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An integrated model for prediction of shallow landslides at regional scale with the integration of satellite hydrological data

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1. THE PROBLEM

- **Rainfall-induced shalllow landslides**: triggered by short-period but very intense rainfall events

- Triggering linked with the hydrological and mechanical response of a usually unsaturated soil to rainfall events

- **Causing widespread damages to the terrain, infrastructure, as well as urban and rural developments**

- High density of phenomena in little catchments

- **Increase in their occurrence related to the increase of extreme rainfall events due to climate change**

2. BACKGROUND

Rainfall thresholds for the assessment of shallow landslides occurrence

Empirical-statistical rainfall thresholds

+ Rainfall features representative of the triggering conditions
+ Easily to be implemented at regional scale
- Soil features and geomophological predisposing factors are not considered
- Uncertainties related to the quality and the amount of the rainfall data

Physically-based rainfall thresholds

+ Quantitative analysis of the rainfall triggering conditions leading to the triggering
+ Consideration of the soil hydrological and geotechnical parameters and of the geomorphological attributes
+ Analysis of change in time of stable/unstable areas
- Significant amount of input data, difficult to be implemented at large scale
- Uncertainties on the boundary conditions of the model

3. OBJECTIVES

Comparison of rainfall thresholds for the occurrence of shallow landslides at large scale (catchement, regional), realized by means of empirical-statistical and physically-based approaches

The work was realized in the frame of ANDROMEDA project, funded by Fondazione Cariplo and realized by University of Pavia and CNR-IRPI Perugia, which aims to develop a prototypal early-warning system for the assessment of shallow landslides and flood occurrence in Oltrepò Pavese area

*A **N**ew integrate**D** hyd**RO**geological **M**odel to ass**E**ss landsli**D**es and flood prone **A**reas in Oltrepò Pavese*

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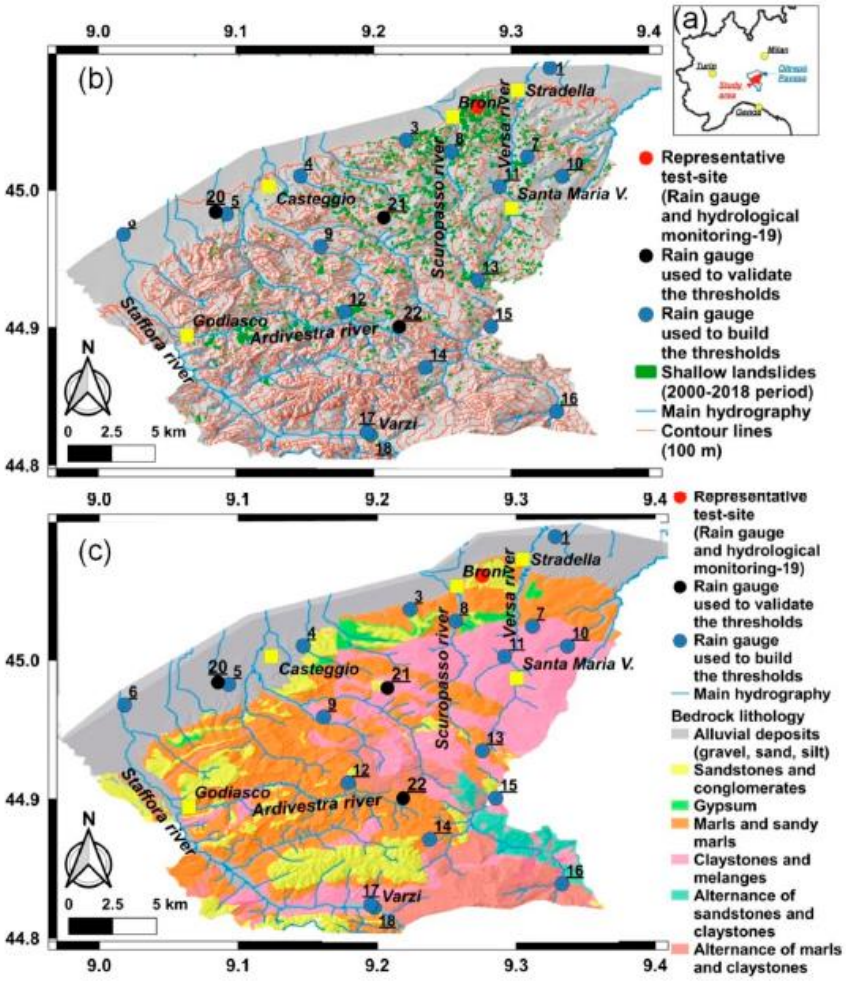
4. STUDY AREA

Oltrepò Pavese area (720 km^2)

- Representative of northern Italian Apennines
- Different geomorphological settings: steep slopes (>15-20°) and narrow valleys with marly, areanaceous, conglomeratic bedrocks - medium steep slopes (10-15°) and large valleys with marly, clayey and chaotic bedrocks
- Soil heterogeneity: clayey-sandy silts/silty sands with thickness around 1 m - silty clays with thickness > 1-1.5 m
- High susceptibility towards shallow landslides (density till > 50 landslides per km^2)
- Three catchments representative of the typical geological and geomorphological settings: **Ardivestra (medium steep slopes, clayey and chaotic bedrocks) Scuropasso-Versa (very steep slopes, marly, areanaceous, conglomeratic bedrocks)**



Bordoni et al., 2019

4. STUDY AREA

Rain gauge network and shallow landslides inventory

Rain gauge network

- 21 stations (ARPA Lombardia, ARPAE Emilia Romagna, COPROVI)
- Rainfall data since 2000
- Hourly resolution

Shallow landslides inventory

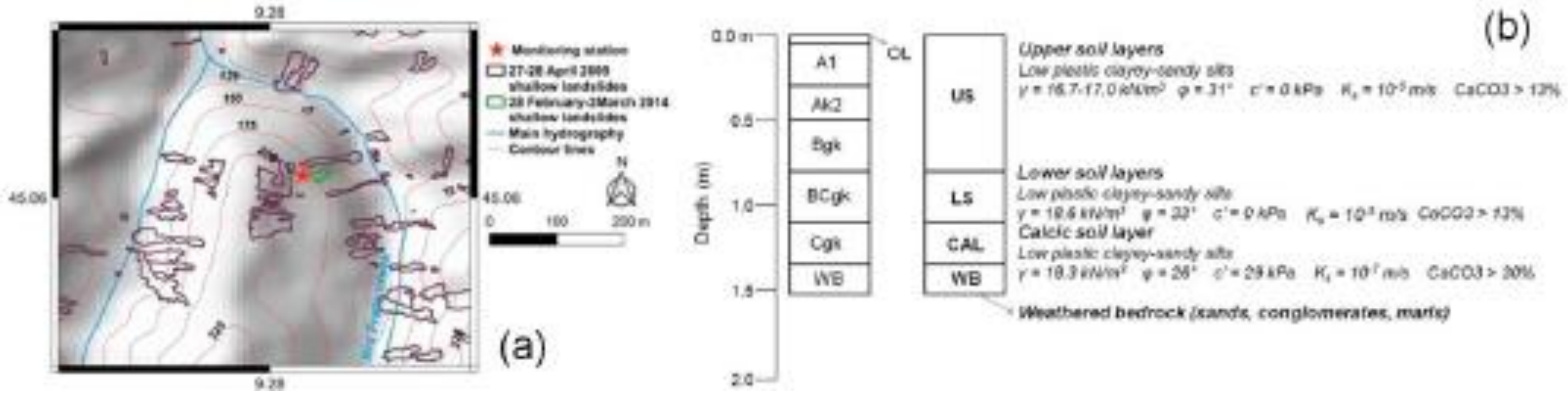
- 143 triggering events since 2000
- Location of the phenomena: Google Earth, high resolution aerial images (April 2009 event), Pleiades images (2013 events), local and national newspapers, report of municipalities and province

4. STUDY AREA

Hydrological monitoring station

Montuè test-site slope

1) **Past shallow landslides** (27-28 April 2009, 28 February-2 March 2014)
2) **Geological setting**: sands and poorly cemented conglomerates overlying marls
3) Soils: silty clay with a thickness of about 1,3 m
4) **Geomorphological features**: steep slopes (26-30°), narrow valley. Elevation: 185 m a.s.l.

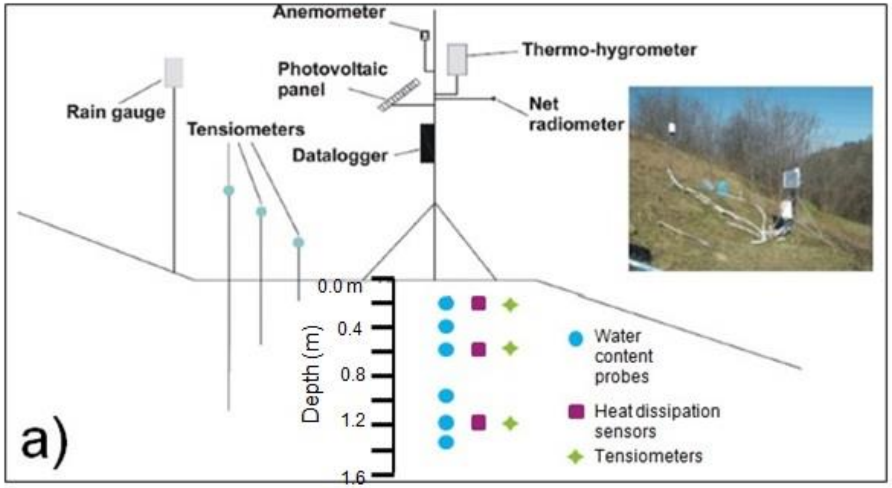


Bordoni et al., 2019

4. STUDY AREA

Hydrological monitoring station

Montuè test-site slope



Device	Model	Range of measure	Accuracy
Heat Dissipation sensors	Model HD229 - Campbell Scientific	-10000 / -10 kPa	1.5 – 2 kPa
Tensiometers	Model Jet-Fill 2725 - Soilmoisture Equipment Corporation	-80 / 10 kPa	1.5 – 2 kPa
TDR probes	Model CS610 - Campbell Scientific	0.05 / 1.0 $m^3 \cdot m^{-3}$	0.01 – 0.02 $m^3 \cdot m^{-3}$

- **Soil devices installed in** a trench pit
- **Data collection since 27/03/2012**
- Temporal resolution: **10 minutes**
- **Datalogger (CR1000X, Campbell Scientific, Inc.) powered by a photovoltaic panel (20 W)**

5. METHODS

Empirical-statistical rainfall thresholds

INPUT

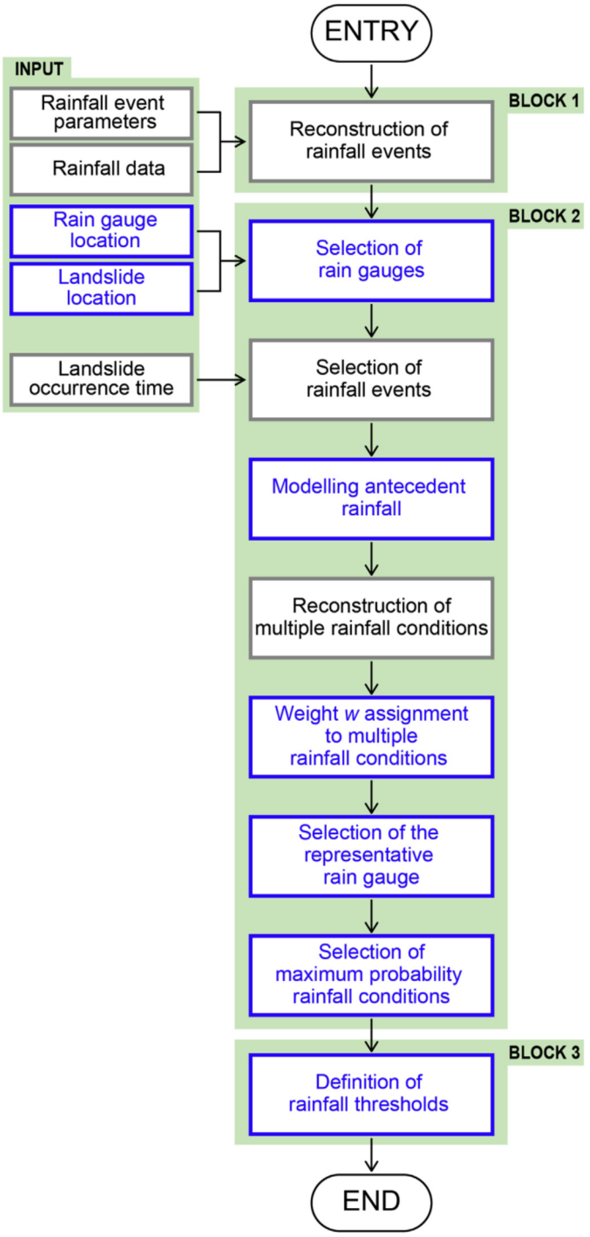
- RAINFALL DATA
- LOCATION OF RAIN GAUGES
- LANDSLIDES INVENTORY

METHOD

CTRL-T ALGORITHM (Melillo et al., 2015, 2018)

OUTPUT

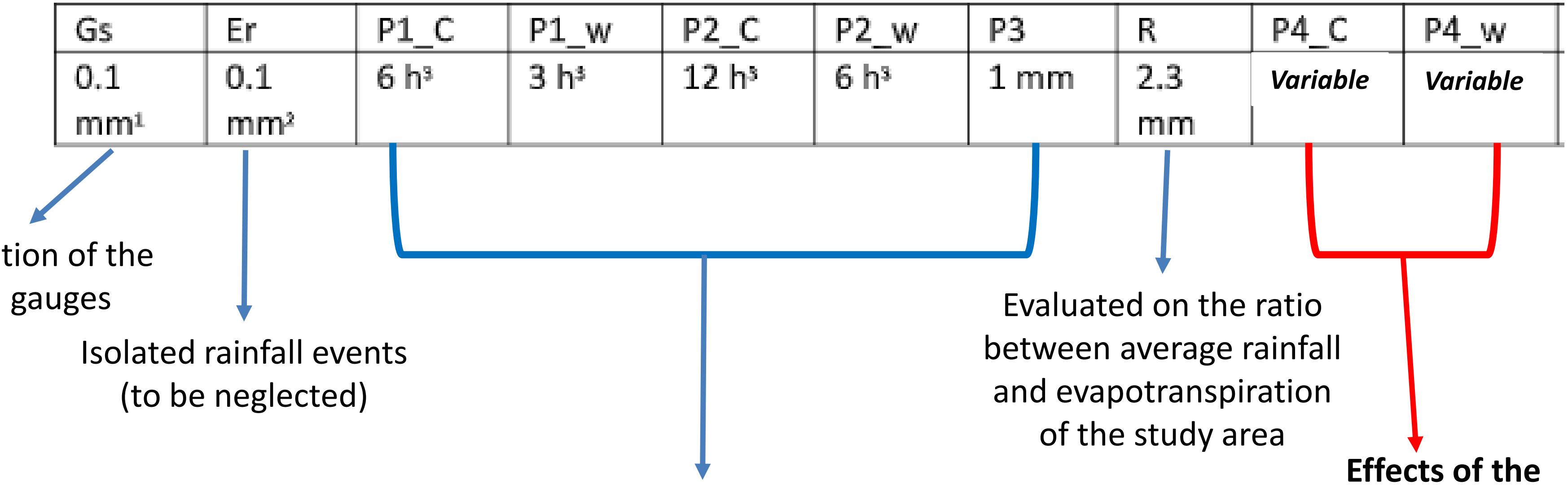
- RAINFALL EVENTS
- RAINFALL TRIGGERING CONDITIONS
- RAINFALL THRESHOLDS



(Melillo et al., 2015, 2018)

5. METHODS

Empirical-statistical rainfall thresholds



Gs	Er	P1_C	P1_w	P2_C	P2_w	P3	R	P4_C	P4_w
0.1 mm[1]	0.1 mm[2]	6 h[3]	3 h[3]	12 h[3]	6 h[3]	1 mm	2.3 mm	***Variable***	***Variable***

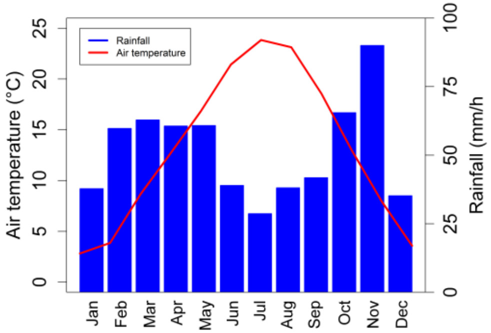
Resolution of the rain gauges

Isolated rainfall events (to be neglected)

Typical of Italian climate (Melillo et al., 2015)

Evaluated on the ratio between average rainfall and evapotranspiration of the study area

Effects of the length of the dry periods between two events on rainfall thresholds



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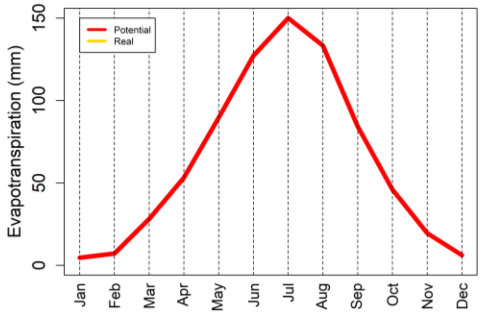

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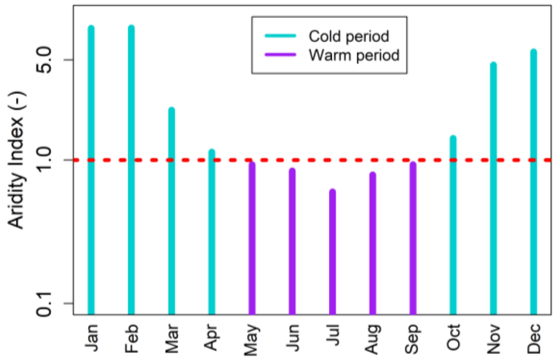
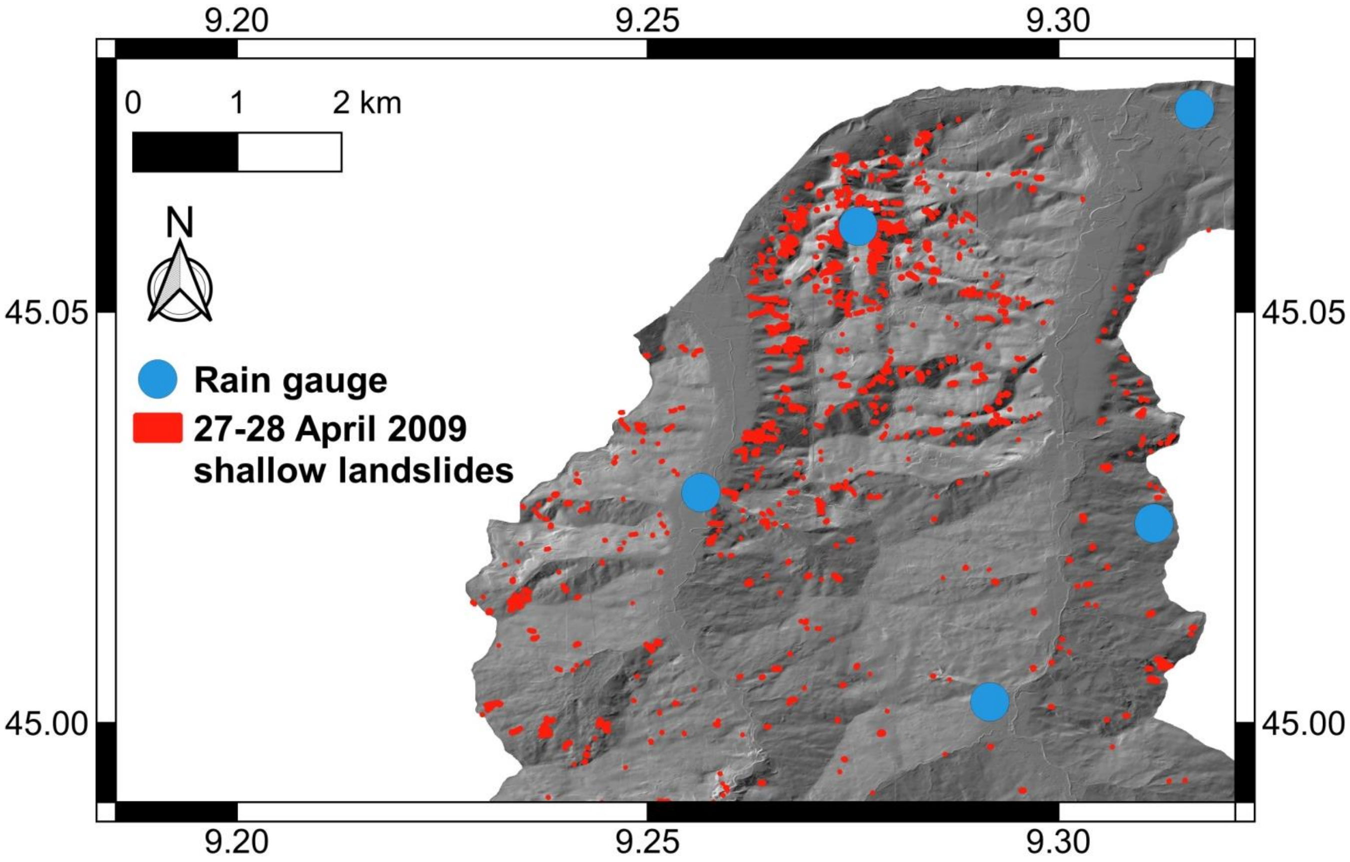


5. METHODS

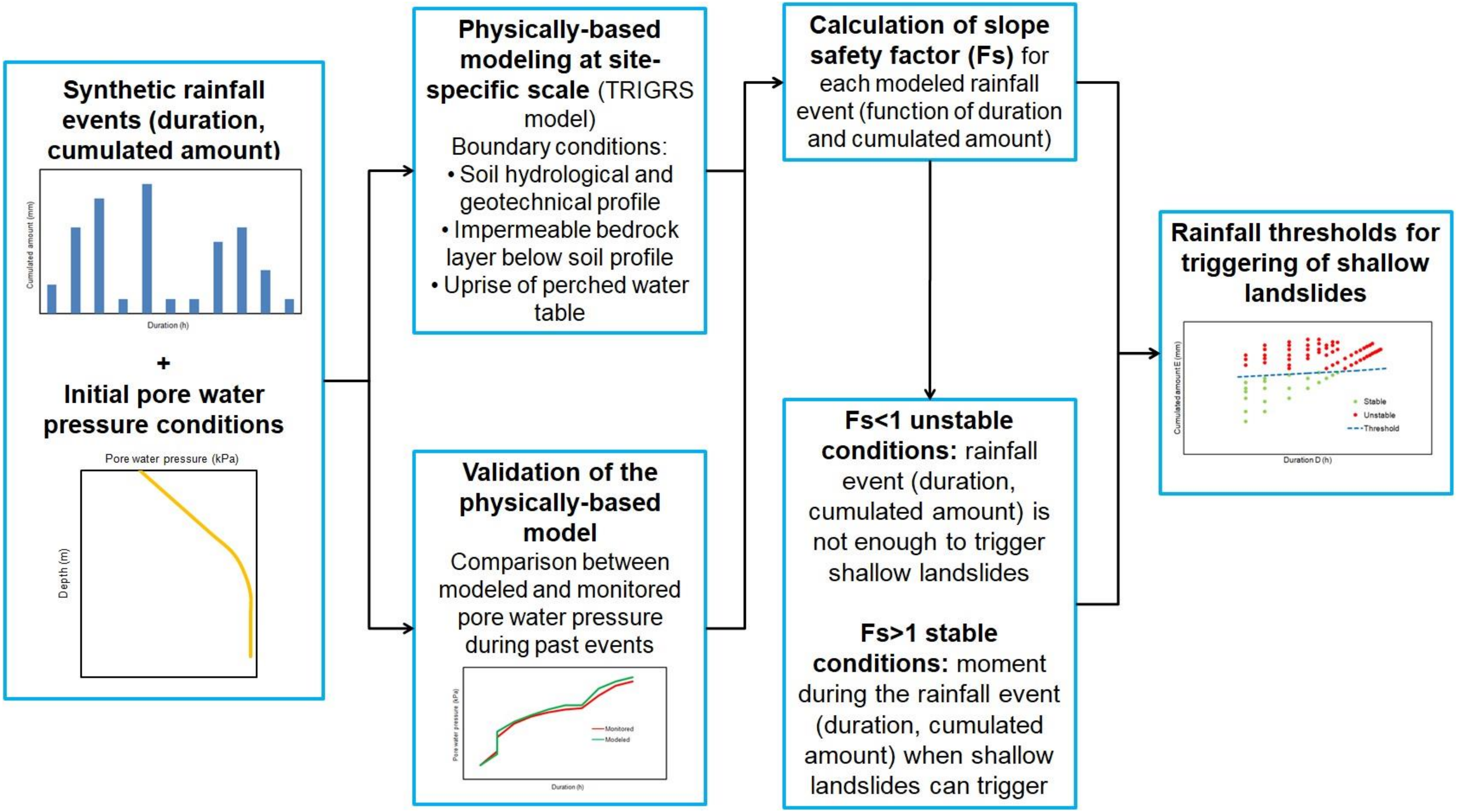
Empirical-statistical rainfall thresholds

Rainfall attributes measured by a particular rain gauge are representative of a triggering event if a **shallow landslide occurred in that day in a radius of less than 10 km from the rain gauge**



5. METHODS

Physically-based rainfall thresholds



Synthetic rainfall events (duration, cumulated amount)

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Initial pore water pressure conditions

Physically-based modeling at site-specific scale (TRIGRS model)
Boundary conditions:
- Soil hydrological and geotechnical profile
- Impermeable bedrock layer below soil profile
- Uprise of perched water table

Validation of the physically-based model
Comparison between modeled and monitored pore water pressure during past events

Calculation of slope safety factor (Fs) for each modeled rainfall event (function of duration and cumulated amount)

Fs<1 unstable conditions: rainfall event (duration, cumulated amount) is not enough to trigger shallow landslides

Fs>1 stable conditions: moment during the rainfall event (duration, cumulated amount) when shallow landslides can trigger

Rainfall thresholds for triggering of shallow landslides

5. METHODS

Physically-based rainfall thresholds

Test-site: Montuè monitored slope

Representative of the study area:

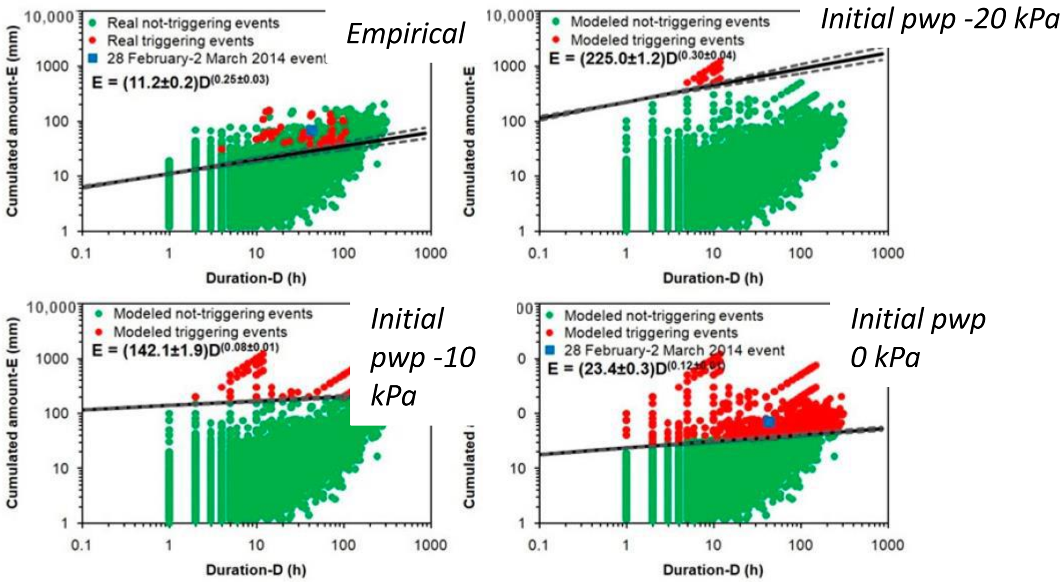
- Past shallow landslides (27-28 April 2009, 28 February-2 March 2014)
- Susceptible geomorphological (steep slopes) and geological (silty-clayey soils) setting towards shallow landslides
- Detailed soil profile: shallow landslides sliding surface, geotechnical and hydrological properties
- Monitoring of pore water pressure: validation of the physically-based model

Parameter	Value	Unit
ϑ_s	0.42	m^3/m^3
ϑ_r	0.03	m^3/m^3
ω	0.006	kPa^{-1}
K_s	$1.5 \cdot 10^{-6}$	m/s
φ'	33	°
c'	0	kPa
γ	18.3	kN/m^3
z	1	m
β	30	°

Parameters used in the model for reconstructing physically-based thresholds: θ_s) saturated water content; θ_r) residual water content; ω) fitting parameter of soil water characteristic curve; K_s) saturated hydraulic conductivity; ϕ') soil friction angle; c') soil effective cohesion; γ) soil unit weight; z) soil depth; β) slope angle.

6. RESULTS

Reconstruction (2007-2018)



Empirical

Initial pwp -20 kPa

Initial pwp -10 kPa

Initial pwp 0 kPa

Validation (1992-1996)

Threshold	TP (%)	TN (%)	FP (%)	FN (%)
Empirical thresholds	95 ± 2	76 ± 3	24 ± 3	5 ± 2
Physicallybased thresholds (−20 kPa) (TRIGRS/−20)	-	100 ± 0	0 ± 0	-
Physicallybased thresholds (−10 kPa) (TRIGRS/−10)	-	100 ± 0	0 ± 0	-
Physicallybased thresholds (0 kPa) (TRIGRS/0)	100 ± 0	93 ± 1	7 ± 1	0 ± 0

- **Significant differences on the rainfall cumulated amount for the same duration**
- **Significant effects of the initial pore water pressure**
- **Low values of triggering rainfall for empirical-statistical thresholds**
- **Better estimation of rainfall triggering conditions since thresholds reconstructed through physically-based methods**
- **Significant amount of input data, difficult to be implemented at large scale**

7. CONCLUSIONS AND FUTURE DEVELOPMENTS

- Significant differences on the thresholds obtained through different methodologies
- Several false positives for threshold created through empirical-statistical approach
- Evident effects of initial pore water pressure on physically-based thresholds
- For the same duration of an event, low values of triggering rainfall for empirical-statistical thresholds

Future developments

☐ **Physically-based thresholds for other contexts (e.g. slopes with clayey soils)**

☐ **Integration with rainfall data measured by satellites**

8. REFERENCES

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THANKS FOR THE ATTENTION

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