Technical Symposium / General Assembly 2019 in Italy

Field measurements of hydrological conditions for shallow land-slide triggering in the Oltrepo' Pavese

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UNIVERSITÀ DI PAVIA

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA DIPARTIMENTO DI SCIENZE AGRARIE

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1 Introduction – The shallow landslides and their consequences



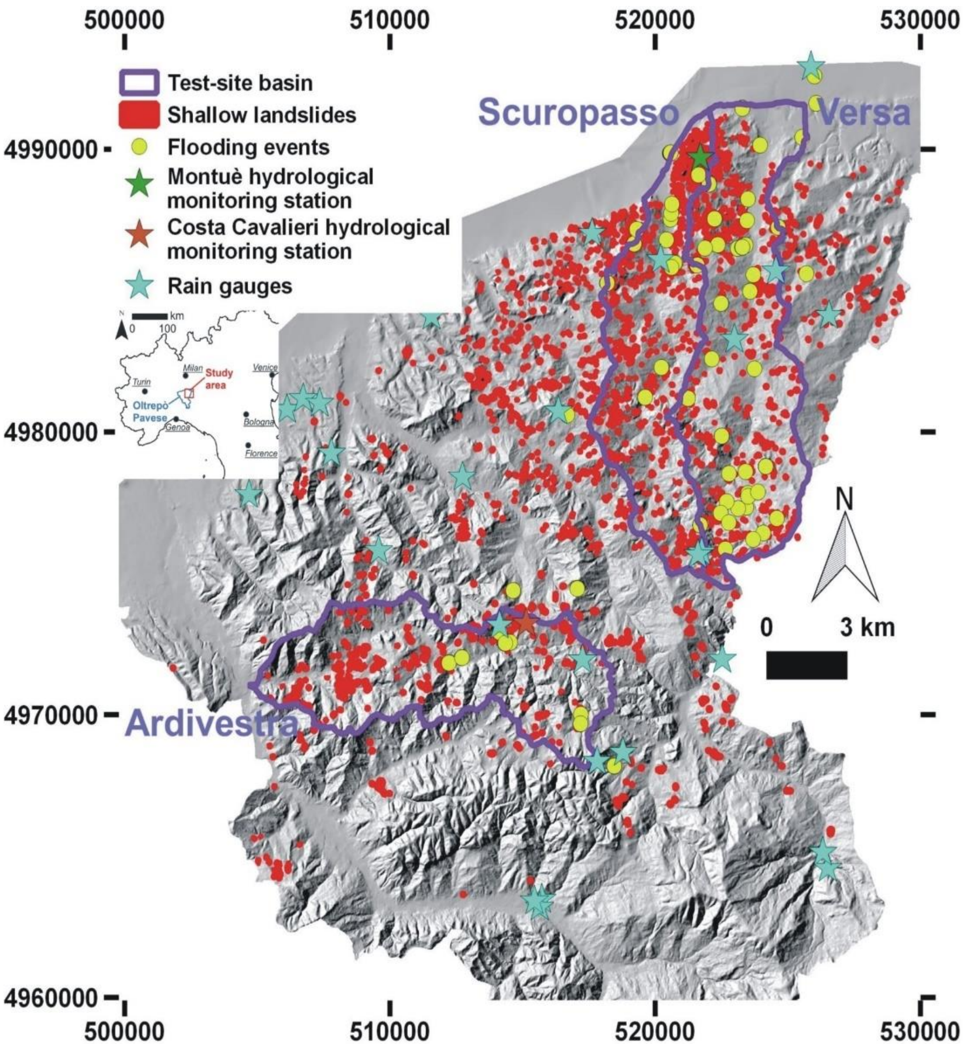




✓ **limited volume of soil** mobilized, but **severe damages** to cultivations, infrastructures, urban settlements, loss of human lives

✓ a **continuous monitoring** of unsaturated soil hydrological properties related to rainfall conditions is needed to understand the **landslide triggering mechanisms**.

1 Introduction – The shallow landslides in Oltrepo Pavese



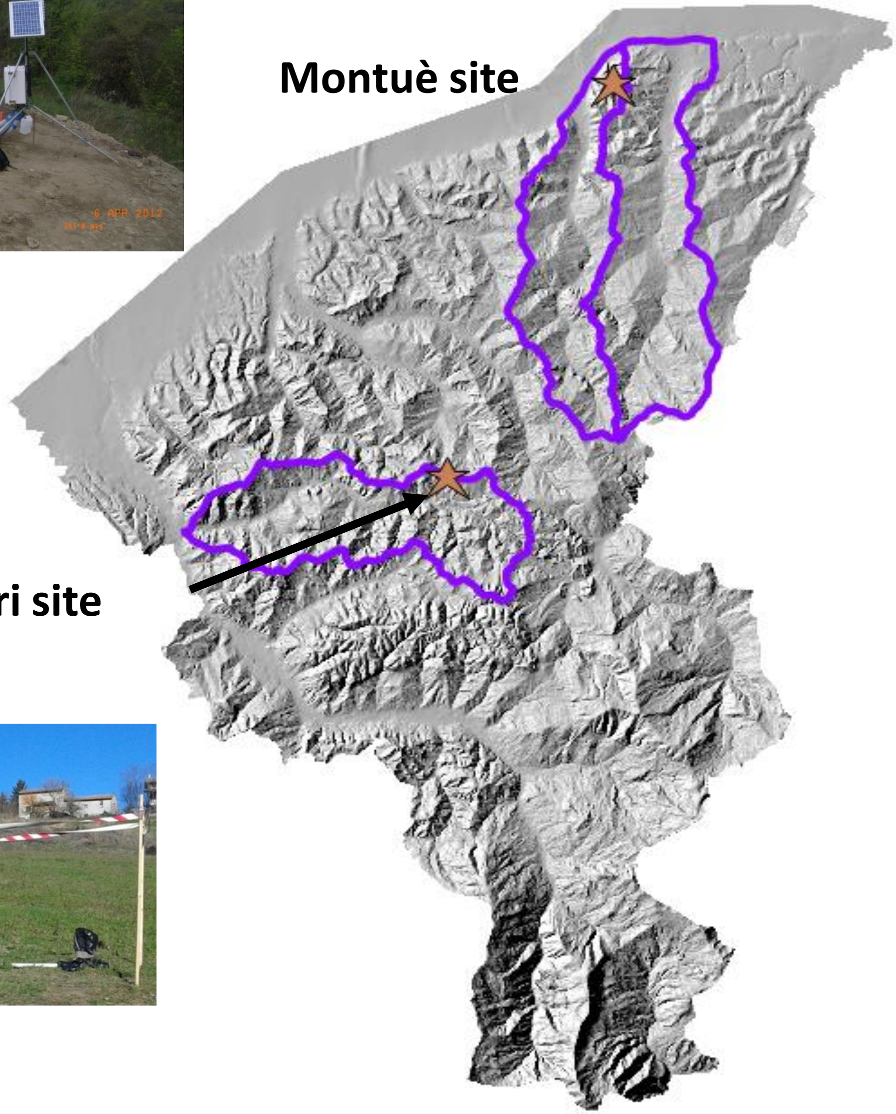
27th-28th April 2009 Event in Oltrepò Pavese (1639 shallow landslides in about 250 km^2)

2 Objective of the research

to test an integrated hydro-meteorological monitoring system for slopes prone to shallow landslides

1. to test different typologies of devices
2. to identify the main soil hydrological behaviors
3. to identify the shallow landslide triggering mechanisms

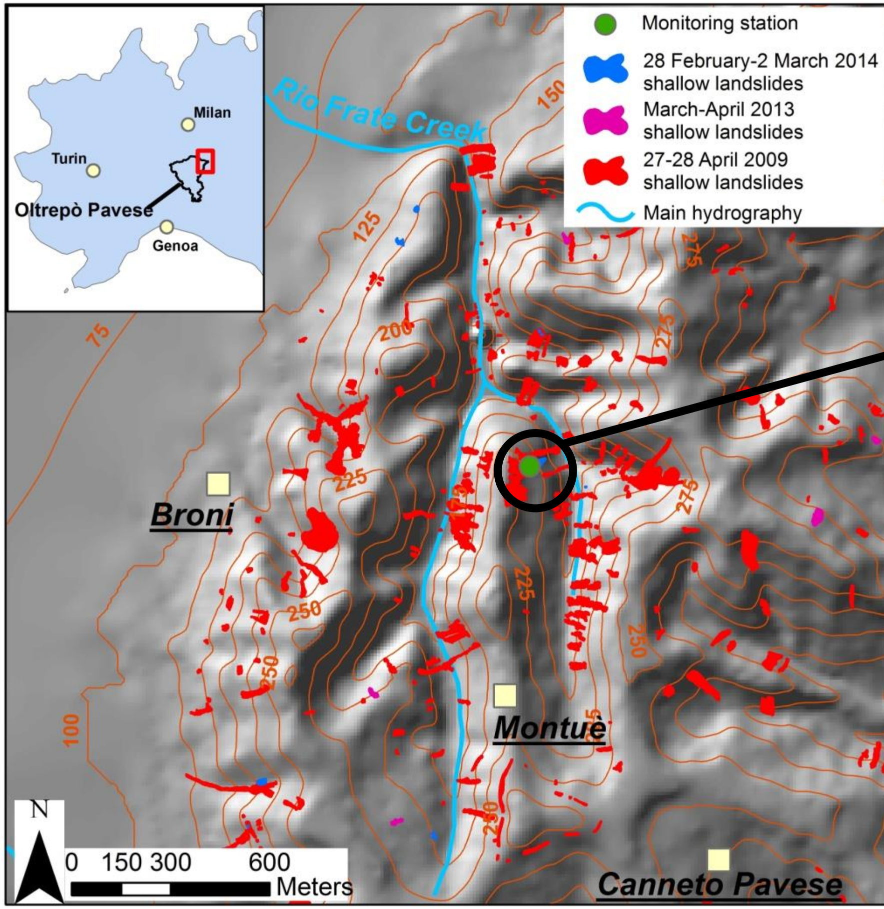
3 The monitored slopes



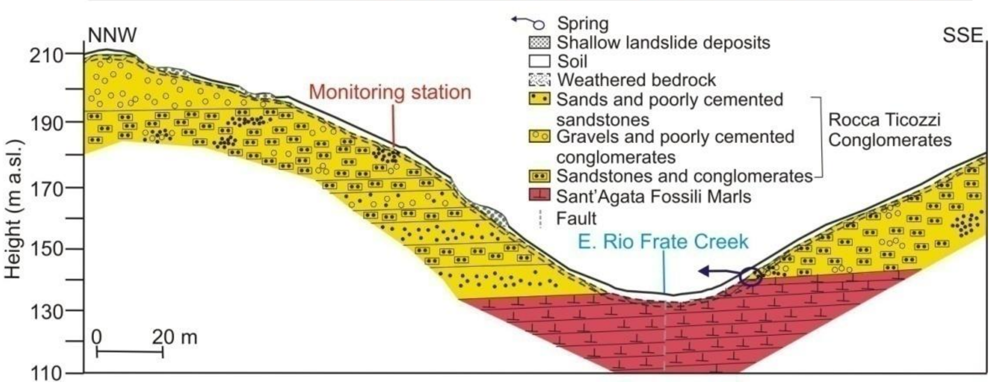
Costa Cavalieri site

3 The monitored slopes

1. North-eastern Oltrepò Pavese



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

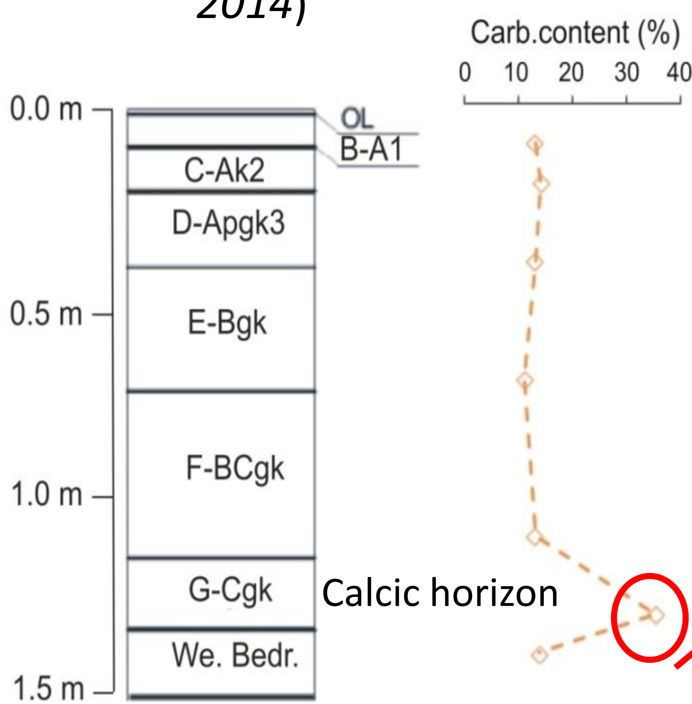
4) **Geomorphological features**: steep slopes (26-30°), narrow valley. Elevation: 185 m a.s.l.

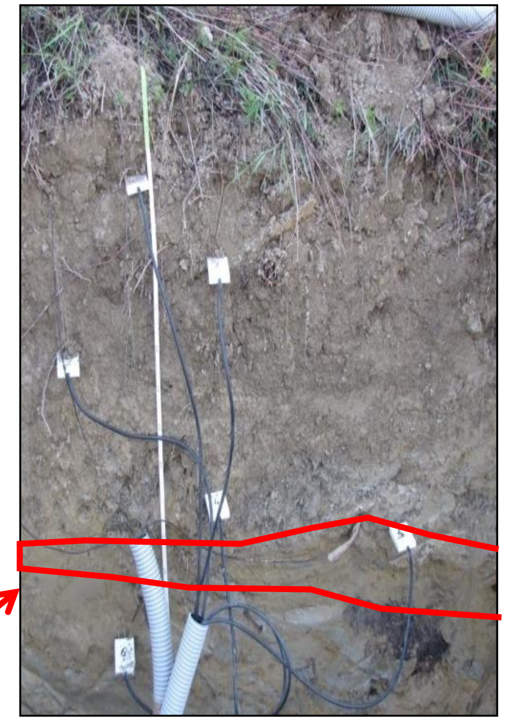
3 The monitored slopes

Montuè test-site slope – 3d Model

3 The monitored slopes

Calcic Gleysol (*IUSS, 2007, 2014*)



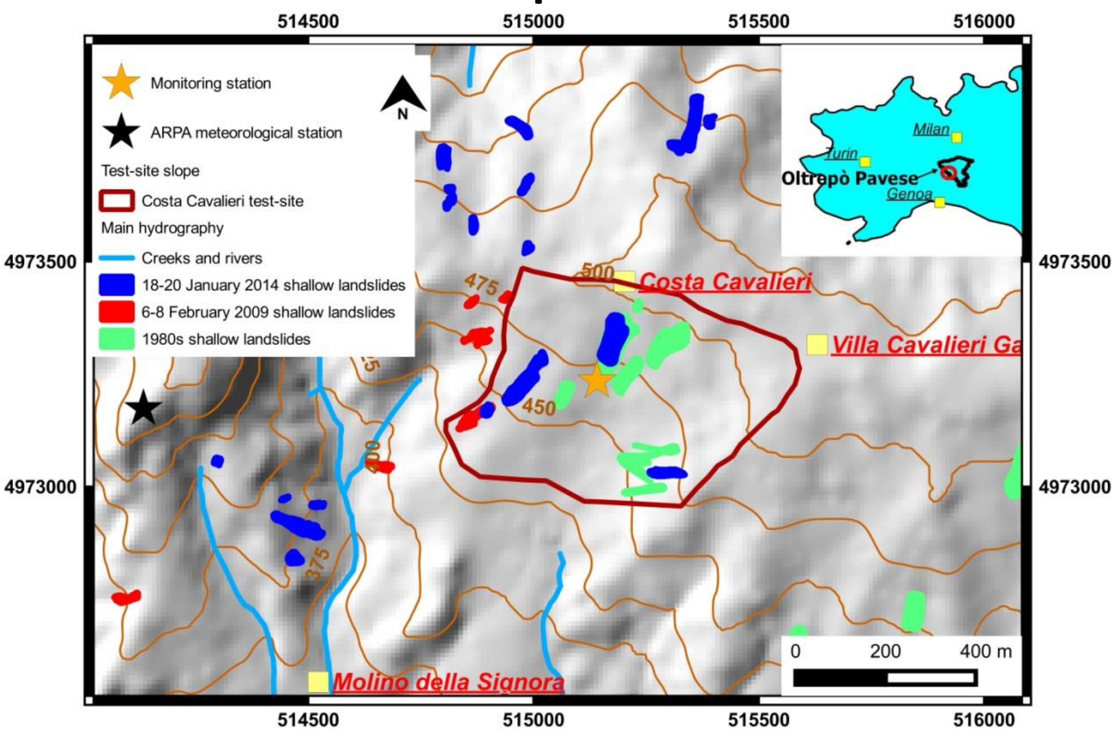


	Depth (m)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	USCS	γ (kN/m^3)
C	0.2	12.3	12.5	53.9	21.3	CL	17.0
D	0.4	1.5	11.4	59.4	27.7	CL	16.7
E	0.6	8.5	13.2	51.1	27.2	CL	16.7
F	1.0	2.4	12.2	56.4	29.0	CL	18.6
G	1.2	0.5	7.5	65.6	26.4	CL	18.3
R	1.4	0.2	75.0	24.8	0.0	-	18.1

Multidisciplinary (**pedological, mineralogical, geotechnical, mechanical**) characterization of the test-site slope soils

3 The monitored slopes

2. Central Oltrepò Pavese

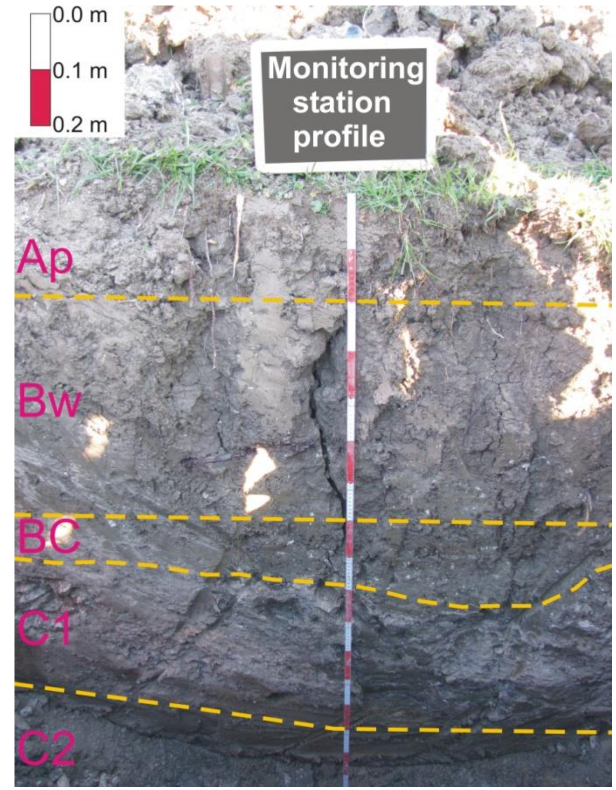


1) **Past shallow landslides** (6-8 february 2009, 18-20 January 2014)

2) **Geological setting**: clayey and clayey-marly deposits covered by silty clay (1.7 m)

3) **Geomorphological features**: Low gradient slopes (10-15°), large creek valleys

Costa Cavalieri test-site slope



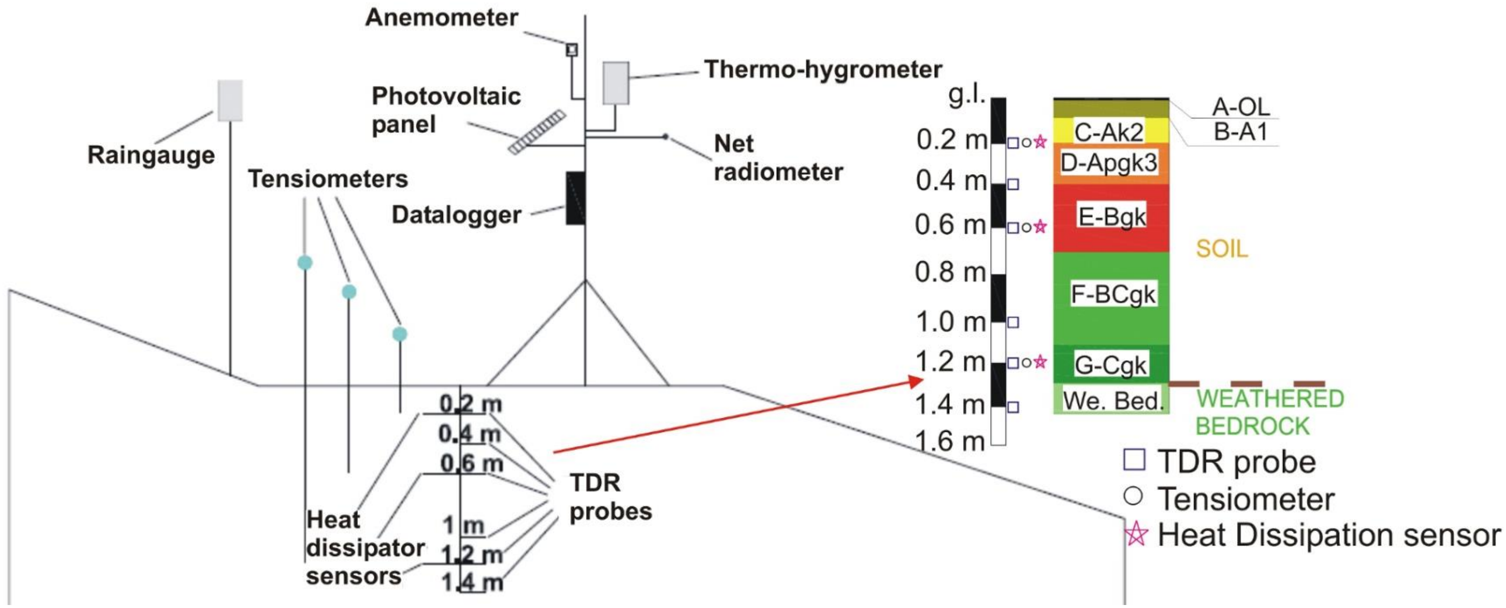
	Depth (m)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	USCS	γ (kN/m^3)
Ap	-0.10	1.00	2.30	42.20	54.50	CH	
Bw	-0.44	0.55	2.25	39.70	57.50	CH	18.7
BC	-0.80	0.55	2.25	45.70	51.50	CH	19.0
C1	-1.18	2.45	3.20	46.85	47.50	CH	
C2	-1.72	0.10	0.65	42.25	57.00	CH	

3 The monitored slopes

Costa Cavalieri test-site slope – 3d Model

4 The monitoring system

1. Montuè test-site slope

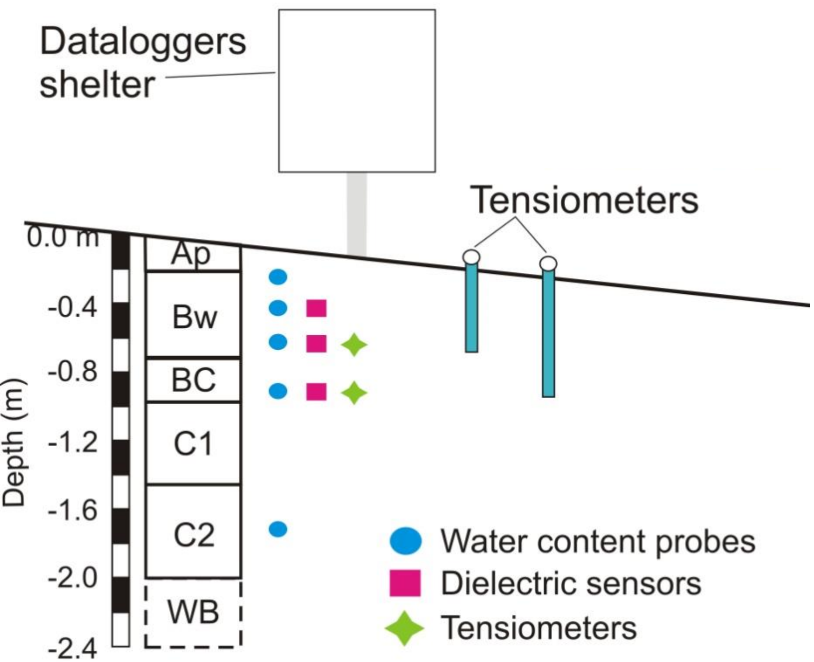


Device	Model	Range of measure	Accuracy
Heat Dissipation sensors	Model HD229 - Campbell Scientific	-10000 / -10 kPa	1.5 – 2 kPa
Tensiometers	Model Jet-Fill 2725 - Soilmoisture Equipment Corporation	-80 / 10 kPa	1.5 – 2 kPa
TDR probes	Model CS610 - Campbell Scientific	0.05 / 1.0 $m^3 \cdot m^{-3}$	0.01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

4 The monitoring system

2. Central Oltrepò Pavese

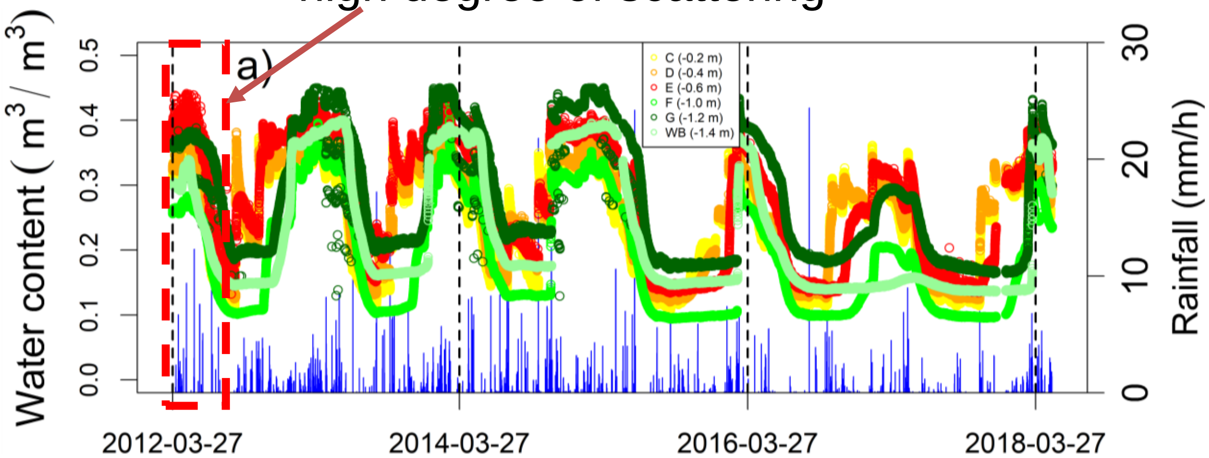


Device	Model	Range of measure	Accuracy
Dielectric sensors	Model MPS-6 – Decagon Devices	-100000 / -9 kPa	3 kPa
Tensiometers	Model T4e-UMS GmbH	-85 / 10 kPa	0.5 kPa
Water content probes	Model GS3 – Decagon Devices	0.05 / 1.0 $m^3 \cdot m^{-3}$	0.01 – 0.02 $m^3 \cdot m^{-3}$

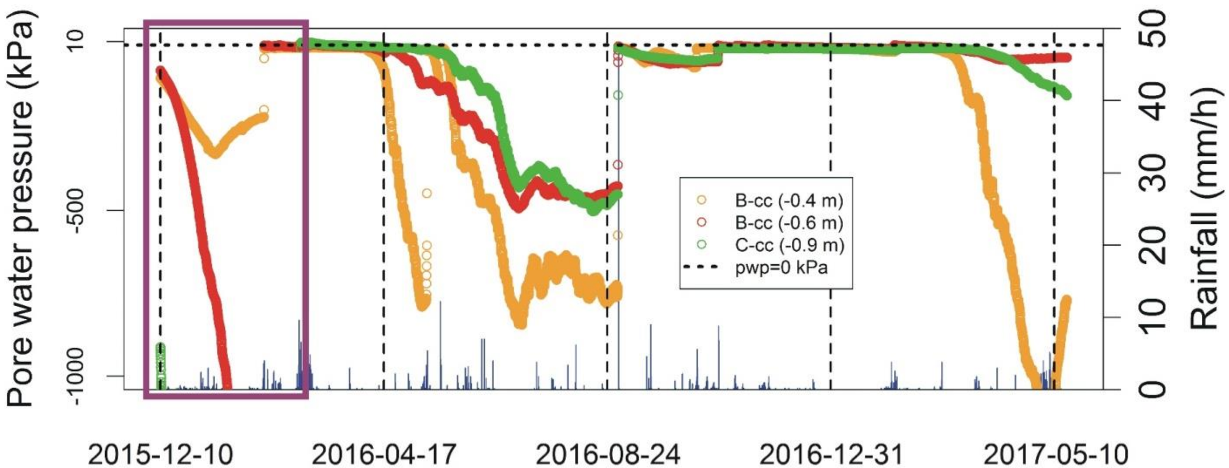
- **Soil devices installed in** a trench pit
- **Data collection since 27/11/2015**
- Temporal resolution: **10 minutes**
- **datalogger (DL-6te, EM-50) powered by batteries**

5.1 Results - Behaviour of devices

high degree of scattering

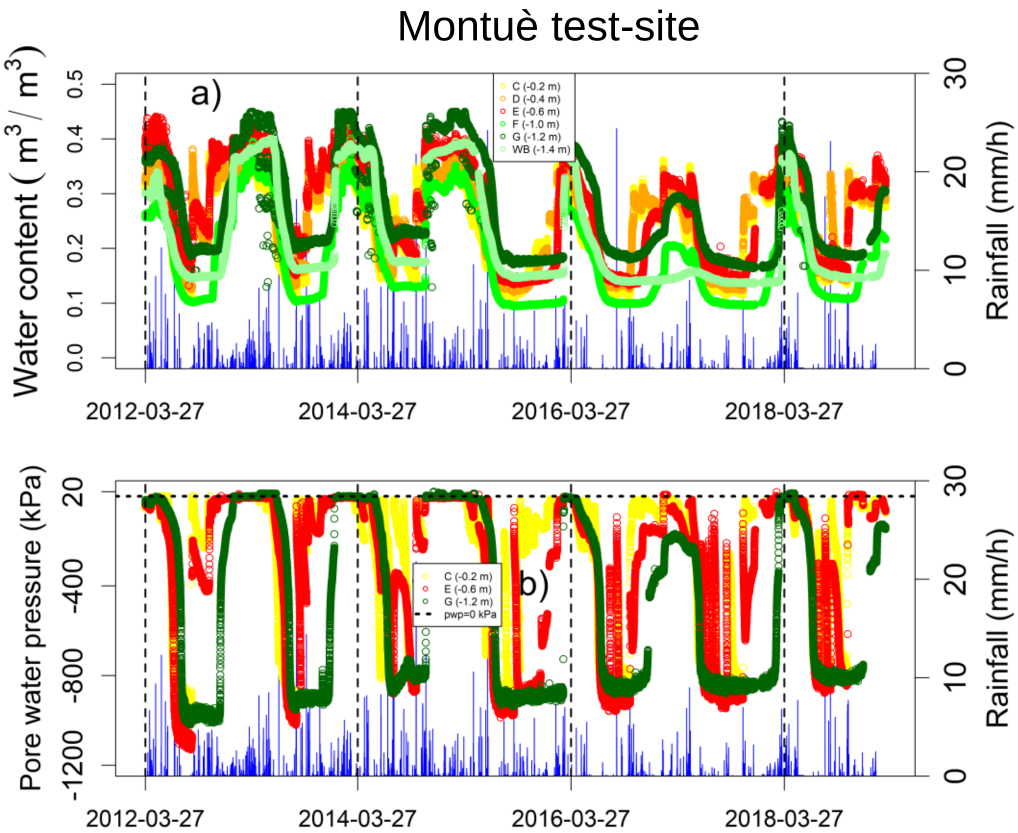


Montué station: required initial period in which sensors had to progressively adhere to the surrounding soil after installation

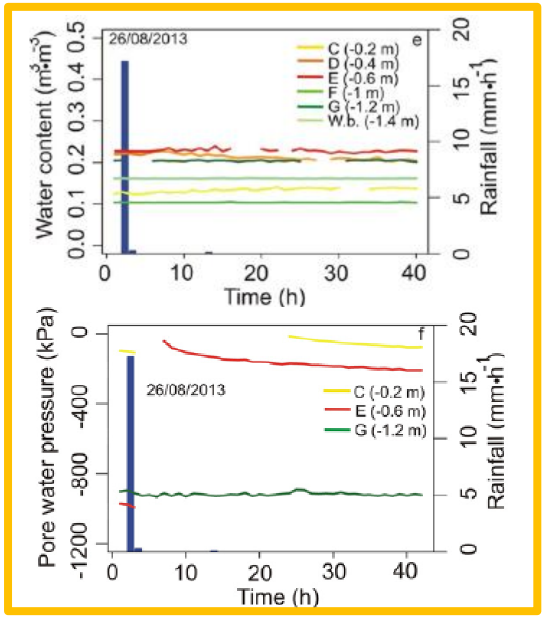


Costa Cavlieri station: shrinkage/swelling processes required initial period in which sensors had to progressively adhere to the surrounding soil after installation

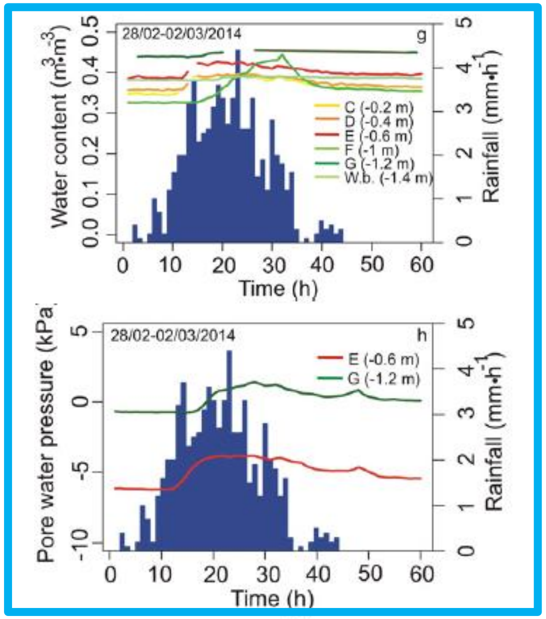
5.2 Results – Monitored hydrological behaviours



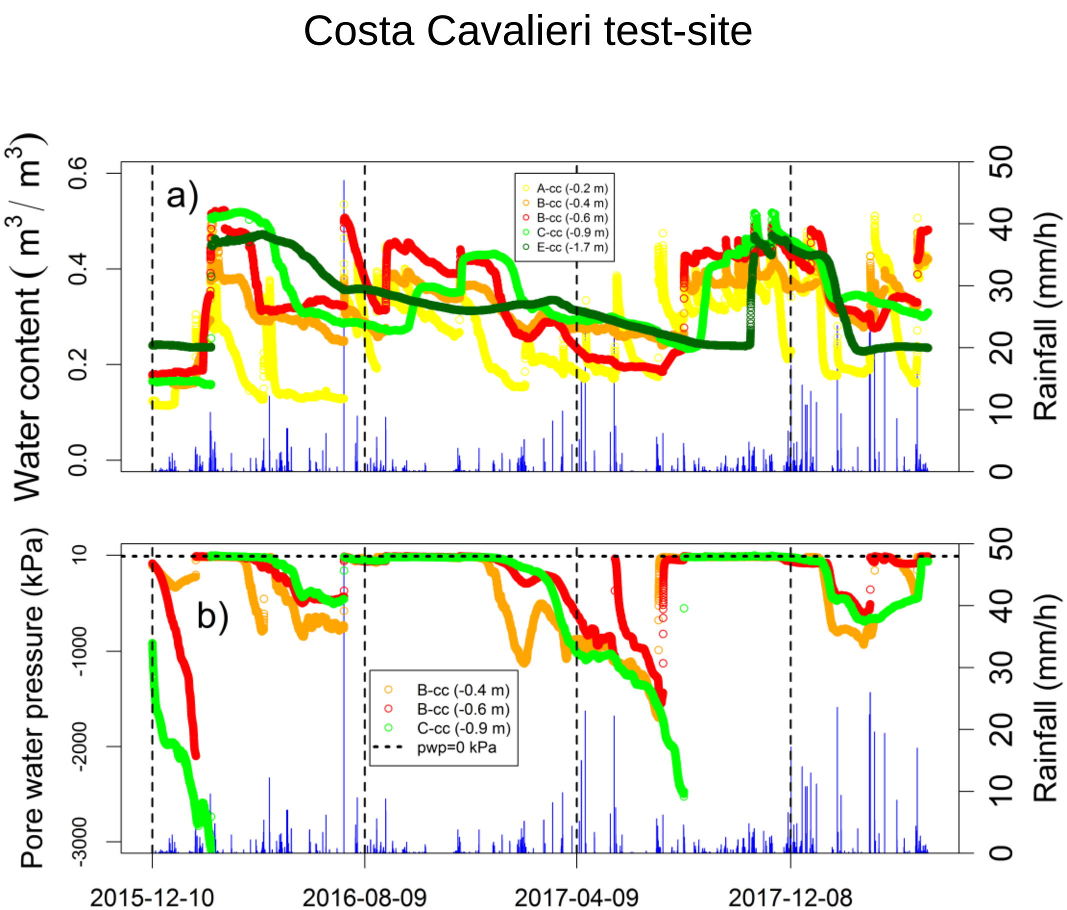
Drying periods



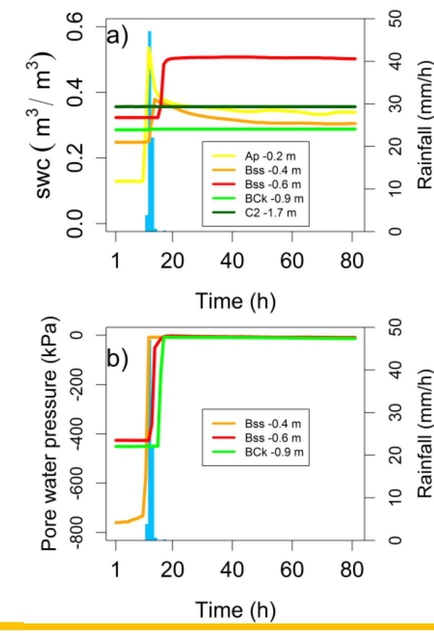
Wetting periods



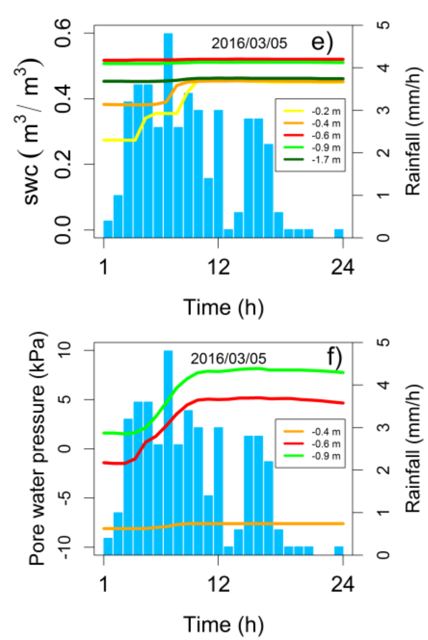
5.2 Results – Monitored hydrological behaviours



Drying periods



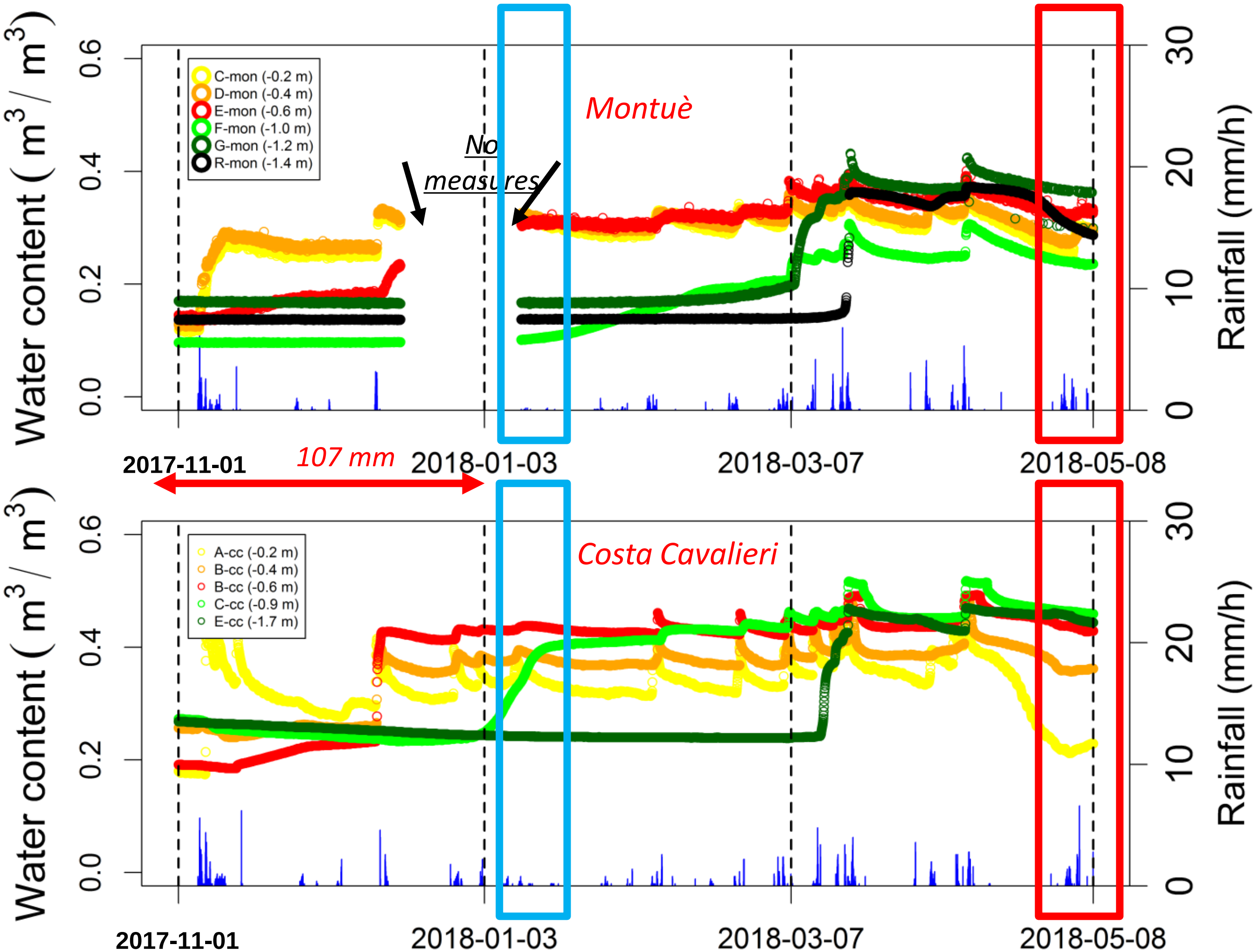
Wetting periods



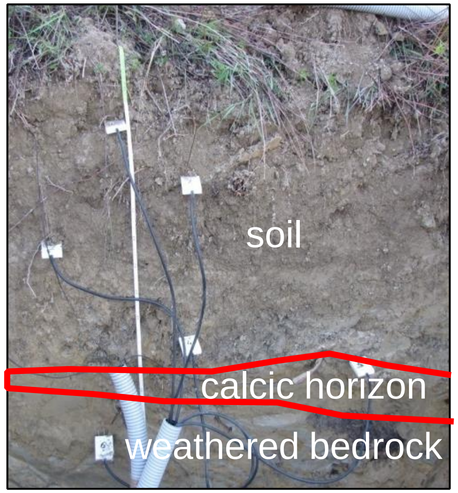
5.2 Results – Monitored hydrological behaviours

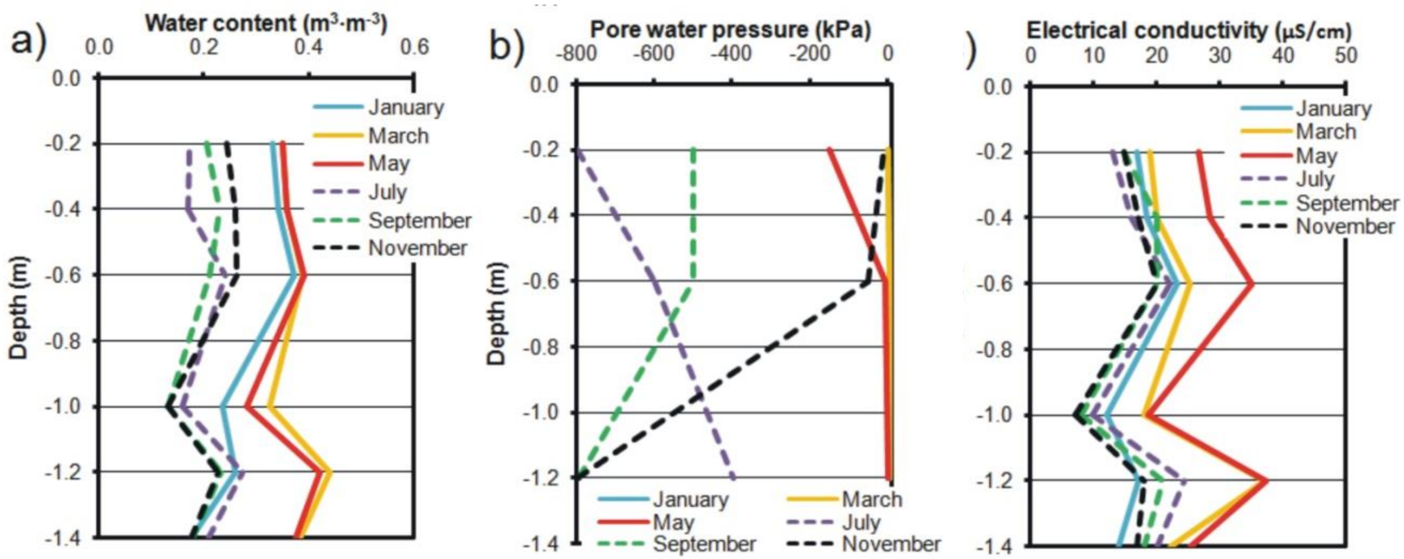
WETTING PHASE

DRYING PHASE



5.2 Results – Monitored hydrological behaviours





wet period

dry period

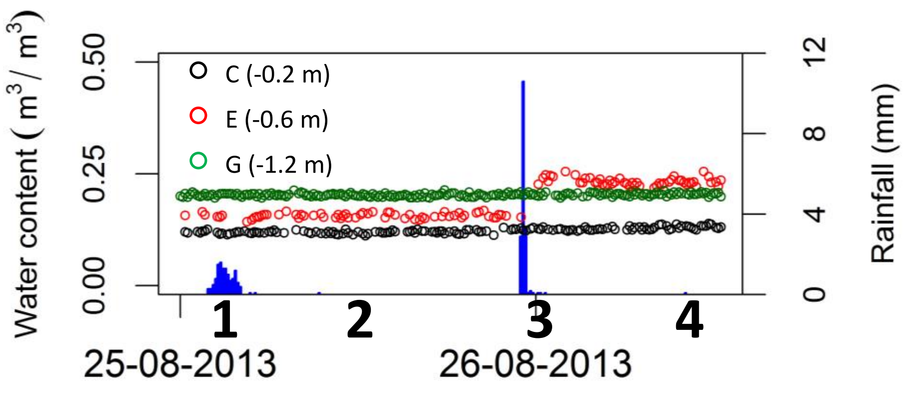
wet period --> prologed rainy periods provoke an increase of pore water pressure and water content in soil horizons >0.7 m

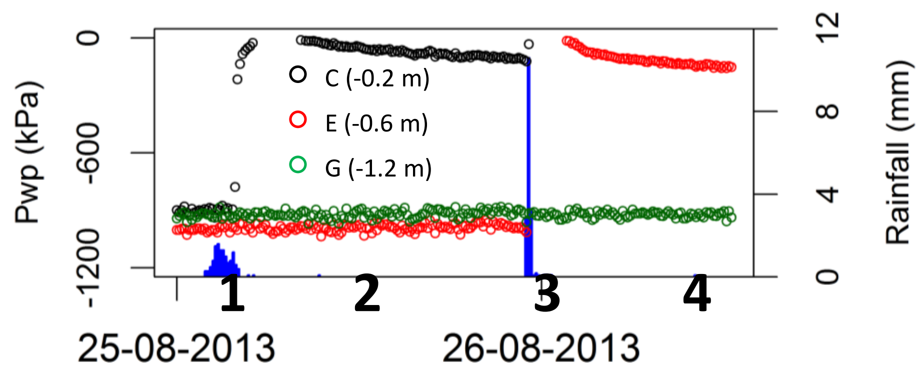
perched water table at the interface between the shallow soil and the weathered bedrock

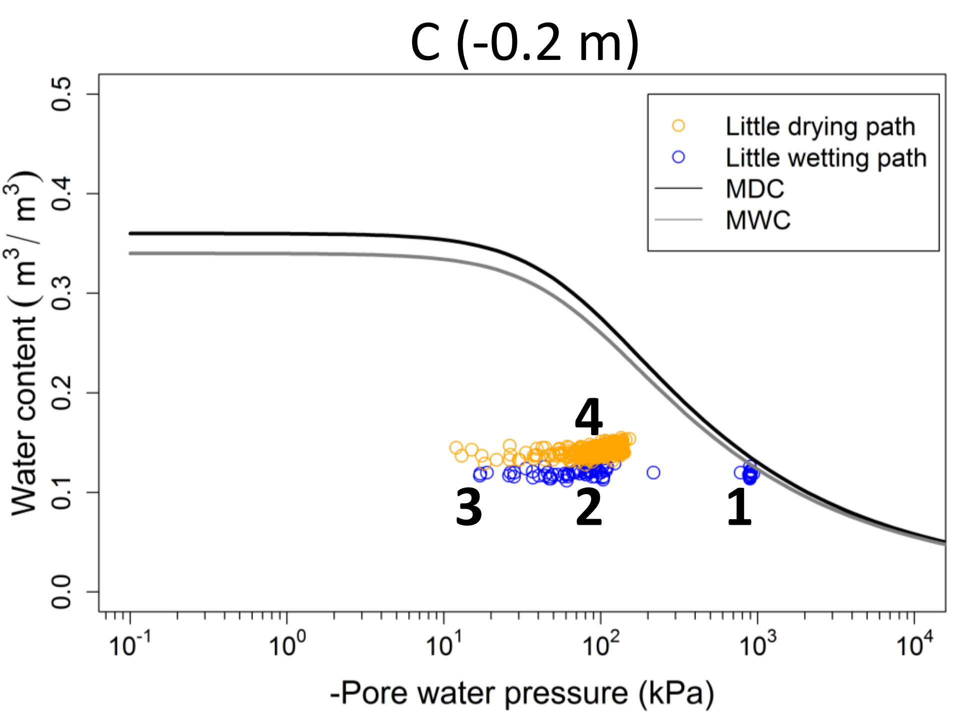
5.3 Results –Hydraulic non-equilibrium processes

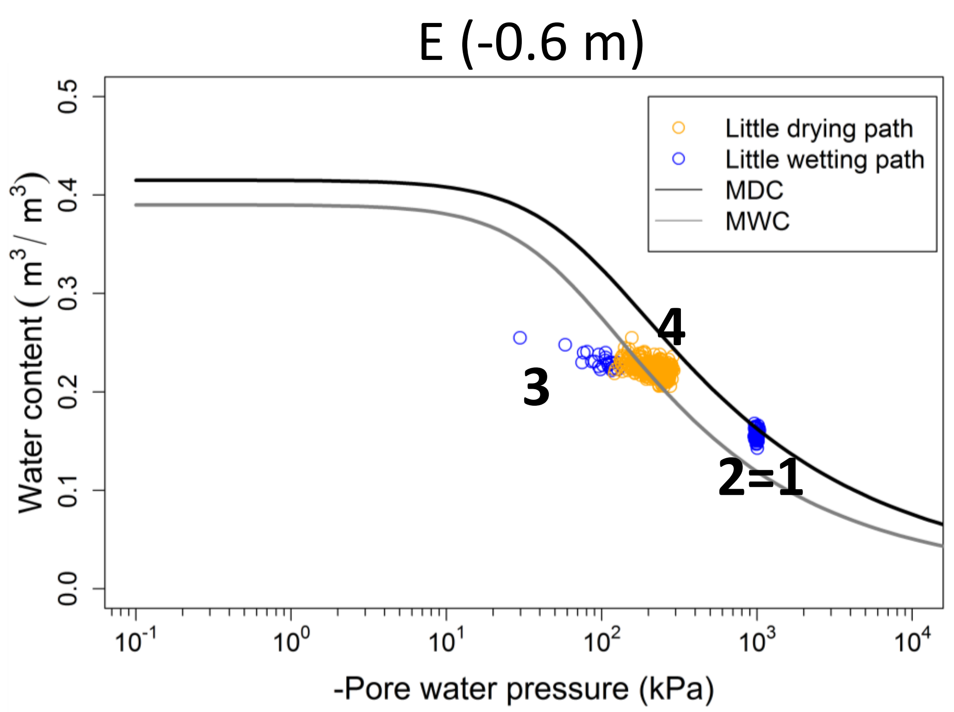
dry period --> very rapid rewetting of the soil horizons < 0,7m

summer rainstorm (>10mm/2h) --> increase of pore water pressure not coupled with an increase of the water content

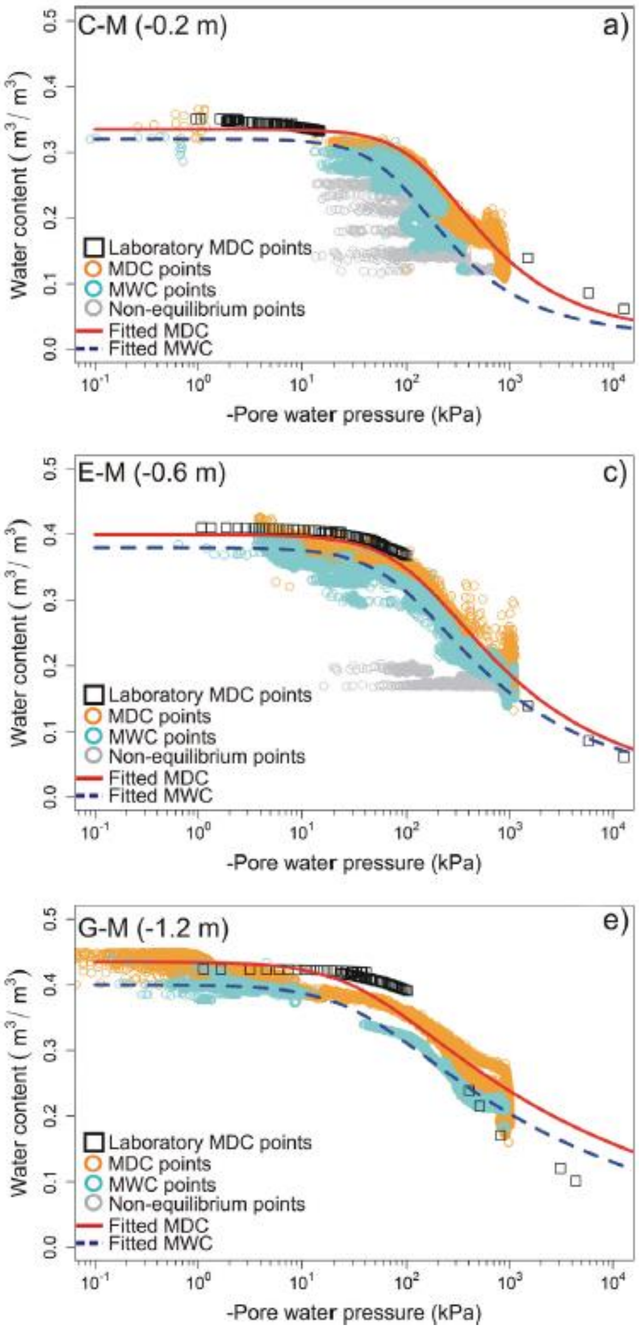






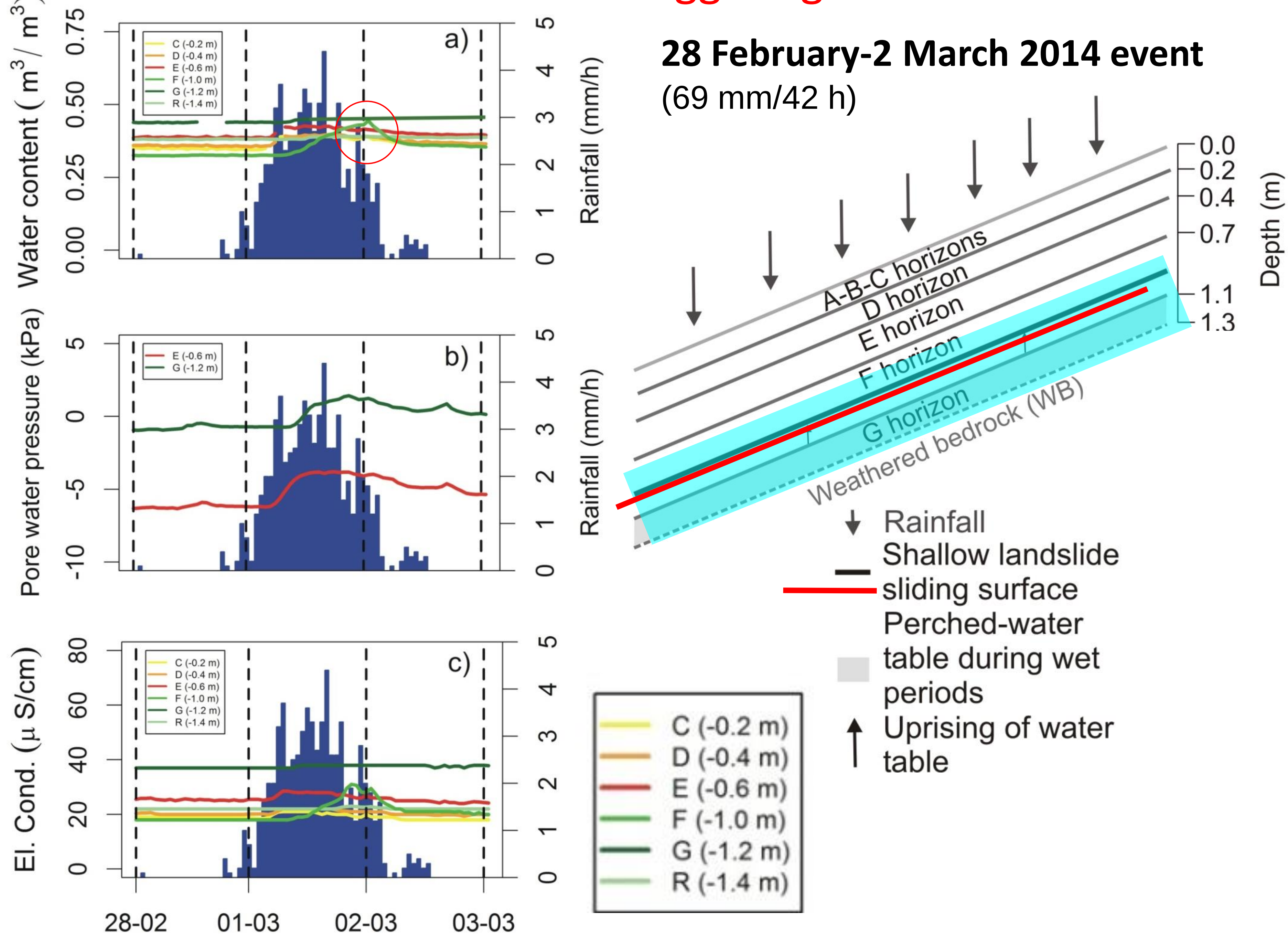


5.4 Results – Hysteretic Soil Water Characteristic Curves



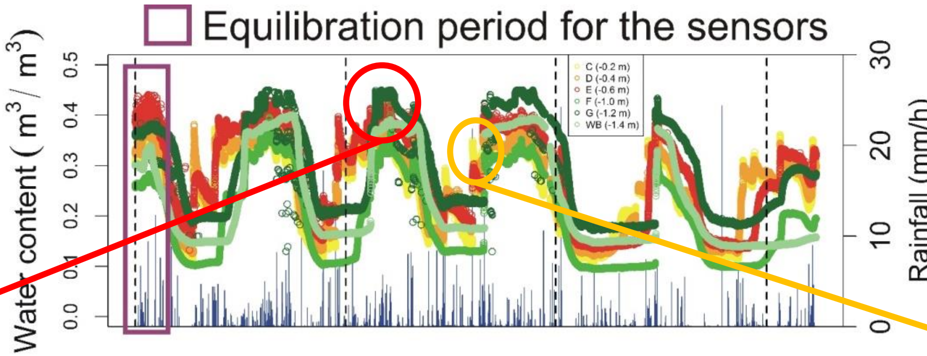
Field – Hourly data	Drying					Wetting				
	θ_{sd} (m^3/m^3)	θ_{rd} (m^3/m^3)	α_d (kPa^{-1})	n_d (–)	RMSE (m^3/m^3)	θ_{sw} (m^3/m^3)	θ_{rw} (m^3/m^3)	α_w (kPa^{-1})	n_w (–)	RMSE (m^3/m^3)
C-M (0.2 m)-I cycle	0.33	0.02	0.006	1.51	0.0142	0.32	0.02	0.007	1.62	0.0146
C-M (0.2 m)-II cycle	0.33	0.02	0.004	1.55	0.0167	0.32	0.02	0.007	1.62	0.0168
C-M (0.2 m)-III cycle	0.33	0.01	0.002	1.57	0.0178	0.32	0.01	0.004	1.62	0.0173
C-M (0.2 m)-IV cycle	0.33	0.01	0.002	1.61	0.0173	0.32	0.01	0.004	1.62	0.0154
C-M (0.2 m)-All cycles	0.33	0.02	0.003	1.57	0.0163	0.32	0.02	0.007	1.62	0.0164
E-M (0.6 m)-I cycle	0.40	0.01	0.012	1.38	0.0179	0.37	0.01	0.017	1.40	0.0177
E-M (0.6 m)-II cycle	0.39	0.01	0.012	1.38	0.0126	0.37	0.01	0.017	1.40	0.0133
E-M (0.6 m)-III cycle	0.40	0.01	0.014	1.38	0.0140	0.37	0.01	0.017	1.40	0.0133
E-M (0.6 m)-IV cycle	0.40	0.01	0.012	1.38	0.0133	0.37	0.01	0.017	1.40	0.0143
E-M (0.6 m)-All cycles	0.40	0.01	0.012	1.38	0.0137	0.37	0.01	0.017	1.40	0.0136
G-M (1.2 m)-I cycle	0.43	0.01	0.013	1.16	0.0167	0.40	0.01	0.015	1.20	0.1070
G-M (1.2 m)-II cycle	0.44	0.01	0.010	1.22	0.0127	0.40	0.01	0.011	1.23	0.0135
G-M (1.2 m)-III cycle	0.43	0.01	0.010	1.21	0.0166	0.40	0.01	0.011	1.22	0.0124
G-M (1.2 m)-IV cycle	0.44	0.01	0.010	1.24	0.0171	0.40	0.01	0.011	1.22	0.0121
G-M (1.2 m)-All cycles	0.44	0.01	0.013	1.19	0.0158	0.40	0.01	0.014	1.21	0.0128

5.5 Results – Shallow landslides triggering mechanism

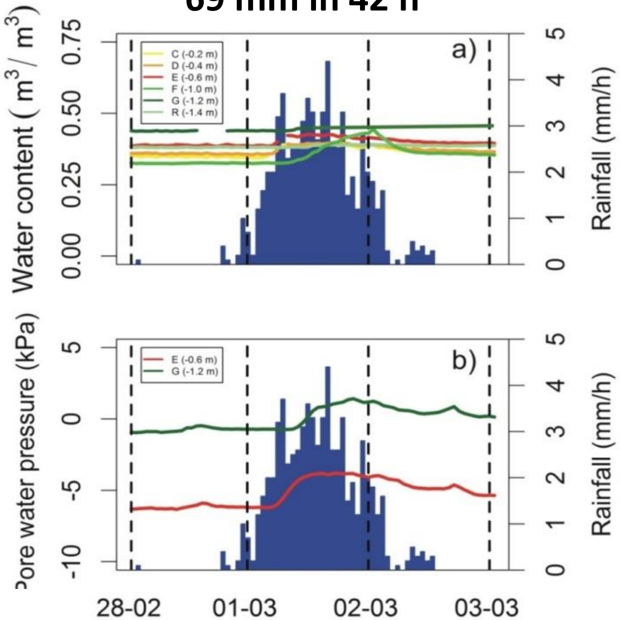


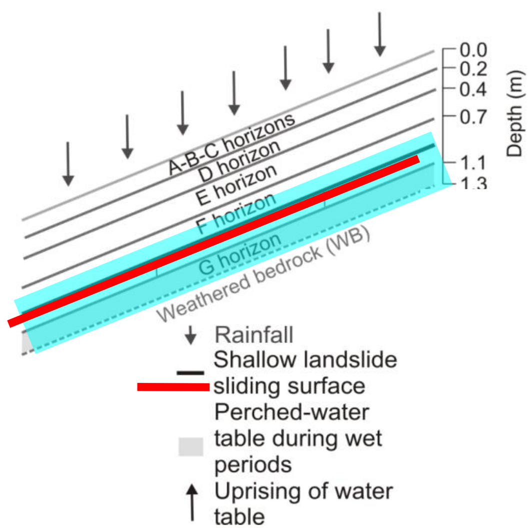
5.6 Results – Role of antecedent soil moisture conditions in shallow landslides triggering

MONTUE' TEST SITE

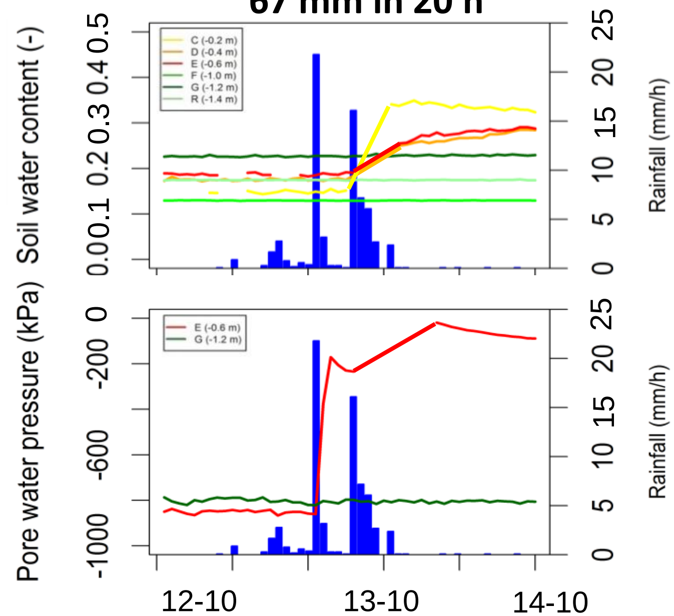


28 February-2 March 2014
69 mm in 42 h





13 October 2014
67 mm in 20 h



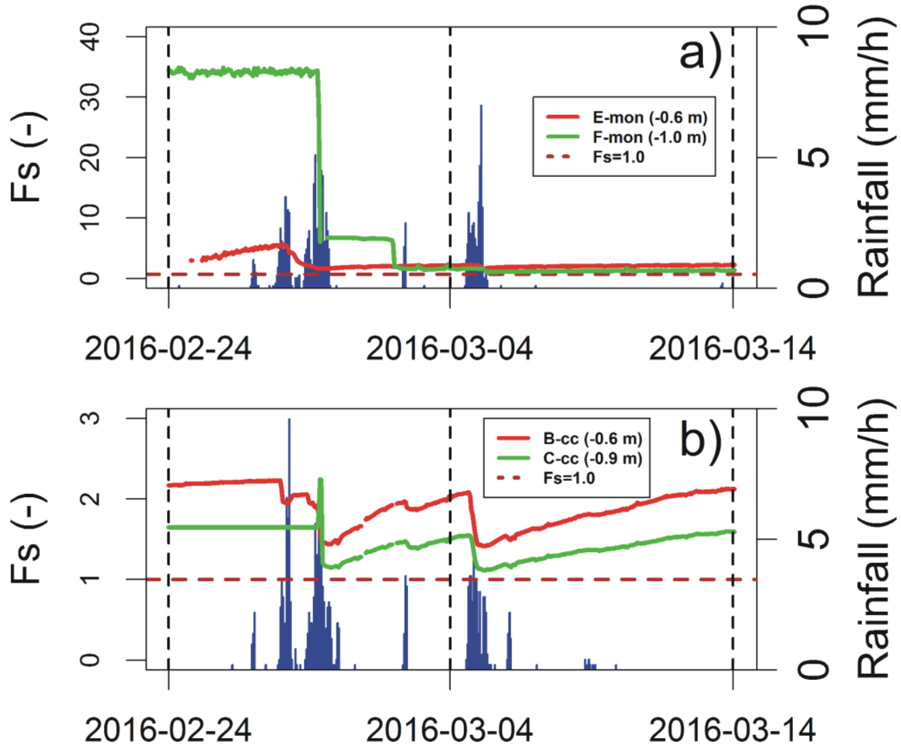
6.1 Results – Slope stability analysis at site-specific scale

Lu and Godt's model (Lu and Godt, 2008)

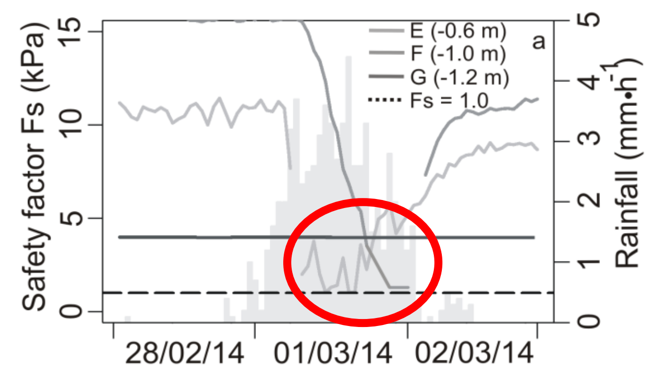
$$Fs = \frac{\tan\varphi'}{\tan\beta} + \frac{2c'}{\gamma z \sin 2\beta} - \frac{\sigma^s}{\gamma z}\left[(\tan\beta + \cot\beta)\tan\varphi'\right]$$

φ' = friction angle of the soil
β = slope angle
c' = effective cohesion
γ = unit weight
z = depth
σ^s = suction stress

Modeled safety factor (Fs) during 24 February-14 March 2016: a) Montuè slope; b) Costa Cavalieri slope.



Montuè 28 February-2 March 2014 event



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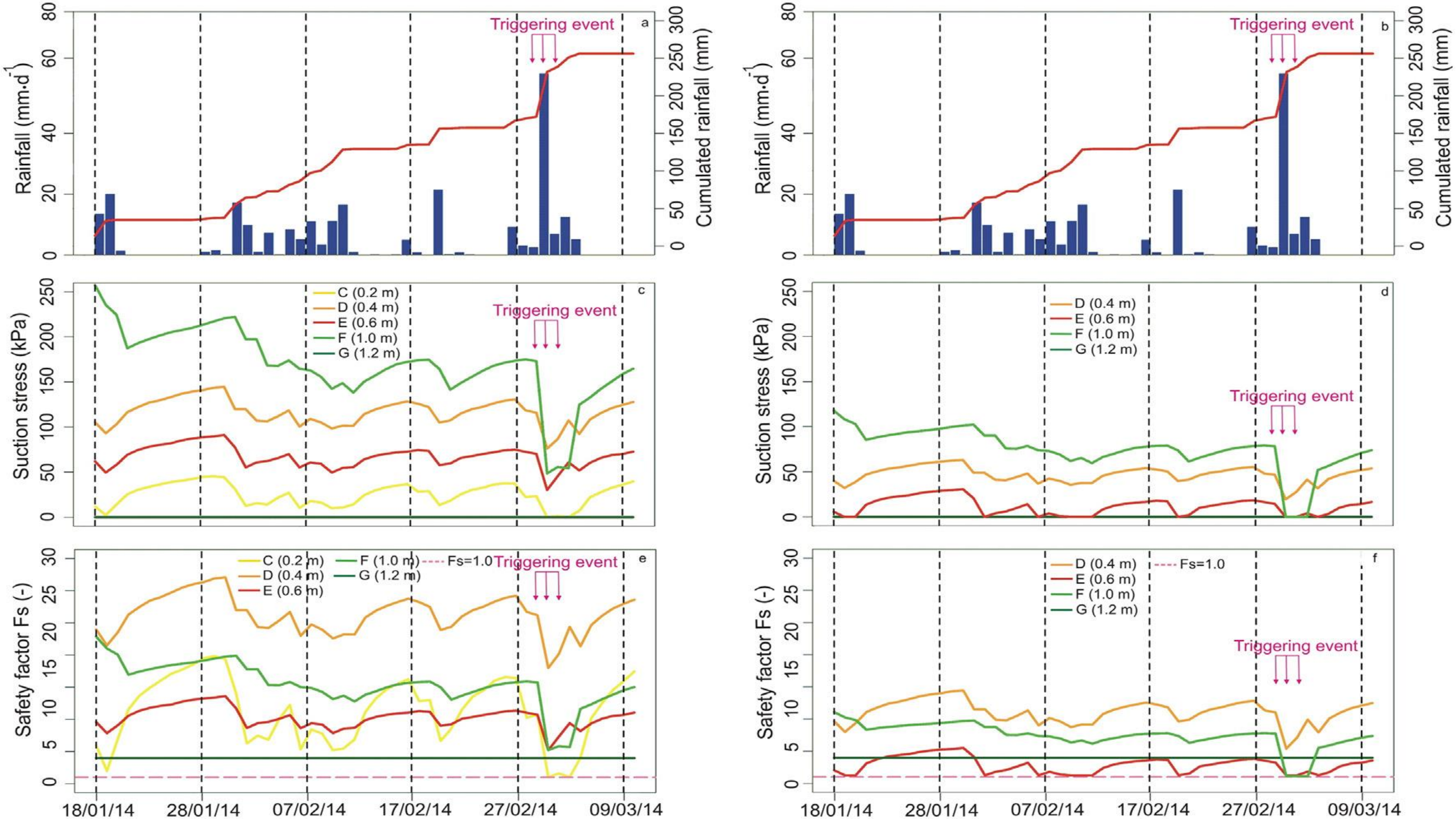
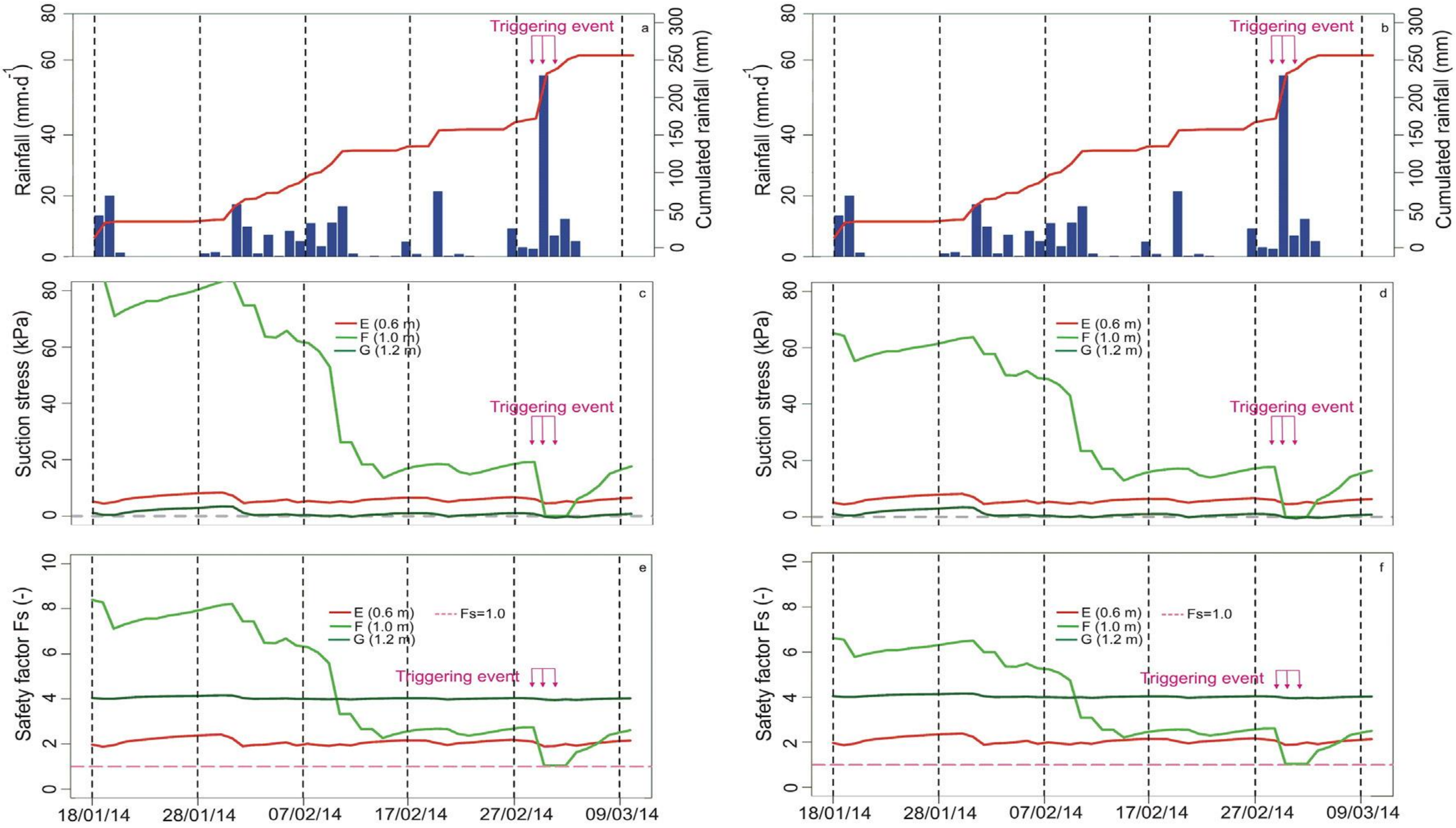


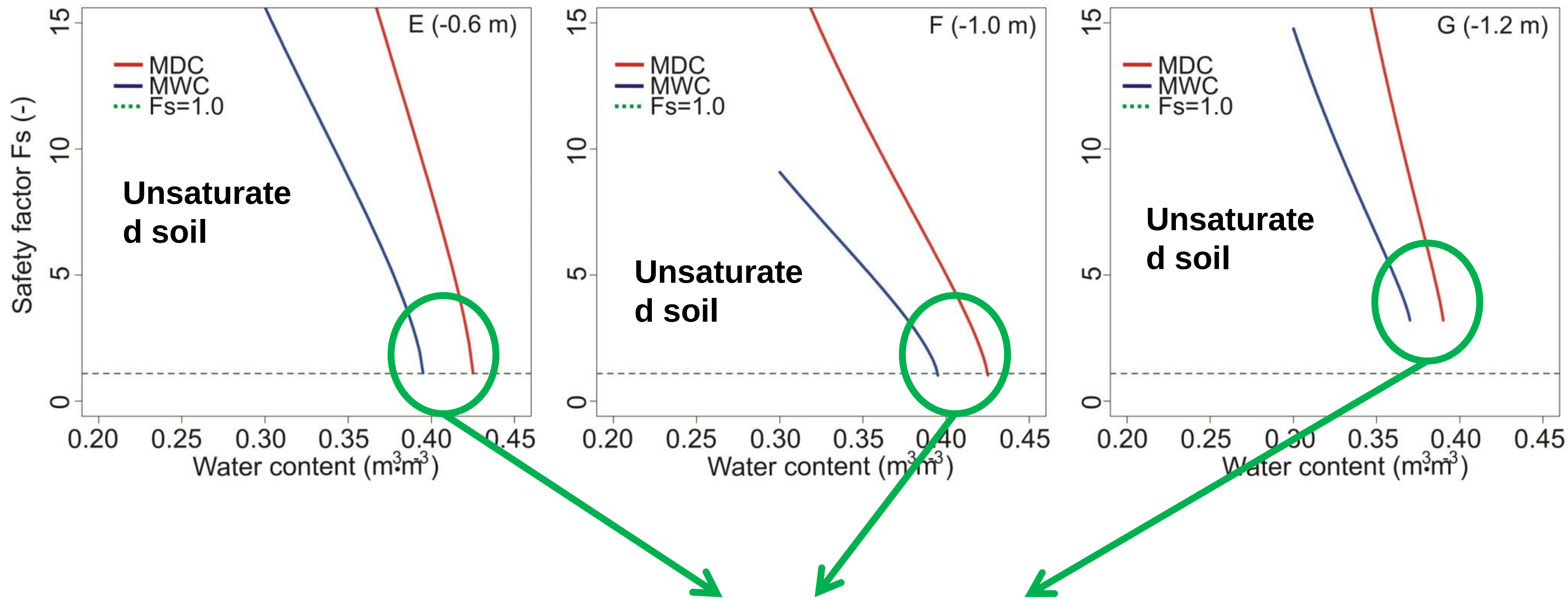
Safety factor trends reconstructed using Lu and Godt's model since water content data between 18 January and 9 March 2014: a, b) cumulated rainfall amount of the period; c, d) suction stress modeled using MDC orMWC properties; and e, f) safety factor modeled using MDC or MWC properties.

6.1 Results – Slope stability analysis at site-specific scale



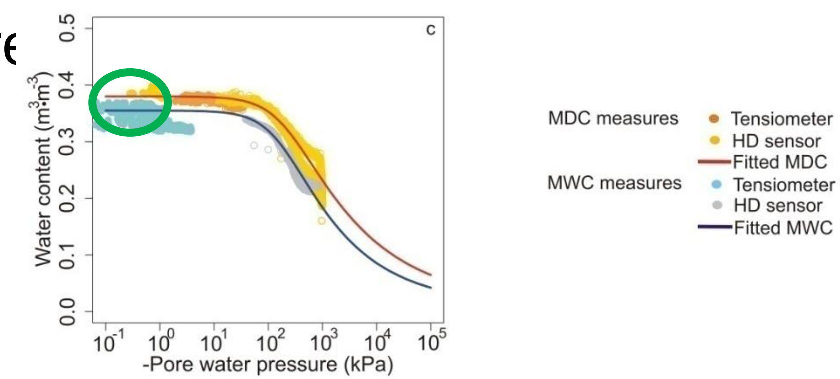
Safety factor trends reconstructed using Lu and Godt's model since pore water pressure data between 18 January and 9 March 2014: a, b) cumulated rainfall amount of the period; c, d) suction stress modeled using MDC or MWC properties; and e, f) safety factor modeled using MDC orMWC properties.

6.2 Results: Safety factor charts

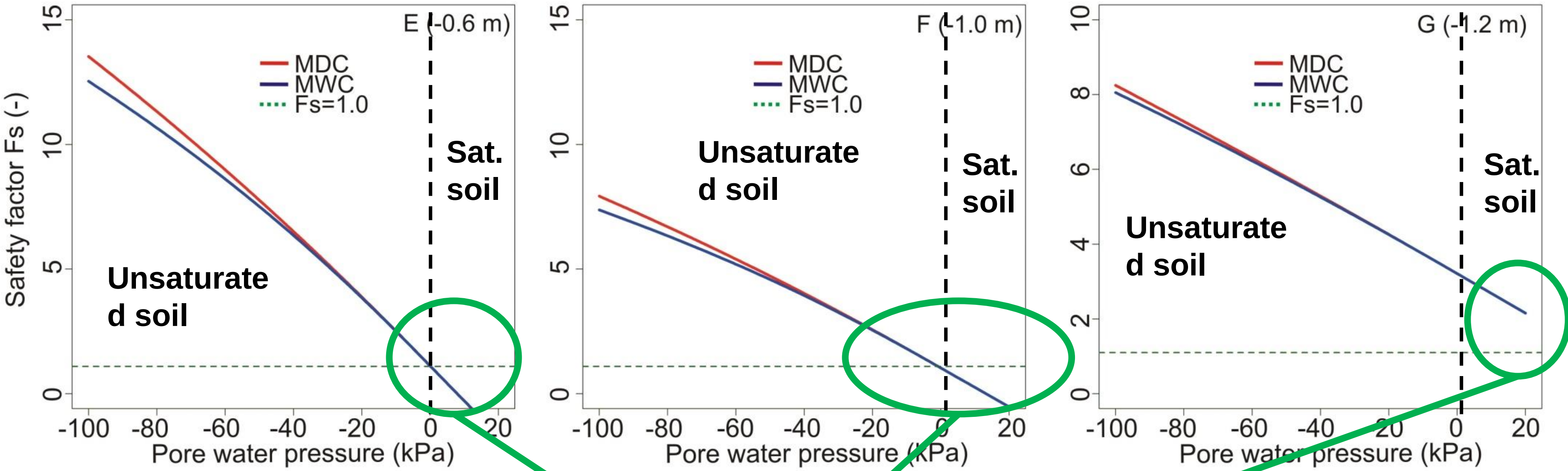


- ➢No further decrease in safety factor when soil is saturated → θ cannot be higher than θ_s

- ➢Significant differe hysteresis

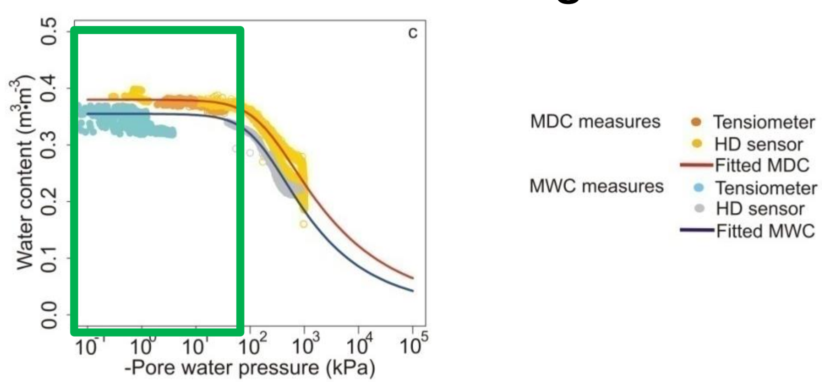


6.2 Results: Safety factor charts



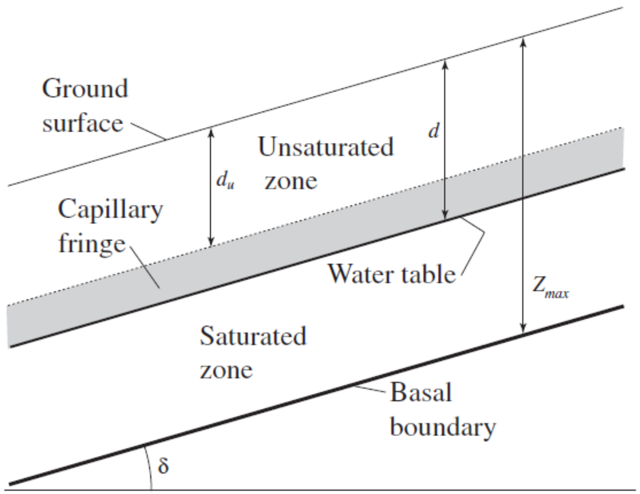
- ➢Further decrease in safety factor also when soil is saturated → pore water pressure can be higher than 0 kPa

- ➢No significant differences considering or not hysteresis



6.3 Results – Slope stability analysis at catchment scale

TRIGRS-Unsaturated model (Baum et al., 2008)



Baum et al., 2008

Rainfall distribution

+

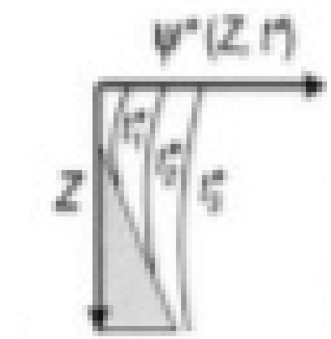
Initial pore water pressure distribution

+

SWCC parameters of Gardner's equation (α_G, θ_s, θ_r)

=

Transient pore water pressure distribution



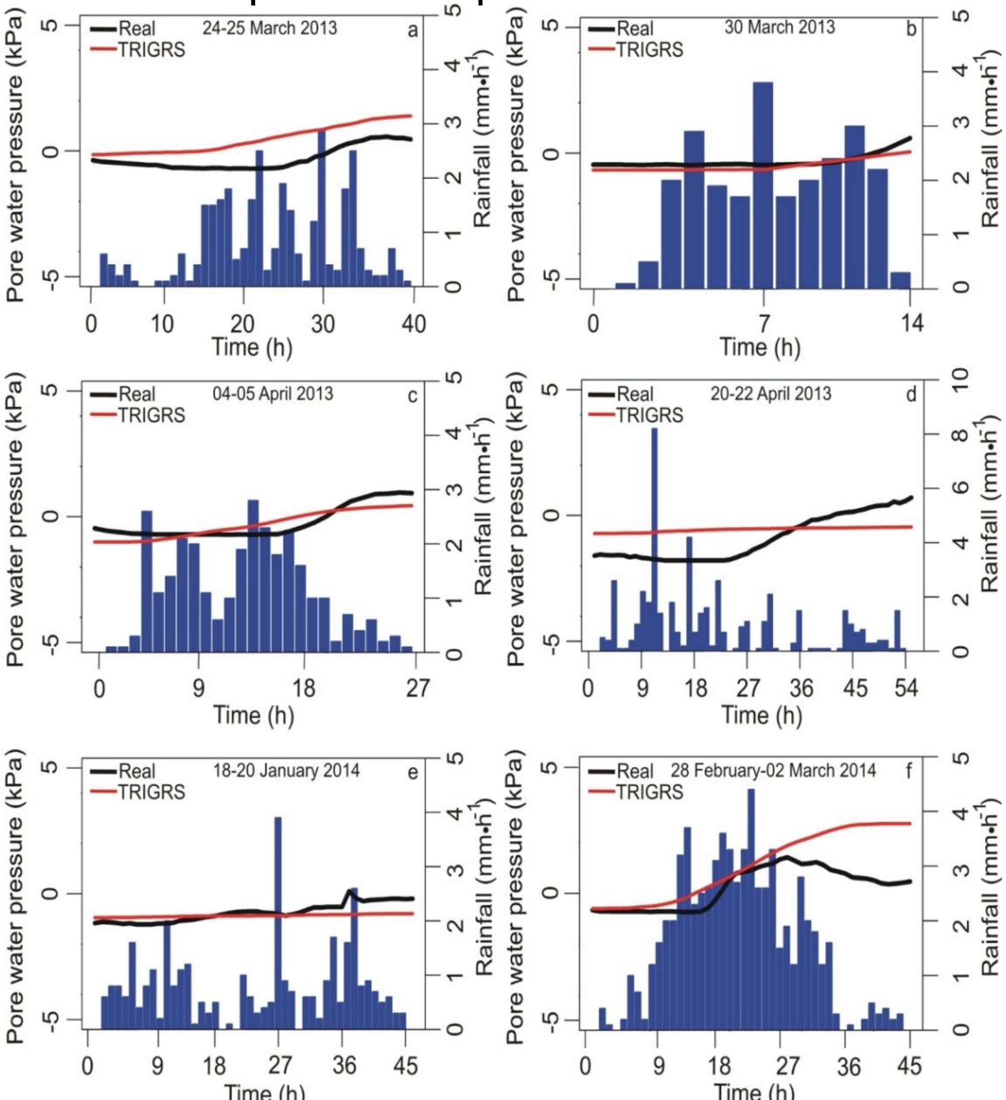
$$F_S(Z,t) = \frac{\tan\phi'}{\tan\delta} + \frac{c' - \psi(Z,t)\gamma_W \tan\phi'}{\gamma_S Z \sin\delta\cos\delta}$$

φ'= friction angle of the soil
δ= slope angle
c '= effective cohesion
γ_s = soil unit weight
γ_w = water unit weight
Z = depth
ψ= pore water pressure

6.3 Results – Slope stability analysis at catchment scale

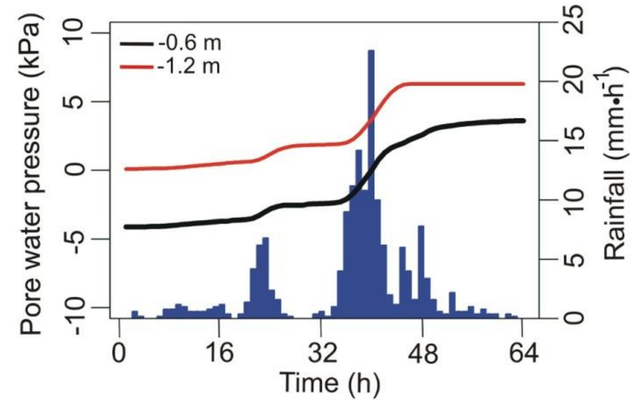
Calibration of the model at site-specific scale

1) Comparison between real and estimated pore water pressure trends



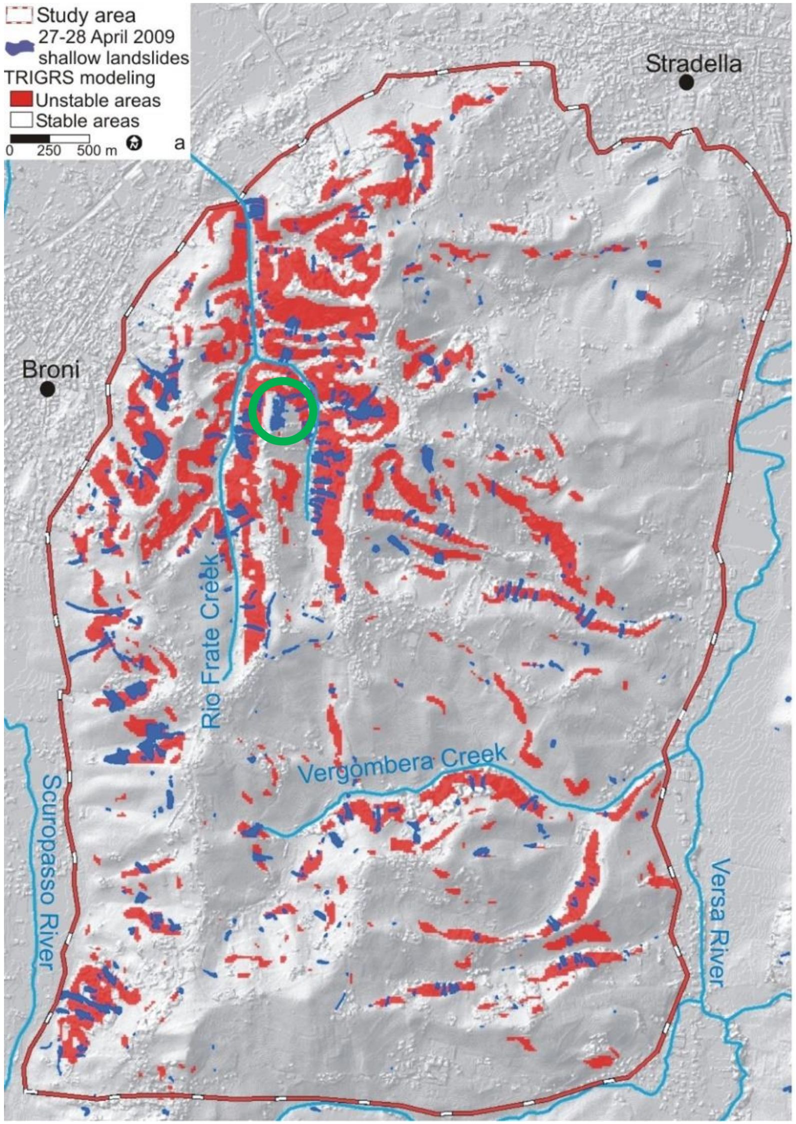
Good assessment (RMSE = 0.2-1.2 kPa)

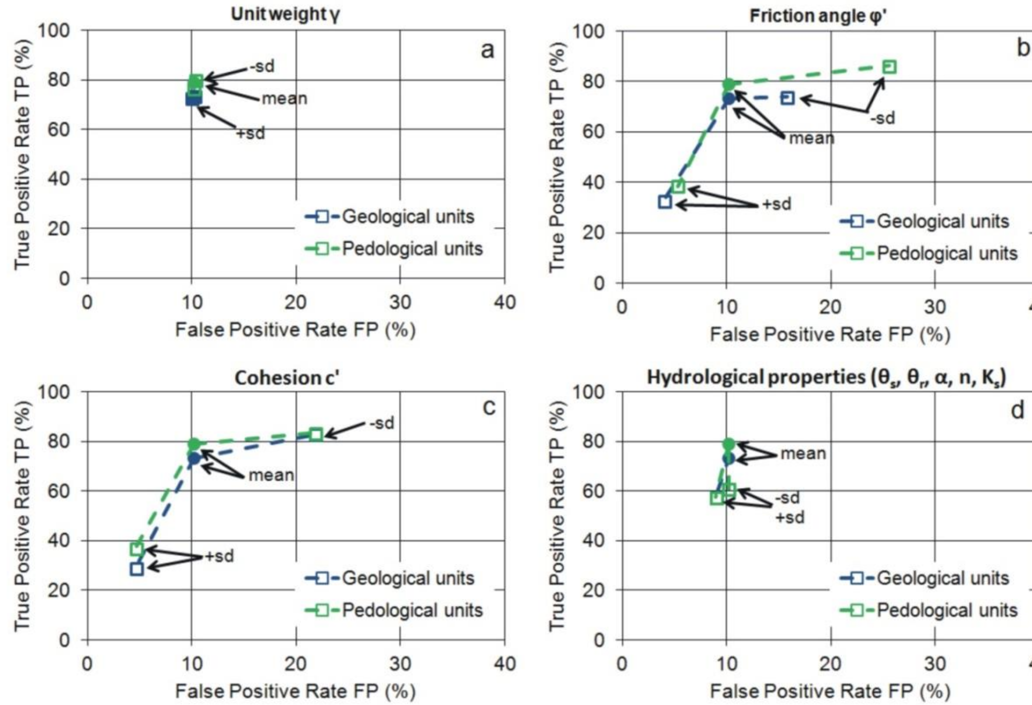
2) Estimated pore water pressure trend of 27-28 April 2009 event



3) Shallow landslides triggering zone assessment at monitored slope

6.3 Results – Slope stability analysis at catchment scale





Units	FP	TP	ratio TP/FP
Geological	10.2	73.3	7.2
Pedological	10.2	78.9	7.7

1) **Good predictive capability at local scale**
2) **No significant differences using geological or pedological units**
3) **Mean values of soil properties give the best results**

7. Conclusions

- **Simultaneous measurements of water content and pore water pressure are required** to identify different soil hydrological behaviors and main shallow landslide triggering mechanisms

- **Coupling different sensors (HD or MPS-6 sensors and tensiometers)** allows to cover the entire range of variation of pore water pressure and identify complete soil hydrological behaviour

- **Monitoring data allows to a better calibration and implementation of physically-based models**, both at site-specific and catchement scale

- **Main problems and open question**
  - Soil devices installed in trench pit (slow collapse of the trench backfill)
  - No data were acquired in periods of prolonged absence of solar light able to recharge the alimentation system through the solar panel.
  - analysis of hydraulic non-equilibrium processes

8. Andromeda project

A New integrateD hydROgeological Model to assEss landsliDes and flood prone Areas in Oltrepò Pavese

UNIVERSITÀ DI PAVIA

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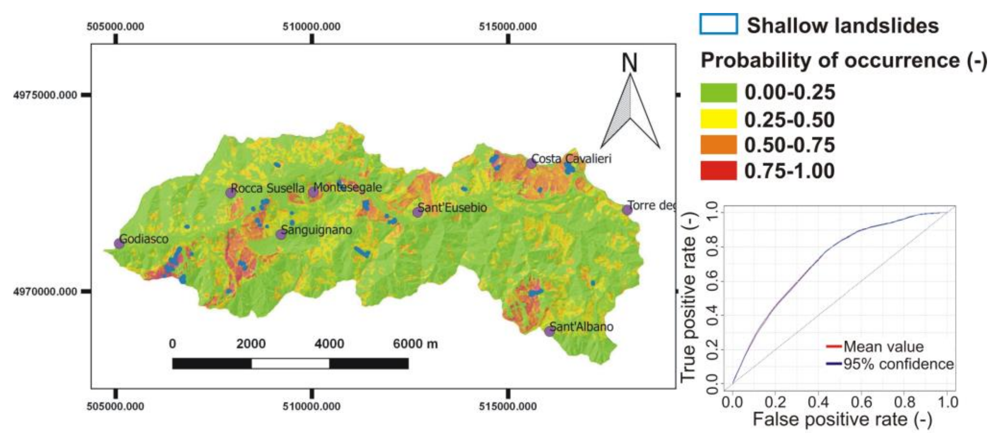
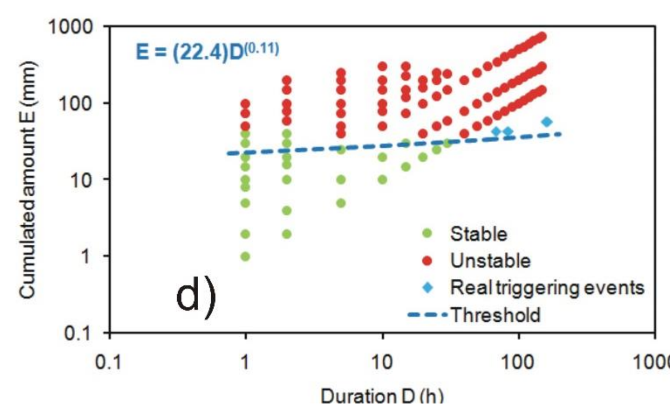
Aims

1. Development and implementation of a **hydrogeological model for the identification of the triggering moments and areas of shallow landslides and floods, using also satellite measures of rainfalls and soil water content**

2. **Prototypal Early Warning System Tool** for shallow landslides and floods based on rainfall thresholds integrating rainfall and soil water content





8. Andromeda project

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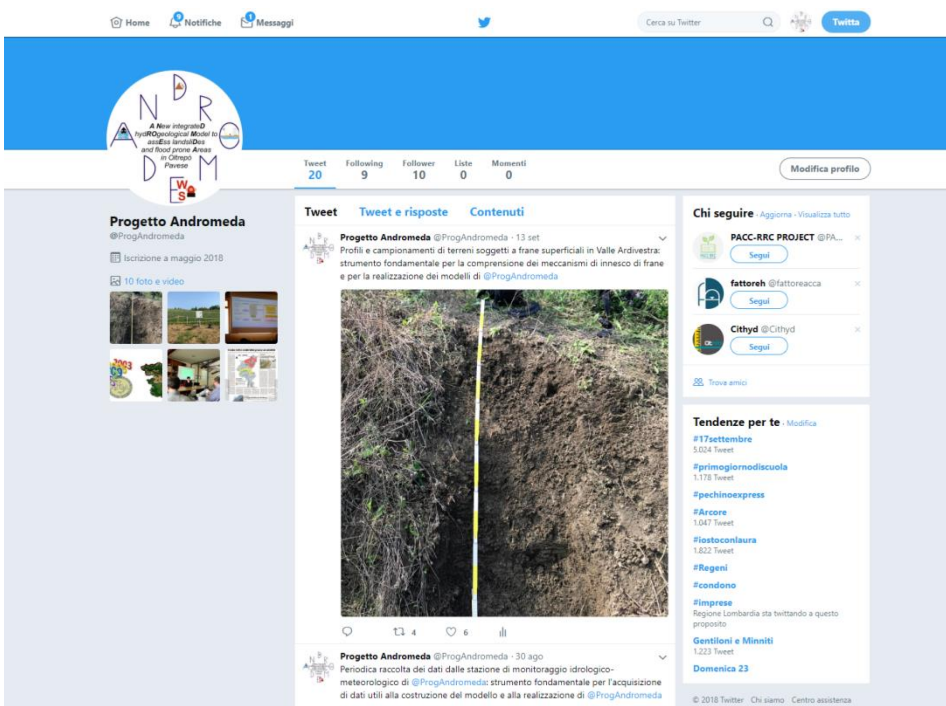

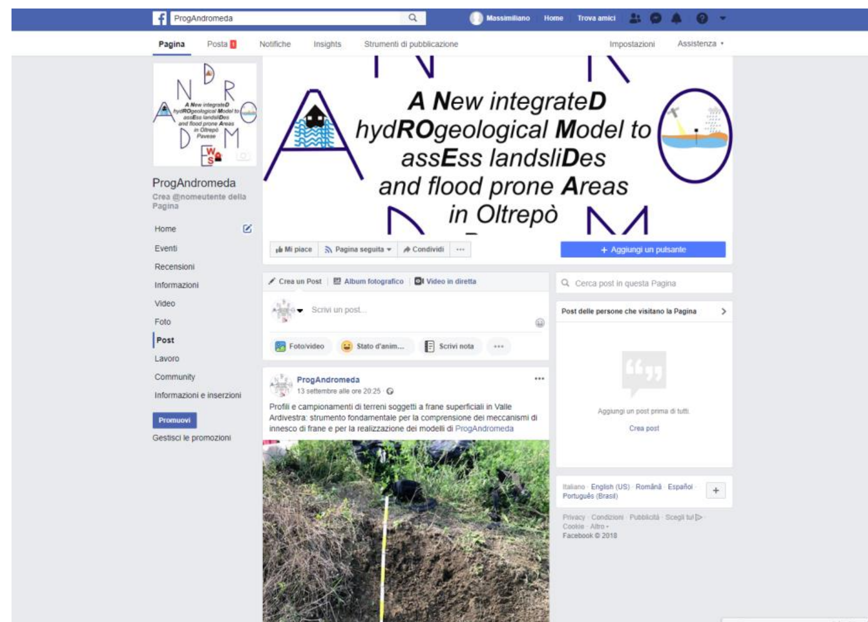

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THANKS FOR THE ATTENTION