

Glacier Lake Outburst Flood Risk Assessment

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Glacier Lake

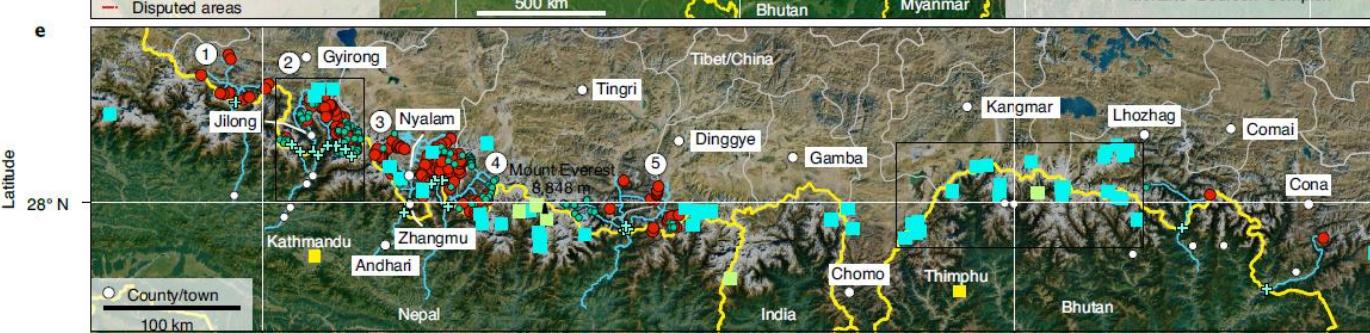
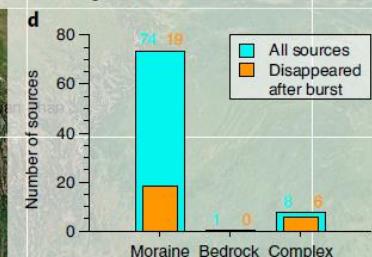
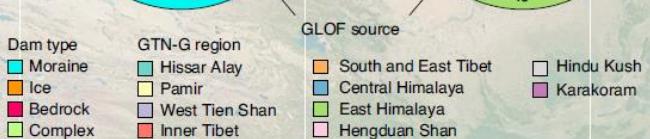
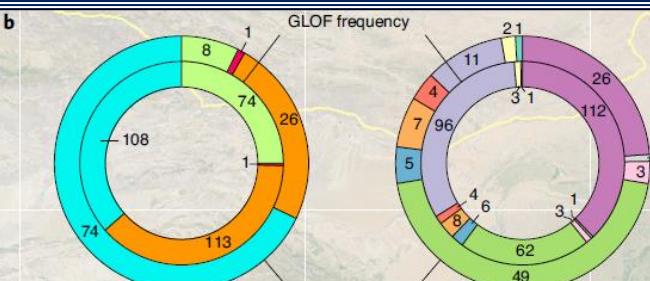
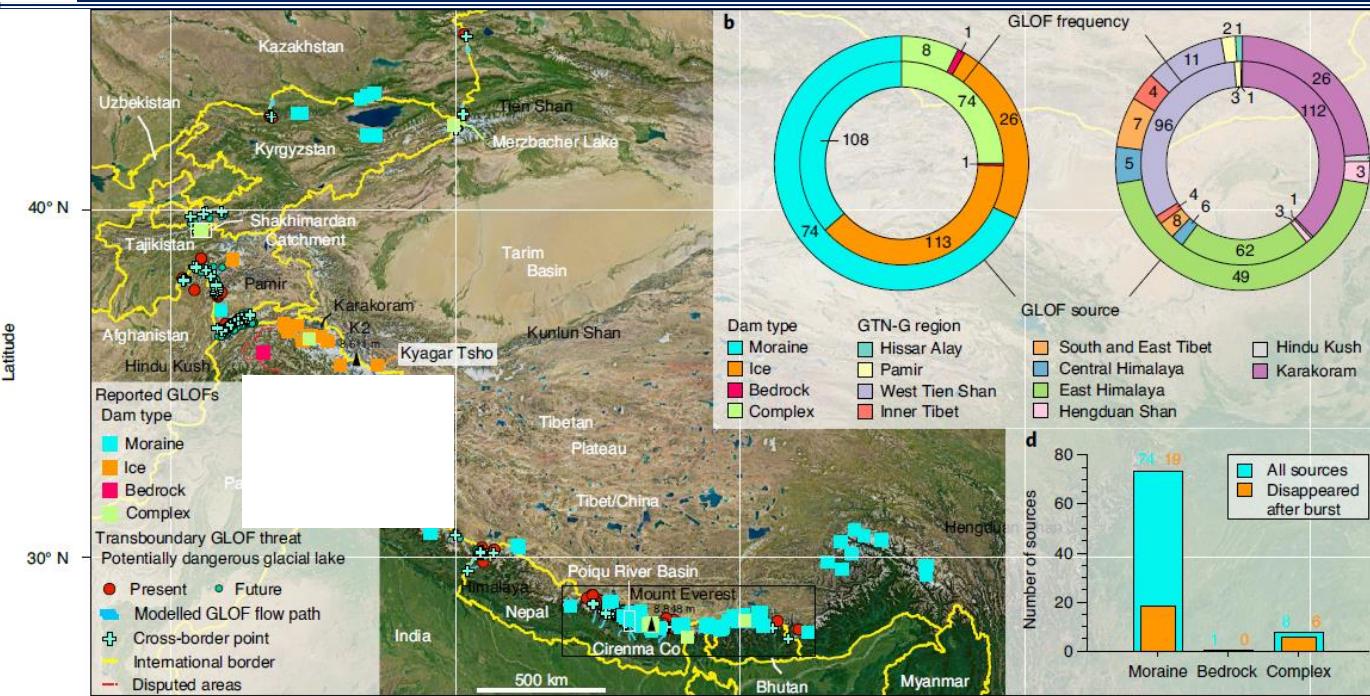
A glacier lake is defined as a water mass existing in a sufficient amount and extending with a free surface beside and/or in front of a glacier and originated by glacier activities and/or retreating processes of a glacier.



- Glacial lakes associated with 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

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

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

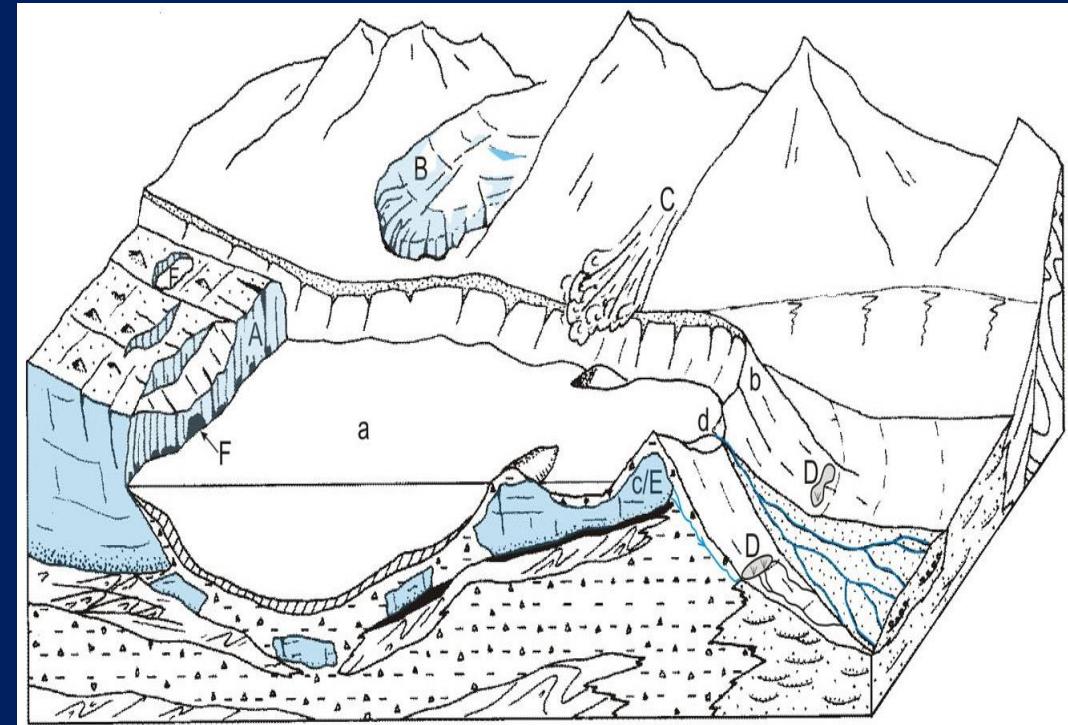
(Source: Richardson, S.D.
and J.M. Reynolds ,2000)

Potential outburst flood triggers include
avalanche displacement waves from

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

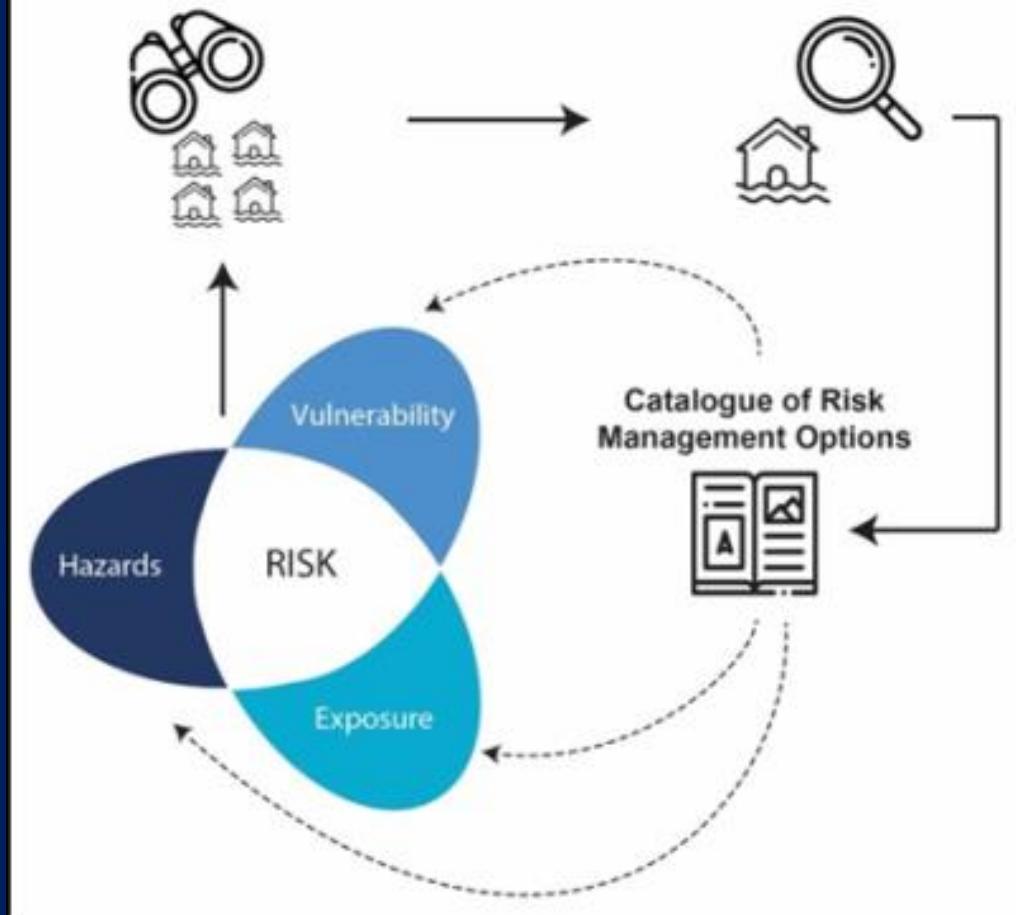
External Triggering Events

- Cloud burst
- Earth quake



GLOF Risk Assessment

First Order Risk Assessment Detailed Risk Assessment

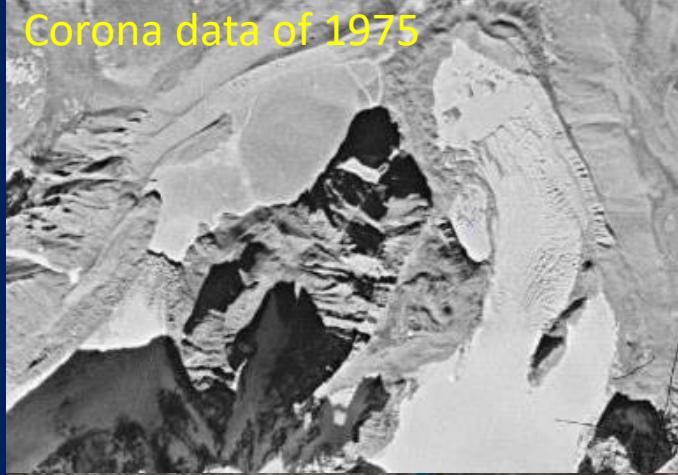


Glacial Lake
Characteristics

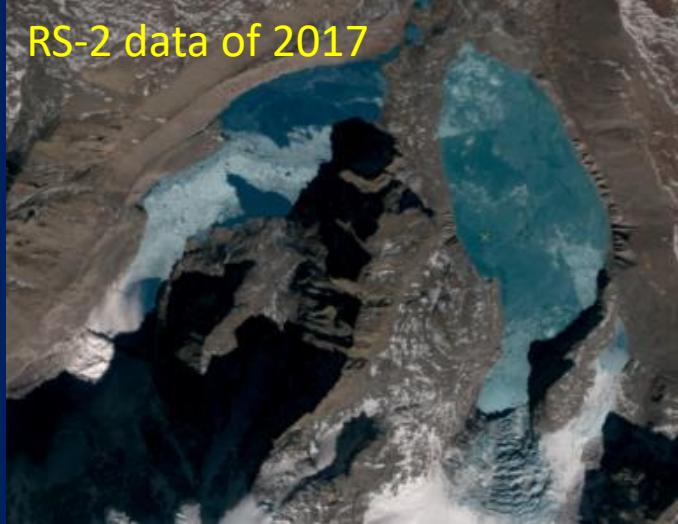
Criteria for Identifying Critical Glacial Lakes

- 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

Corona data of 1975



RS-2 data of 2017



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



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)

Criteria for Identifying Critical Glacial Lakes

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

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° or > 33.3%)

Step 1: Preliminary Screening

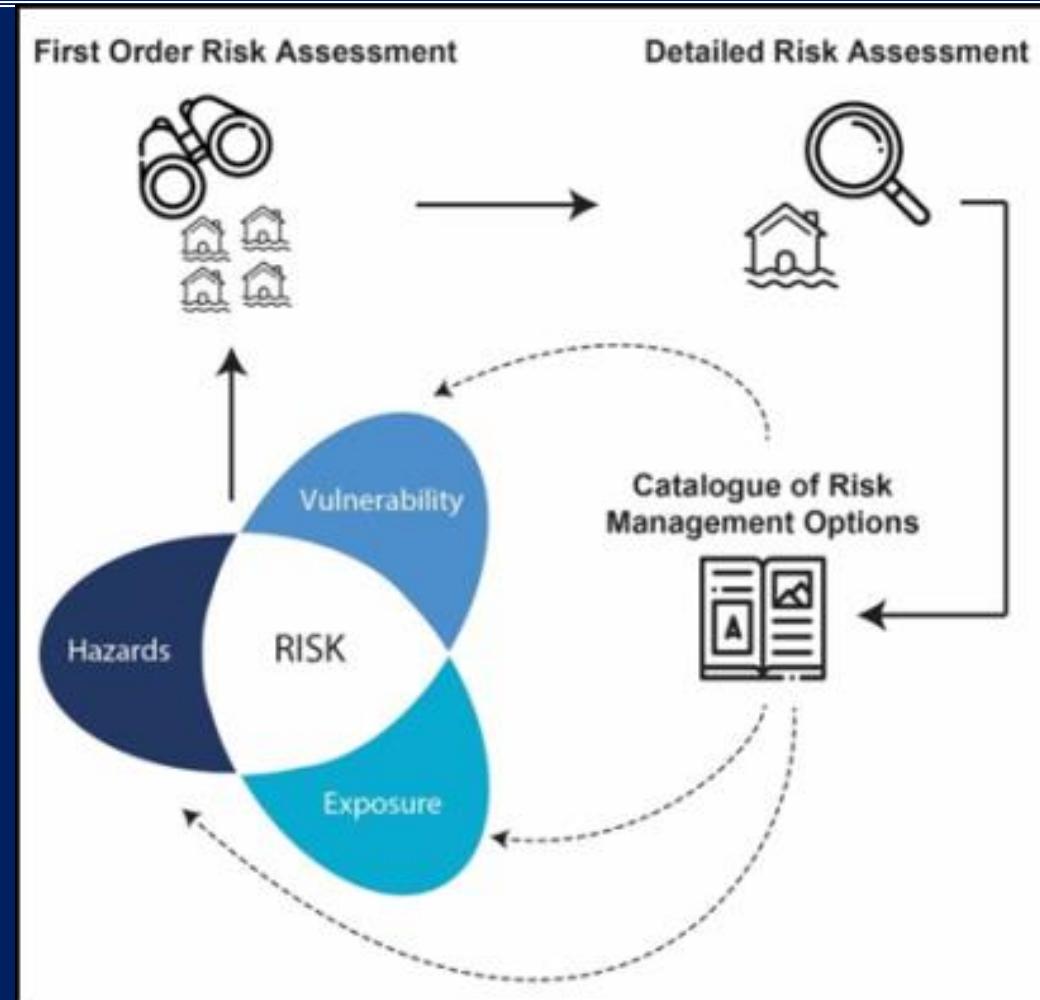
1. Lake Type
2. Lake Area > 1 ha
3. Glacier Association
4. Contributing to WB (w/o Sett.)

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

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)**



GLOF Modelling

Dry Weather

Various GLOF Scenarios

Froehlich's Dam
Breach Parameters

High resolution
DTM

2D unsteady fully
hydrodynamic modelling

Flood Severity

Flood Arrival Time

GLOF Inundation
Maps

Inclement Weather

CartoSAT 30 m
DEM

IMD Rainfall data

Estimation of
PMP

Estimation of PMF

Boundary
Conditions

GLOF Modelling and Risk Assessment Methodology

Infrastructure Mapping

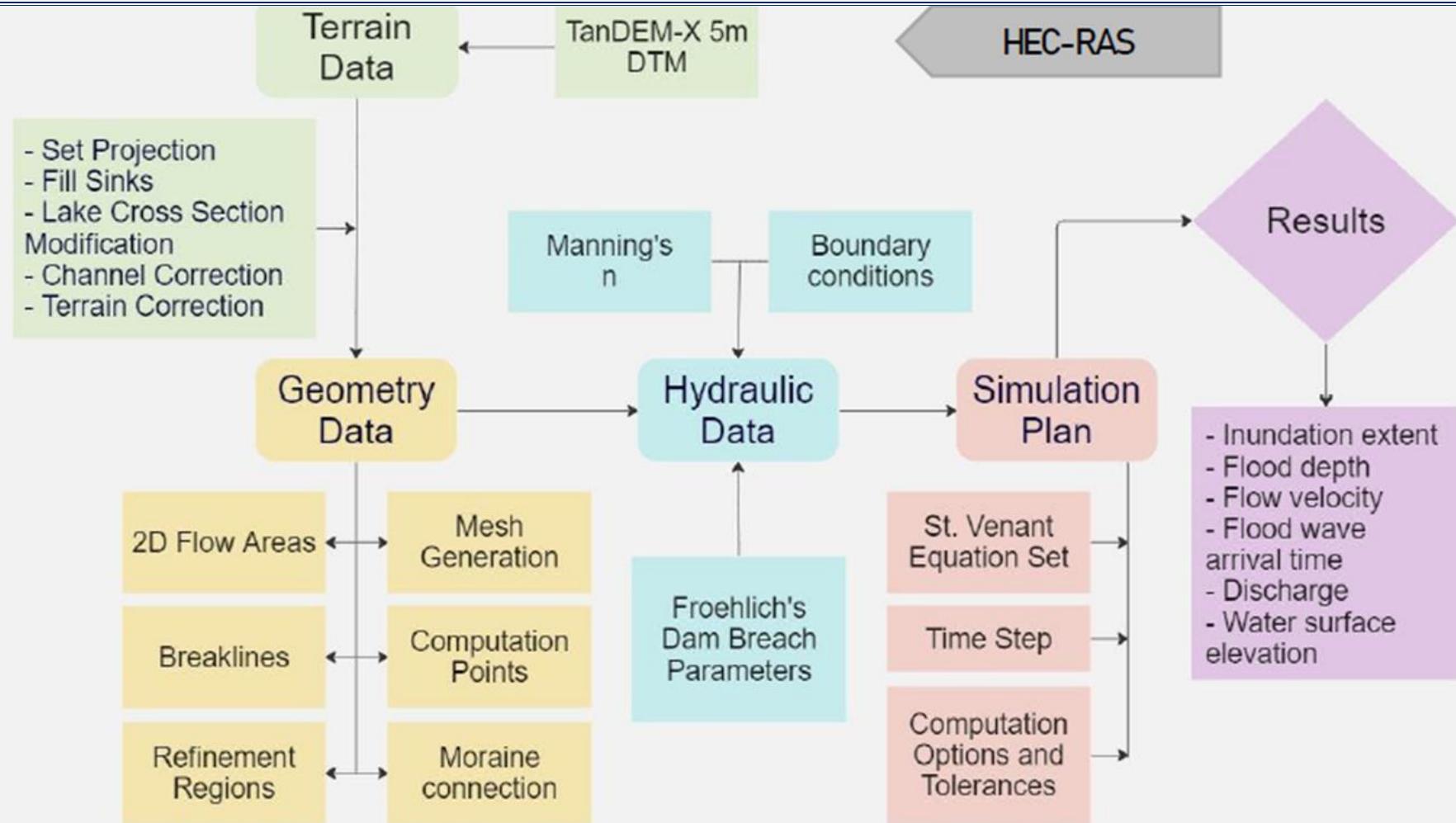
High resolution
satellite data

Geofabrik and
OSM data

Infrastructure
Maps

GLOF Risk Maps

GLOF Modelling



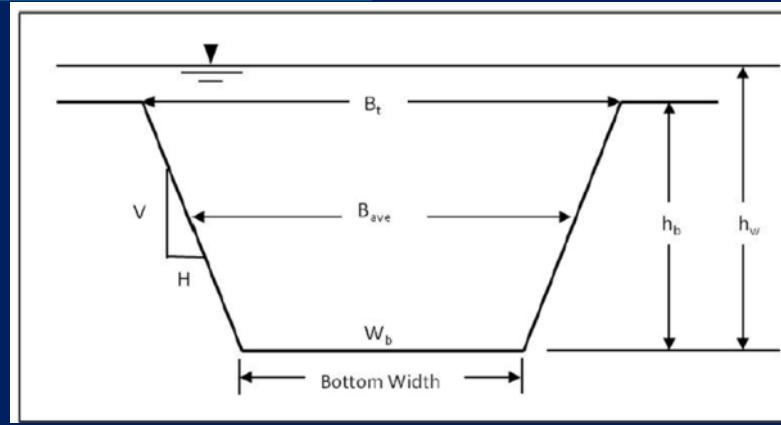
GLOF Modelling requires

- 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

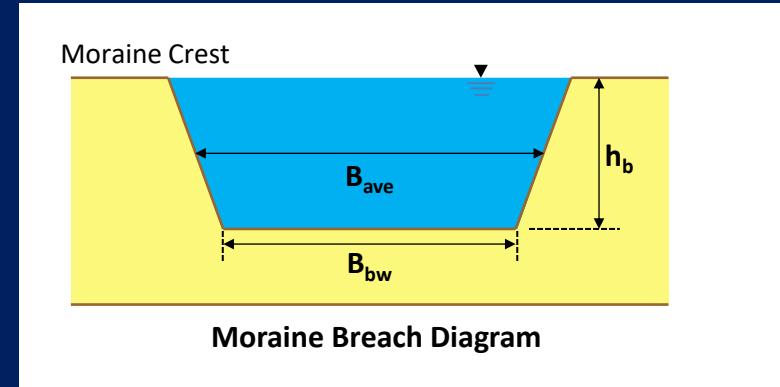
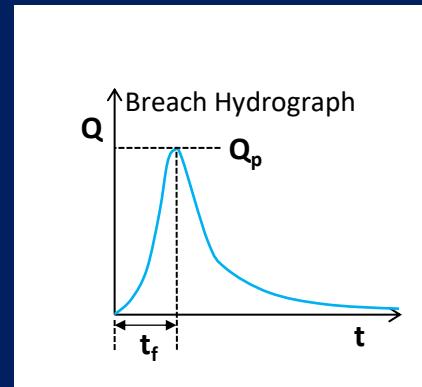
B_{ave} – average breach width
 t_f - breach formation time (s)
 W_b – breach bottom width
 H_b – breach height

Regression Equations:

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



GLOF Scenarios



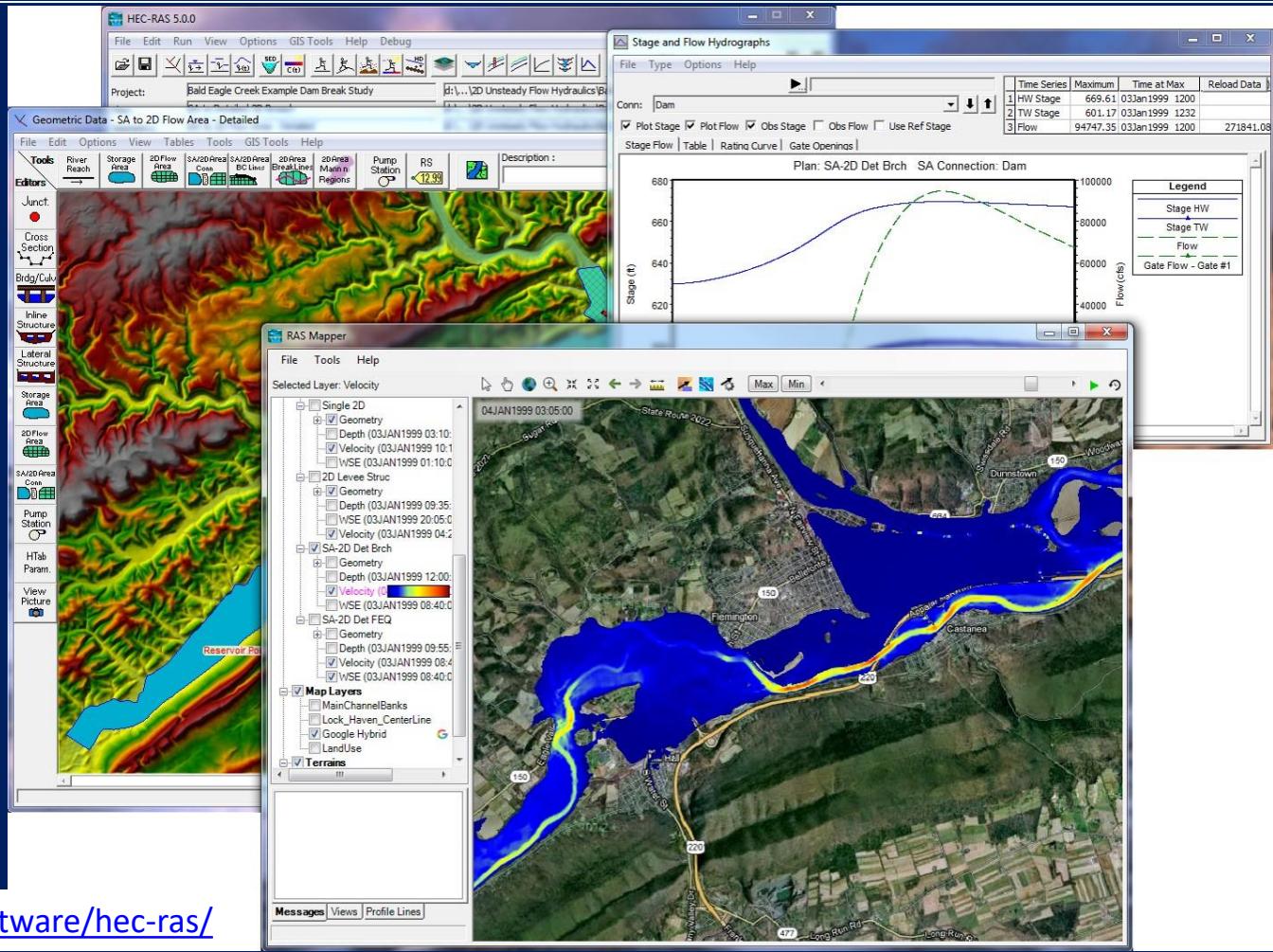
Breach Parameters

Scenario	Failure Mode	Volume Discharge	Breach bottom elevation (m)	h_b (m)	B_{ave} (m)	t_f (hrs)	B_{bw} (m)
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

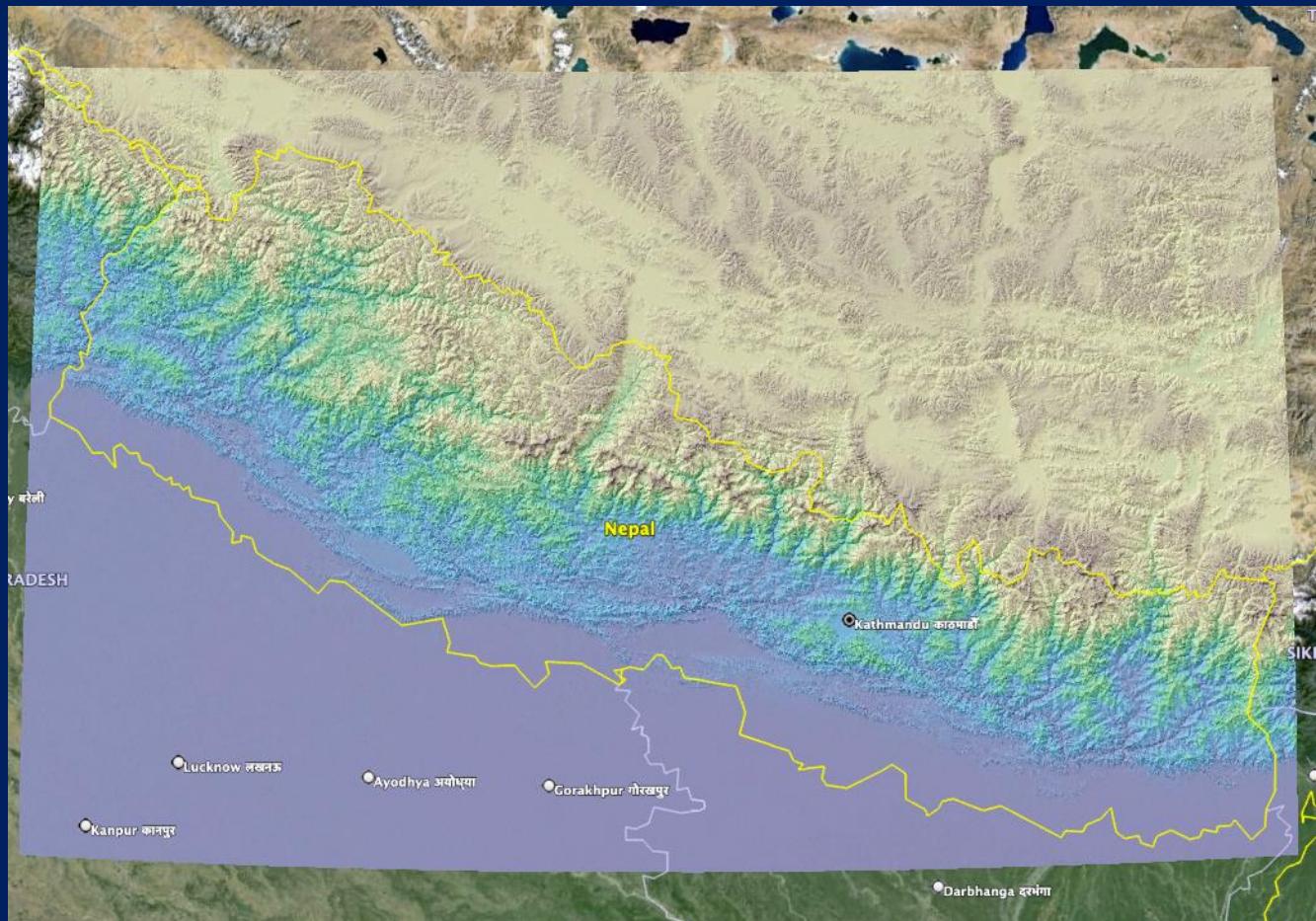
HEC-RAS : Hydrologic Engineering Center River Analysis System

- 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

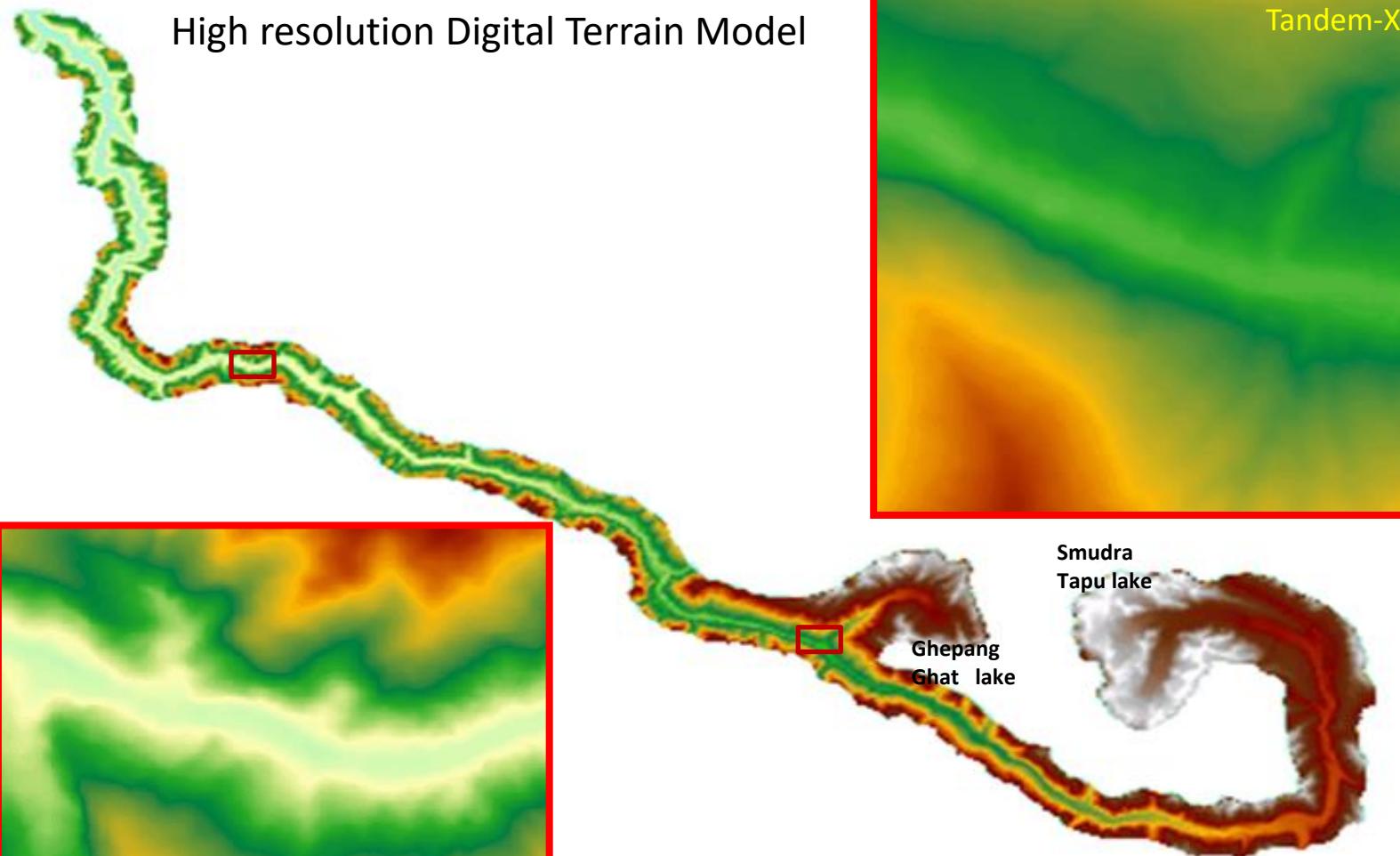


Digital Elevation Models

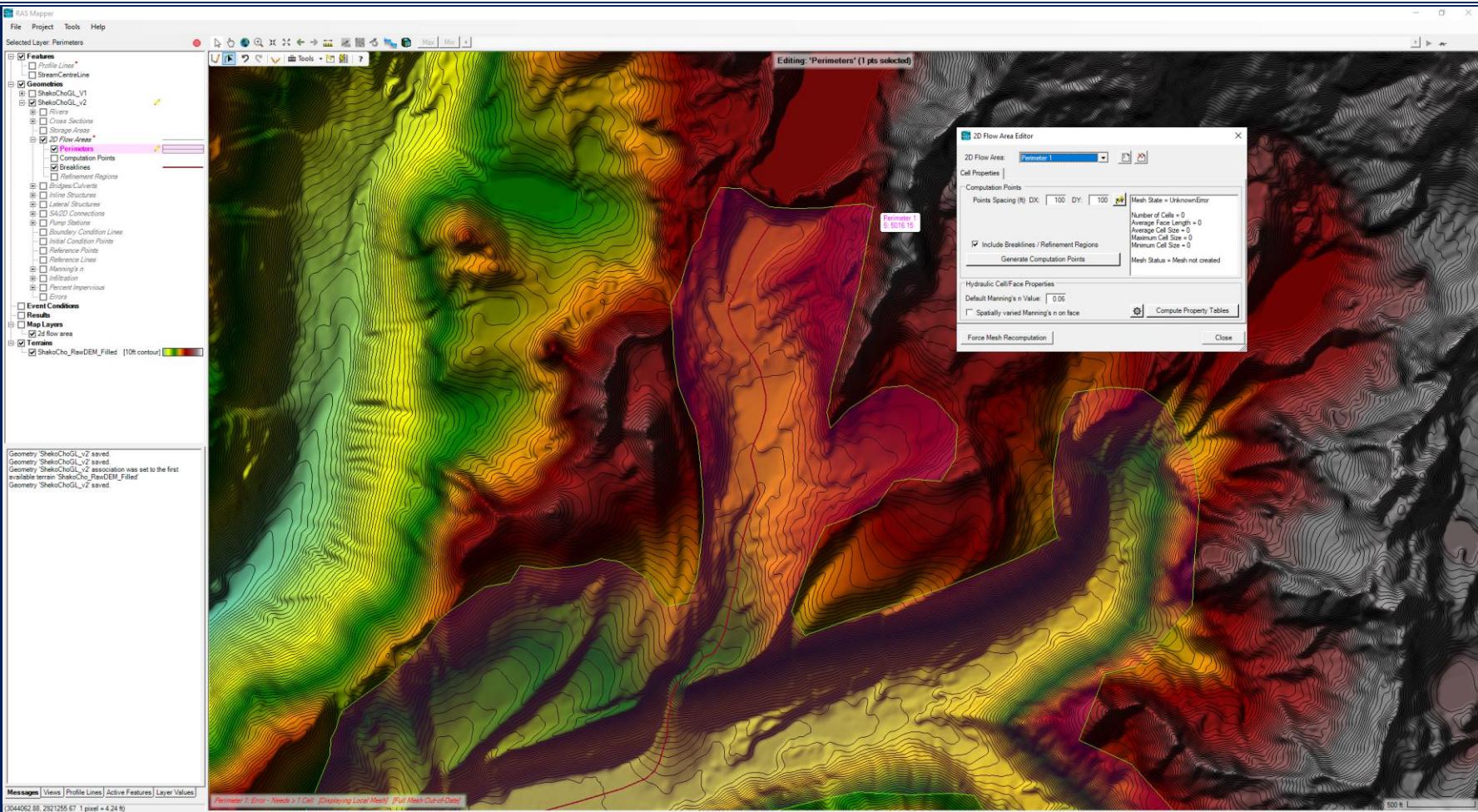
- SRTM
- ASTER
- ALOS World 3D
- Copernicus

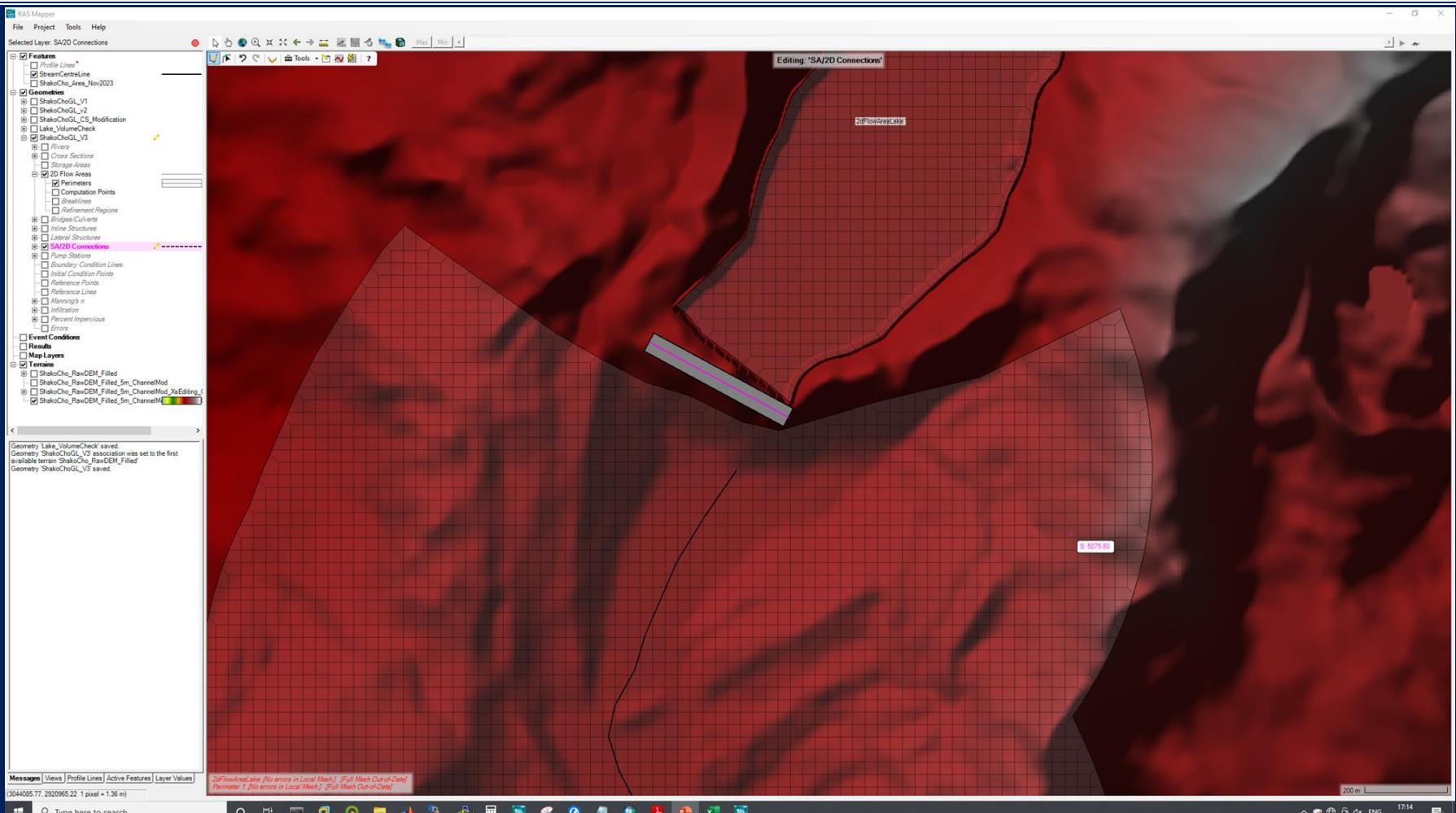


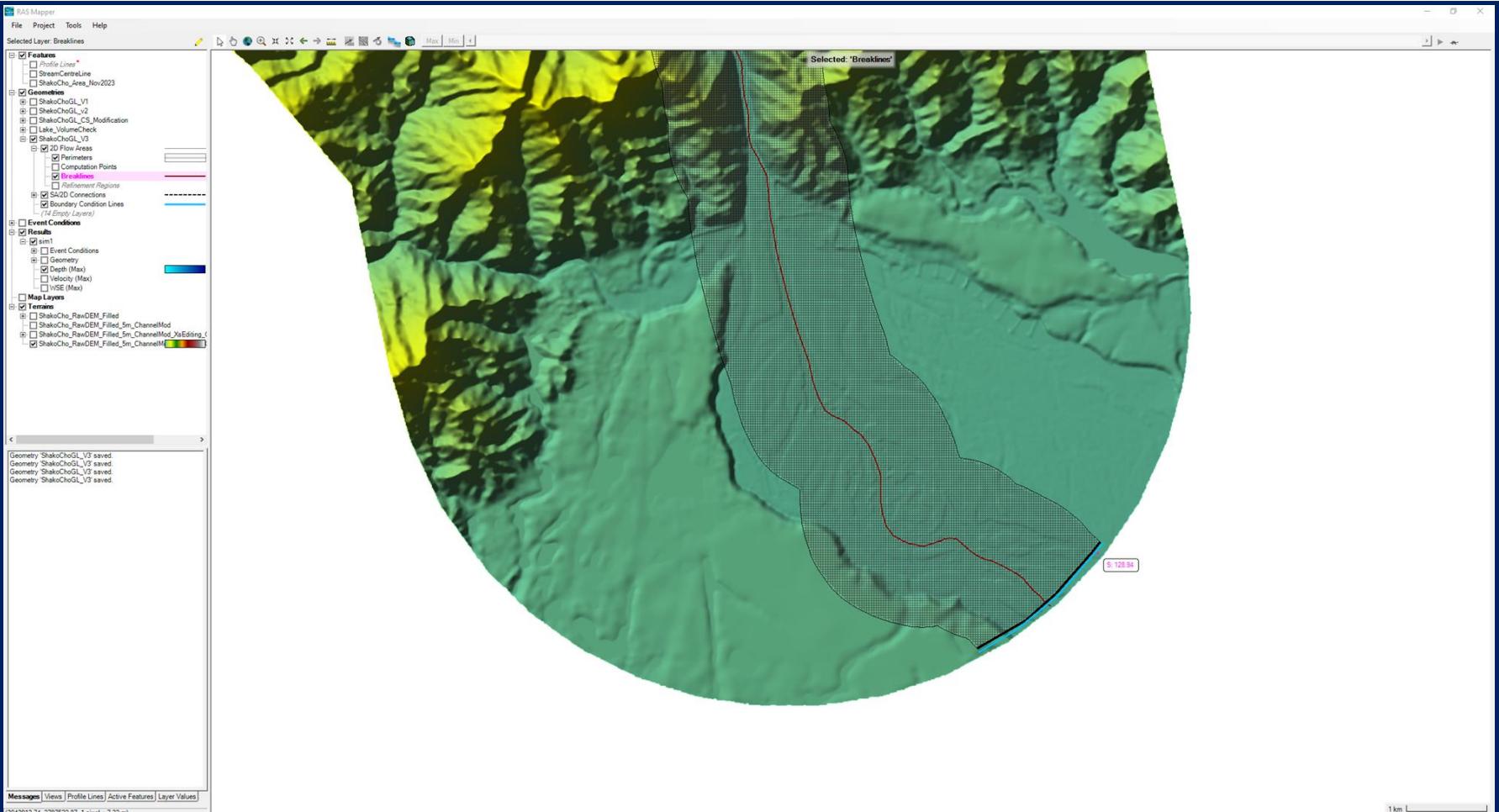
High resolution Digital Terrain Model

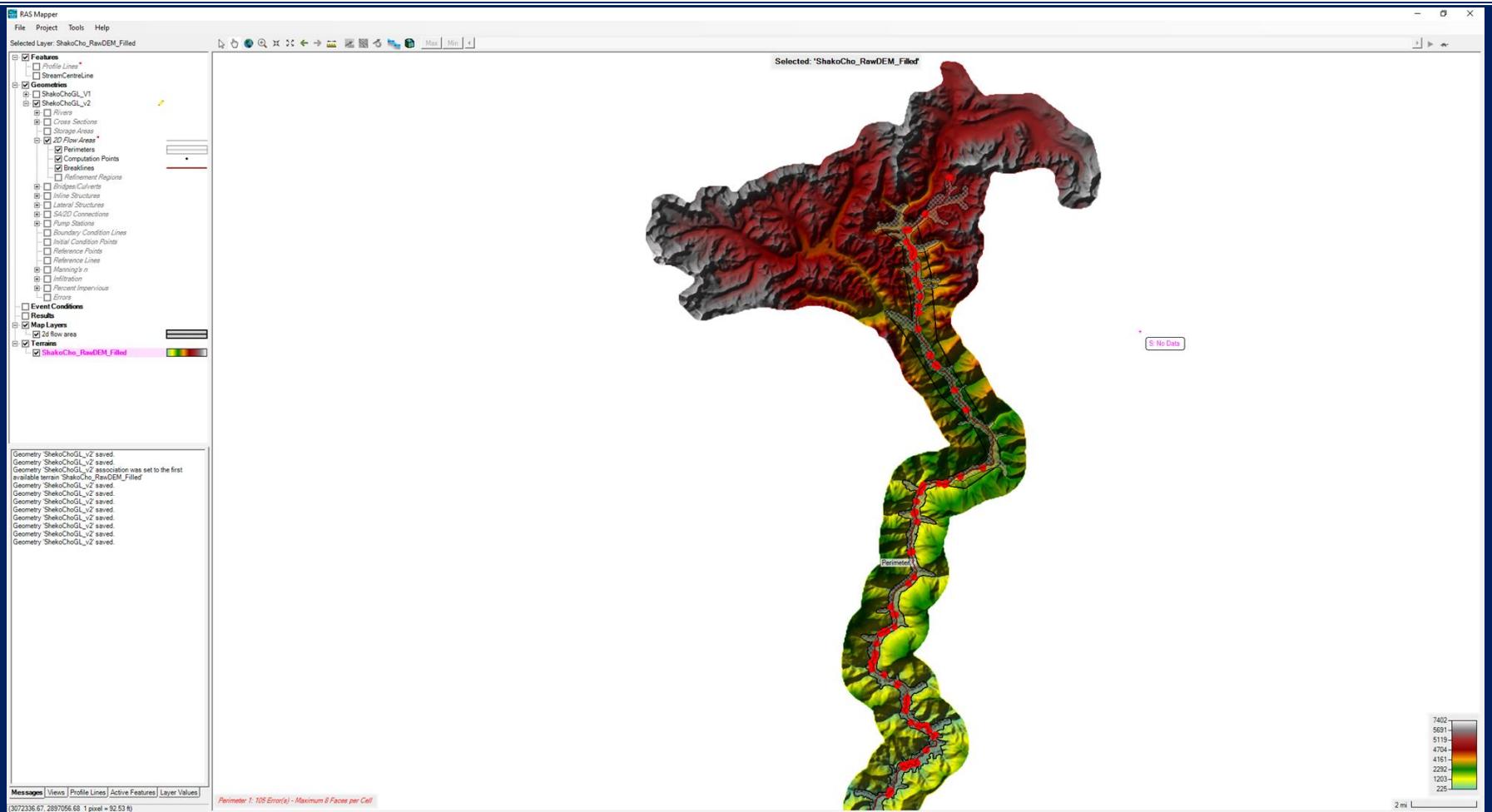


Glacier Lake Outburst Flood Risk Assessment

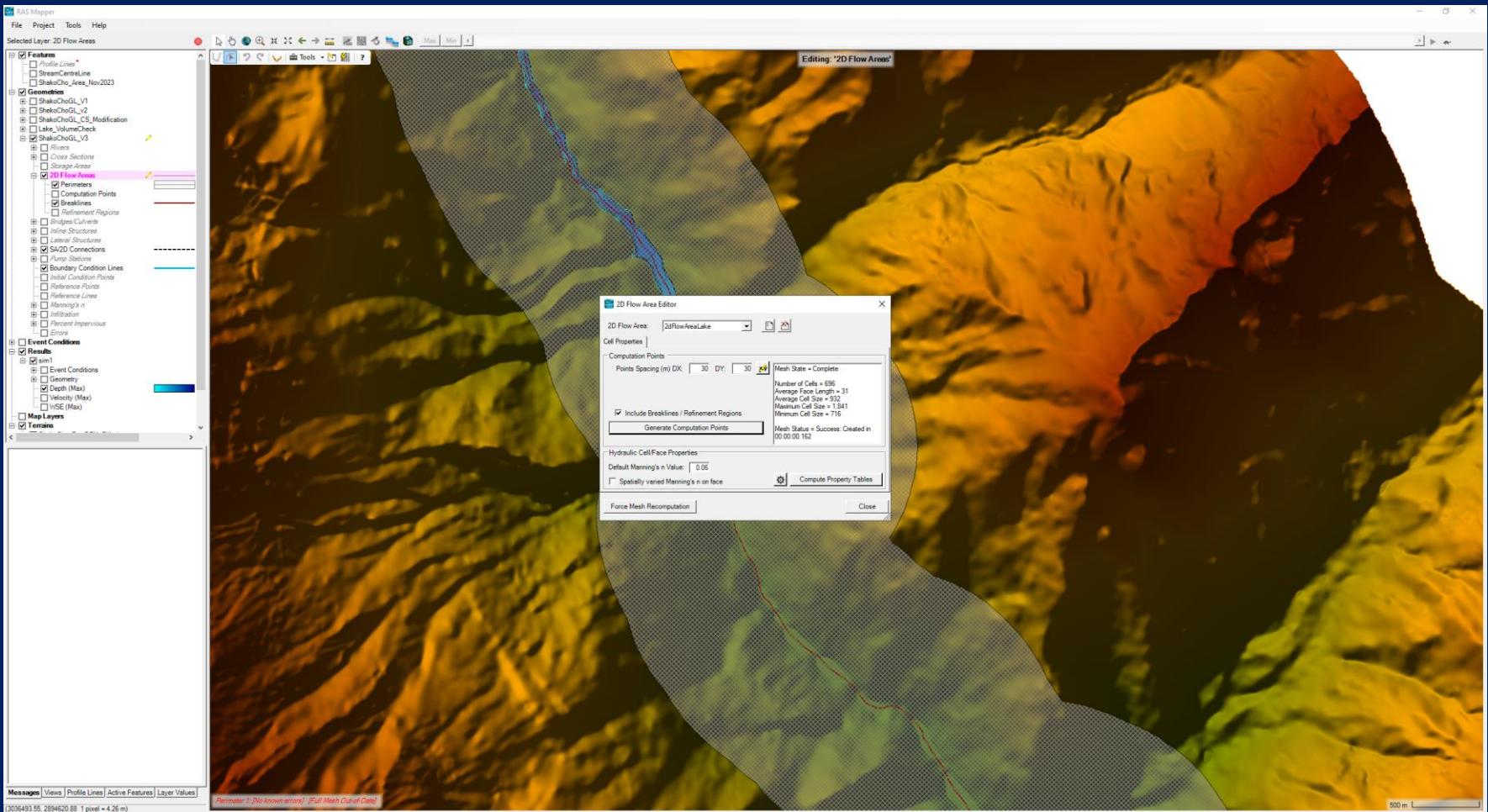




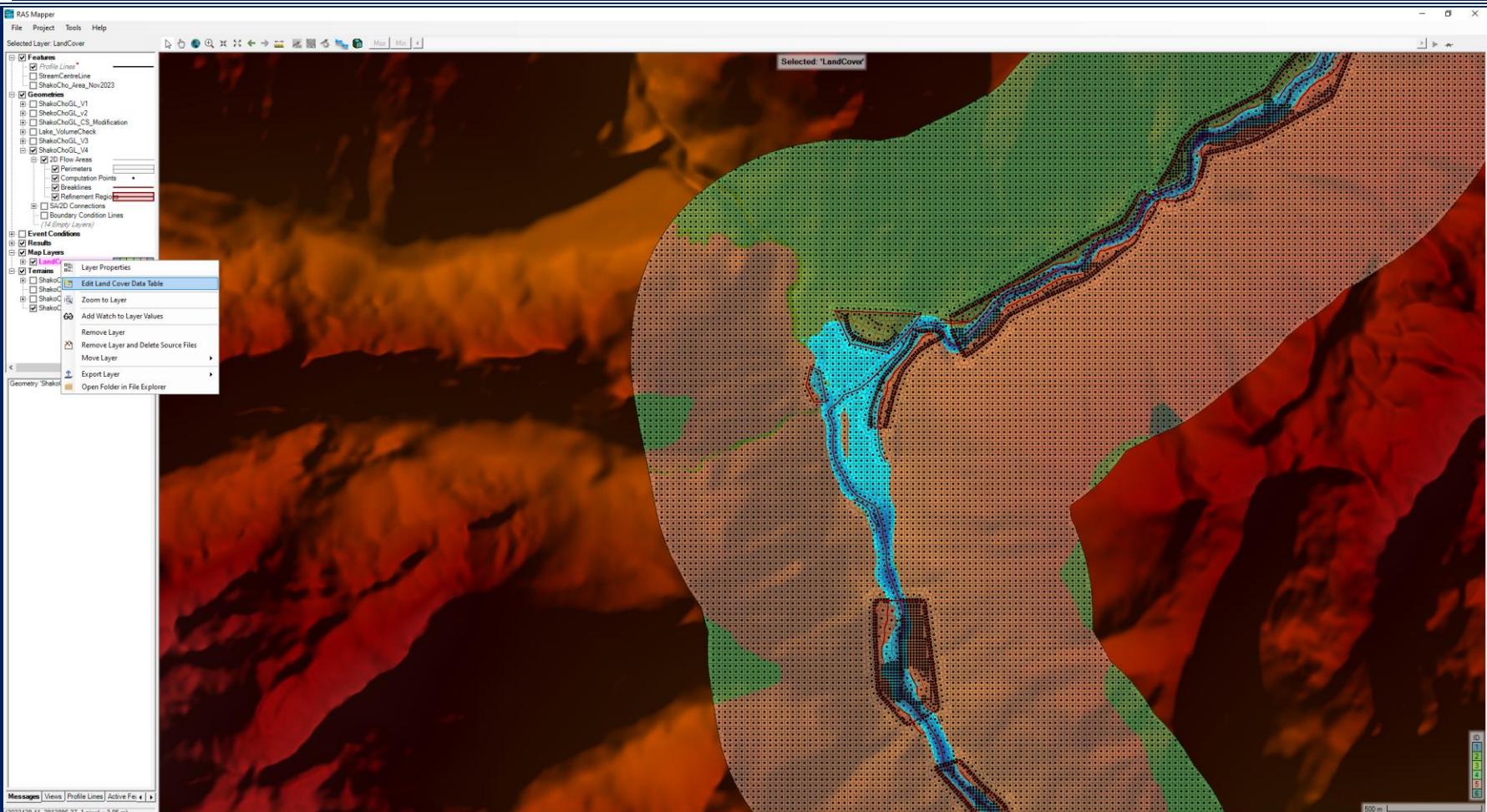


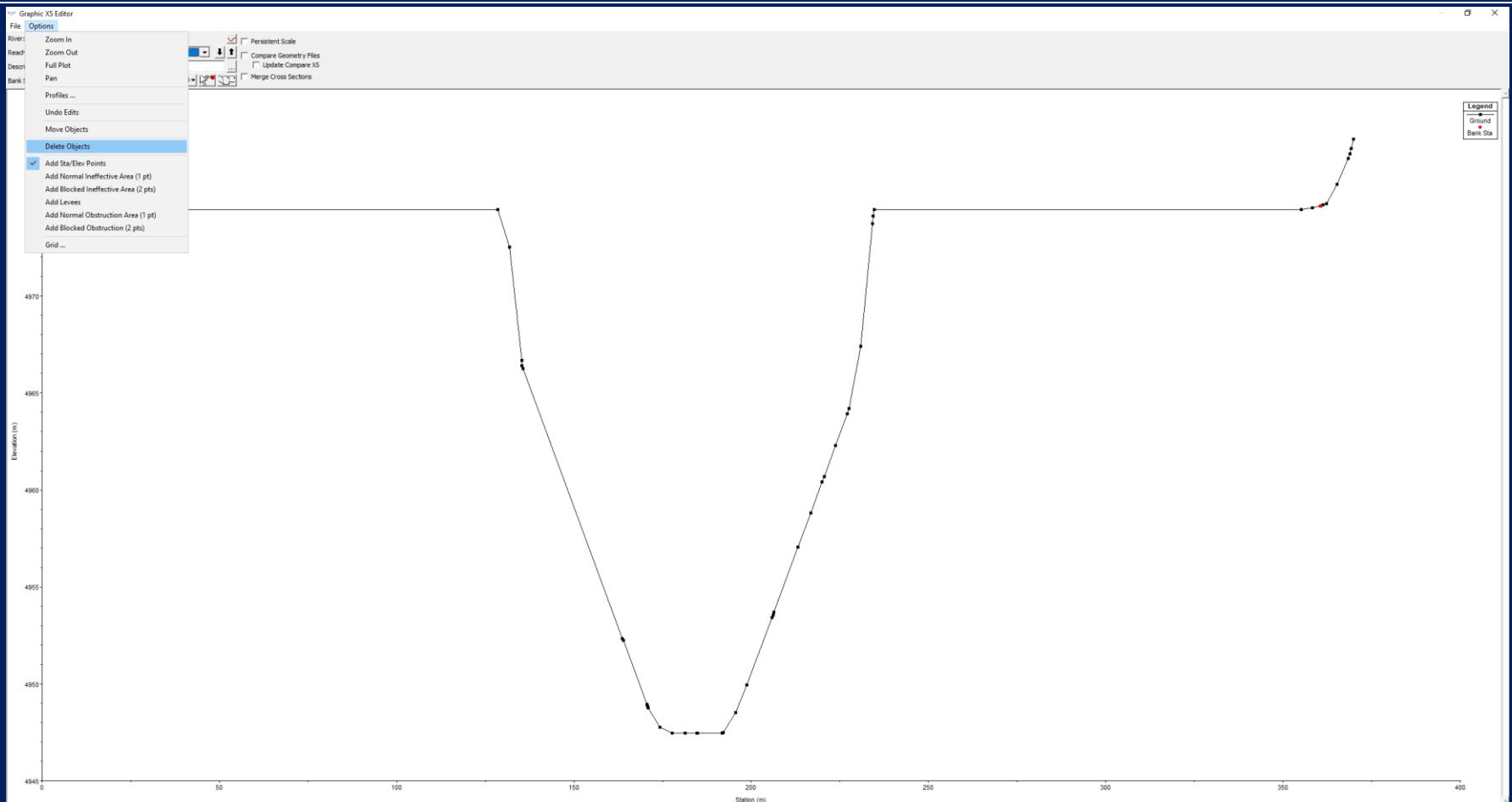


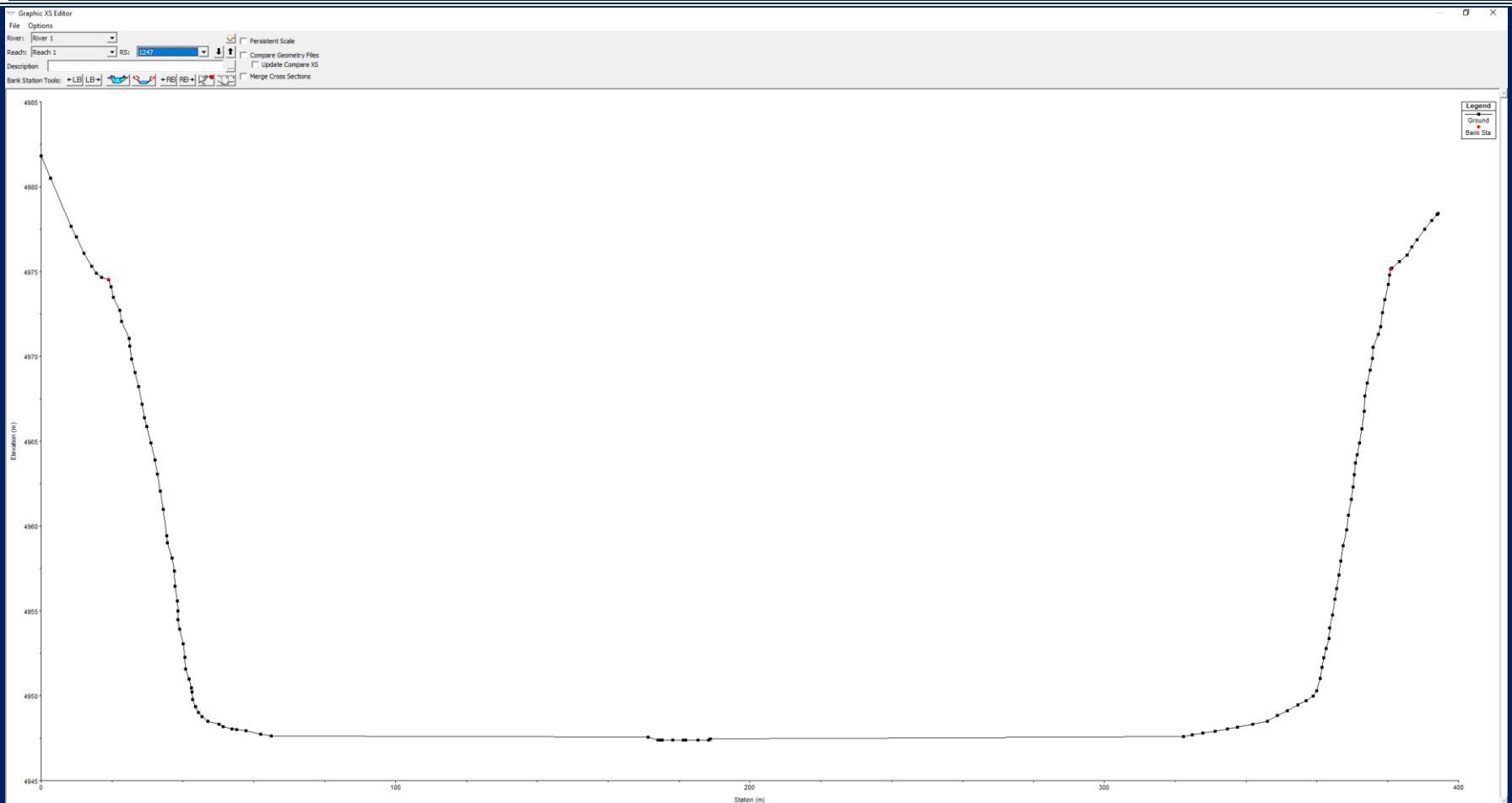
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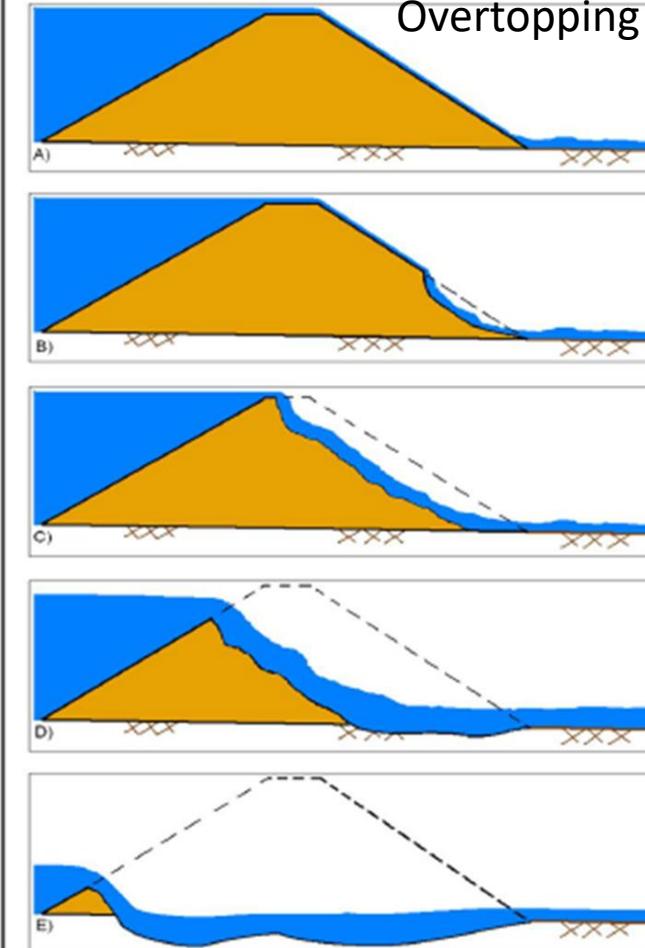
Glacier Lake Outburst Flood Risk Assessment







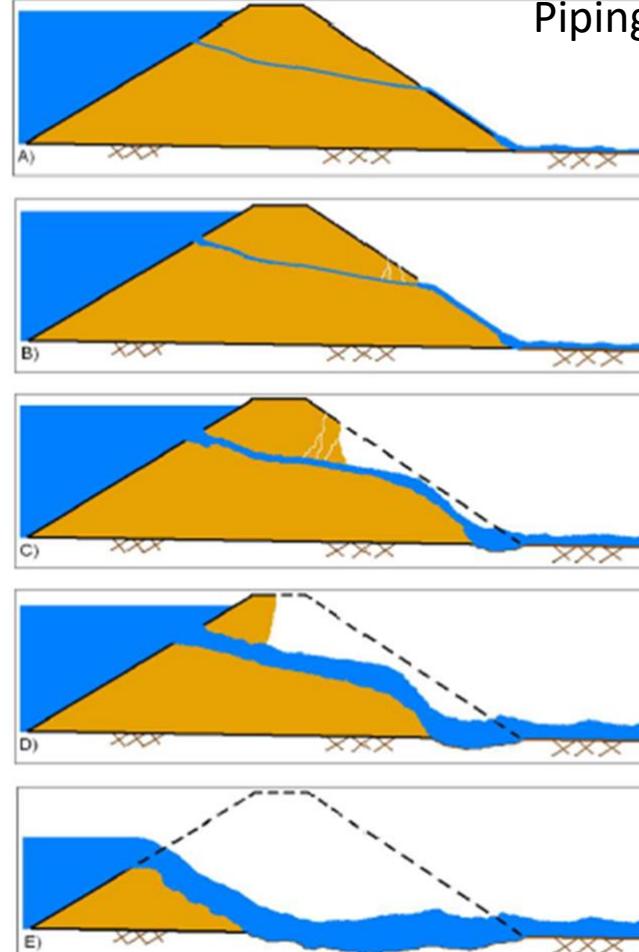
Failure Modes



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.

Failure Modes



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.

Dam (Inline Structure) Breach Data

Inline Structure: Bald Eagle Loc Hav 81500

Breach This Structure

Breach Method: Simplified Physical

Center Station: 3900
Max Possible Bottom Width: 1800
Min Possible Bottom Elev: 592
Left Side Slope: 2
Right Side Slope: 2
Breach Weir Coef: 2.6
Breach Formation Time (hrs): 1
Failure Mode: Piping
Piping Coefficient: 0.6
Initial Piping Elev: 620
Initial Piping Diameter: 1
 Mass Wasting Feature:
Trigger Failure at: WS Elev
Starting WS: 668.1

Breach Plot | Breach Progression | Simplified Physical | Breach Repair (optional) | Parameter Calculator | Overtopping Downcutting | Widening Relationship

	Velocity (ft/s)	Downcutting Rate (ft/hr)
1	0	0
2	2	0
3	3	1
4	4	2
5	5	5
6	7	15
7	10	30
8	20	50
9	30	100
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		

	Velocity (ft/s)	Widening Rate (ft/hr)
1	0	0
2	2	0
3	3	1
4	4	2
5	5	5
6	7	15
7	10	30
8	20	50
9	30	100
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		

The screenshot shows the ShakoChoGL_V3 software interface for a breach analysis. The main window displays a cross-section of a river reach with a breach, showing elevation (m) on the y-axis (4960 to 4955) and station (m) on the x-axis (0 to 400). A grey shaded area represents the river channel, and a red line indicates the breach profile. A legend on the right shows 'Spillway' (red), 'Centerline Terrain' (grey), and 'Final Breach' (red).

Unsteady Flow Analysis Dialog (Top Right):

- Plan: ShakoChoGL_V3
- Geometry File: ShakoChoGL_V3
- Unsteady Flow File: (dropdown)
- Programs to Run:
 - Geometry Preprocessor
 - Unsteady Flow Simulation
 - Sediment
 - Post Processor
 - Floodplain Mapping
- Simulation Time Window:
 - Starting Date: (dropdown)
 - Ending Date: (dropdown)
 - Starting Time: (dropdown)
 - Ending Time: (dropdown)
- Computation Settings:
 - Computation Interval: 1 Minute
 - Hydrograph Output Interval: 1 Hour
 - Mapping Output Interval: 1 Hour
 - Detailed Output Interval: 1 Hour

Storage Area Connection Breach Data Dialog (Bottom Center):

SA Connection: Perimeter 1 To 2

Breach This Structure

Breach Method: User Entered Data

Center Station: 200

Final Bottom Width: 56.71

Final Bottom Elevation: 4946.72

Left Side Slope: 1.4

Right Side Slope: 1.4

Breach Weir Coef: 1.44

Breach Formation Time (hrs): 0.84

Failure Mode: Overtopping

Piping Coefficient: 0.5

Initial Piping Elev: (dropdown)

Trigger Failure at: WS Elev

Starting WS: 4974

Breach Plot (Bottom Center):

ShakoCho_GLOF_Simulations Plan:

Legend: Spillway, Centerline Terrain, Final Breach

The plot shows Elevation (m) on the y-axis (4940 to 5000) and Station (m) on the x-axis (0 to 400). It displays a grey shaded area representing the river channel, a red line for the breach profile, and a red rectangle indicating the breach location. The plot shows a significant drop in elevation at the breach point, with water levels rising upstream and falling downstream.

HEC-RAS Finished Computations

Write Geometry Information
Layer: COMPLETE

Geometry Processor
River: RS:
Reach: Node Type:
IB Curve: Finished

Unsteady Flow Simulation
Simulation: Time: 2.0000 05JUL2024 02:00:00 Iteration (1D): Iteration (2D): 4
Unsteady Flow Computations

Stored Map Generation
Map:

Computation Messages

05JUL2024 01:40:55	Perimeter 1	Cell #	64454	2723.36	0.004	20
05JUL2024 01:40:56	Perimeter 1	Cell #	64454	2723.38	0.004	20
05JUL2024 01:40:57	Perimeter 1	Cell #	64454	2723.40	0.003	20

Overall Volume Accounting Error in 1000 m³: 1.580
Overall Volume Accounting Error as percentage: 0.009710
Please review "Computational Log File" output for volume accounting details

Writing Results to DSS

Finished Unsteady Flow Simulation

1D Post Process Skipped (simulation is all 2D)

Computing Stored Results Maps

Computations Summary

Computation Task	Time(hh:mm:ss)
Completing Geometry	5:02
Preprocessing Geometry	<1
Completing Event Conditions	1
Unsteady Flow Computations	22:03
Computing Maps	<1
Complete Process	27:09

Computation Speed	Simulation/Runtime
Unsteady Flow Computations	5.44x
Complete Process	4.42x

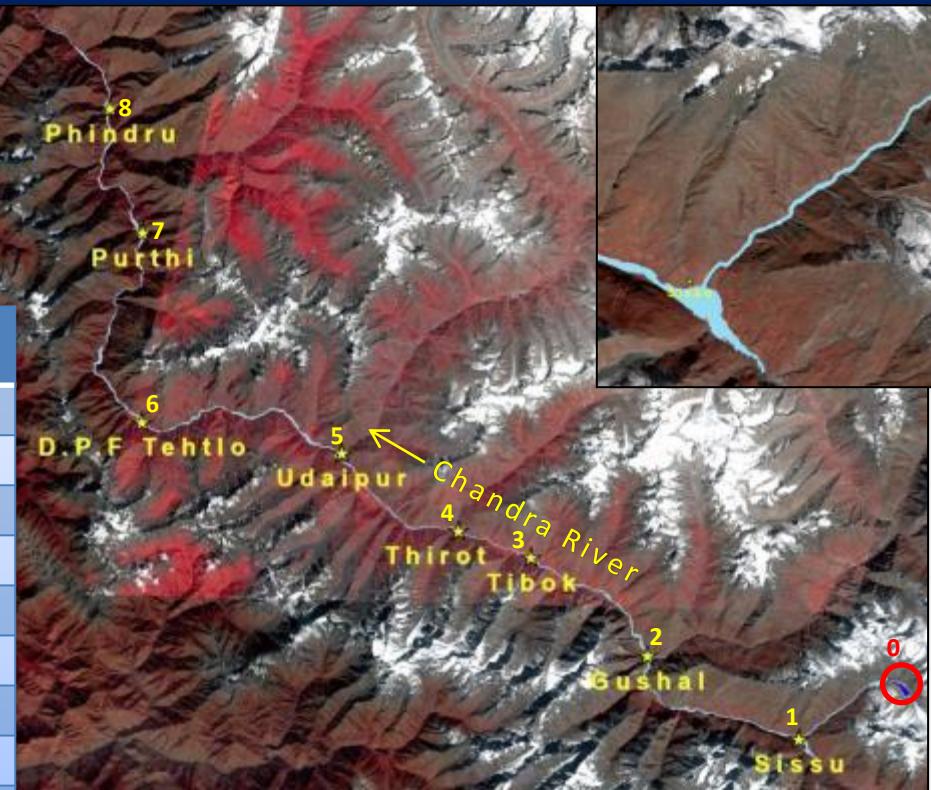
Downstream Flood Routing/ Modelling Issues

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.N o	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



0

10000

9000

8000

7000

6000

5000

4000

3000

2000

1000

0

Discharge (cumecs)

8

7

6

2

3

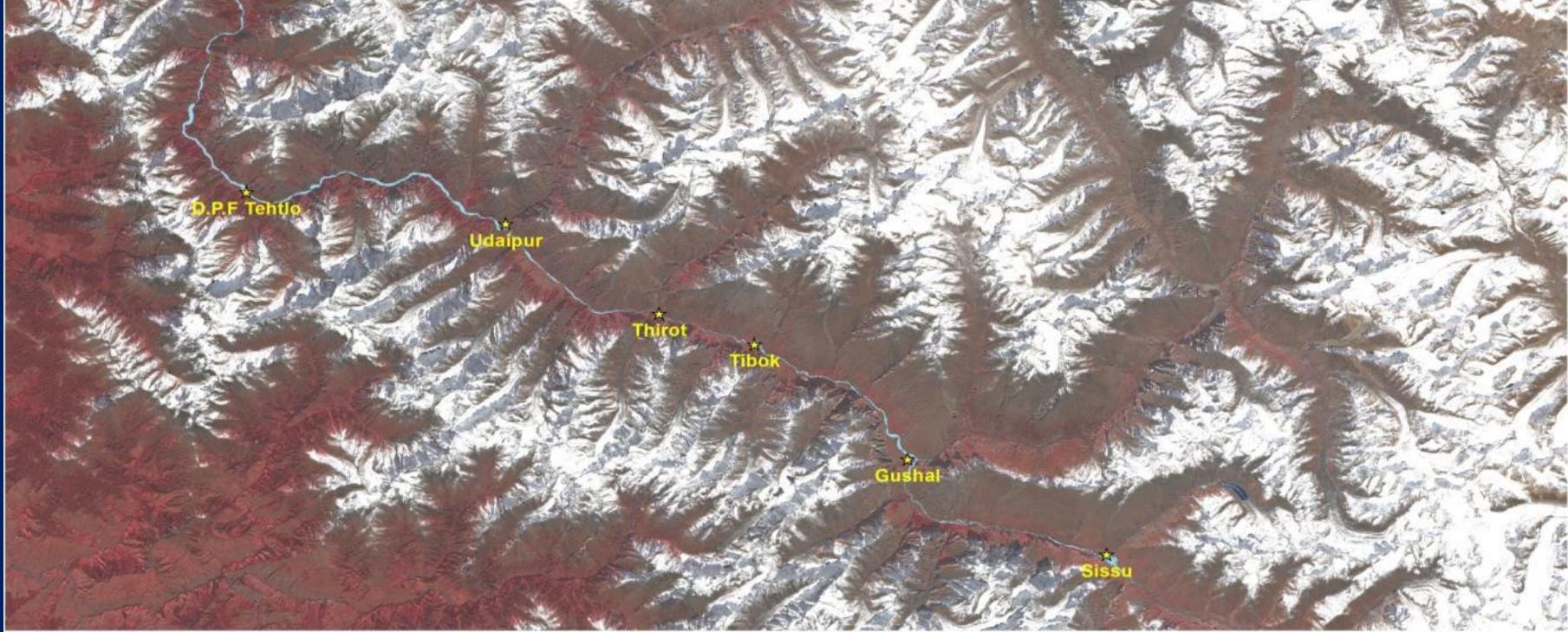
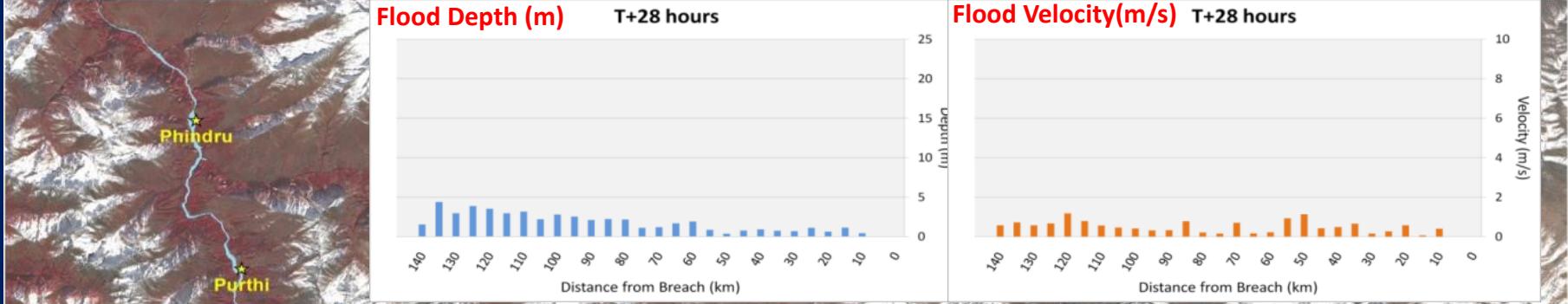
4

5

1

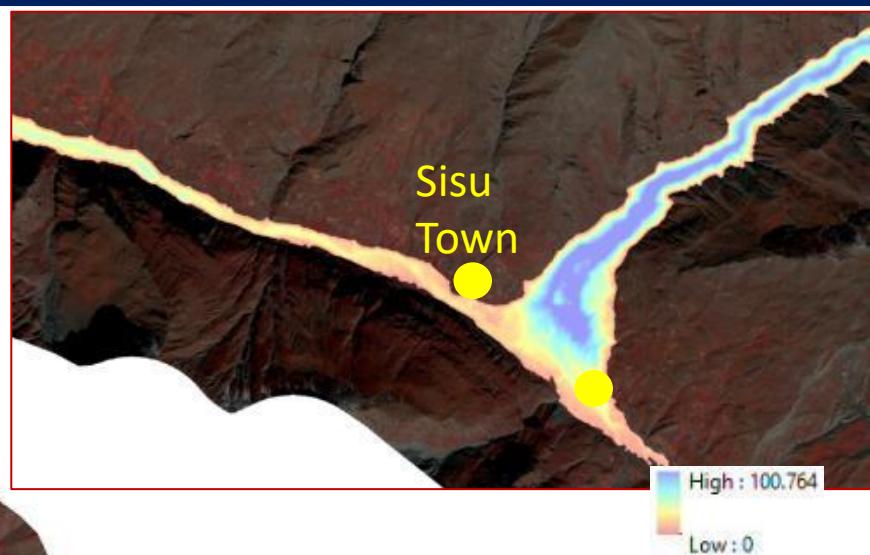
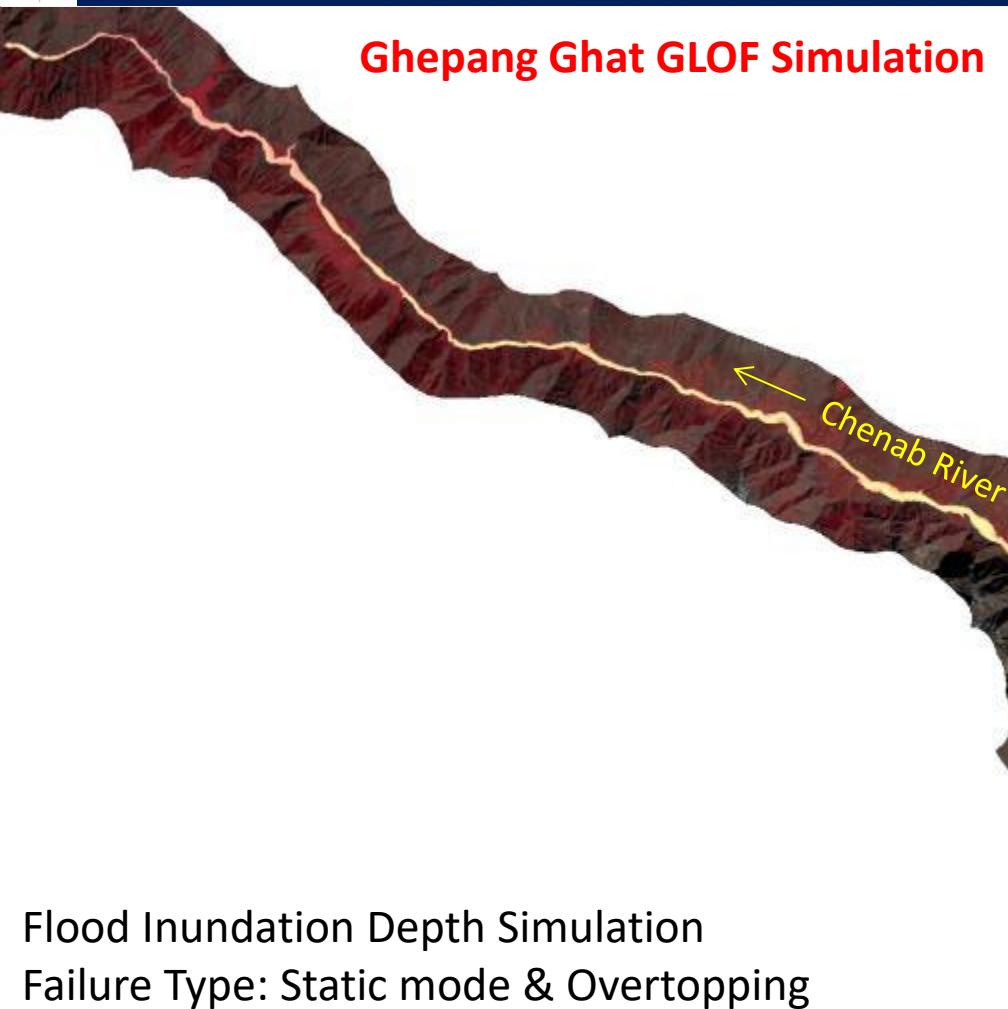
← Simulation Duration (hrs)

T+36 T+35 T+34 T+33 T+32 T+31 T+30 T+29 T+28 T+27 T+26 T+25 T+24 T+23 T+22 T+21 T+20 T+19 T+18 T+17 T+16 T+15 T+14 T+13 T+12 T+11 T+10 T+9 T+8 T+7 T+6 T+5 T+4 T+3 T+2 T+1 T+0

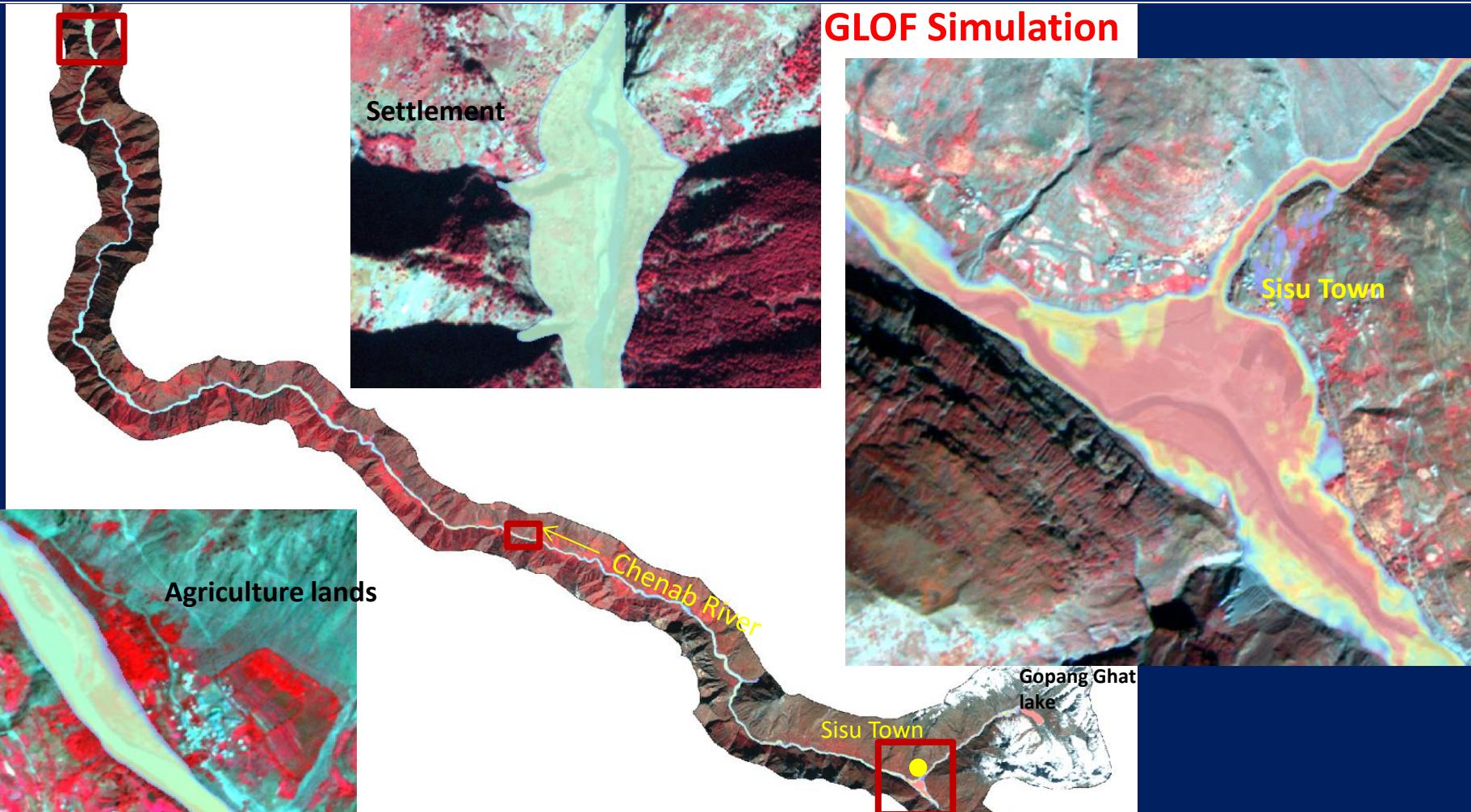


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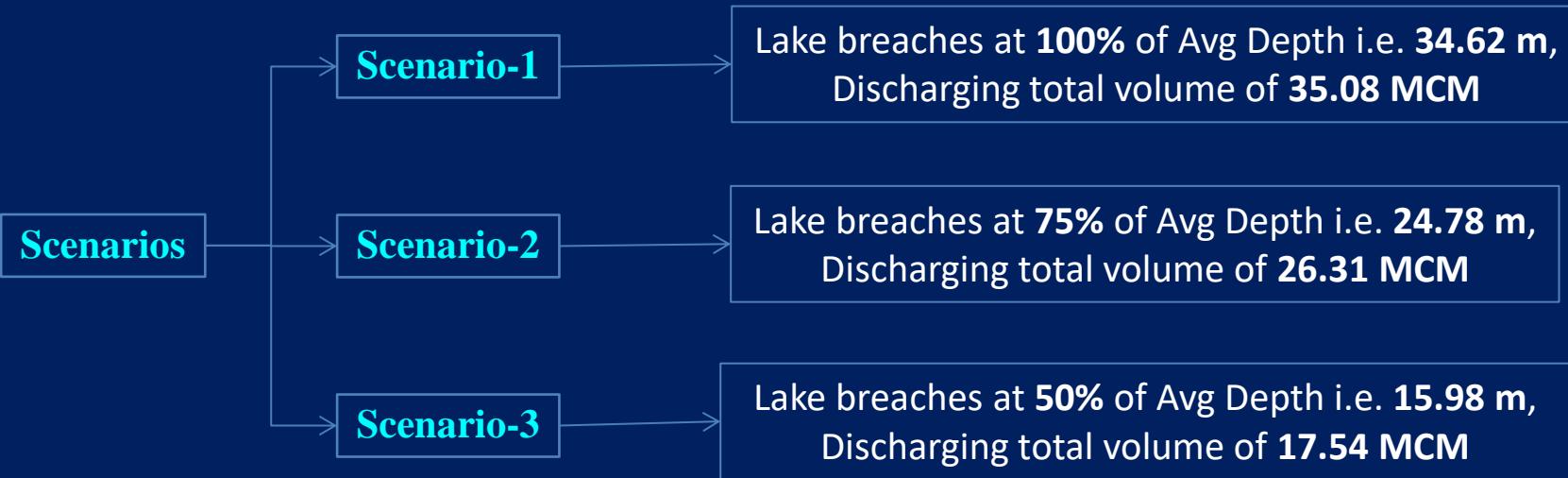
Ghepang Ghat GLOF Simulation



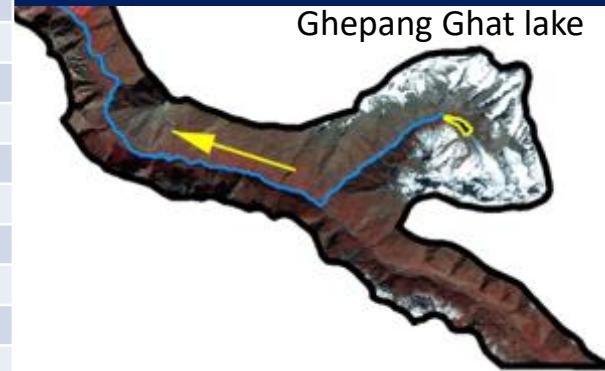
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Glacier Lake Outburst Flood Risk Assessment



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)	$8,274 \text{ m}^3/\text{s}$
9	Outflow Minimum Discharge	$4,342 \text{ m}^3/\text{s}$
10	Outflow Maximum Discharge	$18,956 \text{ m}^3/\text{s}$



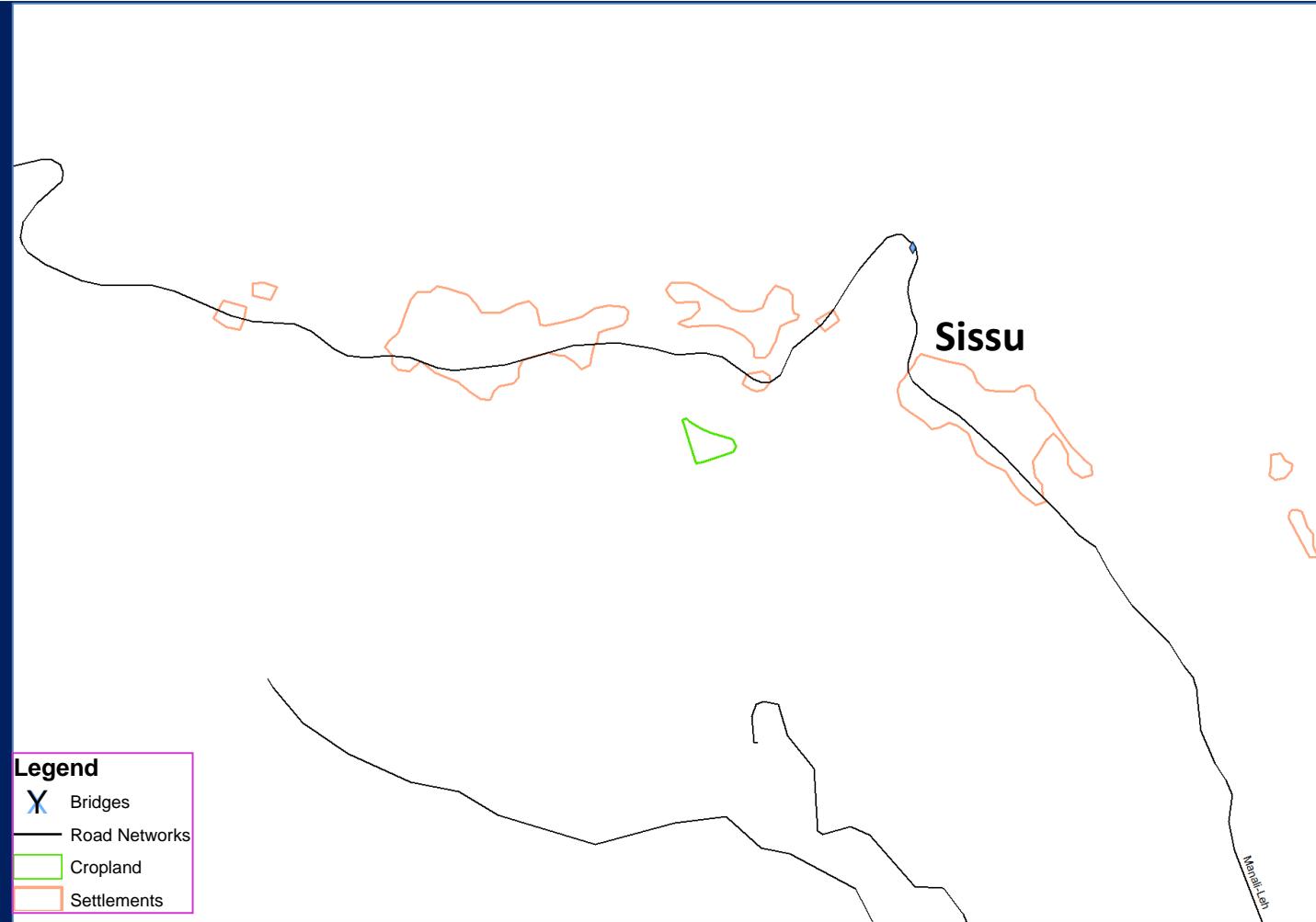
Indus River Basin

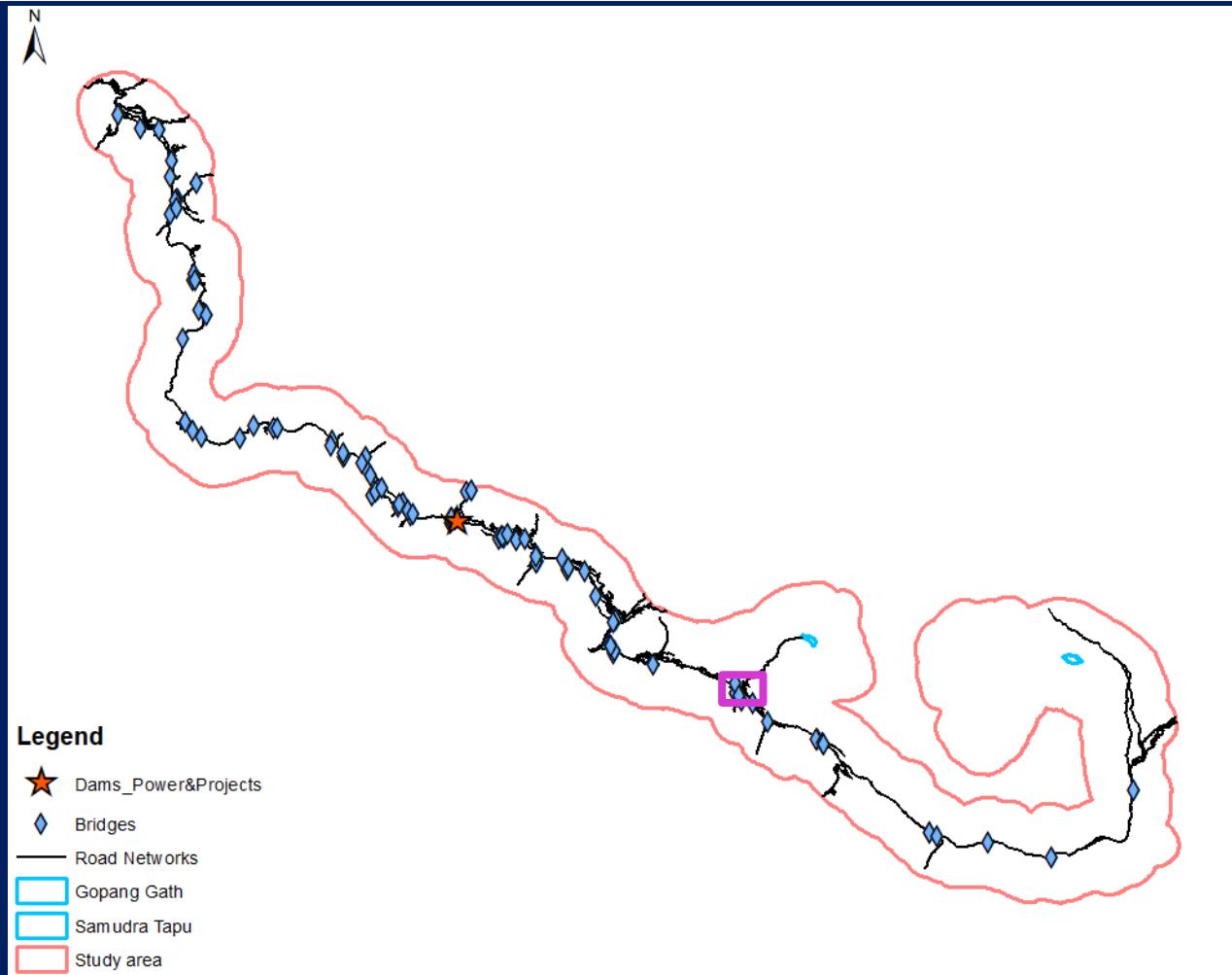


GLOF Vulnerable Infrastructure

Glacier Lake Outburst Flood Risk Assessment

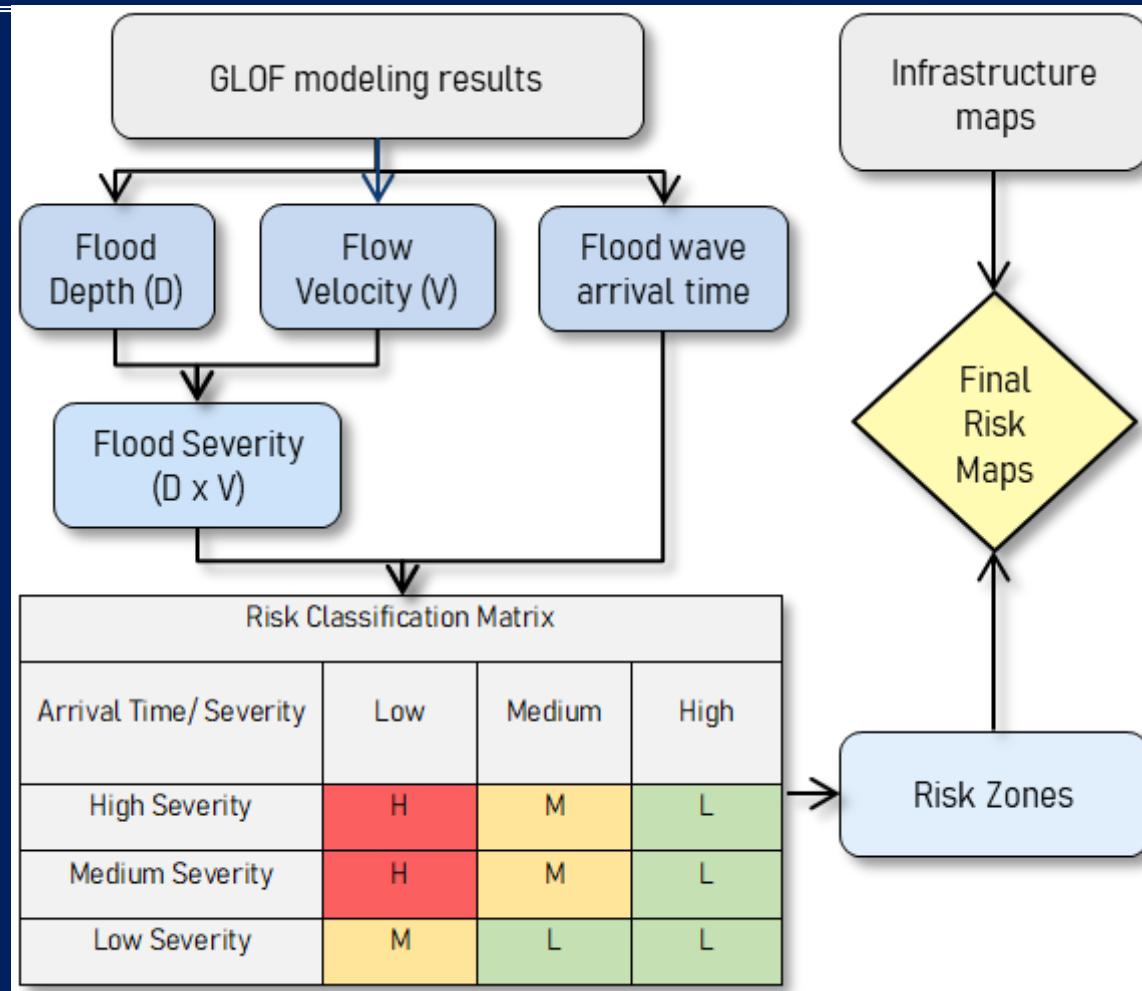






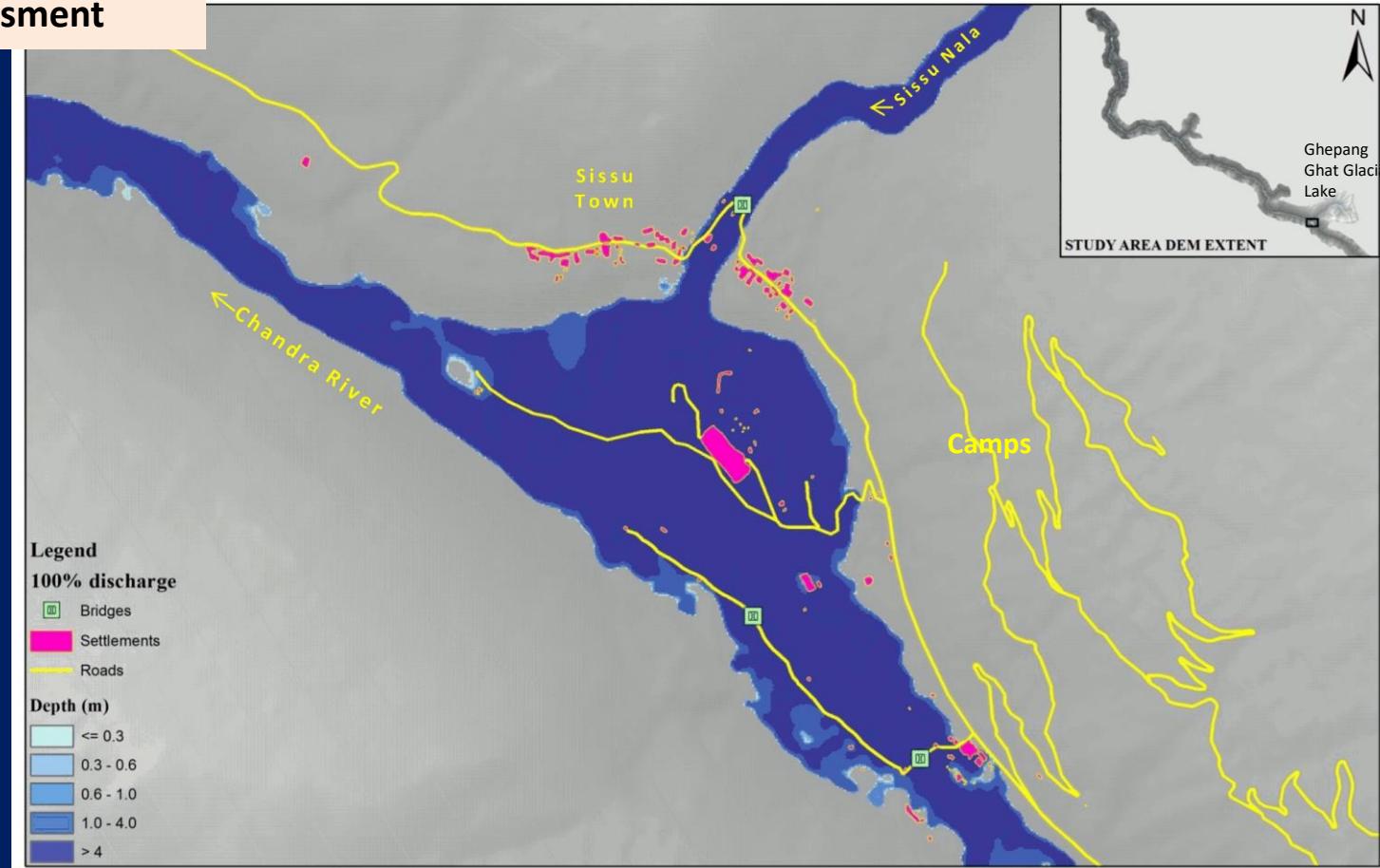
GLOF Risk Assessment

Glacier Lake Outburst Flood Risk Assessment



GLOF Risk
Assessment

FLOOD DEPTH MAP



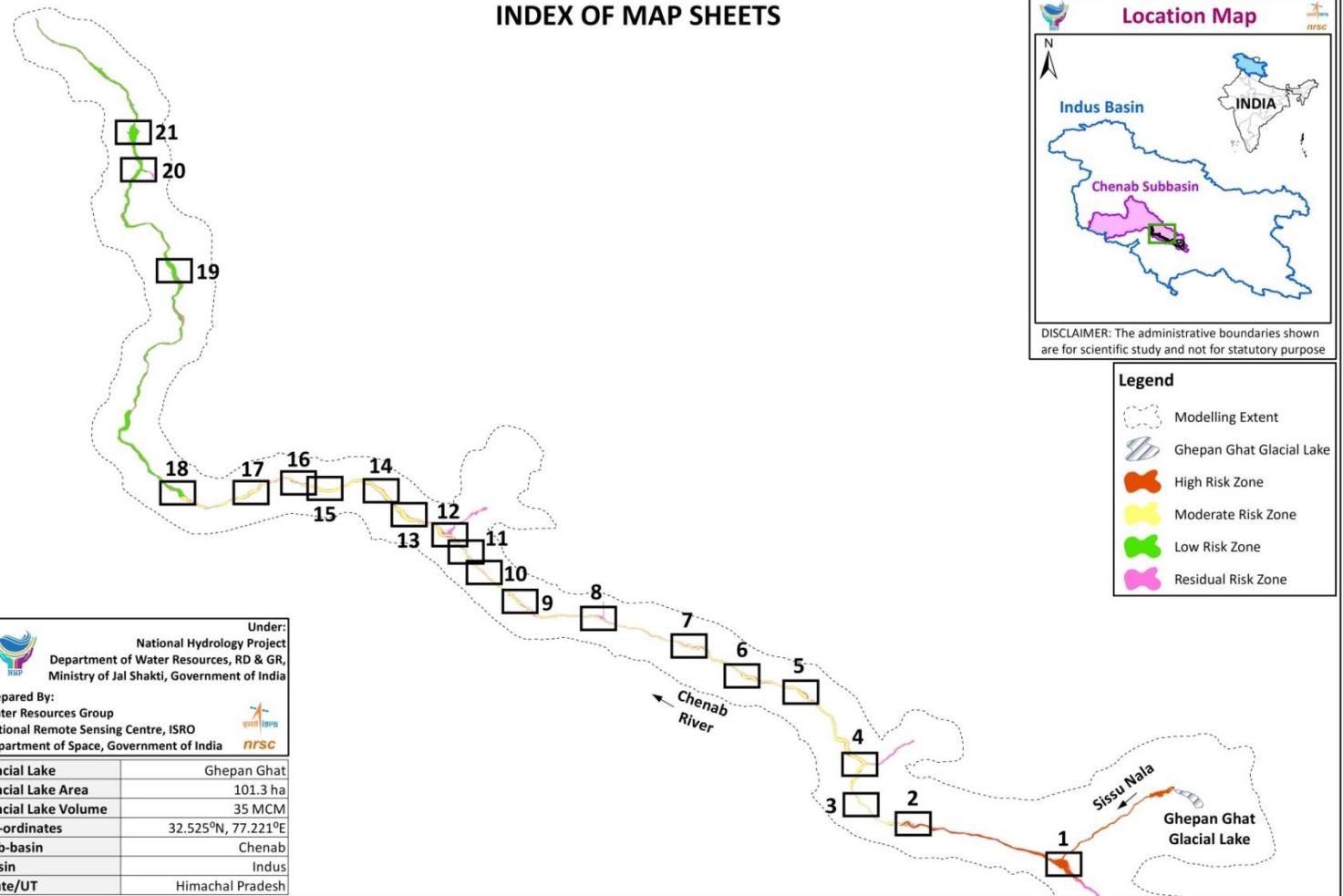
GLOF Risk Assessment

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

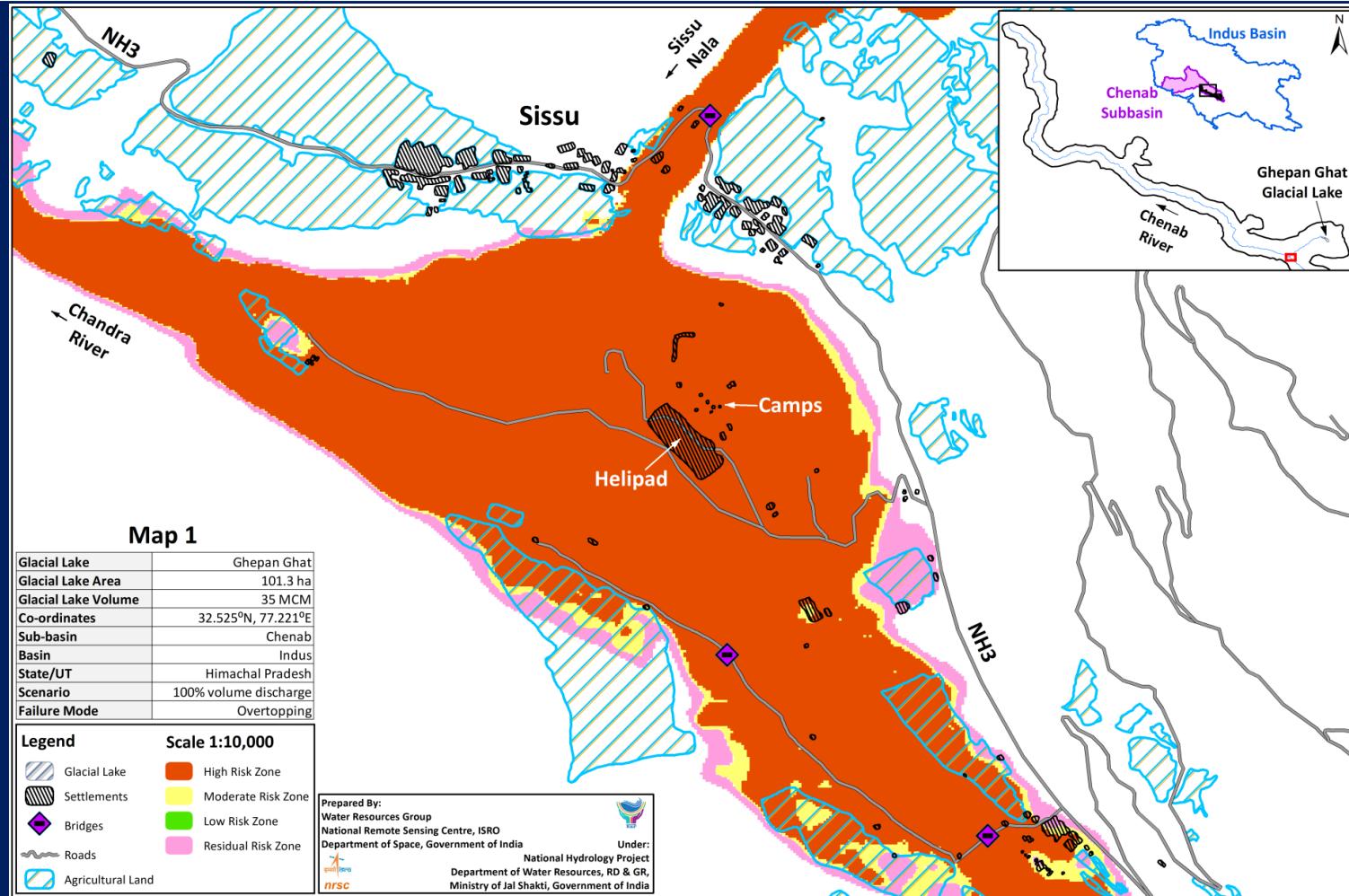
Scenario		Risk Zone	Flood Inundated Area (ha)	No. of Settlements	Agricultural Land (ha)	No. of Bridges	Length of Road (km)
3	3	High	300	1	9.7	3	3.4
		Moderate	919	22	41.3	25	15.2
		Low	915	7	32	13	16.0
Total			2,134	30	83	41	34.6

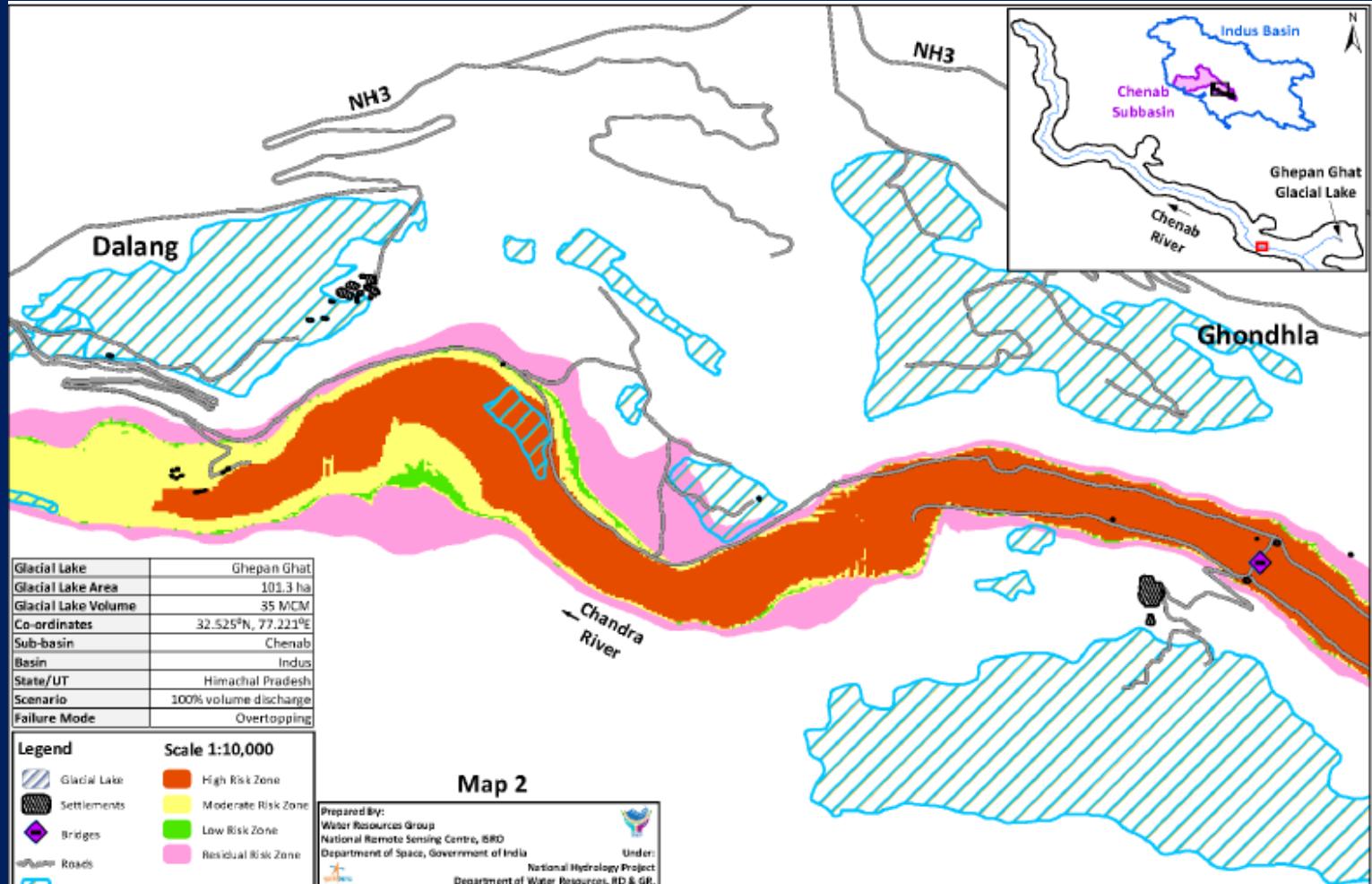
Glacier Lake Outburst Flood Risk Assessment

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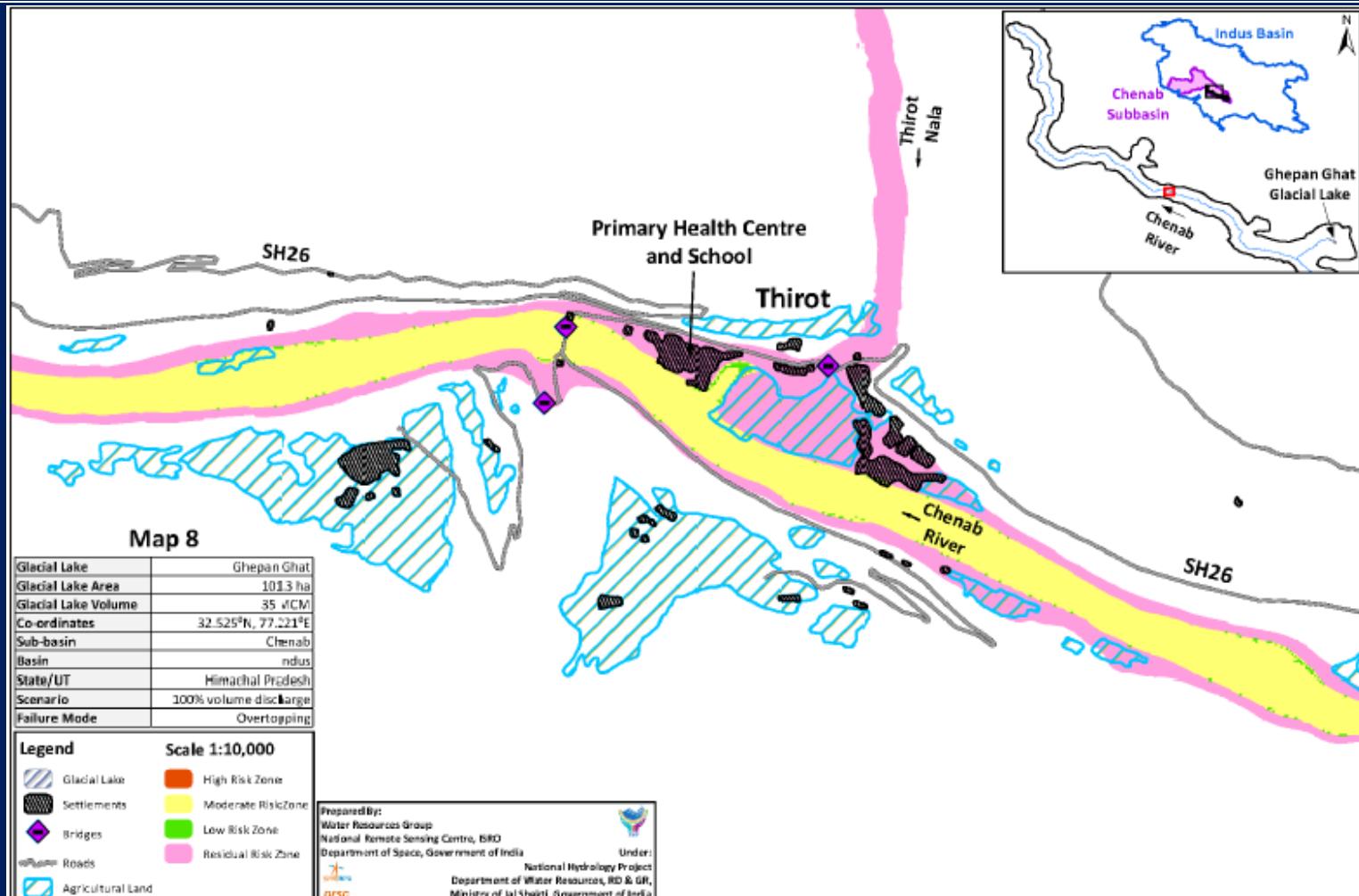


Glacier Lake Outburst Flood Risk Assessment





Glacier Lake Outburst Flood Risk Assessment



Options for Risk Management of Glacial Lakes

Structural measures
Non-structural measures

	Reduction of Hazard	Reduction of Exposure	Reduction of Vulnerability
Short term measures	<ul style="list-style-type: none"> Lower of lake level by Siphoning or pumping 	<ul style="list-style-type: none"> Evacuation (based on monitoring / Early warning) 	
Long term measures	<ul style="list-style-type: none"> Artificial drainage channel Reinforcement / increase of height of dam Enhancement of river cross section / protection from erosion 	<p style="text-align: center;">Early Warning Systems</p> <ul style="list-style-type: none"> Spatial planning according to hazard maps Protective structures (e.g. retention or deflection dams) 	<ul style="list-style-type: none"> Information (capacity & data) Institutional setup Economic diversity Disaster relief



A photograph of a satellite in low Earth orbit. The satellite has a large solar panel array deployed, showing its black and gold panels against the dark void of space. A smaller, articulated solar panel is also visible. The Earth is in the background, showing a bright blue atmosphere and white clouds. The satellite's body is gold-colored with various equipment and instruments attached.

THANK YOU