Hydro-geophysical techniques for environmental applications: monitoring, modeling and future challenges.

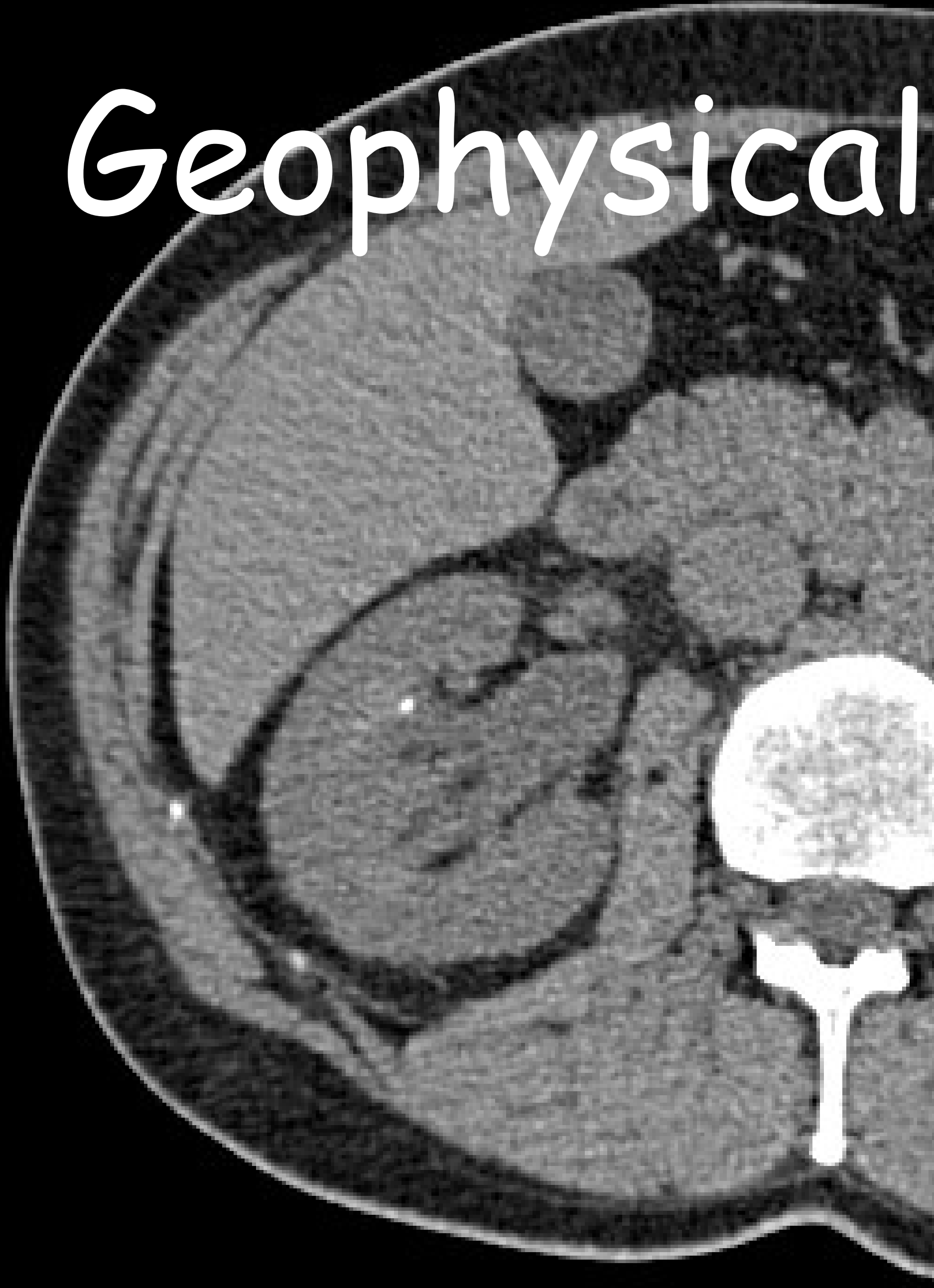
Giorgio Cassiani

with (in Random Order):

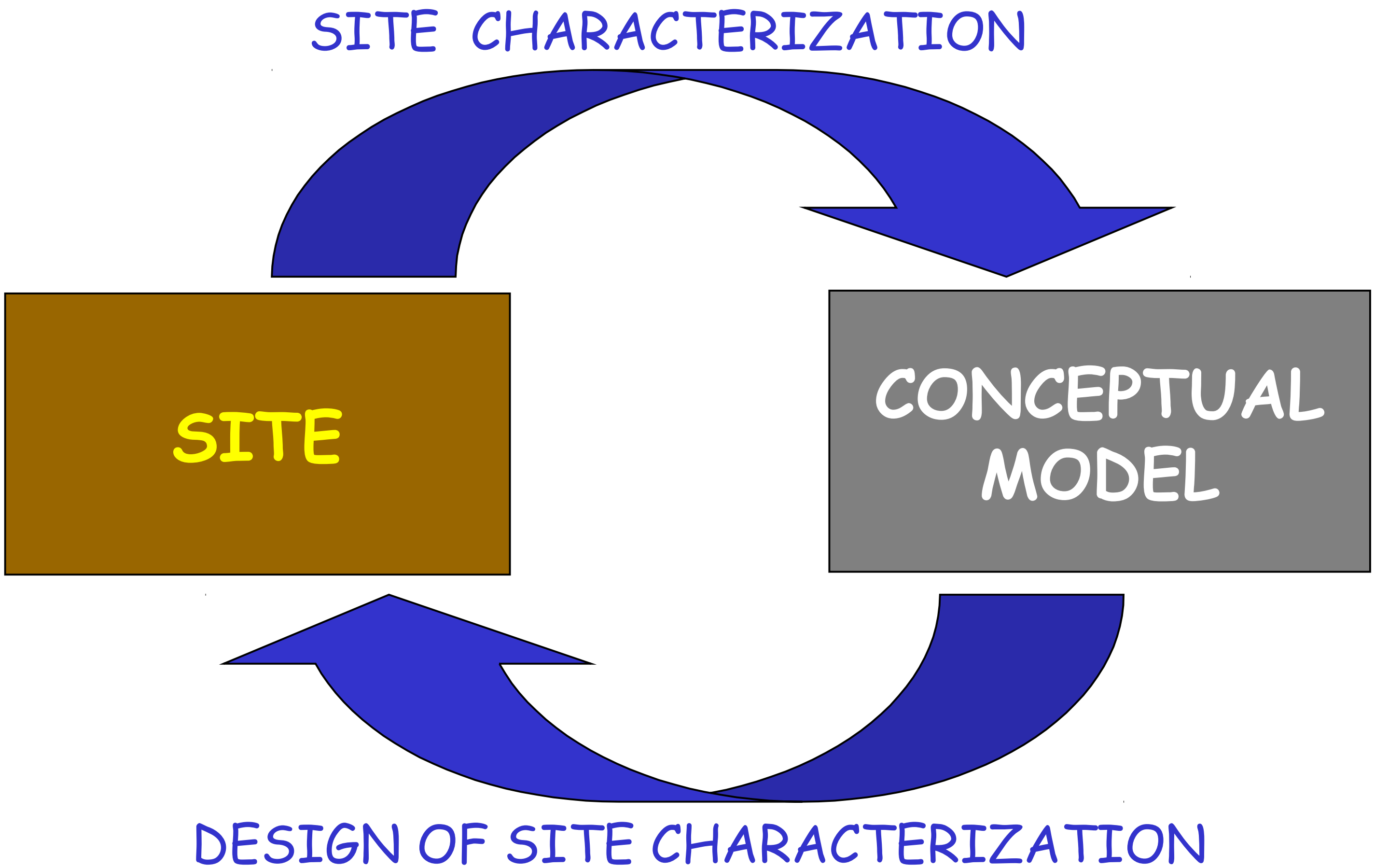
Markus Wehrer, Rita Deiana, Klaus Haaken, Jacopo Boaga, Claudio Paniconi, Giulio Vignoli, Matteo Rossi, Maria Teresa Perri, Damiano Pasetto, Mario Putti, Marco Marani, Alberto Bellin, Bruno Majone, Nicoletta Fusi, Sebastiano Piccolroaz, Franco Palmieri, Andy Binley, Andreas Kemna, Enzo Rizzo, Giuseppe Fadda, Simona Consoli, Daniela Vanella, Adrian Flores Orozco, Gabriele Manoli, Peter Dietrich, Ulrike Werban, Gian Piero Deidda, Nadia Ursino, Andrea D'Alpaos, Matteo Camporese, Oscar Cainelli, Alberto Villa, Paolo Frattini, Giovanni Crosta, Bruno Della Vedova, Paolo Salandin, Isabella Gervasio, Enrico Dezzan, ***and others that I may have forgotten….***

Dipartimento di Geoscienze – Università di Padova

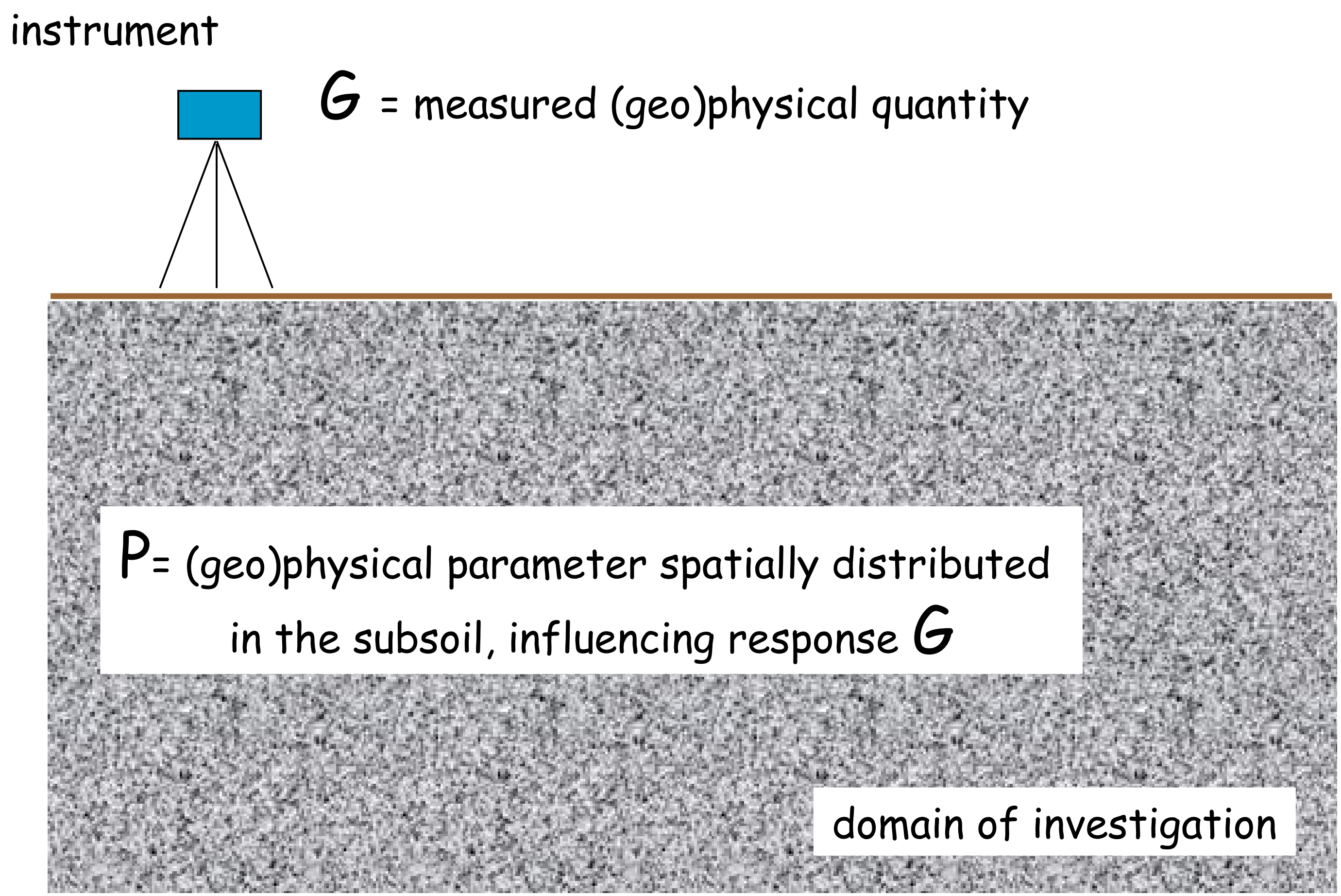
Geophysical Imaging



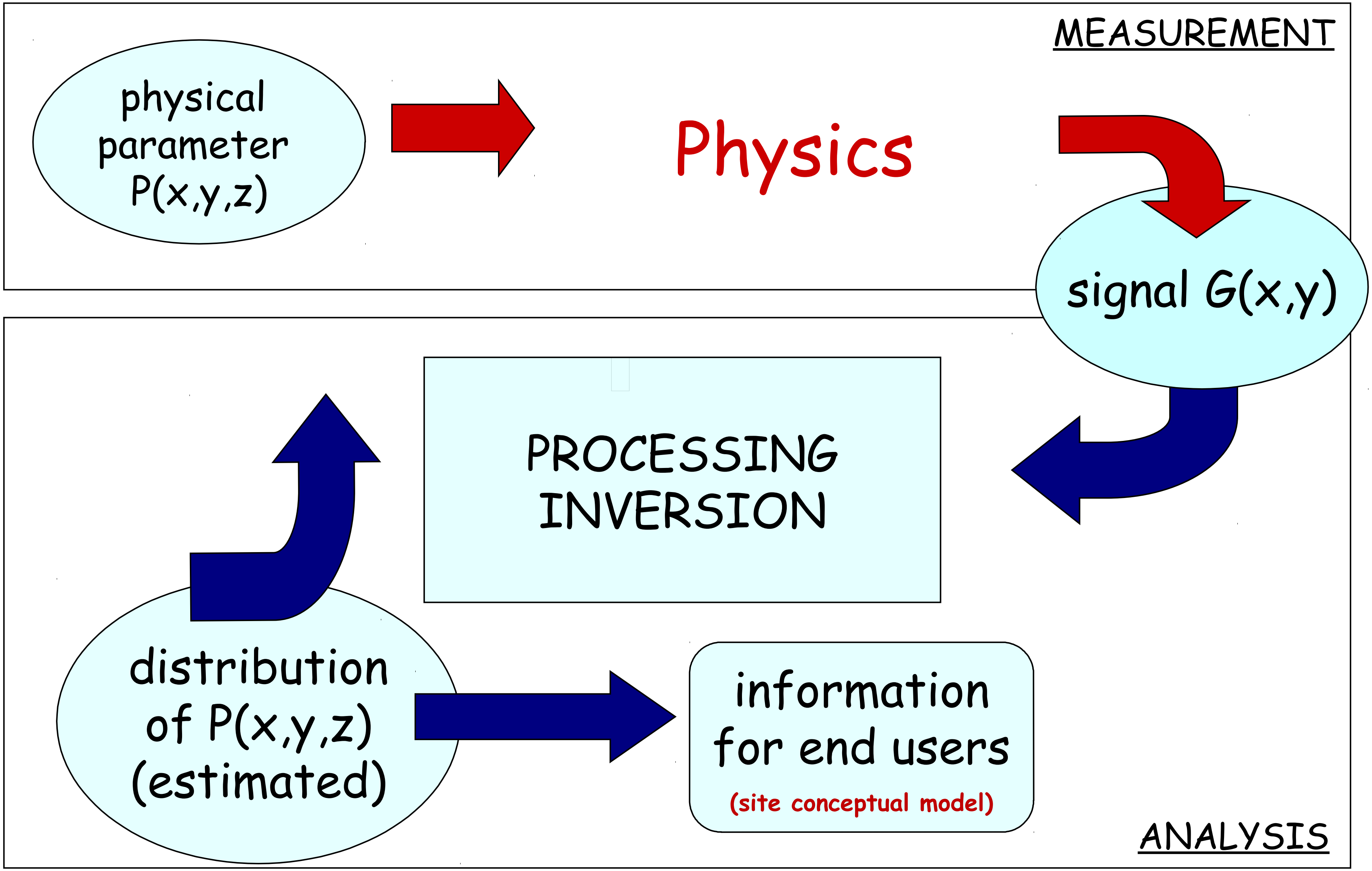
What is the role of applied geophysics ?



Geophysical measurements



$$G = G(P,\ F = \text{forcing conditions})$$


MEASUREMENT
physical parameter P(x,y,z)
Physics
signal G(x,y)
PROCESSING INVERSION
distribution of P(x,y,z) (estimated)
information for end users
(site conceptual model)
ANALYSIS

GEOPHYSICAL METHODS ⟷ **APPLICATIONS**

?

- Geo-electrics
- Seismics
- GPR
- EM methods
- Gravimetry
- Magnetism
- ...

- Hydrocarbon exploration
- Mineral exploration
- Engineering studies
- Hydrogeological studies
- Contaminant identification
- Geological investigations
- Forensic studies
- Archaelogical studies
- ...

GEOPHYSICAL METHODS ⟷ **APPLICATIONS**

The choice should be made according to the following criteria:

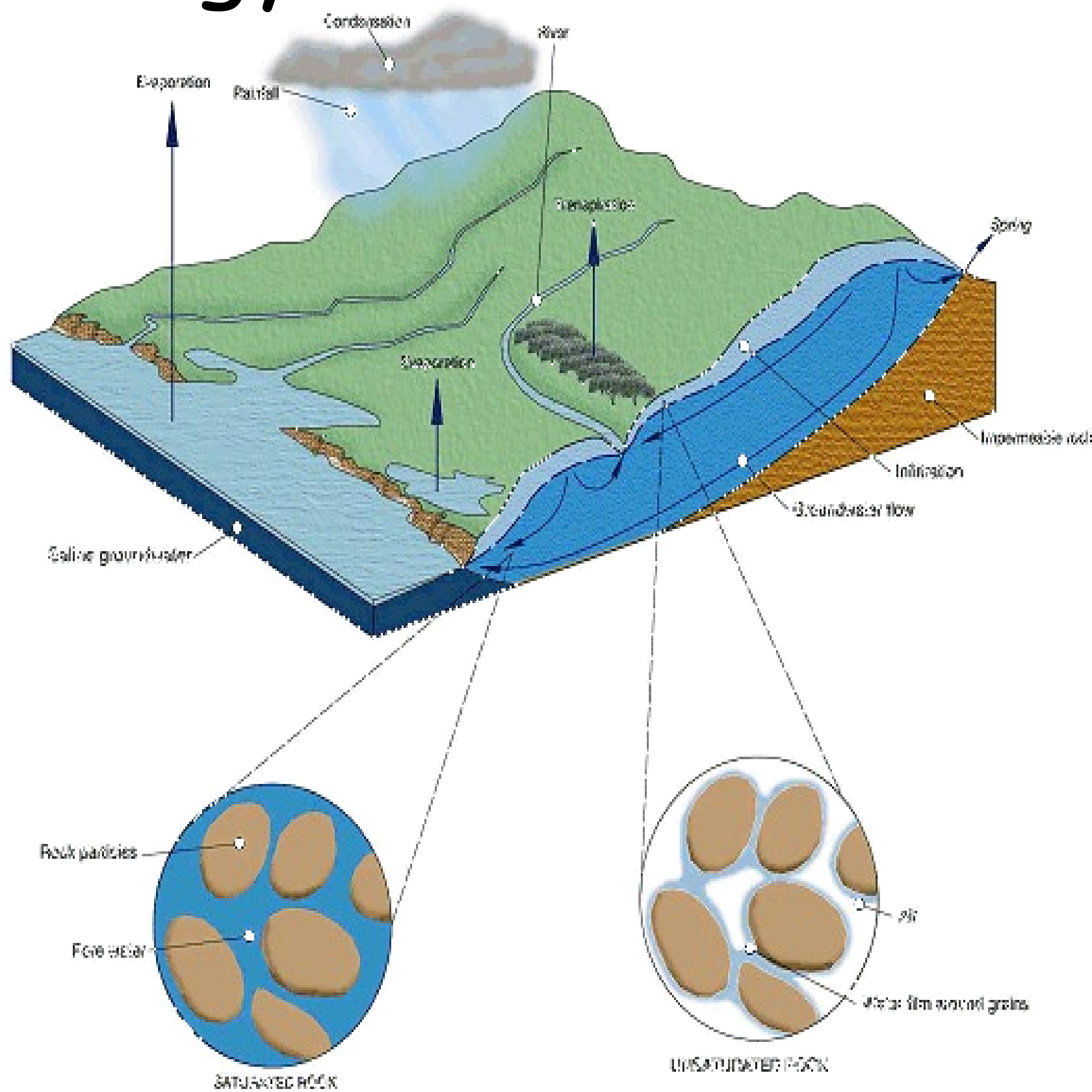
- the goal of the application must be compatible with the measured physical quantity
- the method must have sufficient spatial (and temporal) **resolution** and sufficient **penetration**
- cost
- logistics
- environmental impact

SUMMARY

- Hydro-geophysics: a problem-driven discipline
- A Glimpse to a number of applications
- Conclusions and outlook

Hydrology

Floods
Mountain slope stability
Soil/groundwater contamination



Water in the shallow subsurface
carries energy
modifies the state of stress
carries contaminants

Environmental fluid-dynamics
(hydrology)

Shallow geophysics
(hydro-geophysics)

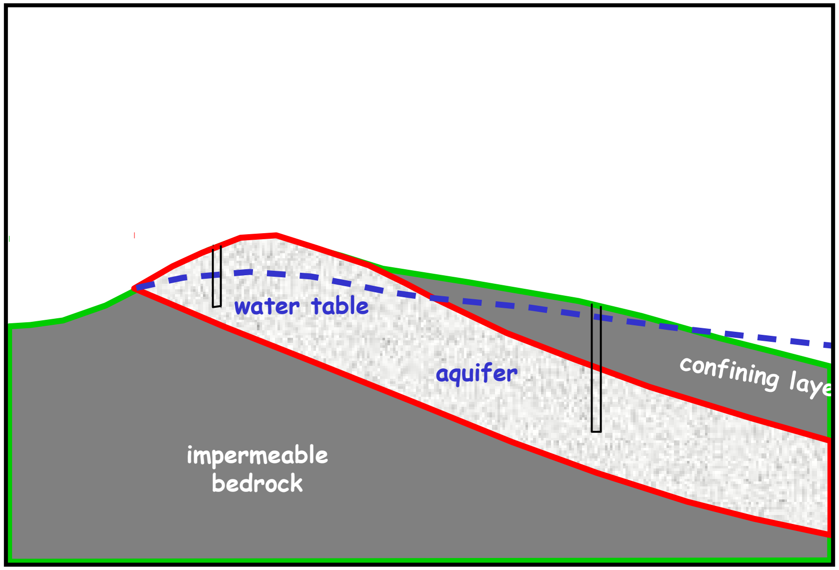
Applicable methods and measured physical quantities

METHOD	PHYSICAL PROPERTY
Seismics	elastic properties and density
Electro-magnetic methods	electrical conductivity /resistivity
DC resistivity methods	electrical conductivity /resistivity
Gamma ray spectrometry	natural gamma radiation
Ground Penetrating Radar	dielectric constant (electrical conductivity)
Magnetics	magnetic susceptibility / permanent magnetization
Gravimetry	density
(Spectral) Induced Polarization	complex electrical conductivity
Self Potential	DC sources
Nuclear Magnetic Resonance	free water content and decay time

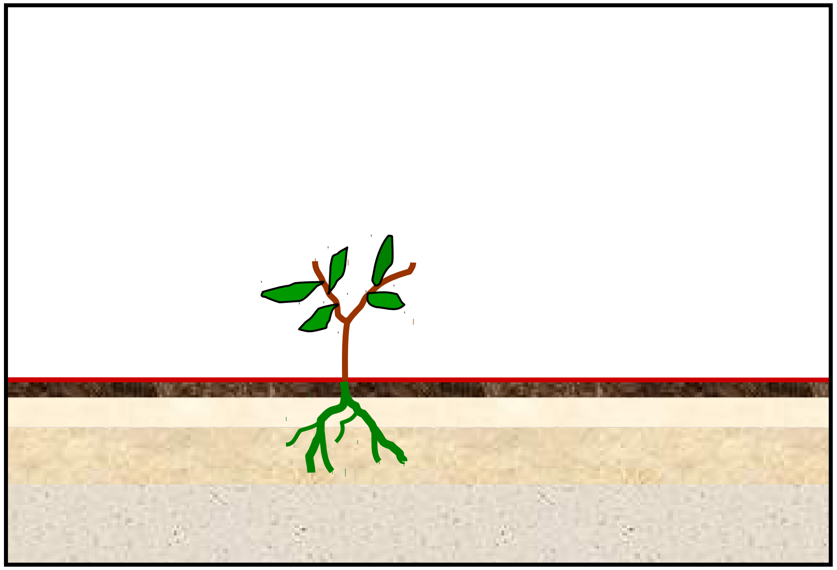
What geophysical methods can help define

What geophysical methods can help define

- structure / texture



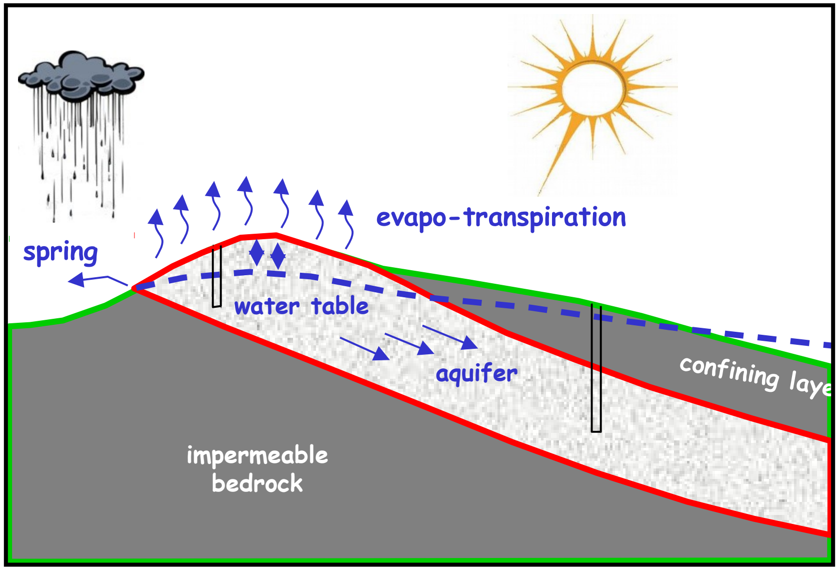
large scale



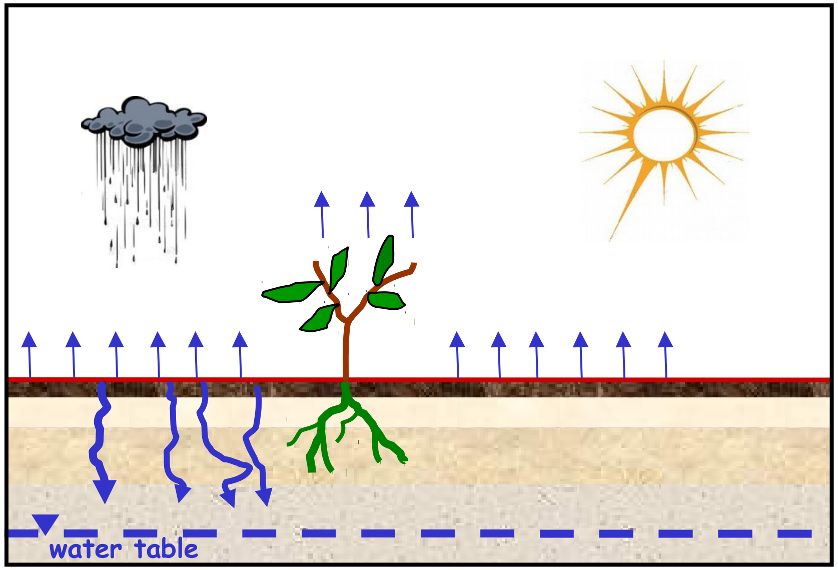
small scale

What geophysical methods can help define

- structure / texture
- fluid-dynamics: e.g. time-lapse evolution of moisture content



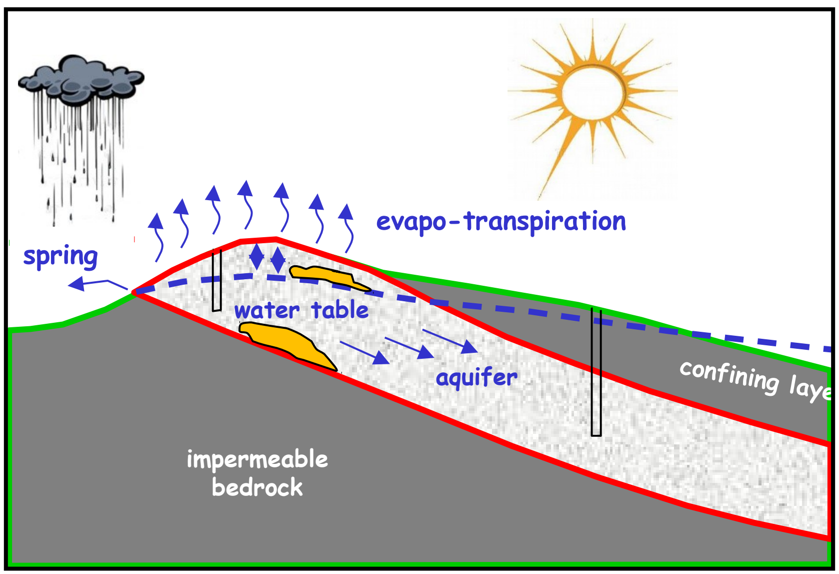
large scale



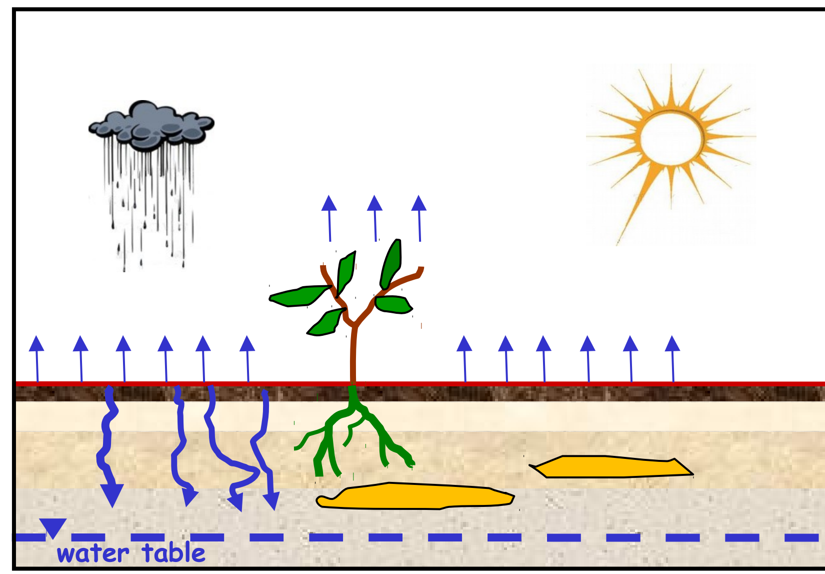
small scale

What geophysical methods can help define

- structure / texture
- fluid-dynamics: e.g. time-lapse evolution of moisture content
- contamination



large scale



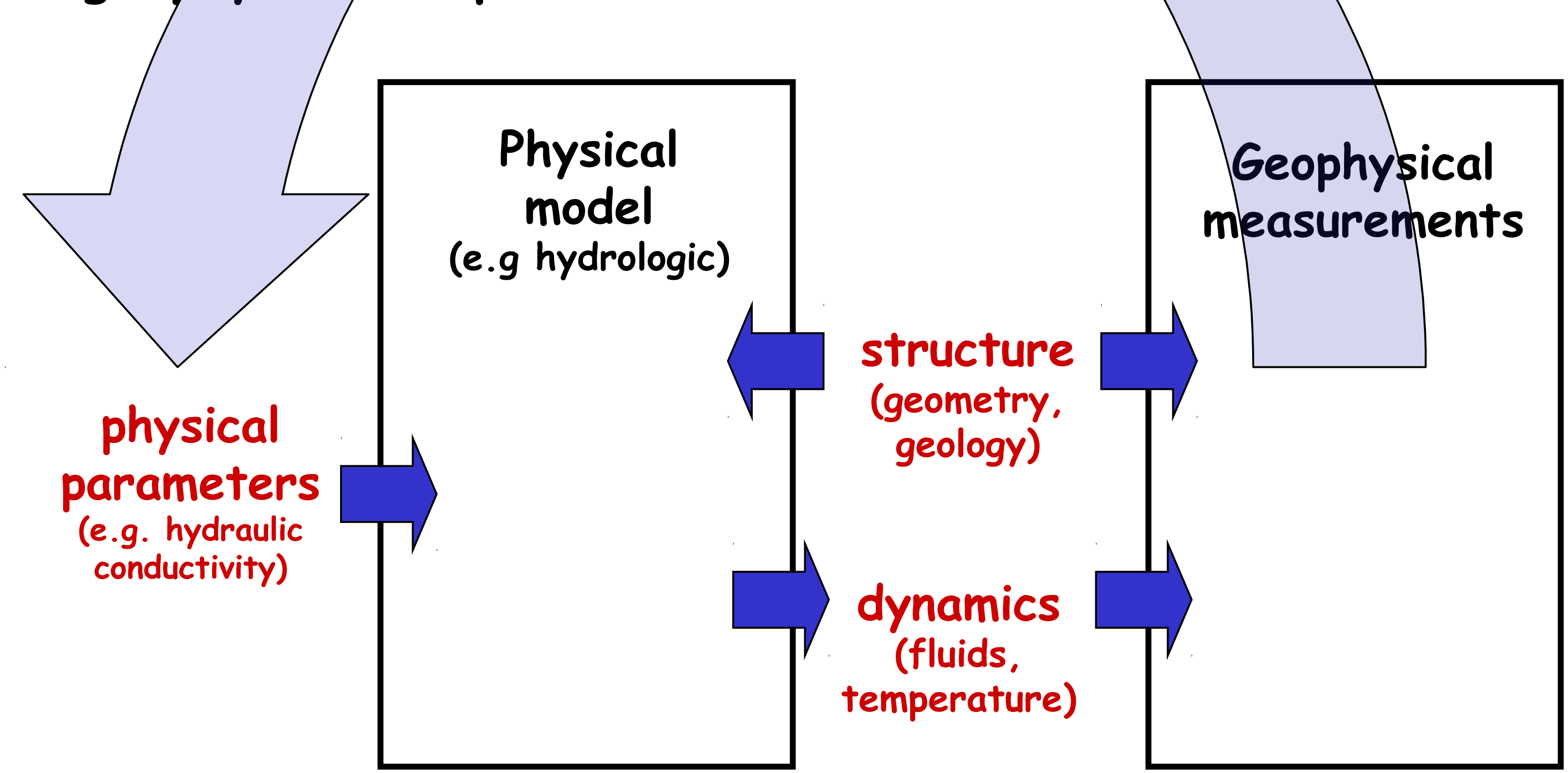
small scale

Applicable methods and subsurface characteristics

METHOD	STRUCTURE	DYNAMICS	CONTAMINATION
Seismics	++		
Electro-magnetic methods	+	++	+
DC resistivity methods	++	++	+
Gamma ray spectrometry	++		
Ground Penetrating Radar	++	++	+
Magnetics	+		
Gravimetry	+	++	
(Spectral) Induced Polarization	+	+	++
Self Potential		++	+
Nuclear Magnetic Resonance	+	++	

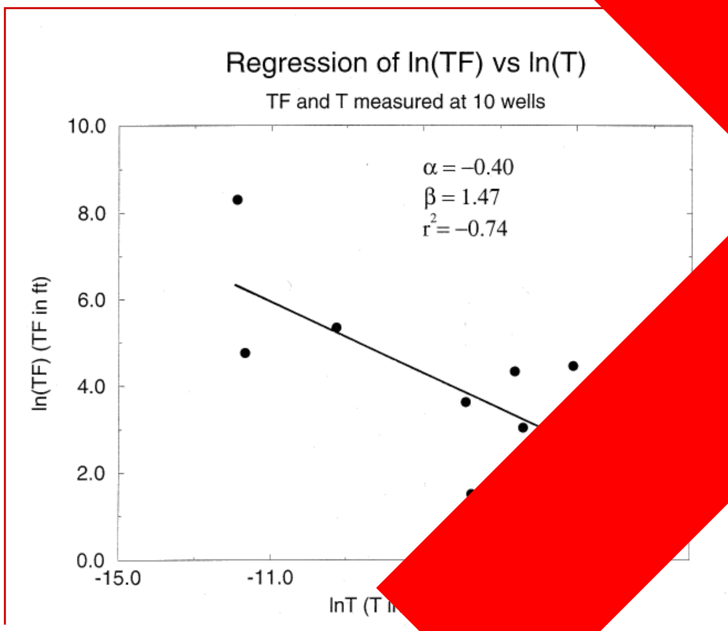
GOAL

Integrate measurements and physical models that explain the **space-time evolution of state variables** such as moisture content, solute concentration and temperature that affect the **space-time changes of geophysical response**.

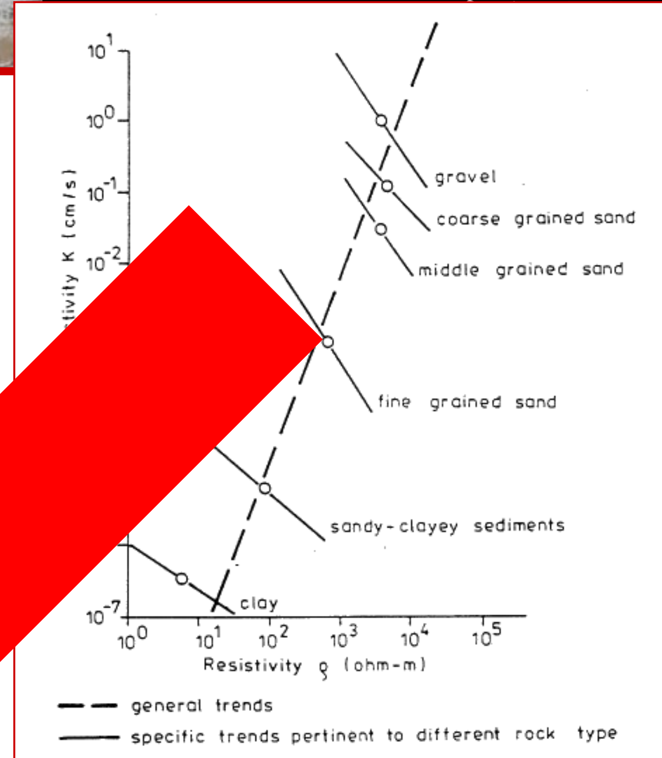


"Vintage" approach:

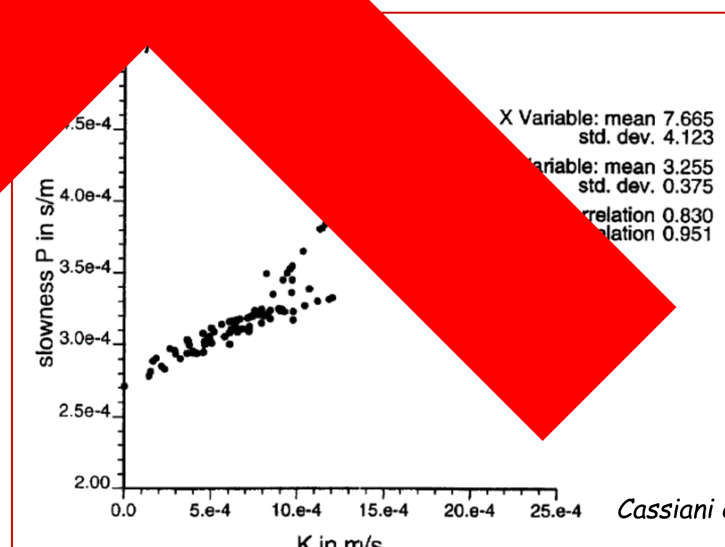
direct link between p... al properties of models and ge... uantities



Cassiani and Medina, GW, 1995



Mazac et al., 1985



Cassiani et al., JH, 1998

measured or simulated geophysical quantity (saturation, concentration)

measured or simulated geophysical data

Applicable methods

Ground-Penetrating Radar (**GPR**)

Electrical Resistivity Tomography (**ERT**)

... etc

Time – lapse geophysics

static aspects (geology)

dynamic aspects (hydrology)

Acquisition geometry (resolution-sensitivity issues)

cross-hole

surface-to-hole

surface-to-surface

Hydrology – Geophysics constitutive relationships

dielectric properties (GPR)

DC resistivity (ERT)

complex resistivity (SIP)

A glimpse to applications

- Vadose zone
- Aquifers
- Hillslope
- Catchment
- Contamination
- Critical zone
- Hyporheic zone
- Conclusions
- Acknowledgments

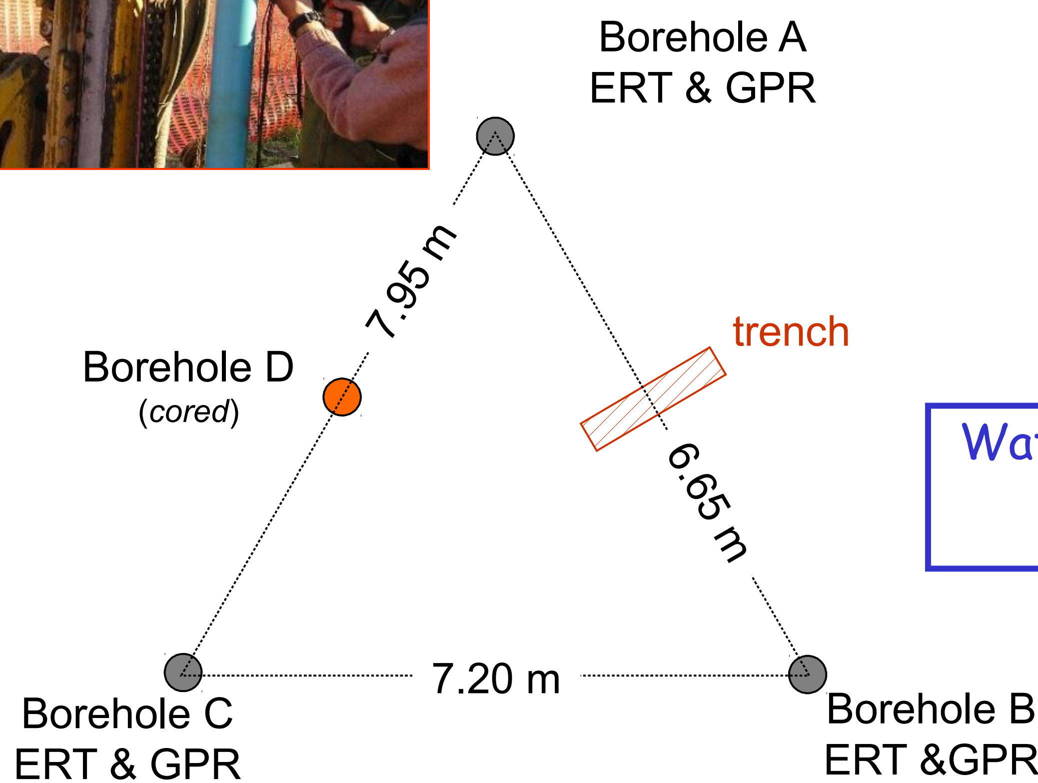
SUMMARY

- Hydro-geophysics: a problem-driven discipline
- A Glimpse to a number of applications

Vadose zone characterization

- Conclusions and outlook

Characterisation of the vadose zone of the Po river plain sediments: the Gorgonzola (Milan) test site

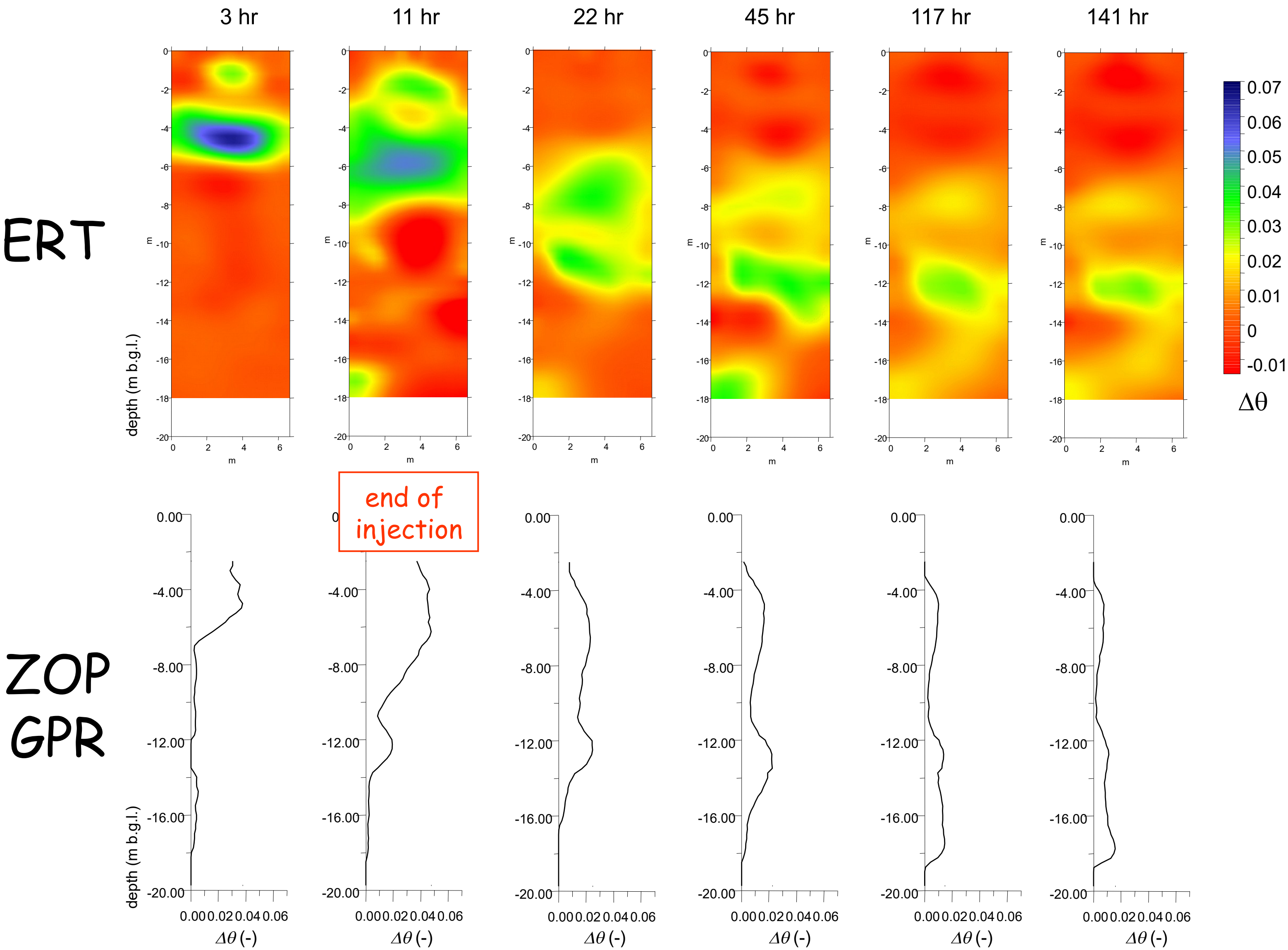


Water injection experiment in trench

22 m³ of water in 10 hours

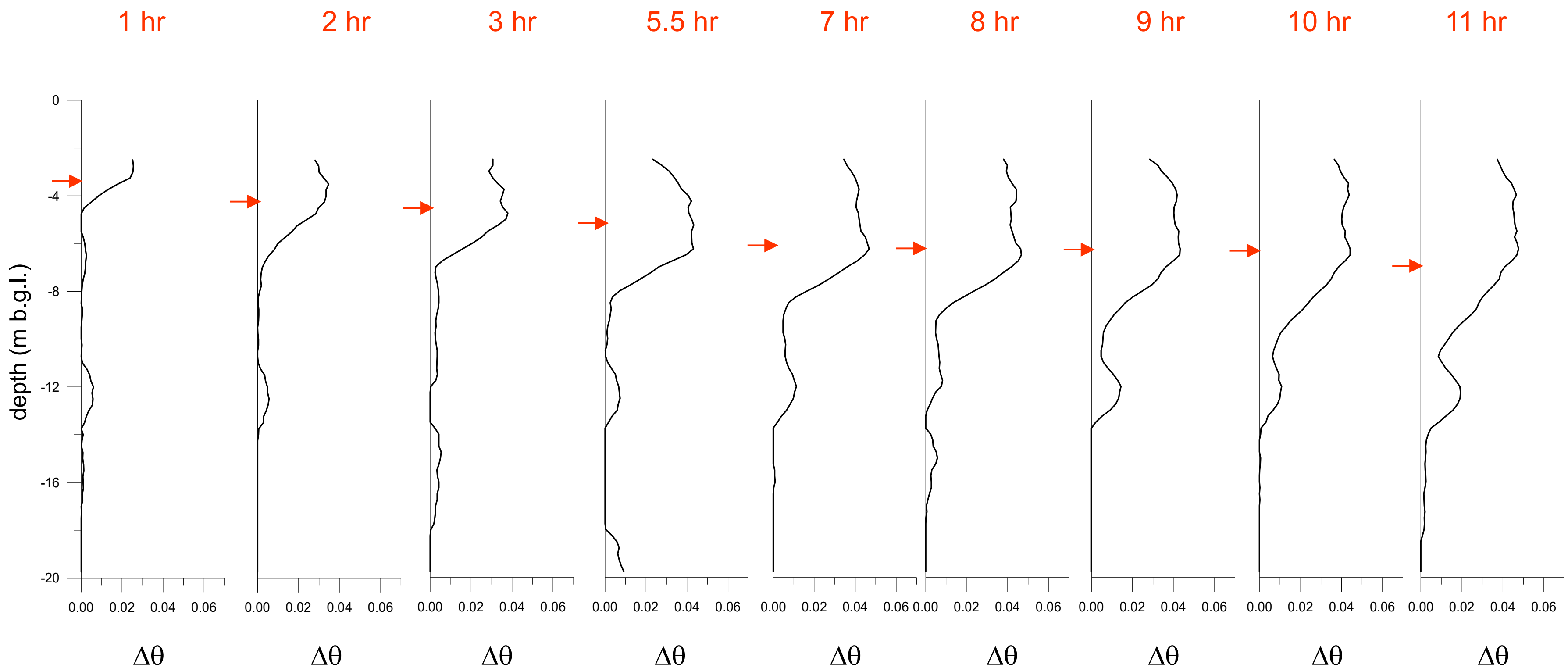
Deiana et al., VZJ, 2008

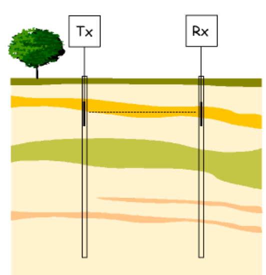
Gorgonzola: injection experiment



Deiana et al., VZJ, 2008

Injection phase





zop GPR

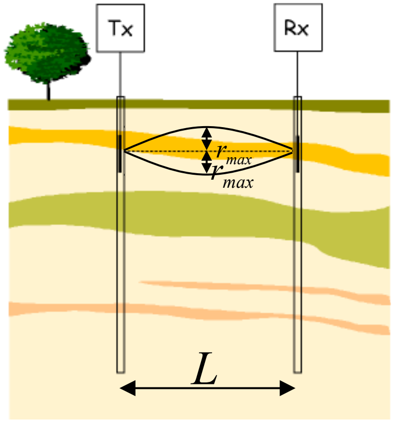
Deiana et al., VZJ, 2008

MASS BALANCE

known injected mass

MODEL

Fresnel volume

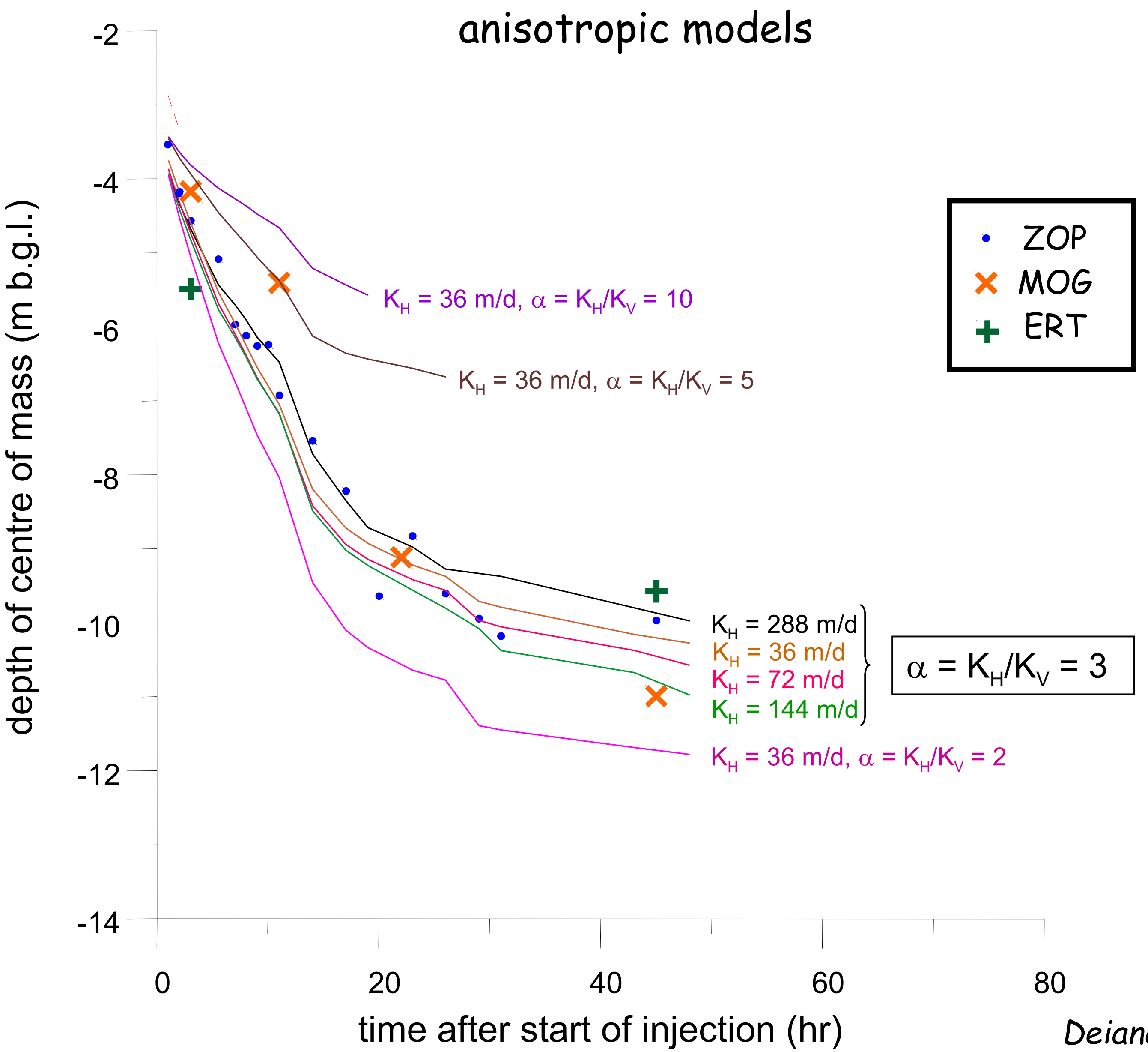


FIELD DATA

mass in given control volume

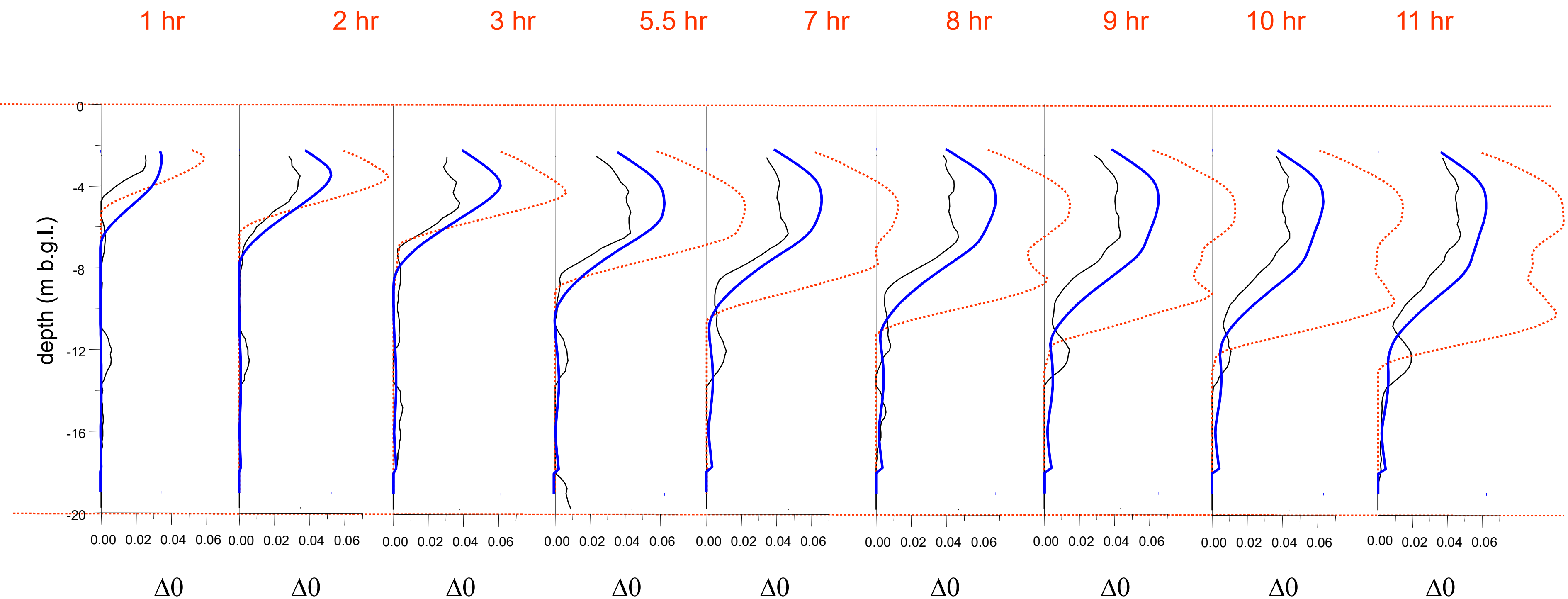
mass in given control volume

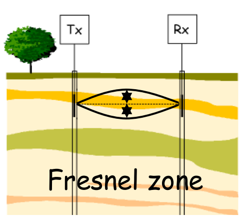
Model calibration on the centre of mass



Deiana et al., VZJ, 2008

Injection phase





measured using zop GPR

simulation results: isotropic model with K_s = 5 m/d

simulation results: anisotropic model with K_{sH} = 288 m/d, $\alpha = K_{sH}/K_{sV} = 3$

Deiana et al., VZJ, 2008

SUMMARY

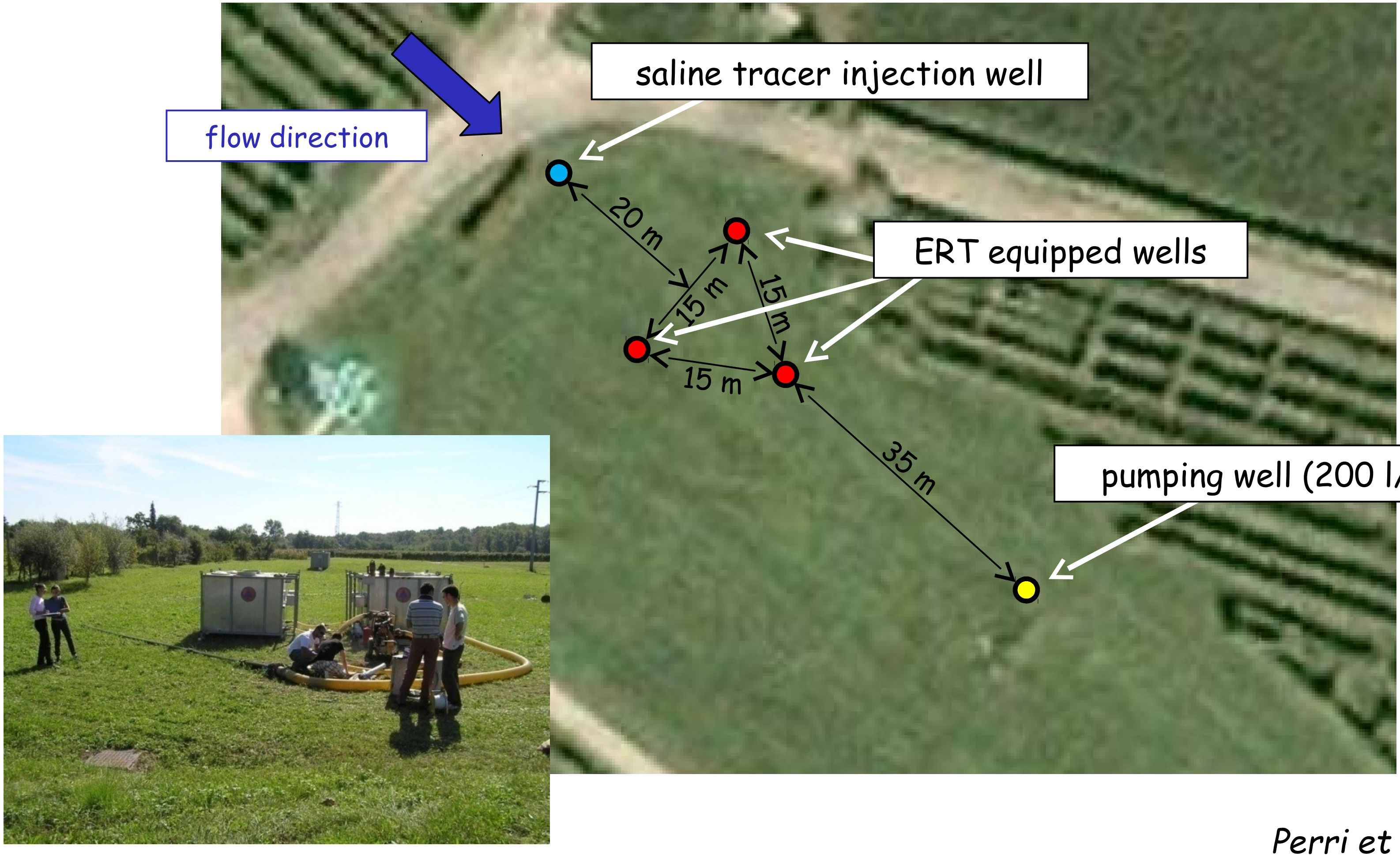
- ❑ Hydro-geophysics: a problem-driven discipline
- ❑ A Glimpse to a number of applications

Aquifer characterization

- ❑ Conclusions and outlook

EXPERIMENTAL TEST AREA – Valdobbiadene – NE Italy

saline tracer test to identify travel times and hydraulic conductivity structure



Perri et al., JAG, 2012

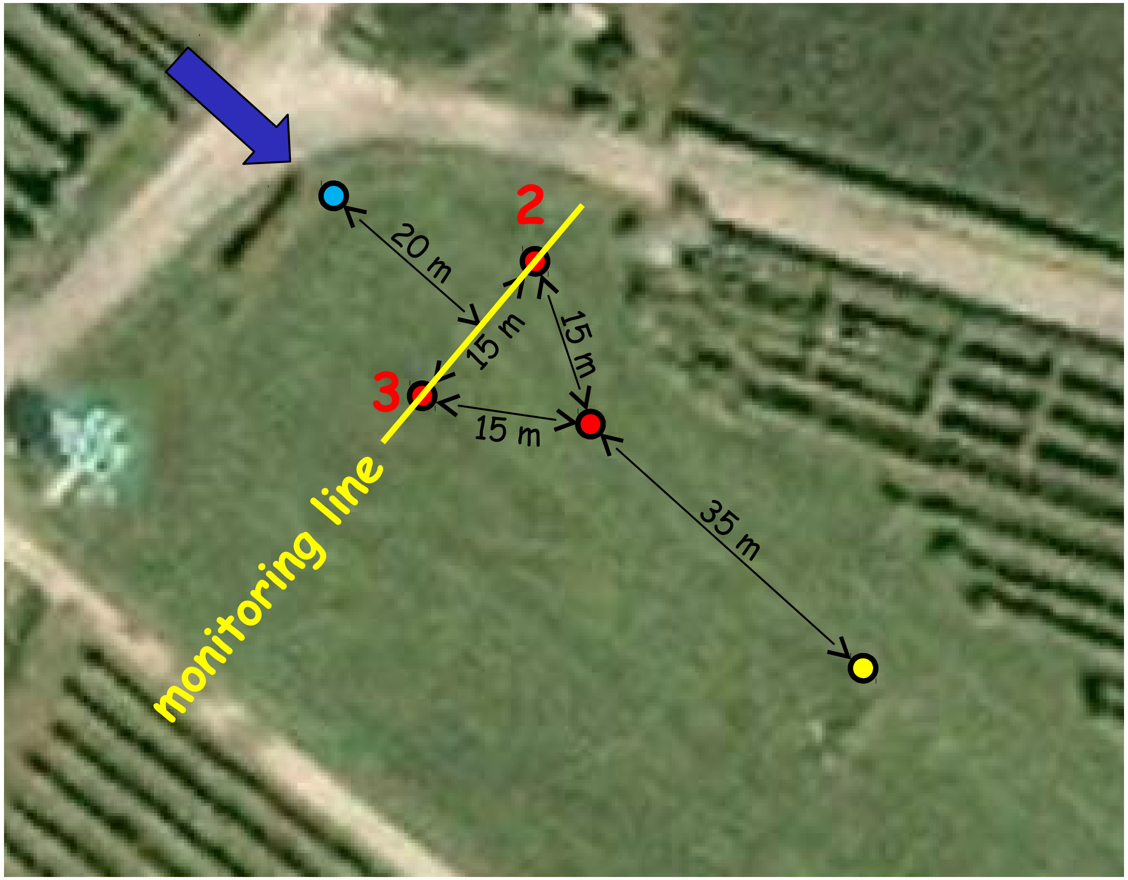
EXPERIMENTAL TEST AREA – Valdobbiadene – NE Italy

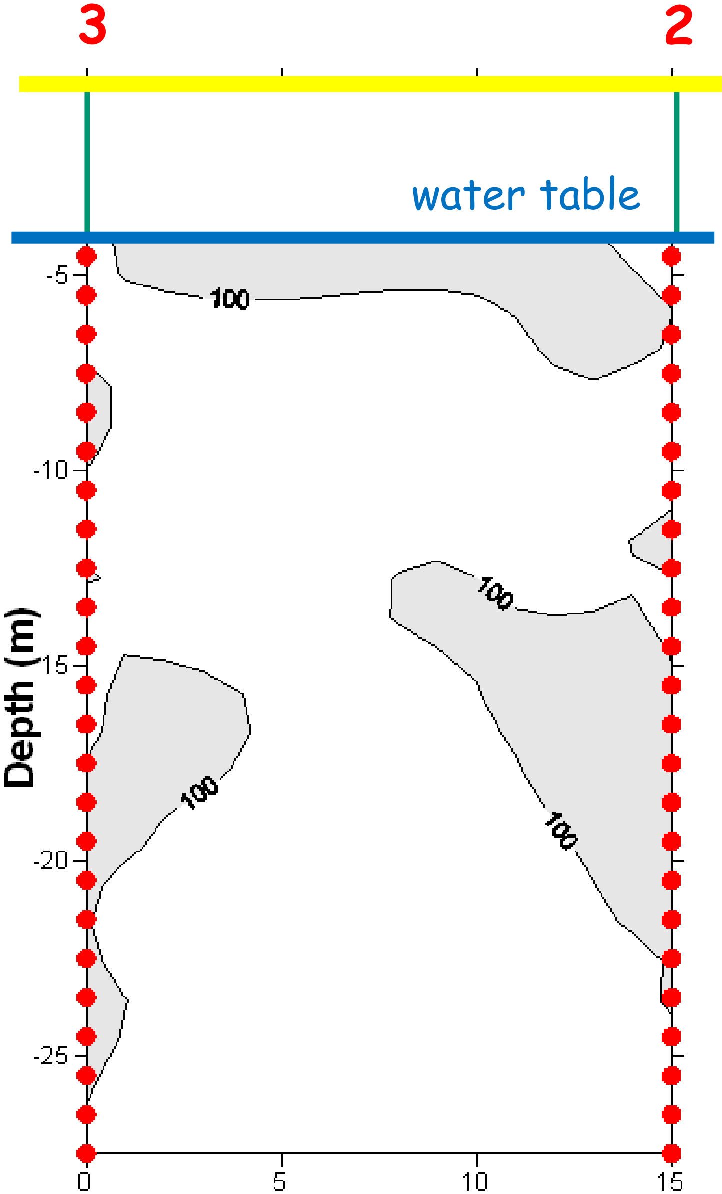
Time 1 (hh:mm): 00:34 after injection

resistivity ratio w.r.t. background

75	80	85	90	95	100

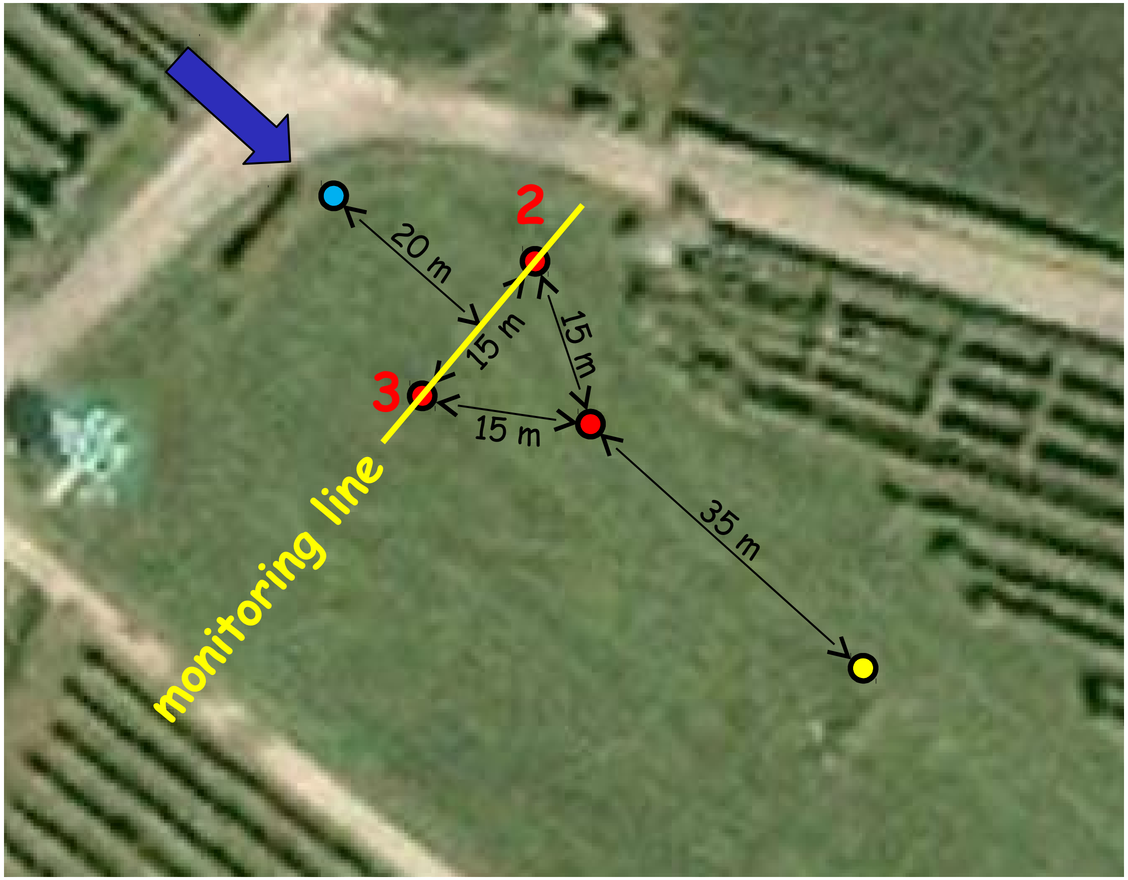
%

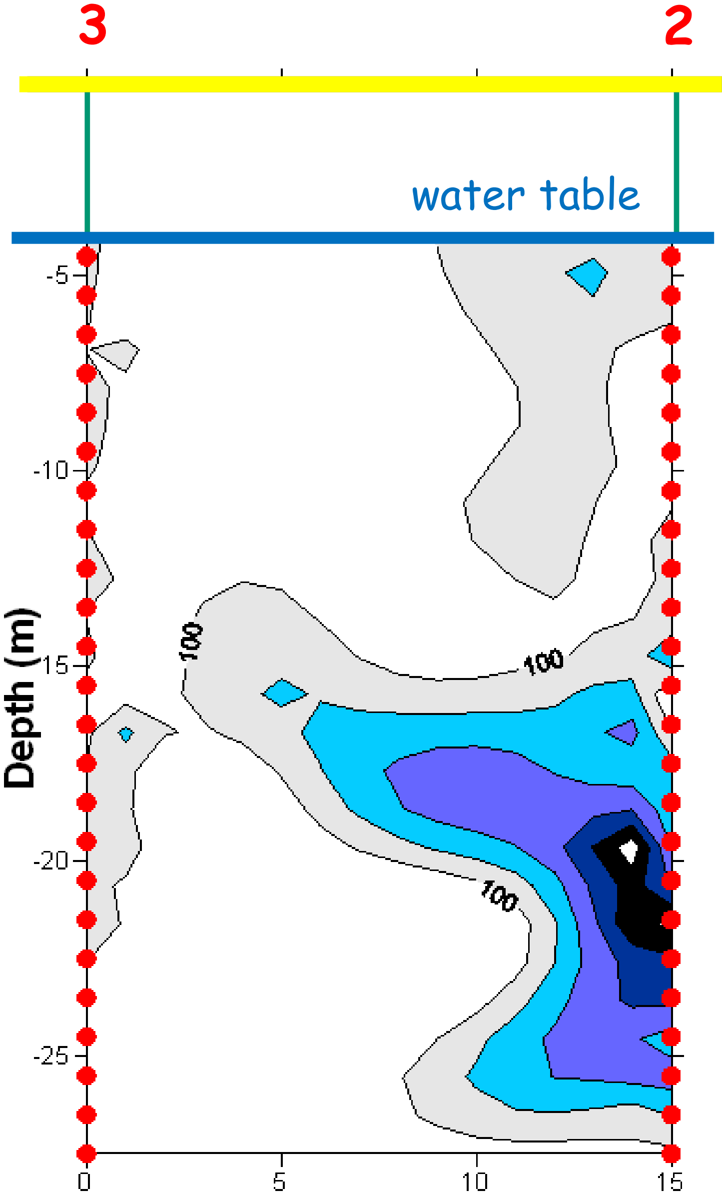




EXPERIMENTAL TEST AREA – Valdobbiadene – NE Italy

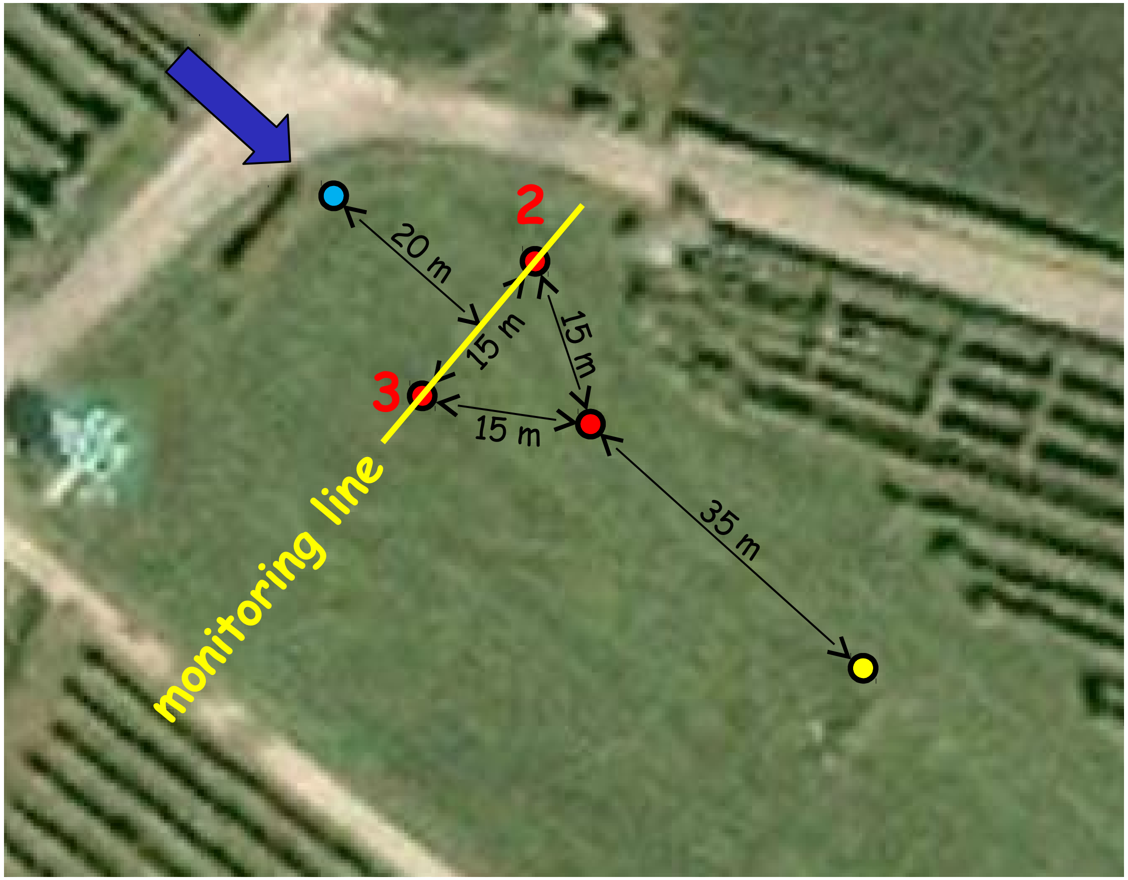
Time 4 (hh:mm): 03:27 after injection

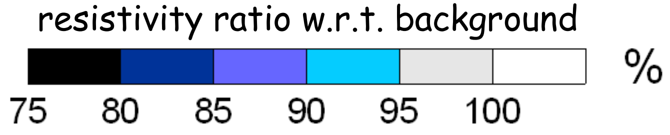


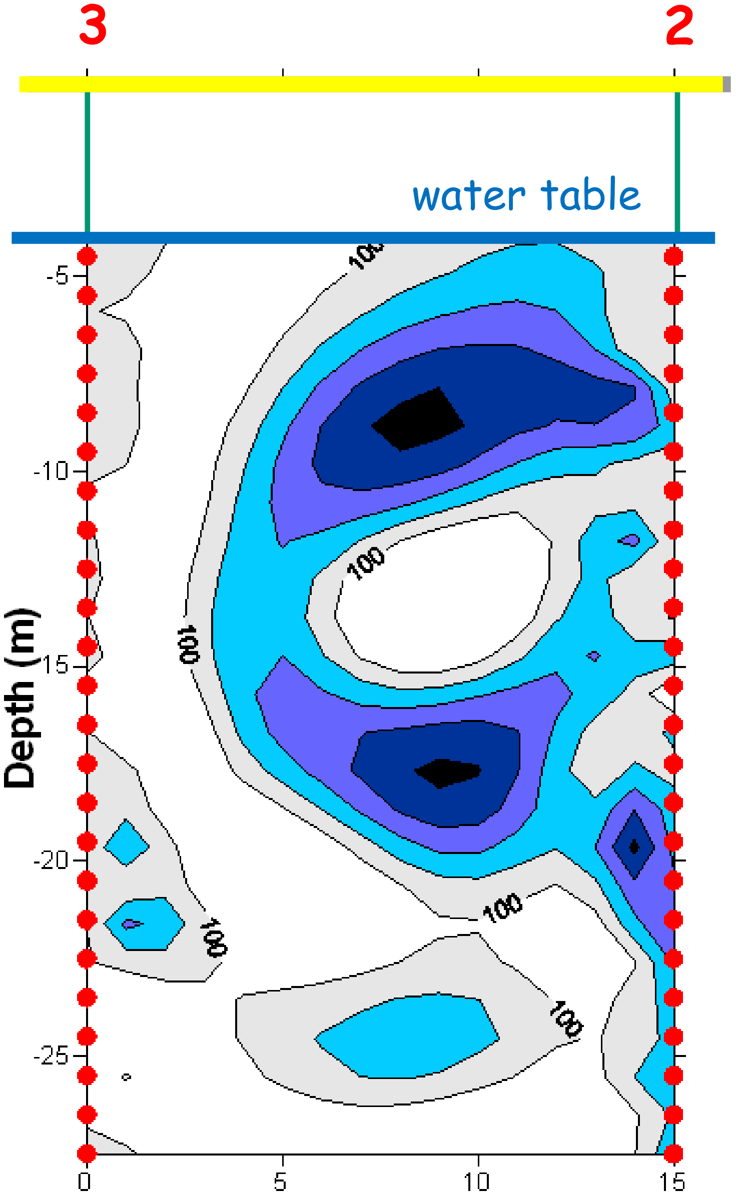


EXPERIMENTAL TEST AREA – Valdobbiadene – NE Italy

Time 13 (hh:mm): 11:30 after injection

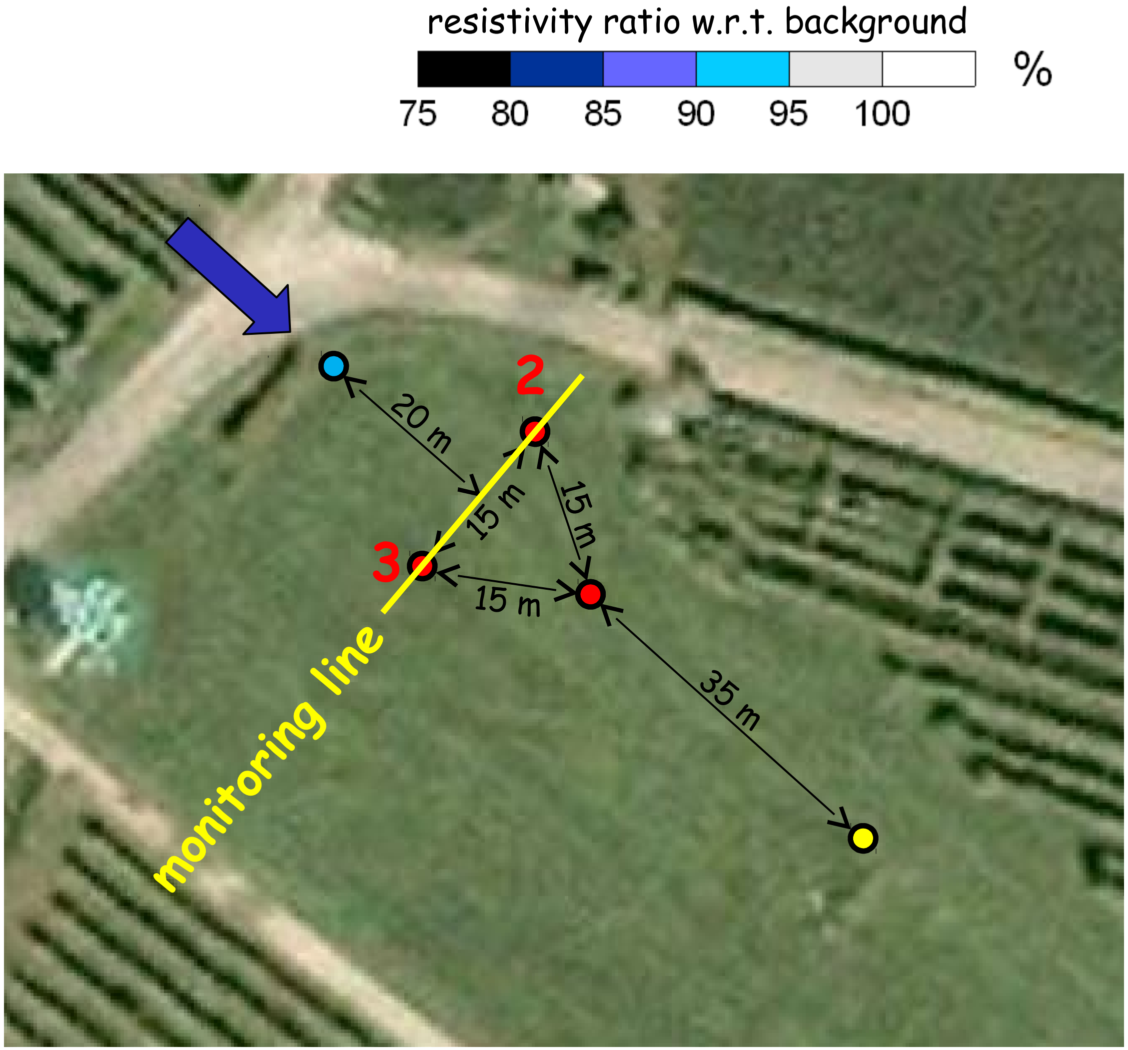


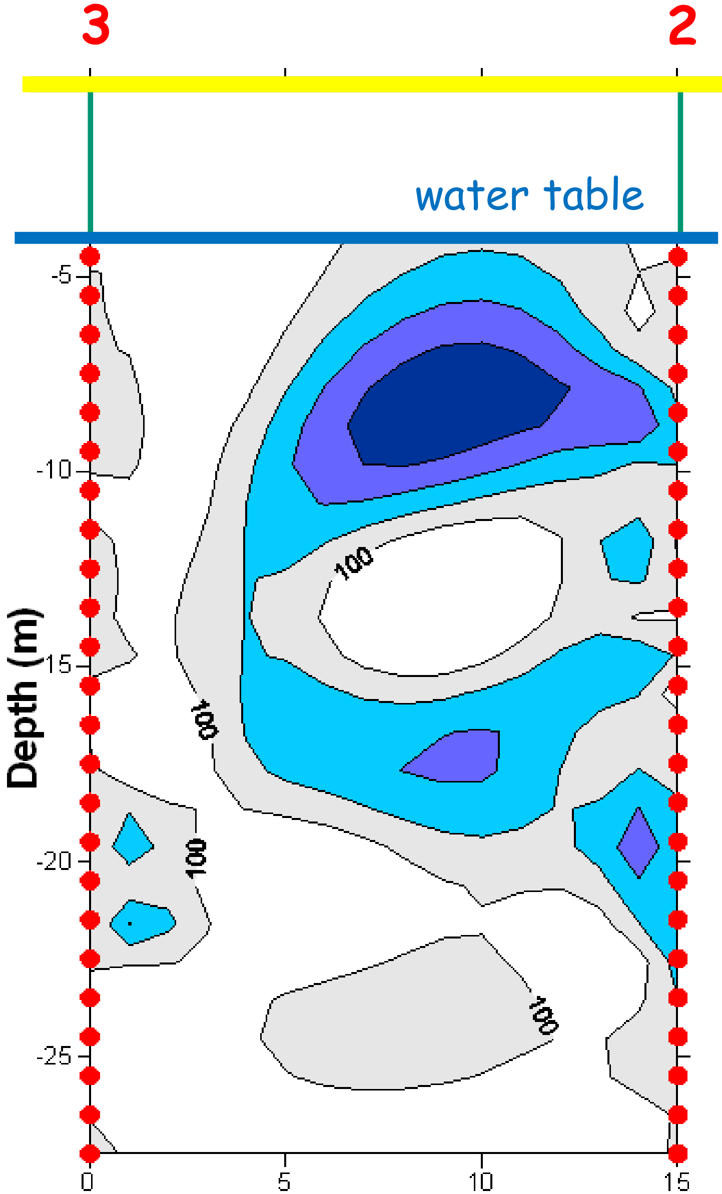




EXPERIMENTAL TEST AREA – Valdobbiadene – NE Italy

Time 21 (hh:mm): 21:43 after injection





G. Cassiani et al.

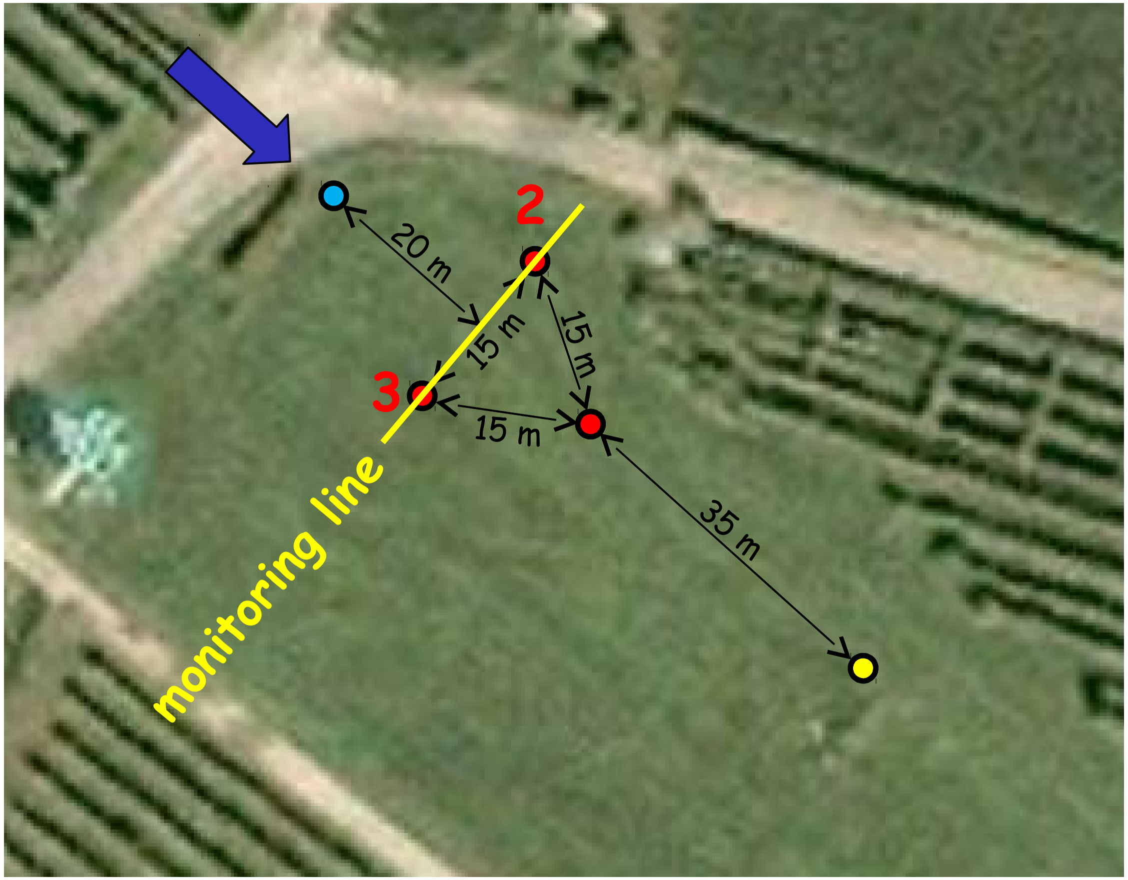
EXPERIMENTAL TEST AREA – Valdobbiadene – NE Italy

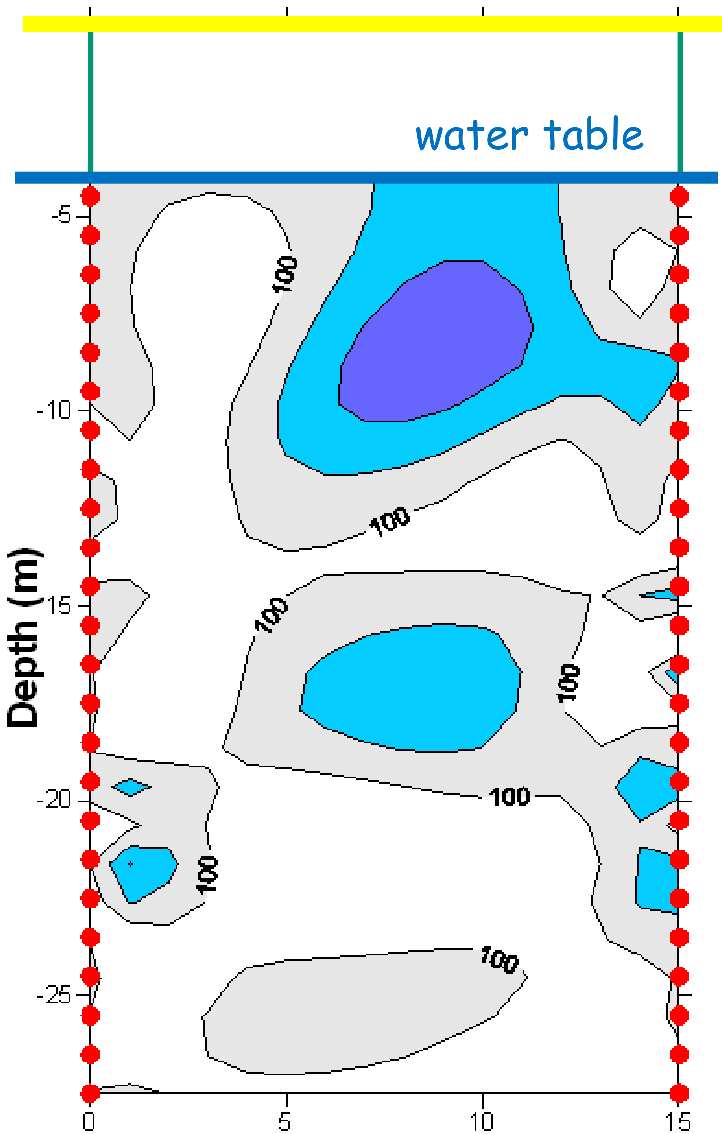
Time 26 (hh:mm): 54:27 after injection

resistivity ratio w.r.t. background

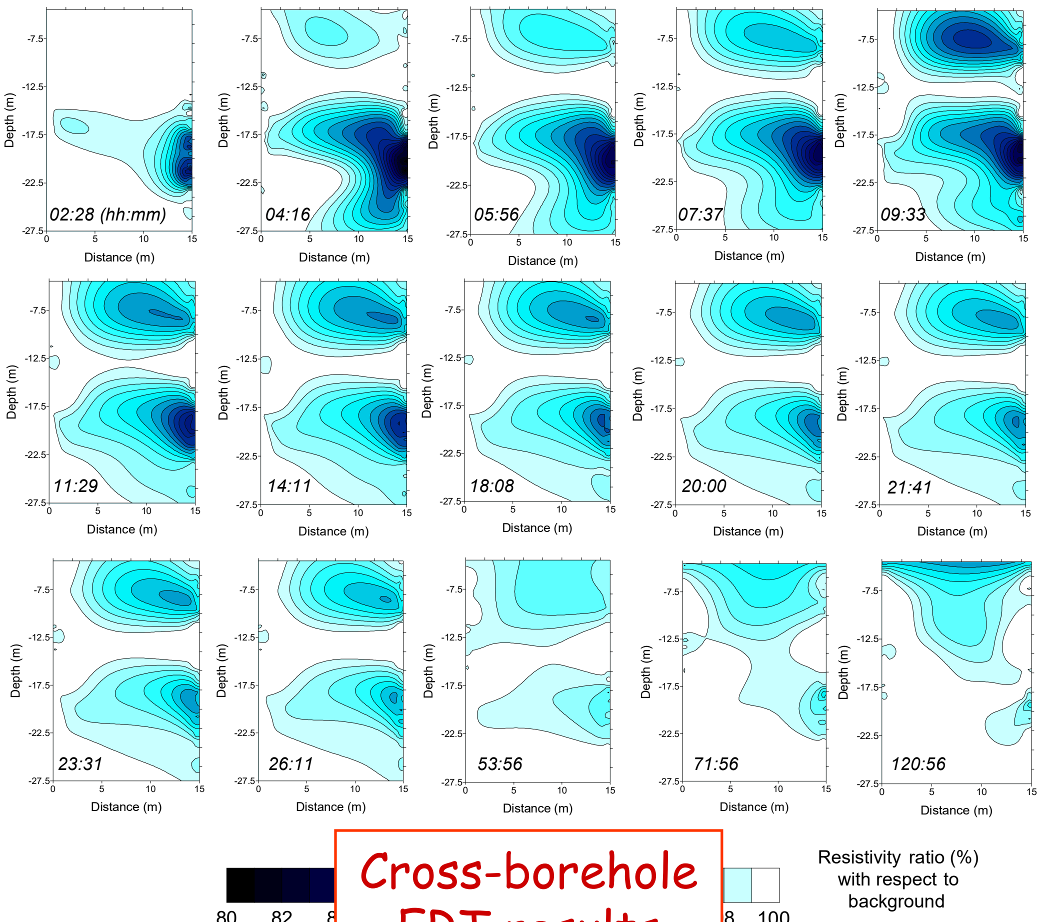
75	80	85	90	95	100

%

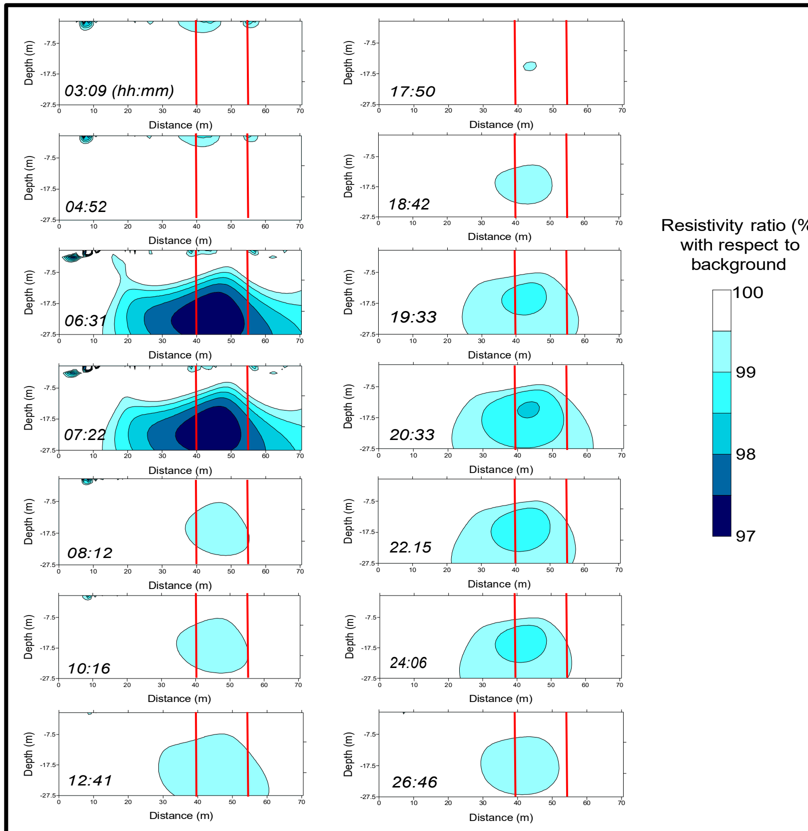




INFORMATION CONTENT IN TRACER TEST EXPERIMENTS MONITORED WITH ERT



Cross-borehole ERT results



Surface ERT results

Perri et al., JAG, 2012

SUMMARY

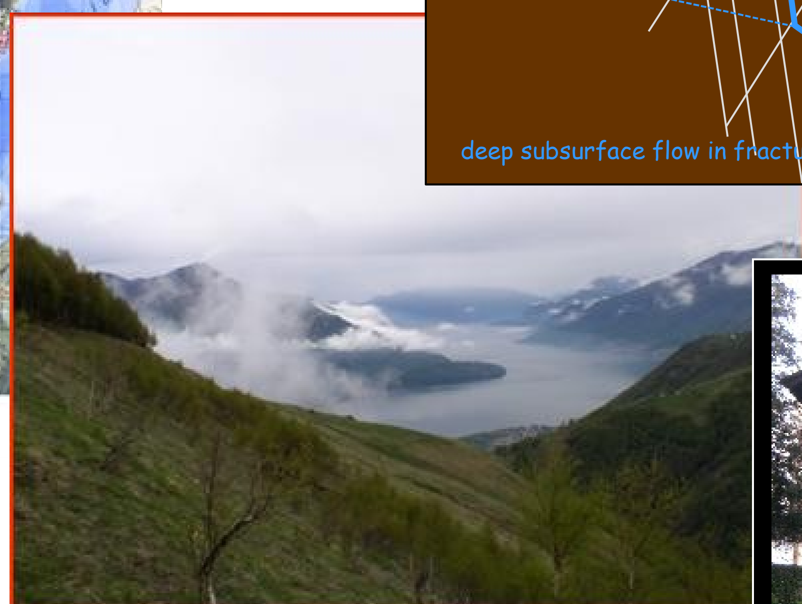
- Hydro-geophysics: a problem-driven discipline
- A Glimpse to a number of applications

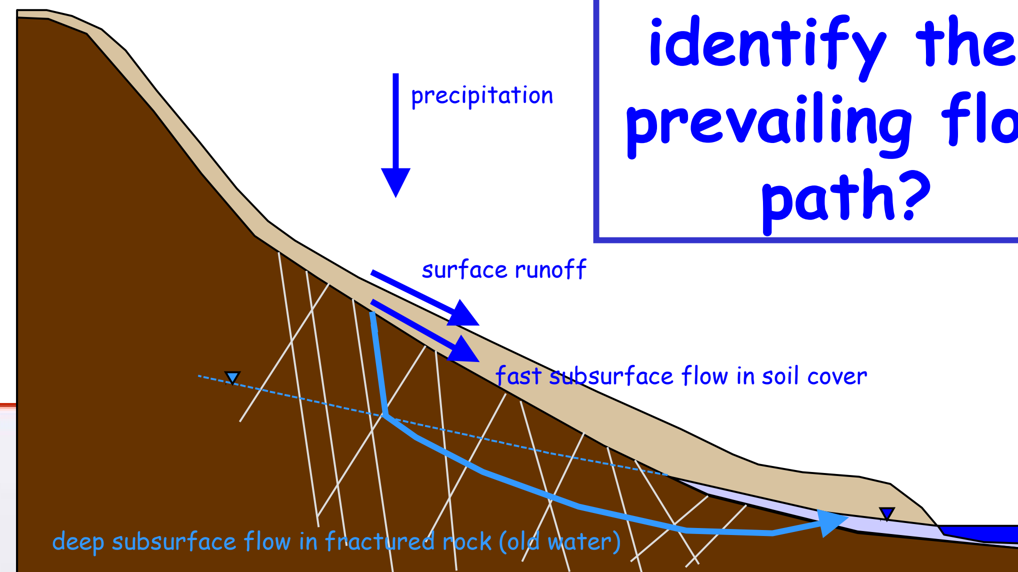
Hillslope characterization

- Conclusions and outlook

Montemezzo project

Can we identify the prevailing flow path?

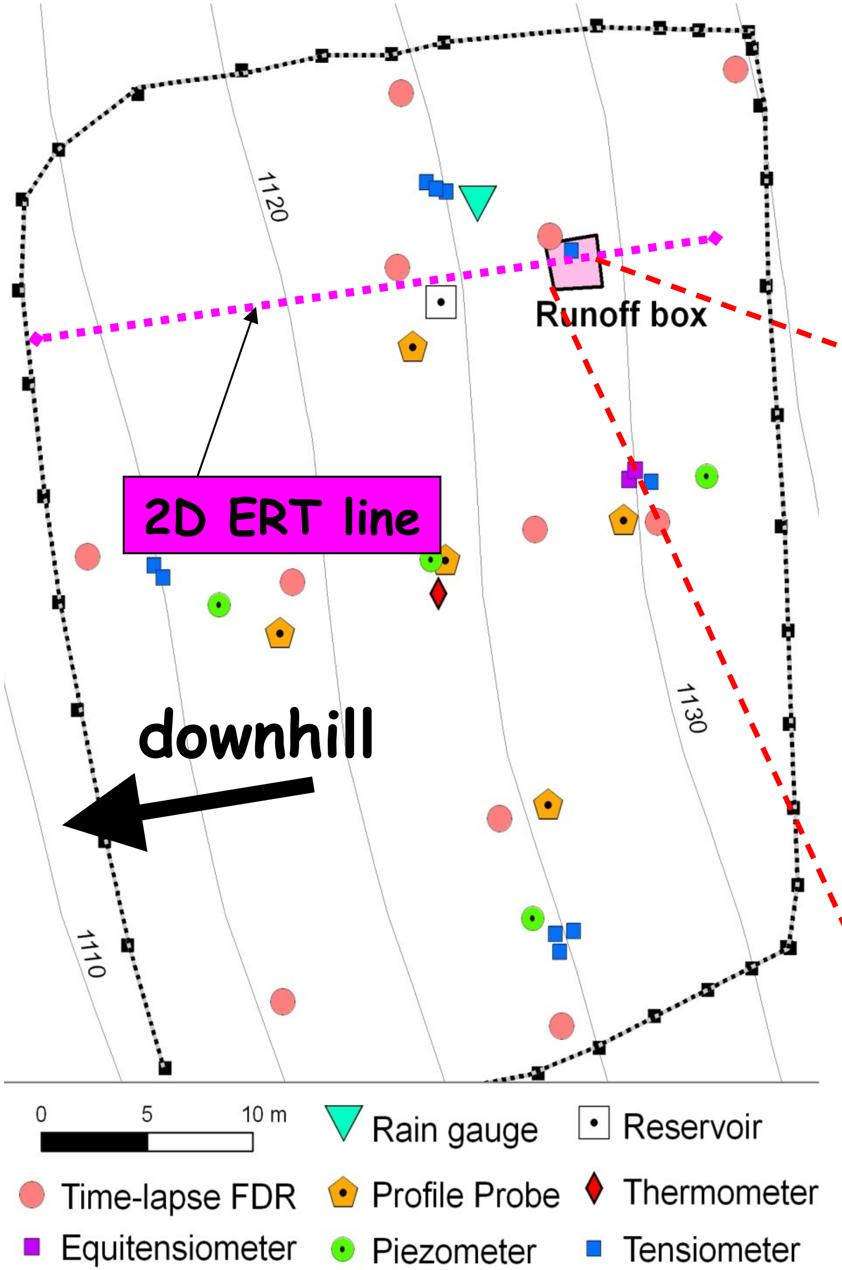


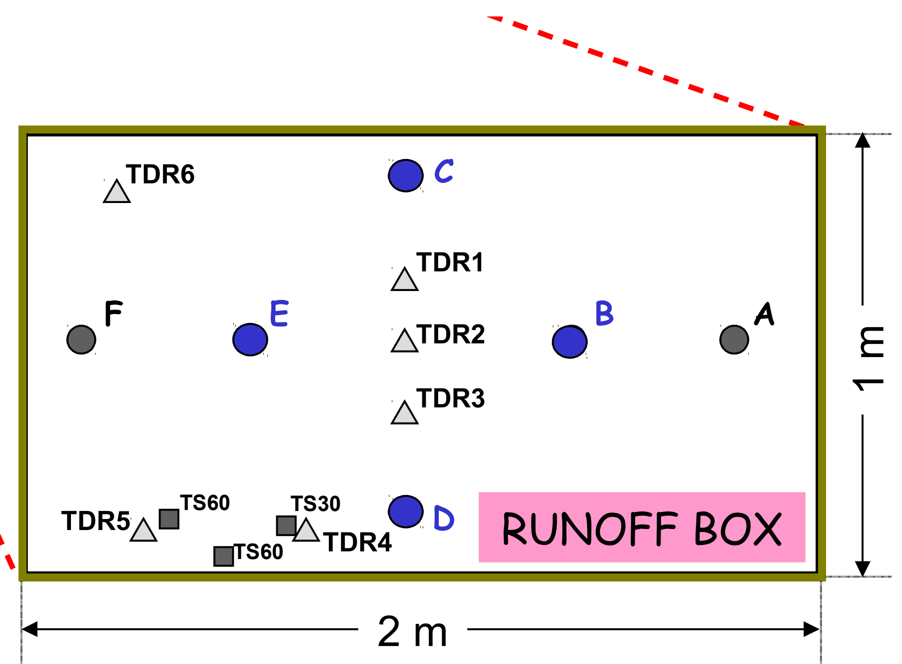


Cassiani et al., NSG, 2009

Controlled irrigation tests

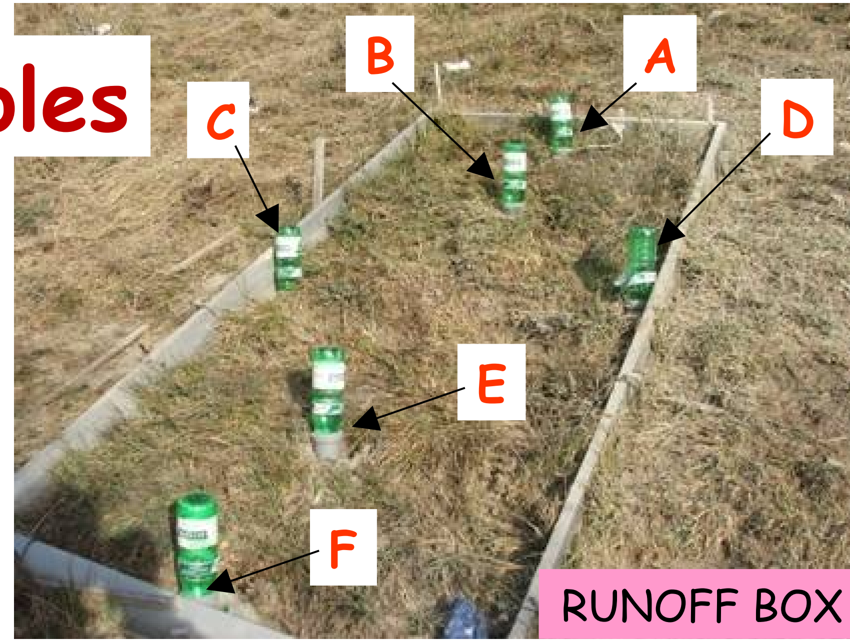
We conducted two irrigation tests on a controlled runoff box, equipped with TDR, tensiometers and boreholes having electrodes installed for 3D cross-hole ERT.





Cassiani et al., NSG, 2009

Installation of boreholes

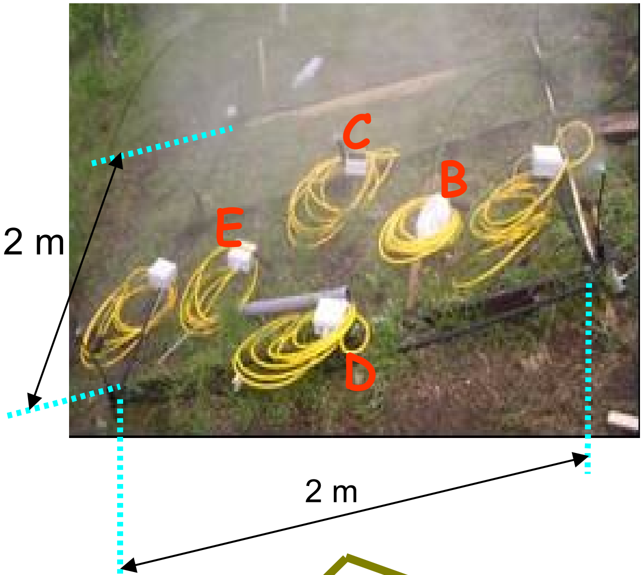


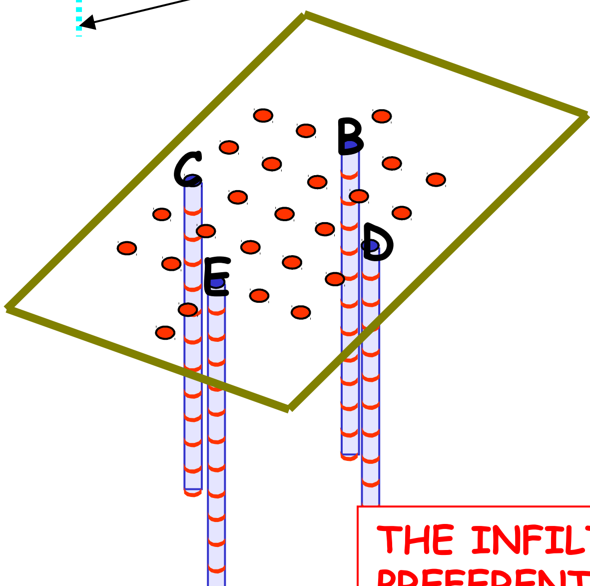
Cassiani et al., NSG, 2009

Six boreholes, 2 m deep.

12 electrodes in each borehole.

3D ERT – Resistivity ratio inversion w.r.t. background

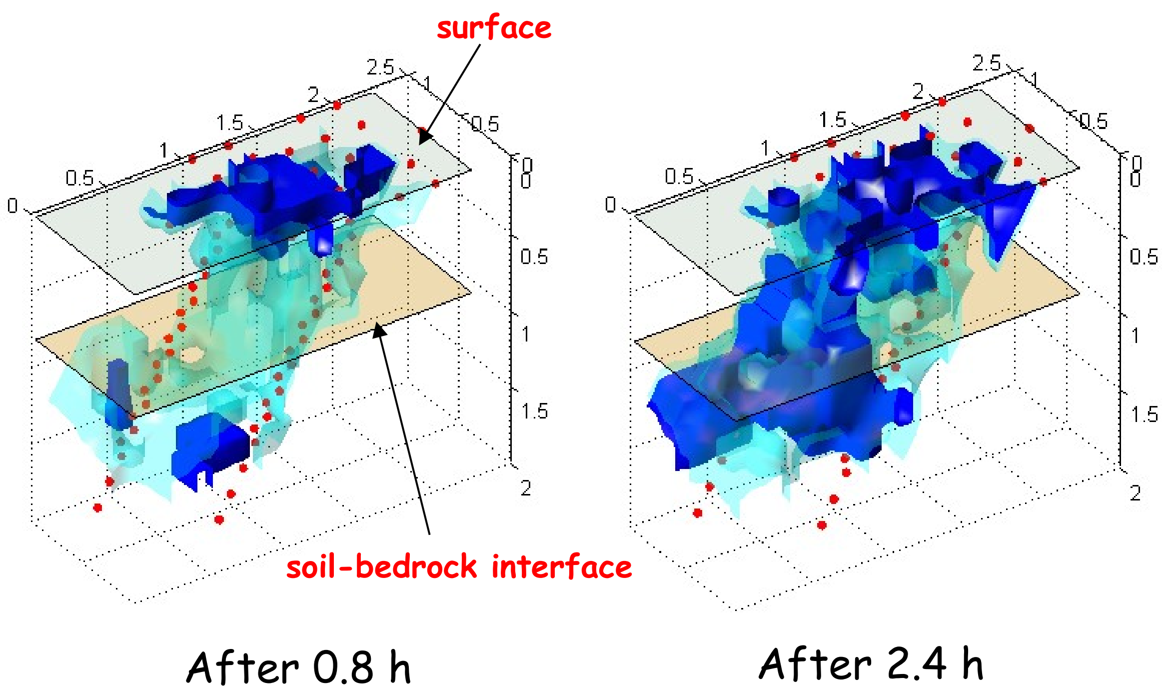




RUNOFF BOX

dark blue = 30% of background

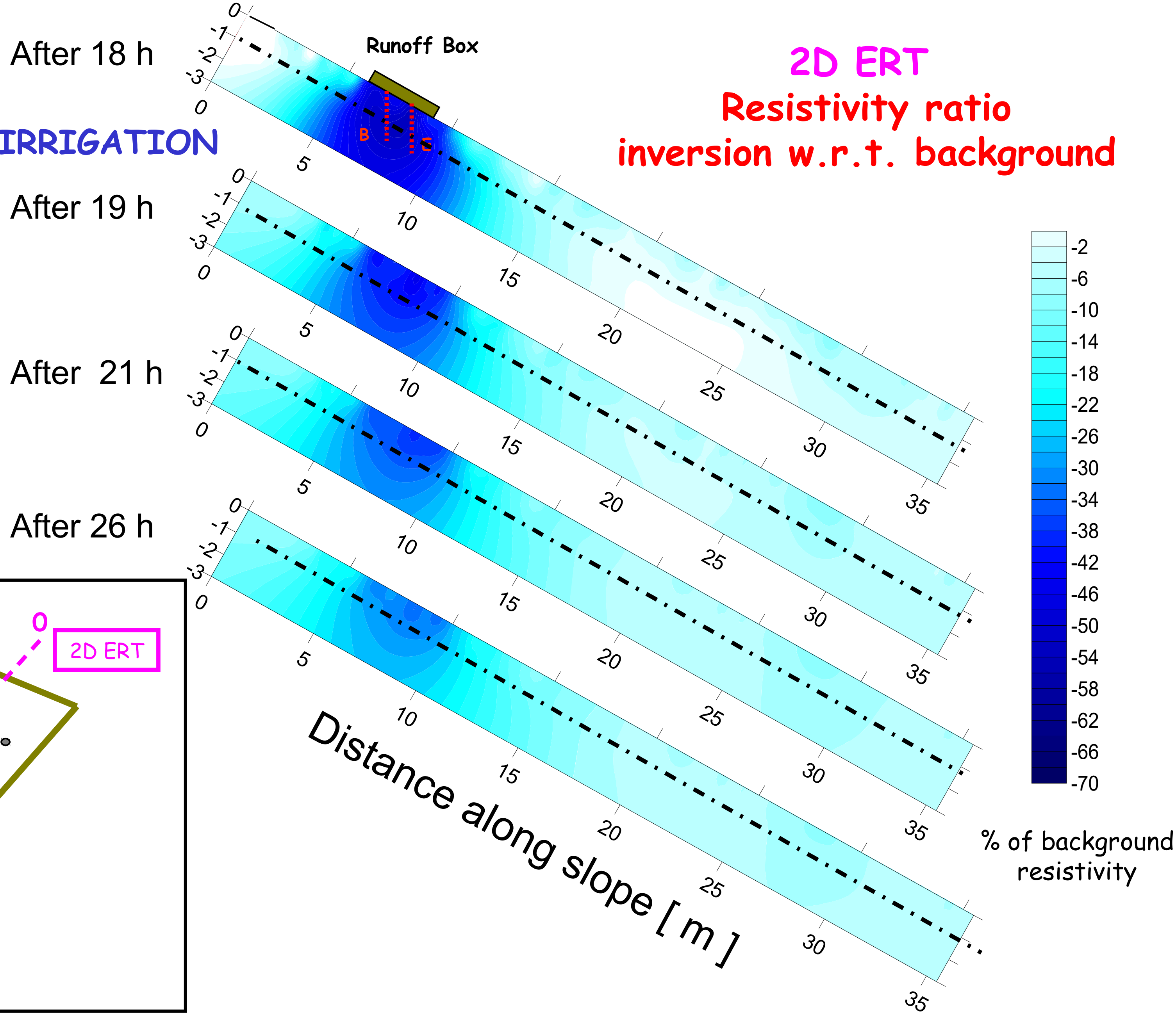
light blue = 70% of background

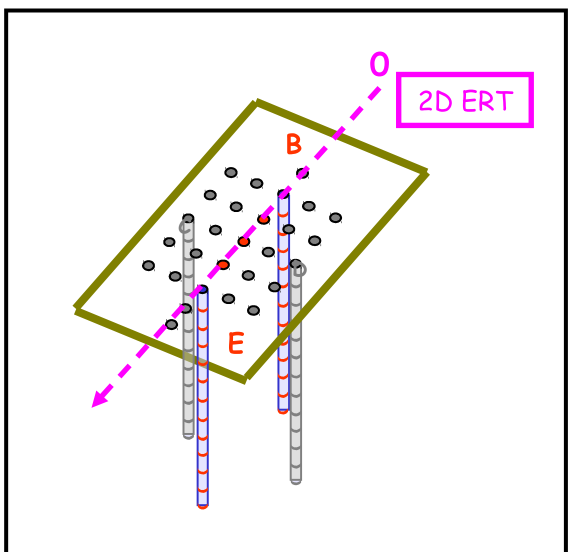


THE INFILTRATION TAKES PLACE VERY QUICKLY, APPARENTLY THROUGH PREFERENTIAL PATHWAYS

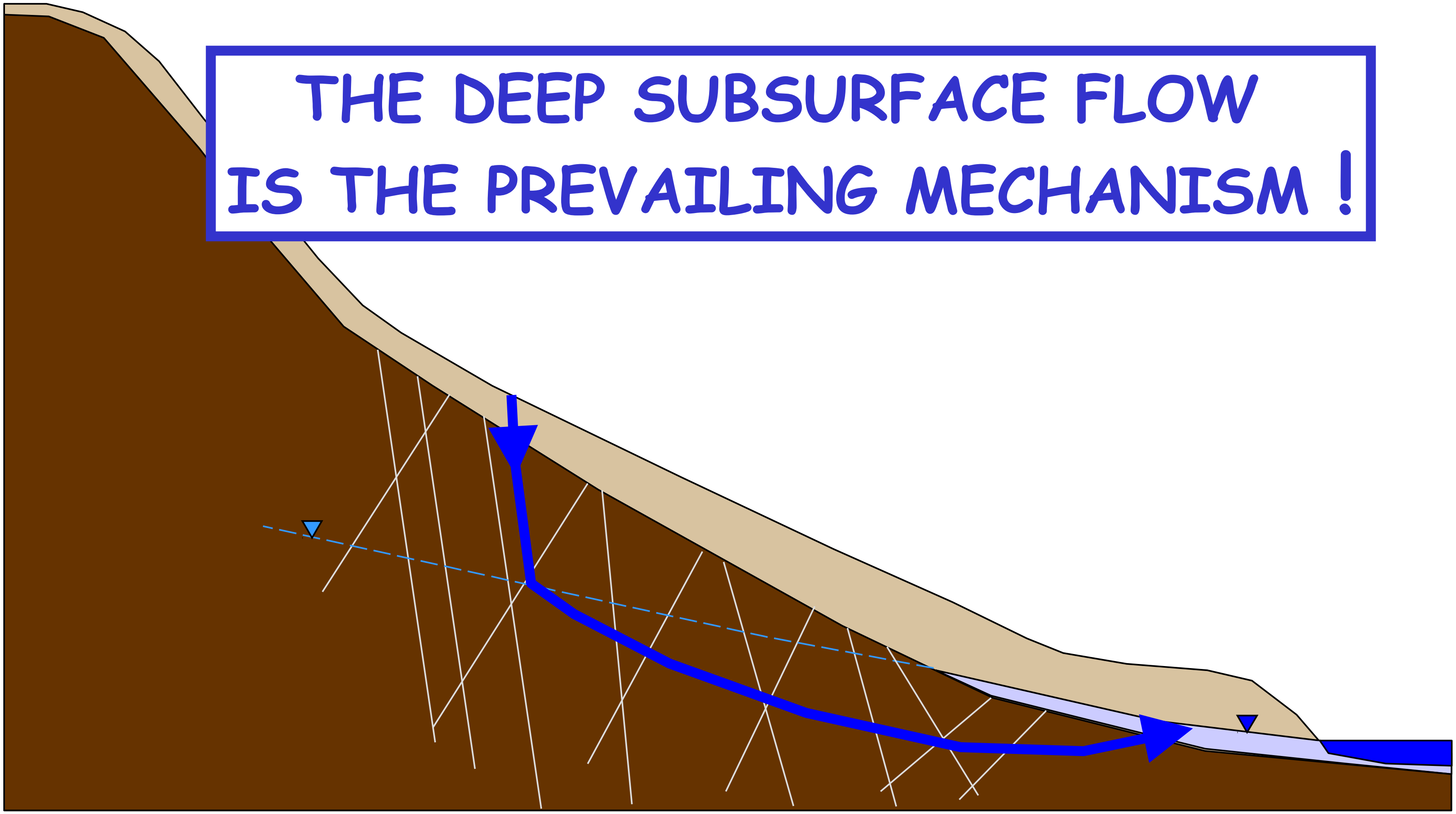
2D ERT
Resistivity ratio inversion w.r.t. background

END OF IRRIGATION





THE DEEP SUBSURFACE FLOW IS THE PREVAILING MECHANISM !



Cassiani et al., NSG, 2009

SUMMARY

- Hydro-geophysics: a problem-driven discipline
- A Glimpse to a number of applications

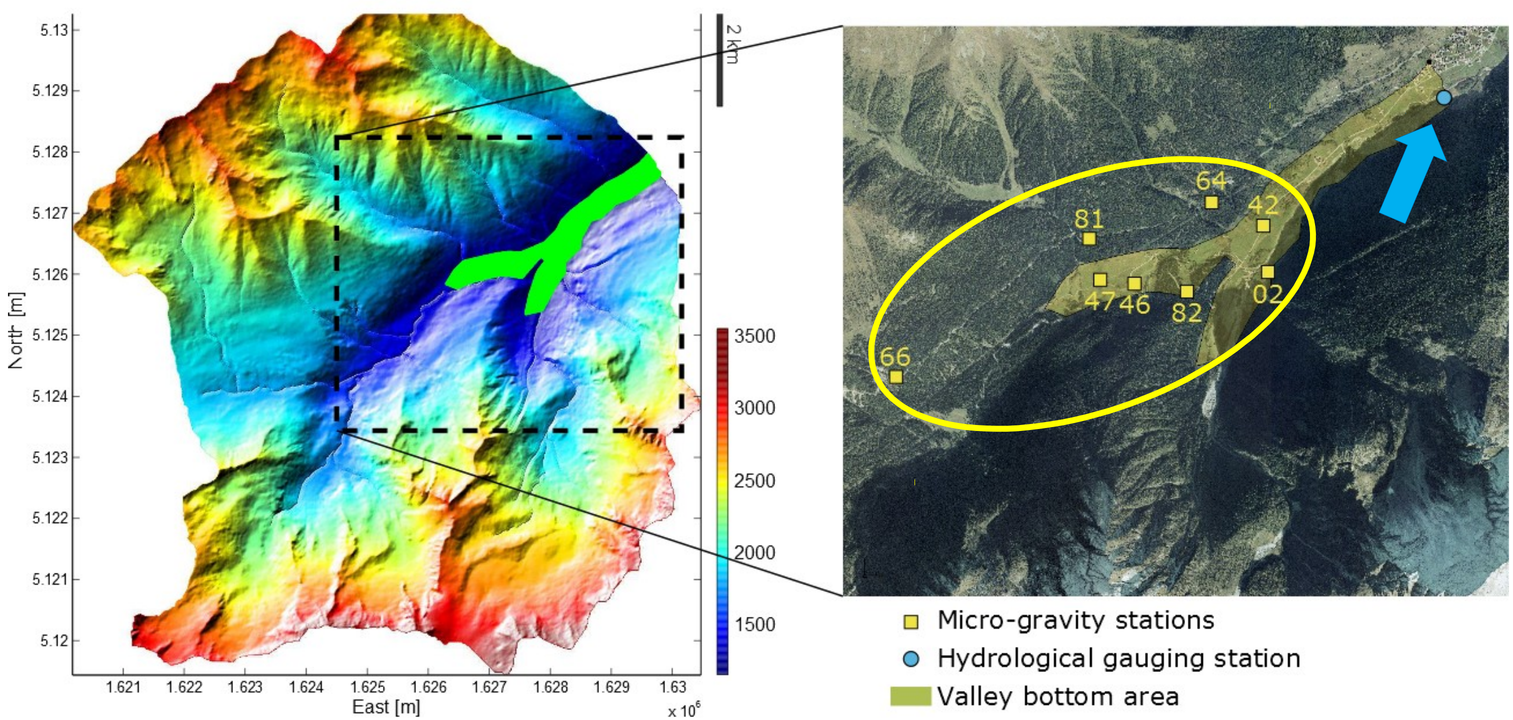
Catchment characterization

- Conclusions and outlook

Val di Sole - Trentino
Micro-gravity time-lapse monitoring

Fieldwork and data acquisition:

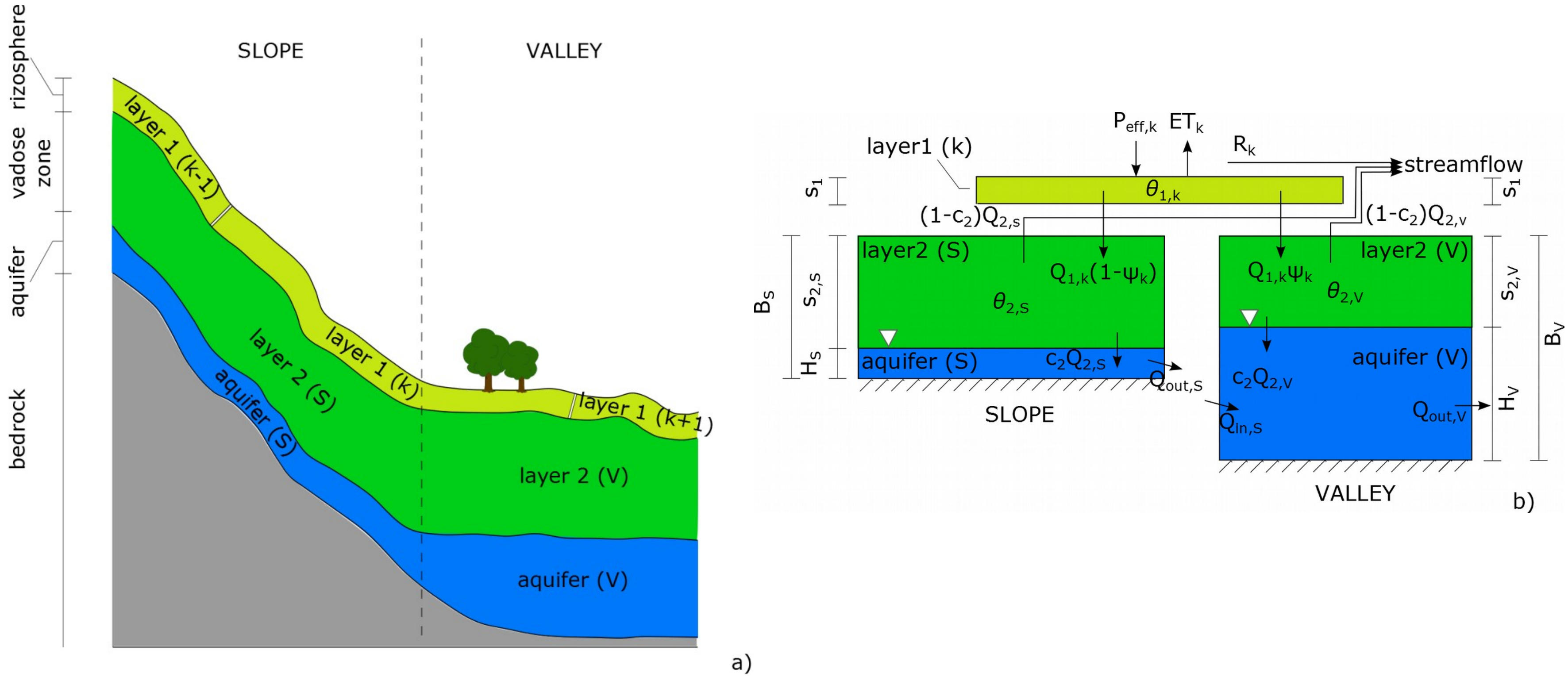
- **6 field campaigns** between June 2009 and May 2011;
- extensive point gravity measurements on a network of **53 stations**;
- the Vermigliana catchment has been monitored through **8 stations**;
- **streamflow data** are available at the Vermiglio stream gauging station.



Piccolroaz et al., WRR, 2014

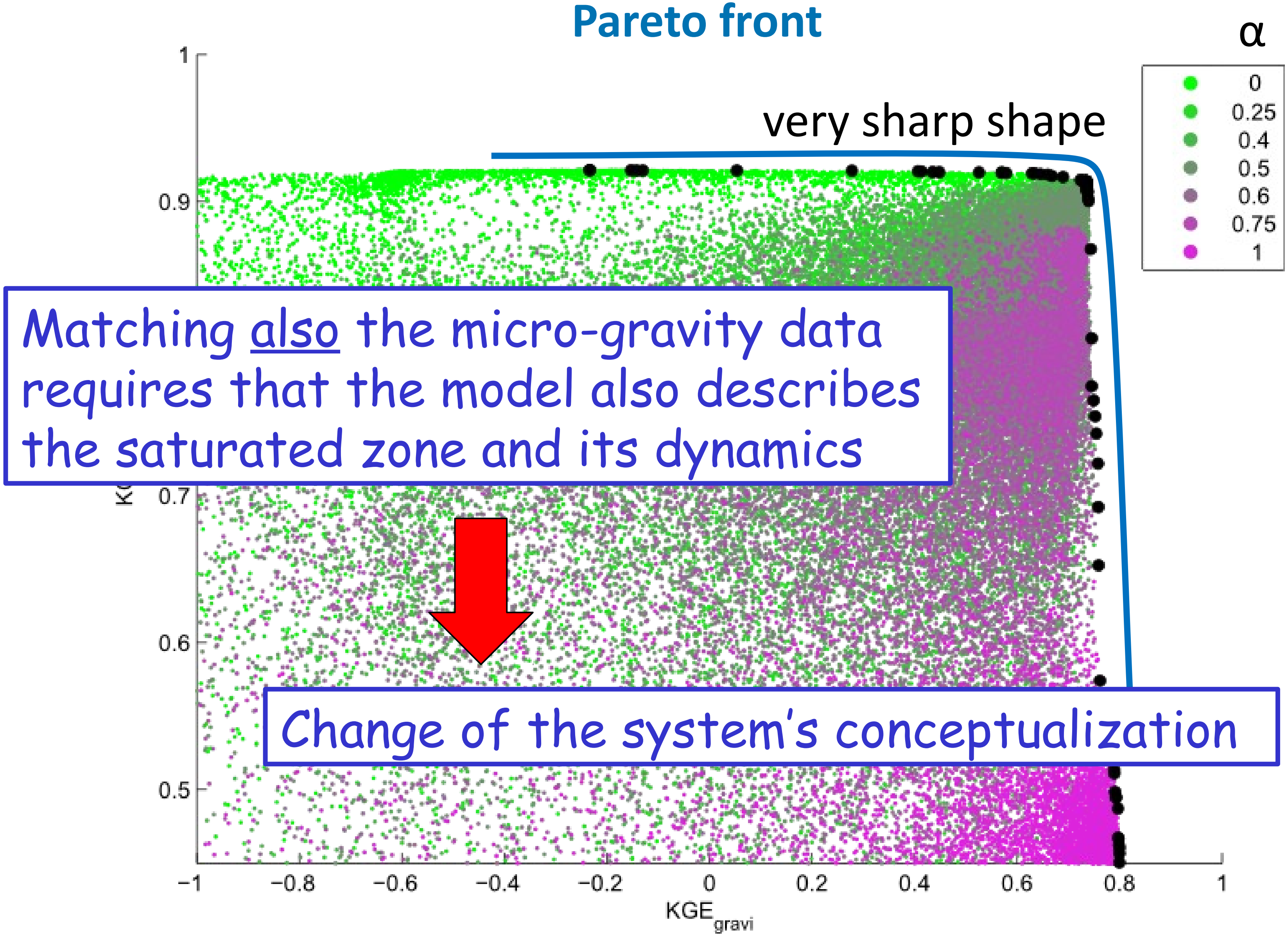
Hydrological model: a modified version of GEOTRANSF (Majone et al., 2012, *WATER RESOUR RES*), a semi-distributed model characterized by:

1. subdividing the catchment into slope and valley bottom areas (governed by inherently different processes);
2. explicitly coupling vadose-zone and groundwater dynamics.



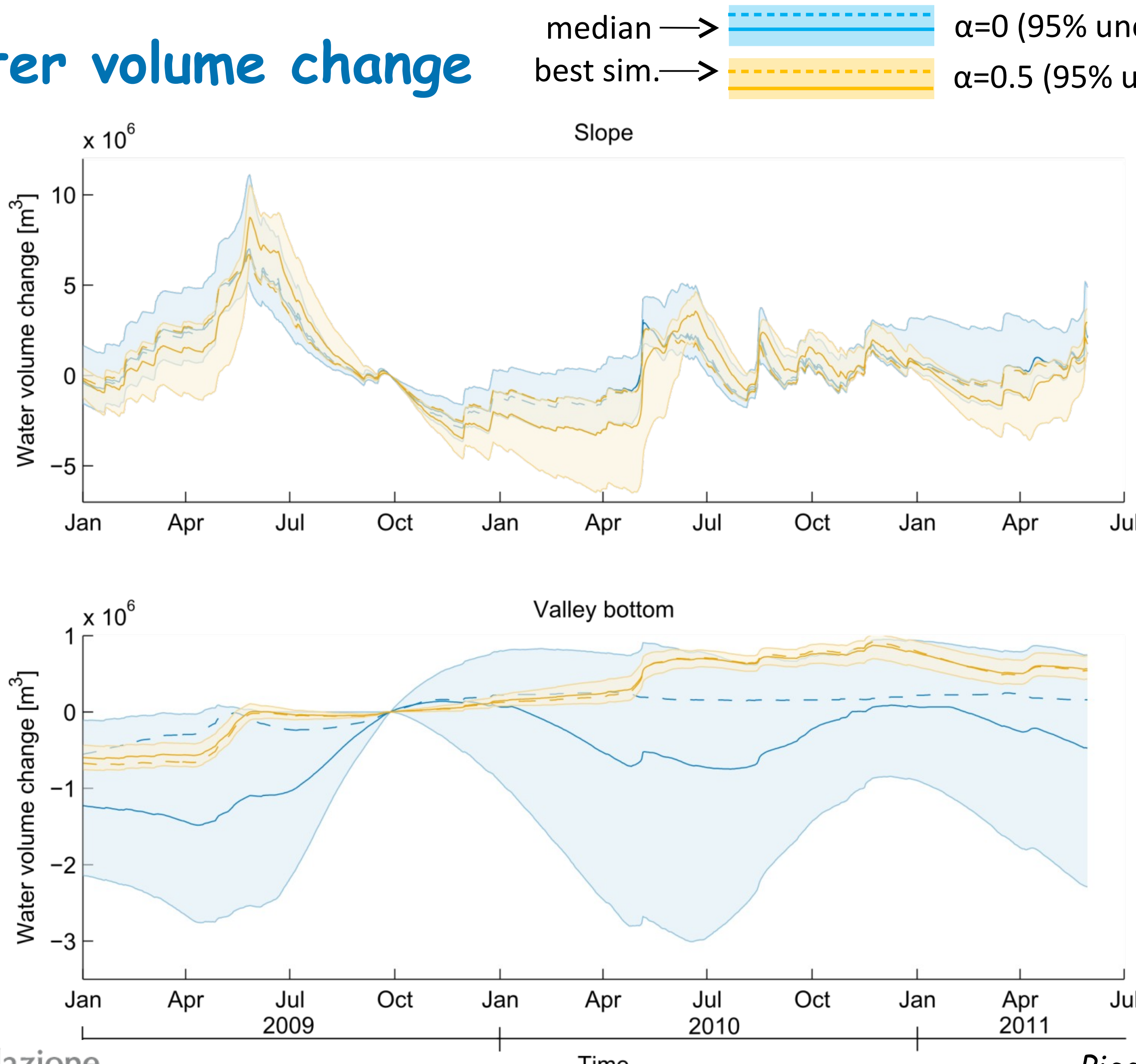
Piccolroaz et al., WRR, 2014

Pareto front



Piccolroaz et al., WRR, 2014

Water volume change



d-factor

2.8E6 m³ = 2.8E6 m³

d-factor

2.2 m³ >> 0.2E6 m³

Piccolroaz et al., WRR, 2014

SUMMARY

- Hydro-geophysics: a problem-driven discipline
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Contamination characterization

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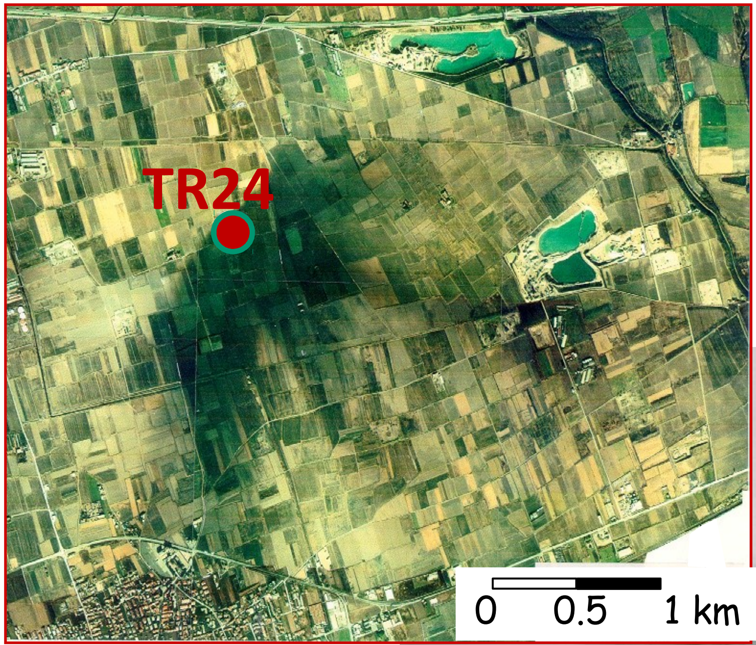
ModelPROBE
Model driven Soil Probing, Site Assessment and Evaluation



Blow out of TR24 oil well
Trecate, Novara
February 28 1994

Cassiani et al., ESPR, 2014

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SoilCAM

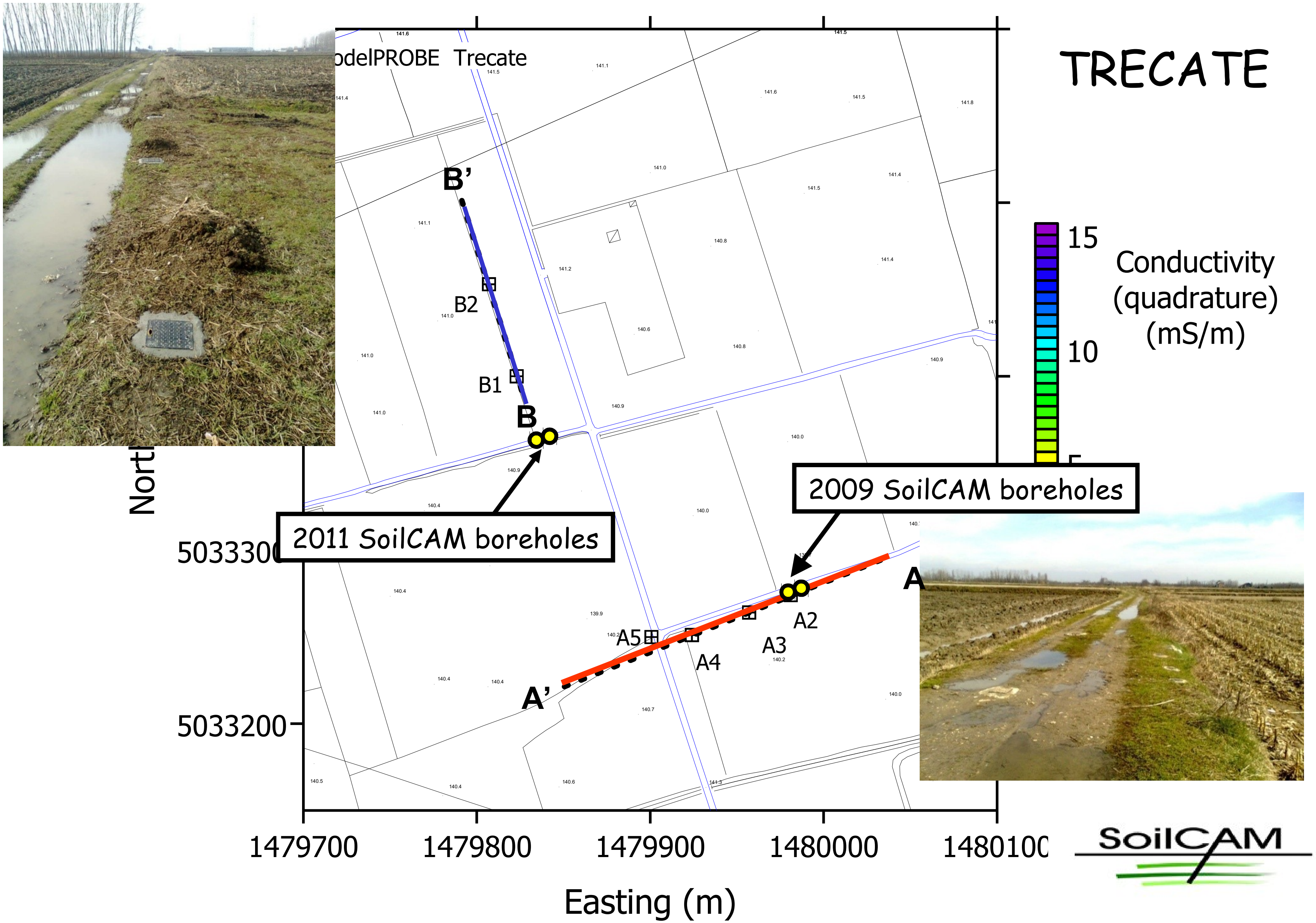
Contamination

The sample in the plastic bottle left is not filtered, it has a thin floating oilphase and the brown aqueous phase below is an emulsion.

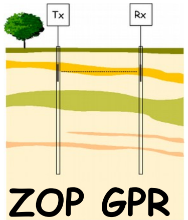
The sample in the tube on the right (which is the same sample but filtered at 0.45 μm), is tranparent

Cassiani et al., ESPR, 2014

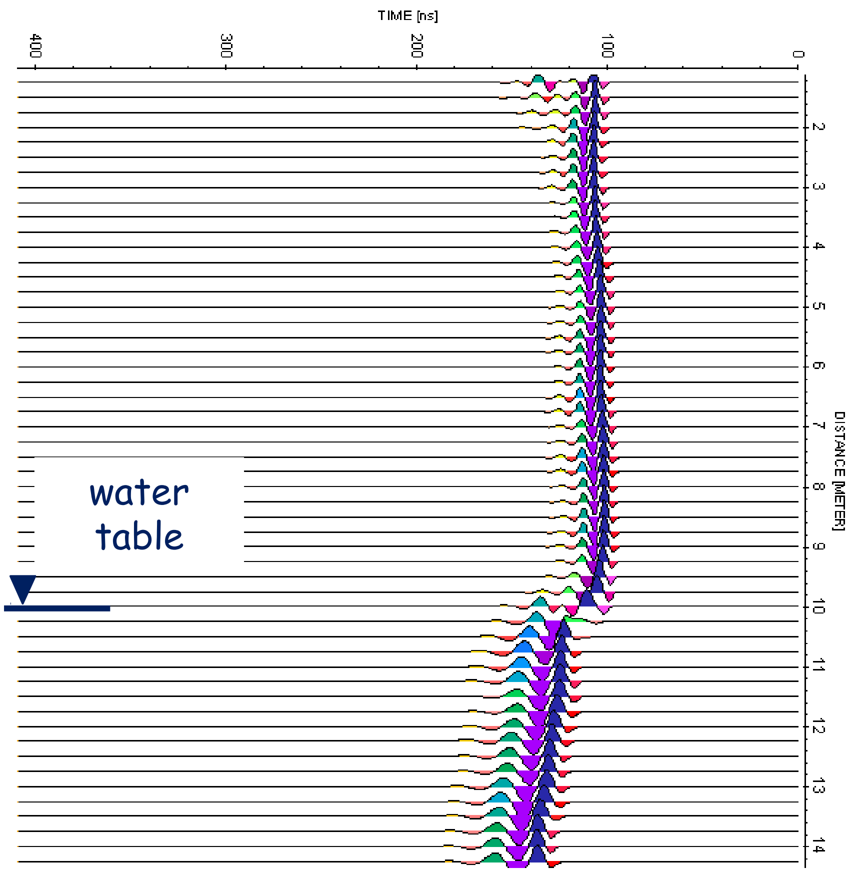
TRECATE



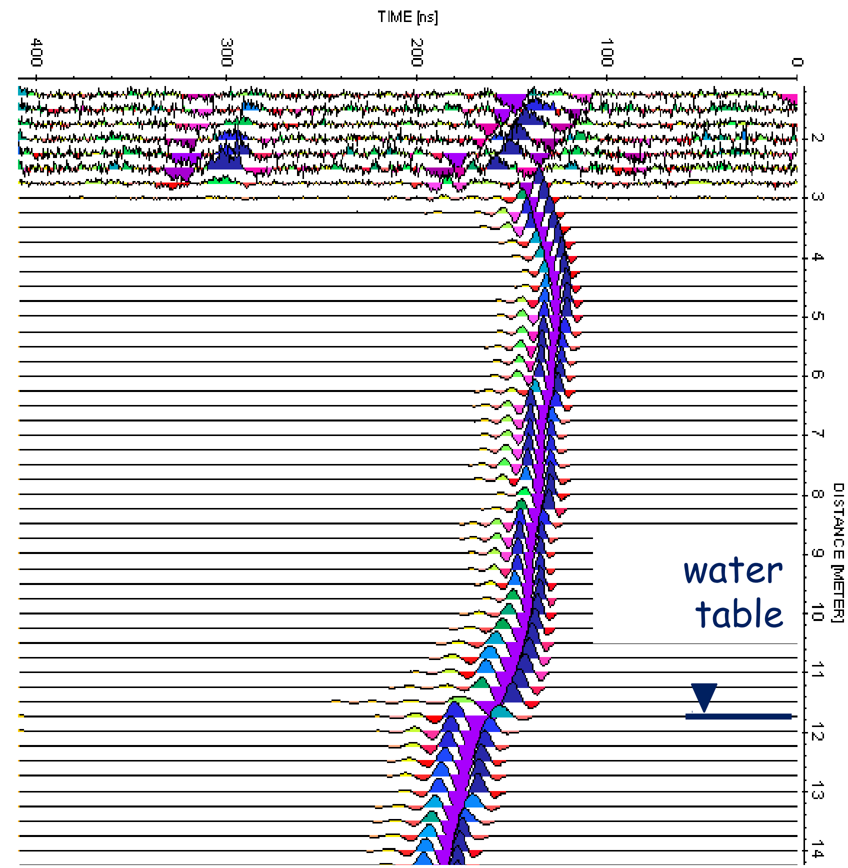
SoilCAM



2011 Soilcam boreholes (uncontaminated)

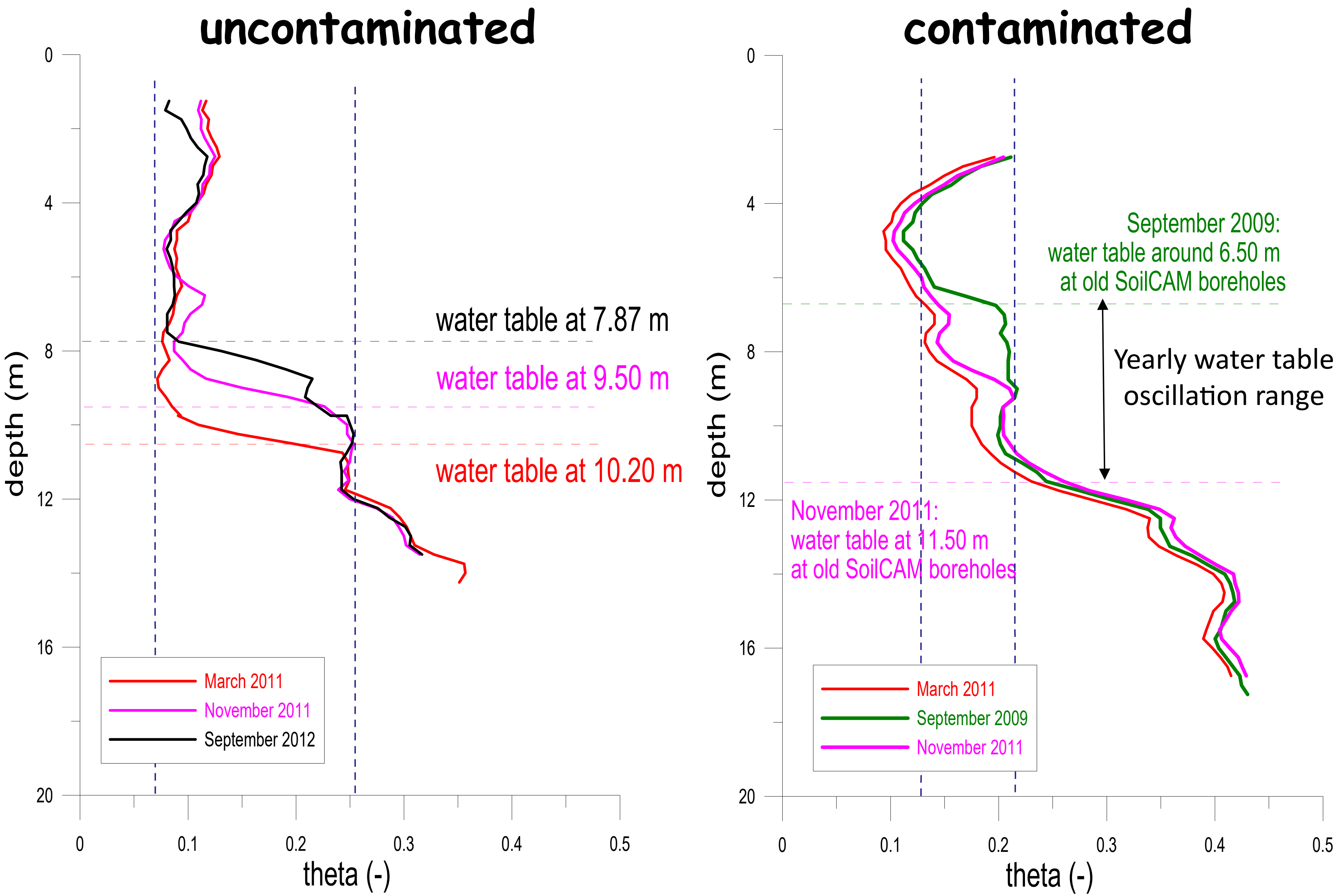


2009 Soilcam boreholes (contaminated)



MARCH 2011

Cassiani et al., ESPR, 2014


uncontaminated
water table at 7.87 m
water table at 9.50 m
water table at 10.20 m
March 2011
November 2011
September 2012
depth (m)
theta (-)
contaminated
September 2009:
water table around 6.50 m
at old SoilCAM boreholes
Yearly water table
oscillation range
November 2011:
water table at 11.50 m
at old SoilCAM boreholes
March 2011
September 2009
November 2011
depth (m)
theta (-)

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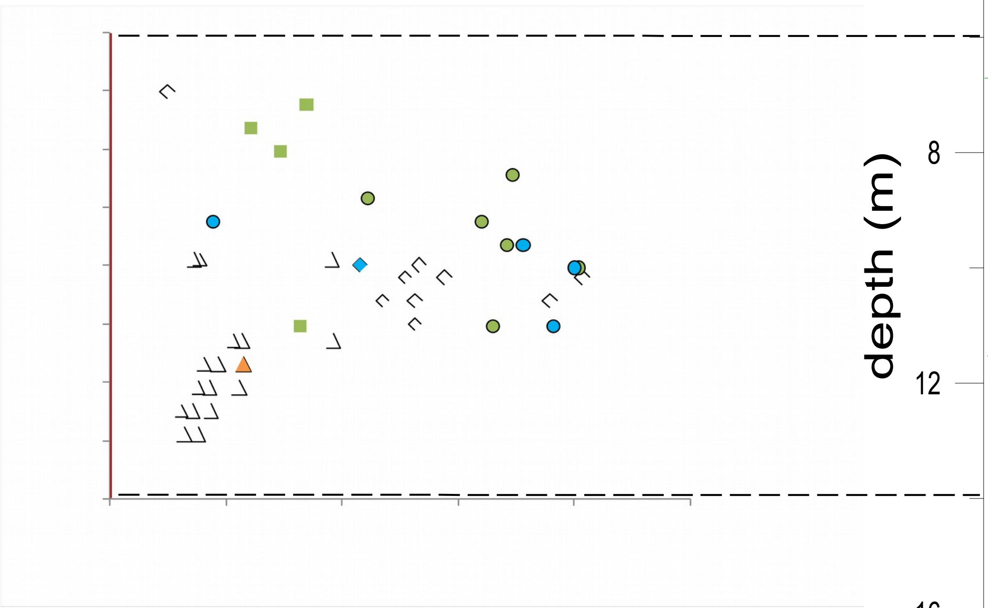
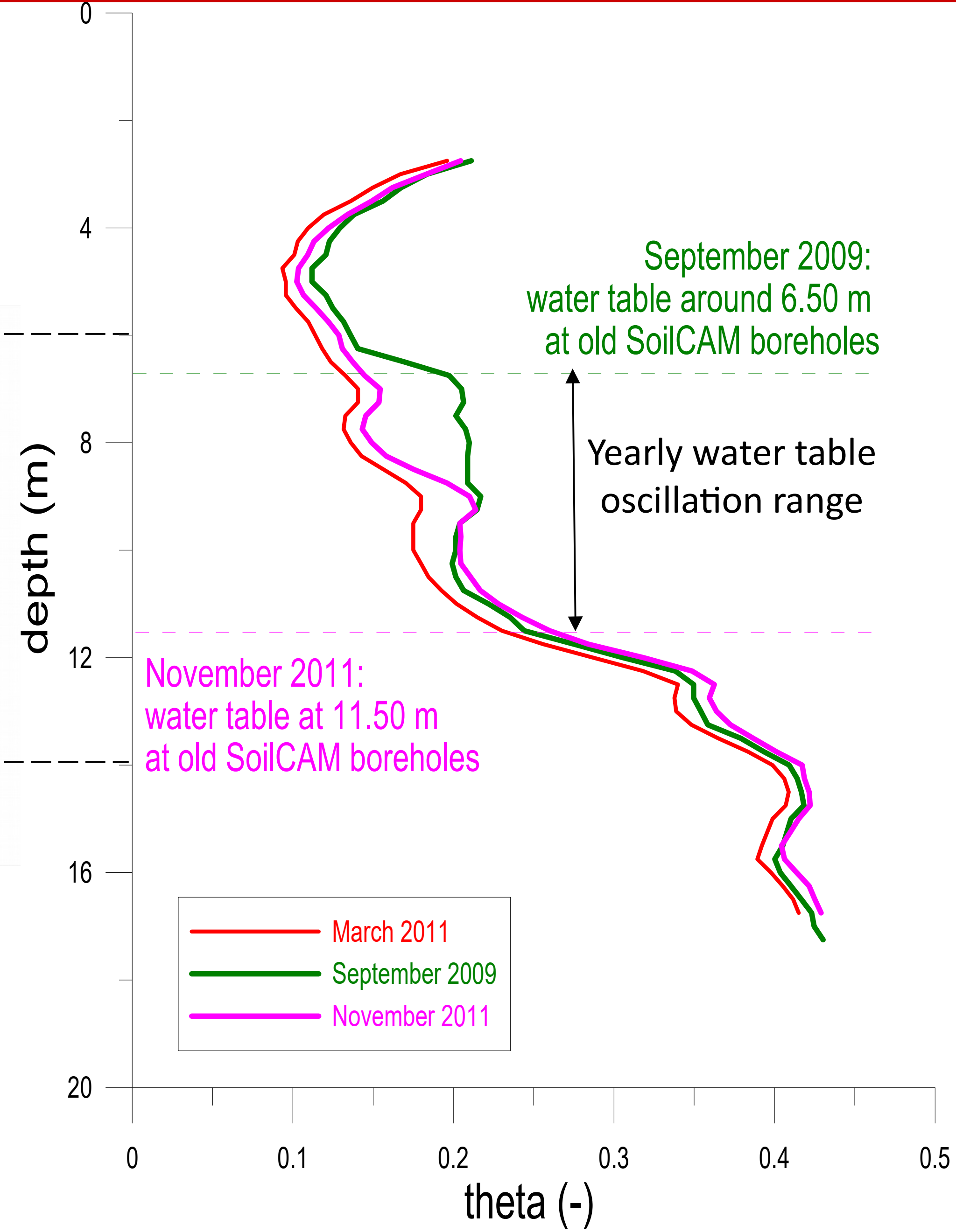


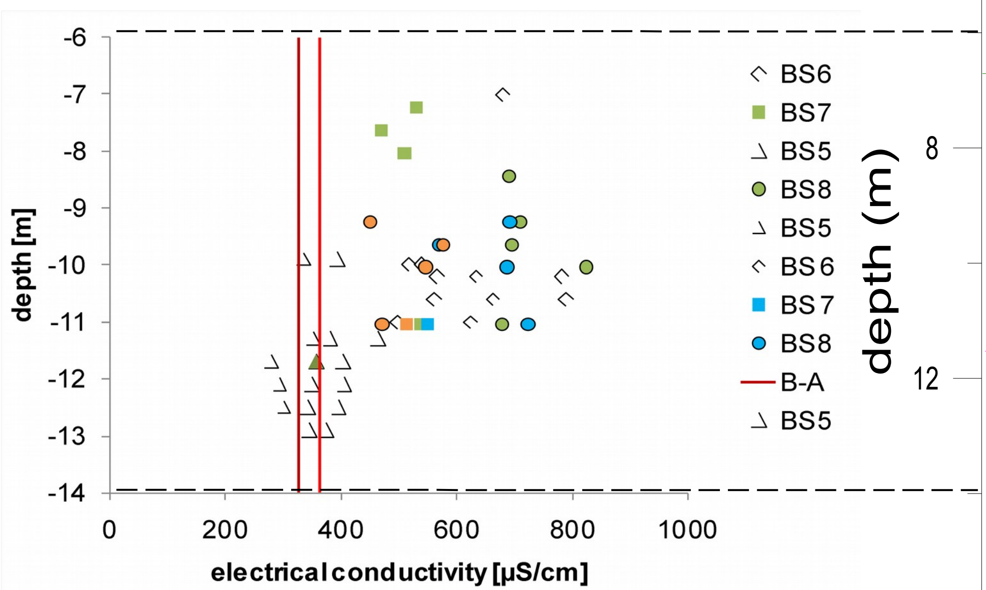


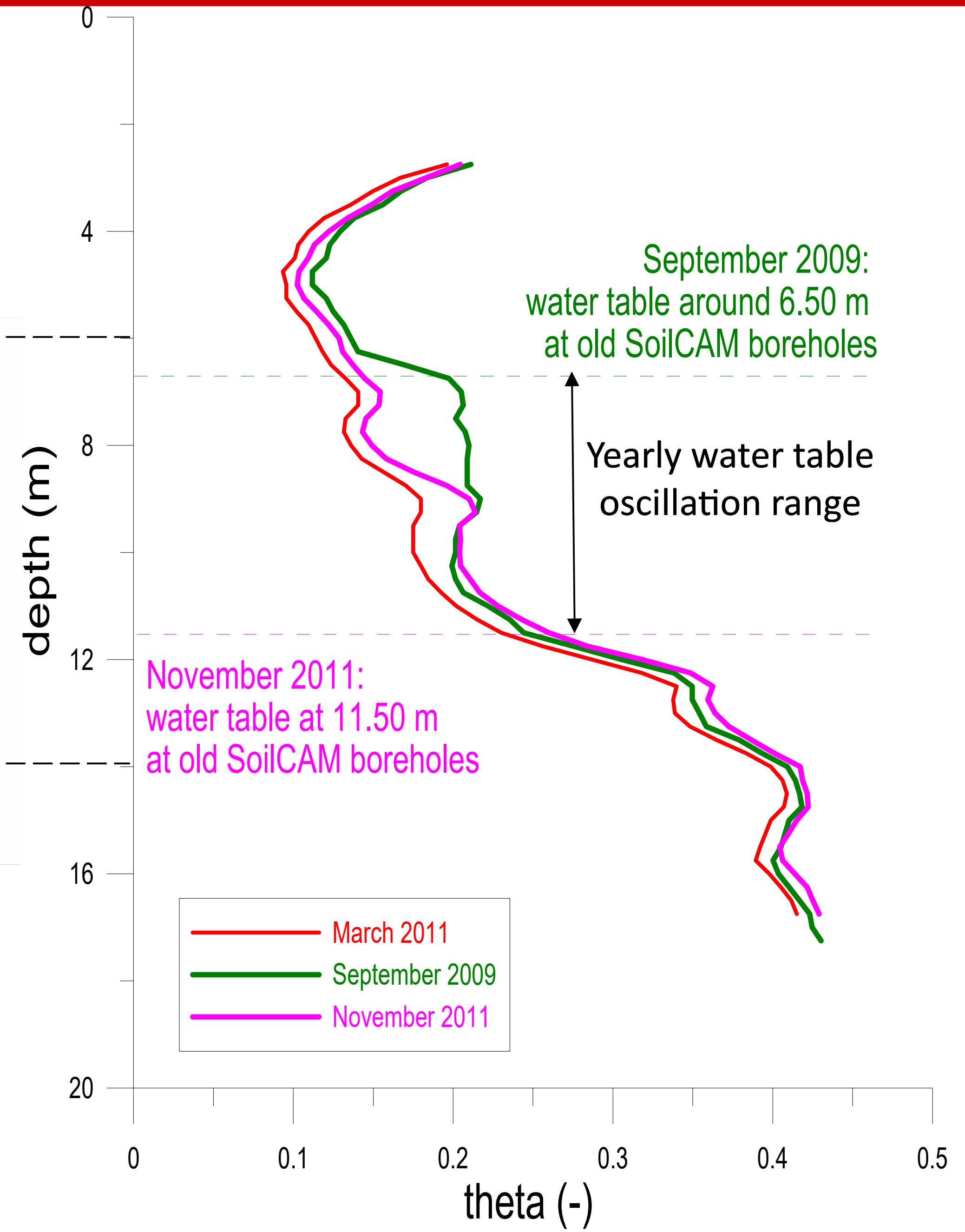
ZOP GPR

vs

multilevel samplers

ModelPROBE
Model driven Soil Probing, Site Assessment and Evaluation

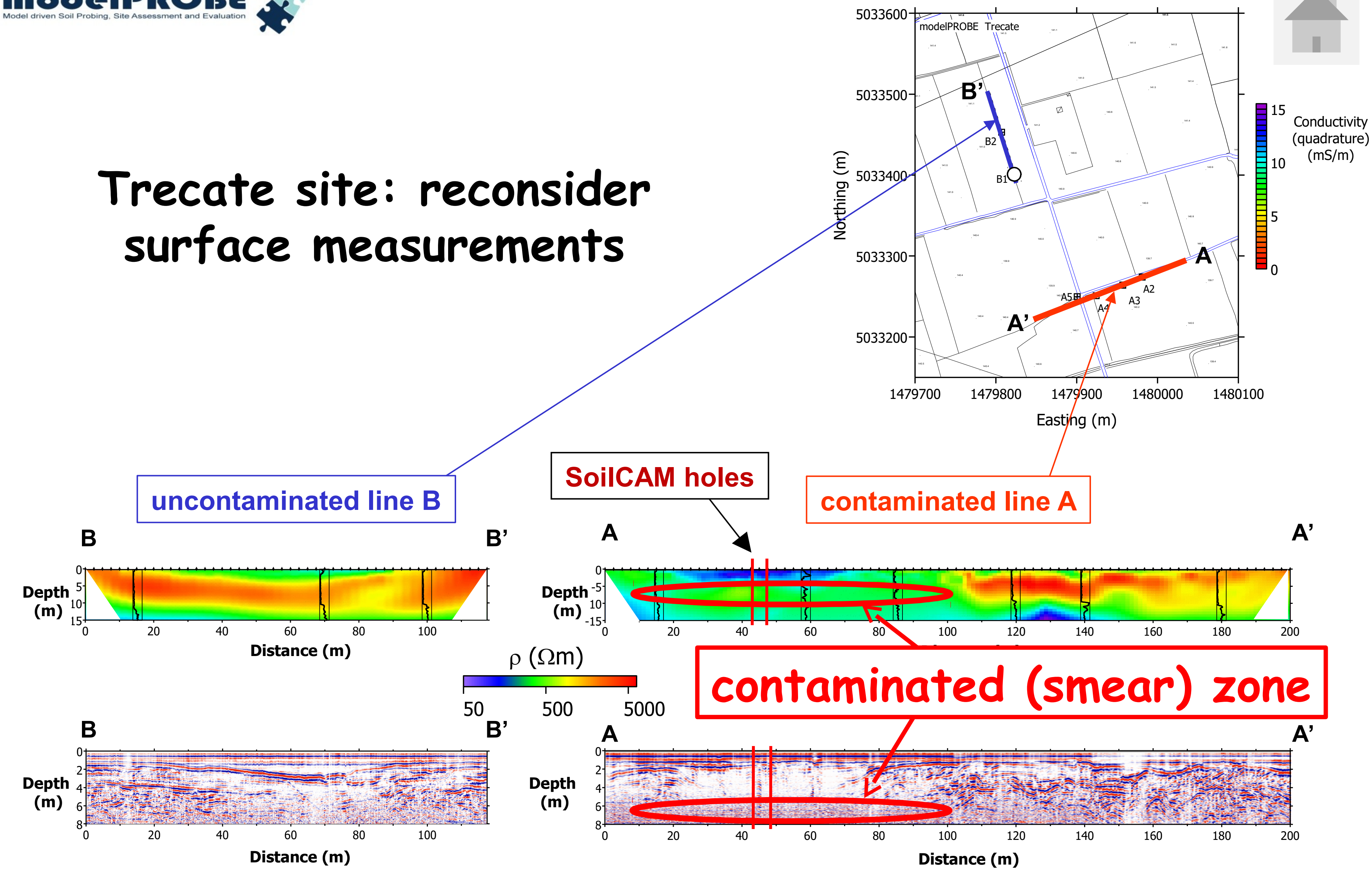




ZOP GPR
vs
multilevel samplers

ModelPROBE
Model driven Soil Probing, Site Assessment and Evaluation

Trecate site: reconsider surface measurements



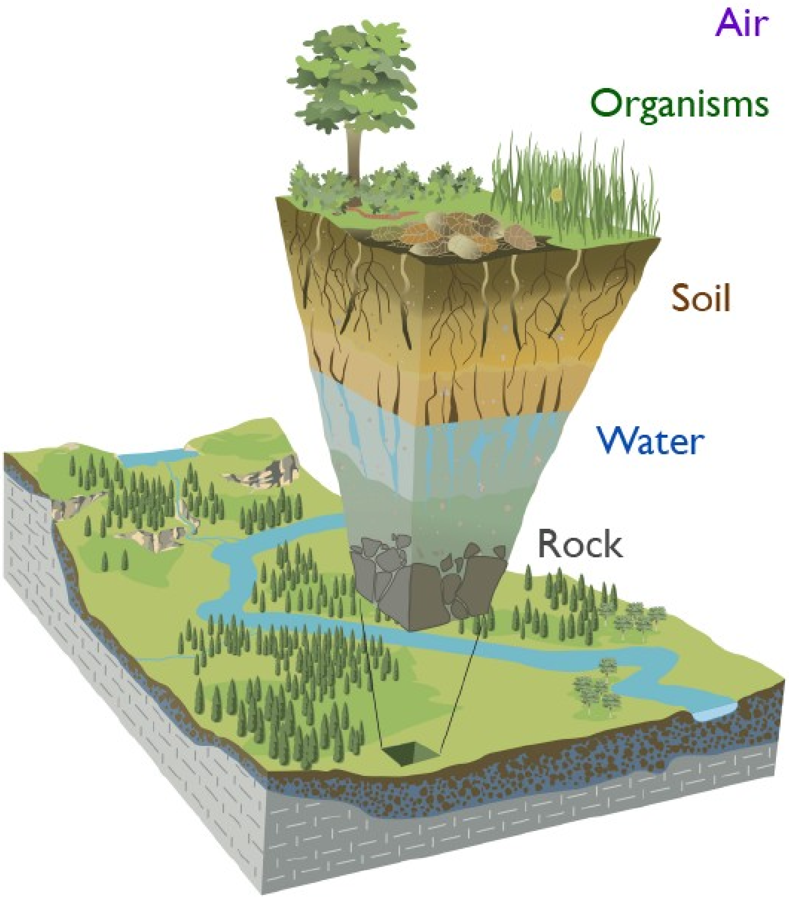
Cassiani et al., ESPR, 2014

General conclusions

- Near surface geophysics is strongly affected by both static and dynamic soil/subsoil characteristics.
- This fact, if properly recognized, is potentially full of information on the soil/subsoil structure and behaviour.
- The information is maximized if geophysical data are collected in time-lapse mode.
- Constitutive laws linking hydrology and geophysics are essential together with a full understanding of the acquisition and inversion characteristics of the adopted methods
- Integration with physical-mathematical models is essential to capture the meaning of space-time changes.

The Earth's Critical Zone

OUTLOOK

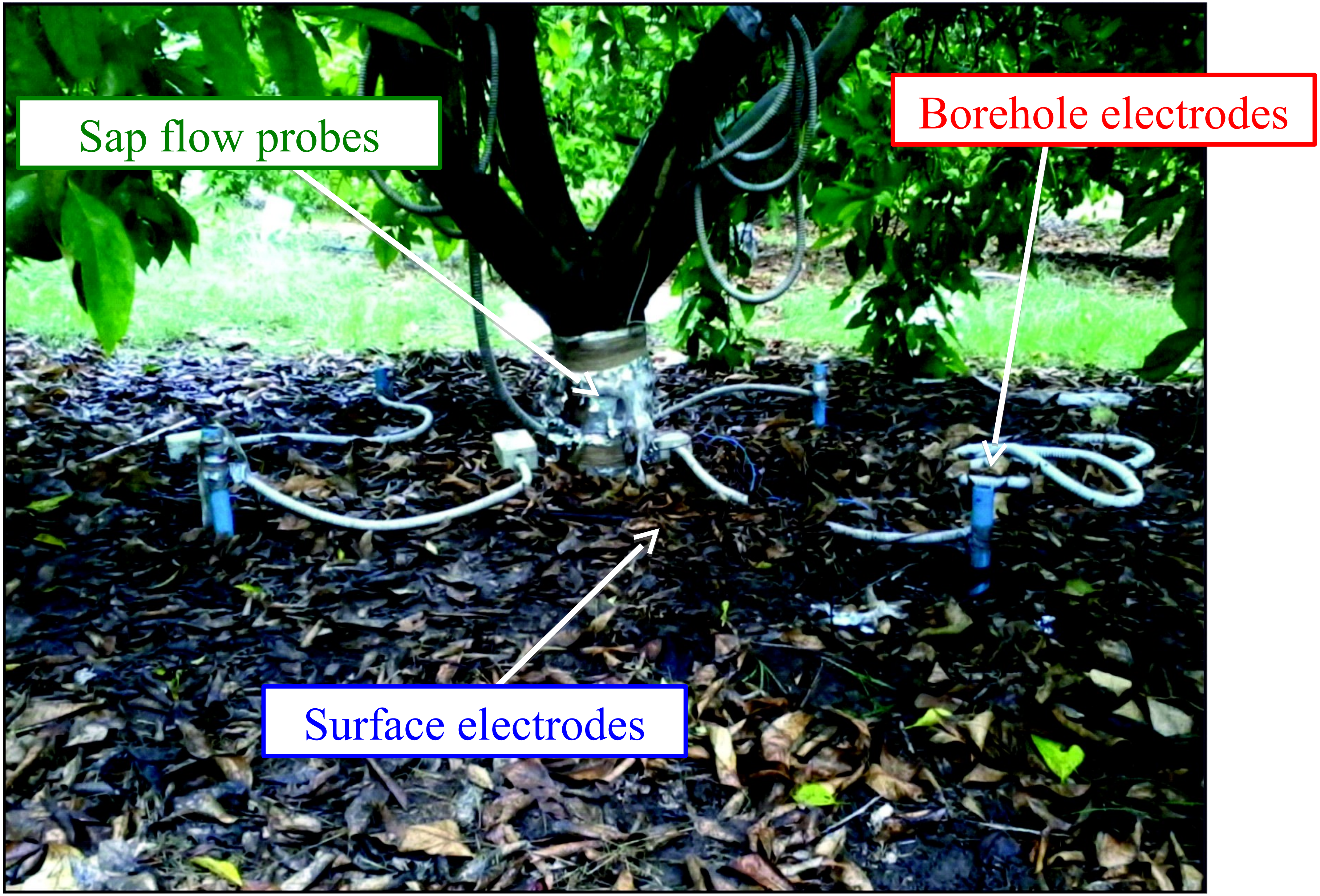


The Earth's Critical Zone (CZ) is the thin outer veneer of our planet from the top of the tree canopy to the bottom of our drinking water aquifers.

The CZ supports almost all human activity.

Particular attention shall be devoted to the soil-plant-atmosphere (SPA) interactions,

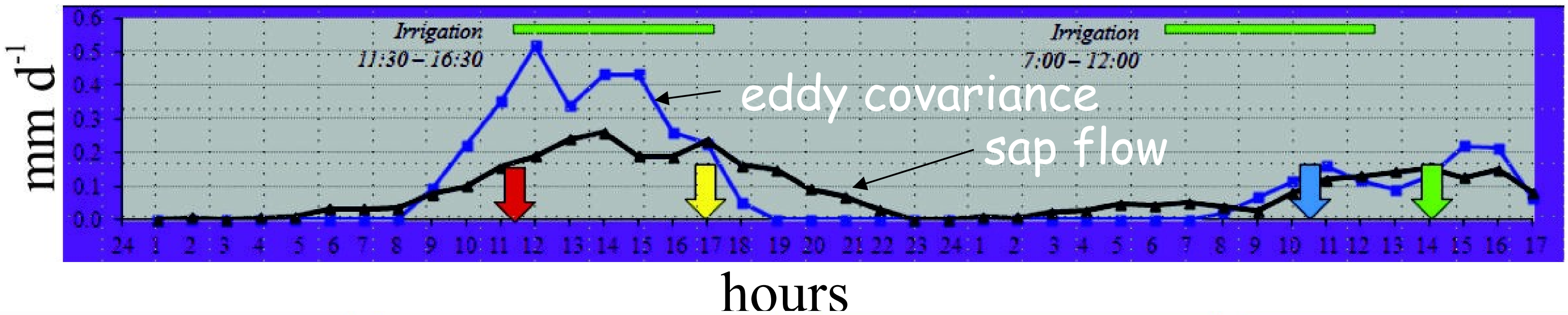
National Research Council (2001)

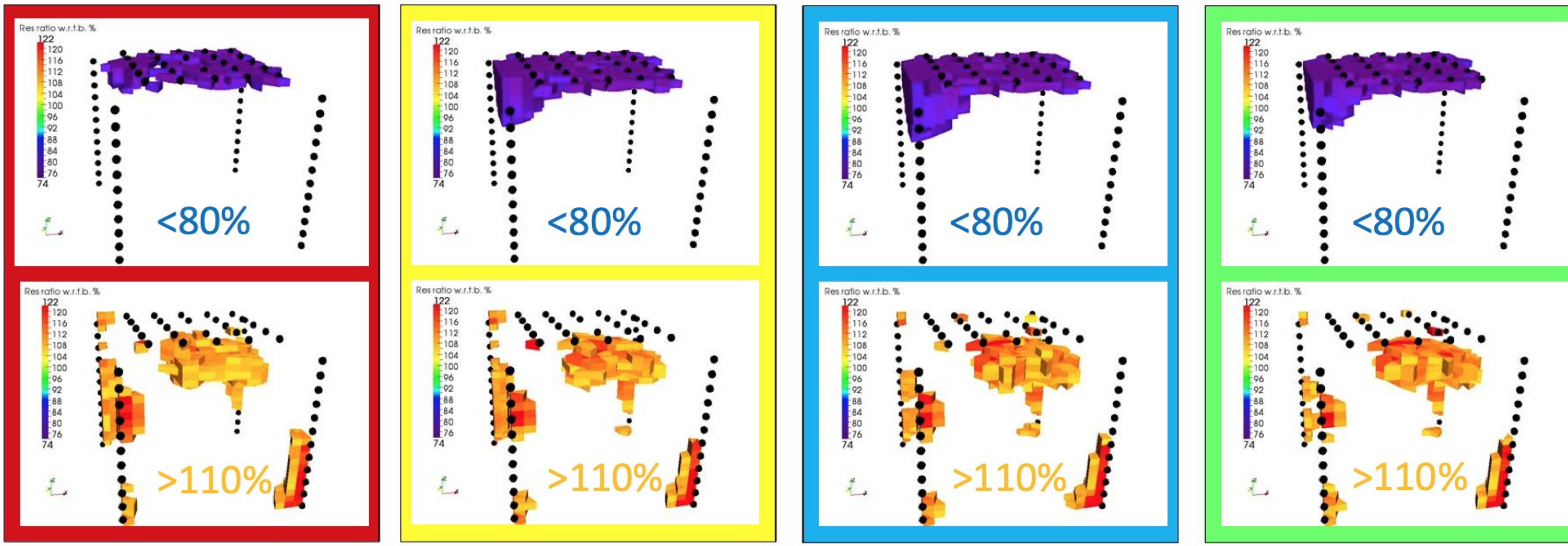

Sap flow probes
Borehole electrodes
Surface electrodes

Time-lapse monitoring during irrigation

(4 liters/min per dripper, 4 drippers per tree – spaced 1 m)

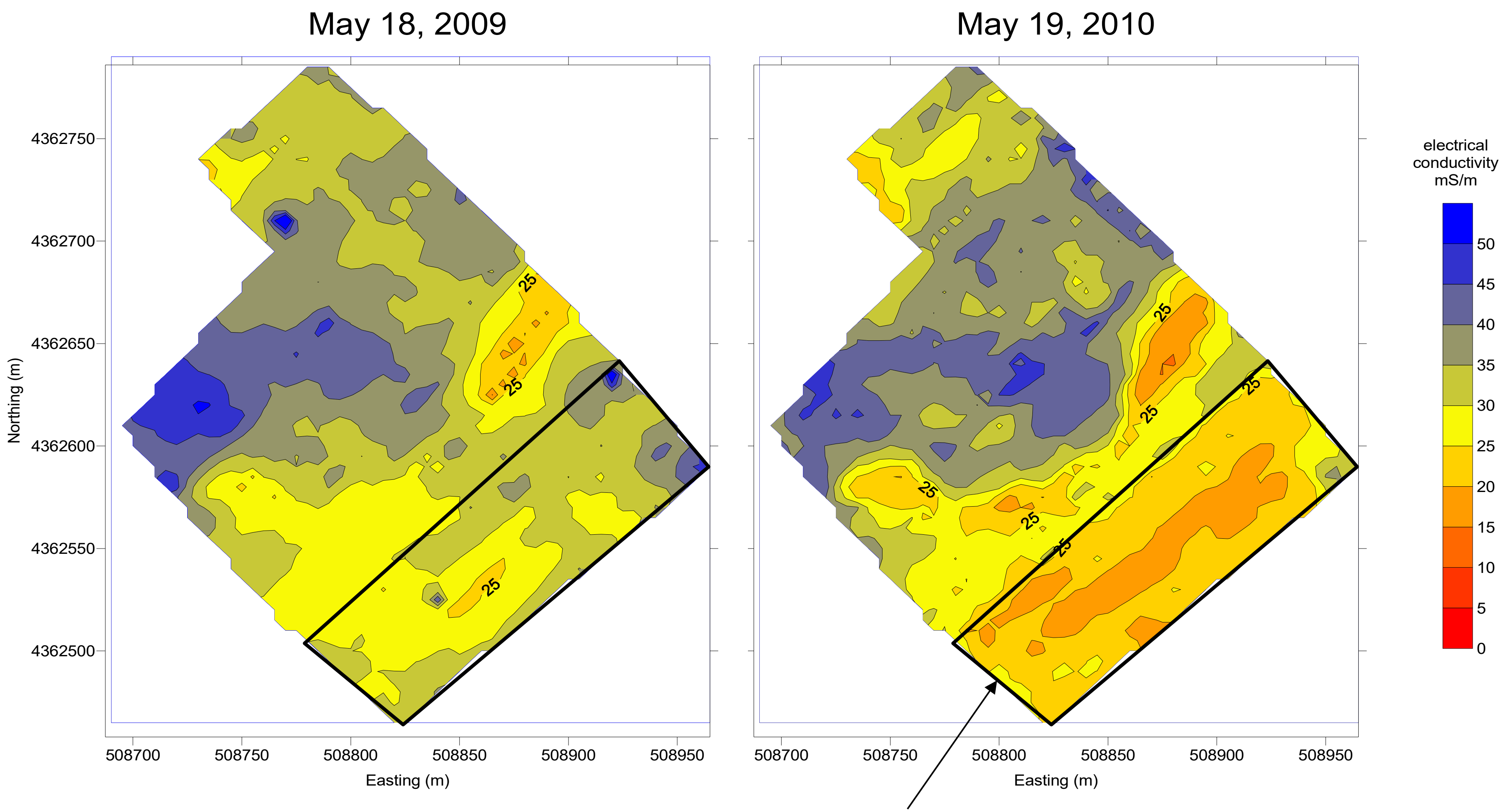
October 2-3, 2013





AGRIS San Michele experimental farm - Ussana - Sardinia

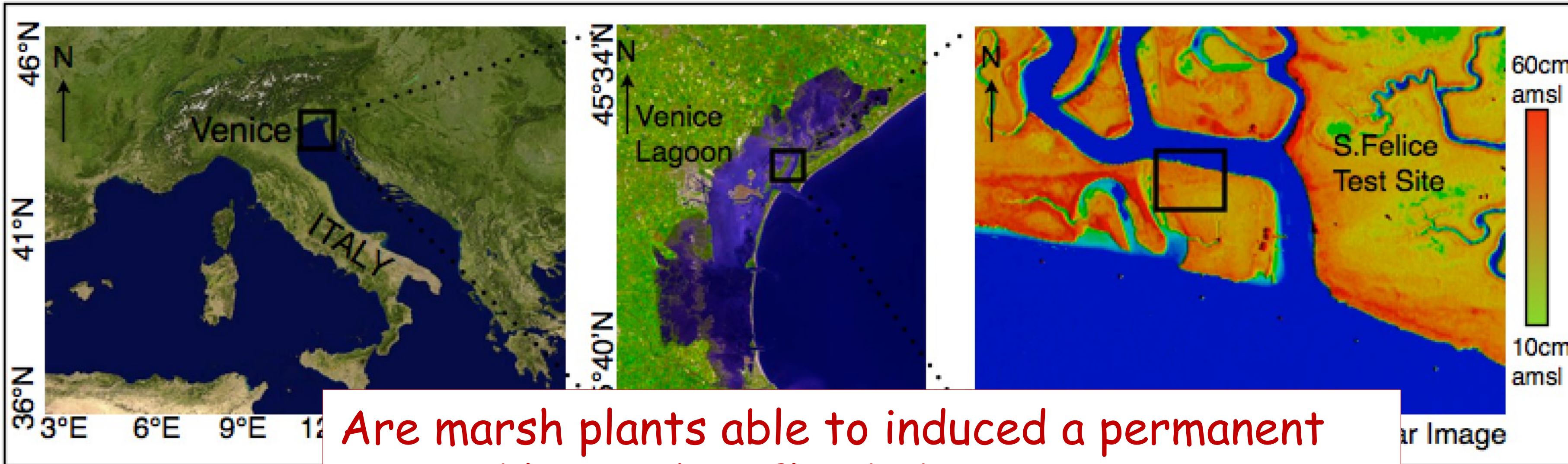
Digital soil mapping using frequency-domain EM



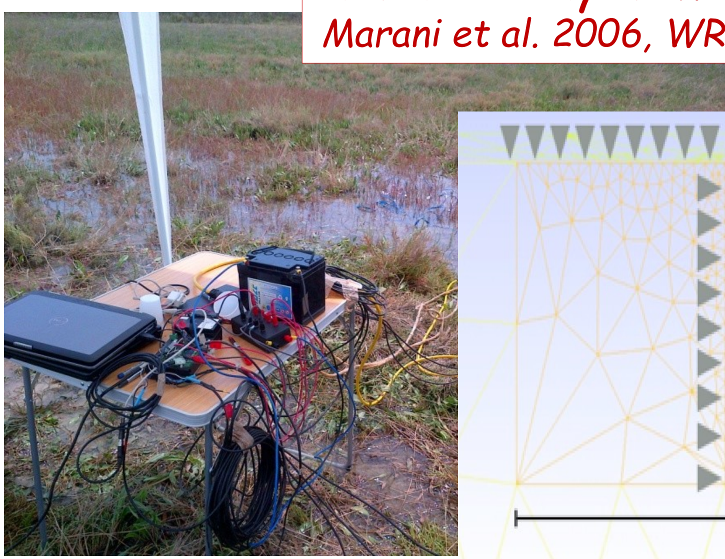
Wheat crop was planted in Jan 2010 on part of an otherwise bare soil field

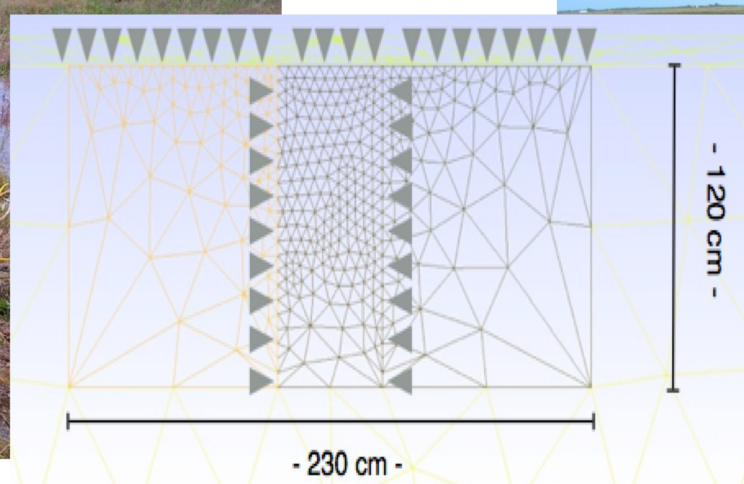
This area is considerably drier than the bare soil

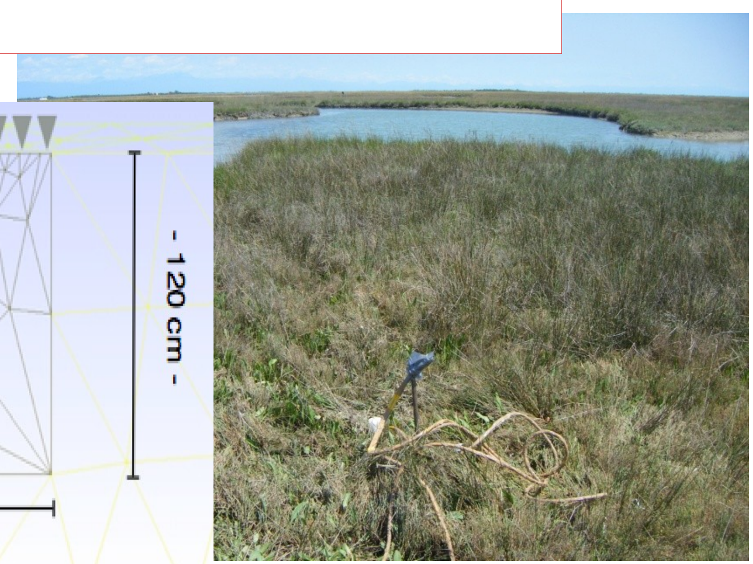
TIME LAPSE MICRO-ERT in the Venice Lagoon



Are marsh plants able to induced a permanent aerated layer when flooded ?
Marani et al. 2006, WRR

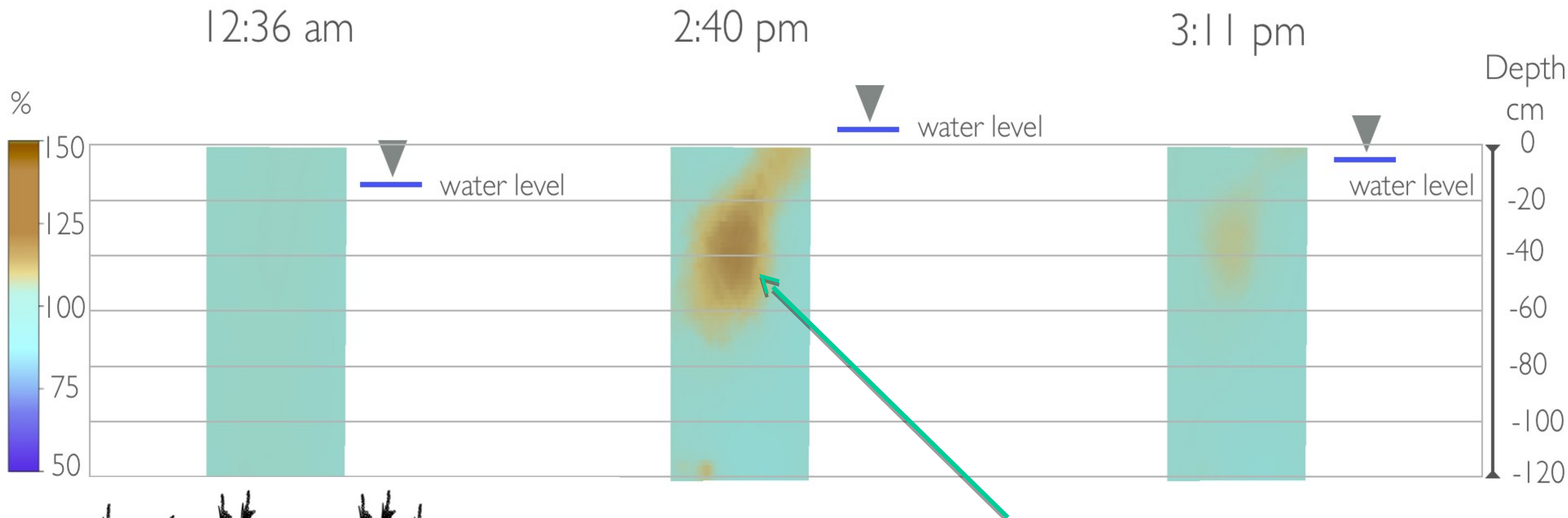


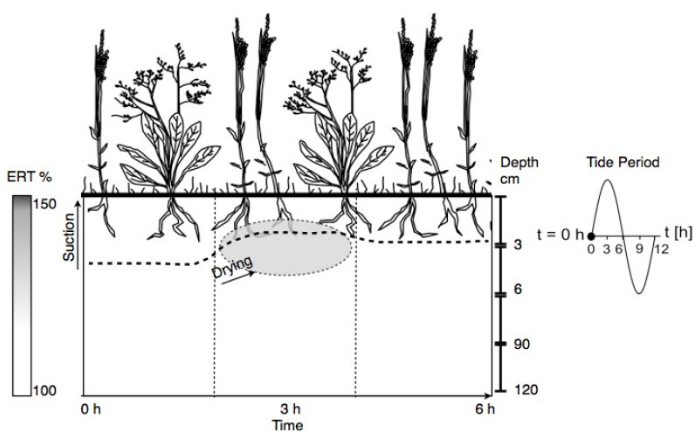




TIME LAPSE MICRO-ERT in the Venice Lagoon

July 2012 experiment: resistivity ratio with respect to background at 3 time steps during marsh flooding



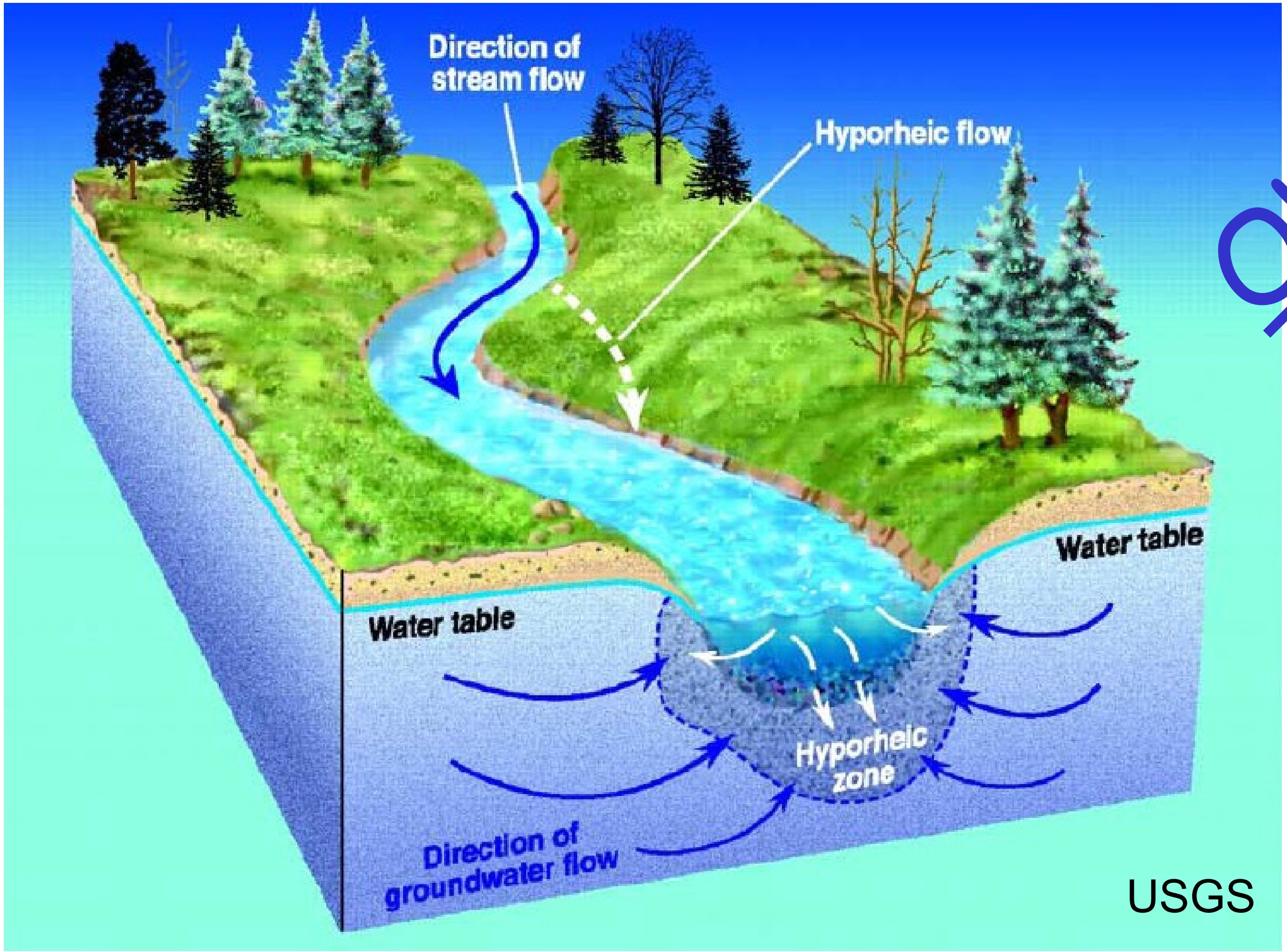


Dryer zone at roots depth

Boaga et al. 2014

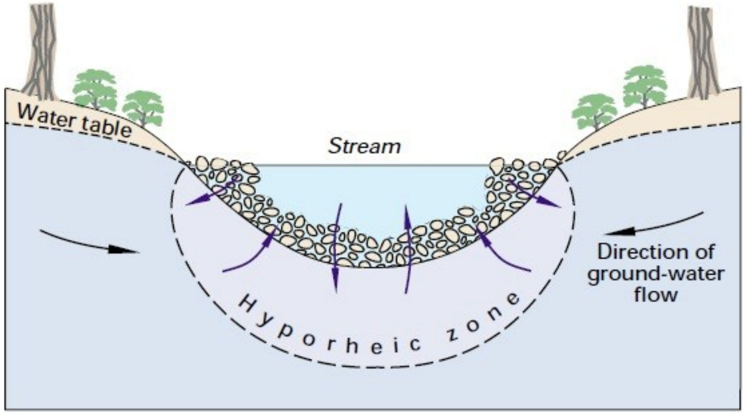
The hyporheic zone

OUTLOOK

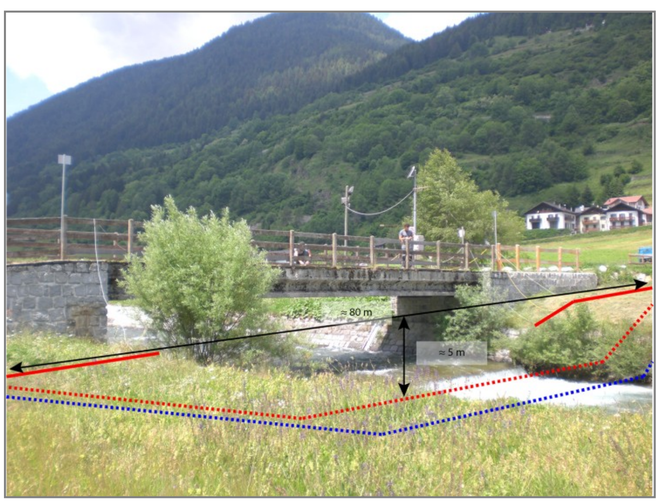


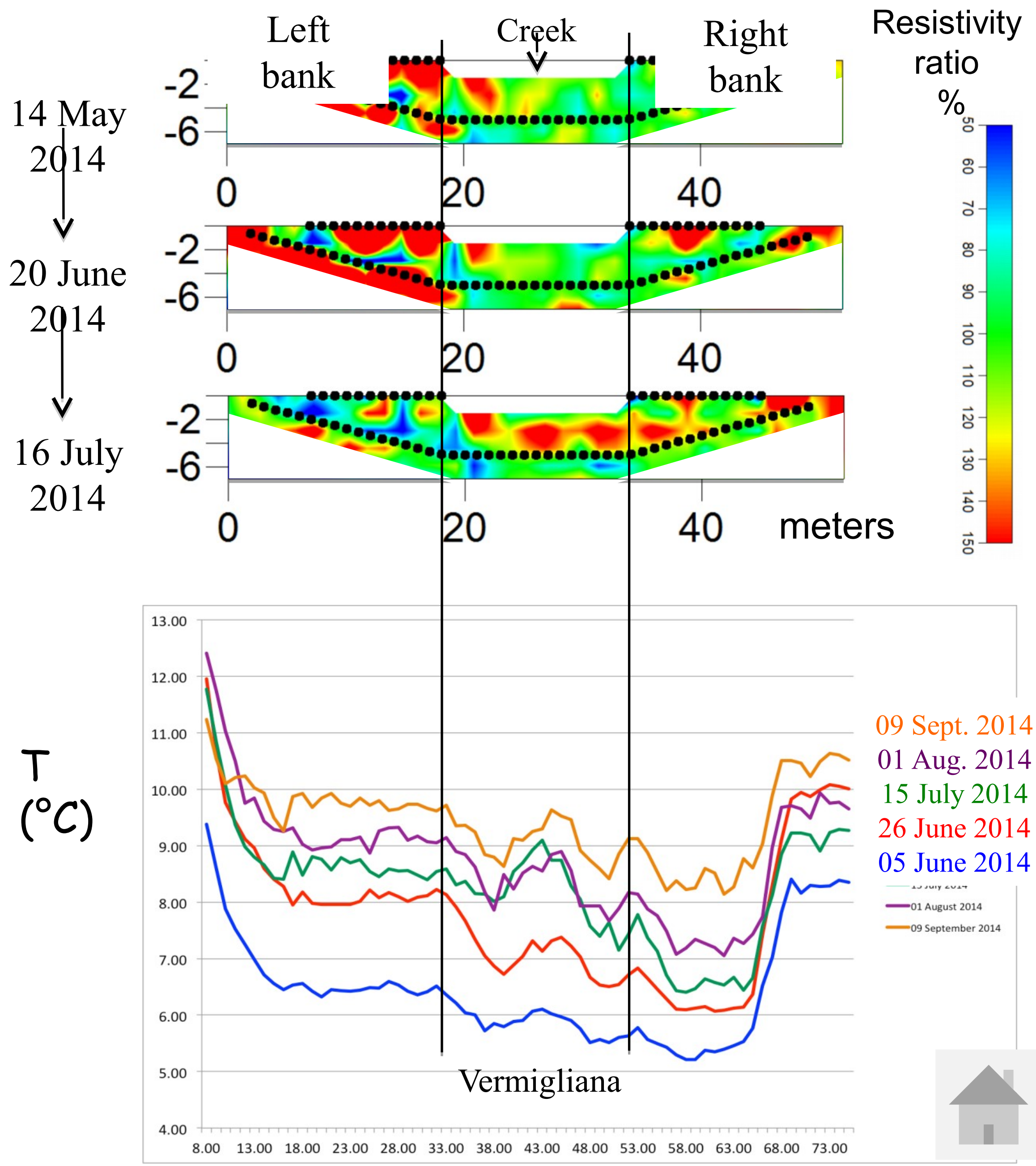
Vermigliana creek (hyporheic and riparian zones)

- Upper Val di Sole (TN)
- Presena glacier
- Nivo-glacial regime



ERT and **DTS** systems placed using directional drilling below the river bed.





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- MIUR PRIN 2011
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RICORDO DI CARLO MORELLI

(1917-2007)