EGU General Assembly 2020

Back analysis numerical modelling of Cardoso (Apuan Alps, Italy) flood on 19th June 1996: from gravitational movements to their evolution in debris flows

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Motivation

On the 19th June 1996, a severe rainstorm affected north-western Tuscany, destroying the Cardoso village with 14 deaths.

Until now, the attention was focused on geological-geomorphological settings on shallow landslides; initiation of rainfall-induced debris flows; landslides susceptibility; large scale debris flow hazard assessment and the analysis of the rainstorm.

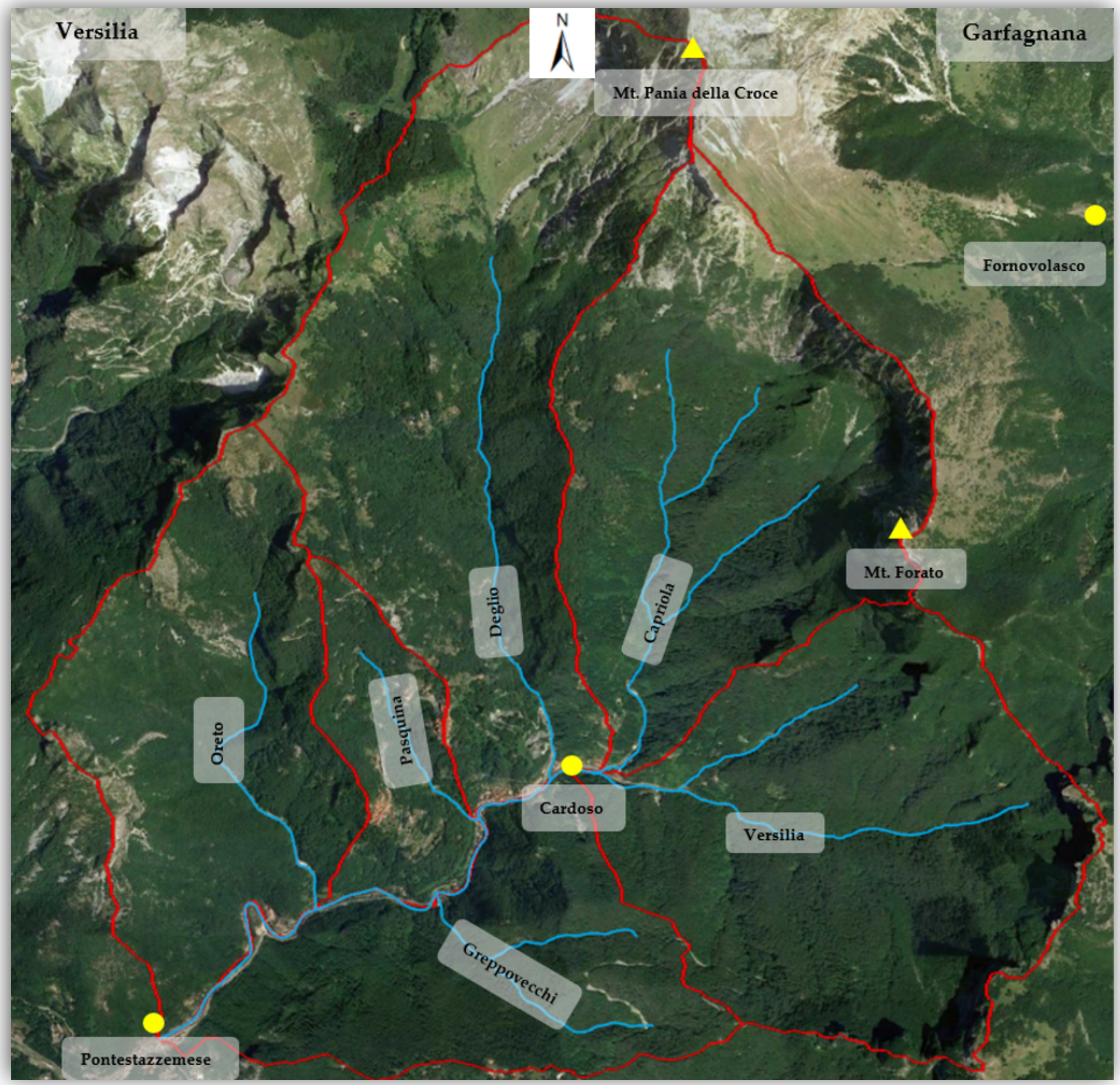
Goals

Quantitative numerical modelling of the event:

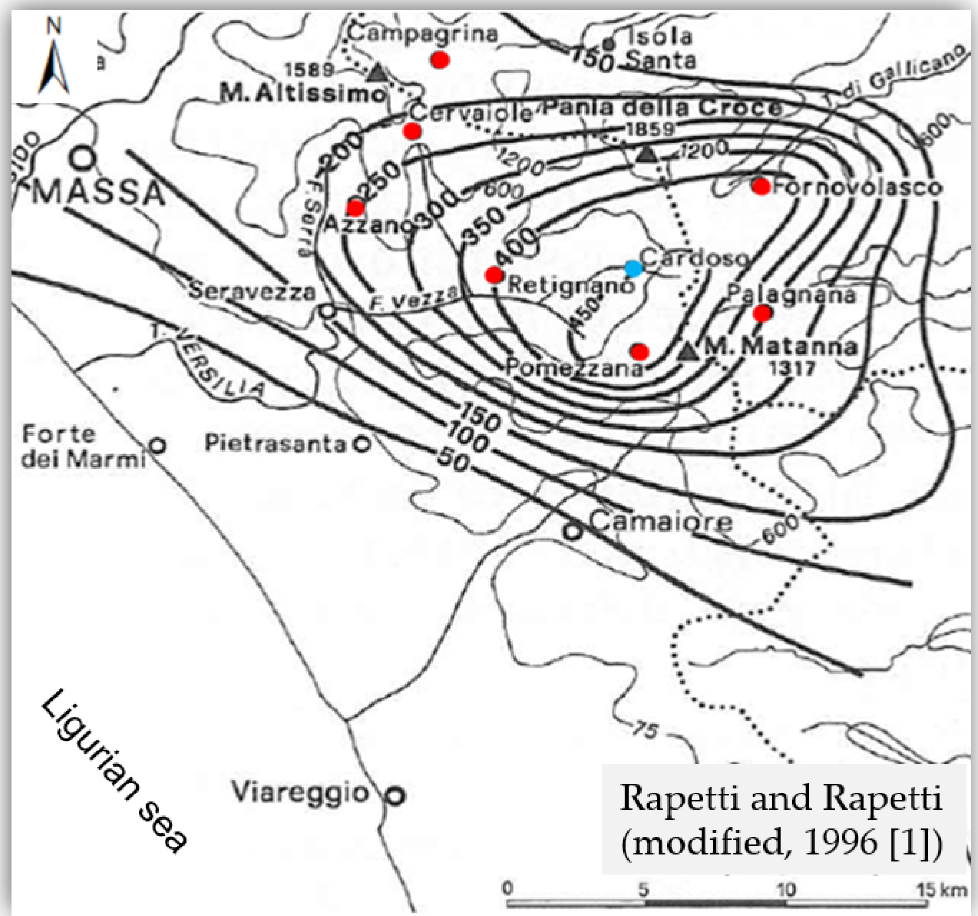
- **Assessment of the solid volume mobilized from slopes and hydrographic network**
- **Rainfall back analysis**
- **Debris flows run-out back analysis**

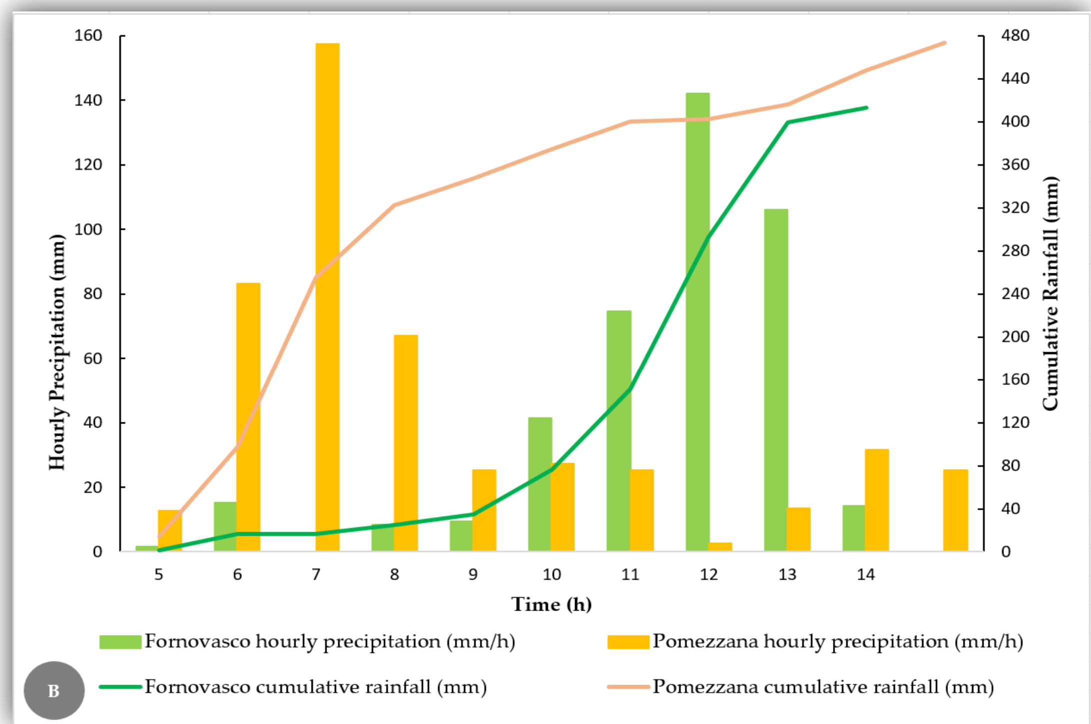
Study area

Basin area (km²): 13
Elevation (m a.s.l.): 163-1859
Mean slope of the six main channels (°): 11-15
Geology: metamorphic sandstone (mainly) and dolomitic limestones, limestones and marls



The intense rainstorm on 19th June 1996 in Versilia and Garfagnana regions





- **Involved area**: 60 km², between Lucca and Massa Carrara provinces
- **Max total rainfall**: 474 mm/12 h*
- **Max peak intensity**: 158 mm/h*

*Registered at the Pomezzana rain gauge

Two different phases of heavy rainfall:

1. The first affecting mainly the Versilia region with max peak intensity at 7 a.m
2. The second spreading over on the crests and the western side of Garfagnana region between 12-1 p.m. (triggering rainfall)

Landsliding and flooding of Cardoso catchment

From gravitational movements…


D'Amato Avanzi et al., 2004 [2]

… to debris flows

Material and methods

2.1 Field surveys

Individuation of channel sections possibly interested by **dam-break**; individuation of the **max height of debris flows** and their relative check measures along the Cardoso village, starting from the analysis of the archive photos of the event.

2.2 Assessment of the solid volume mobilized from slopes and hydrographic network

Post-event aerial photo interpretation; GIS analysis (flow accumulation); Map of slope deposits thickness (unsupervised classification for superficial deposit depth mapping method [3])

Back analysis numerical modelling using FLO-2D model [4]

2.3 Rainfall back analysis

Data input

- LiDAR
- Pluviograph
- Roughness map (n Manning)
- Infiltration map (CN method using a dataset about soil thickness and hydraulic conductivity of slope deposits (SD))

Output

- **Hydrographs**
- **Flooded area**
- **Max height of debris flows**

2.4 Debris flows run-out back analysis

Data input

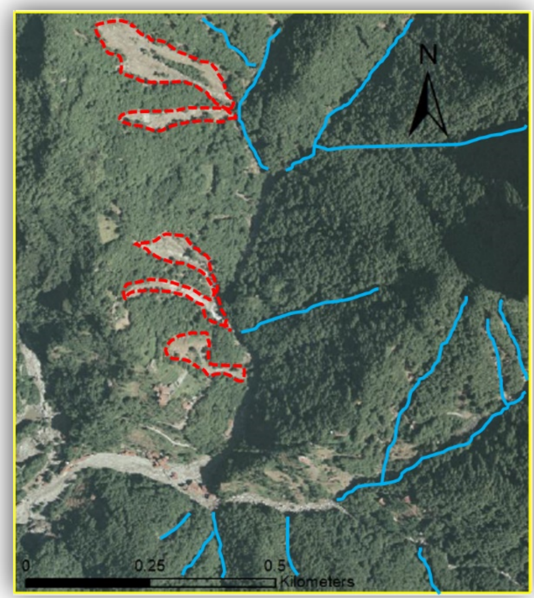
- LiDAR
- Roughness map (n Manning)
- Debris-graphs
- Rheological parameters (μ_N, τ_y; K; TOL)

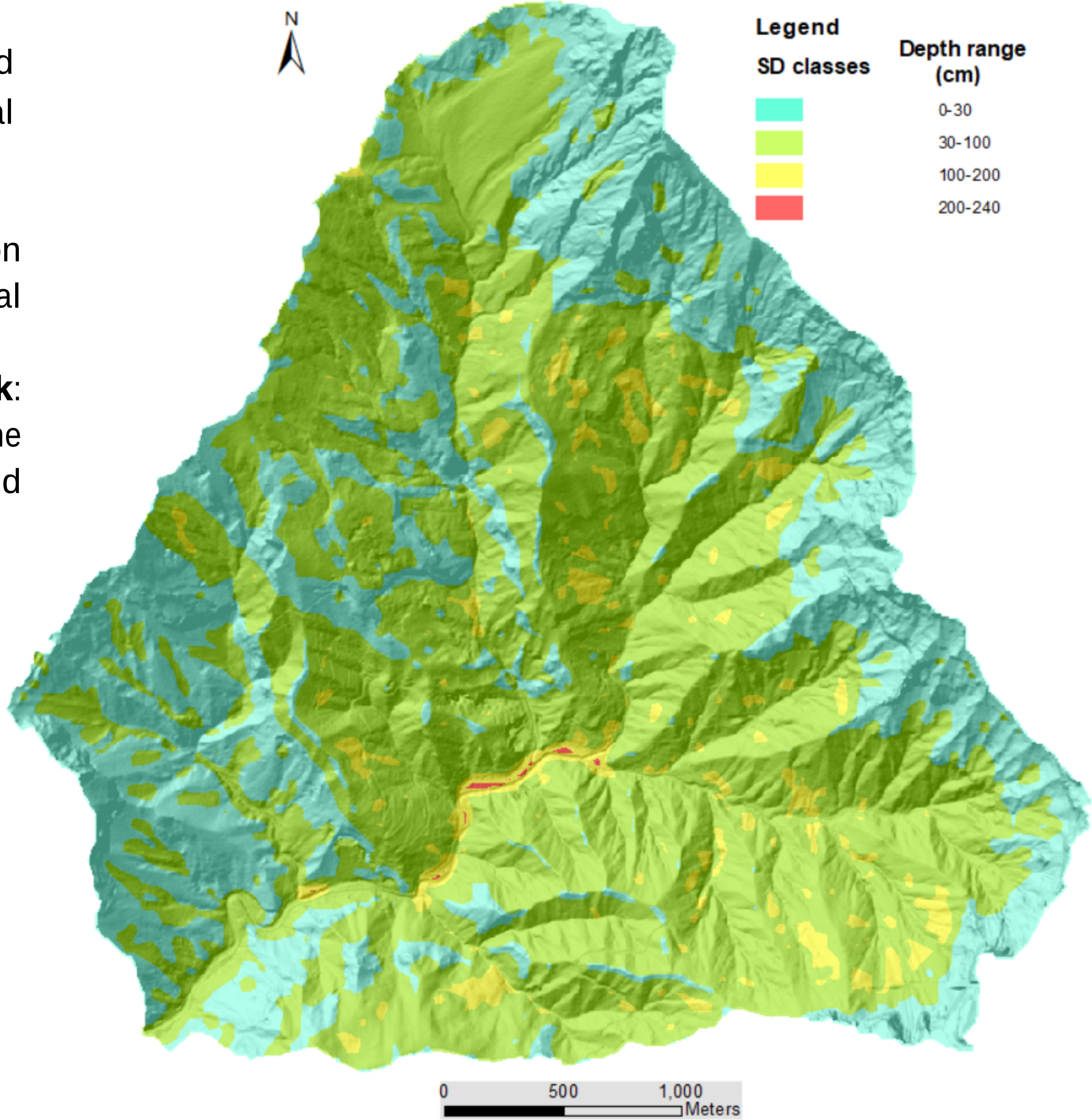
Material and methods

Assessment of the solid volume mobilized from slopes and hydrographic network

The **map of the slope deposits thickness** was obtained using the unsupervised classification for superficial deposit depth mapping method [3].

- **Assessment of landslides area**: identification and drawing of landslides areas analysing aerial post-event photos.
- **Assessment of the eroded drainage network**: GIS analysis using flow accumulation. The typical width of erosion was 10 meters, evaluated by statistical analysis on 20% of channels.





Material and methods

Rainfall back analysis

Data input for the hydrological numerical modelling with FLO-2D:

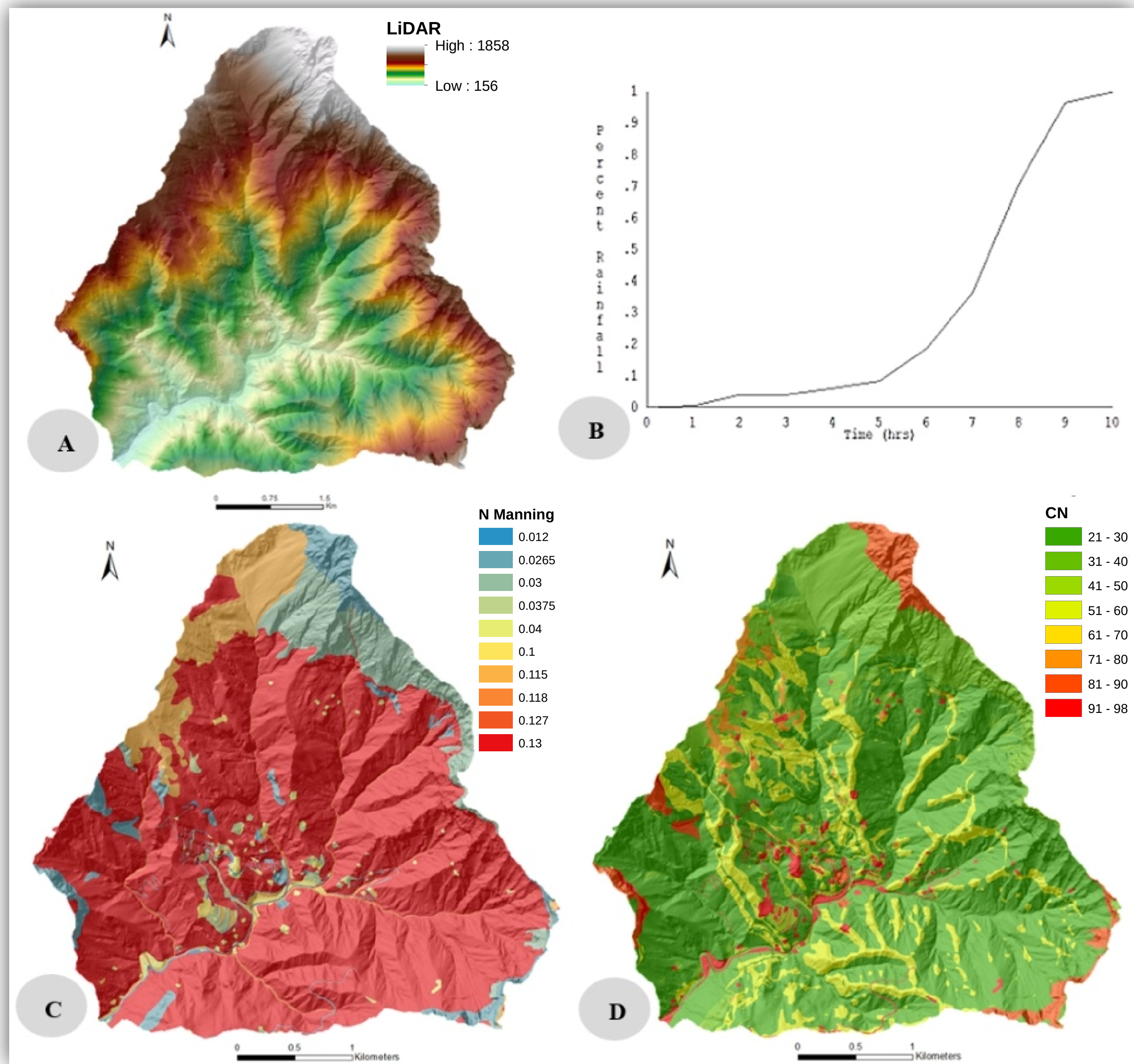
(A) **LiDAR**;

(B) **Pluviograph** of Fornovolasco rain gauge;

(C) **Roughness map** (n Manning)
To reproduce the terrain roughness, n values were assigned based on land use (NLCD [5]);

(D) **Infiltration map** (CN method) [6]
The NRSC-USDA method [7] was used to assess the hydrologic soil group classes (HSG), intersecting the thickness of SD with their hydraulic conductivity (Ks) values. The Ks values ranging from a min values of 12 mm/hr for limestones to a max value of 21 mm/hr for metamorphic sandstone. The CN map was obtained intersecting the HSG classes with the land use categories [8].

(E) **Surface detention** (TOL): 0.03 m (after calibration tests)



Material and methods

Debris flows run-out back analysis

Data input for the hydraulic numerical modelling with FLO-2D model

(A) **LiDAR;**
(B) **Debris-graphs**
The Smart and Jaeggi [9] and Mizuyama et al. [10] relations, respectively equations (1) and (2), was adopted for assessing debris flows discharge.
- Simulation of **sediment transport**: the **Smart and Jaeggi** simplified relation,
- Simulation of **dam break**: implementation of the **Mizuyama et al. (1992)** equation for Capriola, Versilia and Greppovecchi channels;

(C) **Roughness map** (n Manning);
(D) **Rheological properties**
For the Cardoso event there was no data available about rheological parameters of the debris material., therefore have been tested two types of rheological scheme reported in the literature: "**Aspen Pit 1**" [11] for **granular debris flow** and **Kang and Zhang** [12] for **muddy debris flow.**

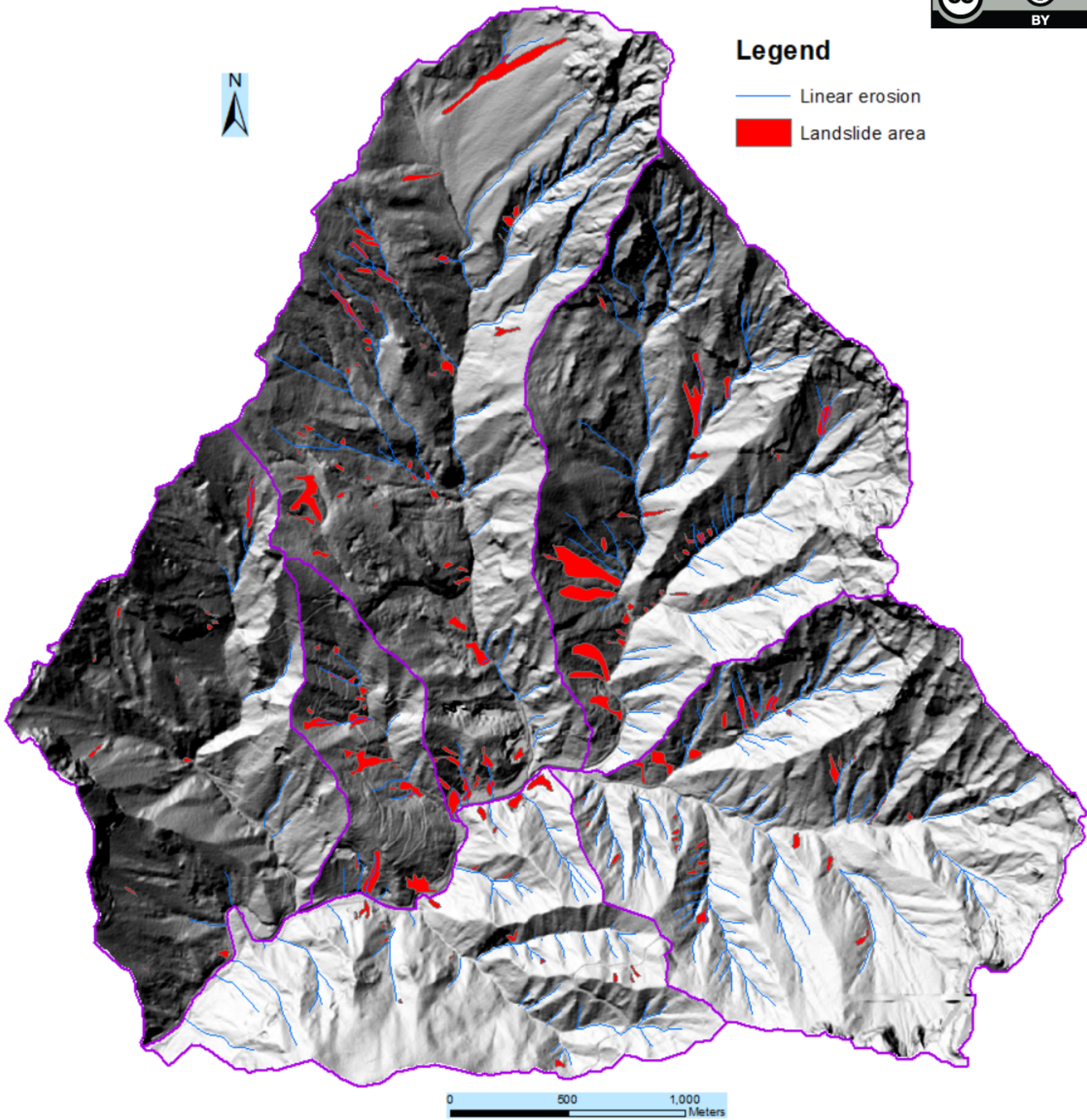
$Q_s = 2.5 \cdot Q_l \cdot S^{1.6}$	(1)
$Q_d = 0.0188 \cdot V^{0.79}$	(2)
Where: Q_s: solid discharge (m^3/s), Q_l: liquid discharge (m^3/s), S : average channel slope; Q_d : debris flow discharge (m^3/s), V: total solid volume (m^3).	

Results

The solid volume mobilized from slopes and hydrographic network

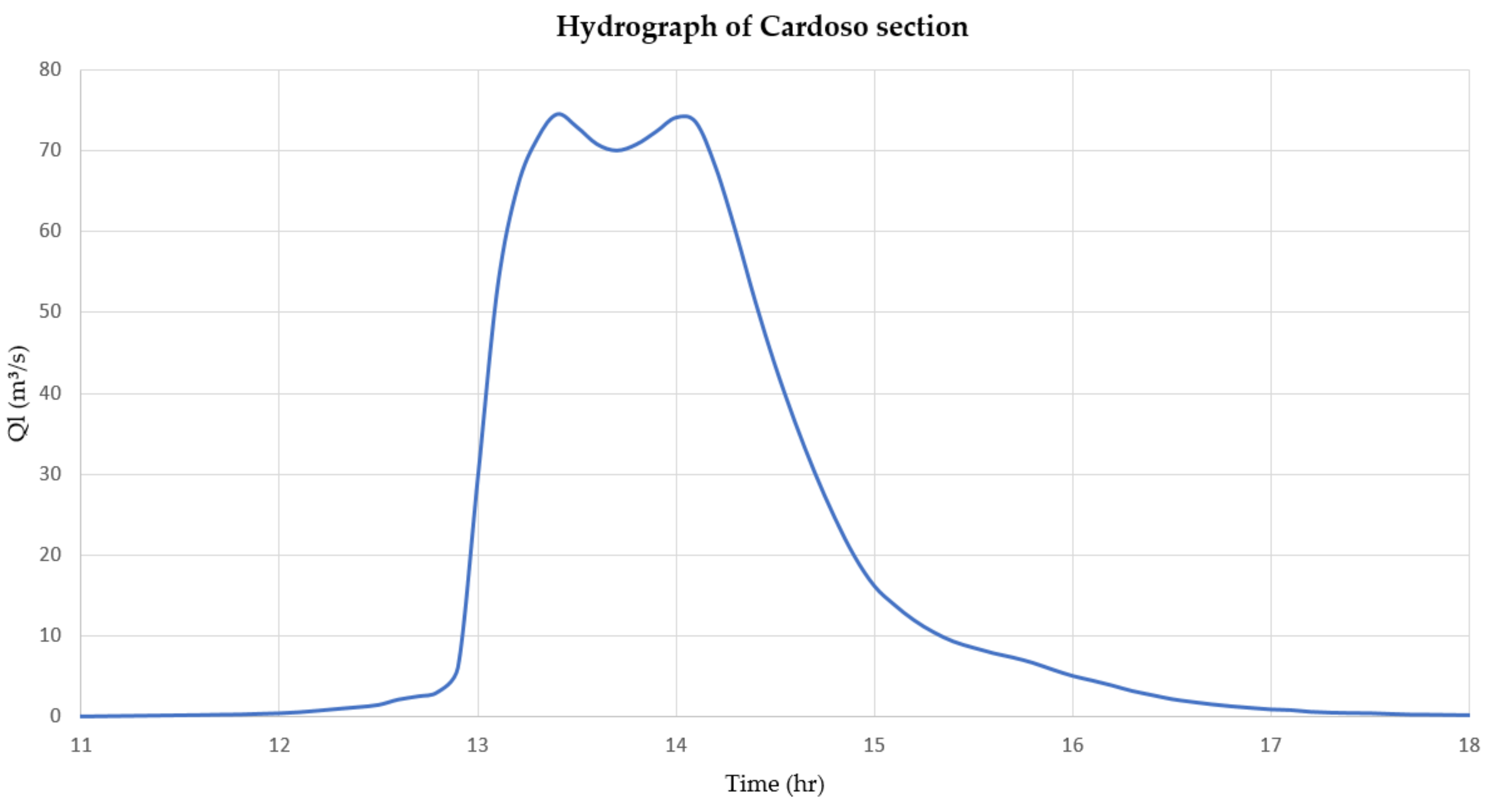
Type of erosive processes	N°	Involved area (m²)
Landslides	173	265.000
Linear erosion (channels and gullies)	250	450.000

Sub-basin	Volume mobilized (m³)
Greppovecchi	105.000
Pasquina	60.000
Oreto	29.000
Capriola	241.000
Deglio	228.000
Versilia	222.000
Total	885.000



Results

Rainfall back analysis



- **About 30% of the rainfall contributes to the runoff**, while the rest of it was intercepted, as a consequence of soil and land use features, correspondent to a general soil thickness greater than 0.5 m, covered by a dense forest.
- The hydrograph of Cardoso section shown **two peaks between 1:30-2 p.m.**, when the village was destroyed by severe debris flows.

Results

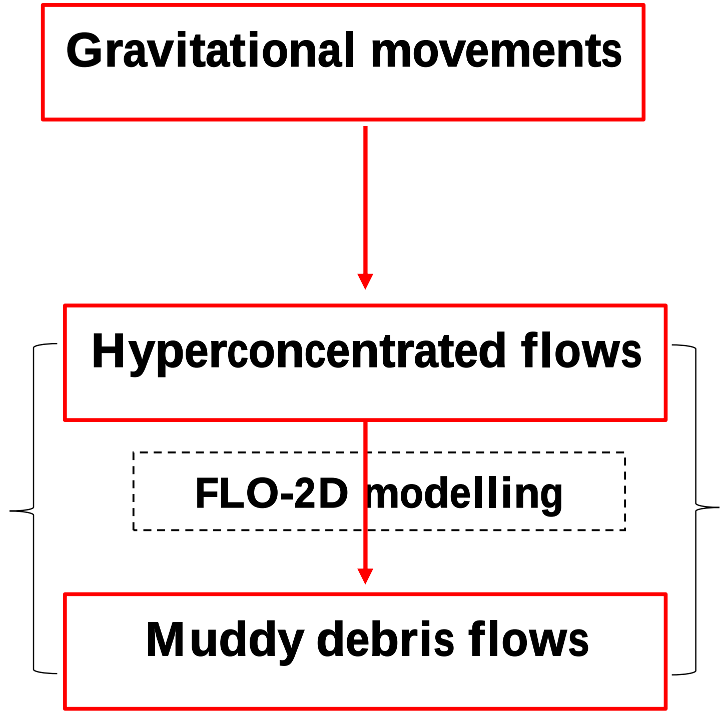
Debris flows run-out back analysis

For the debris flows modelling, numerous tests have been carried out with different combinations of rheological schemes, debris-graphs, K and TOL.
The best set of rheological parameters and mass movement features are shown below.

Rheological parameters				
	μ_N (Pa·s) [1]	τy (Pa) [1]	K (-)	TOL (m)
	$\alpha_1 = 1.75$; $\beta_1 = 7.82$	$\alpha_2 = 0.0405$; $\beta_2 = 8.29$	20000	0.03

Flows features		
Channel	**Cv max**	**Type of transport**
Deglio	0.25	Hyperconcentrated flow[2]
Oreto	0.29	Hyperconcentrated flow[2]
Pasquina	0.29	Hyperconcentrated flow[2]
Capriola	0.64	Muddy debris flow[3]
Greppovecchi	0.64	Muddy debris flow[3]
Versilia	0.64	Muddy debris flow[3]

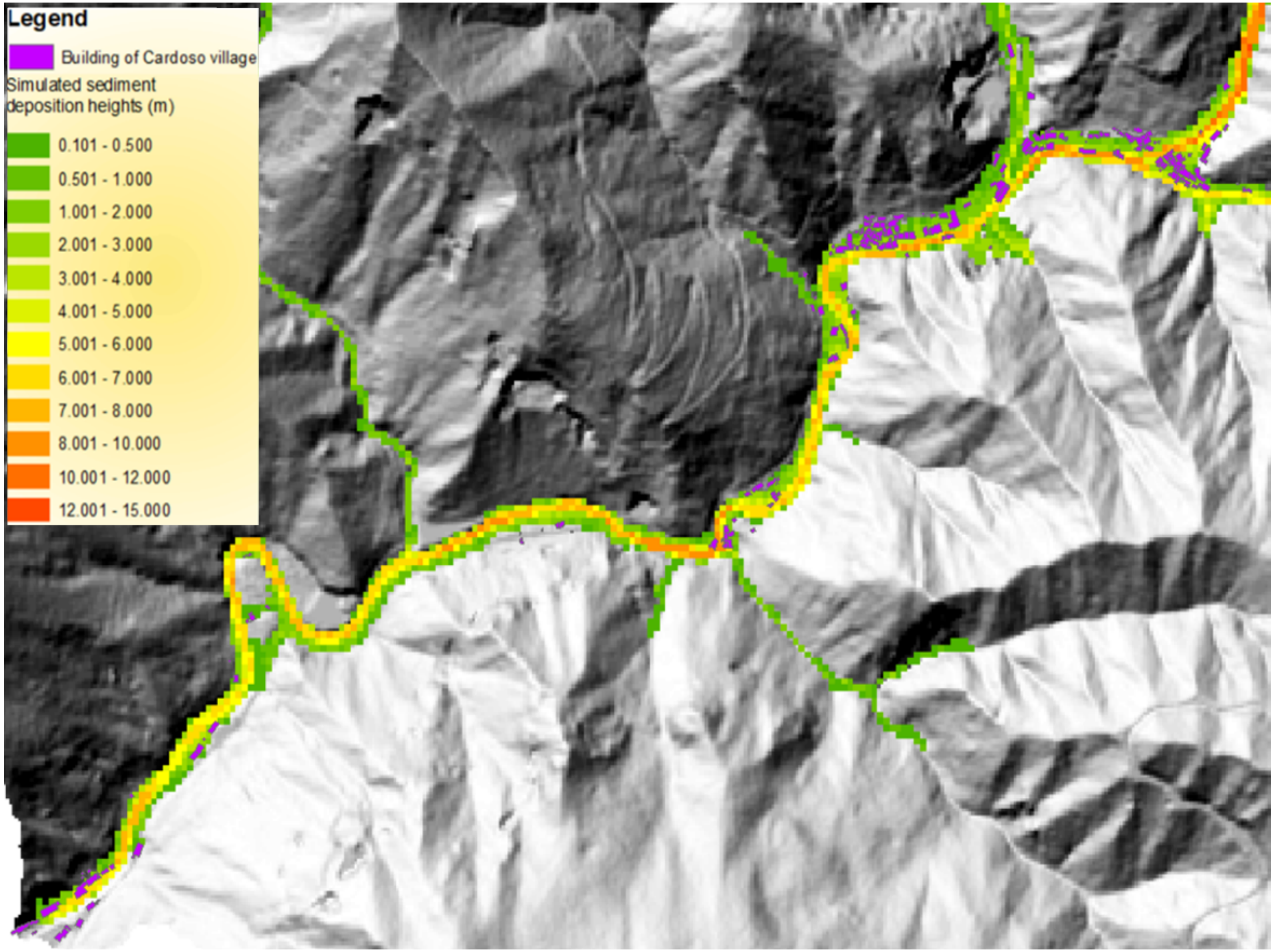
[1] Kang and Zhang (1980) [12]
[2] Smart and Jaeggy (1983) equation [9]
[3] Mizuyama et al. (1992) [10]



Results

Debris flows run-out back analysis

- **Solid volume mobilized:**
- **885.000 m³**
- **Solid volume deposited** along Cardoso valley: **550.000 m³**
- **Solid volume deposited** along **hydrographic network** and on the **slopes**: **335.000 m³**.
- **Max height** of sediments deposited along Cardoso valley was about **12 m**.



Discussions

The solid volume mobilized from slopes and hydrographic network

	D'Amato Avanzi et al. (2004) [1]	FLO-2D modelling
Solid volume mobilized (m^3)	1.495.000	885.000

Comparison between literature data: different methods was used for the assessment of the slope deposits thickness. Analysing the post-event aerial orthophoto and the result of modelled sediment deposition (about 550.000 m^3) along Cardoso valley, 1.5M of mobilized solid material seems to be overestimated.

Rainfall back analysis

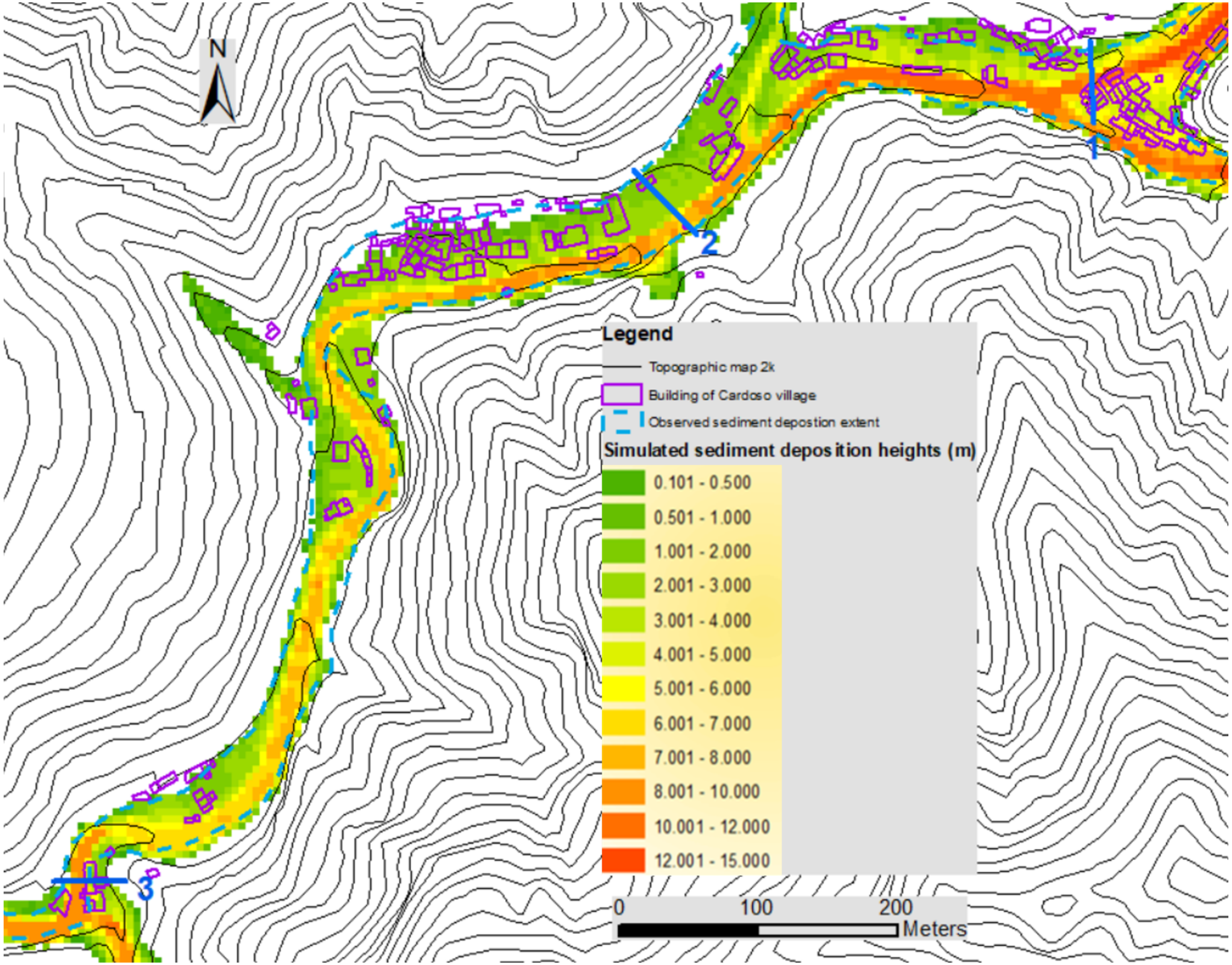
Section	Ql peak (m^3/s), Burlando and Rosso (1998) [13]	Ql peak (m^3/s), FLO-2D modelling
Pontestazzemese	201	183
Cardoso	95	75
Deglio	76	68

Comparison between literature data: the modelled results are in agreement with Burlando and Rosso (1998). Their result was calibrated with the variation of the water volume registered during the event at the Trombacco dam, located 8 km NE of Cardoso village.

Discussions

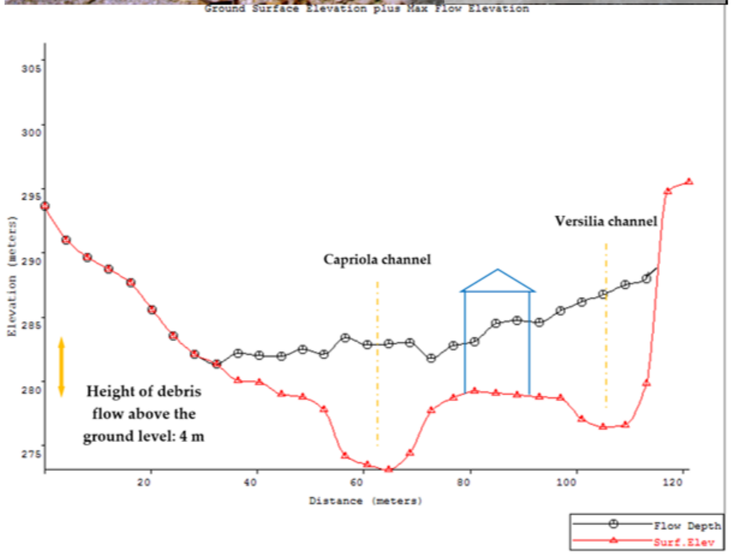
Debris flows run-out back analysis

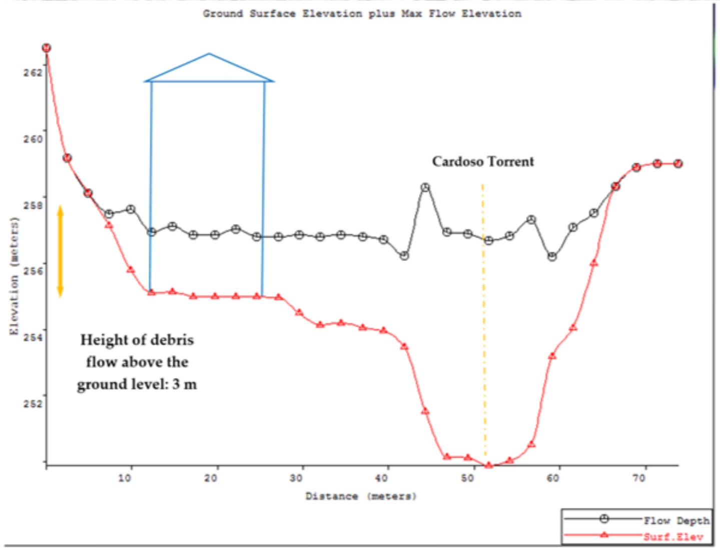
Validation of modelling results: comparison between observed and simulated overflooded area and max height of debris flows along the Cardoso valley.

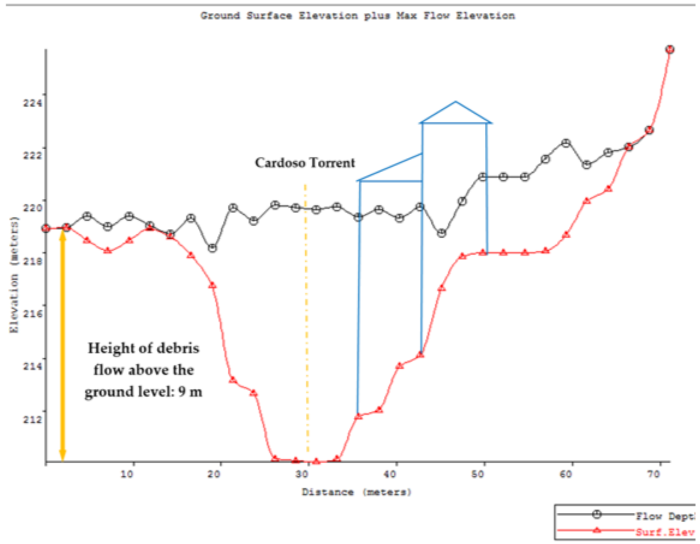


Discussions

Debris flows run-out back analysis







Conclusions

- The **mobilized solid volume** from landslides and torrential erosion was about **885.000 m³**; much of this material represented the source of hypercontrated flows and debris flows.
- **The Cardoso valley was overflowed by 550.000 m³ debris material**, with a **max height of 12 m**, as a consequence of the peak rainfall occurred between 12-1 p.m.
- The best combination of both rheologic parameters and transport type correspond to **hyperconcentrated flows evolved in muddy debris flows**, probably caused by **dam-breaks**.
- The good agreement between obtained results, literature and analysis of archive photos and post-event aerial orthophotos, indicates how it is possible to obtain realistic estimates using these methods; although in case of more available data about debris material, rigorous equations could be used for the assessment of solid discharge.
- **Next steps**: comparison between different methods for the assessment of liquid discharge (e.g. the Green Ampt analysis) and different numerical models to simulate triggering and run-out of debris flows.

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