Models for the spatio-temporal assessment of shallow landslides hazard with the integration of satellite soil moisture and rainfall data in Oltrepò Pavese (northern Italy)

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1. THE PROBLEM

- **Rainfall-induced shallow 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 (Gariano and Guzzetti, 2016; Ciabatta et al., 2017; Haque et al., 2019)**

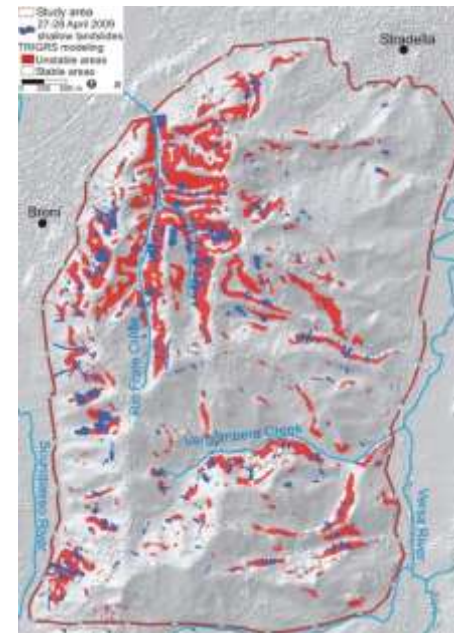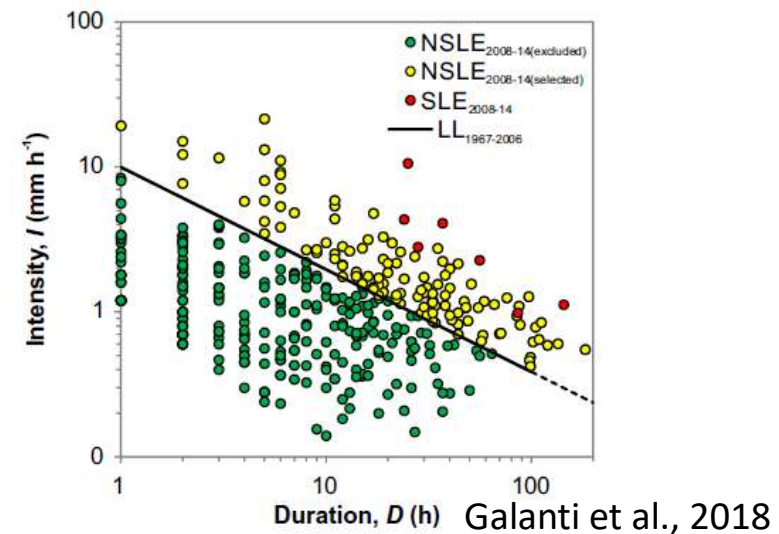27th-28th April 2009 event in Oltrepò Pavese (1639 shallow landslides in about 250 km^2)

2. BACKGROUND

Methodologies for the assessment of spatial and temporal probability of occurrence or hazard of shallow landslides

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

Galanti et al., 2018

Physically-based methods

+ 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

Bordoni et al., 2015

2. BACKGROUND

Methodologies for the assessment of spatial and temporal probability of occurrence or hazard of shallow landslides

Knowledge-driven or data-driven methods
+ Consideration of the soil and geomorphological features leading to shallow landslides triggering
+ Easily to be implemented at regional scale
+ Modeling of different triggering events, characterized by peculiar inventories
- Dynamic triggering factors (rainfall, soil hydrological features) are generally not taken into account (susceptibility)
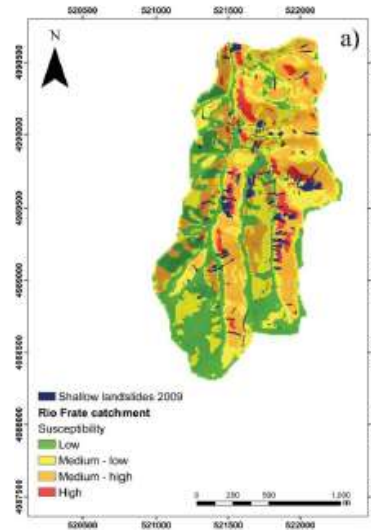
Persichillo et al., 2017

It is necessary to develop an **innovative methodology** which integrates all the advantages of the previous methods and fills their gaps

• **Considering both soil and geomorphological predisposing factors and dynamic triggering factors** (rainfall, soil hydrological features)
• **Dynamic analysis of change in time of stable/unstable areas**
• **Easily to be implemented at large scale** (catchment, regional)
• **Able to model different typologies of triggering events for the same area**

3. OBJECTIVES

Development and test of a dynamic data-driven method for the assessment of spatial and temporal probability of occurrence and hazard of rainfall-induced shallow landslides at large scale (catchement, regional), with the integration of satellite measures of rainfall and soil moisture
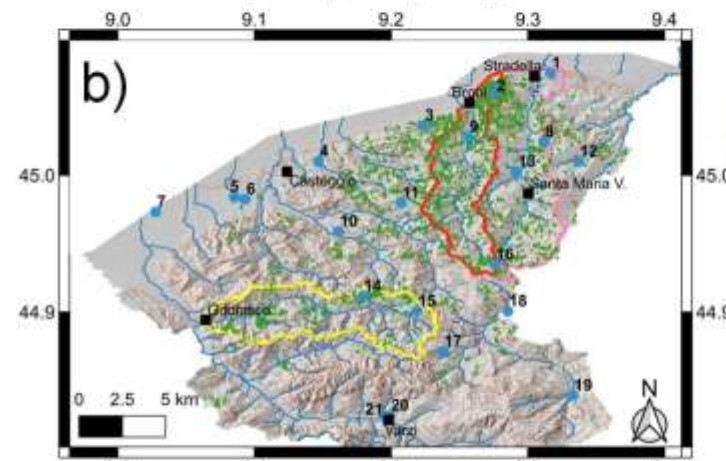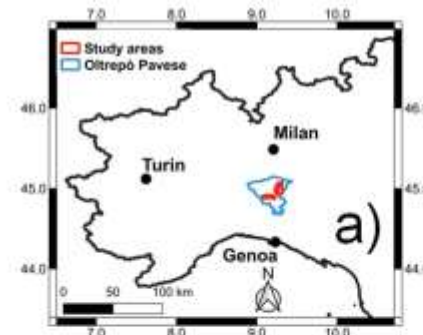
The work was realized in the frame of ANDROMEDA project, funded by Fondazione Cariplo and realized by University of Pavia and CNR-IRPI Perugia, which aims to develop a prototypal early-warning system for the assessment of shallow landslides and flood occurrence in Oltrepò Pavese area

4. STUDY AREAS

Oltrepò Pavese area (720 km²)

• 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 km²)

• 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)**
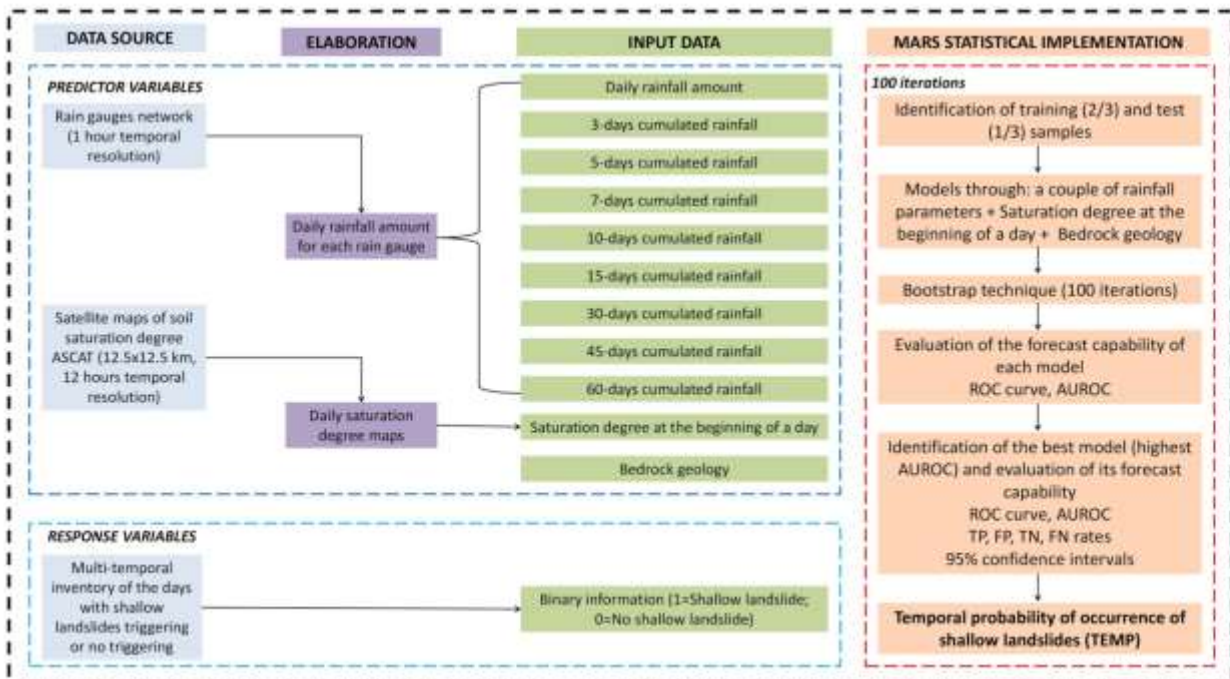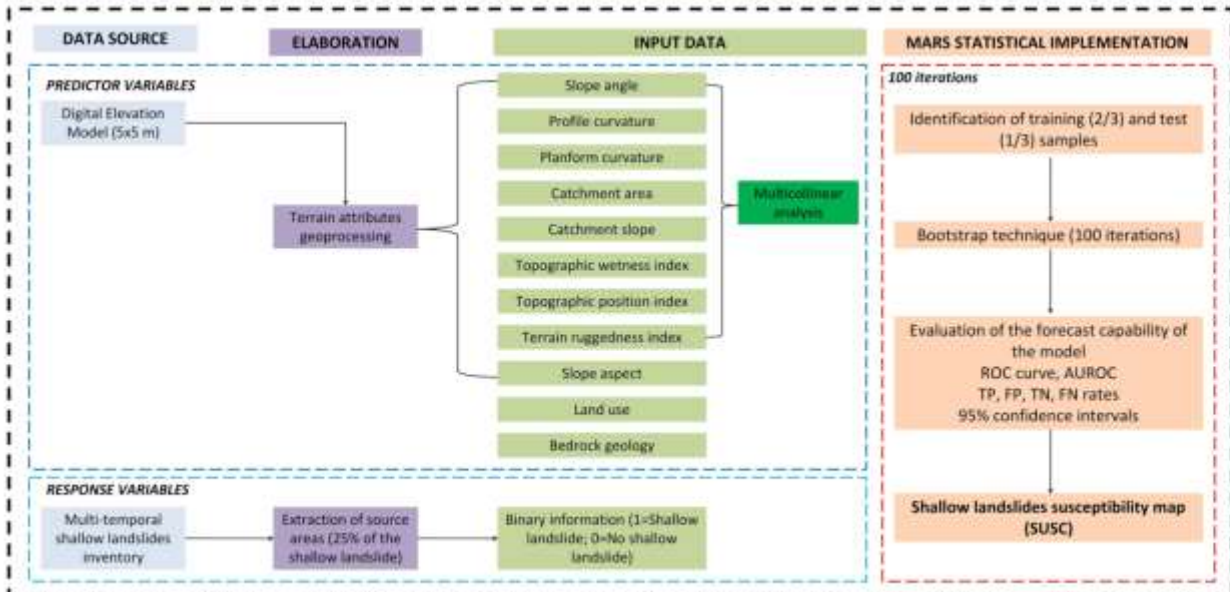
5. METHODS

5. METHODS

Model of temporal probability of occurrence of shallow landslides TEMP

DATA SOURCE	ELABORATION	INPUT DATA	GAM STATISTICAL IMPLEMENTATION

PREDICTOR VARIABLES

Rain gauges network (10 minutes, 1 hour temporal resolution)

Daily rainfall amount for each rain gauge

- Daily rainfall amount
- 3-days cumulated rainfall
- 5-days cumulated rainfall
- 7-days cumulated rainfall
- 10-days cumulated rainfall
- 15-days cumulated rainfall
- 30-days cumulated rainfall
- 45-days cumulated rainfall
- 60-days cumulated rainfall

Satellite maps of soil saturation degree ASCAT (12.5x12.5 km, 12 hours temporal resolution) Sentinel-1 (1x1 km, 2-3 days temporal resolution)

Daily saturation degree maps

- Saturation degree at the beginning of a day
- 3-days average saturation degree
- 5-days average saturation degree
- 7-days average saturation degree
- 10-days average saturation degree
- 15-days average saturation degree
- Soil lithotechnical units

RESPONSE VARIABLES

Multi-temporal inventory of the days with shallow landslides triggering or no triggering

Binary information (1=Shallow landslide; 0=No shallow landslide)

GAM STATISTICAL IMPLEMENTATION

100 iterations

Identification of training (2/3) and test (1/3) samples

Identification of the most significant parameters (>80 selected on the models of the training samples)

Bootstrap technique (100 iterations)

Evaluation of the forecast capability of the model
95% confidence intervals
ROC curve, AUROC
TP, FP, TN, FN rates
Efficiency (Ef)
Hanssen and Kuipers skill score (HK)

Temporal probability of occurrence of shallow landslides (TEMP)

5. METHODS

For a certain day, 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**
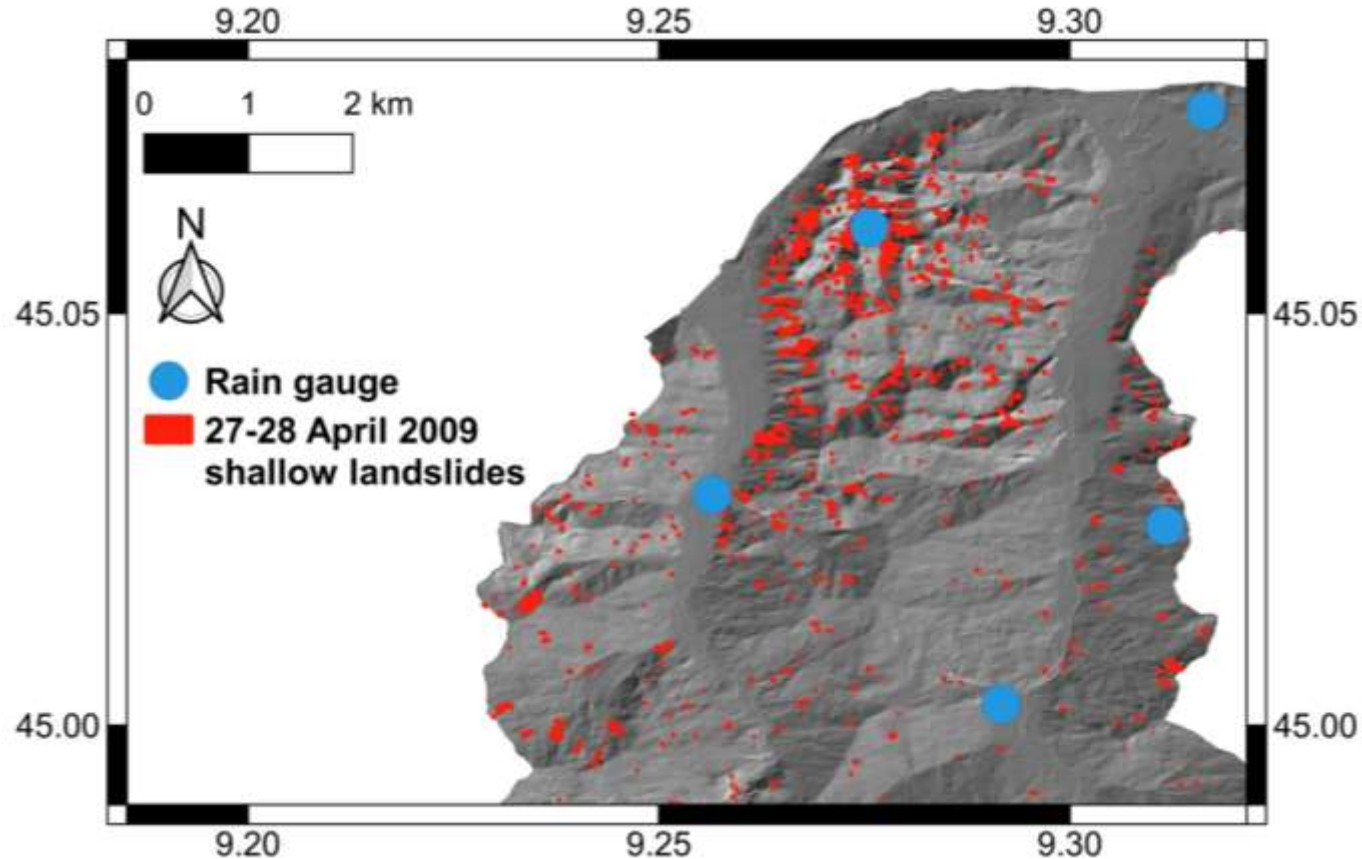
5. METHODS

Available data

For SUSC:

• Digital Elevation Model 5x5 m, land use map, bedrock geological map, soil lithotechnical map, inventory of deep landslides
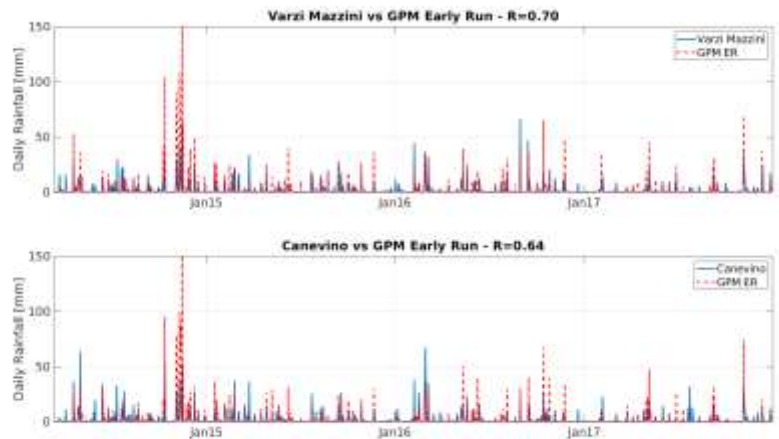• Multi-temporal inventory of shallow landslides occurred since 2008

For TEMP:

• Rainfall data from rain gauge network, since 2008
• Kriging-interpolated maps of rainfall attributes since data measured in correspondence of the rain gauges of the network
• Satellite maps of soil moisture acquired through ASCAT (since 2008) and Sentinel-1 (since 2015)
• Satellite maps of rainfall acquired through GPM since 2014
• Rainfall derived from satellite maps of soil moisture (SM2RAIN; Brocca et al., 2014) since 2008

6. RESULTS

Comparison between satellite and field measured rainfall and soil moisture

Rainfall
Rain gauge vs GPM: R=0.64-0.70

Soil moisture
Field vs ASCAT: R=0.64-0.71

Rain gauge vs SM2RAIN: R=0.69-0.74
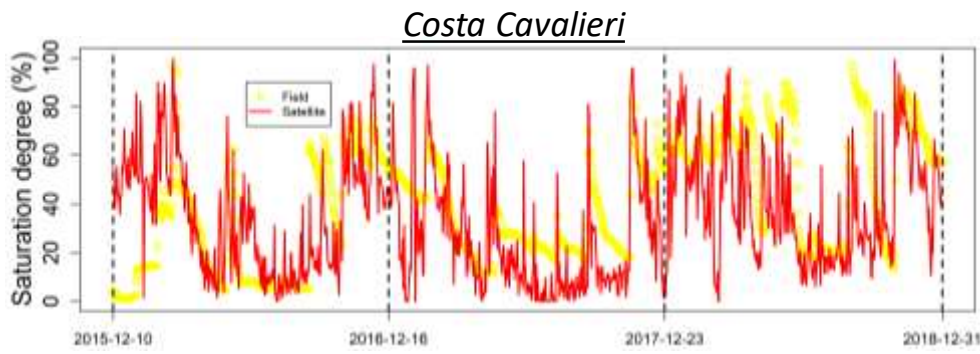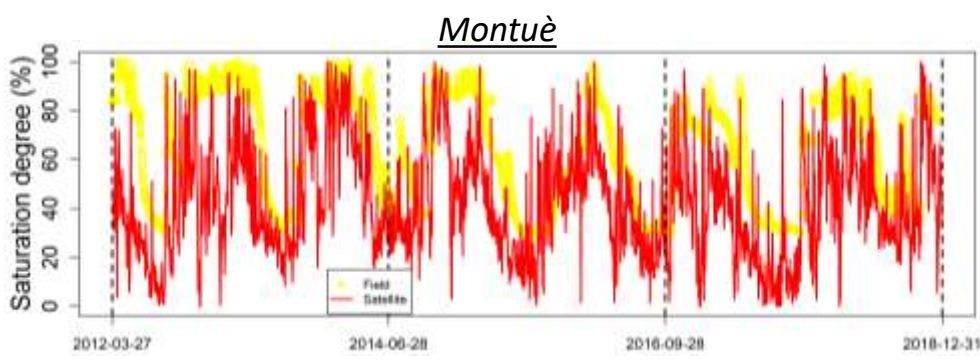
6. RESULTS

Susceptibility maps

Ardivestra
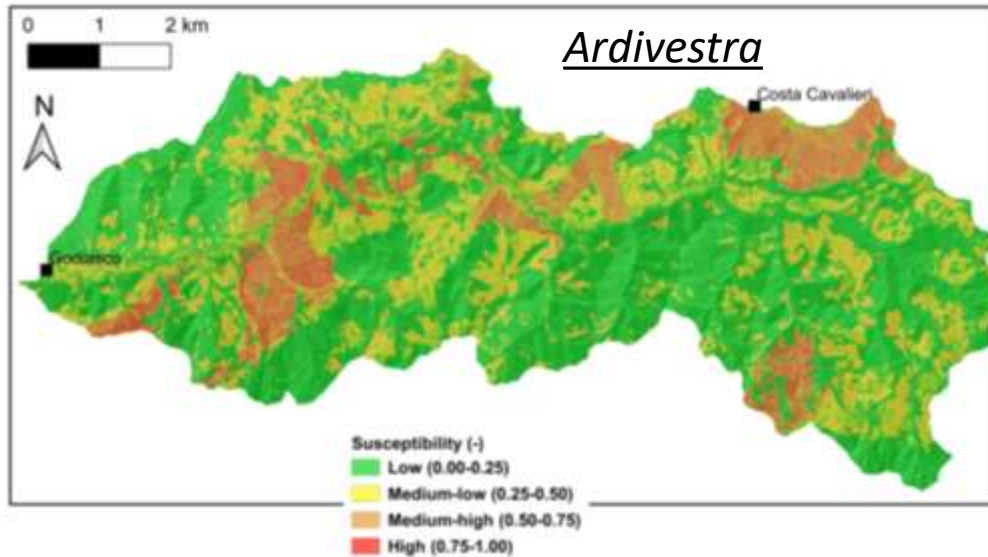
Scuropasso-Versa

Significant parameters: slope angle (non-linear), tpi (non-linear), catchment area, land use, lithotechnical units
AUROC=0.90
TP=85%, TN=75%, FP=25%, FN=15%
Ef=86%, HK=70%
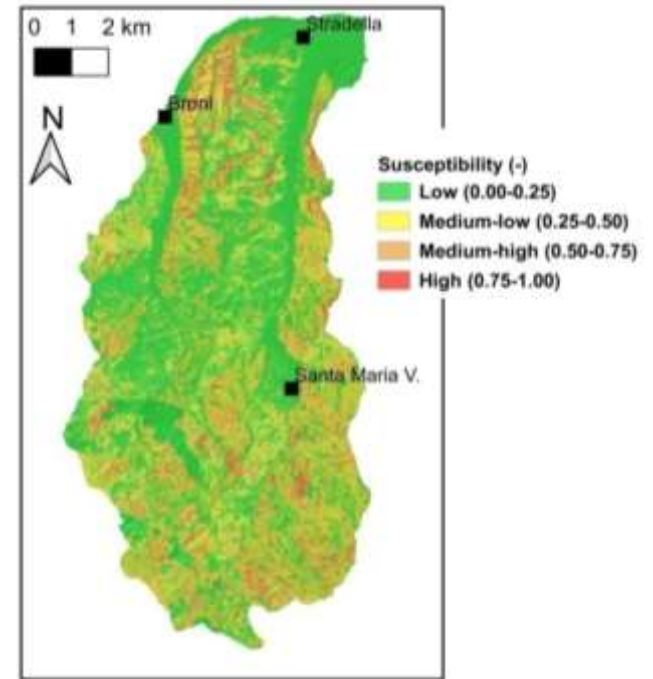
Significant parameters: slope angle (non-linear), tpi (non-linear), twi (non-linear), planform curvature (non-linear), catchment slope (non-linear), slope aspect, land use, lithotechnical units
AUROC=0.89
TP=88%, TN=76%, FP=24%, FN=12%
Ef=82%, HK=76%

6. RESULTS

Temporal probability of occurrence

Significant parameters: 3-days cumulated rainfall, 30-days cumulated rainfall, saturation degree at the beginning of the day
AUROC=0.98
TP=98%, TN=98%, FP=2%, FN=2%
Ef=98%, HK=96%
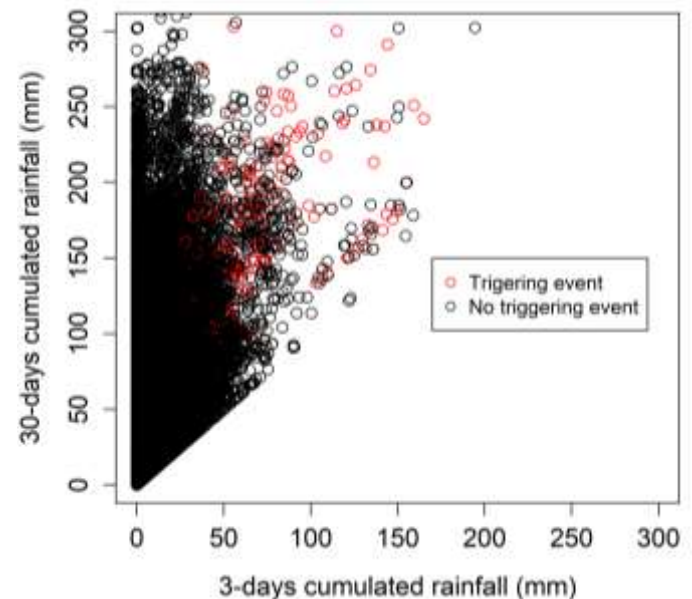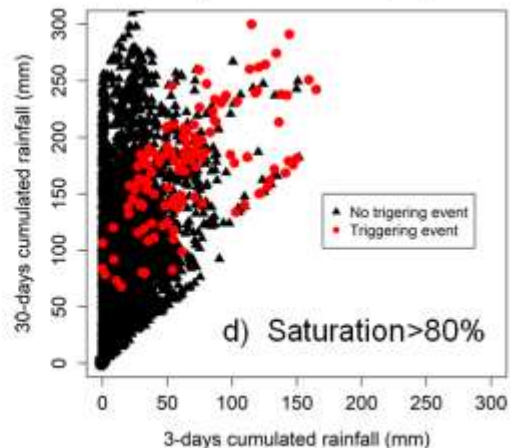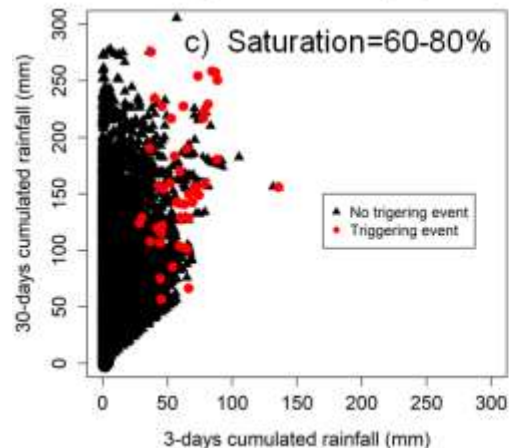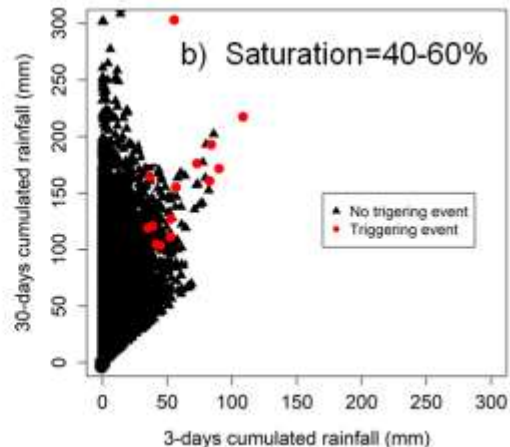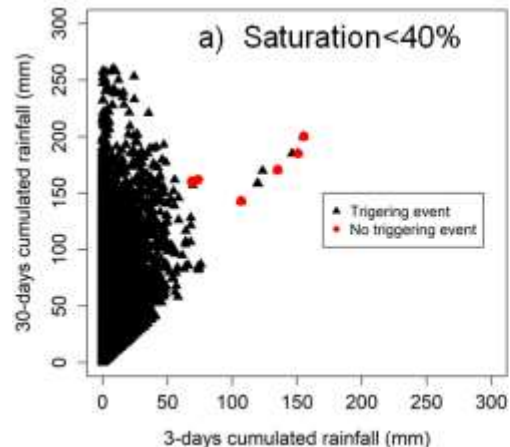
6. RESULTS
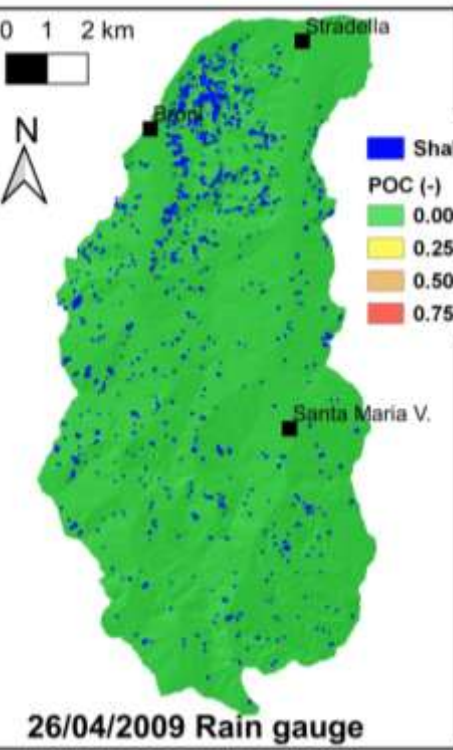
Scuropasso and Versa catchments - 25/04/2009
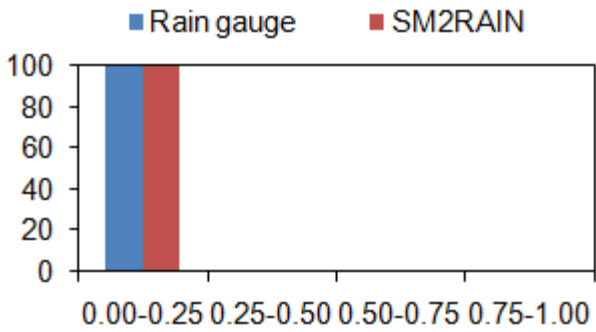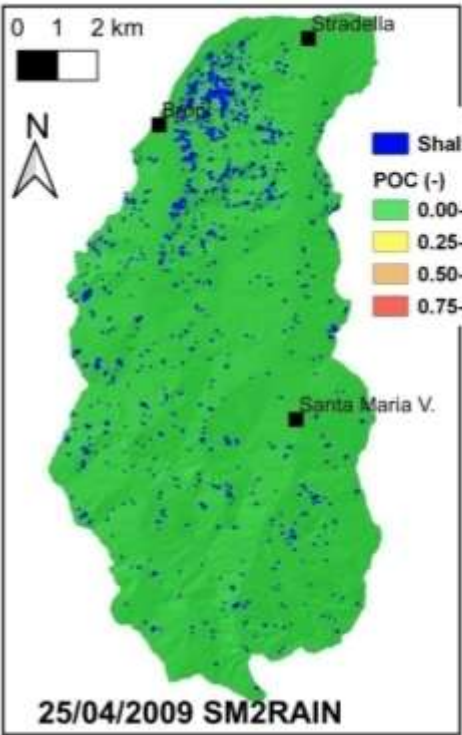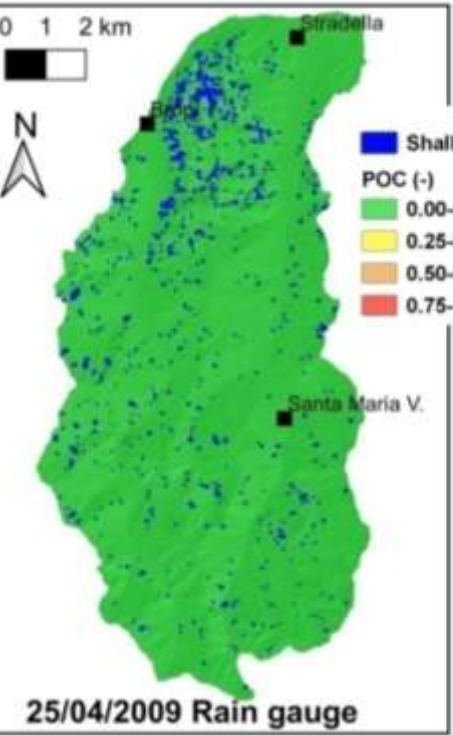
3d-rain=0.4-0.6 mm
30d-rain=141.6-149.8 mm
Sat.=56%

3d-rain=0.0-5.0 mm
30d-rain=141.0-193.0 mm
Sat.=56%

Kappa index=1.00
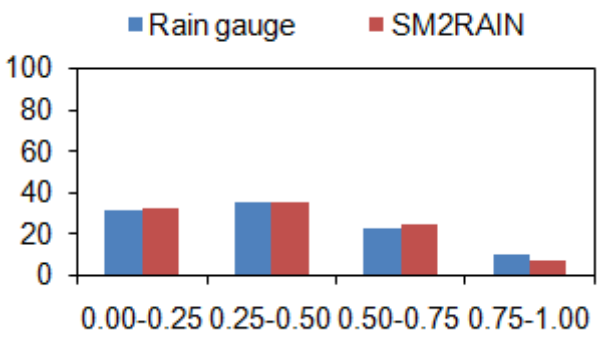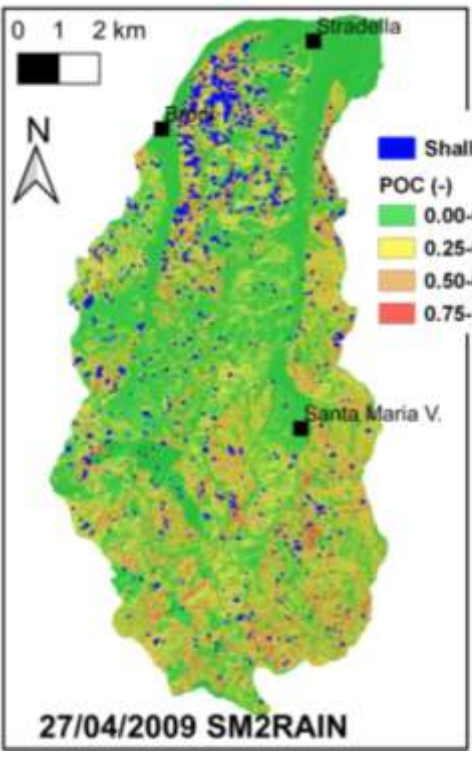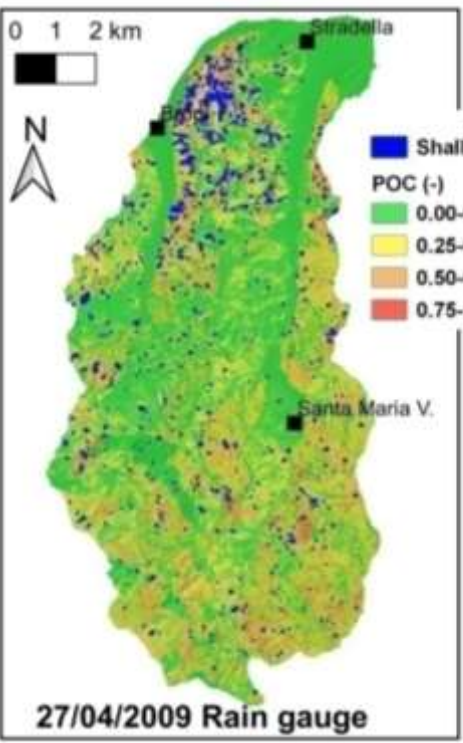
6. RESULTS

Scuropasso and Versa catchments - 26/04/2009
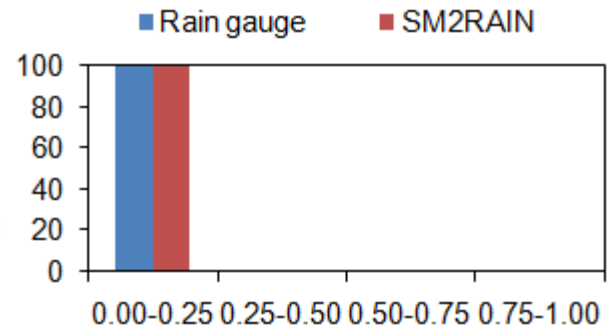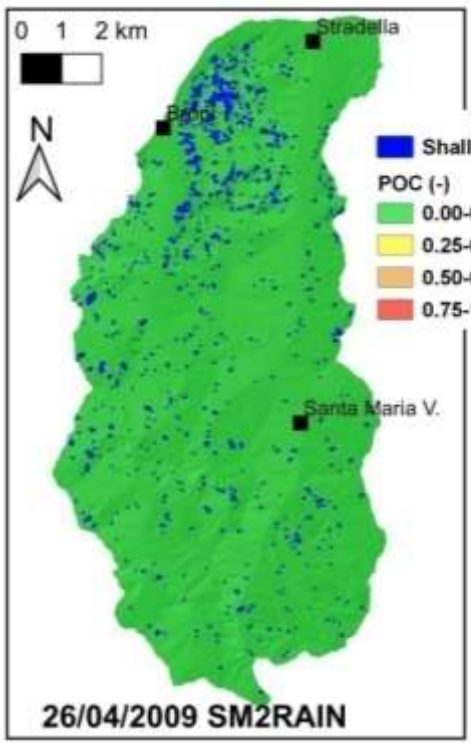
3d-rain=10.8-11.4 mm
30d-rain=152.0-161.2 mm
Sat.=53-54%

3d-rain=15.0-17.5 mm
30d-rain=158.5-203.0 mm
Sat.=53-54%

Kappa index=1.00

6. RESULTS

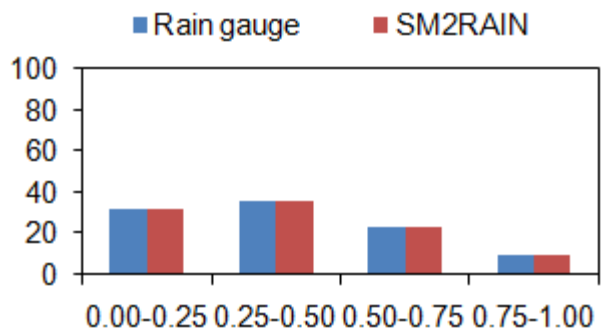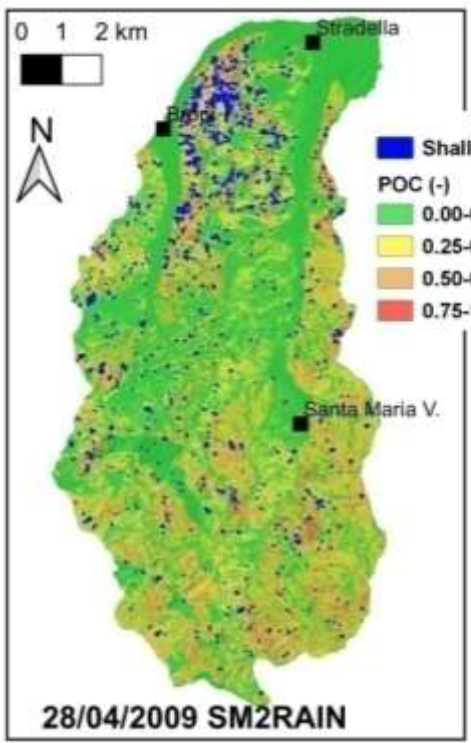## Scuropasso and Versa catchments - 27/04/2009 → Triggering moment

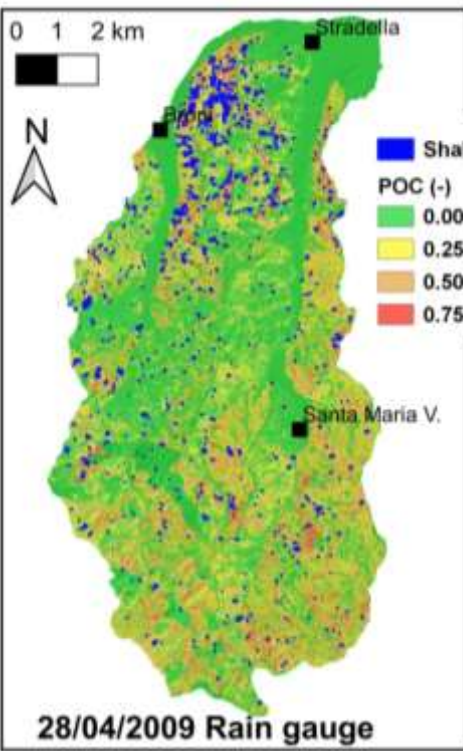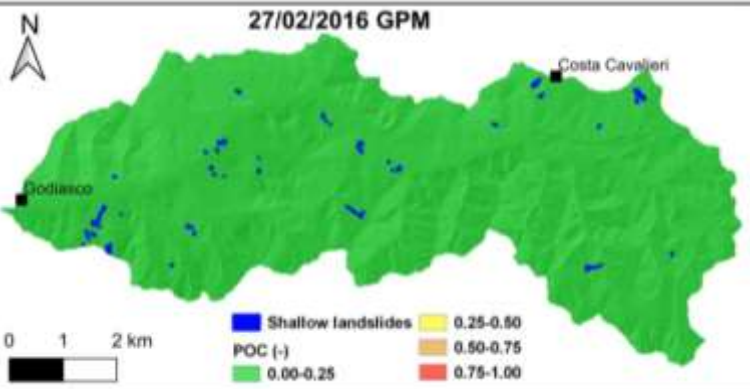27/04/2009 Rain gauge

27/04/2009 SM2RAIN

3d-rain=113.6-125.8 mm
30d-rain=260.2-264.4 mm
Sat.=80%

3d-rain=63.0-75.0 mm
30d-rain=176.5-211.0 mm
Sat.=80%

Kappa index=0.97-0.99

6. RESULTS

Scuropasso and Versa catchments - 28/04/2009 → Triggering moment

28/04/2009 Rain gauge

28/04/2009 SM2RAIN

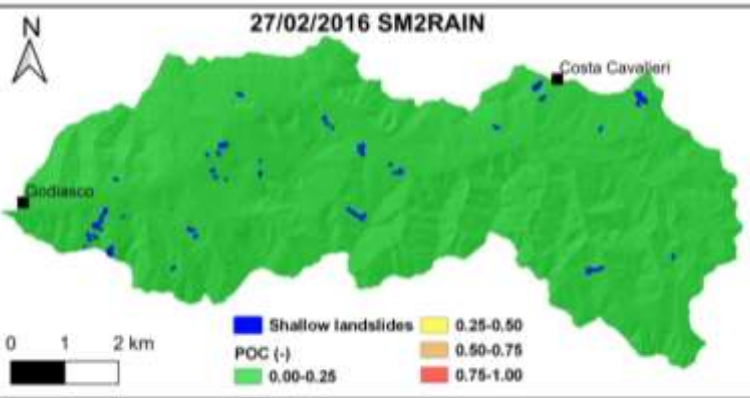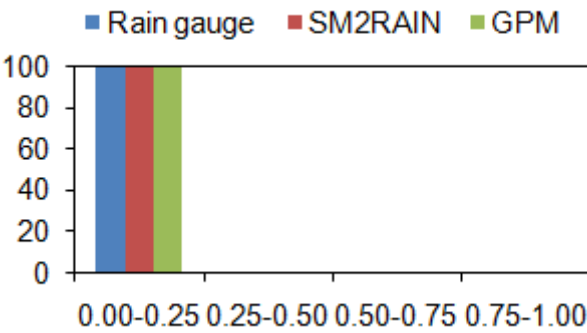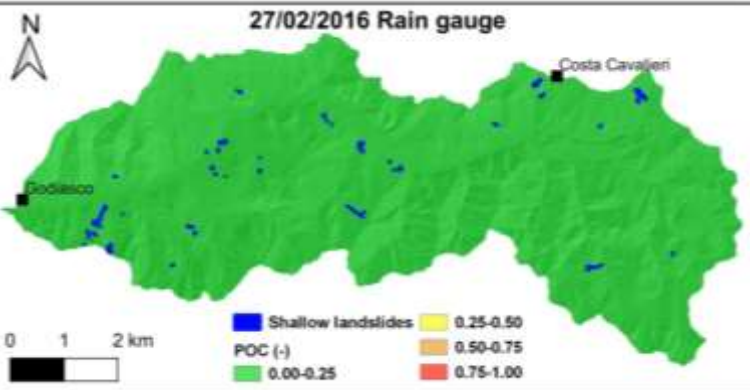|	Rain gauge	SM2RAIN
AUROC	0.88	0.88
TP	91.8	91.8
TN	84.1	84.1
FP	15.9	15.9
FN	8.2	8.2
Ef	85.3	85.3
Hk	75.9	75.9

3d-rain=113.6-125.8 mm
30d-rain=260.2-264.4 mm
Sat.=80%

3d-rain=63.0-75.0 mm
30d-rain=176.5-211.0 mm
Sat.=80%

Kappa index=1.00

6. RESULTS

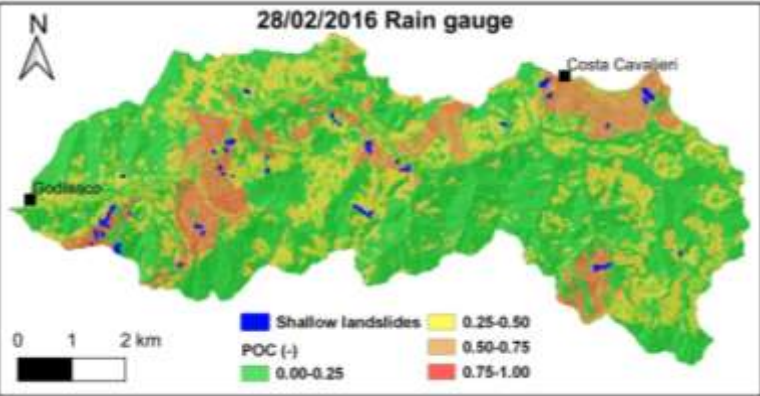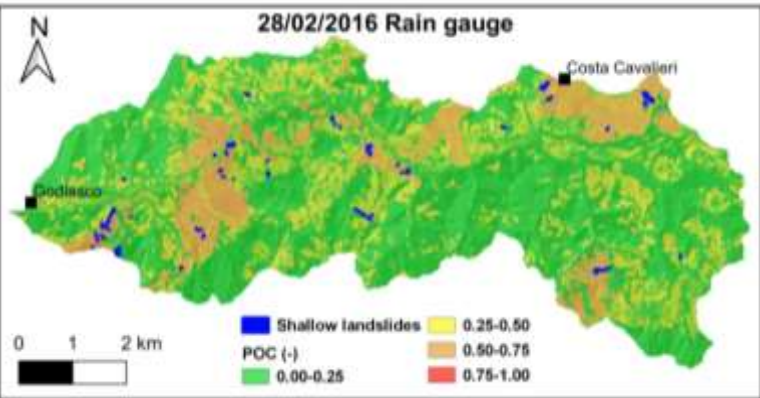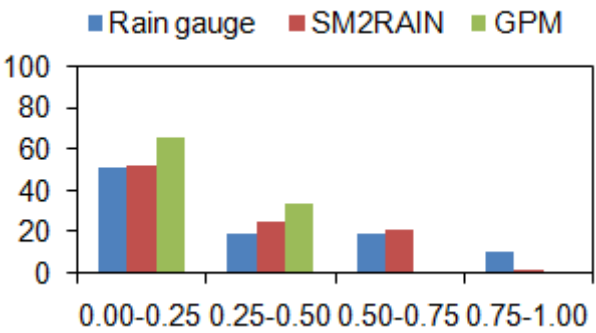## Ardivestra catchment - 27/02/2016

3d-rain=23.2 mm
30d-rain=93.4 mm
Sat.=77%

3d-rain=0.0 mm
30d-rain=42.1 mm
Sat.=77%

3d-rain=1.1 mm
30d-rain=3.5 mm
Sat.=77%

Kappa index=1.00

6. RESULTS
Ardivestra catchment - 28/02/2016 → Triggering moment

28/02/2016 Rain gauge

3d-rain=65.6 mm
30d-rain=135.8 mm
Sat.=95%

Bar chart — Rain gauge, SM2RAIN, GPM across POC classes 0.00-0.25, 0.25-0.50, 0.50-0.75, 0.75-1.00

28/02/2016 Rain gauge

3d-rain=45.2 mm
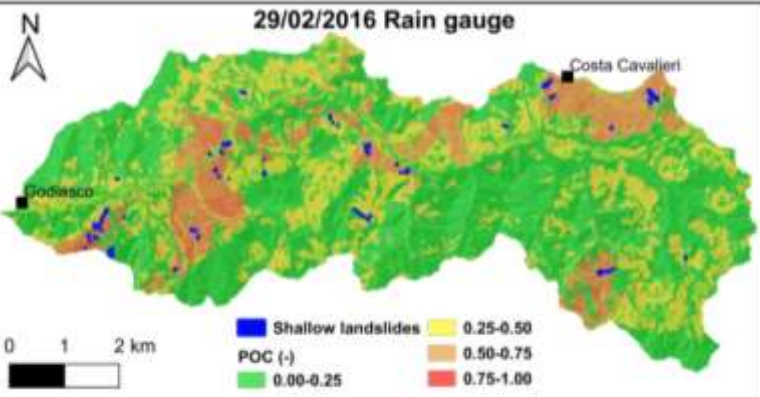30d-rain=82.4 mm
Sat.=95%

28/02/2016 GPM
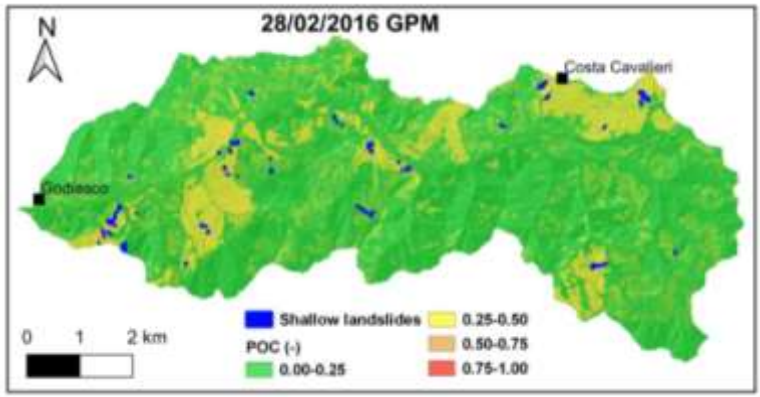
3d-rain=2.1 mm
30d-rain=5.0 mm
Sat.=95%

Kappa index=0.48-0.71

6. RESULTS
Ardivestra catchment - 29/02/2016 → Triggering moment

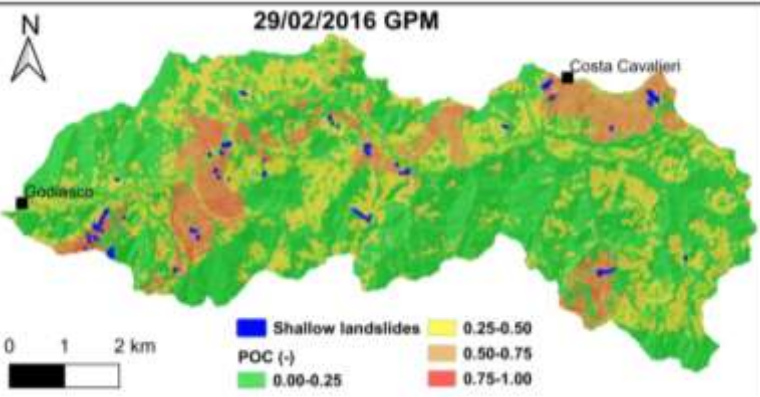29/02/2016 Rain gauge

3d-rain=102.0 mm
30d-rain=177.0 mm
Sat.=99%

29/02/2016 SM2RAIN
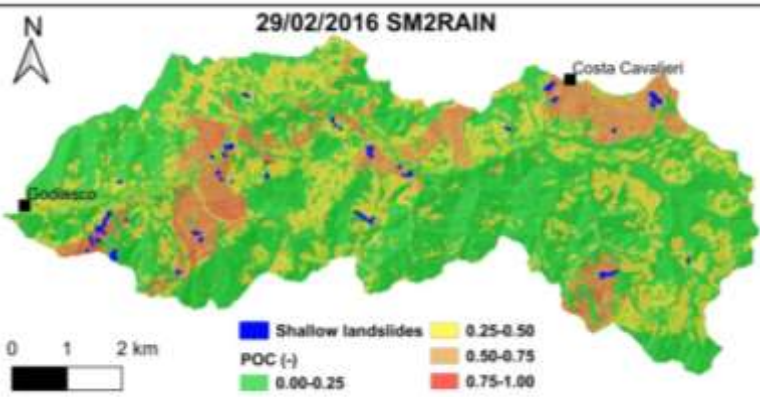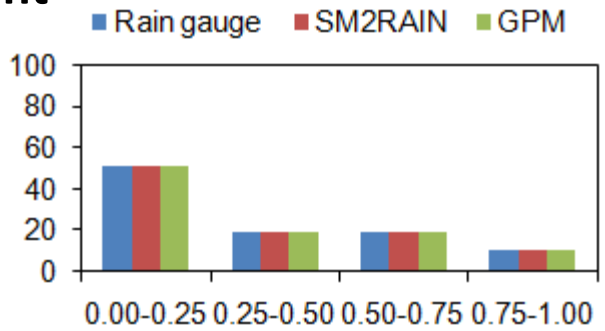
3d-rain=78.2 mm
30d-rain=135.3 mm
Sat.=99%

29/02/2016 GPM

3d-rain=152.1 mm
30d-rain=158.3 mm
Sat.=99%

	Rain gauge	SM2RAIN	GPM
AUROC	0.89	0.89	0.89
TP	94.5	94.5	94.5
TN	83.6	83.6	83.6
FP	16.4	16.4	16.4
FN	5.5	5.5	5.5
Ef	88.6	88.6	88.6
Hk	78.1	78.1	78.1

Kappa index=1.00

6. RESULTS

Ardivestra catchment - 01/03/2016
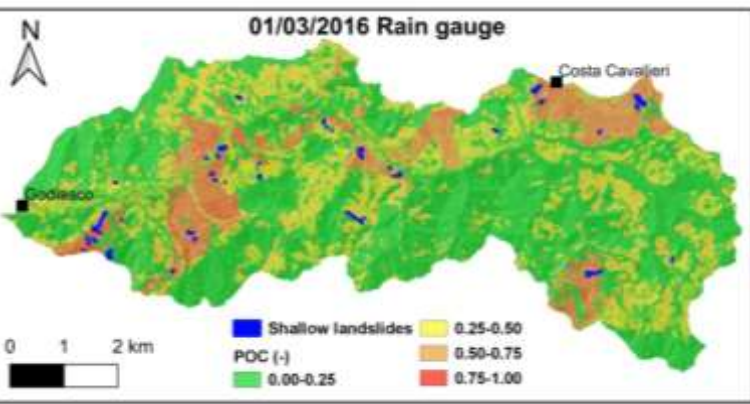
3d-rain=83.8 mm
30d-rain=177.2 mm
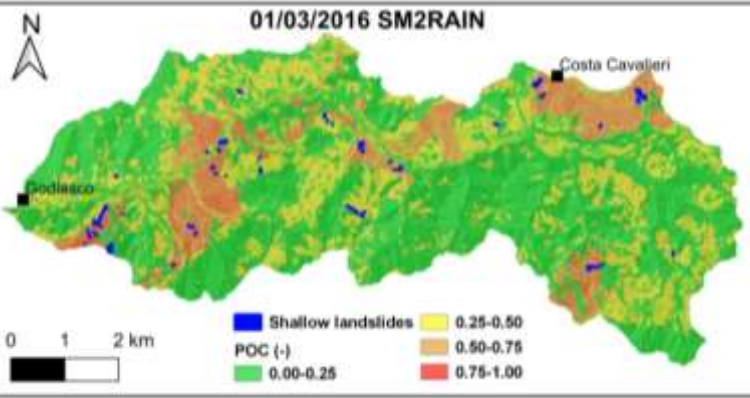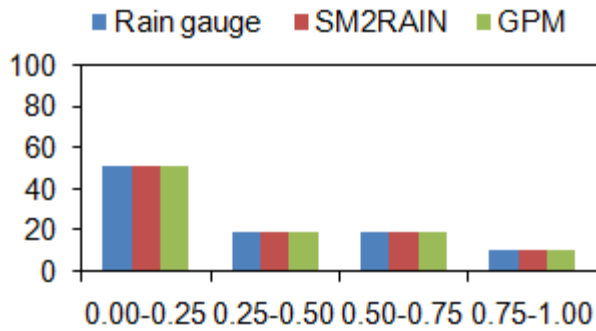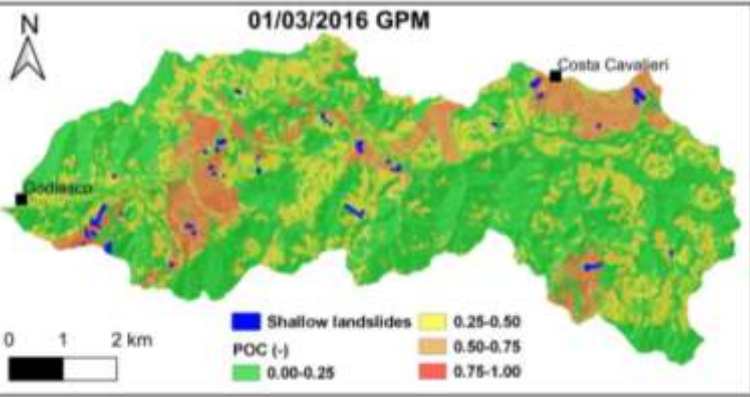Sat.=78%

3d-rain=92.4 mm
30d-rain=135.4 mm
Sat.=78%

3d-rain=155.3 mm
30d-rain=163.1 mm
Sat.=78%

Kappa index=1.00

7. CONCLUSIONS AND FUTURE DEVELOPMENTS

Advantages and limits of the proposed methodology

+ Considering the most important soil and geomorphological predisposing factors and dynamic triggering factors
+ Dynamic assessment of spatial and temporal probability of occurrence of rainfall-induced shallow landslides at large scale, with evaluation of its change in time according to different rainfall-soil moisture features
+ Correct modeling of different triggering events, with reliable assessment of the real events and of the correct day of triggering
+ Integration with satellite maps of rainfall and soil moisture
- Significant number of false positives
- Unstable conditions modeled also for 1-2 days following the triggering moment

Future developments

➢ Integration with more resoluted satellite data (e.g. Sentinel-1, 1x1 km)
➢ Considering maps of soil moisture modeled at typical depths of sliding surfaces (1 m from the ground)
➢ Hazard scenarios for different return times

THANKS FOR THE ATTENTION

For more information on ANDROMEDA project:

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