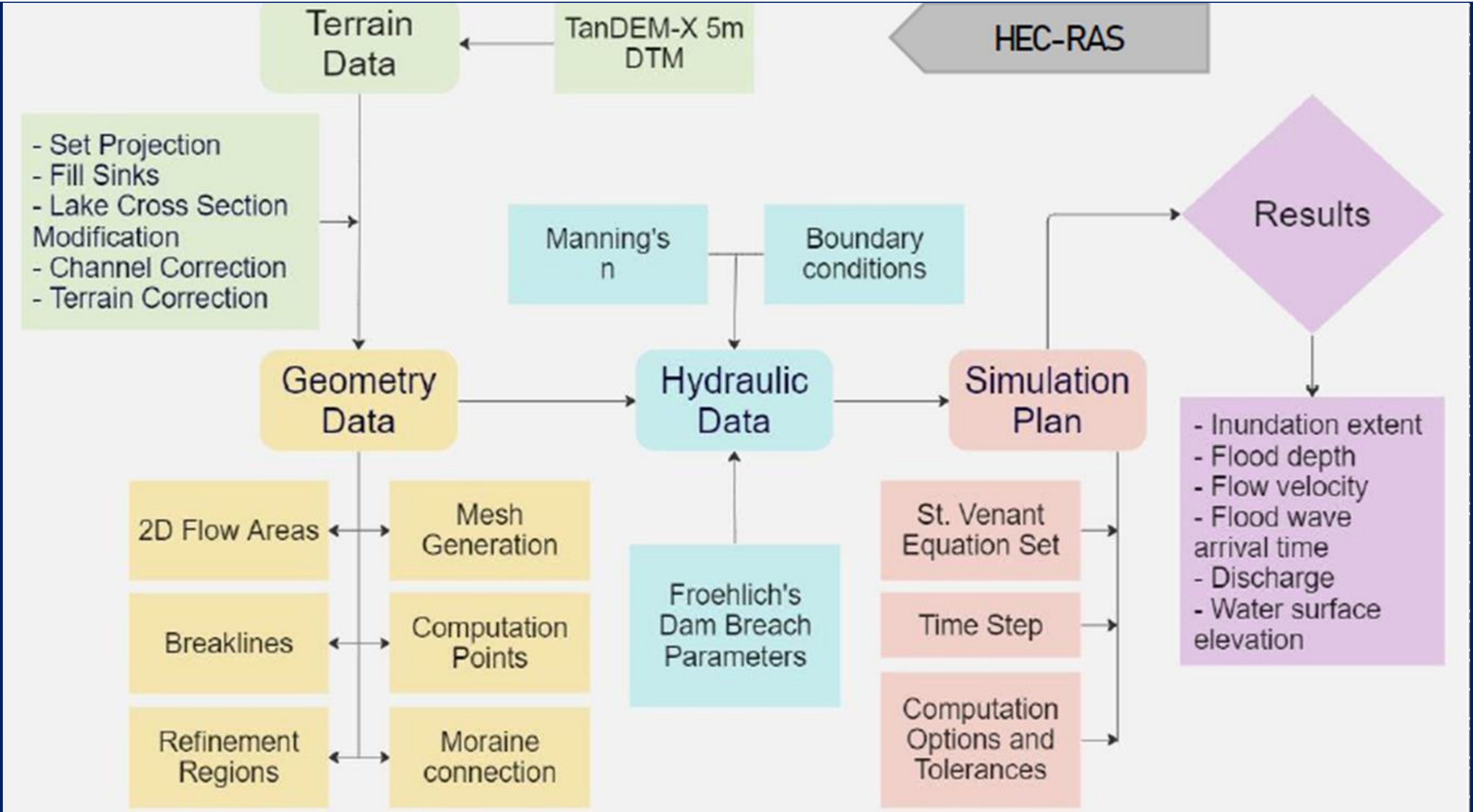


Glacier Lake Outburst Flood Risk Assessment



GLOF Modelling

Glacier Lake Outburst Flood Risk Assessment



Glacier Lake Outburst Flood Risk Assessment

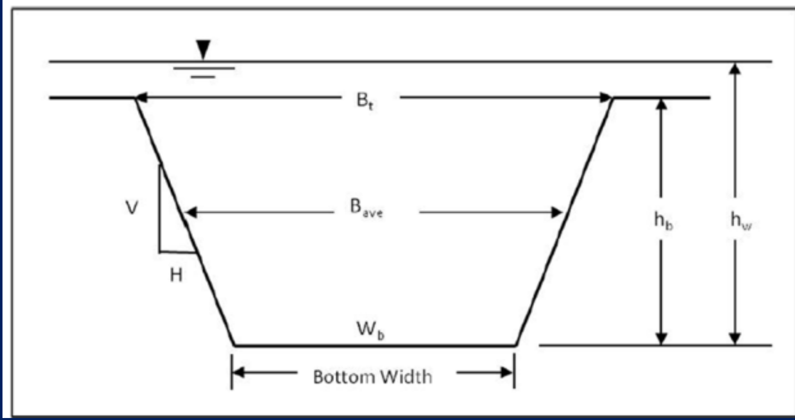
GLOF Modelling requires

- Terrain Data
- Hydrologic Inputs used as boundary conditions
- Model Parameters for (estimated and then calibrated)
  - Terrain roughness
  - Hydraulic Structures
- Breach location, breach dimensions and breach development time
- Breach characteristics can be estimated using regression equations

B_{ave} – average breach width
t_f - breach formation time (s)
W_b – breach bottom width
H_b – breach height

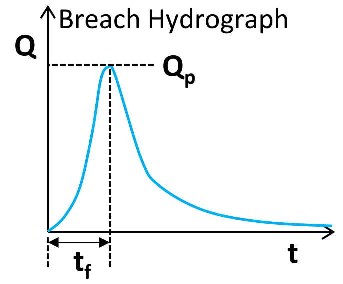
Regression Equations:

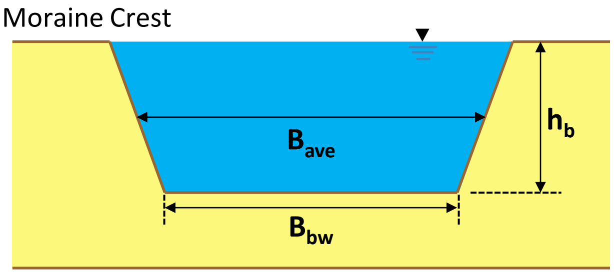
- Froehlich (1995a)
- Froehlich (2008)
- MacDonald and Langridge-Monoppolis (1984)
- Von Thun and Gillette (1990)
- Xu and Zhang (2009)
- Froehlich (2017)



Glacier Lake Outburst Flood Risk Assessment

GLOF Scenarios





Moraine Breach Diagram

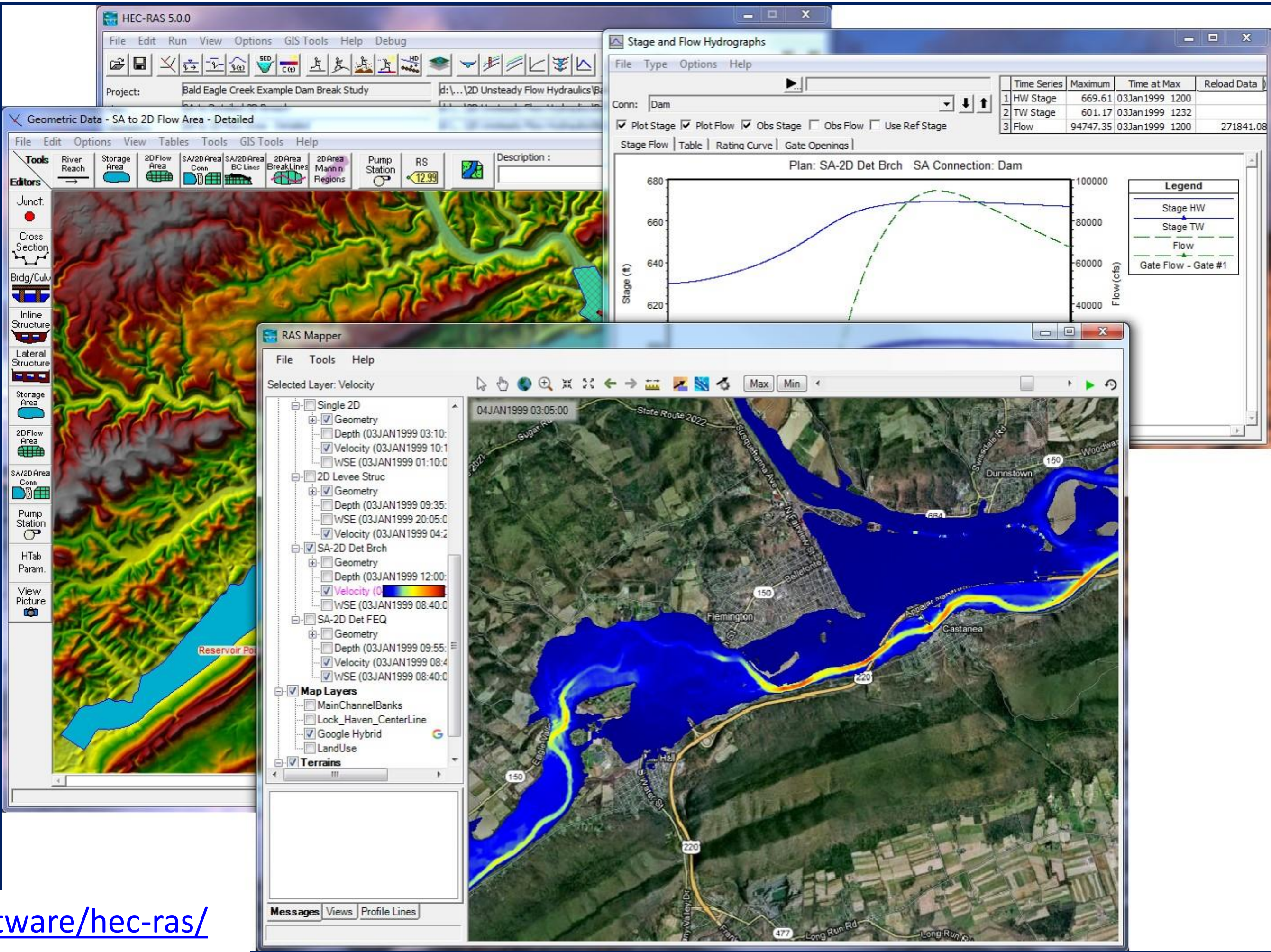
Scenario	Failure Mode	Volume Discharge	Breach bottom elevation (m)	h_b (m)	B_{ave} (m)	t_f (hrs)	B_{bw} (m)
				Breach Parameters			
Scenario-1	Overtopping	**100%**	4034.08	34.62	128.53	1.04	80.06
Scenario-2	Piping				91.81		60.65
Scenario-3	Overtopping	**75%**	4052.86	15.84	110.79	2.11	88.61
Scenario-4	Piping				79.13		64.87
Scenario-5	Overtopping	**50%**	4059.16	9.54	100.61	3.33	87.25
Scenario-6	Piping				71.87		63.28
Scenario-7	Overtopping	**100% with PMP**	4034.08	34.62	128.53	1.04	80.06
Scenario-8	Piping				91.81		60.65

Glacier Lake Outburst Flood Risk Assessment

HEC-RAS :

Hydrologic Engineering Center River Analysis System

- Developed by US Army – Corps Engineers
- Perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling

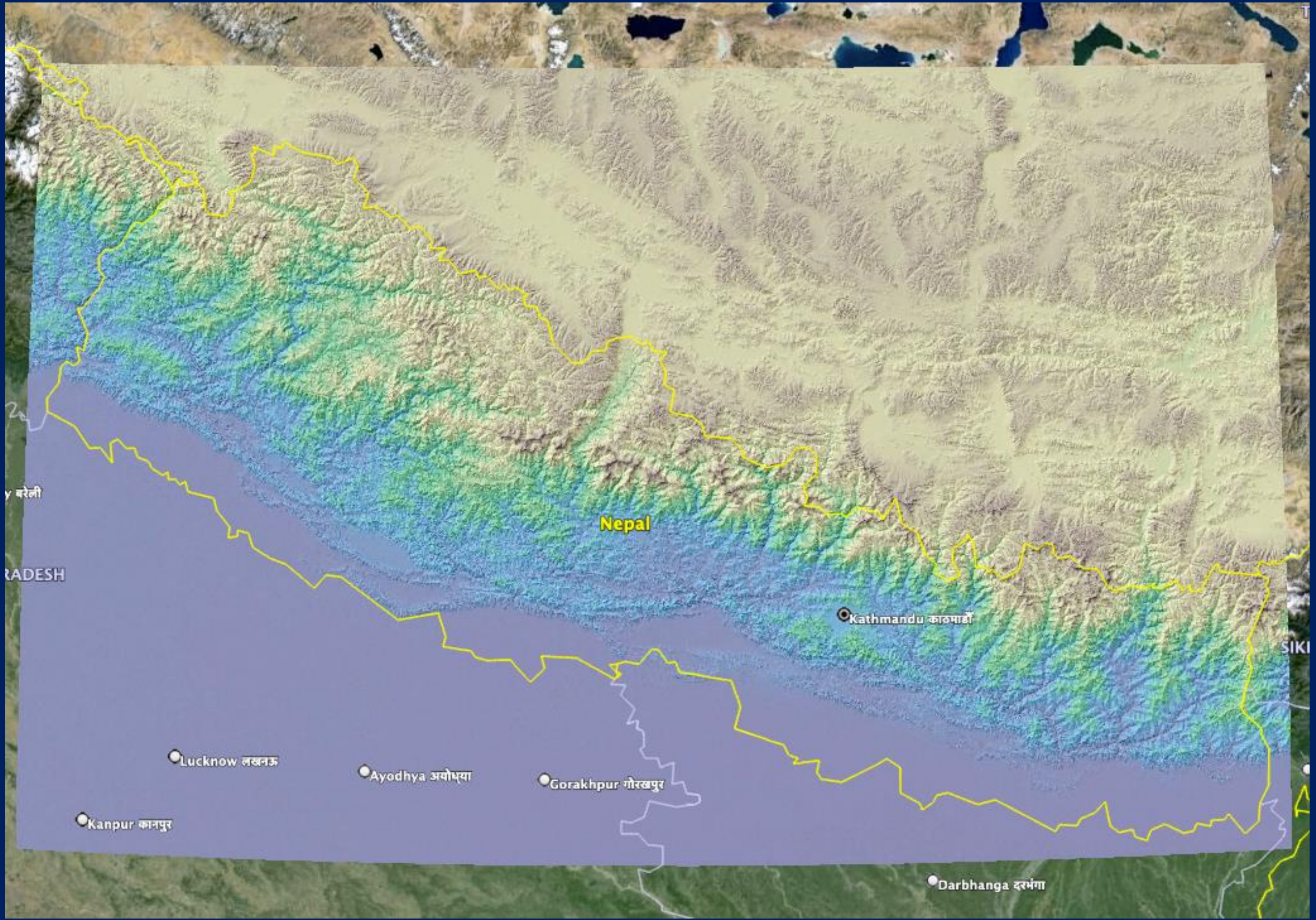


https://www.hec.usace.army.mil/software/hec-ras/

Glacier Lake Outburst Flood Risk Assessment

Digital Elevation Models

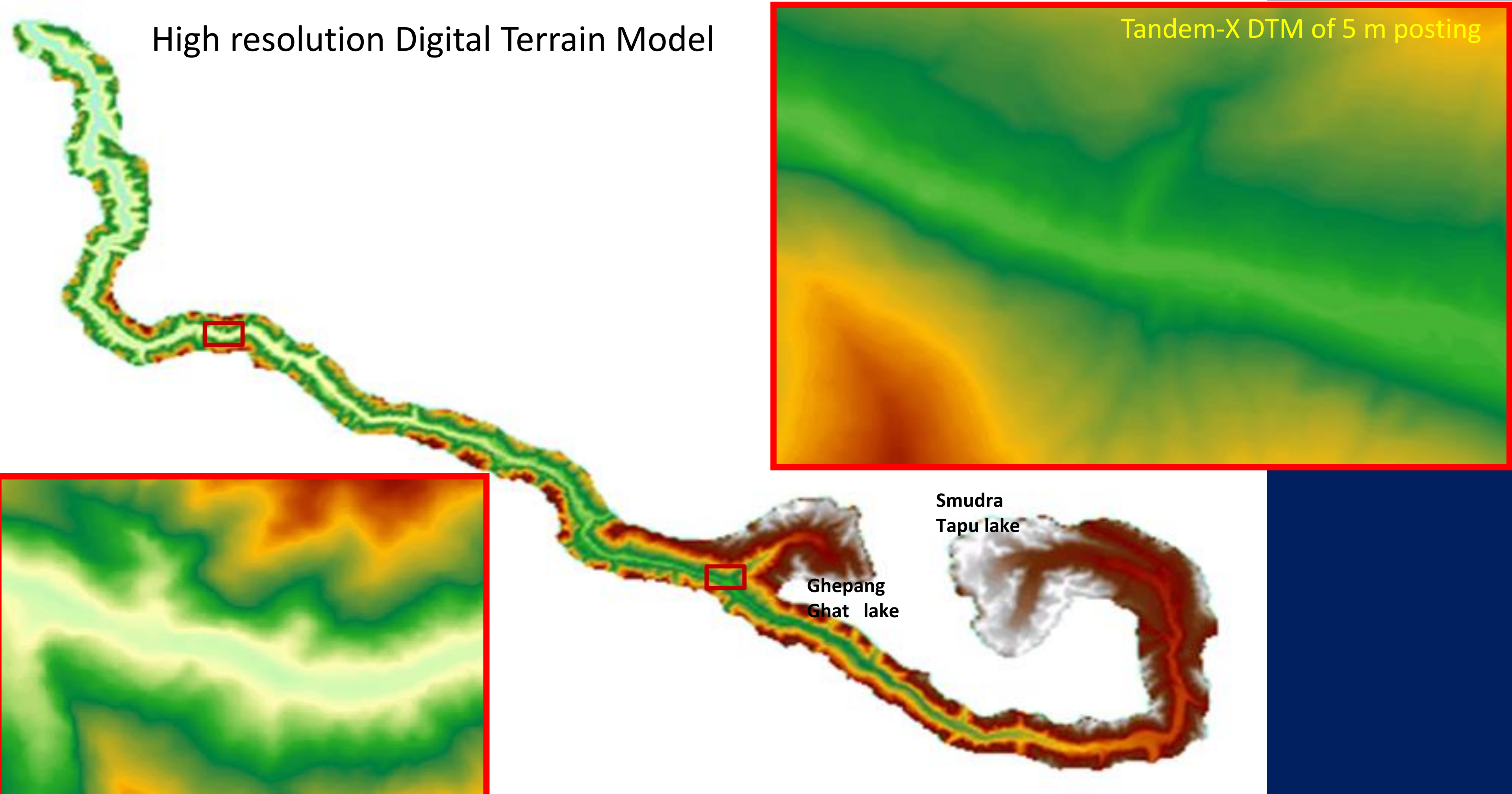
- SRTM
- ASTER
- ALOS World 3D
- Copernicus



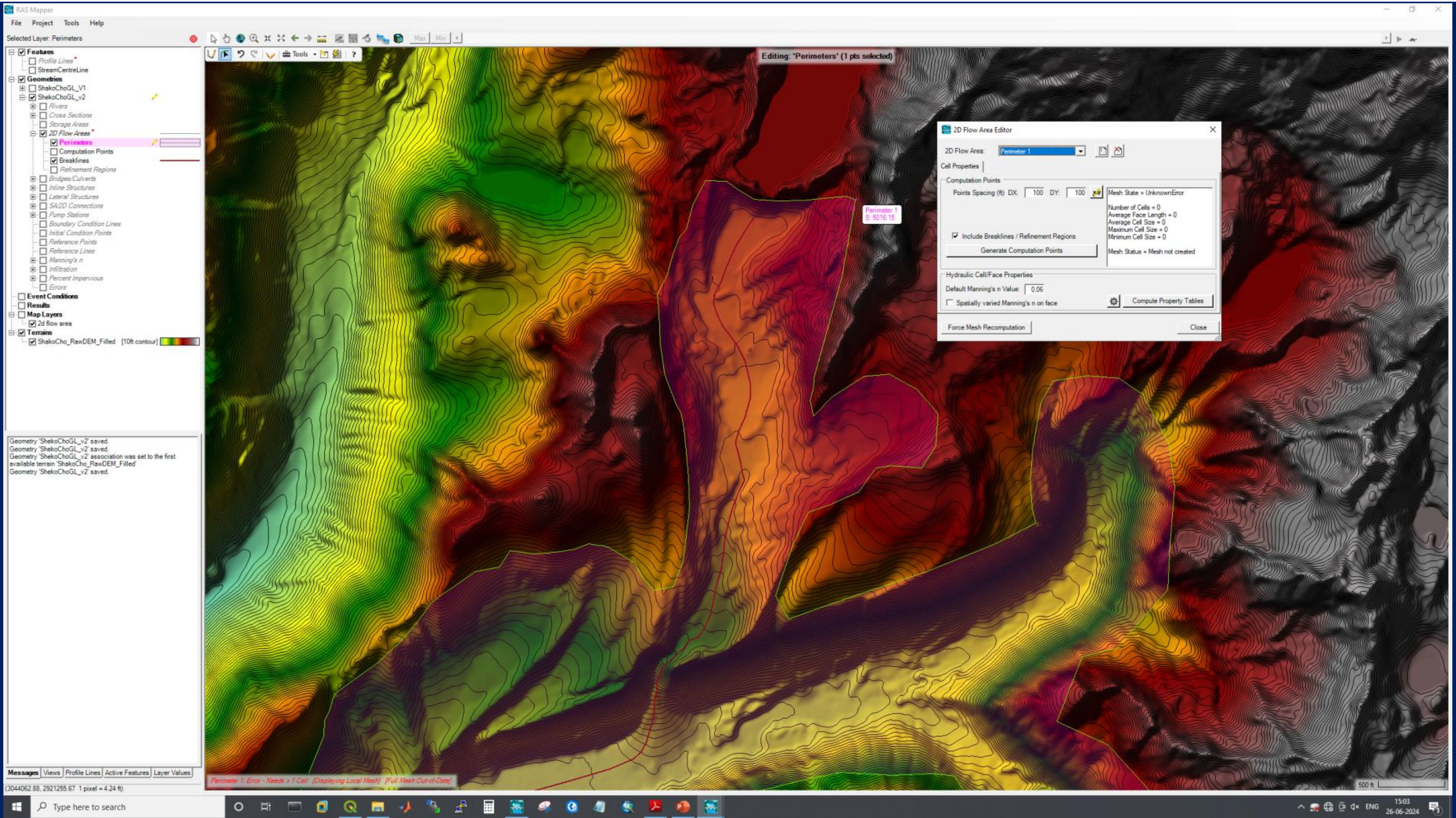
https://opentopography.org/news/updated-copernicus-30m-DEM-available

Glacier Lake Outburst Flood Risk Assessment

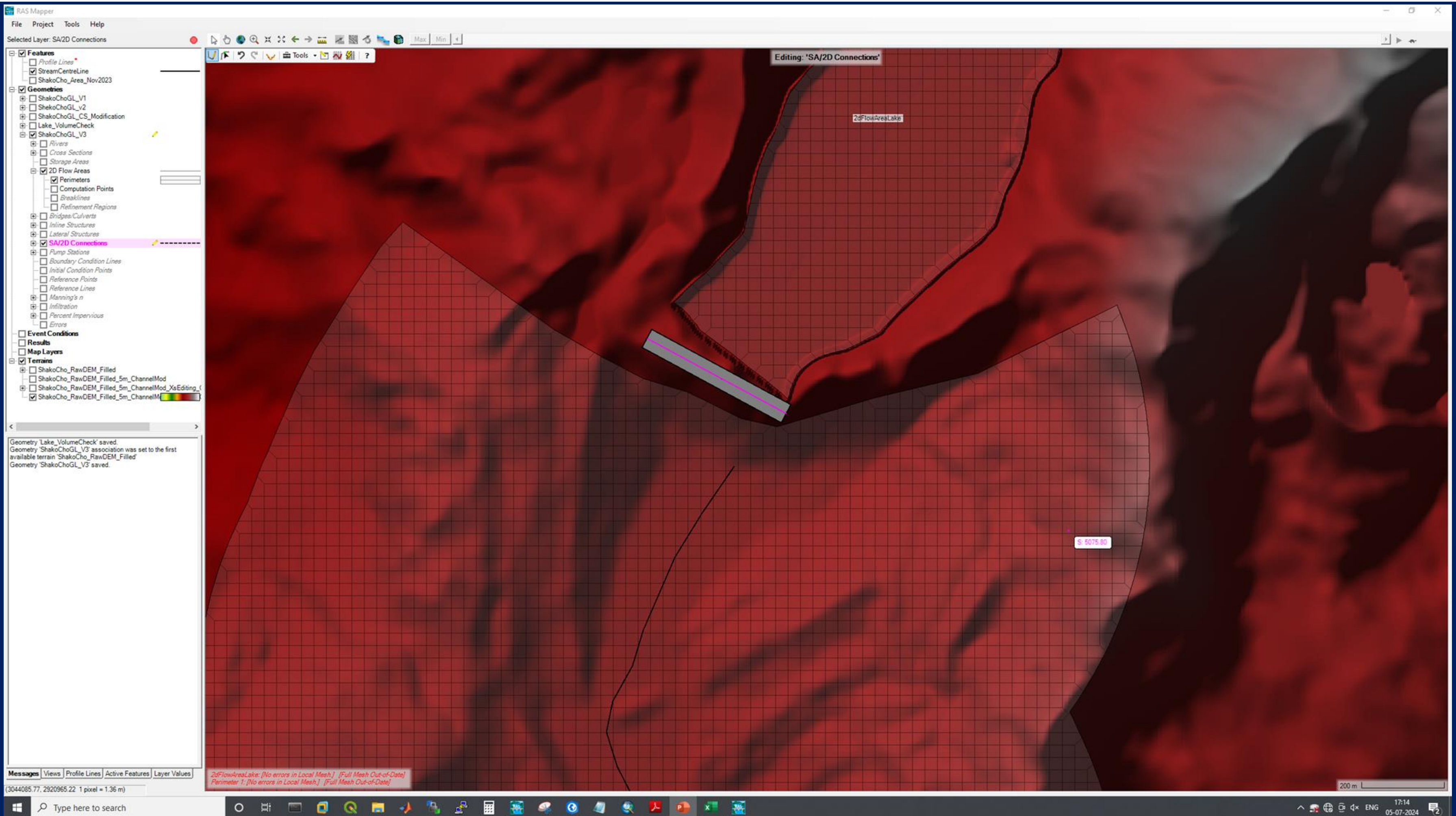
High resolution Digital Terrain Model



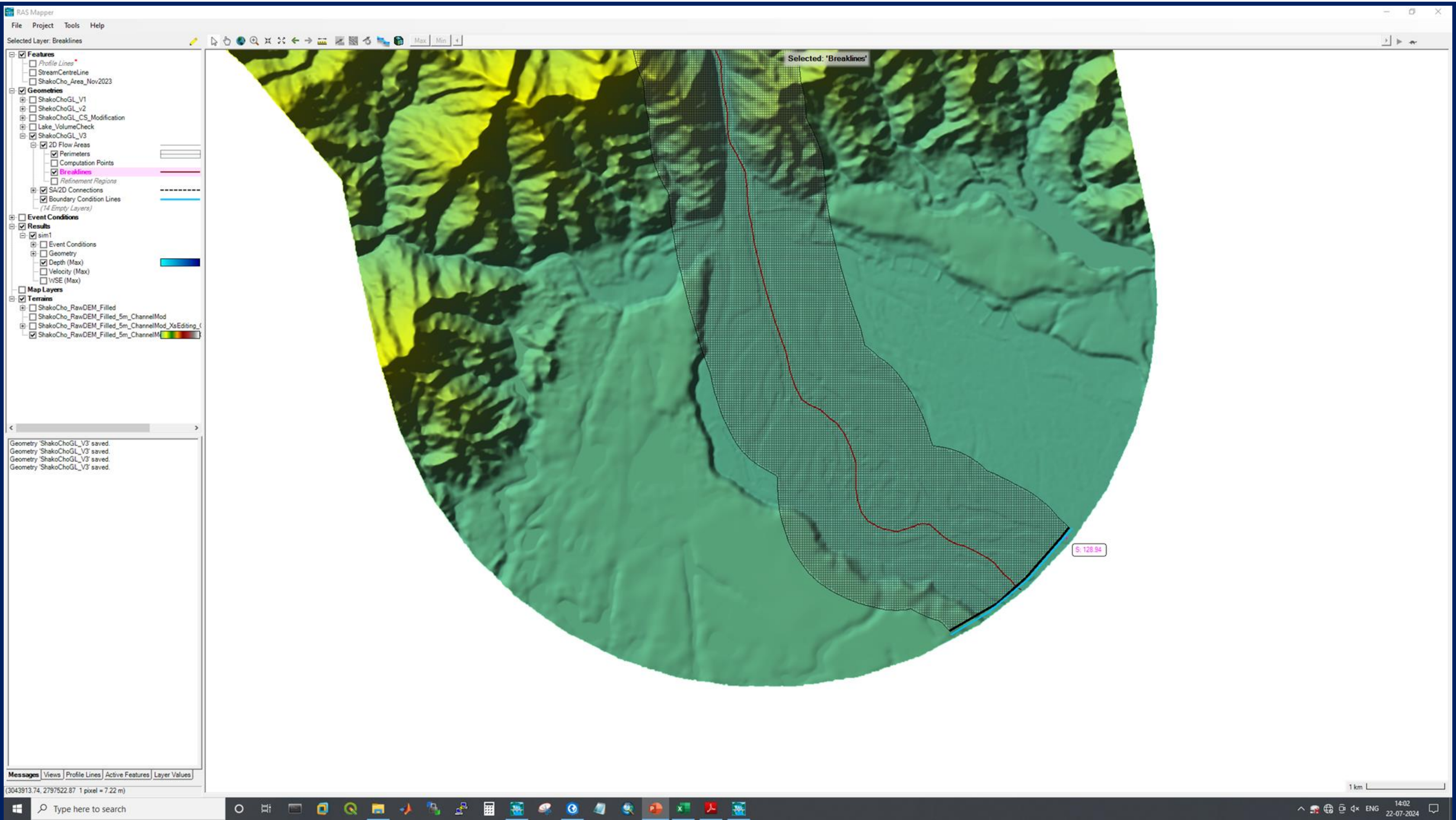
Glacier Lake Outburst Flood Risk Assessment



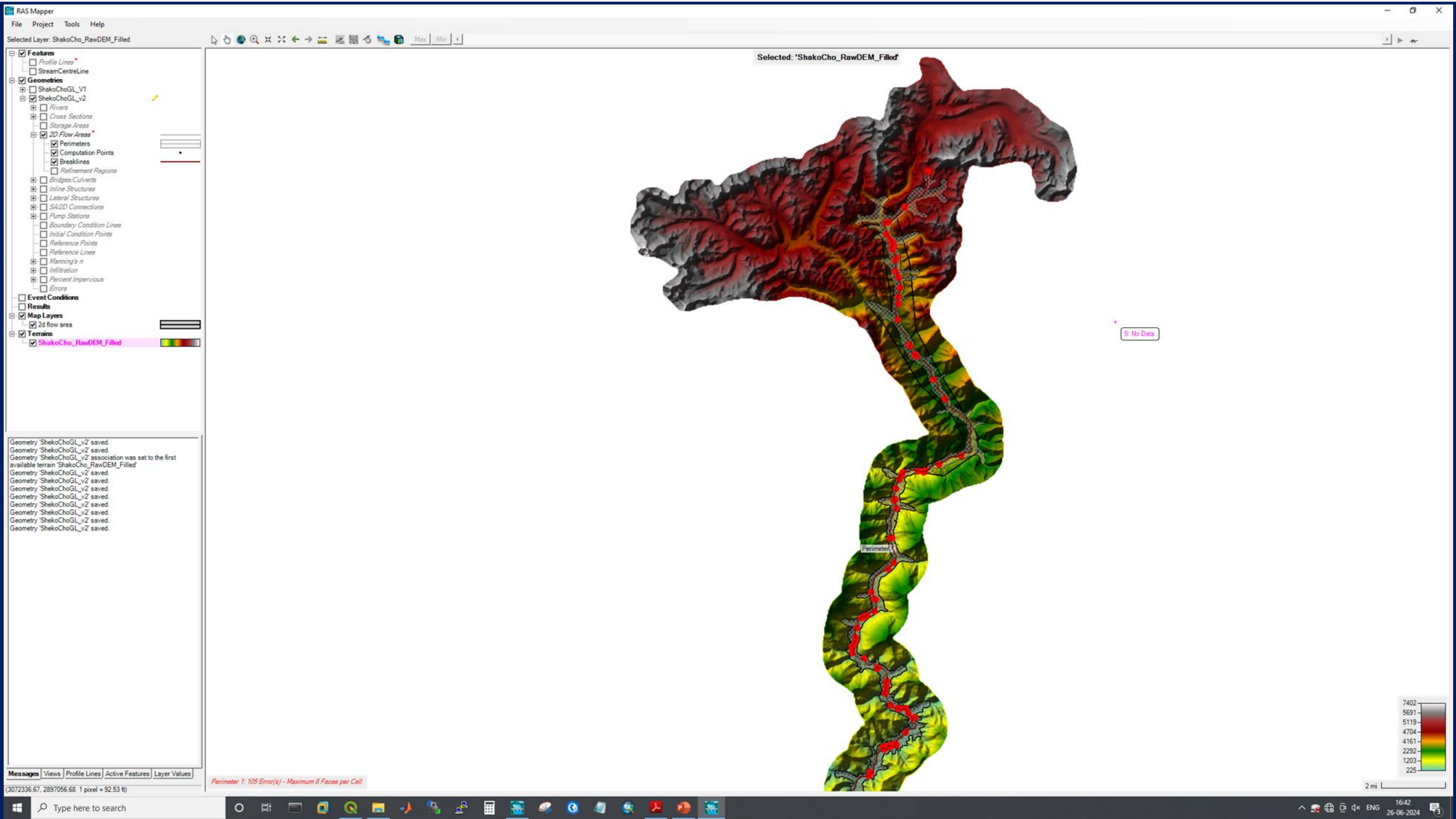
Glacier Lake Outburst Flood Risk Assessment



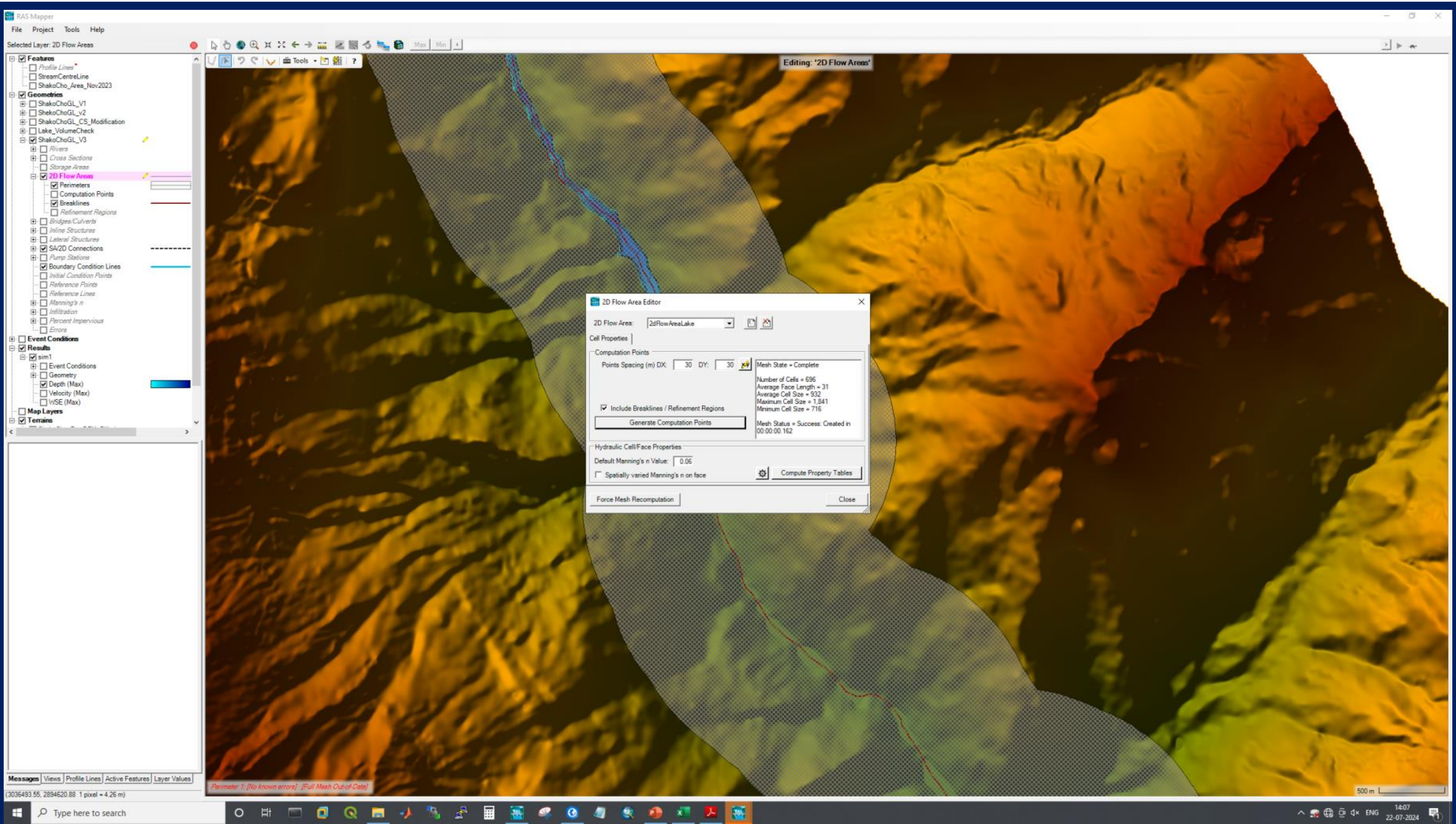
Glacier Lake Outburst Flood Risk Assessment



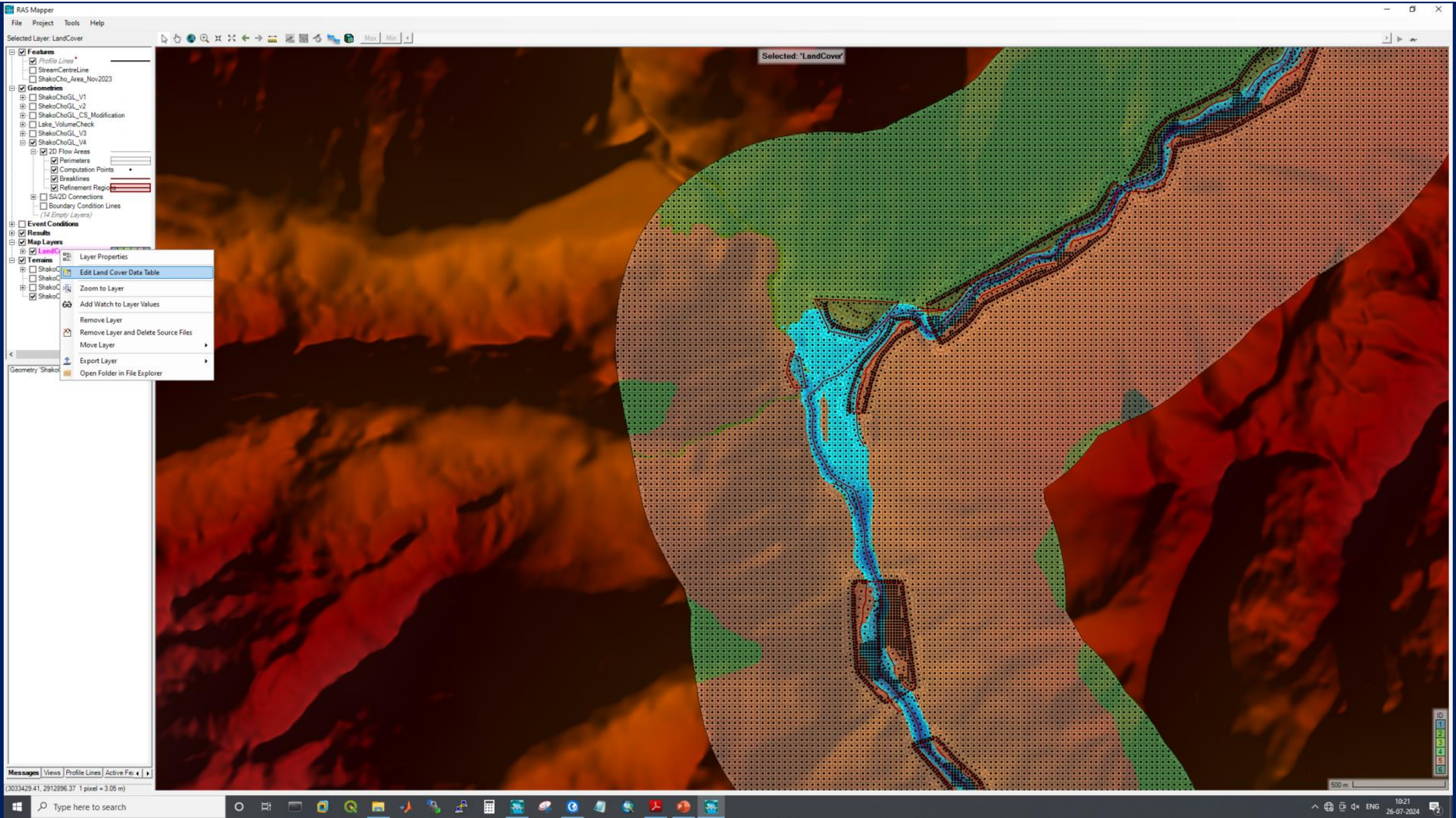
Glacier Lake Outburst Flood Risk Assessment



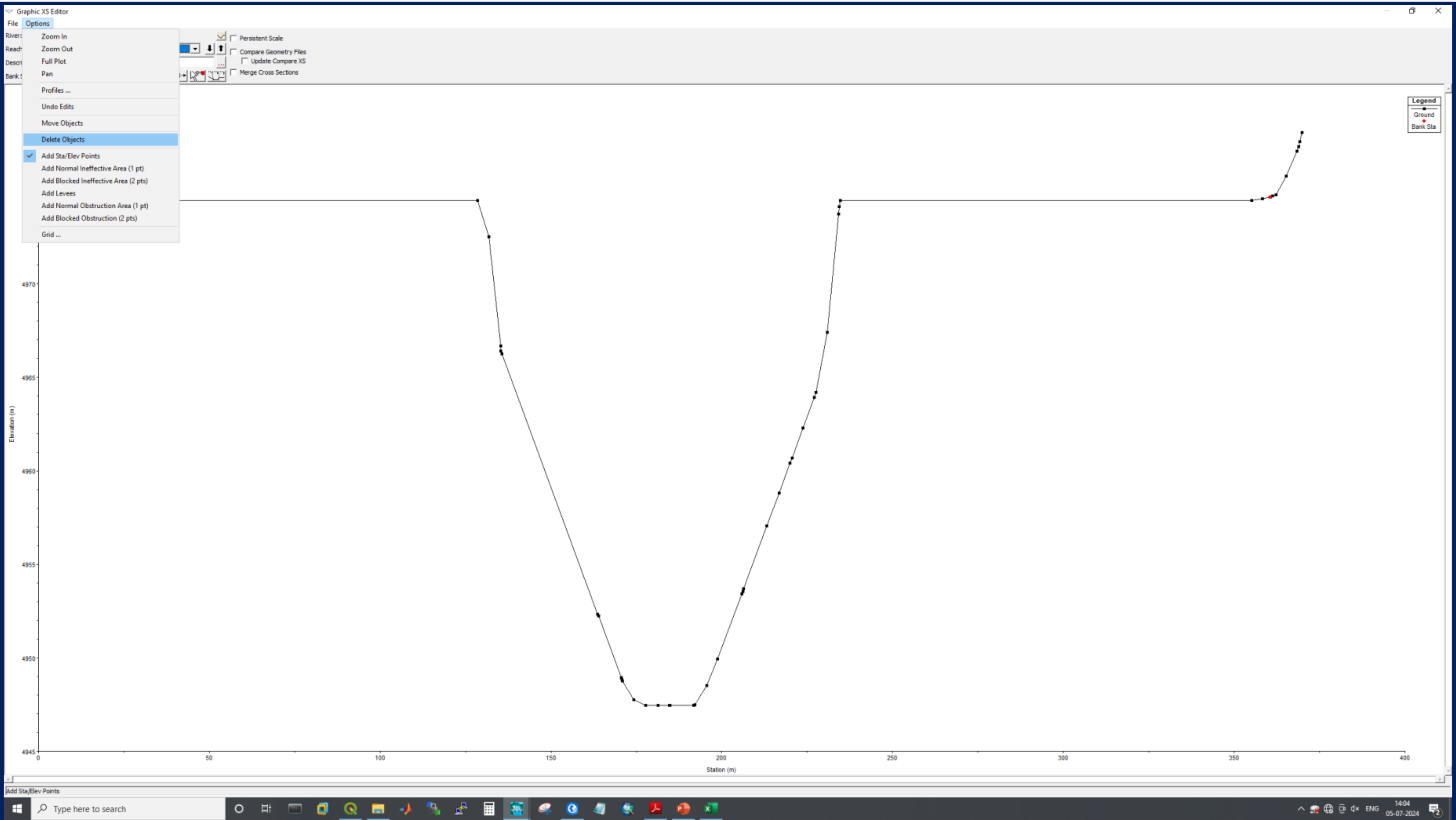
Glacier Lake Outburst Flood Risk Assessment



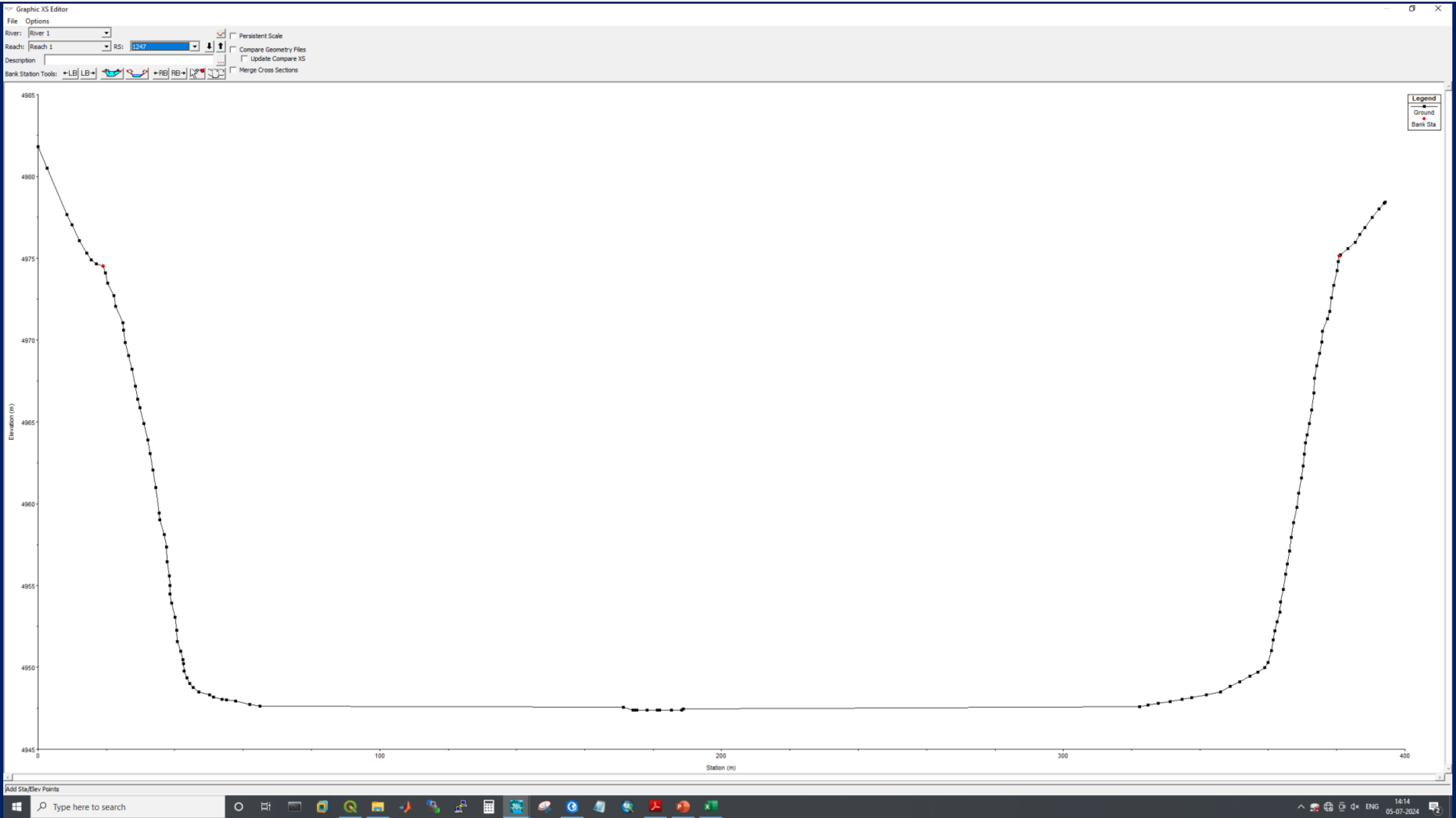
Glacier Lake Outburst Flood Risk Assessment



Glacier Lake Outburst Flood Risk Assessment

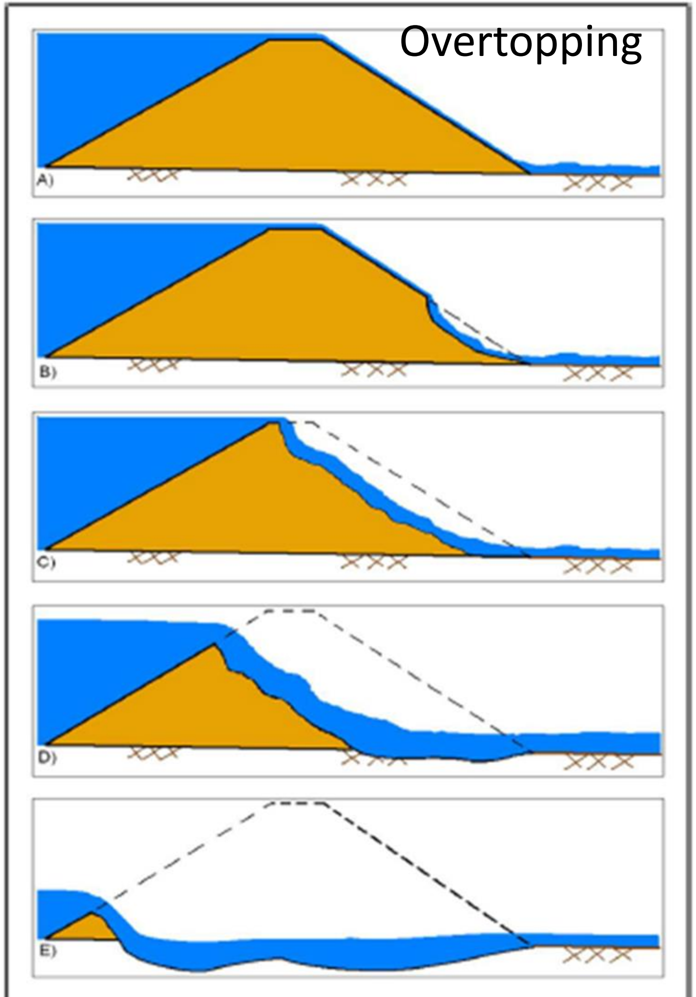


Glacier Lake Outburst Flood Risk Assessment



Glacier Lake Outburst Flood Risk Assessment

Failure Modes



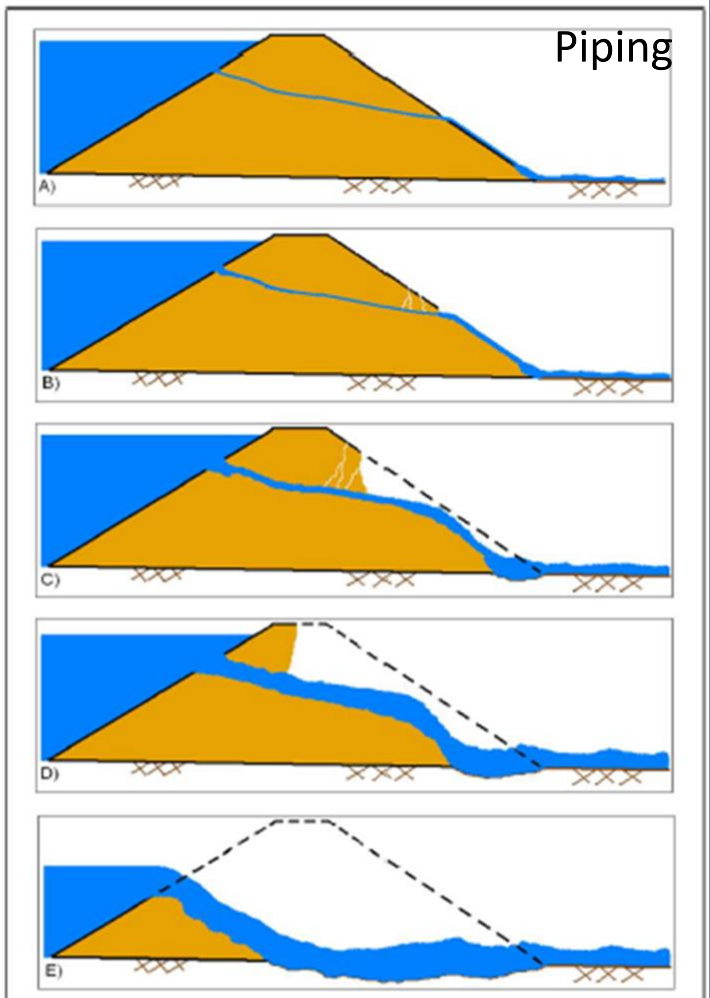
Source: HEC-RAS Manual

Critical breach development time:

- Overtopping failure: The end of the breach development time in HEC-RAS is when the breach is fully formed and significant erosion has stopped.
- The breach development ending time should not include the time to completely drain the reservoir pool.
- Breach weir flow coefficients: These coefficients directly affect the magnitude of the peak outflow hydrograph for any given breach.

Glacier Lake Outburst Flood Risk Assessment

Failure Modes

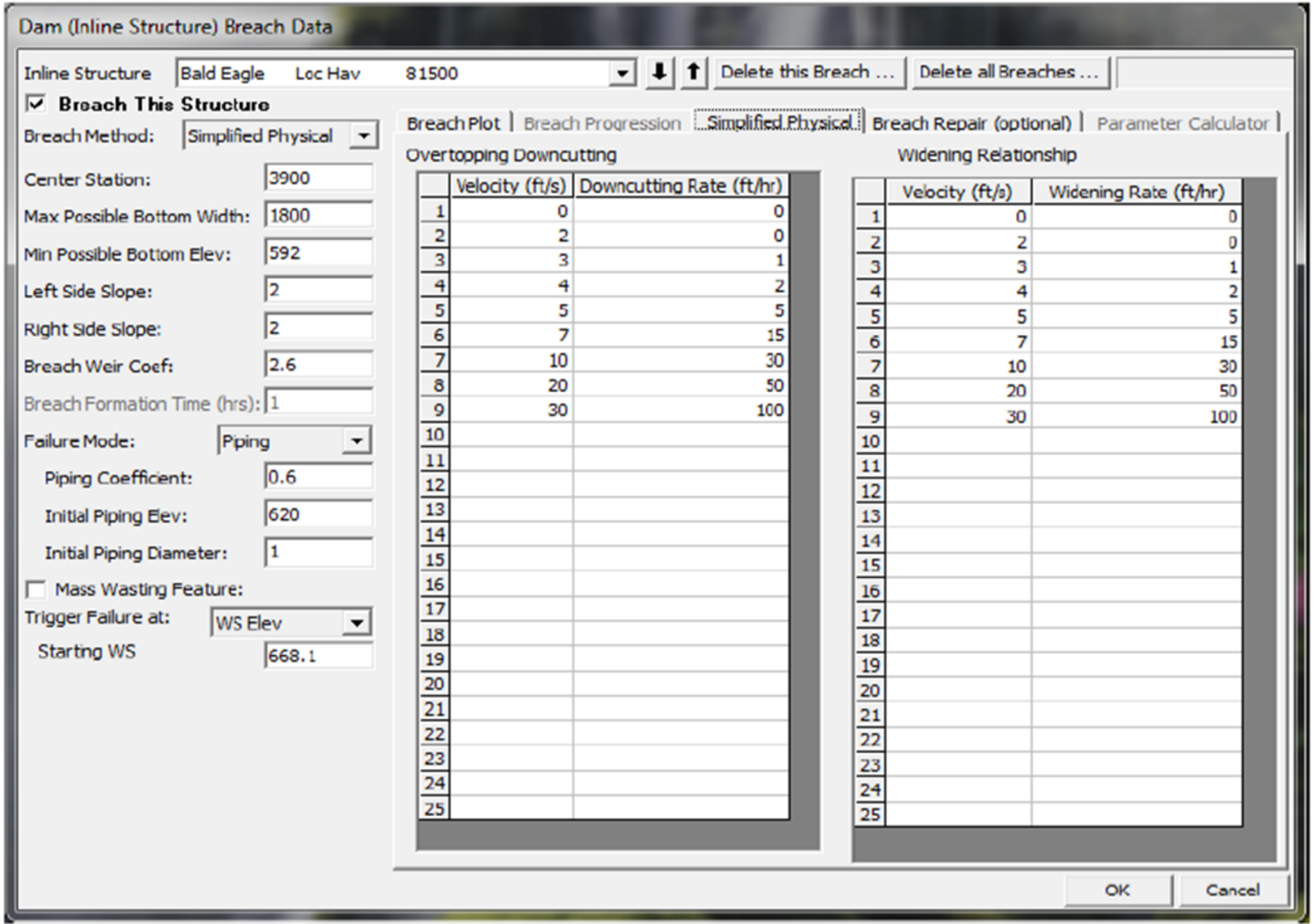


Source: HEC-RAS Manual

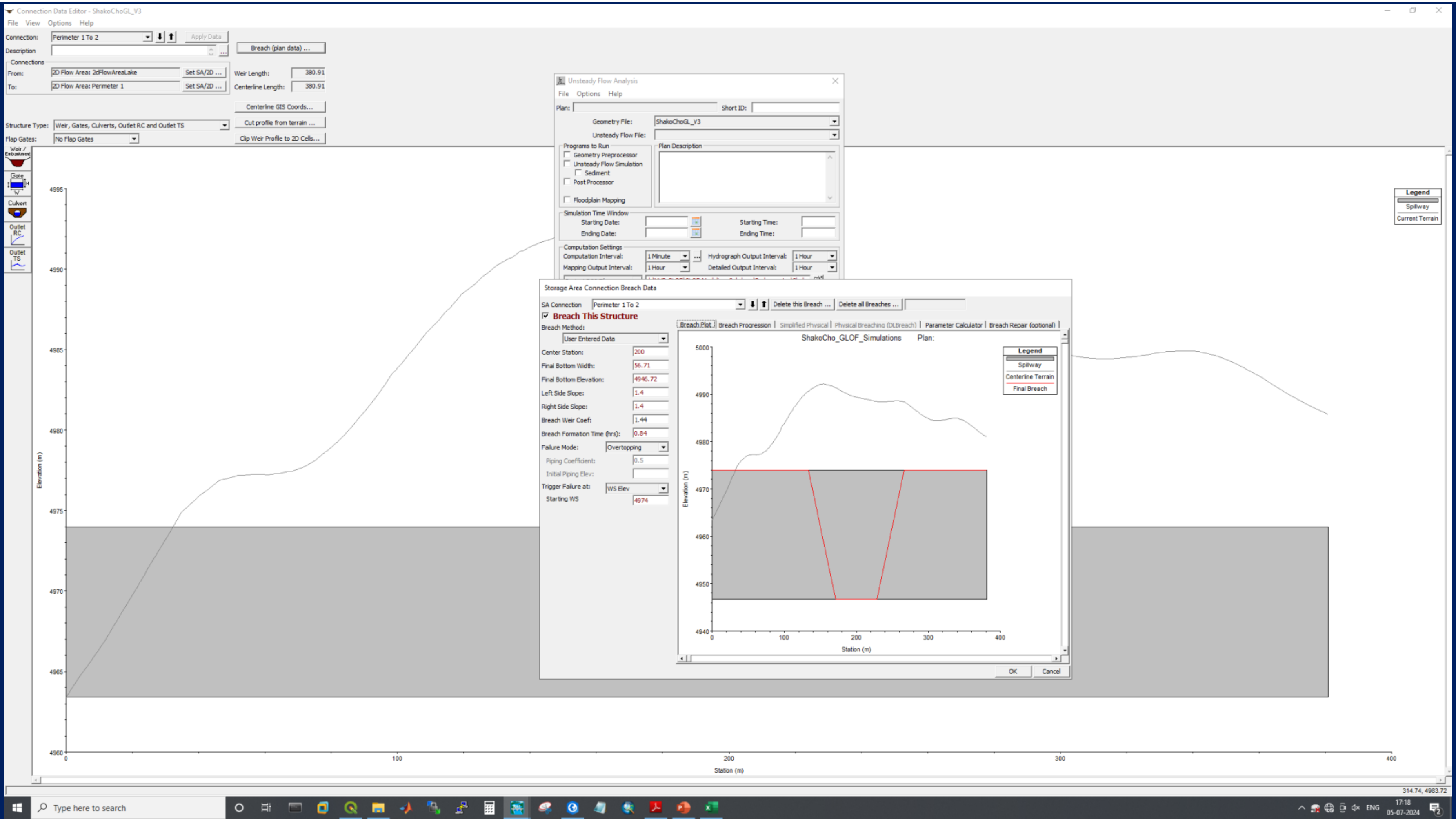
Critical breach development time:

- Piping failure: In HEAC-RAS the breach start time for piping failure is considered to be when a significant amount of flow and material are coming out of the piping hole.
- The breach ending time is considered to be when breach is, for most part, fully formed(significant erosion has stopped, not the time until the reservoir is emptied).
- Breach piping flow coefficients: These coefficients directly affect the magnitude of the peak outflow h/g for any given breach.

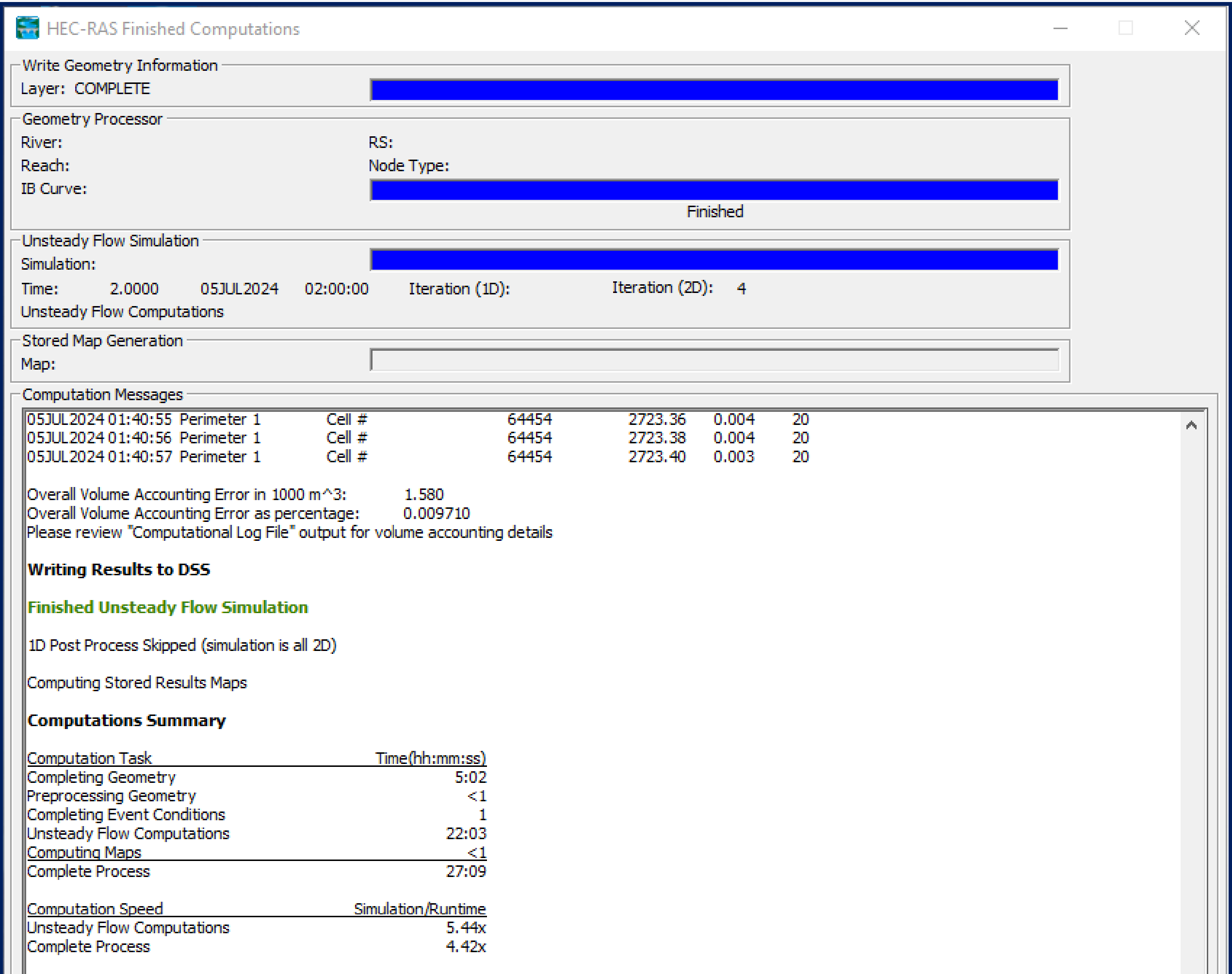
Glacier Lake Outburst Flood Risk Assessment



Glacier Lake Outburst Flood Risk Assessment



Glacier Lake Outburst Flood Risk Assessment



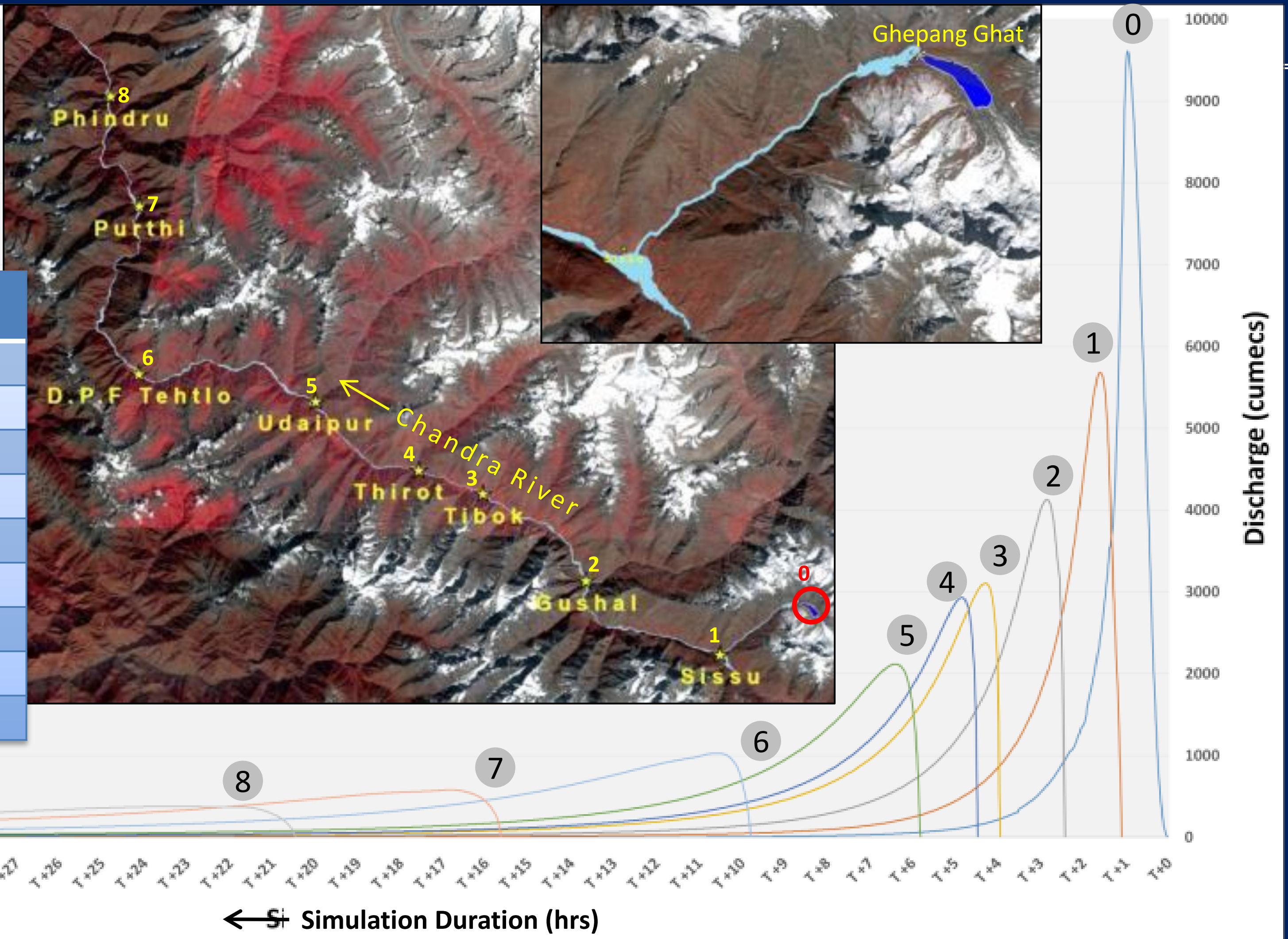
Downstream Flood Routing/ Modelling Issues

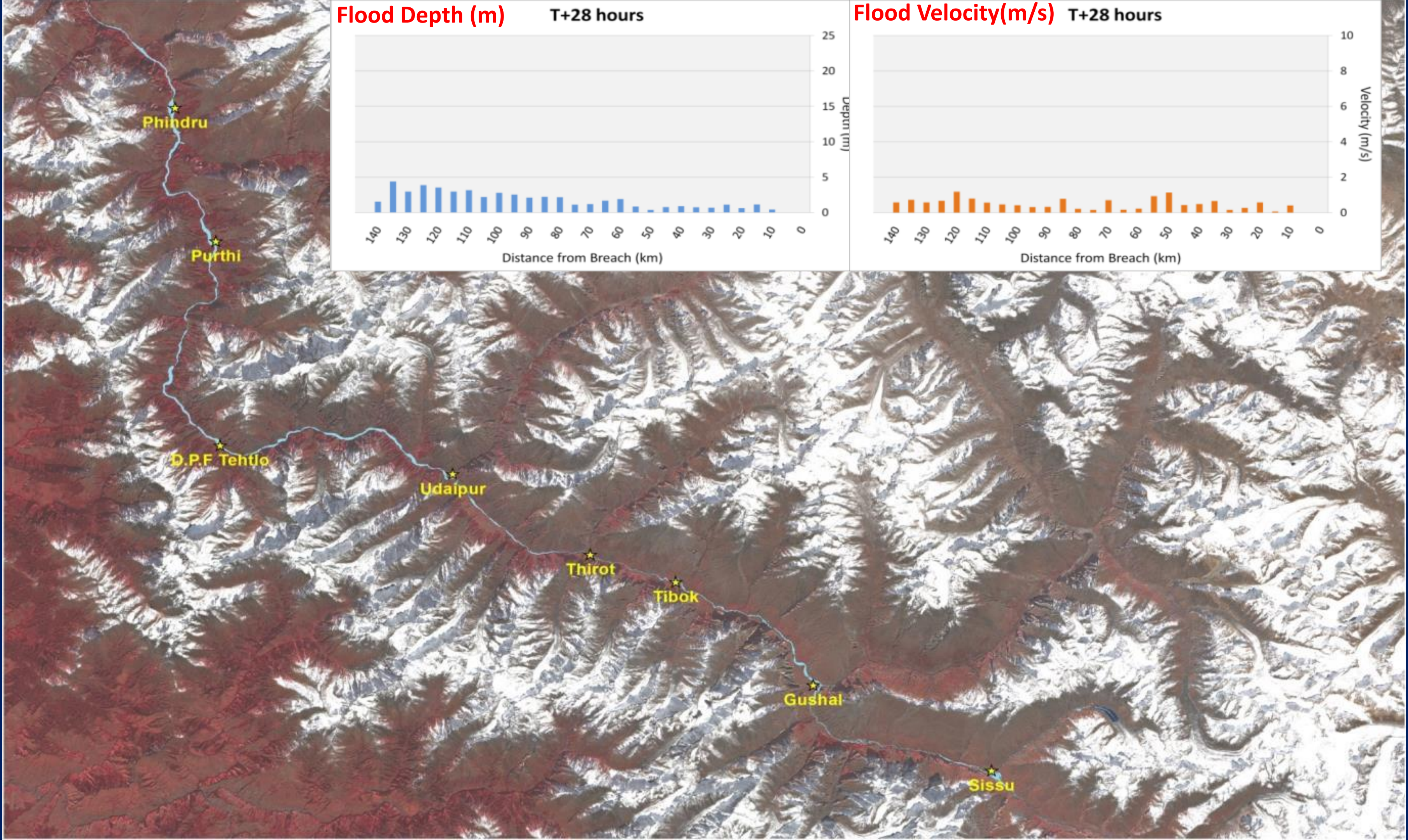
Most of these issues concern for 1D river reach modelling with c/s:

- C/s spacing and hydraulic properties
- Computational time step
- Manning's roughness coefficients
- d/s storage, tributaries and levees
- Modelling bridge and culvert crossing
- Modelling steep streams
- Drops in the bed profile
- Initial conditions and low flow
- d/s boundary conditions

Scenario	100% Volume released
Failure Mode	Overtopping

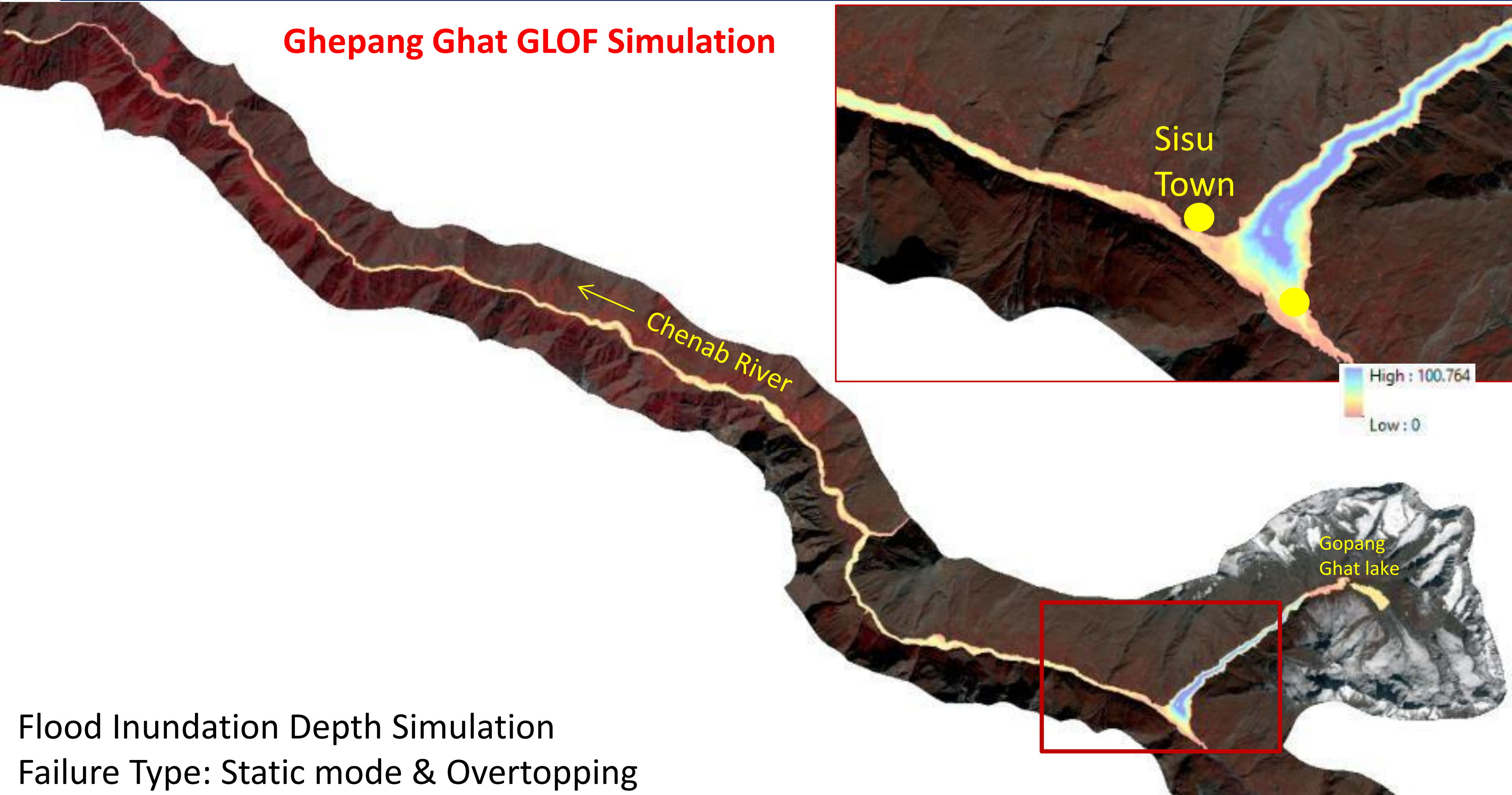
S.No	Location (distance)	Peak discharge
0	Moraine (0 km)	9,611 m^3/s
1	Sissu (10 km)	9,378 m^3/s
2	Gushal (20 km)	4,123 m^3/s
3	Tibok (35 km)	3,105 m^3/s
4	Thirot (45 km)	2,929 m^3/s
5	Udaipur (60 km)	2,117 m^3/s
6	D.P.F. Tehtlo (85 km)	1,026 m^3/s
7	Purthi (110 km)	581 m^3/s
8	Phindru (125 km)	376 m^3/s




Flood Depth (m)
T+28 hours
25
20
15
10
5
0
Depth (m)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Distance from Breach (km)
Flood Velocity(m/s)
T+28 hours
10
8
6
4
2
0
Velocity (m/s)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Distance from Breach (km)
Phindru
Purthi
D.P.F Tehtlo
Udaipur
Thirot
Tibok
Gushal
Sissu

Glacier Lake Outburst Flood Risk Assessment

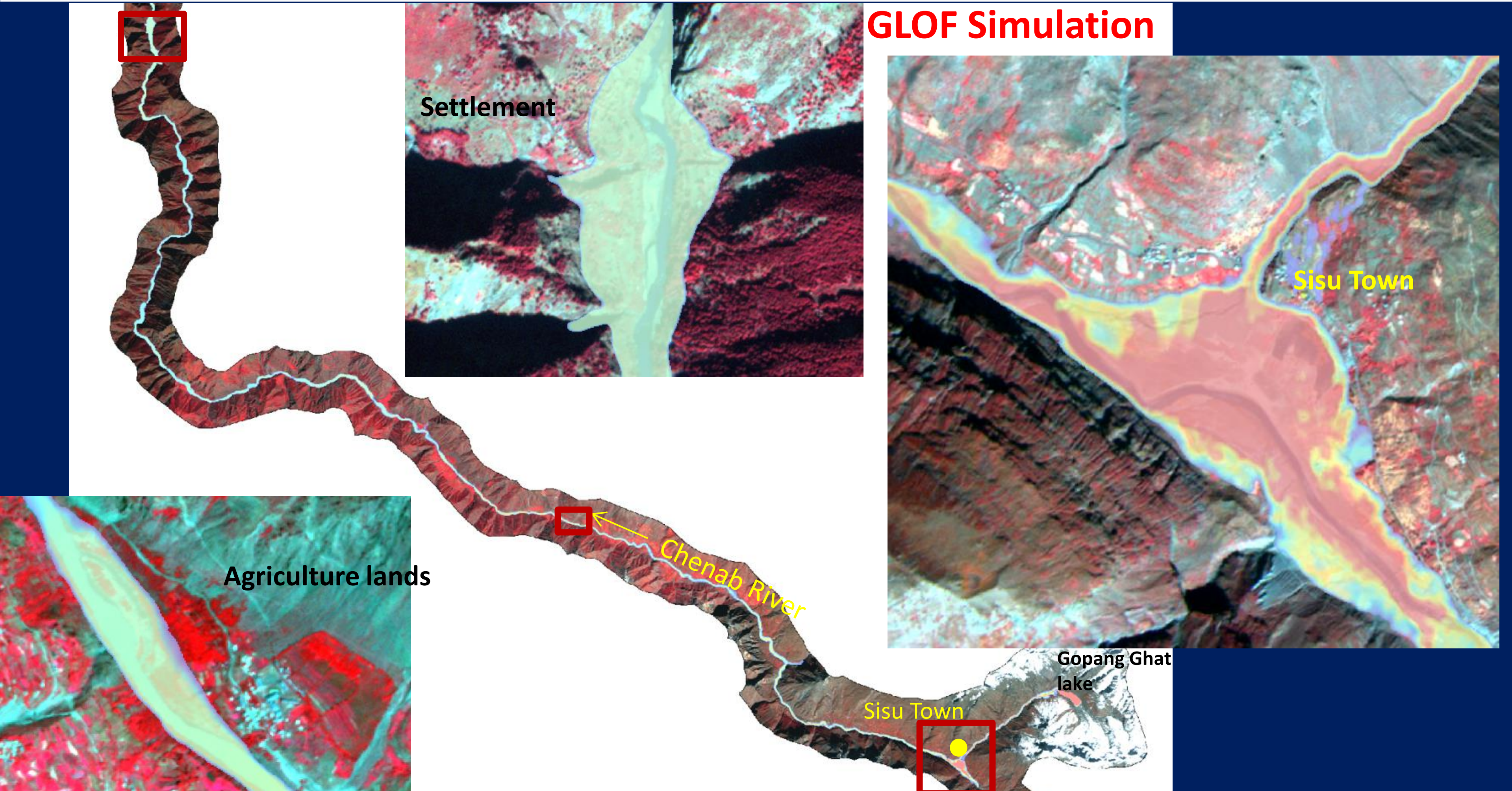
Ghepang Ghat GLOF Simulation



Flood Inundation Depth Simulation

Failure Type: Static mode & Overtopping

Glacier Lake Outburst Flood Risk Assessment



Glacier Lake Outburst Flood Risk Assessment

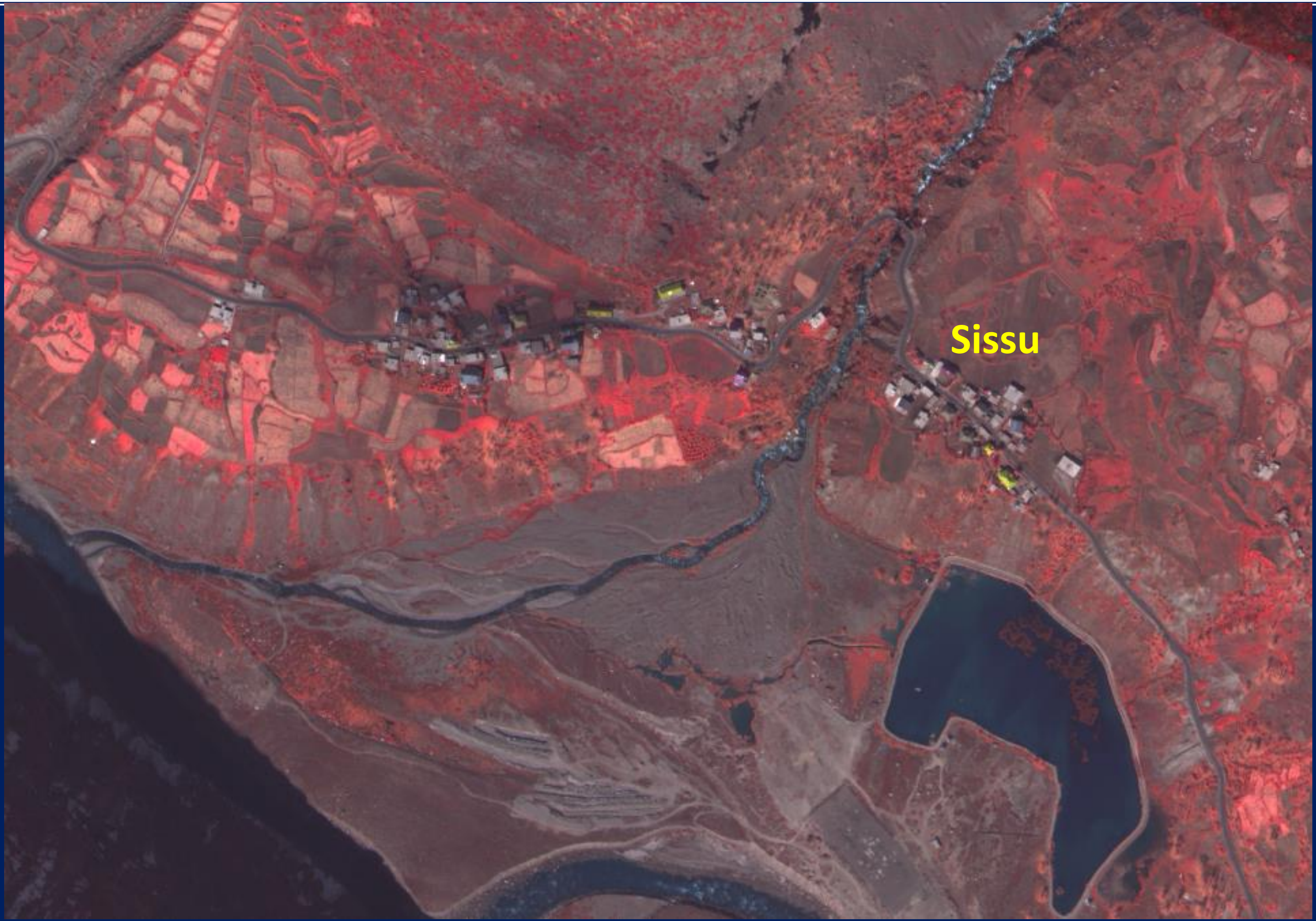
Scenarios

- **Scenario-1** → Lake breaches at **100%** of Avg Depth i.e. **34.62 m**, Discharging total volume of **35.08 MCM**
- **Scenario-2** → Lake breaches at **75%** of Avg Depth i.e. **24.78 m**, Discharging total volume of **26.31 MCM**
- **Scenario-3** → Lake breaches at **50%** of Avg Depth i.e. **15.98 m**, Discharging total volume of **17.54 MCM**

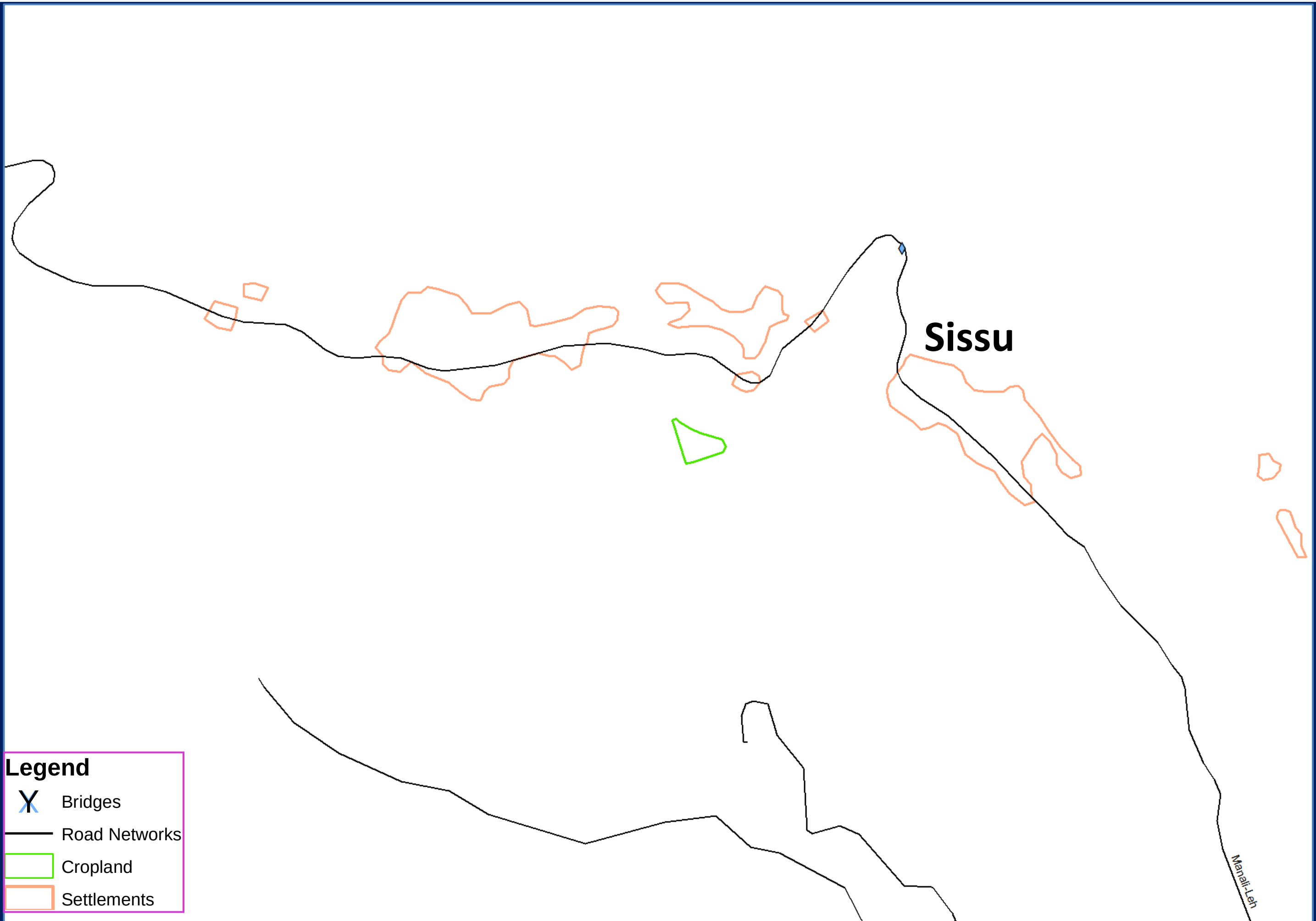
S.No	**Dam Breach Parameters**	**Scenario-1**
1	Breach Moraine Height (B_h)	**34.62 m**
2	Final Bottom Elevation (E_b)	4,034.08 m
3	Water Surface Elevation (E_s)	4,068.70 m
4	Average Breach Width (AB_w)	128.53 m
5	Breach Formation Time (B_{ft})	1.04 hrs
6	Bottom Width (B_w)	80.06 m
7	Breach Progression Rate (V:H)	0.43
8	Outflow Peak Discharge (Q_p)	8,274 m^3/s
9	Outflow Minimum Discharge	4,342 m^3/s
10	Outflow Maximum Discharge	18,956 m^3/s

GLOF Vulnerable Infrastructure

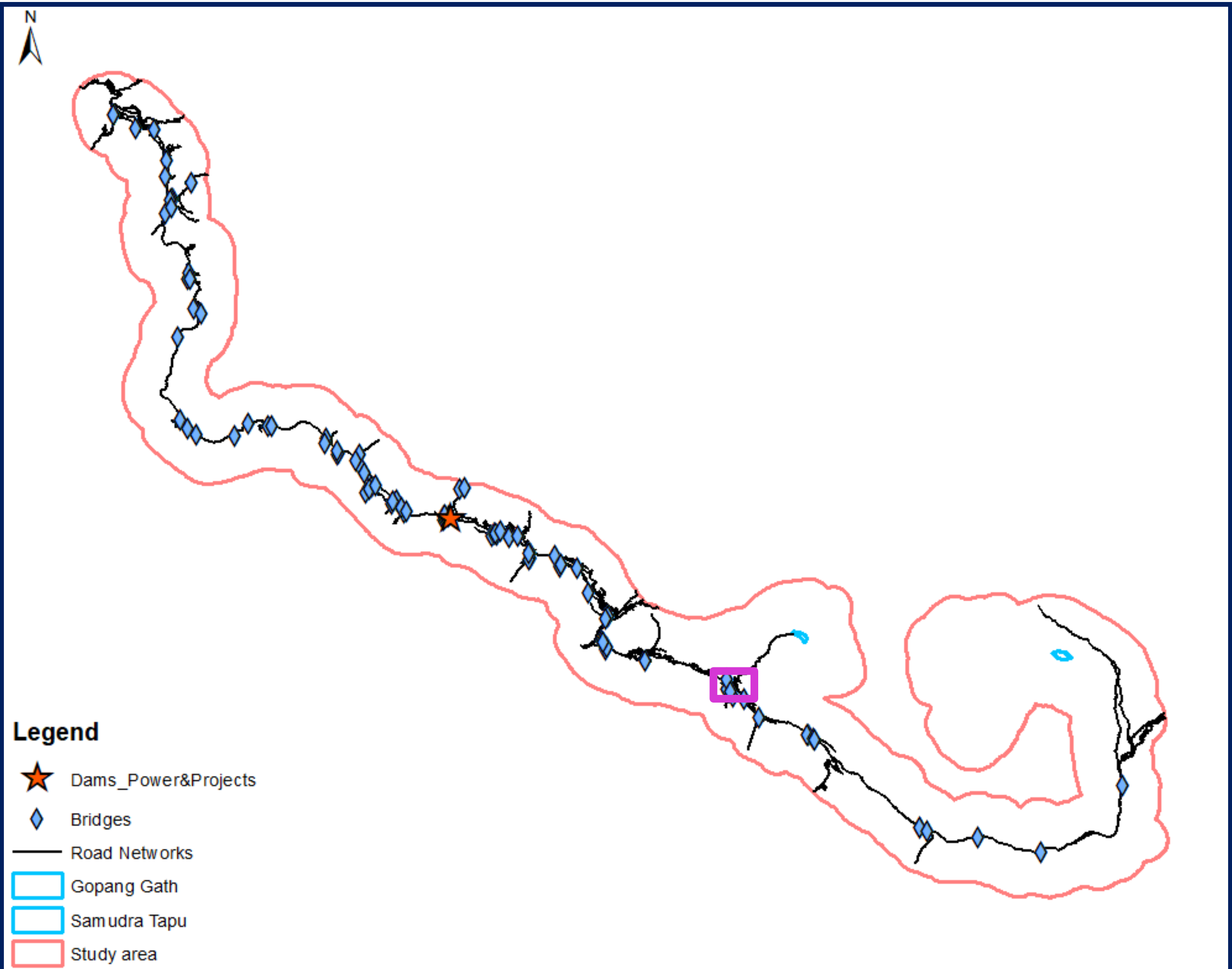
Glacier Lake Outburst Flood Risk Assessment



Glacier Lake Outburst Flood Risk Assessment

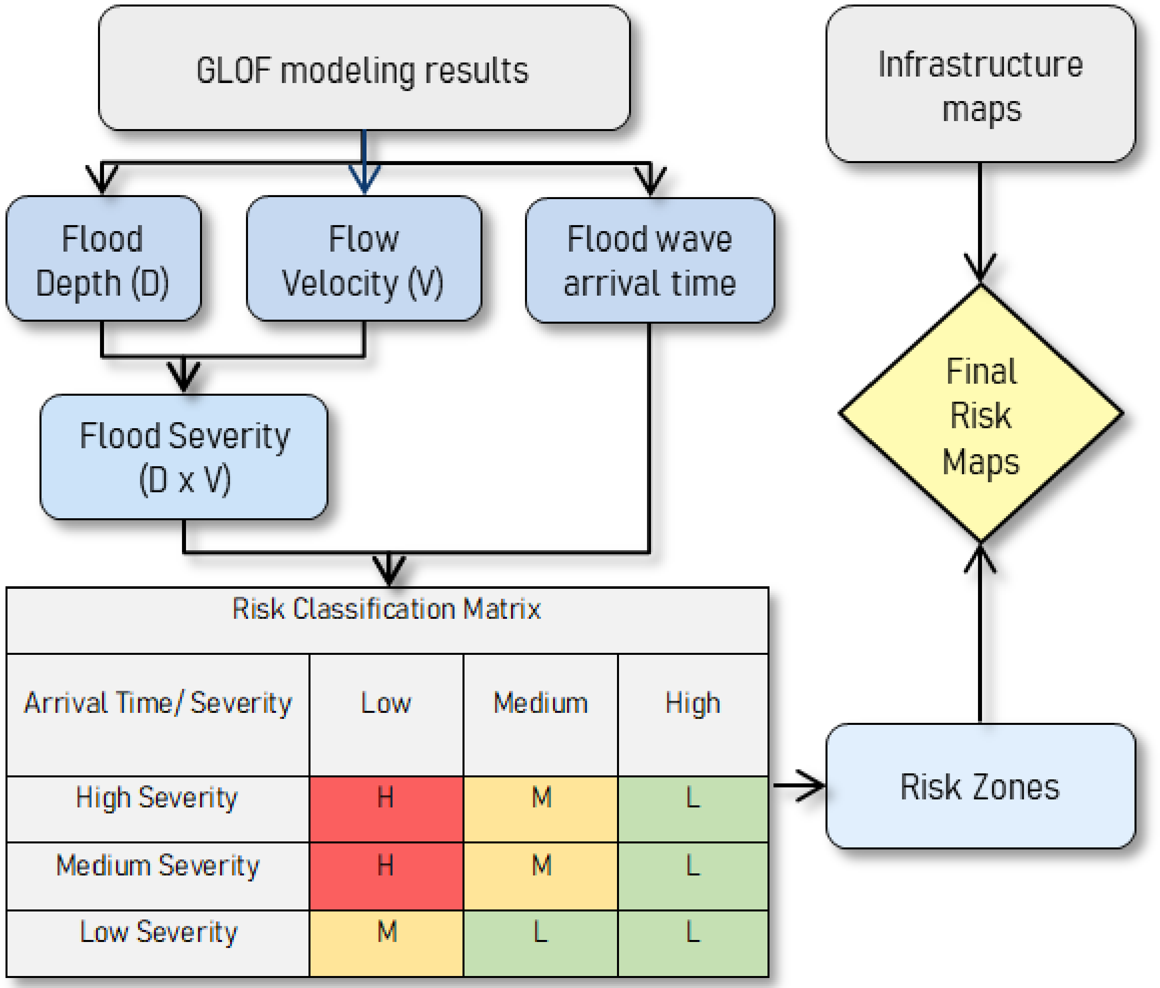


Glacier Lake Outburst Flood Risk Assessment



GLOF Risk Assessment

Glacier Lake Outburst Flood Risk Assessment

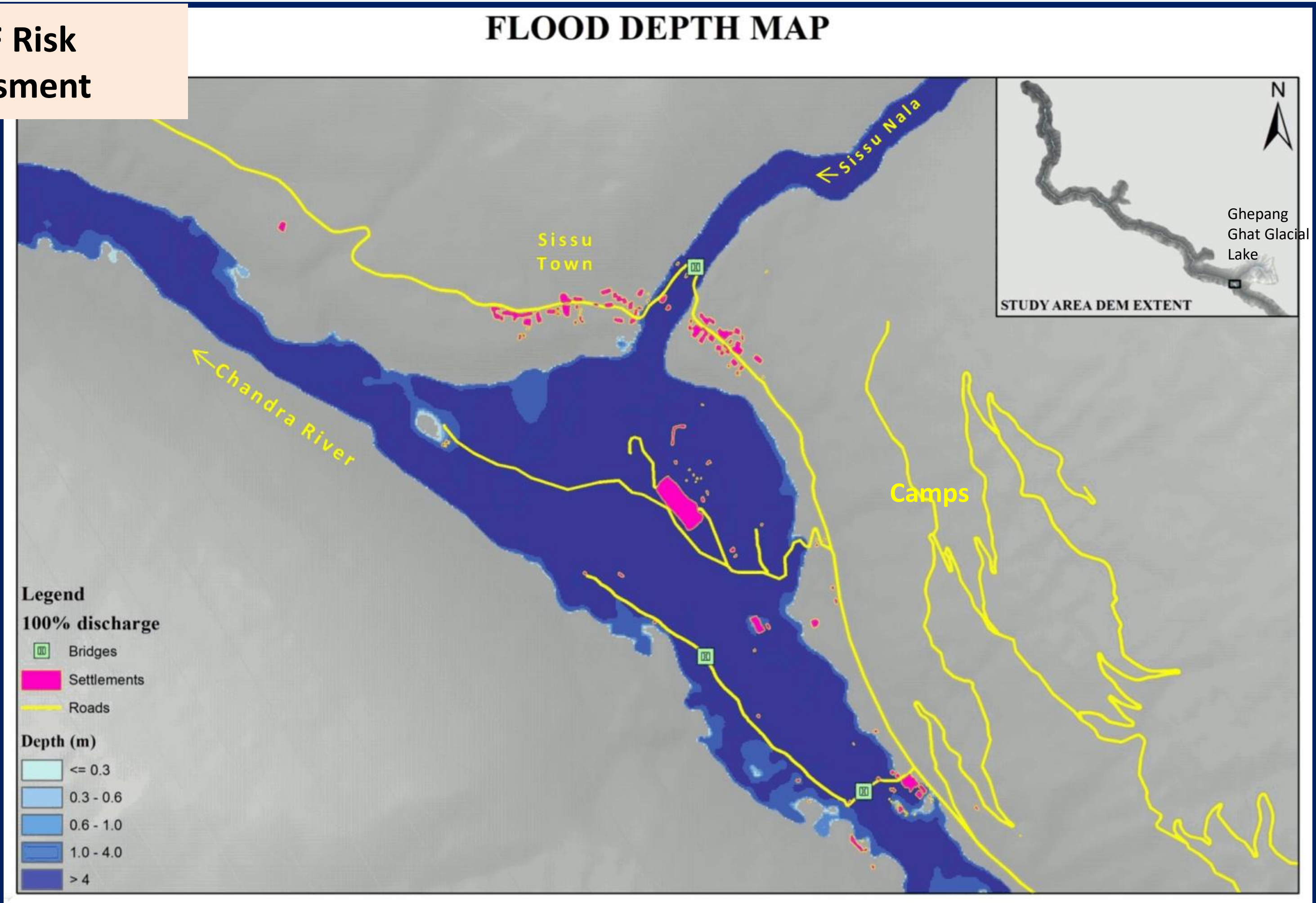


Risk Classification Matrix

Arrival Time/ Severity	Low	Medium	High
High Severity	H	M	L
Medium Severity	H	M	L
Low Severity	M	L	L

Glacier Lake Outburst Flood Risk Assessment

GLOF Risk Assessment



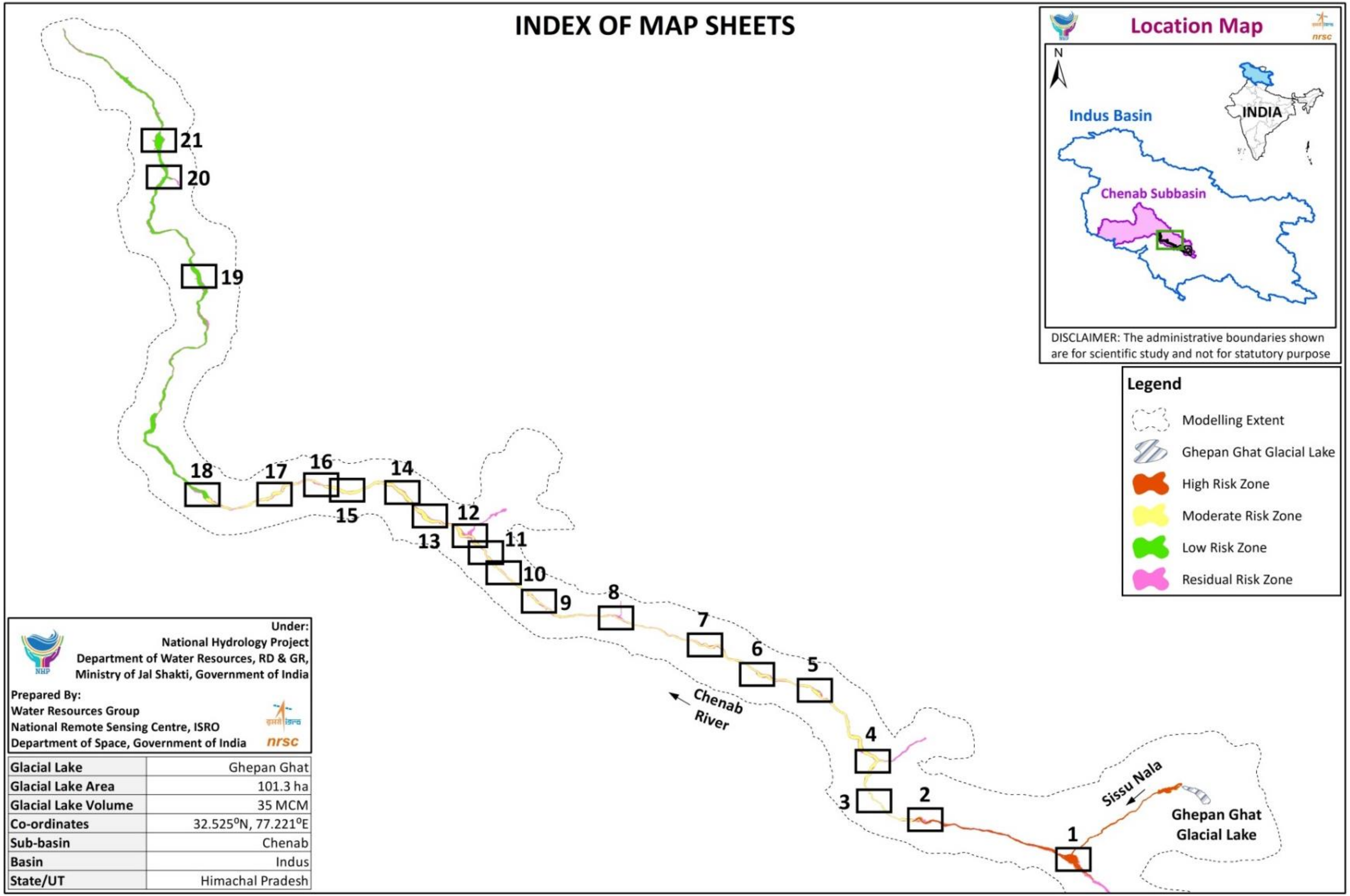
Glacier Lake Outburst Flood Risk Assessment

GLOF Risk Assessment

Scenario		Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
7	1	High	401	3	15.8	4	6.7
		Moderate	1,018	24	46.2	24	17.5
		Low	829	5	32.3	13	13.3
		Residual	3,902	2	110.4	16	69.4
Total			**6,150**	**34**	**204.7**	**57**	**106.9**

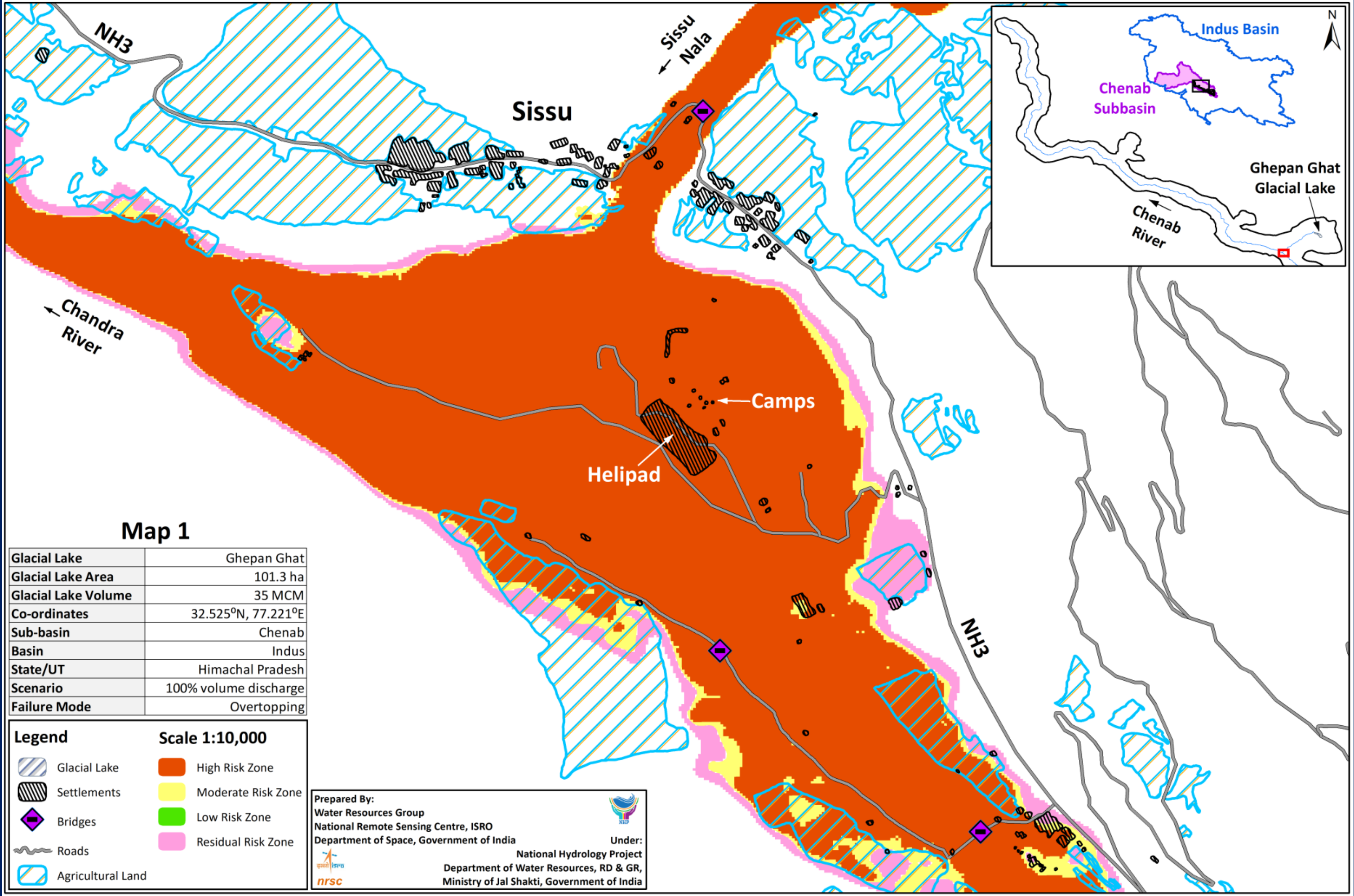
Scenario	Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
3	High	300	1	9.7	3	3.4
	Moderate	919	22	41.3	25	15.2
	Low	915	7	32	13	16.0
Total		**2,134**	**30**	**83**	**41**	**34.6**

Glacier Lake Outburst Flood Risk Assessment



Glacial Lake	Ghepan Ghat
Glacial Lake Area	101.3 ha
Glacial Lake Volume	35 MCM
Co-ordinates	32.525°N, 77.221°E
Sub-basin	Chenab
Basin	Indus
State/UT	Himachal Pradesh

Glacier Lake Outburst Flood Risk Assessment



Map 1

Glacial Lake	Ghepan Ghat
Glacial Lake Area	101.3 ha
Glacial Lake Volume	35 MCM
Co-ordinates	32.525ºN, 77.221ºE
Sub-basin	Chenab
Basin	Indus
State/UT	Himachal Pradesh
Scenario	100% volume discharge
Failure Mode	Overtopping

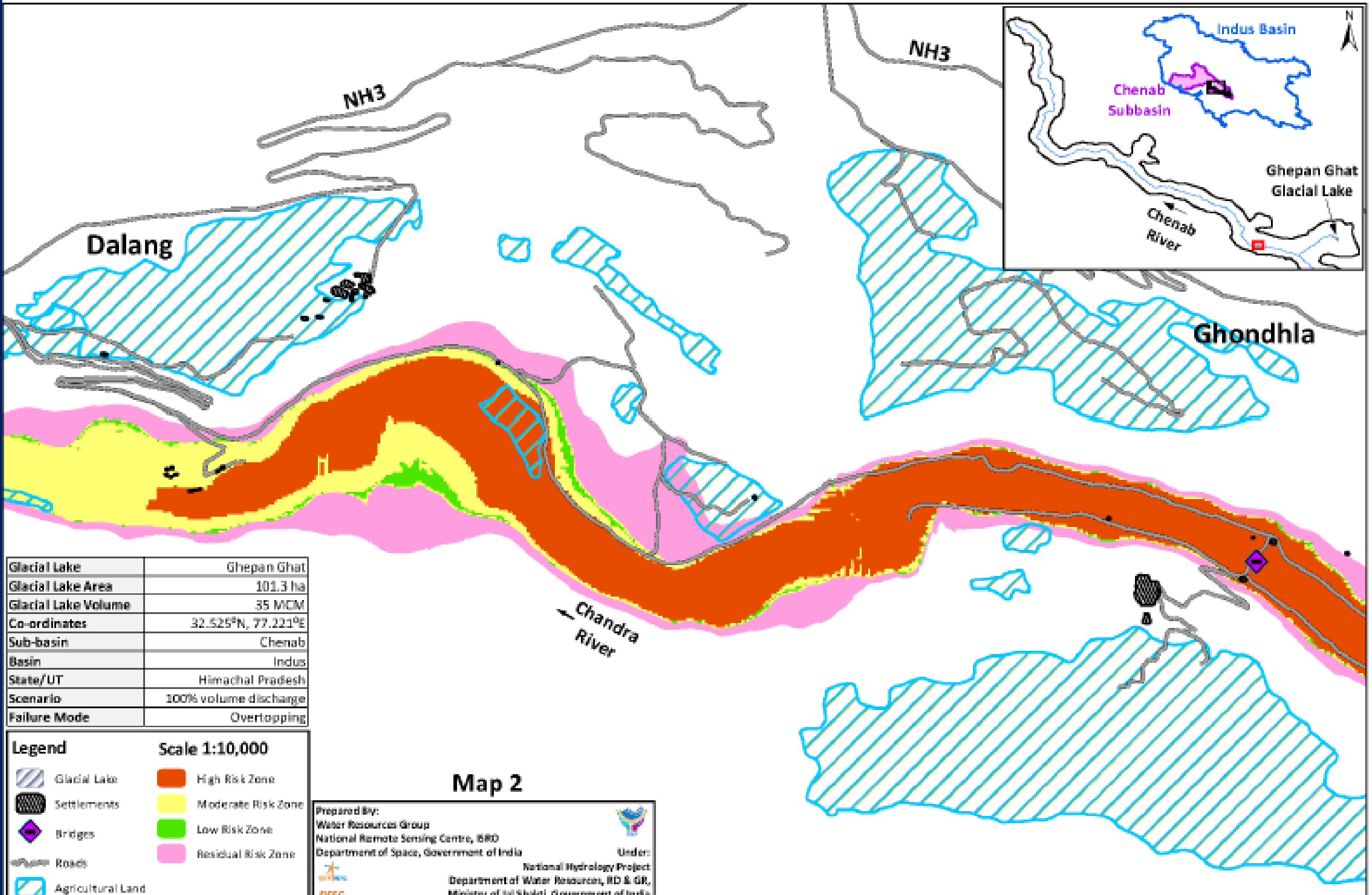
Legend — Scale 1:10,000

- Glacial Lake
- Settlements
- Bridges
- Roads
- Agricultural Land
- High Risk Zone
- Moderate Risk Zone
- Low Risk Zone
- Residual Risk Zone

Prepared By:
Water Resources Group
National Remote Sensing Centre, ISRO
Department of Space, Government of India

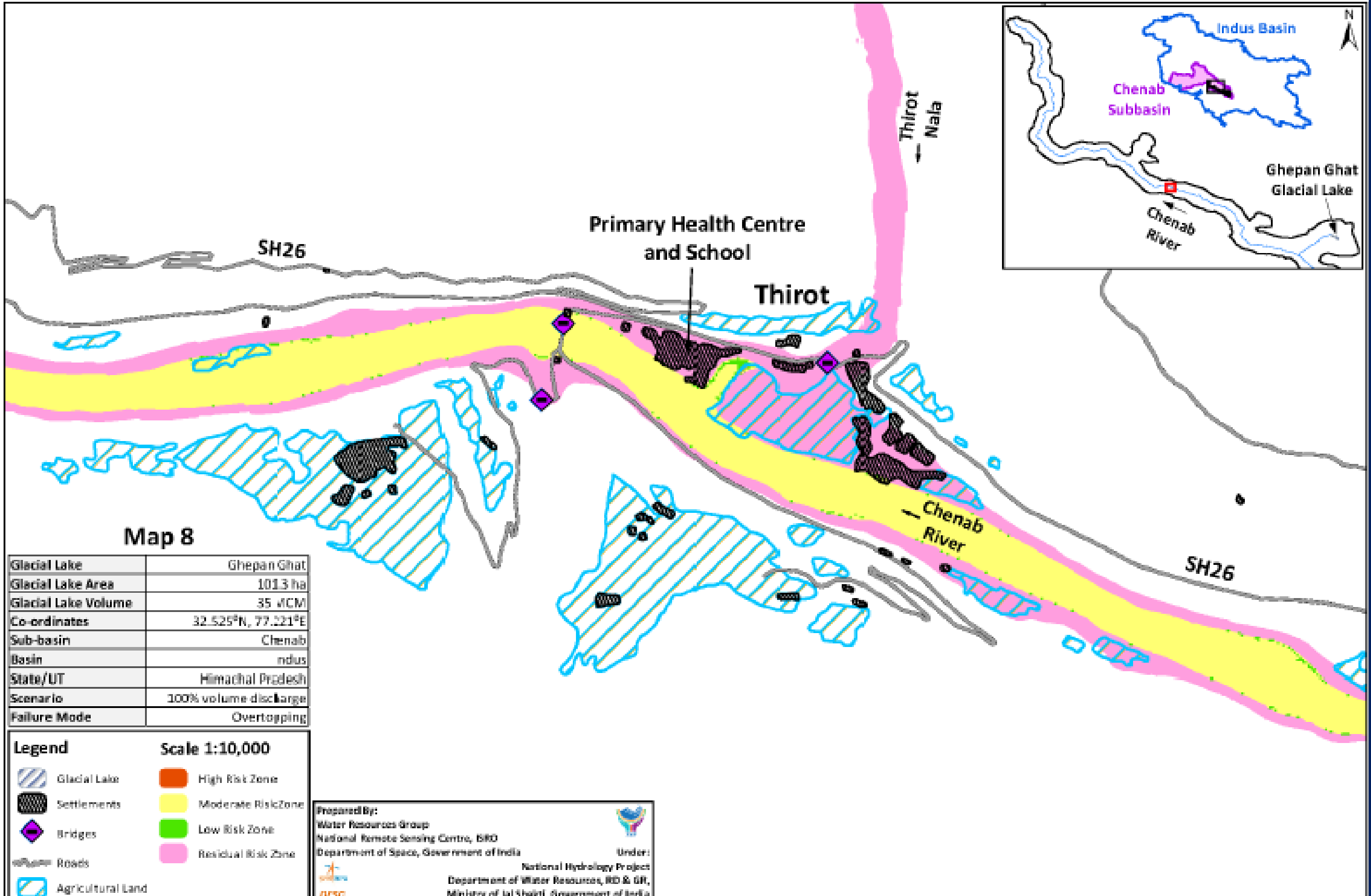
Under:
National Hydrology Project
Department of Water Resources, RD & GR,
Ministry of Jal Shakti, Government of India

Glacier Lake Outburst Flood Risk Assessment



Glacial Lake	Ghepan Ghat
Glacial Lake Area	101.3 ha
Glacial Lake Volume	35 MCM
Co-ordinates	32.525°N, 77.221°E
Sub-basin	Chenab
Basin	Indus
State/UT	Himachal Pradesh
Scenario	100% volume discharge
Failure Mode	Overtopping

Glacier Lake Outburst Flood Risk Assessment

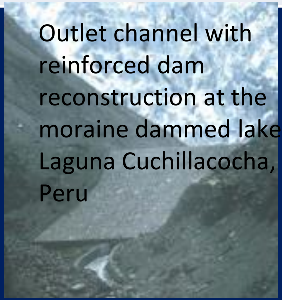


Glacial Lake	Ghepan Ghat
Glacial Lake Area	101.3 ha
Glacial Lake Volume	35 MCM
Co-ordinates	32.525°N, 77.221°E
Sub-basin	Chenab
Basin	Indus
State/UT	Himachal Pradesh
Scenario	100% volume discharge
Failure Mode	Overtopping

Options for Risk Management of Glacial Lakes

Structural measures
Non-structural measures

	Reduction of Hazard	Reduction of Exposure	Reduction of Vulnerability
Short term measures	• Lower of lake level by Siphoning or pumping	• Evacuation (based on monitoring / Early warning)	
Long term measures	• Artificial drainage channel • Reinforcement / increase of height of dam • Enhancement of river cross section / protection from erosion	Early Warning Systems • Spatial planning according to hazard maps • Protective structures (e.g. retention or deflection dams)	• Information (capacity & data) • Institutional setup • Economic diversity • Disaster relief


Outlet channel with reinforced dam reconstruction at the moraine dammed lake Laguna Cuchillacocha, Peru


Artificial Channel Enlargement of Imja Lake, Nepal, 26 September 2016

Source: Guidelines on Management of GLOF


THANK YOU