Simulation of river morphodynamics induced by the 1996 Lake Ha! Ha! breakout flood

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Andrea Antonella Graziano - PhD at University of Calabria (Italy)

ETH zürich

Laboratory of Hydraulics, Hydrology and Glaciology

UNIVERSITÀ DELLA CALABRIA

Introduction

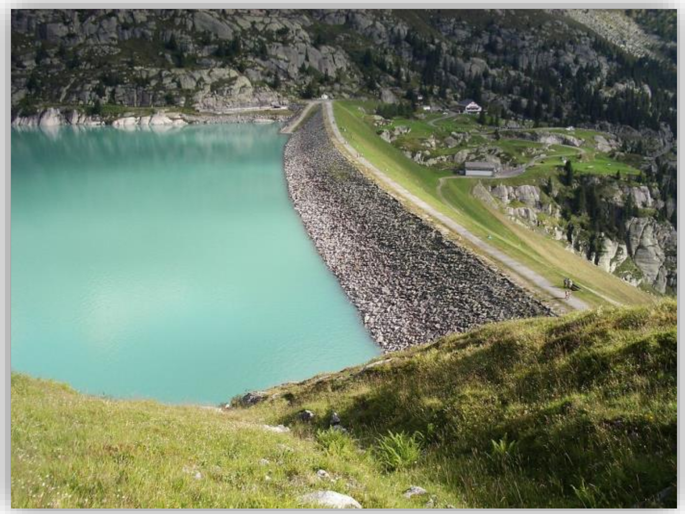
DAMS

- Several benefits
- Significant risk

Concrete dams

DAM-BREAK: sudden collapse (partial or total) of the dam body

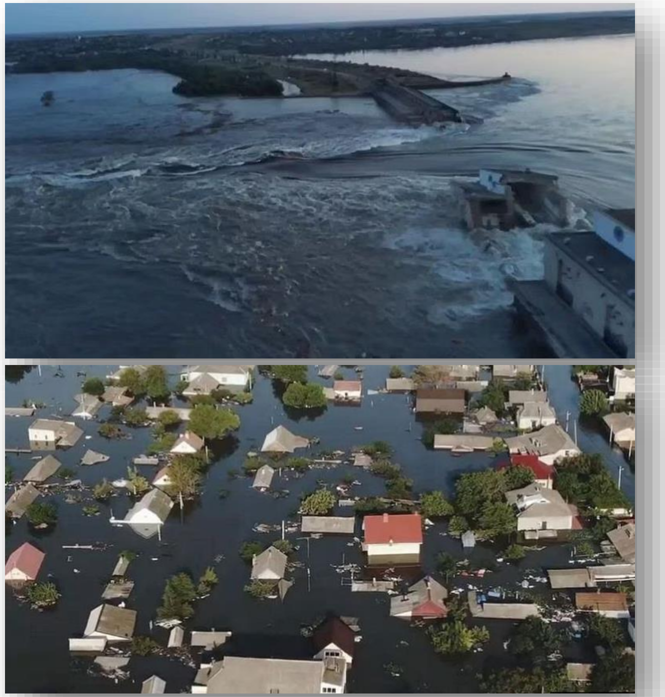
Embankment dams



DAM-BREACH: progressive erosion of the dam body

Introduction

Dam failures → Artificial floods → Catastrophic events → Drastic morphological changes



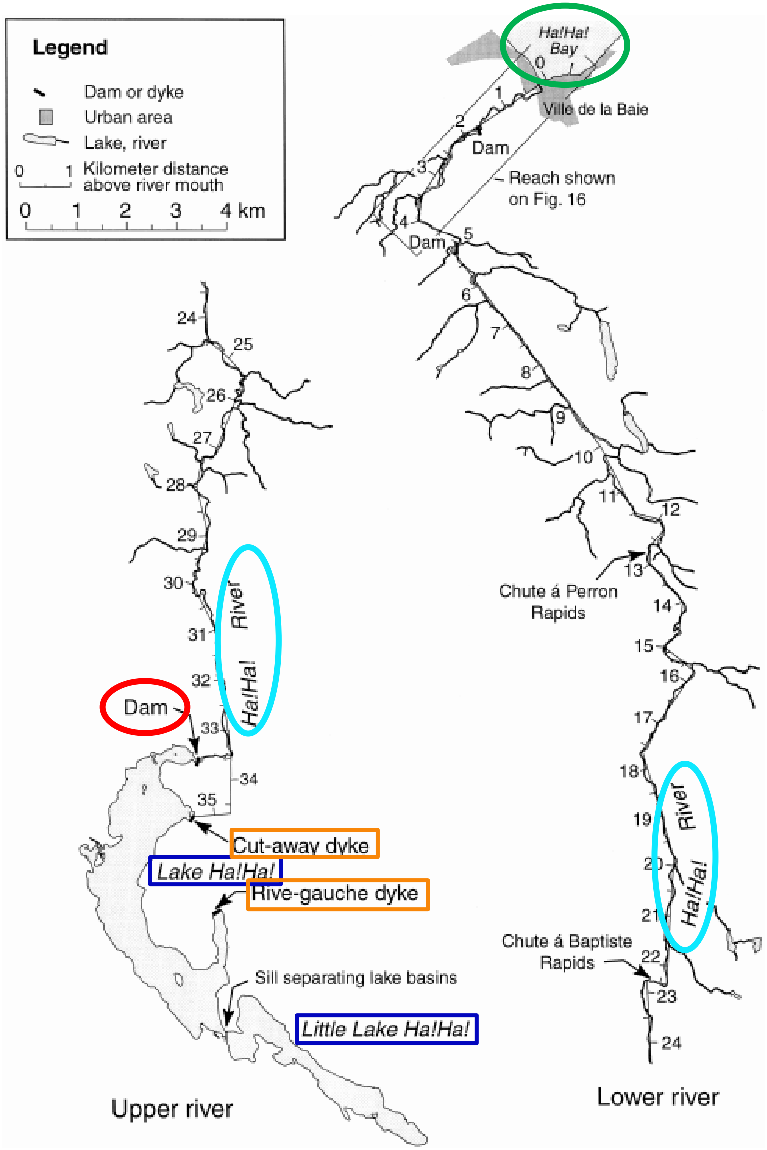
Kakhovka Dam failure (Ukraine), June 2023

Derna Dams failure (Libya), September 2023

Case study: Lake Ha! Ha!

- Located in the Canadian province of Quebec
- Reservoir 12 km long
- Surface area of 8.1 km^2
- Purpose: energy production by means of two run-of-river hydropower stations along the Ha! Ha! River

Case study: Lake Ha! Ha!

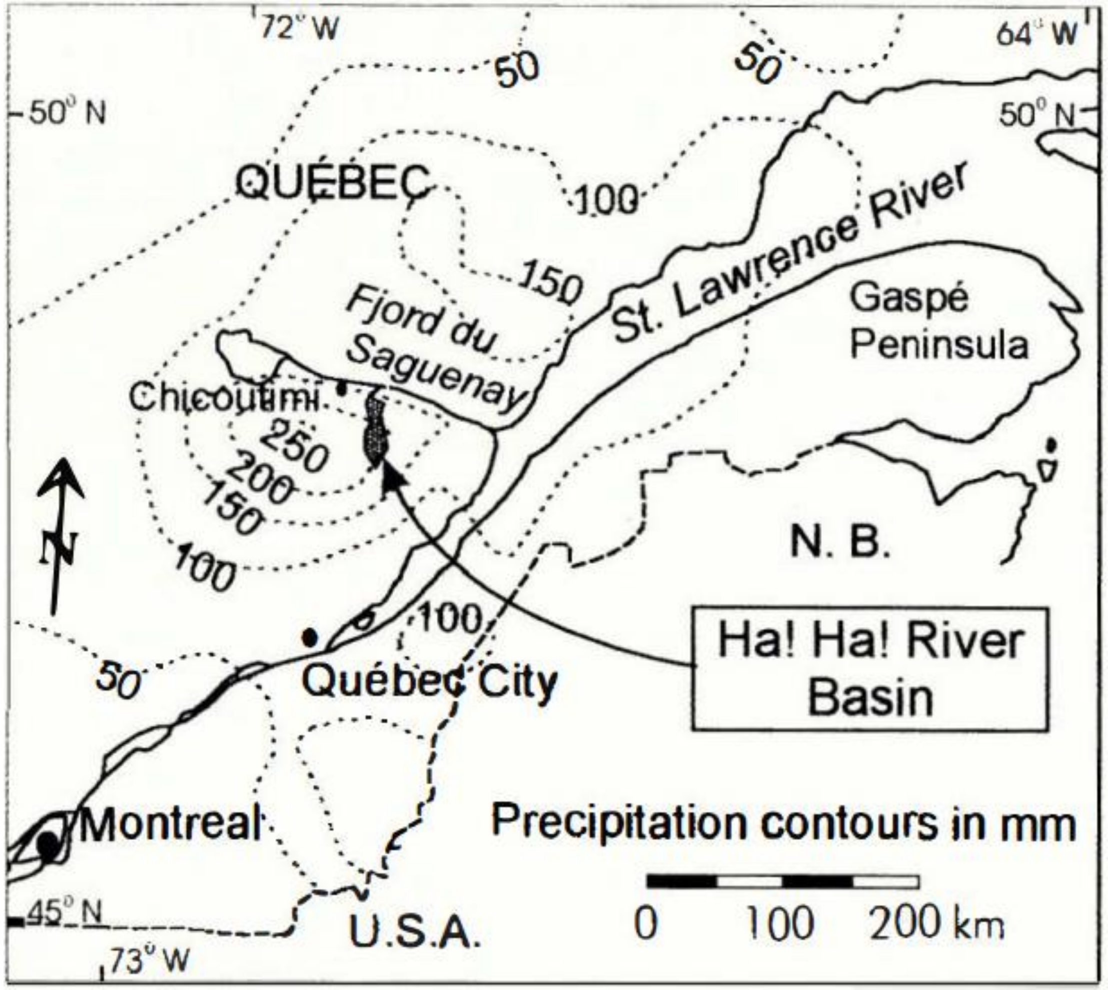


Source: Brooks & Lawrence (1999)

- Reservoir made by two separated but connected **lake basins**
- Impounded by a **concrete-gravity dam** 8.2 m high
- Two small **earthfill dykes** located on the right side of the lake
- **Downstream river** 34 km long from the Lake Ha! Ha! to the **mouth** (Ha! Ha! Bay)
- Catchment of 610 km^2
- Contributing area of the reservoir representing 37.5% of the total catchment area

Source: Capart et al. (2007)

1996 Lake Ha! Ha! breakout flood

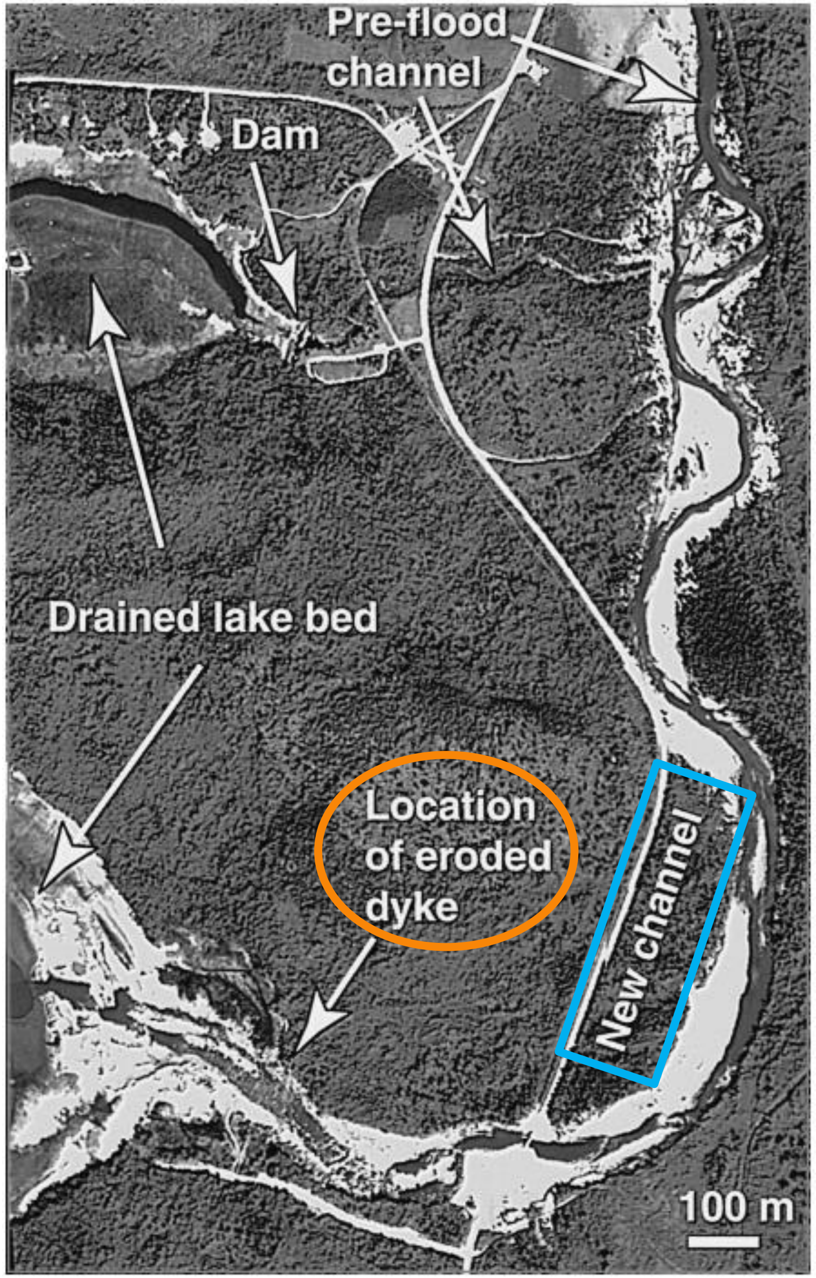


- From July 19 to 21,1996: 48-hour precipitation totals of 210 mm affected the eastern part of the Quebec province
- Precipitation values 2 to 3 times greater than the maximum recorded values

48-hour precipitation totals for eastern Quebec, Canada, from 8:00 a.m. July 19 to 8:00 a.m. July 21, 1996.
<u>Source:</u> Lapointe et al. (1998)

1996 Lake Ha! Ha! breakout flood

- Lake Ha! Ha! level rise up to a maximum of 380.65 m a.s.l.
- Overtopping of one of the two earthfill dykes by 0.26 m
- Consequent **erosion of the cut-away dyke** and drainage of the lake
- Incision of a **new outlet channel** bypassing the concrete dam



Source: Brooks & Lawrence (1999)

1996 Lake Ha! Ha! breakout flood

The new outlet at the Lake Ha! Ha! reservoir that was eroded through the Cut-away dyke, (a) looking downstream and (b) looking upstream. Source: Brooks & Lawrence (1999)

1996 Lake Ha! Ha! breakout flood

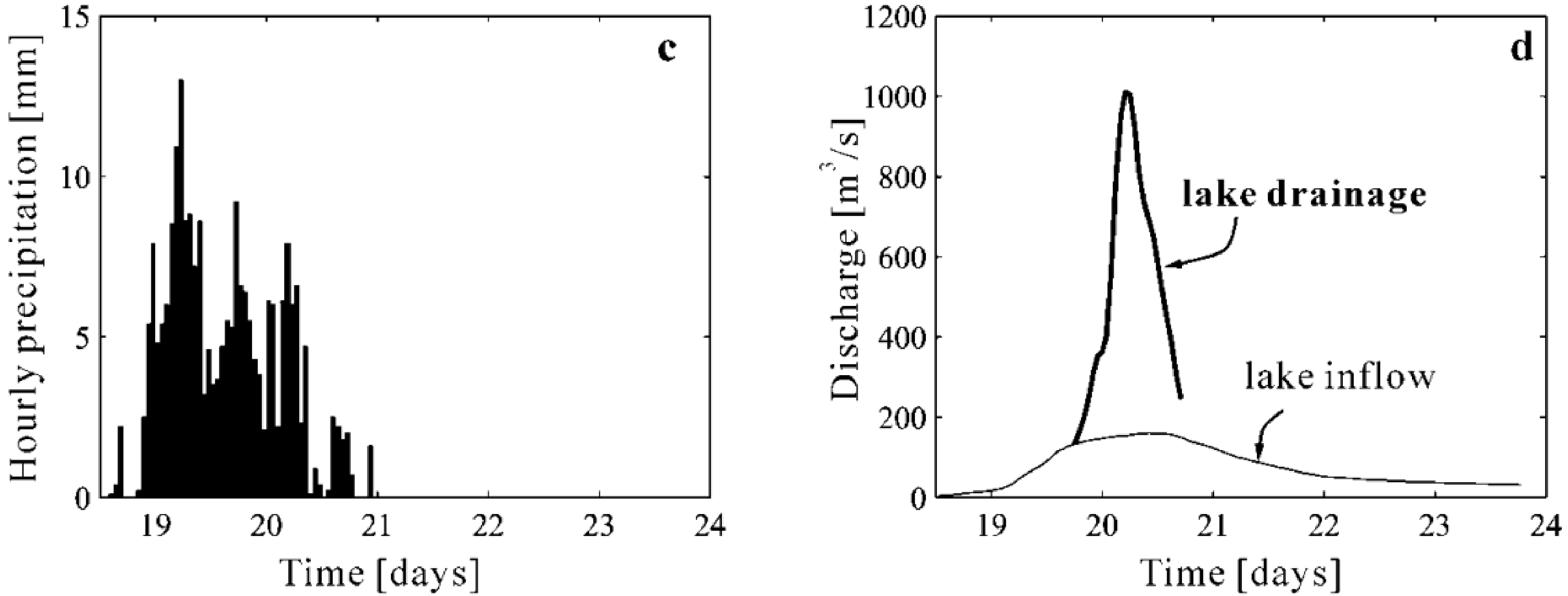
Unusually heavy rains
+
Reservoir drainage

→

Peak discharge estimated at some **1010 m^3/s** based on the reconstructed time history of the lake level drop (Capart et al., 2007)

→

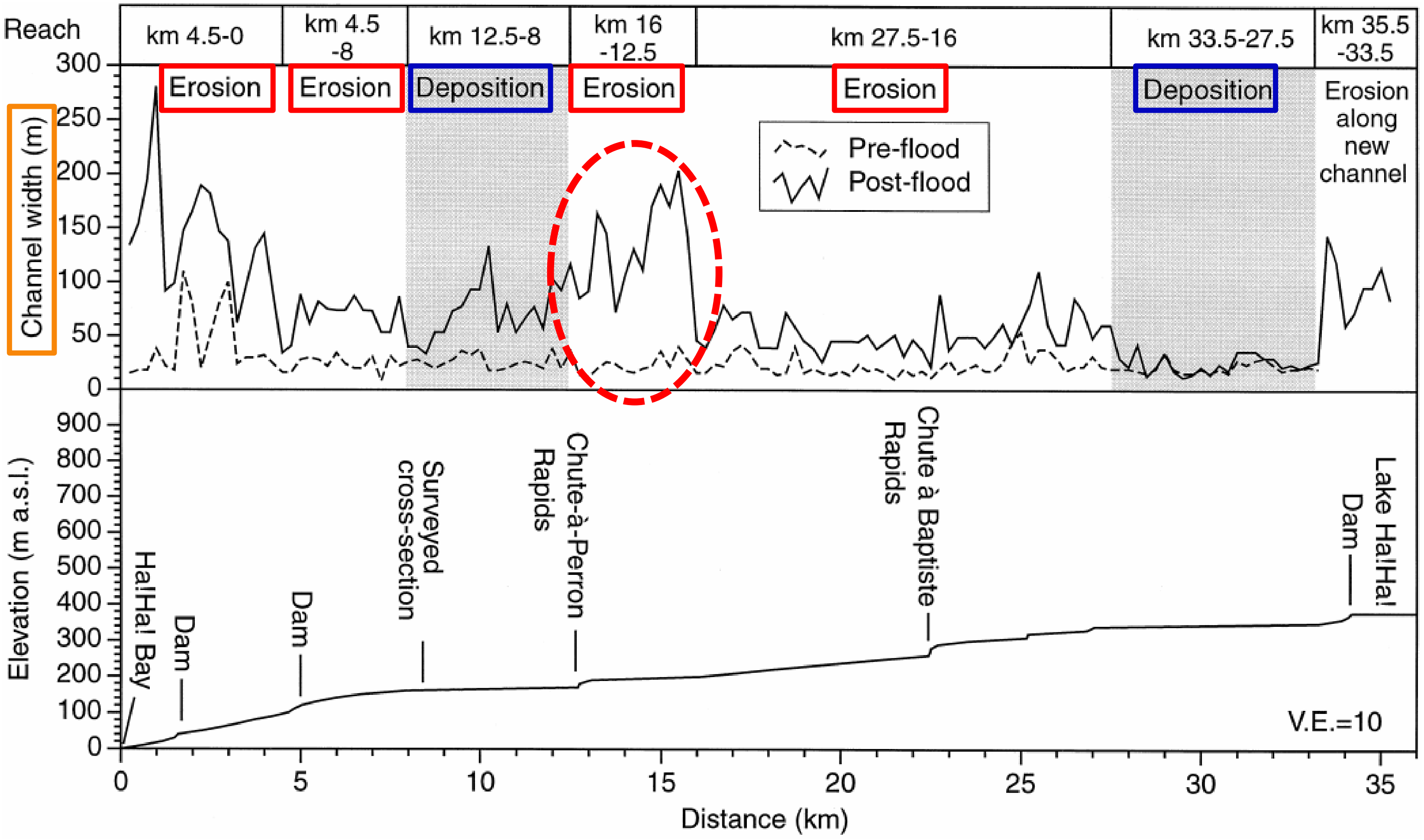
8 times over the 100-year return period flood ($130\ m^3/s$)



Source: Capart et al. (2007)

Downstream impacts of the flood

Flow direction



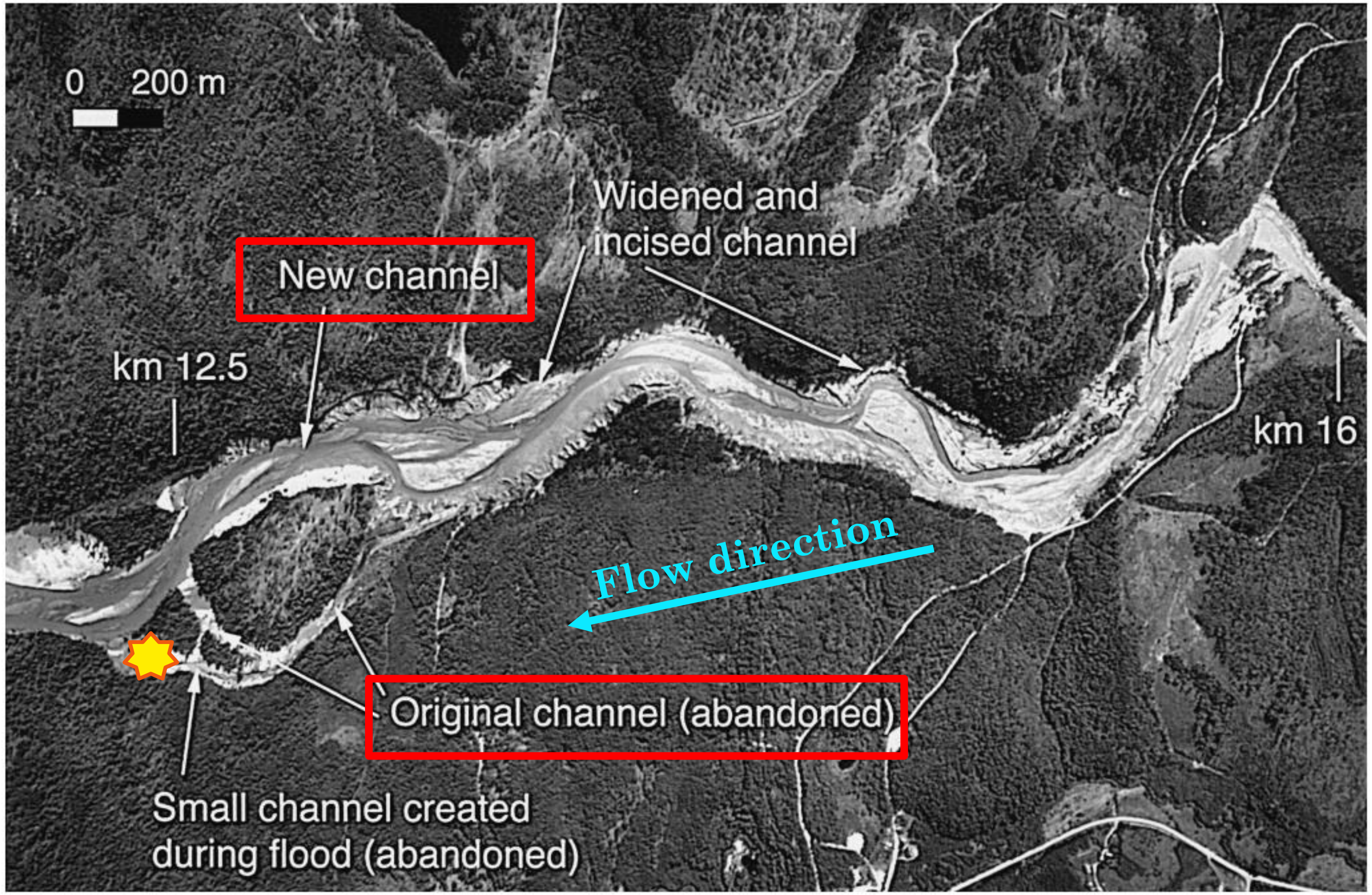
Source: Brooks & Lawrence (1999)

Channel widening

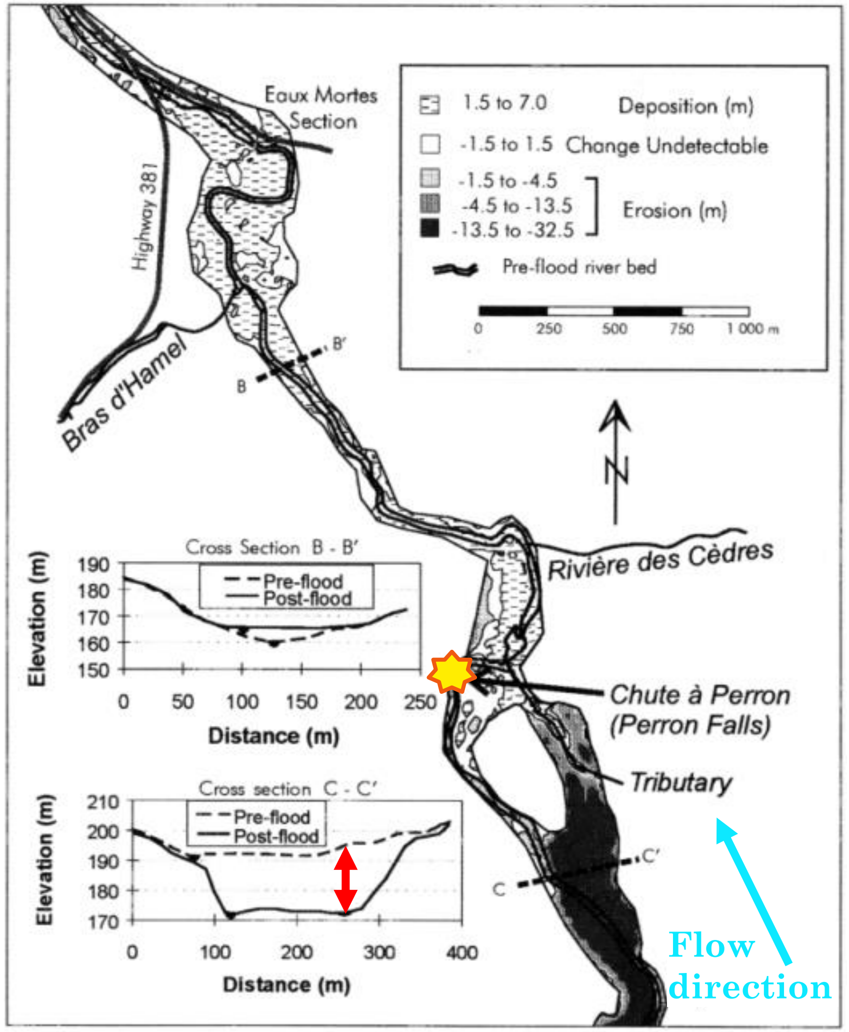
Predominant erosion

Deposition in some reaches

Downstream impacts of the flood

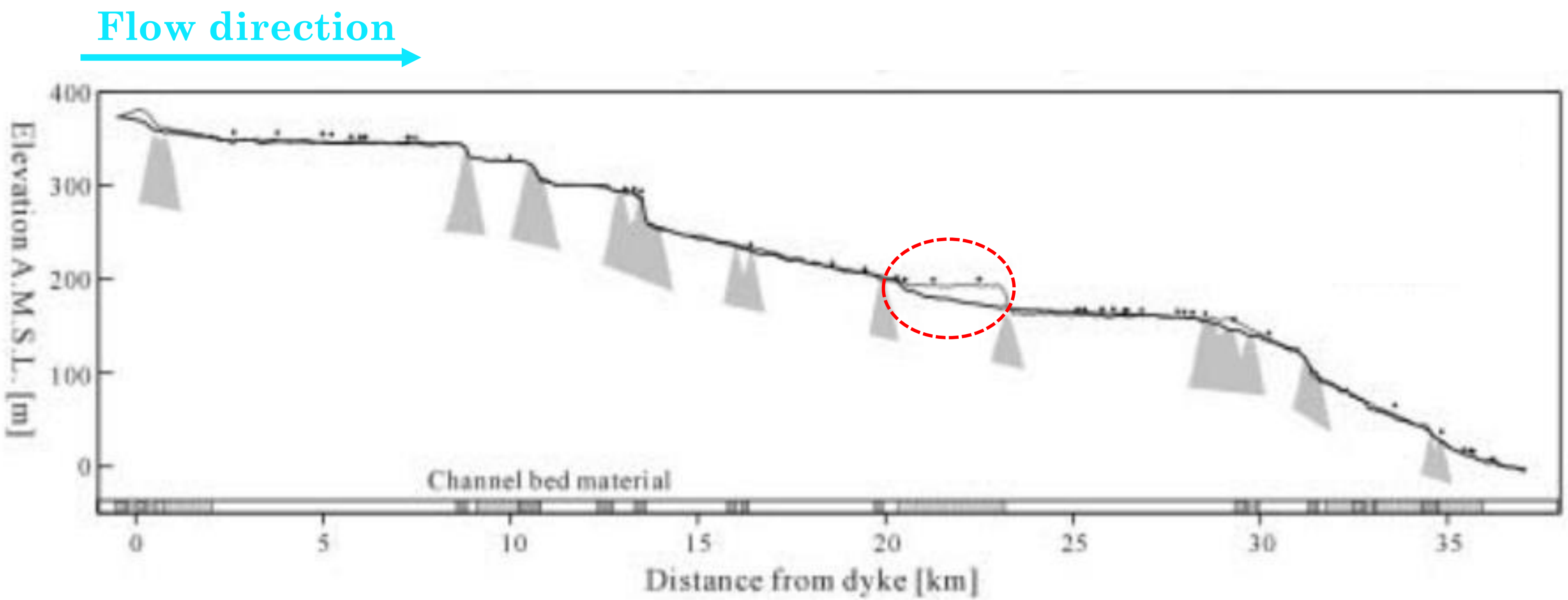


Source: Brooks & Lawrence (1999)



Source: Lapointe et al. (1998)

Downstream impacts of the flood



Source: Capart et al. (2007)

Erosion governed by important **rock outcrops**

References

- Lapointe, M. F., Secretan, Y., Driscoll, S. N., Bergeron, N., & Leclerc, M. (1998). Response of the Ha! Ha! River to the flood of July 1996 in the Saguenay Region of Quebec: Large-scale avulsion in a glaciated valley. *Water Resources Research*, *34*(9), 2383–2392. https://doi.org/10.1029/98WR01550

- Brooks, G. R., & Lawrence, D. E. (1999). The drainage of the Lake Ha!Ha! reservoir and downstream geomorphic impacts along Ha!Ha! River, Saguenay area, Quebec, Canada. *Geomorphology*, *28*, 141–168. https://doi.org/10.1016/S0169-555X(98)00109-3

- Capart, H., Spinewine, B., Young, D. L., Zech, Y., Brooks, G. R., Leclerc, M., & Secretan, Y. (2007). The 1996 Lake Ha! Ha! breakout flood, Québec: Test data for geomorphic flood routing methods. *Journal of Hydraulic Research*, *45*(SPEC. ISS.), 97–109. https://doi.org/10.1080/00221686.2007.9521836

Detailed dataset useful for the testing and comparative assessment of geomorphic flood routing methods

Literature simulations

1D morphodynamic models

Mahdi & Marche (2003)
El kadi Abderrezzak & Paquier (2009)

2D morphodynamic models

Duan et al. (2023)

BASEMENT application

- **Version 4.1.0**
- **BASEHPC** module (High Performance Computing)
- **New feature**: mixed-size bedload transport model

$$(1-p)\frac{\partial z_B}{\partial t} + \sum_{g=1}^{N}\left(\frac{\partial q_{s,gx}}{\partial x} + \frac{\partial q_{s,gy}}{\partial y} - S_{s,g}\right) = 0$$

→ Hirano-Exner model (Hirano, 1971)

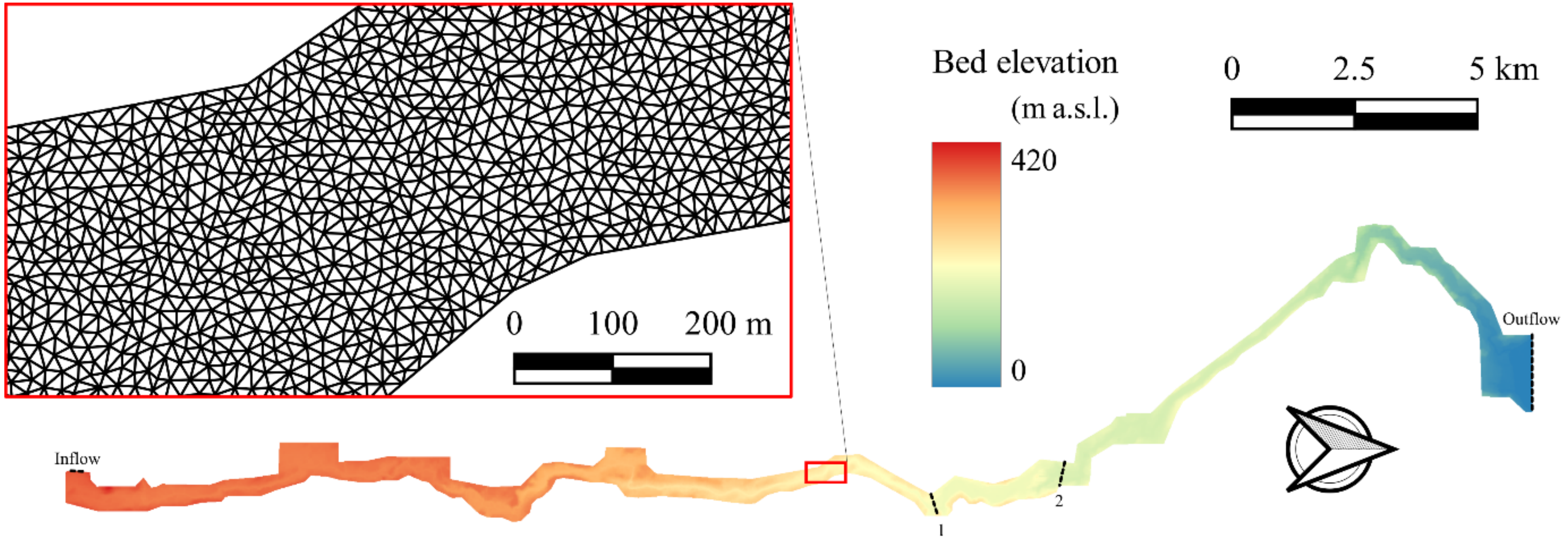
$$q_s = \sum_{g=1}^{N}\left[f_g \psi\, 8\left(\theta_g - \xi_g \theta_{cr}\right)^{1.5}\sqrt{(s-1) g d_g^3}\right]$$

→ Extension of the Meyer-Peter & Müller (1948) formula to non-uniform sediment (see e.g. Ribberink, 1987)

Sediment mixtures discretized by means of ***N* classes**, each one denoted by a subscript “*g*” and characterized by a sediment diameter d_g

Computational mesh

- Topographic information: pre-event DEM (Capart et al., 2007)
- Resolution: 10 m
- Computational domain discretized in 126,541 triangular elements having a maximum area of 100 m^2
- Tool: BASEmesh plugin (QGIS)



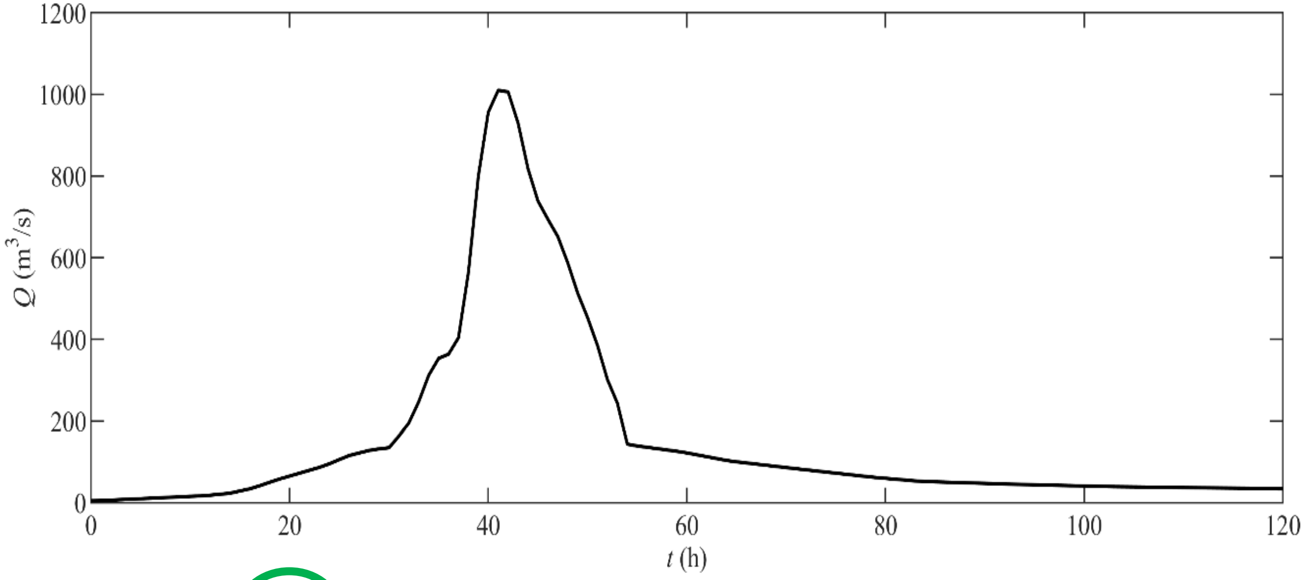
Hydraulic boundary conditions

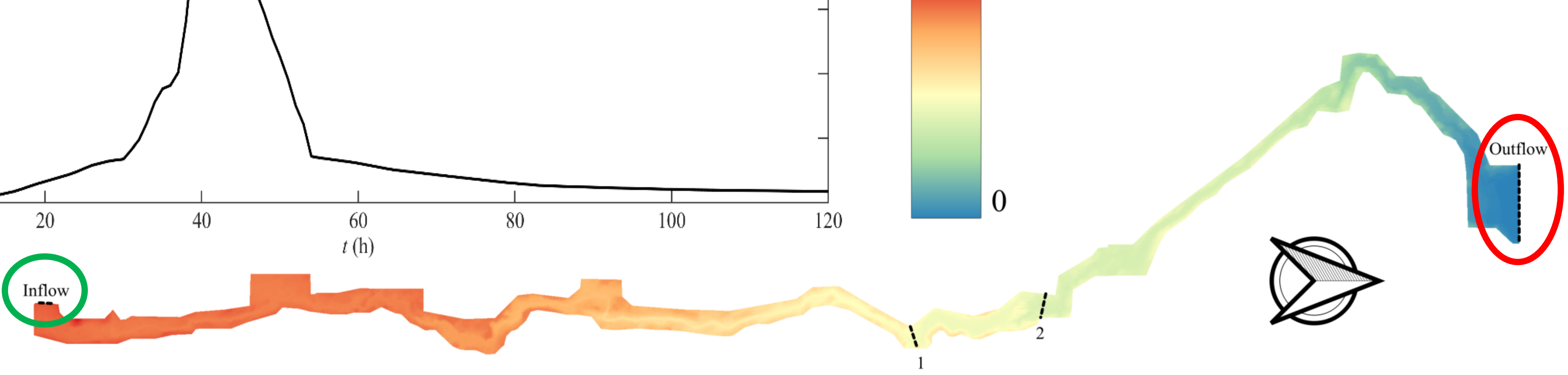
Upstream: recontructed discharge hydrograph

(Capart et al., 2007)

Downstream: constant water surface elevation of 7 m a.s.l.

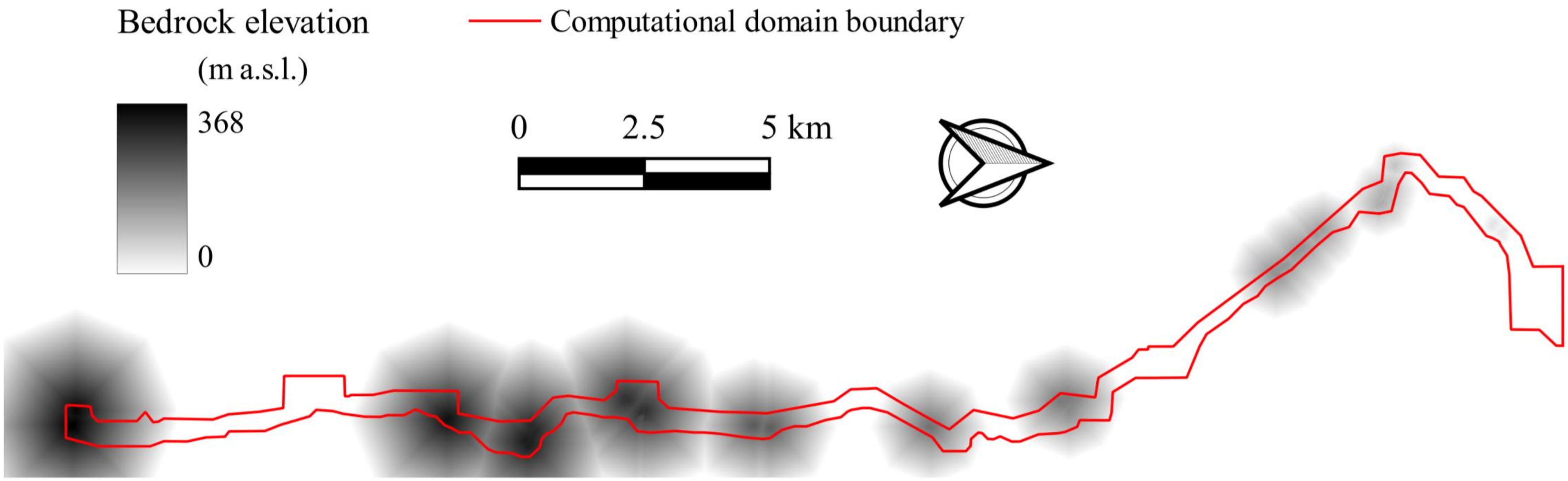
(Capart et al., 2007)





Fixed bed

- Bedrock surface reconstructed through the observation of the rock outcrops (Capart et al., 2007)
- Fixed bed mesh having the same structure of the computational mesh
- Tool: BASEmesh plugin (QGIS)

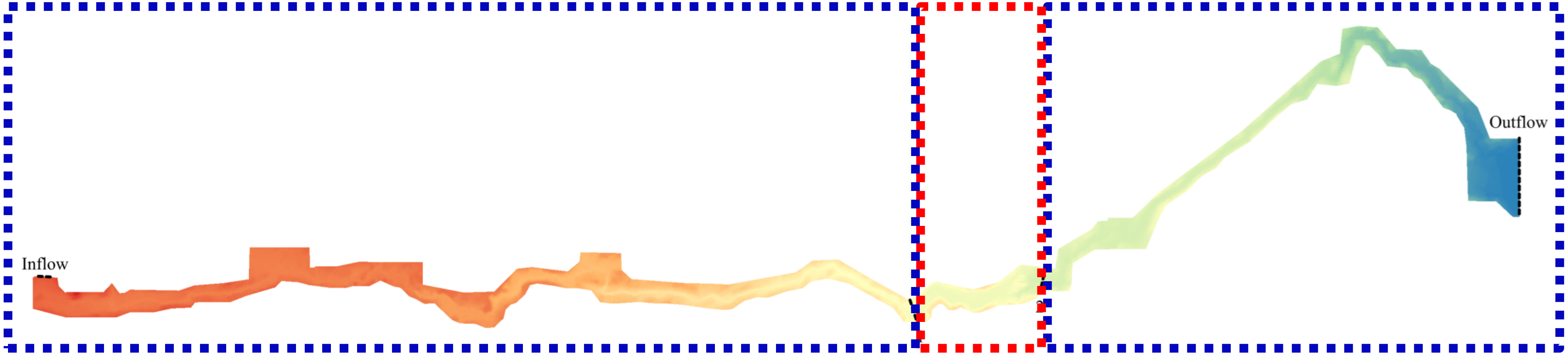


Bed material

- Information about d_m (**0.5 mm**, **0.1 mm**) and GSD (**2.7**, **1.6**) retrieved by Mahdi & Marche (2003) and El Kadi Abderrezzak & Paquier (2009)
- Two sediment mixtures defined based on the available information

Mixture 1		**Mixture 2**	
d_g **(mm)**	f_g **(%)**	d_g **(mm)**	f_g **(%)**
0.185	32	0.063	32
0.500	36	0.100	36
1.350	32	0.160	32

Assumption: GSD centred around the median diameter



Bedload transport

- MPM multi
- Pre-factor **1.5**

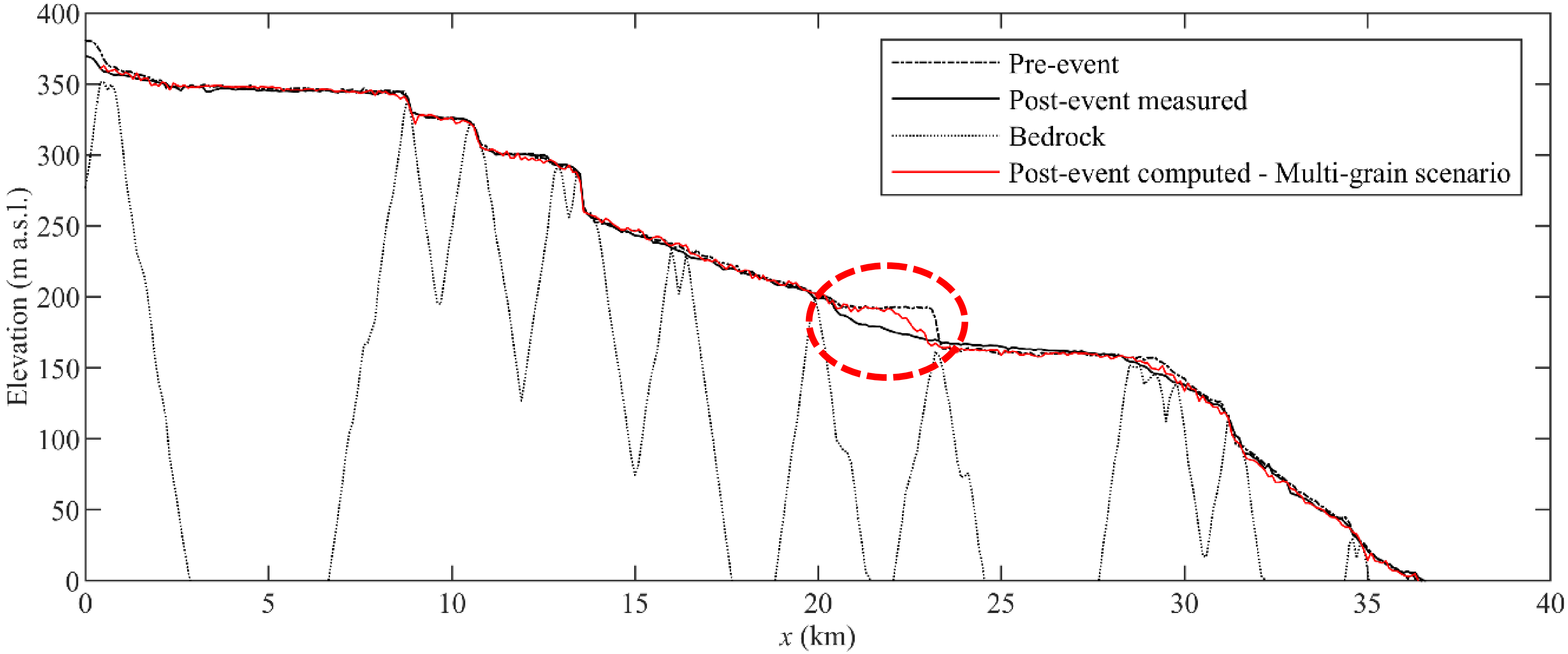
(El kadi Abderrezzak & Paquier, 2009; Duan et al., 2023)

Morphological boundary conditions

- Transport capacity (both upstream and downstream)

Model results

Evolution of the thalweg longitudinal profile



Bed evolution governed by the **bedrock outcrops**

Overall good agreement of the model

The **large scale avulsion reach** represents a challenge

Submitted paper

Graziano, A. A., Halso, M. C., Boes, R. M., Macchione, F., & Vetsch, D. F. (submitted in November 2024), **Flood hazard assessment due to dam breaching considering river morphodynamics**. *Natural Hazards* (under review).

Thank you for listening!

andreaantonella.graziano@unical.it