



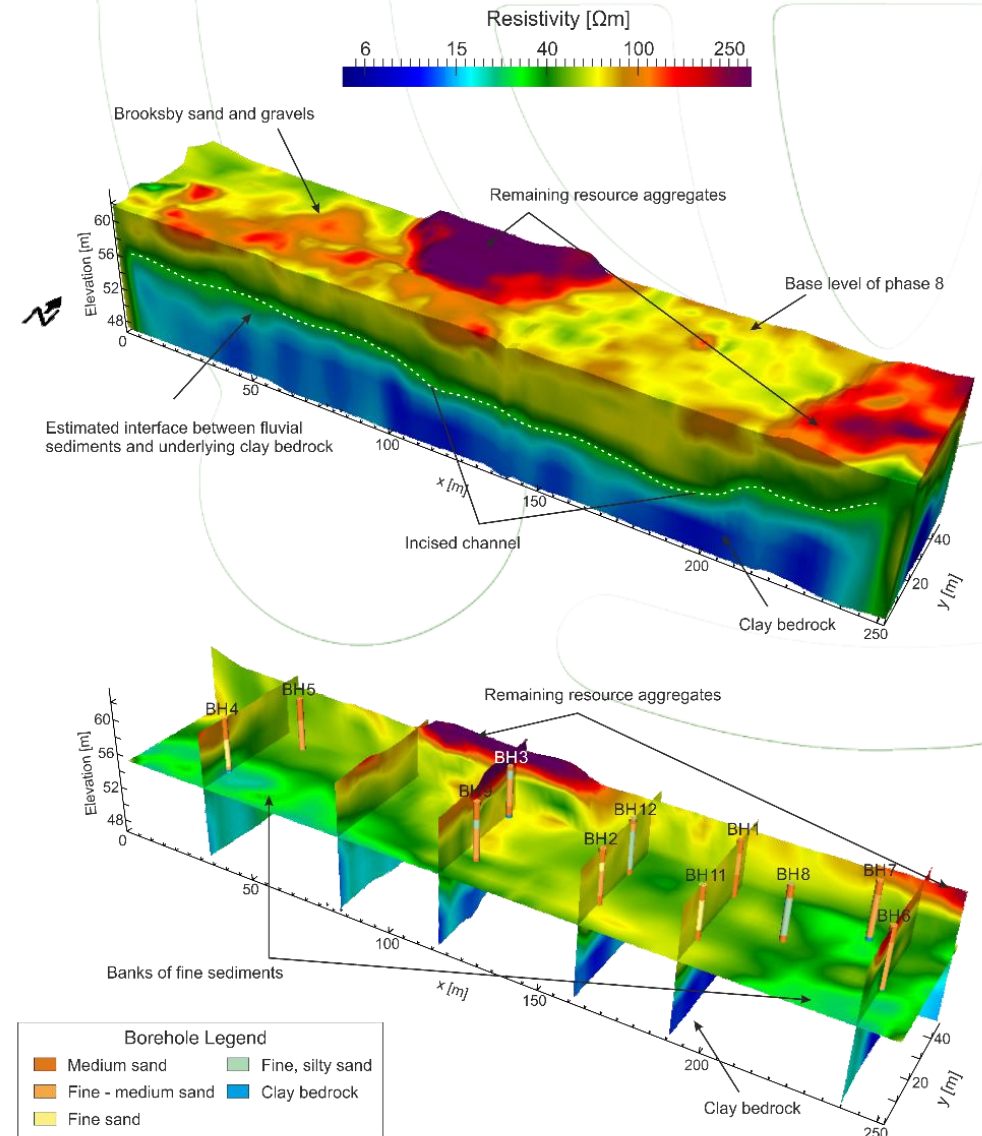
Geophysical monitoring: principles and applications

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 “Education and Research” - Component 2: “From research to business” - Investment
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”



Outline of the day

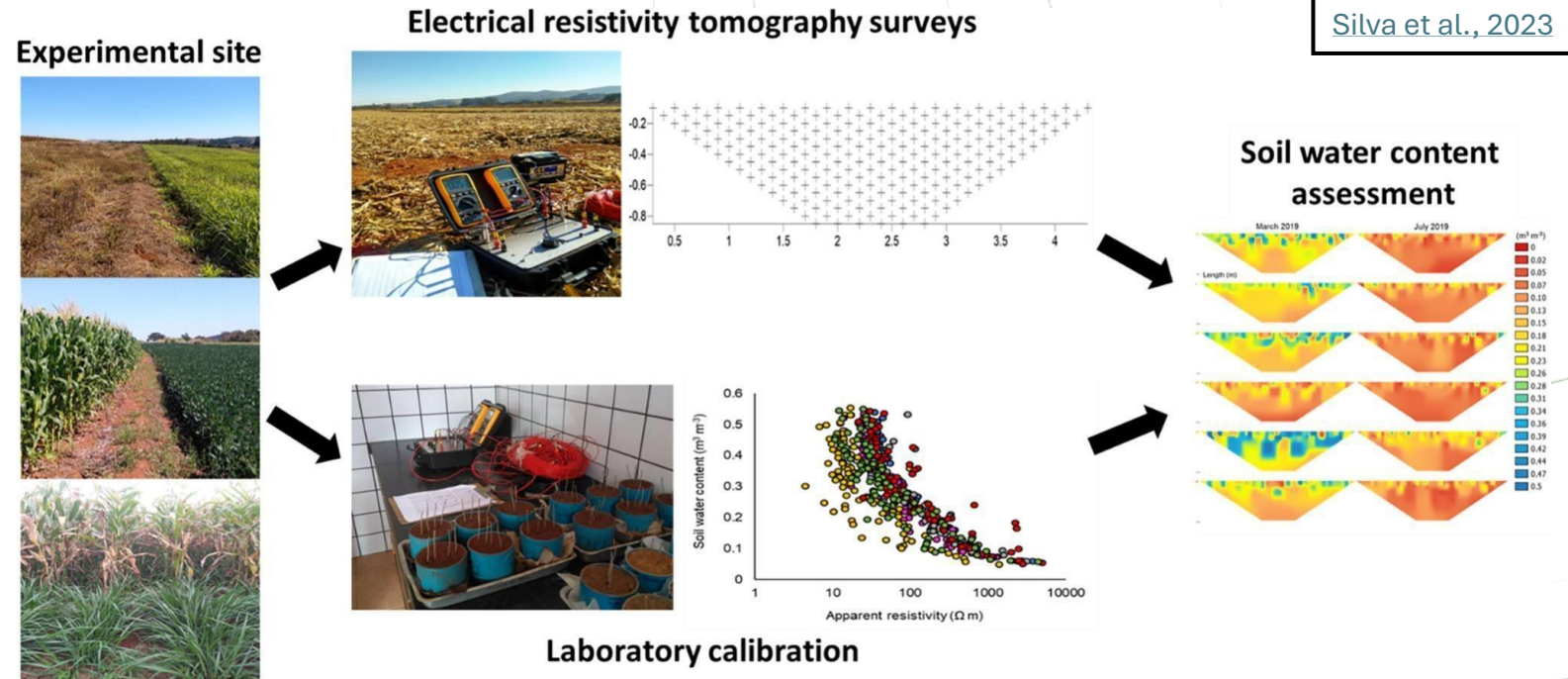
- **Fundamentals of electrical resistivity measurements**
 - Electrical properties of soils and rocks
 - Translating geoelectrical data into hydrogeomechanical properties
- **Principles of Electrical Resistivity & Electromagnetic Measurements**
 - Applications on ground and airborne geophysical characterization
- **Geoelectrical monitoring: Principles and applications**
 - Inversion approaches, practical considerations
 - Monitoring applications
- **Machine Learning for exploiting and assimilating environmental data**



Why electrical and electromagnetic methods?

The electrical resistivity of Earth materials is highly sensitive to variations in the hydraulic properties of the subsurface:

- Porosity
- Saturation
- Grain size distribution (hydraulic conductivity)
- Pore fluid conductivity



Wet, warm,
clay-rich, ion-rich
(salty)

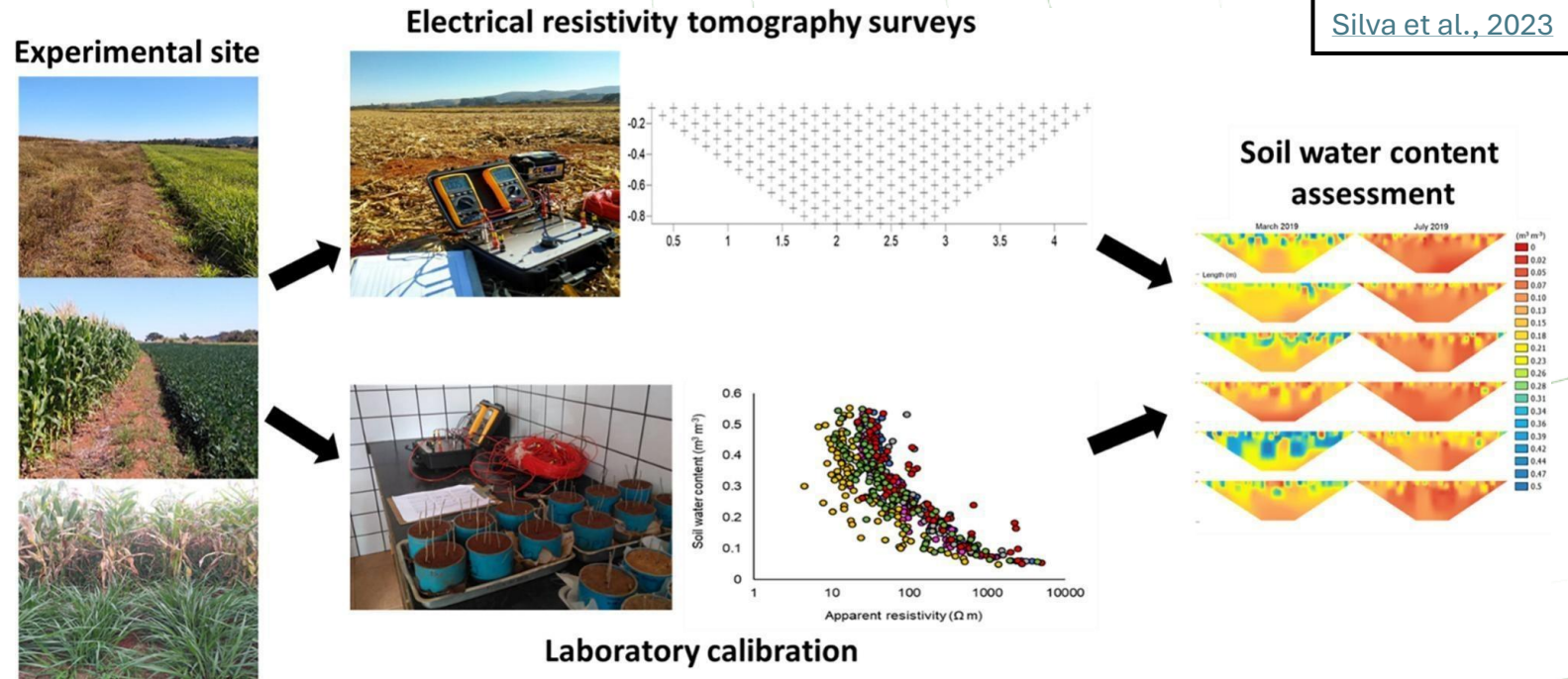
Resistivity

Dry, cold,
no clay, ion-depleted

Why electrical and electromagnetic methods?

The electrical resistivity of Earth materials is highly sensitive to variations in the hydraulic properties of the subsurface:

- Porosity
- Saturation
- Grain size distribution (hydraulic conductivity)
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Relatively constant

Wet, warm,
clay-rich, ion-rich
(salty)

Resistivity

Dry, cold,
no clay, ion-depleted

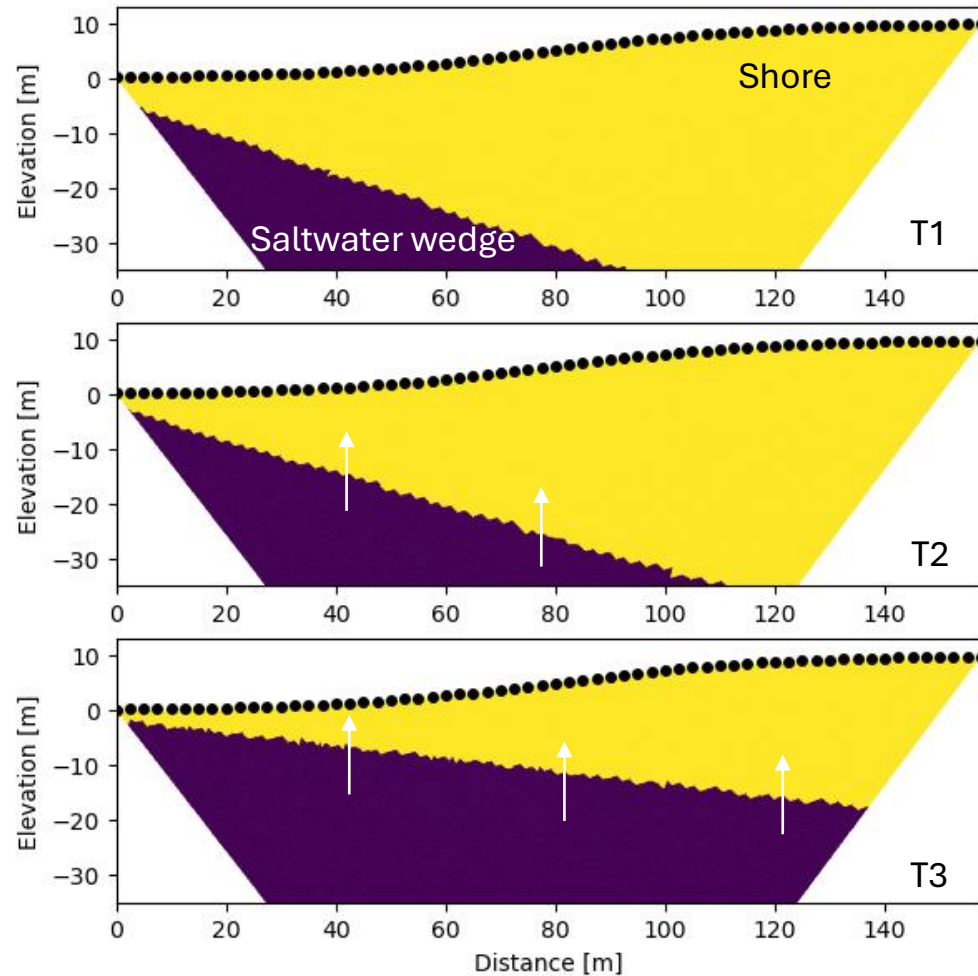
Process-monitoring



From characterization to monitoring

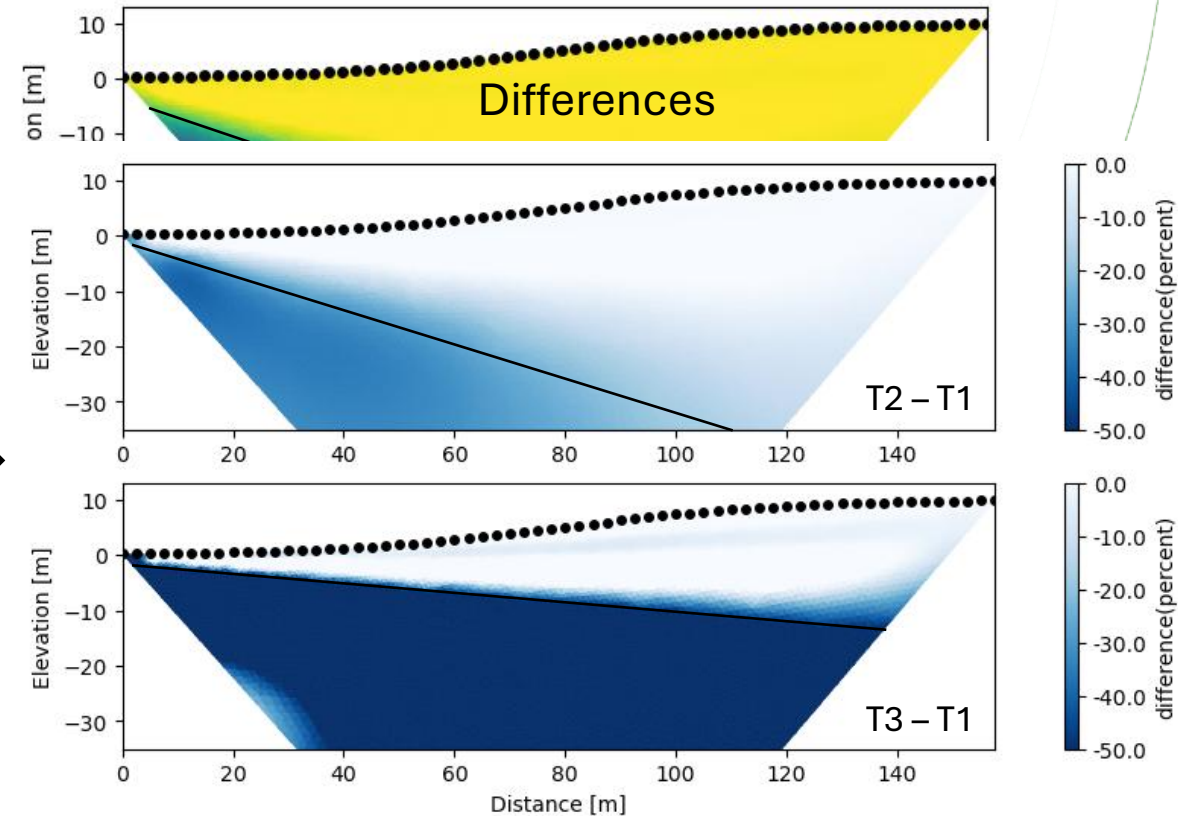
Assumption: Lithology remains constant through time!

Resistivity model



Inversion

Inverted resistivity model

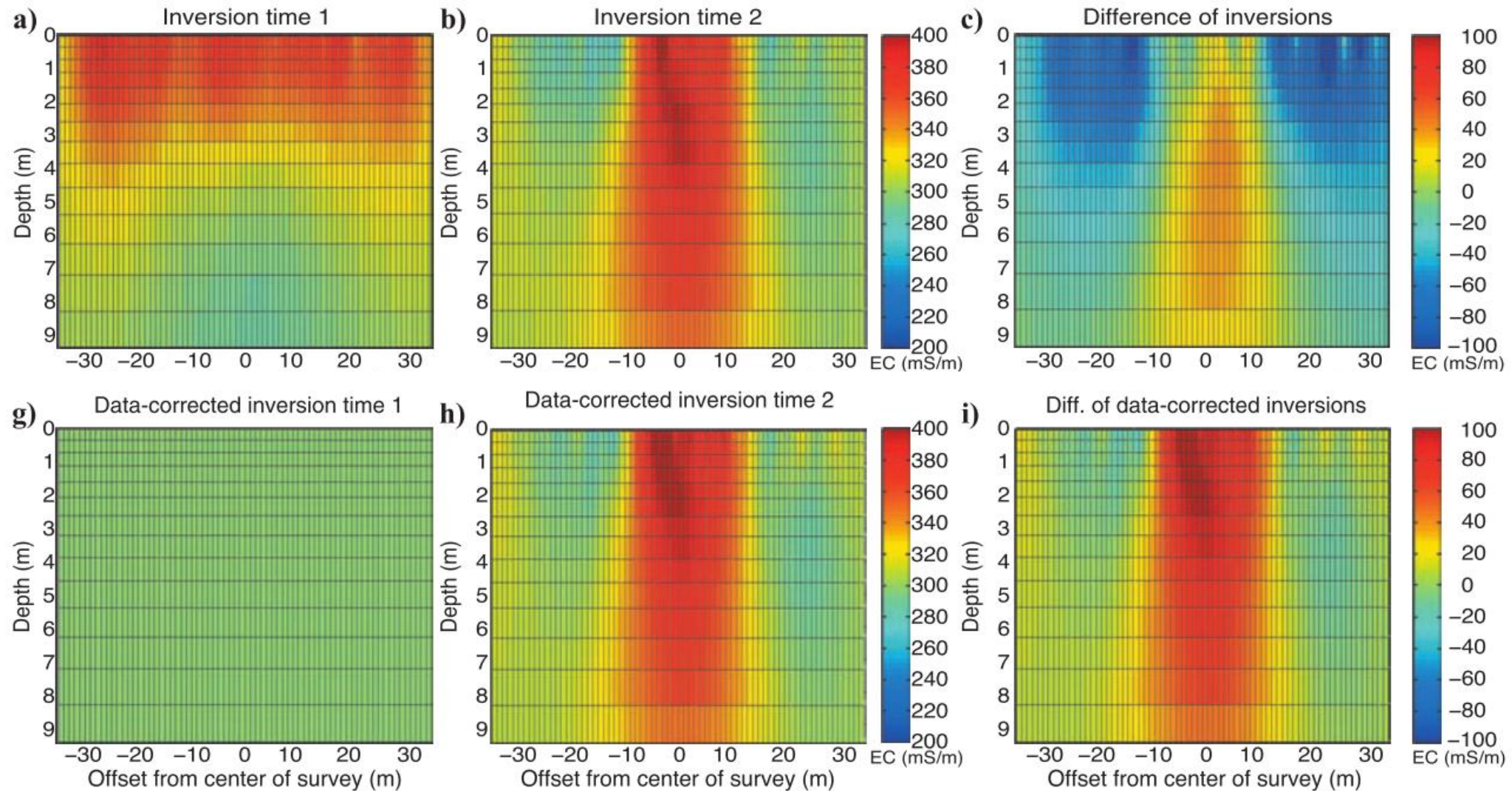


Resistivity monitoring results are usually **shown in terms of change** compared to baseline measurement

- Percent difference
- Ratio

Temperature effects

Subsurface temperatures may change during monitoring



Modelling temperature effects

Simplified heat equation

- Temperature distribution in the subsurface can be modelled using a solution to the heat equation

$$T_{\text{model}}(z, t) = T_{\text{mean}} + \frac{\Delta T}{2} \exp\left(-\frac{z}{d}\right) \sin\left(\frac{2\pi}{365}t + \varphi - \frac{z}{d}\right)$$

Annual mean temperature

Temp. change amplitude

Depth

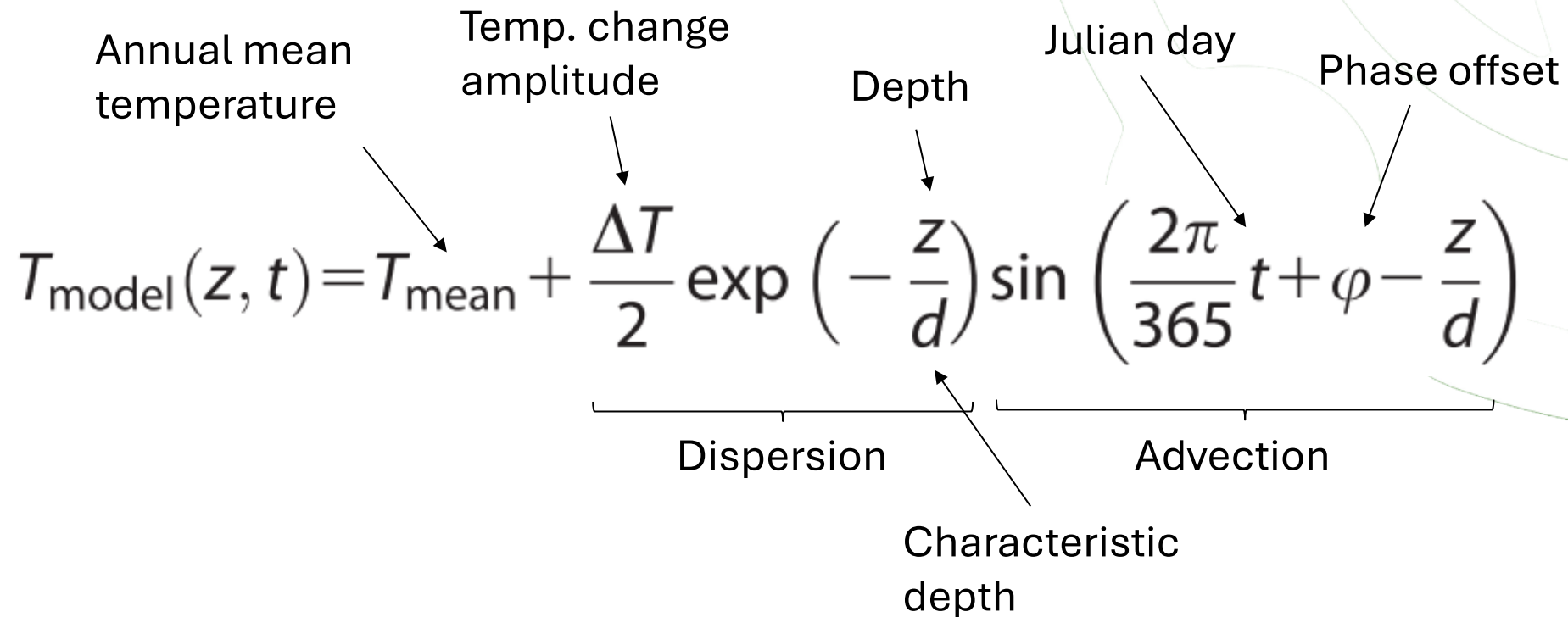
Julian day

Phase offset

Dispersion

Advection

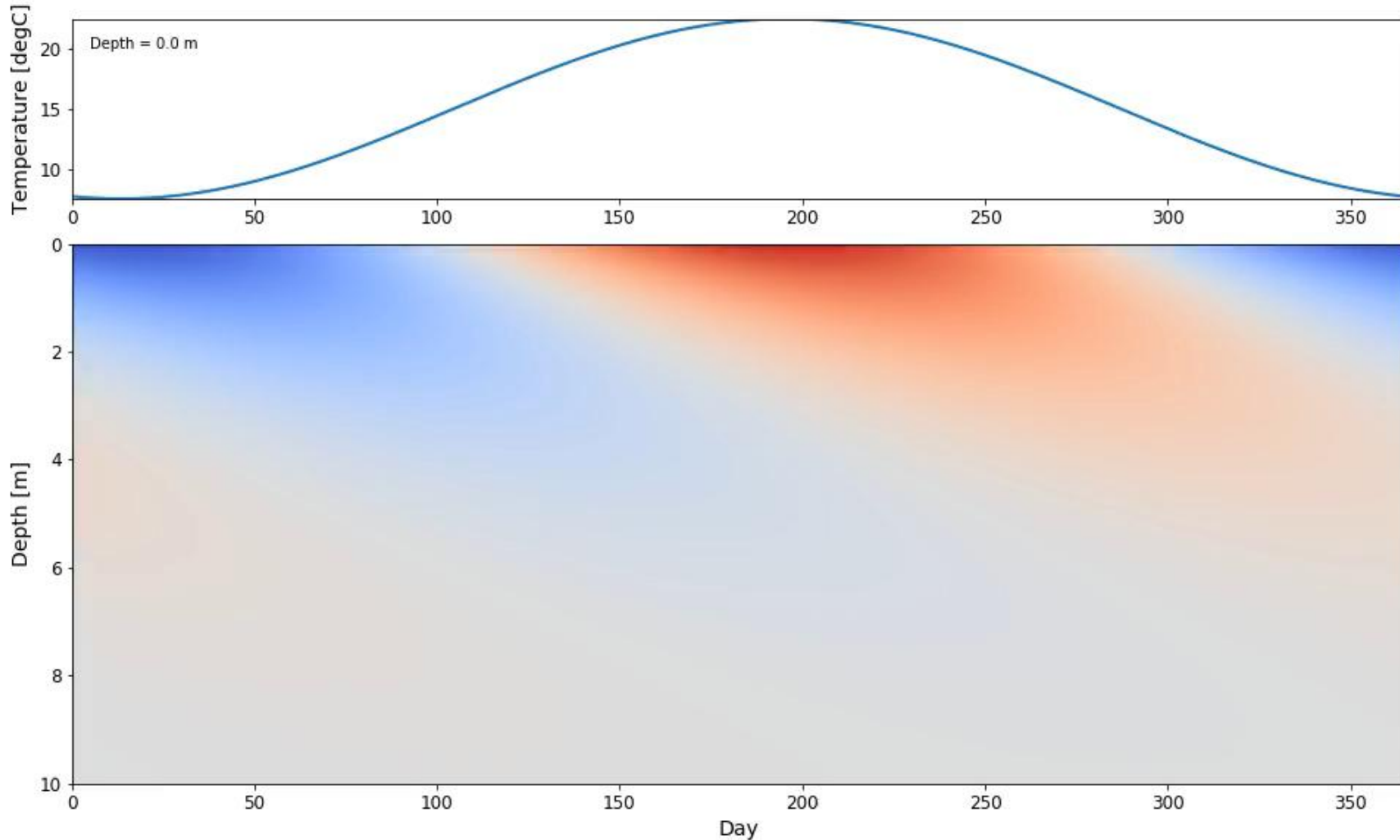
Characteristic depth



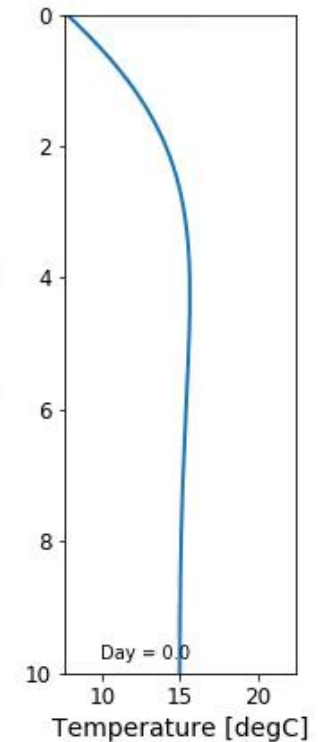
Modelling temperature effects

Results for typical mid-latitude location

$$T_{\text{model}}(z, t) = T_{\text{mean}} + \frac{\Delta T}{2} \exp\left(-\frac{z}{d}\right) \sin\left(\frac{2\pi}{365}t + \phi - \frac{z}{d}\right)$$



$T_{\text{mean}} = 15^\circ\text{C}$
 $\Delta T = 15^\circ\text{C}$
 $d = 2.0 \text{ m}$
 $\phi = -1.8 \text{ rad}$



Temperature correction of resistivity data

Ratio model

If we know the temperature distribution in the subsurface in space and time, we can correct the resistivity data for seasonal temperature variation

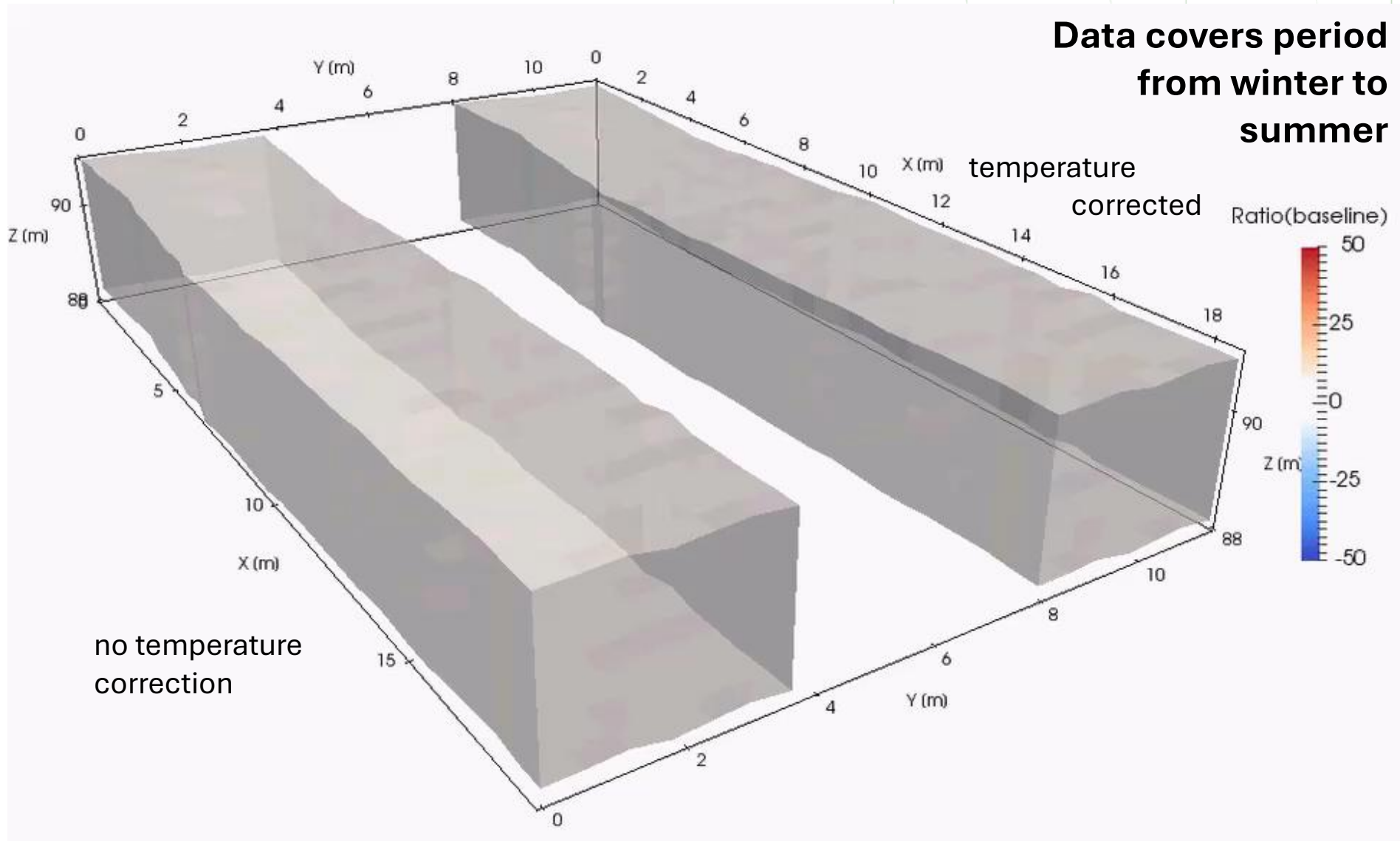
Correction factor $\sim -2.0^{\circ}\text{C}^{-1}$ Modelled temperature

$$\rho_{\text{cor}} = \rho \left[1 + \frac{c}{100} (T_{\text{target}} - T_{\text{model}}) \right]$$

Measured resistivity Standard temperature (e.g. Lab temperature)

Temperature correction of resistivity data

Example of seasonal drying processes



Field deployment

Components and examples – short term deployment

Considerations:

- Required resolution
- Available instrument capability
 - System capability (no of channels/electrodes)
 - Available cables & electrodes
- Measurement time vs. process-dynamics



Field deployment

Components and examples – long term deployments

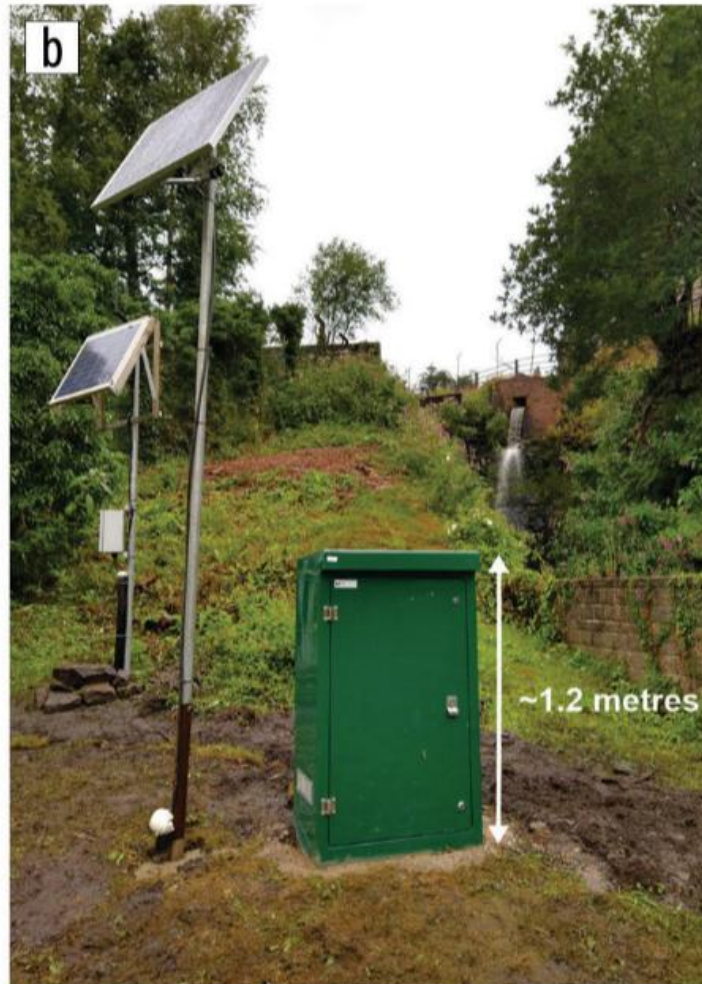
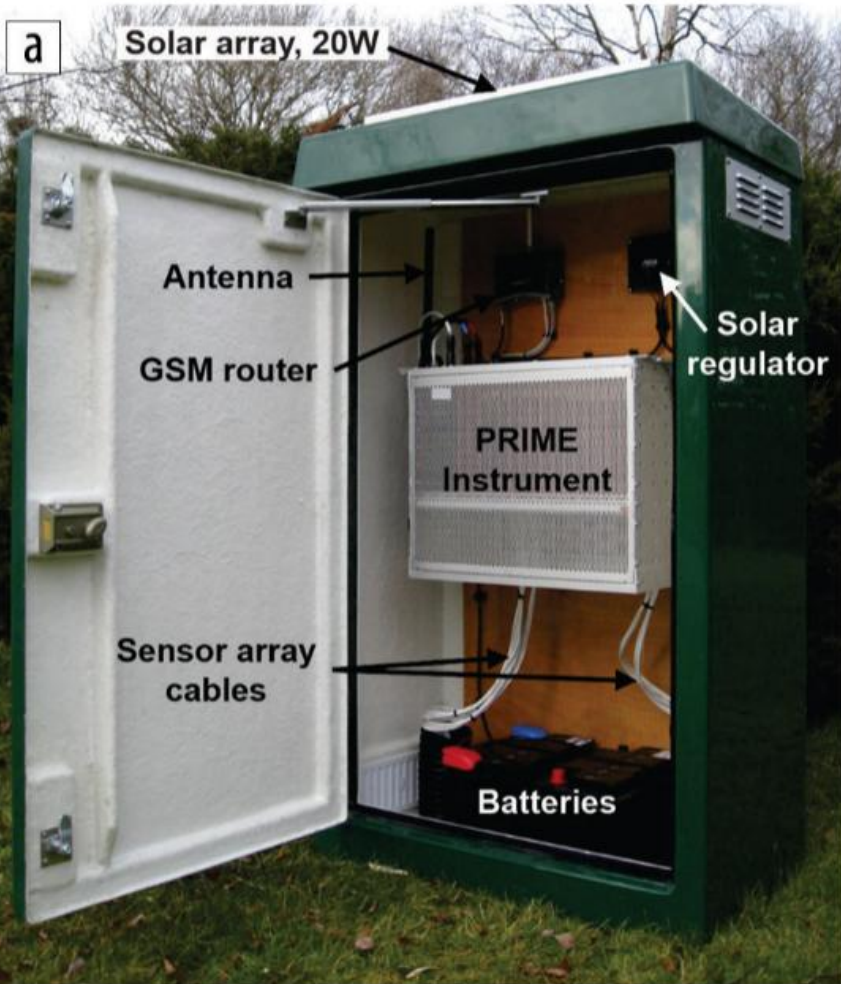


Considerations:

- **Power requirements of ERT system**
 - **The smaller the better, but sometimes higher power systems are needed**
- **How to get the power?**
 - **Solarpanels, wind turbines, fuel cells**
 - **Backup battery power**
- **Reliability of ERT system**
- **Real-time data transmission or storage?**
- **Safety?**

Field deployment

Components and examples – long term deployments – systems



ERT Monitoring system from **Subsurface Insights**



ERT Monitoring system (PRIME) from **BGS**

Field deployment

Components and examples – long term deployments – installation



Buried cables and electrodes for automated measurements

- **Protection against damage by wildlife or humans**
- **Making sure that electrodes stay in place**

For repeat measurements (no permanent installation) mark electrode locations!

Field deployment

Components and examples – long term deployments – installation



Field deployment

Components and examples – long term deployments

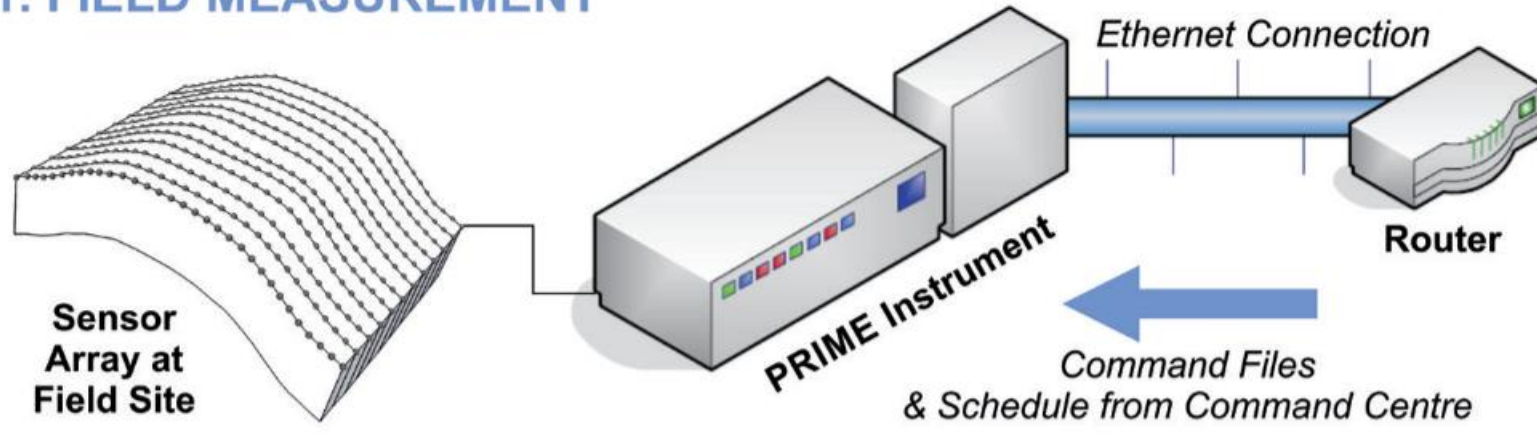


Remote/automated monitoring is great!
BUT: Systems and components may need maintenance
Need a maintenance strategy – and money!

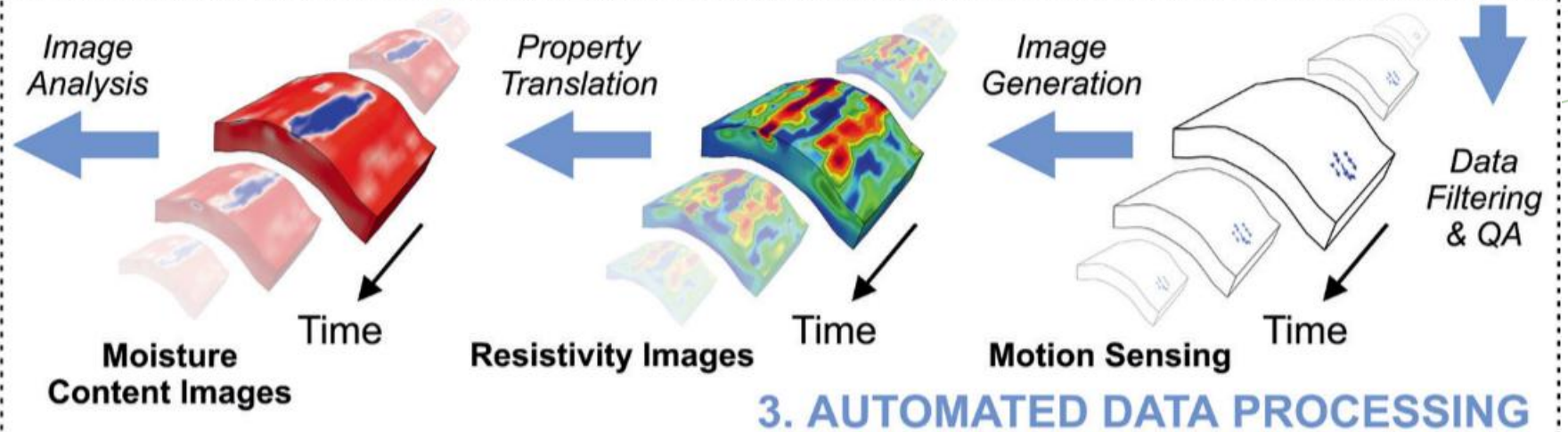
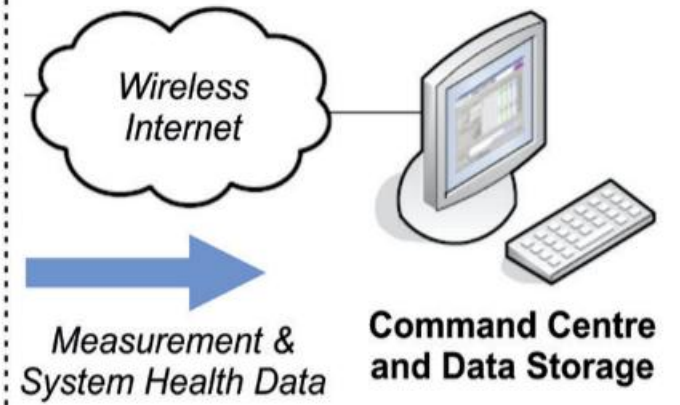
Automated monitoring workflows

Working with lots of data

1. FIELD MEASUREMENT



2. CONTROL & DATA STORAGE



Timelapse-inversion strategies

Overview

Full 4D Inversion

- Invert the entire time series as one dataset
- Enables implementing true smoothness constraints across time
- Requires the entire data set to be acquired

Windowed 4D Inversion

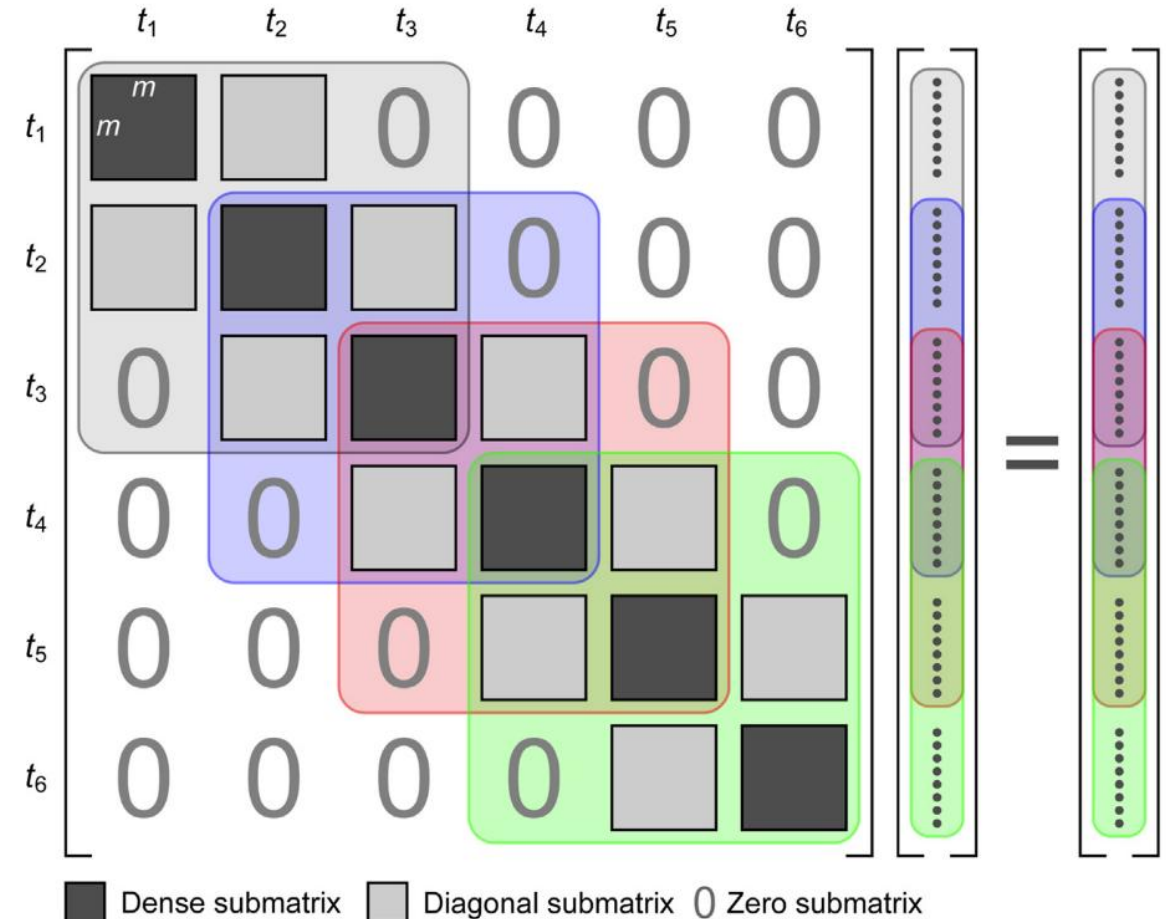
- Full 4D Inversion of data subsets
- Allows for near real-time results (no need for entire time series to be acquired)

Timelapse inversion

- Invert one timestep against a baseline
- Constraints to minimize the difference between two resistivity models

Difference inversion

- Only invert for the differences in the acquired data
- Baseline: invert ρ_a → timesteps: invert $\Delta\rho_a$



Timelapse-inversion strategies

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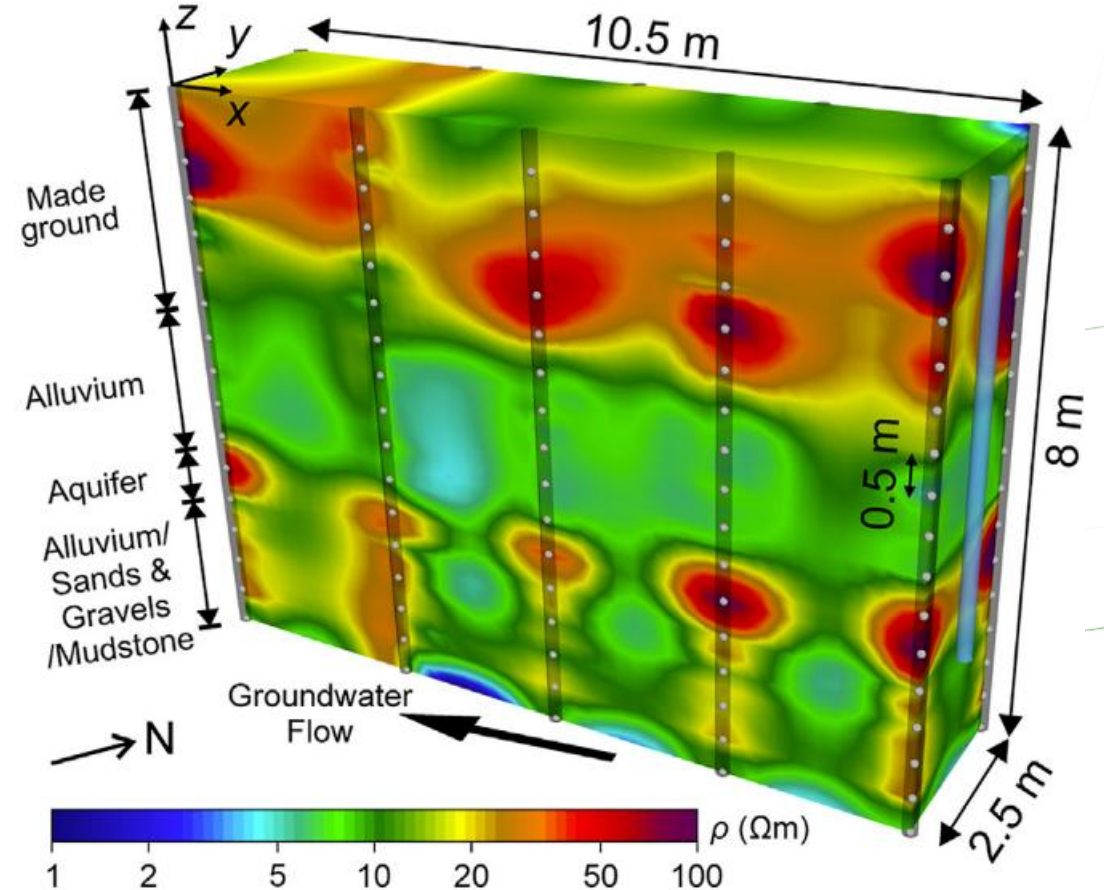
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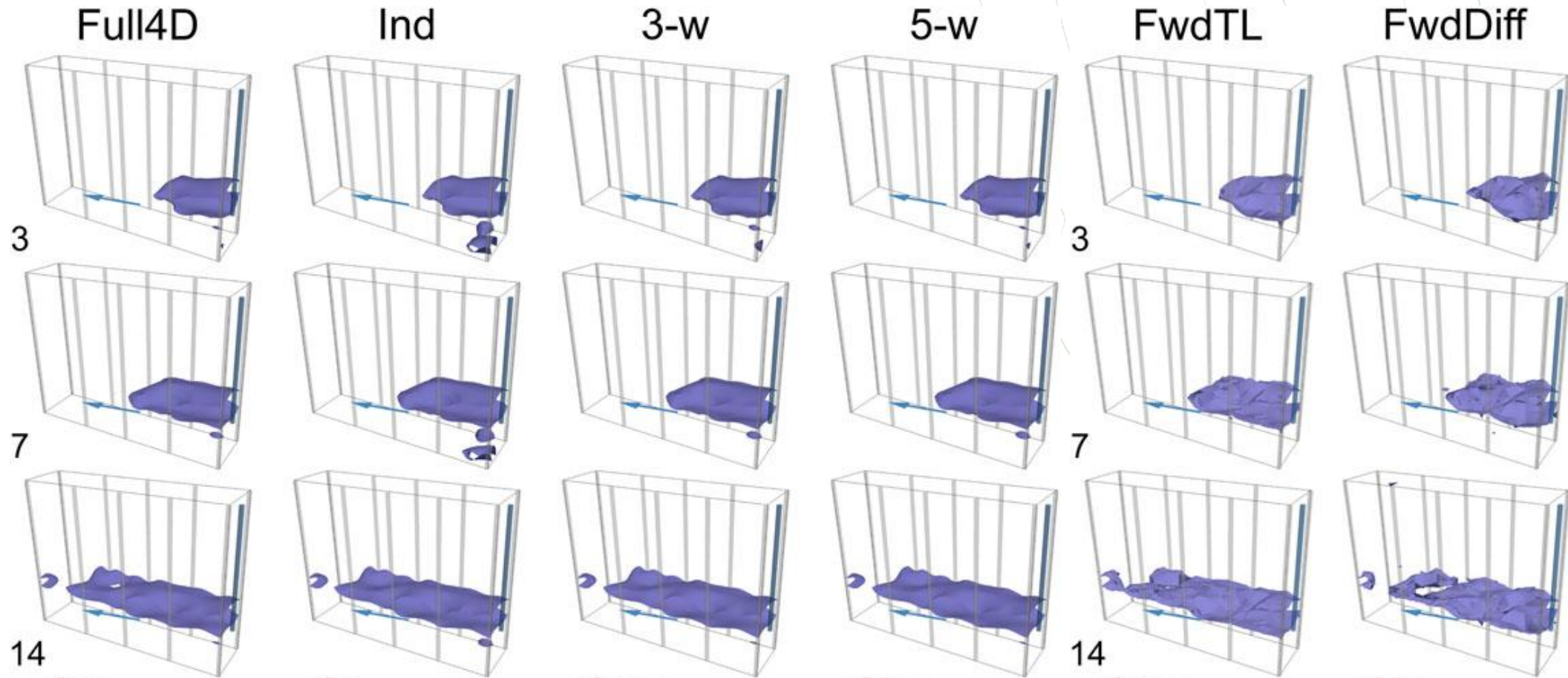
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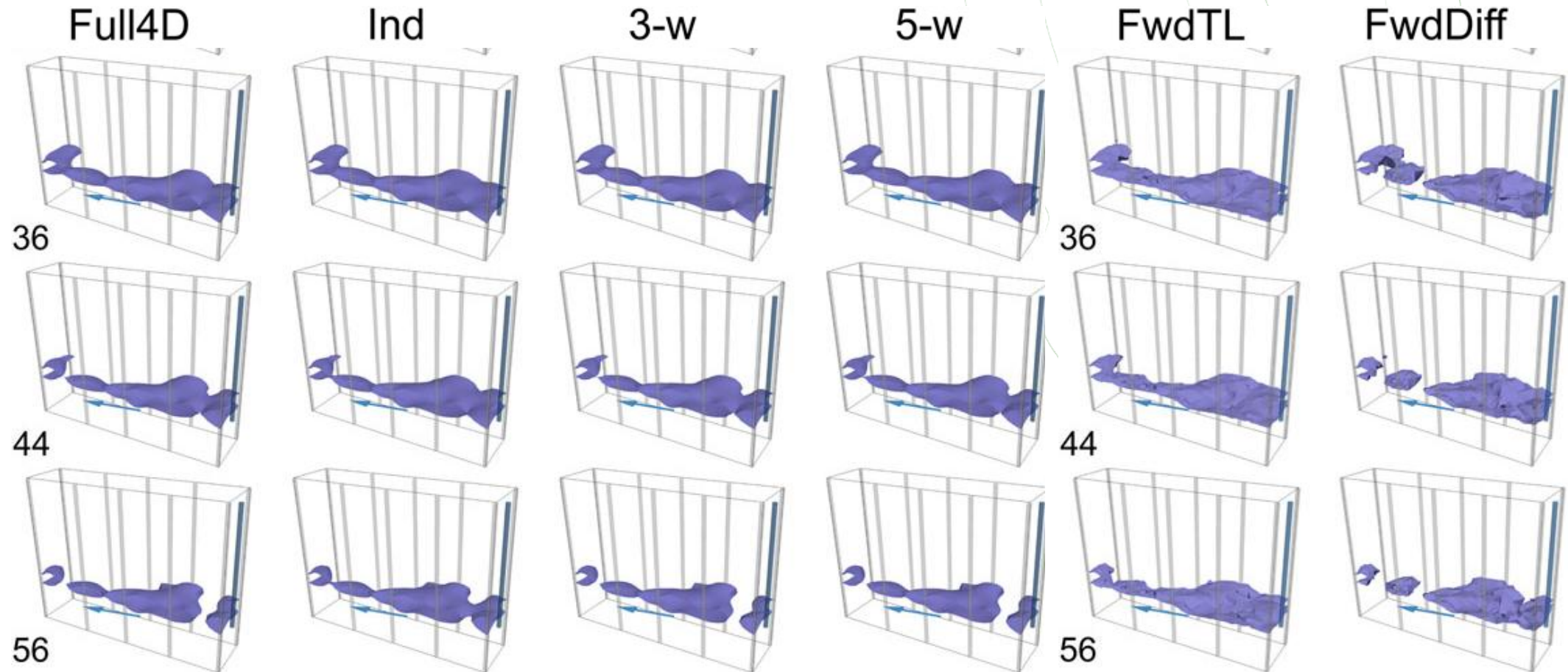
Timelapse-inversion strategies

Overview



Timelapse-inversion strategies

Overview



Timelapse-inversion strategies

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Windowed 4D Inversion

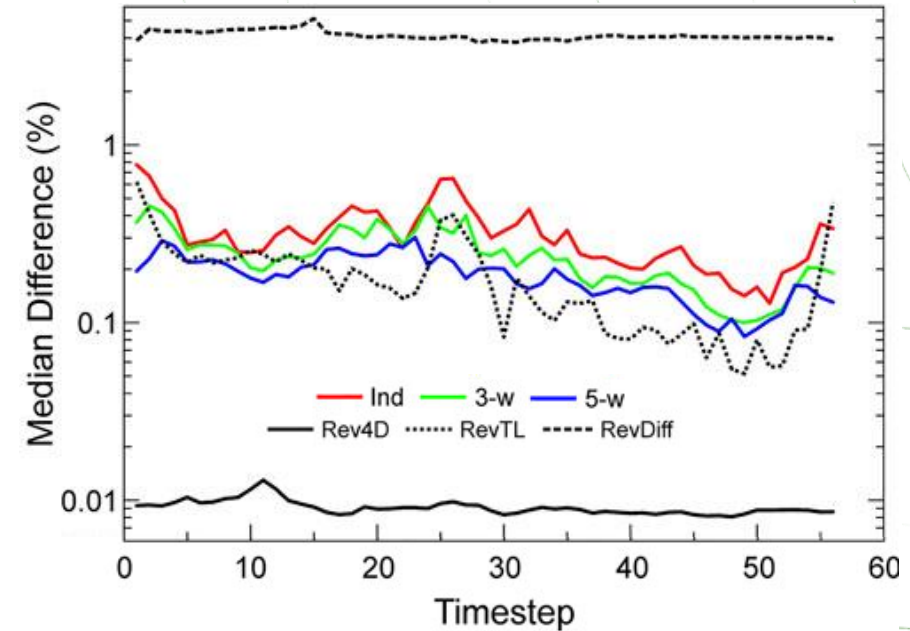
- Full 4D Inversion of data subsets
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Timelapse inversion

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Difference inversion

- Only invert for the differences in the acquired data
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- Full4D shows best performance
- Windowed and timelapse approach similar
- Difference inversion comparatively bad

The Hollin Hill Landslide Observatory

A long-standing research site for understanding landslide processes

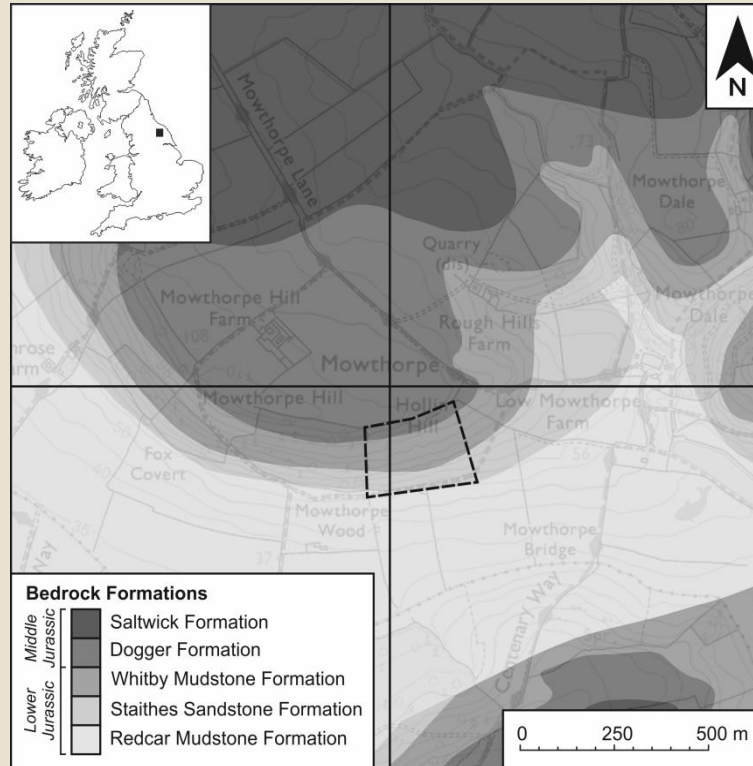
Field Research Site

- Hollin Hill Research Site
- North Yorkshire, North England
- South-facing hill slope
- Lias group of Lower Jurassic
- Instability prone
- Complex site history

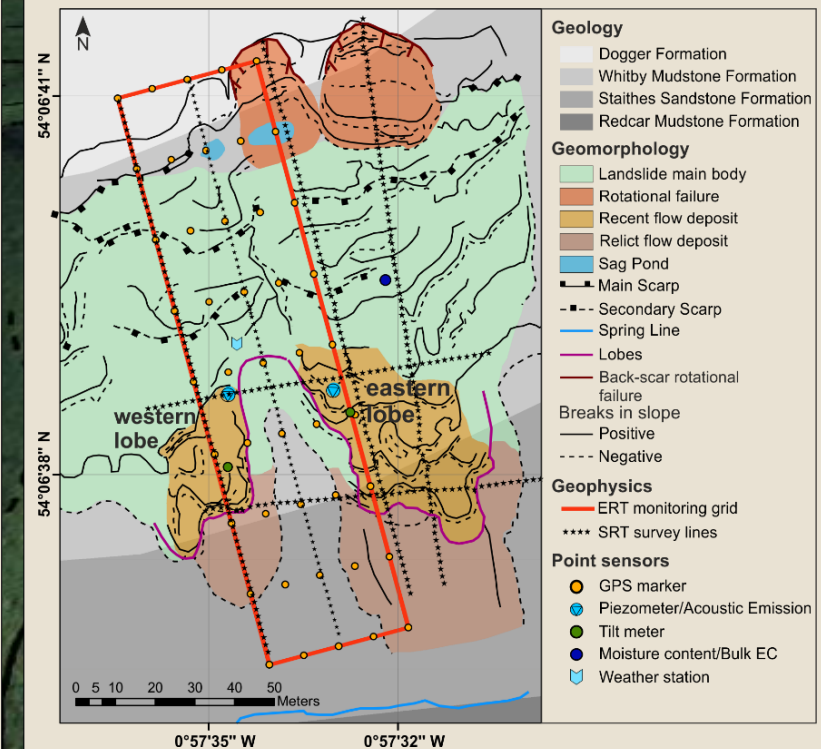
“Very slow to slow composite multiple earth slide-earth flow”
(Chambers et al., 2011)

Landslide Dimensions:

- Back scarp – toe: ~140 m
- Slope gradient: 12°
- Lateral extent: >450 m



Geological Map



Monitoring Instrumentation

Chambers, J. E., Wilkinson, P. B., Kuras, O., et al. (2011). Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK. *Geomorphology*, 125(4), 472–484.

Uhlemann, S., Smith, A., Chambers, J. E., et al. (2016). Assessment of ground-based monitoring techniques applied to landslide investigations, *Geomorphology*, 253, 438–451.

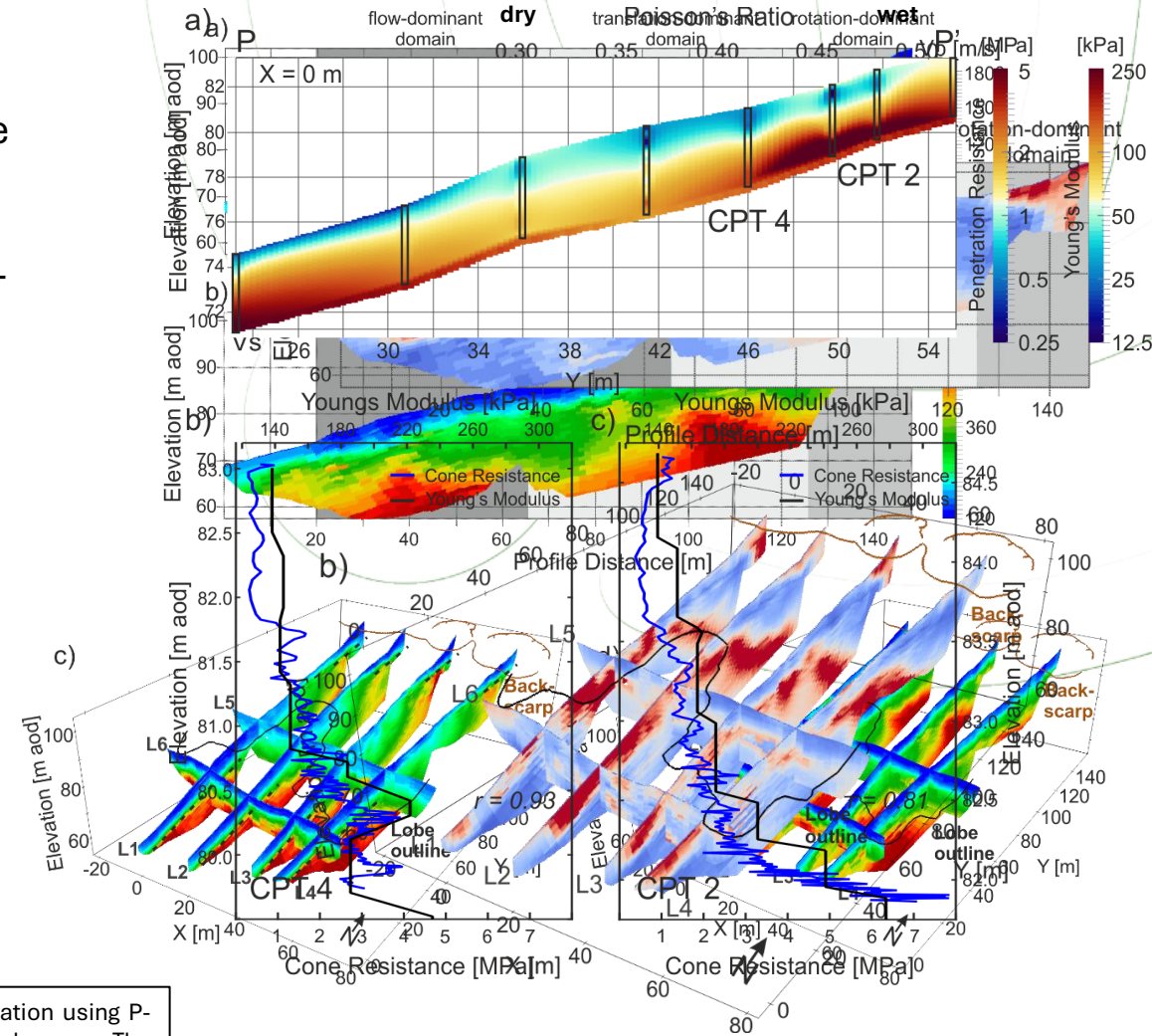
Geophysical Characterization of the Hollin Hill Landslide Observatory

Importance of elastic parameters



- **Seismic characterisation** of the landslide material
- **Novel application** of P- and S-wave seismic refraction tomography
 - > 3000 shots
 - ~ 500 geophone locations
- Seismic results were indicative of “water saturation” of the material

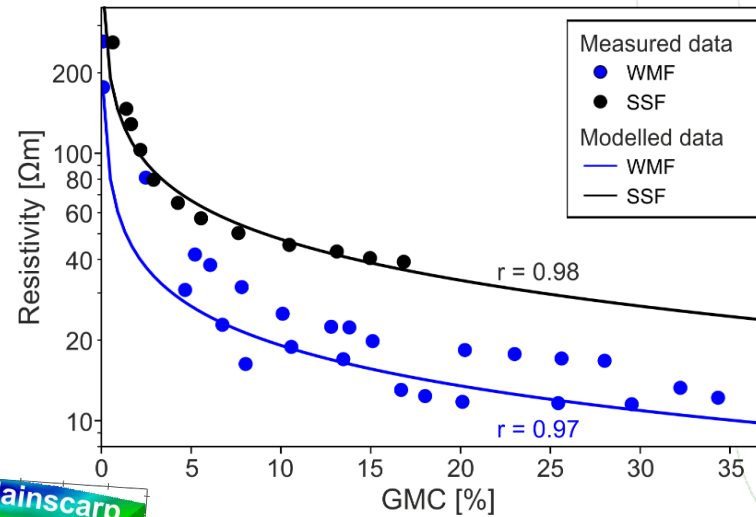
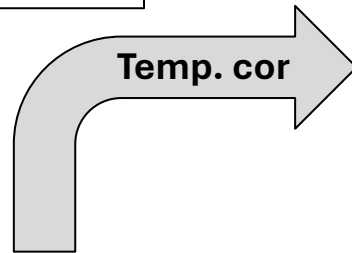
Uhlemann et al. (2016), Landslide characterization using P- and S-wave seismic refraction tomography — The importance of elastic moduli, *J. Appl. Geophys.*, 134



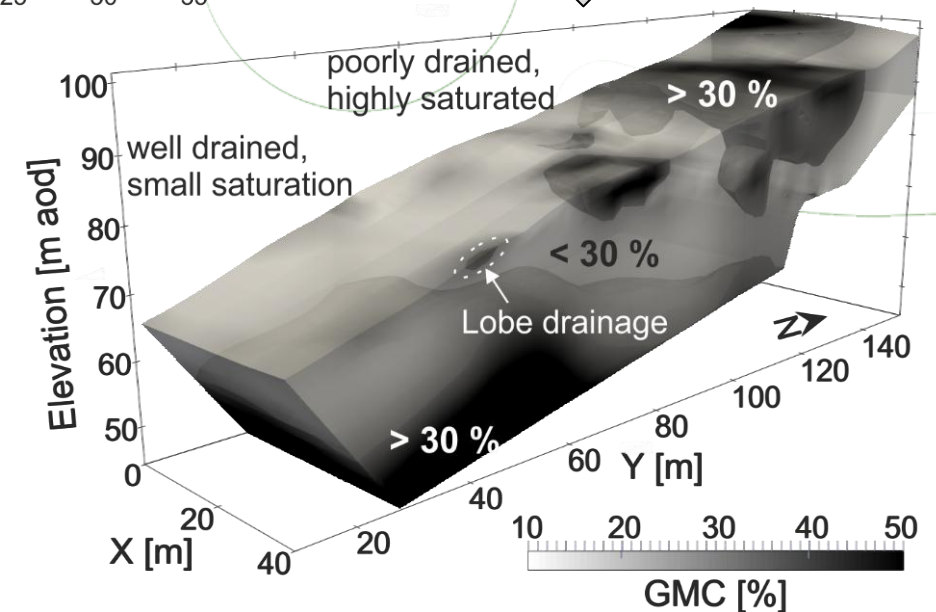
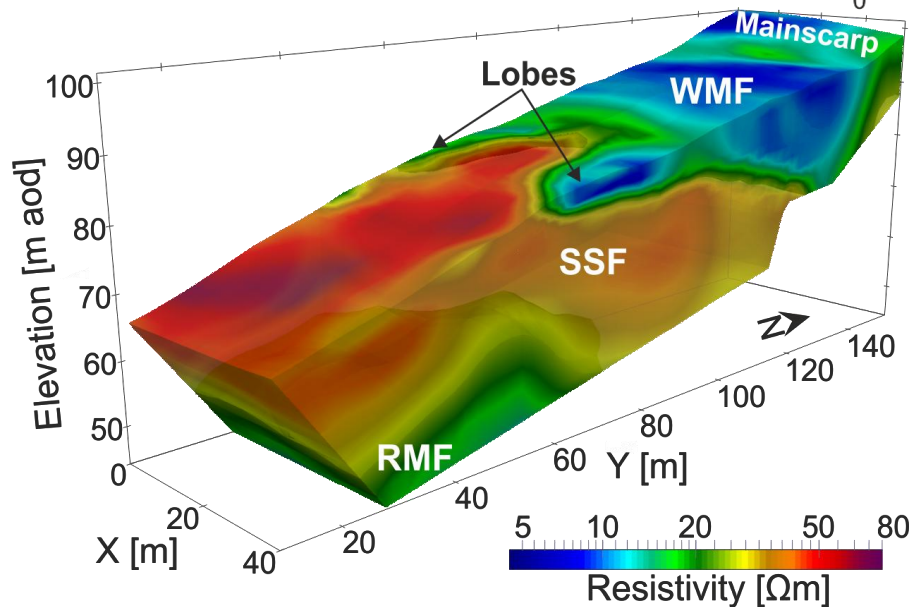
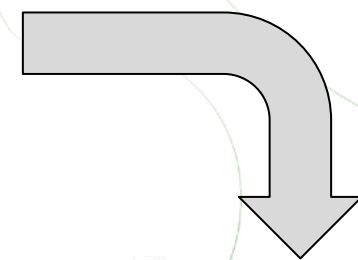
Long-term geoelectrical monitoring of Hollin Hill

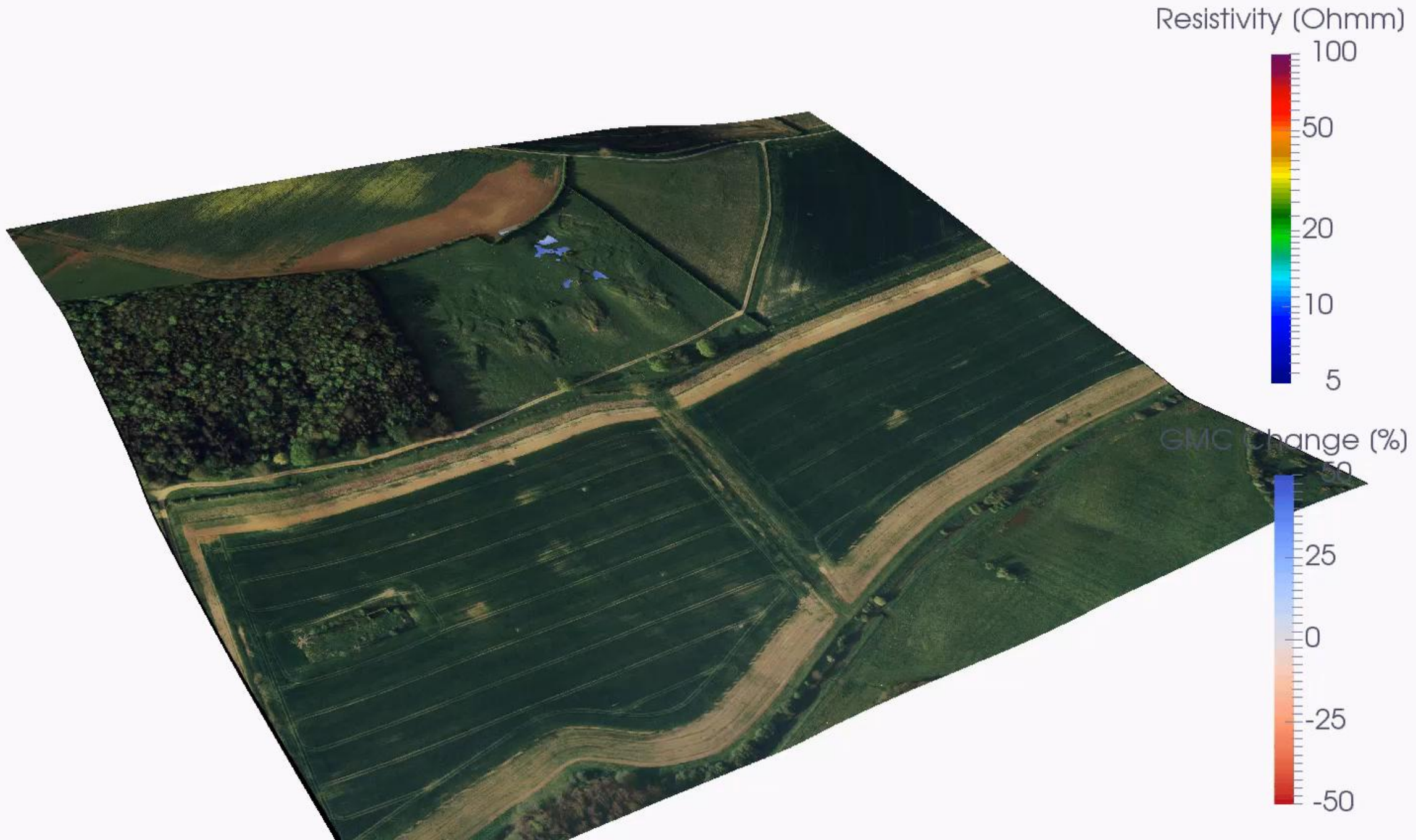
Translating models of electrical resistivity into moisture content

- Monitoring frequency: 2 days
- 3D data acquisition (5x32 = 160 electrodes)
- Operational since 2009



Uhlemann et al. (2017), Four-dimensional imaging of moisture dynamics during landslide reactivation, *JGR: Earth Surf.*, 122(1)

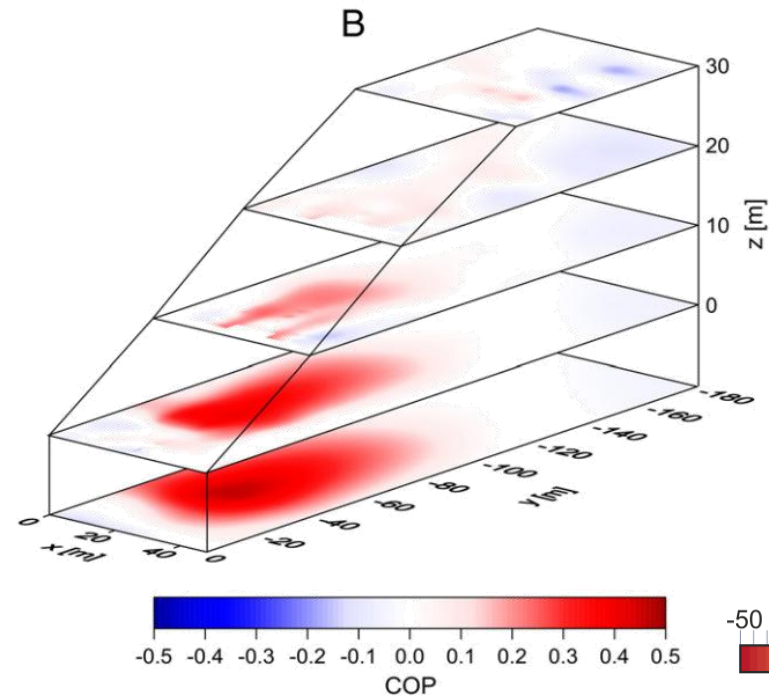
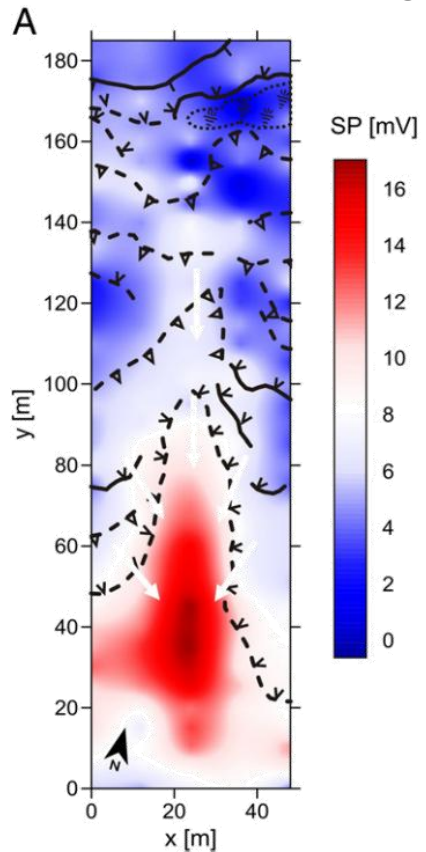




Long-term geoelectrical monitoring of Hollin Hill

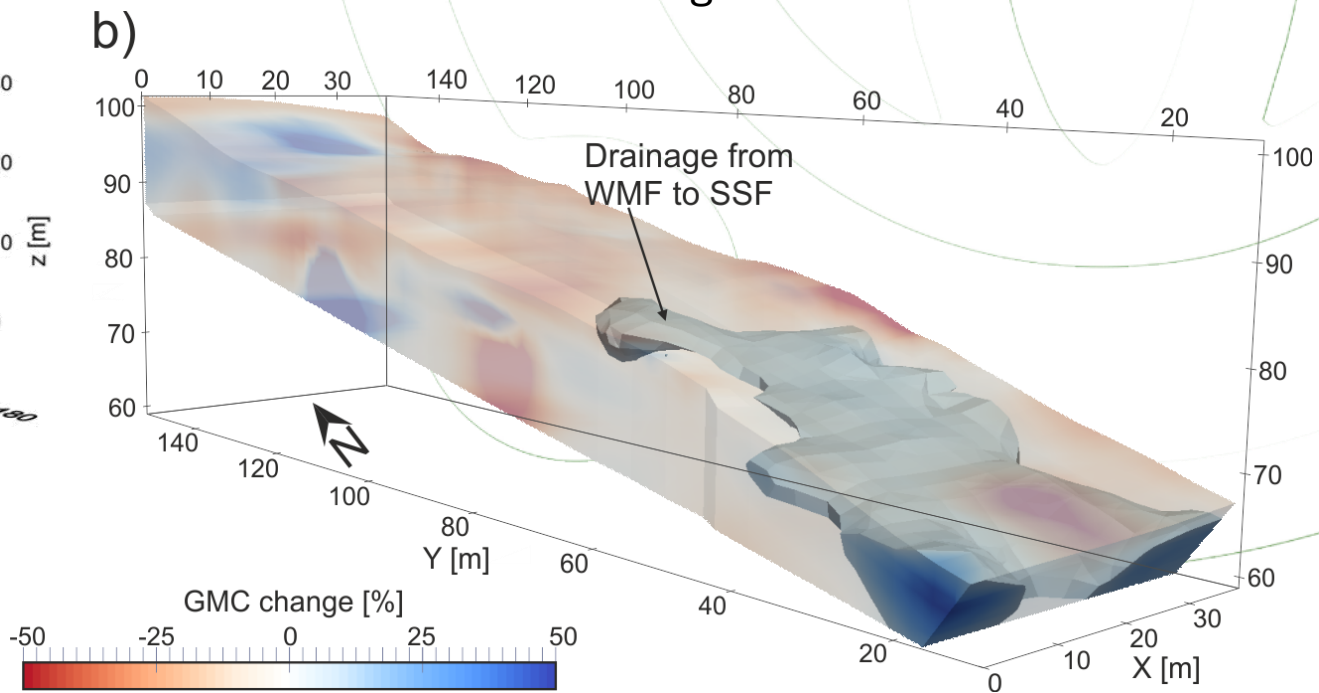
Imaging hydrological processes that control landslide behavior

Self potential mapping



Chambers et al. (2011), Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK, *Geomorphology*, 125(4)

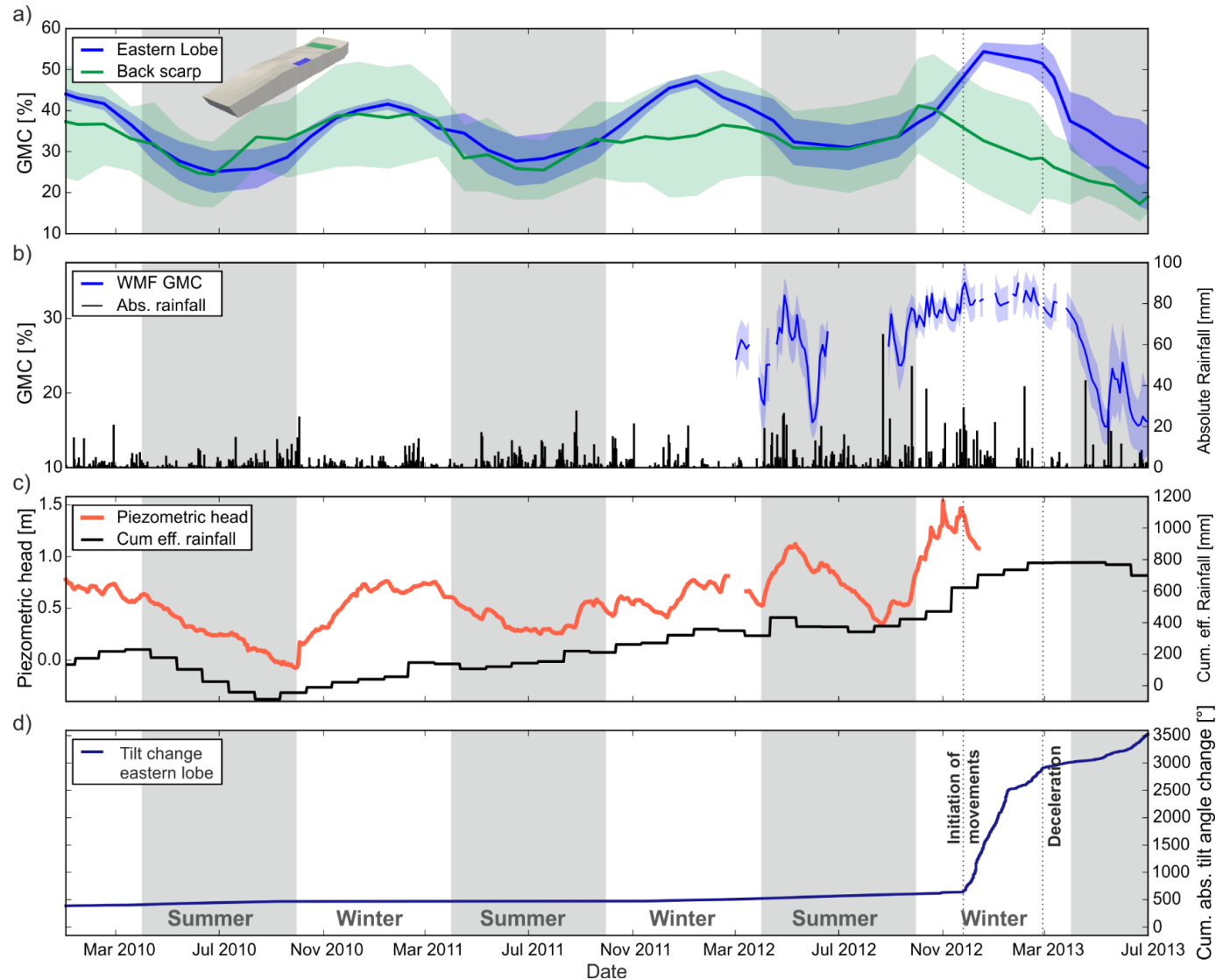
Drainage



Geoelectrical imaging can reveal processes that control landslide movements

Long-term geoelectrical monitoring of Hollin Hill

Imaging hydrological processes that control landslide behavior



- **Geophysical results agree with direct data sources:**
 - Point moisture probes
 - Piezometer
 - Deformation measurements
- This data allows to **set thresholds for early warning**
 - i.e. for **moisture contents >48%** **movements** have to expected
 - This threshold **proved valid** in the last years

Uhlemann et al. (2017), Four-dimensional imaging of moisture dynamics during landslide reactivation, *JGR: Earth Surf.*, 122(1)

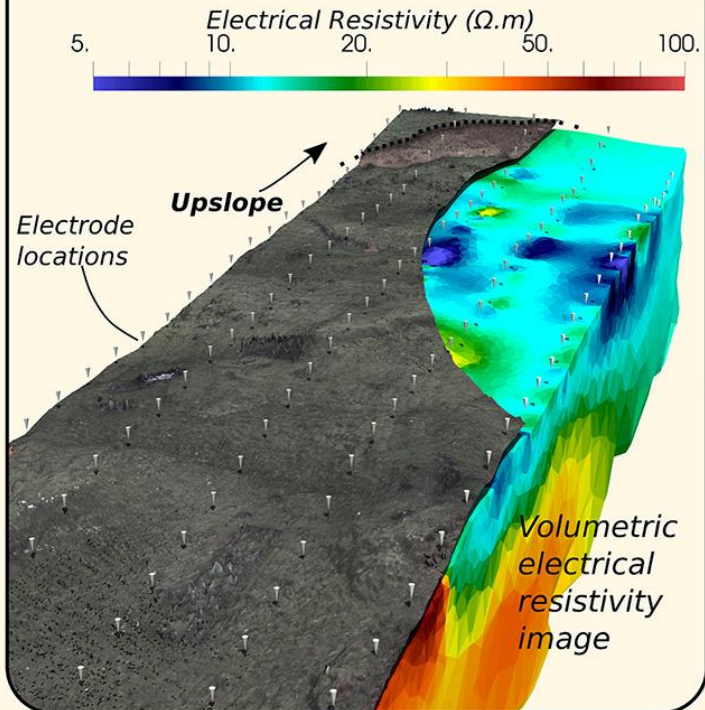
Assessing variations in geomechanical parameters

Translating electrical measurements to matric potentials

Practical considerations for using petrophysics and geoelectrical methods on clay rich landslides

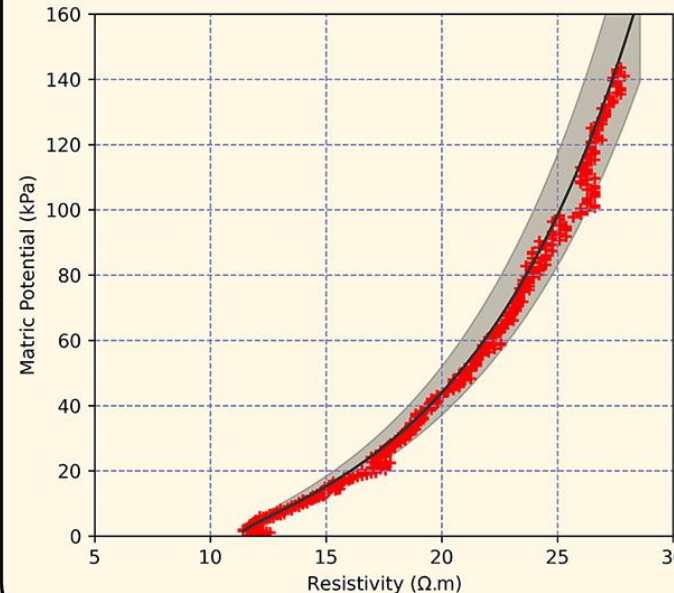
1. Geophysics on Landslides

The electrical properties of the ground are useful for illuminating the subsurface geology, here we study an active landslide.



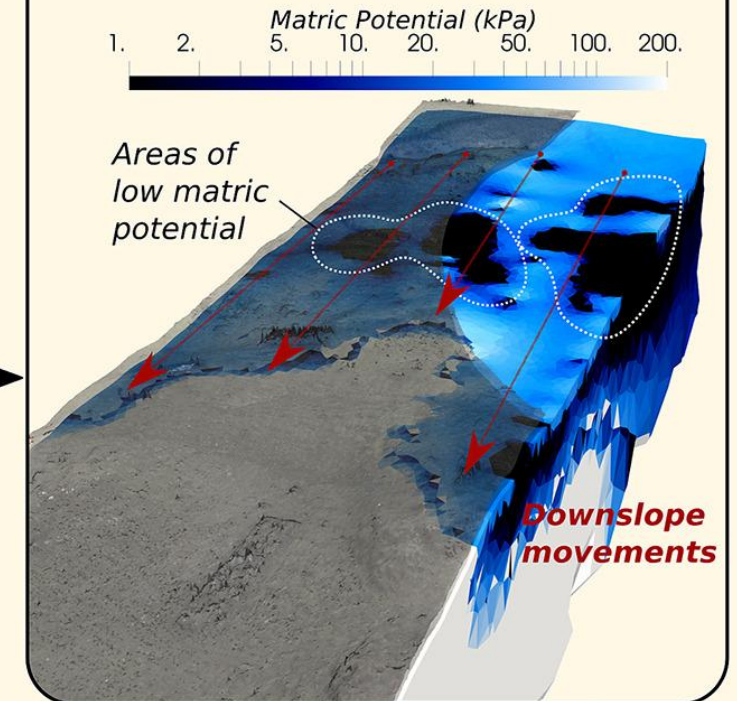
2. Petrophysics

Landslides occur due to changes in soil hydrology. Electrical resistivity measurements can be used to help evaluate stress states in the soil like matric potential.



3. Joint Interpretation of Slope

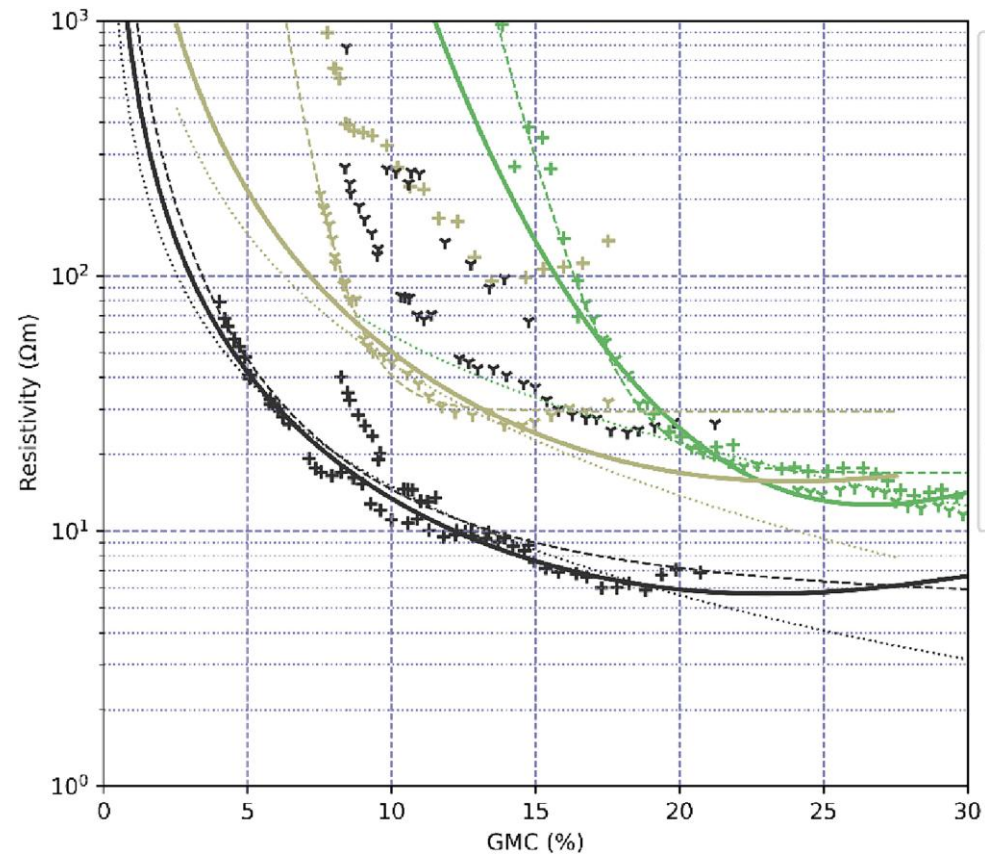
Converting geophysical states (electrical resistivity) to matric potential allows for an assessment of slope stability.



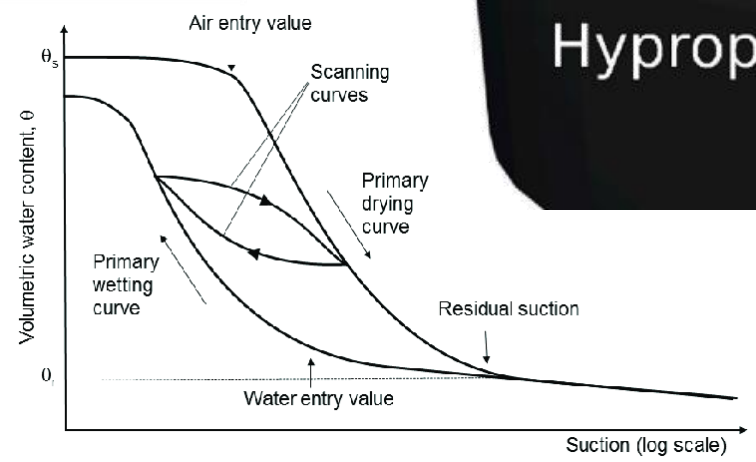
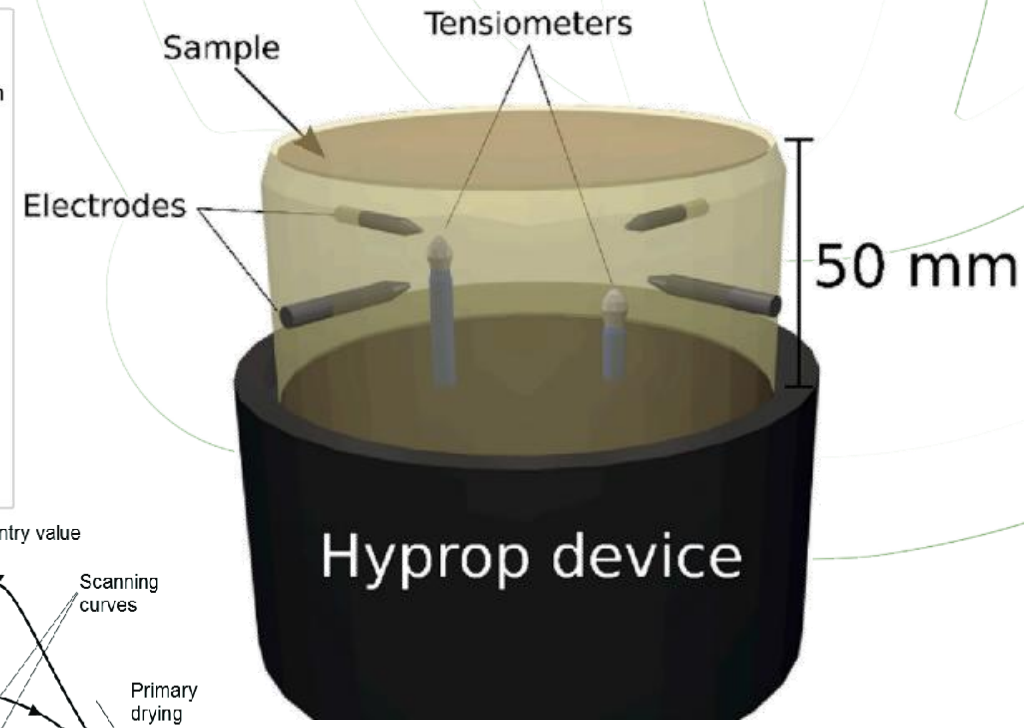
Boyd et al., 2024

Assessing variations in geomechanical parameters

Translating electrical measurements to matric potentials



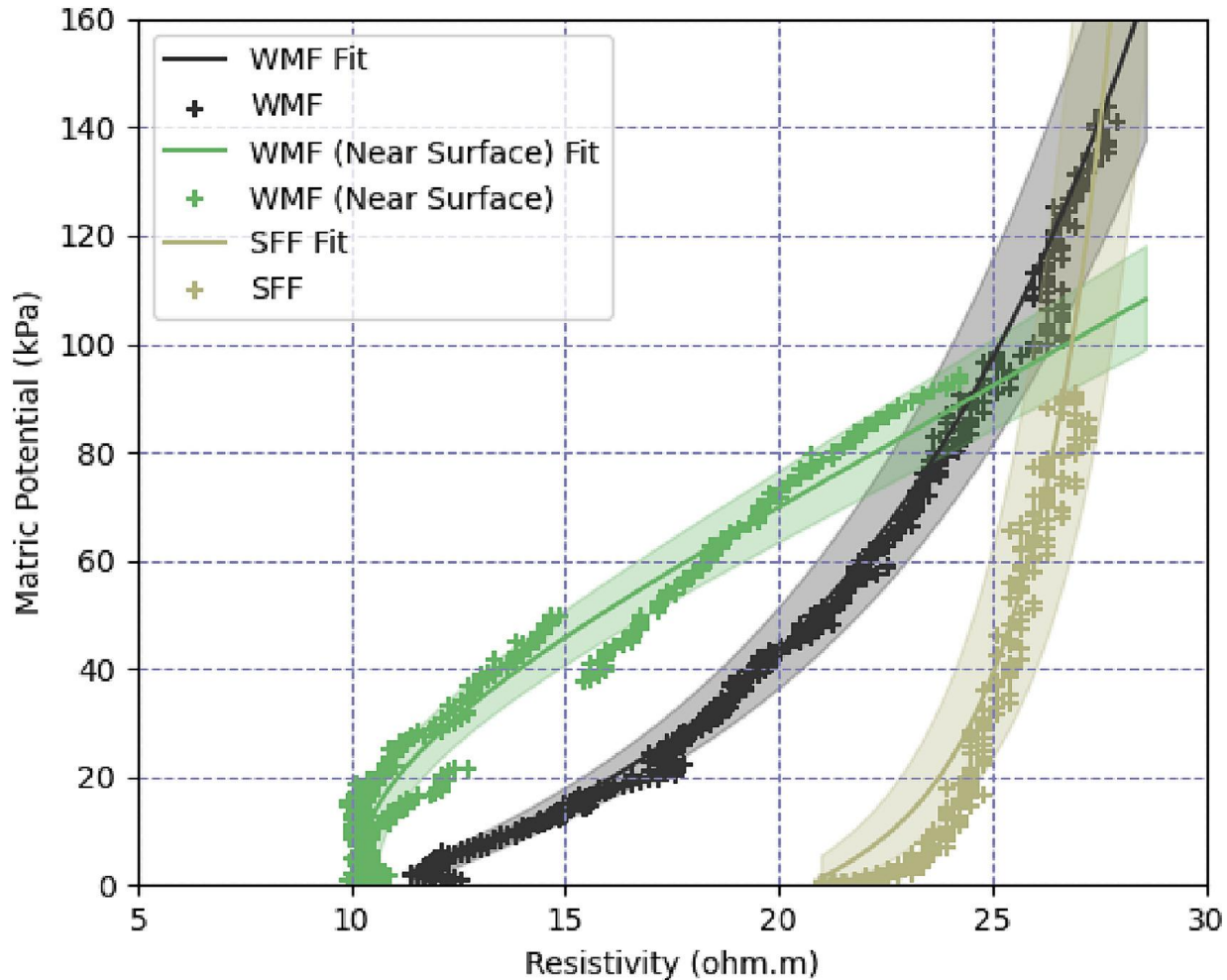
- + SSF Horizontal Orientation
- ∇ SSF Vertical Orientation
- + WMF (Near Surface) Horizontal Orientation
- ∇ WMF (Near Surface) Vertical Orientation
- ∇ WMF Vertical Orientation
- + WMF Horizontal Orientation
- WMF (Near Surface) Fit (Wax.Smit.Vp)
- - - WMF (Near Surface) Fit (Pow.Law)
- ⋯ WMF (Near Surface) Fit (Wax.Smit.Cp)
- WMF Fit (Wax.Smit.Vp)
- - - WMF Fit (Pow.Law)
- ⋯ WMF Fit (Wax.Smit.Cp)
- SSF Fit (Wax.Smit.Vp)
- - - SSF Fit (Pow.Law)
- ⋯ SSF Fit (Wax.Smit.Cp)



Boyd et al., 2024

Assessing variations in geomechanical parameters

Translating electrical measurements to matric potentials



Boyd et al., 2024

The saturation conditions within a clay-rich material can be described as one of three states: **saturated, partially saturated and residual**.

We can treat electrical conductivity (EC) the same as saturation, and can define a relative conductivity EC_{norm}

$$EC_{norm} = \frac{EC_{meas} - EC_{res}}{EC_{sat} - EC_{res}}$$

EC can be related to matric potential h like the **Van Genuchten** equation

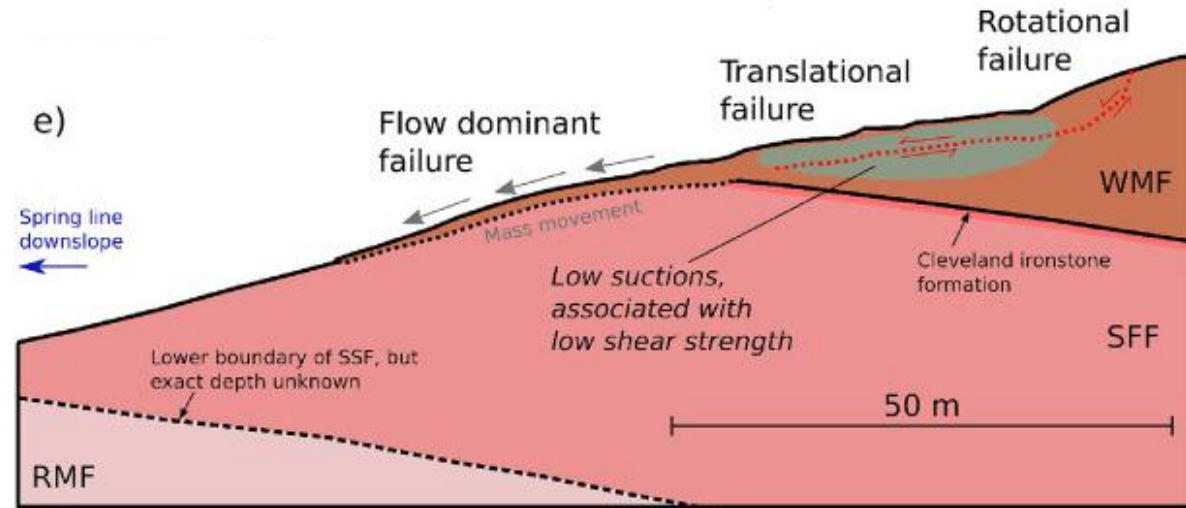
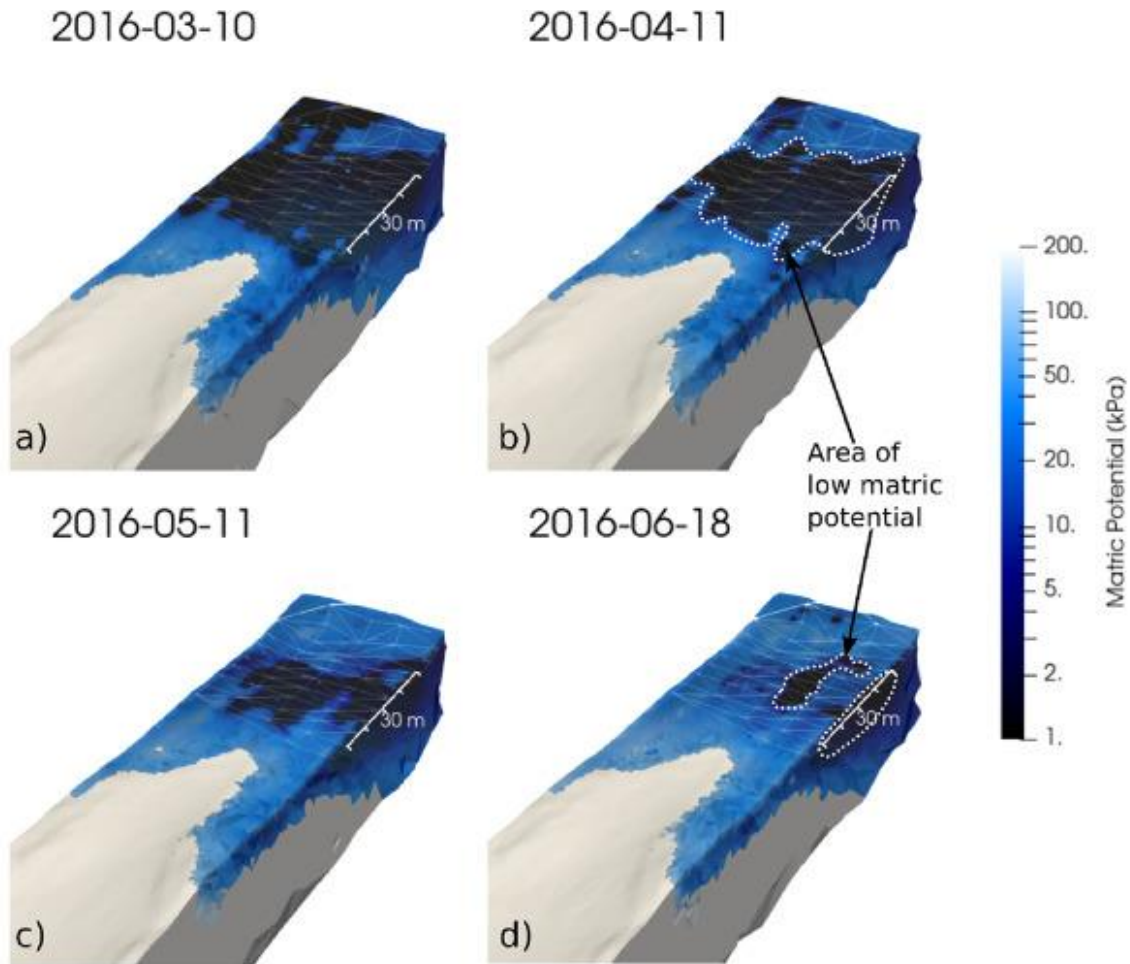
$$EC_{norm} = (1 + [ah]^n)^{-m}$$

Note: a and n do NOT have the same physical meaning as in the Van Genuchten equation!

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^{1-1/n}}$$

Assessing variations in geomechanical parameters

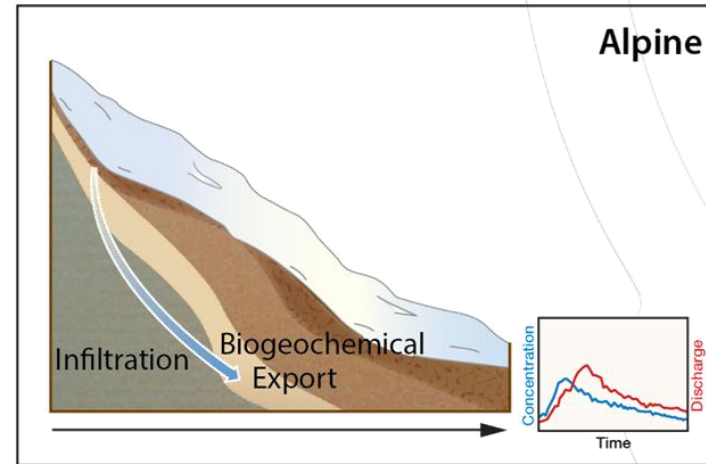
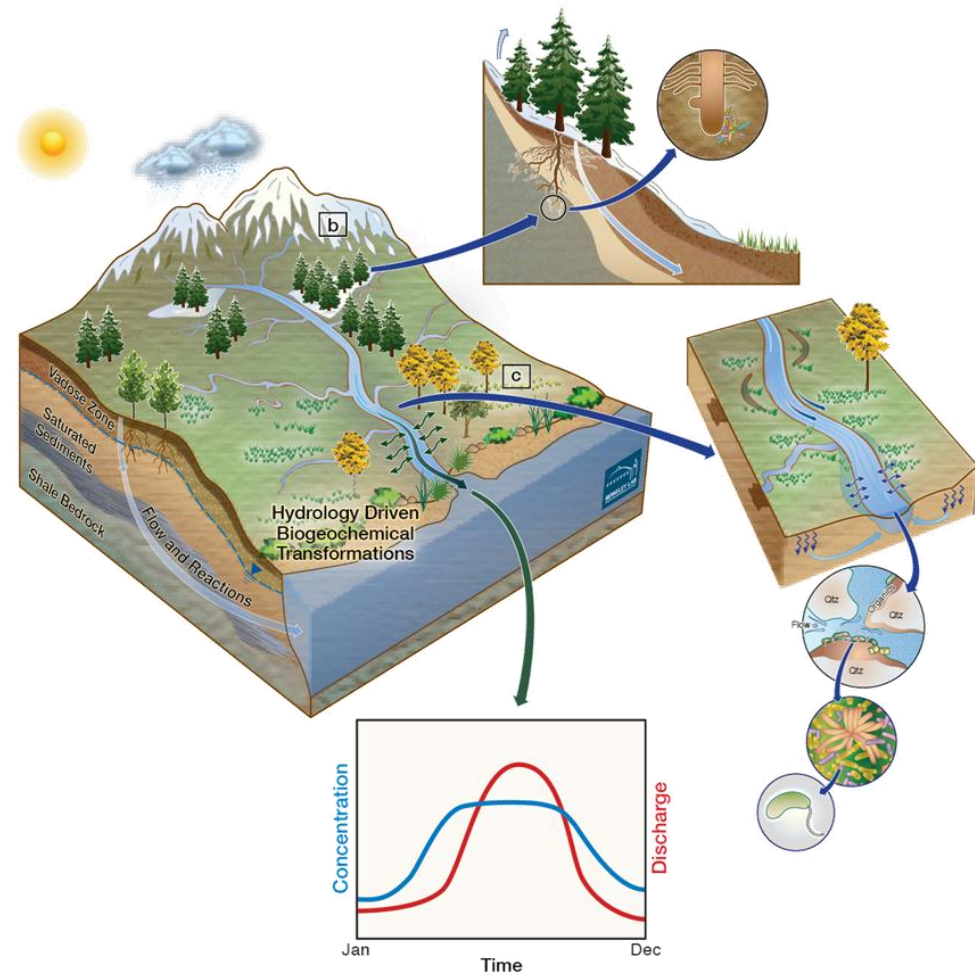
Translating electrical measurements to matric potentials



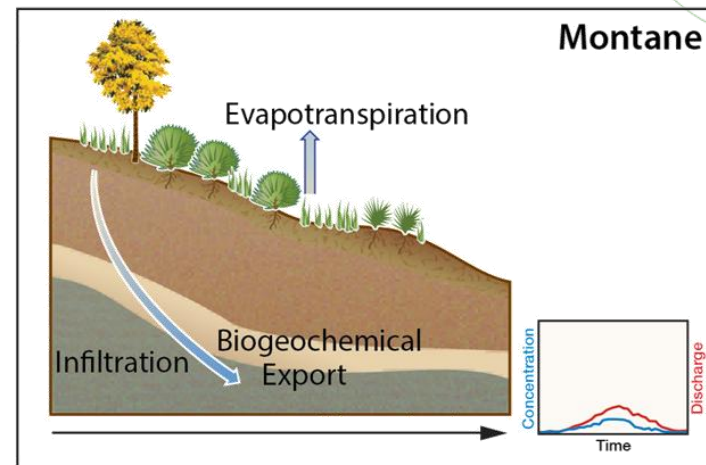
Boyd et al., 2024

Hillslope Hydrology

An integral part to understanding the functioning of mountainous watersheds



How do mountainous watersheds retain and release water, nutrients, carbon and metals over episodic to decadal timeframes?



Understanding **bedrock characteristics and flow** is critical to answering this question.

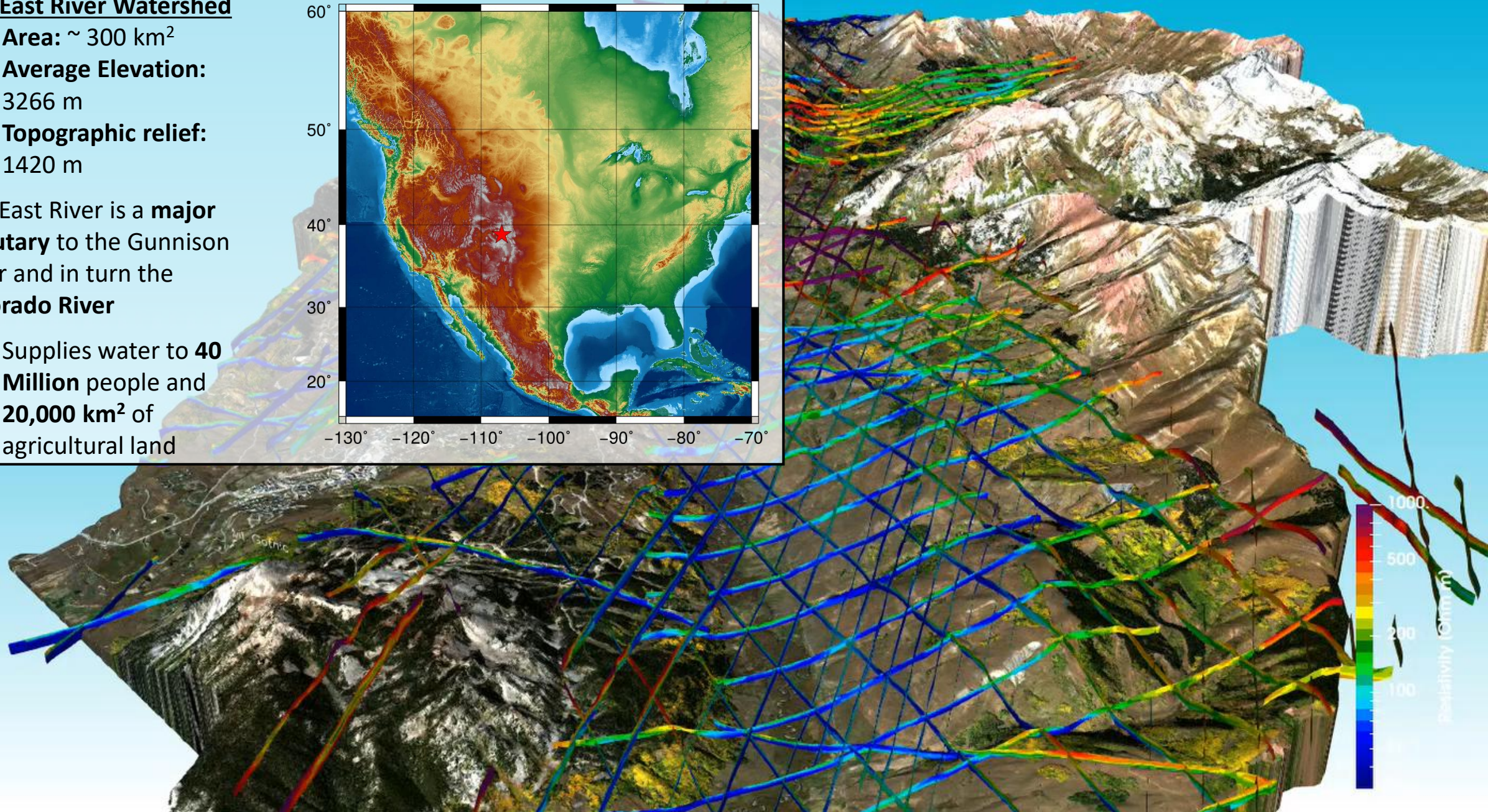
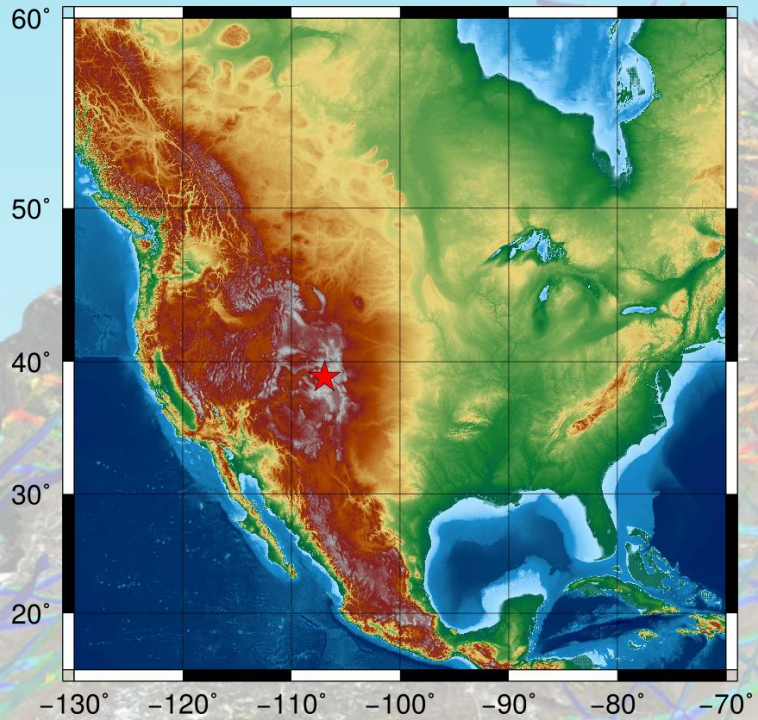
EESA16-013

The East River Watershed

- **Area:** ~ 300 km²
- **Average Elevation:** 3266 m
- **Topographic relief:** 1420 m

The East River is a **major tributary** to the Gunnison River and in turn the **Colorado River**

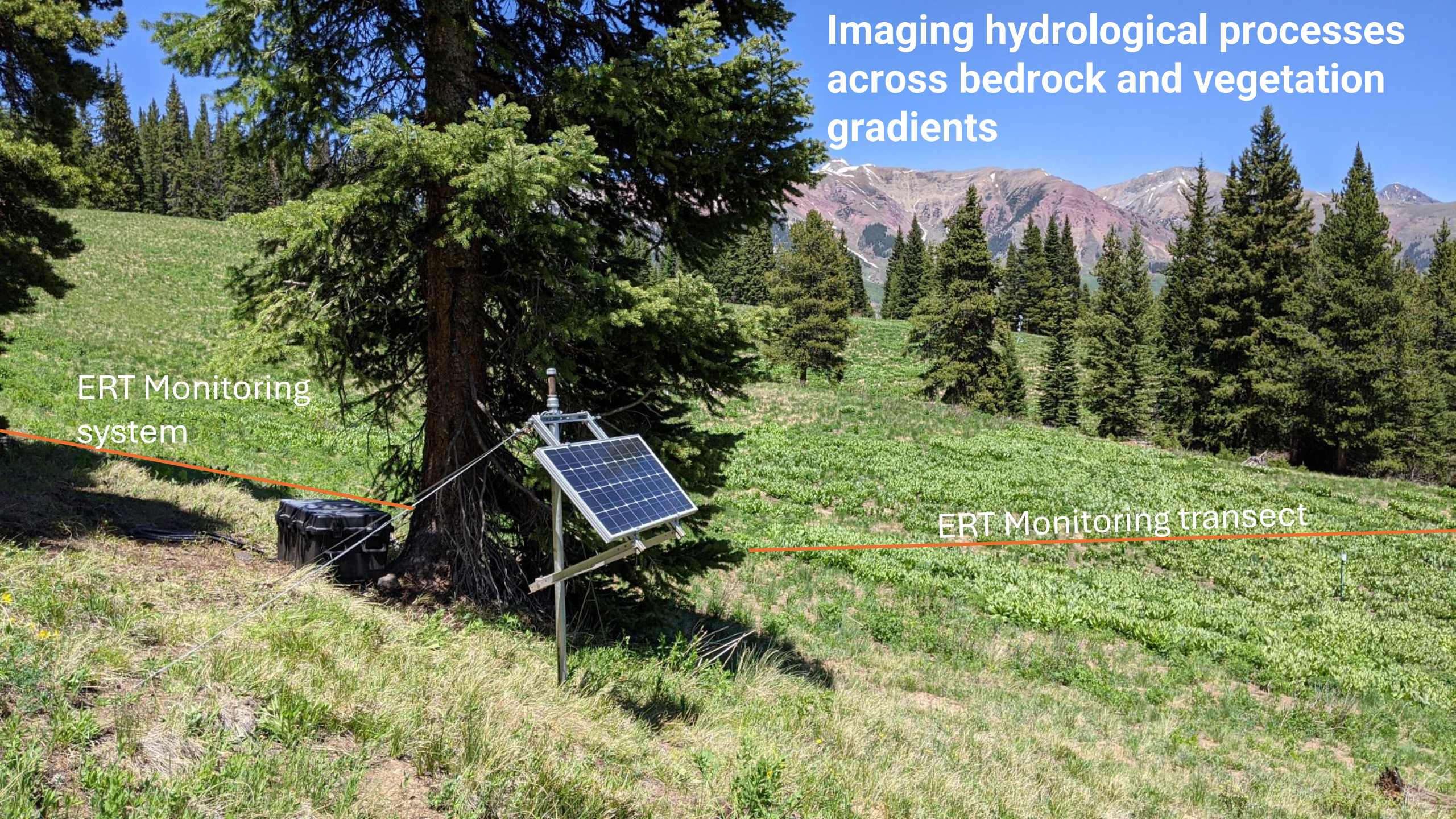
- Supplies water to **40 Million** people and **20,000 km²** of agricultural land



Imaging hydrological processes across bedrock and vegetation gradients

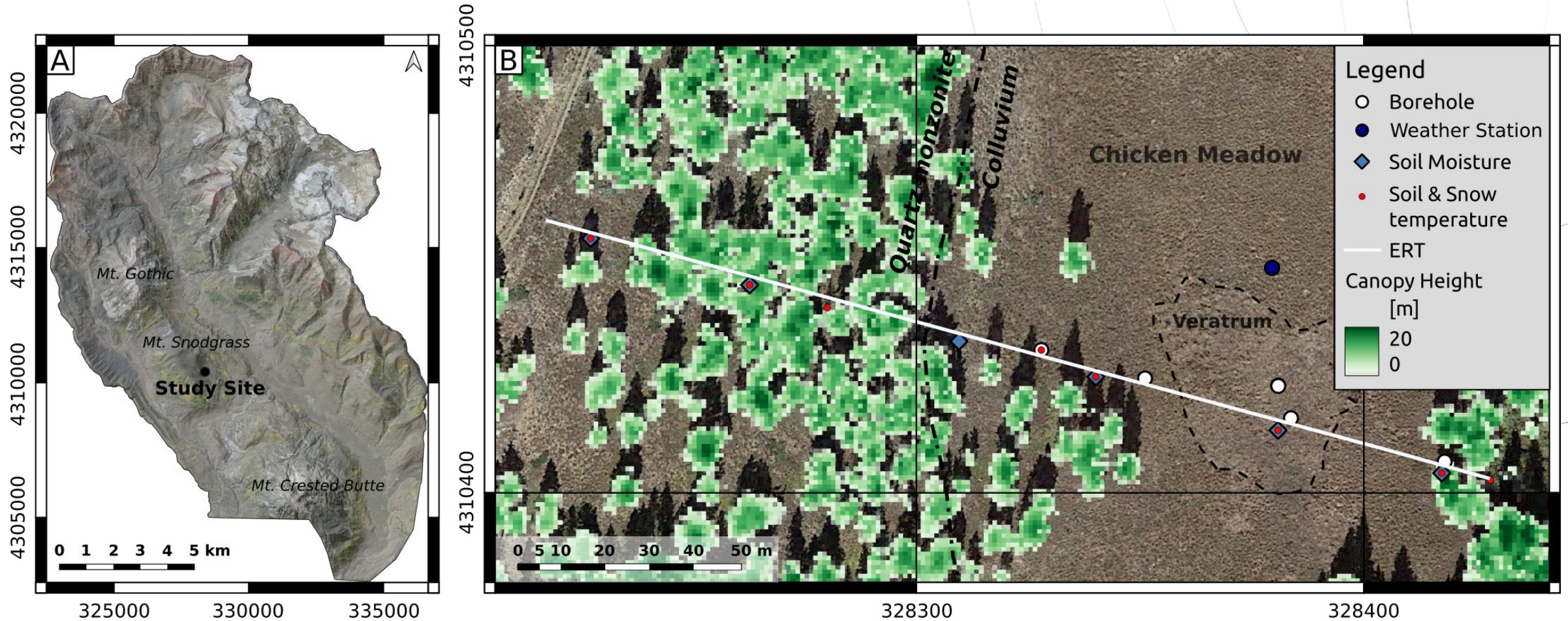
ERT Monitoring
system

ERT Monitoring transect



Assessing the hydrological impact of vegetation and bedrock gradients

Going into the mid-elevations of Mt. Snodgrass

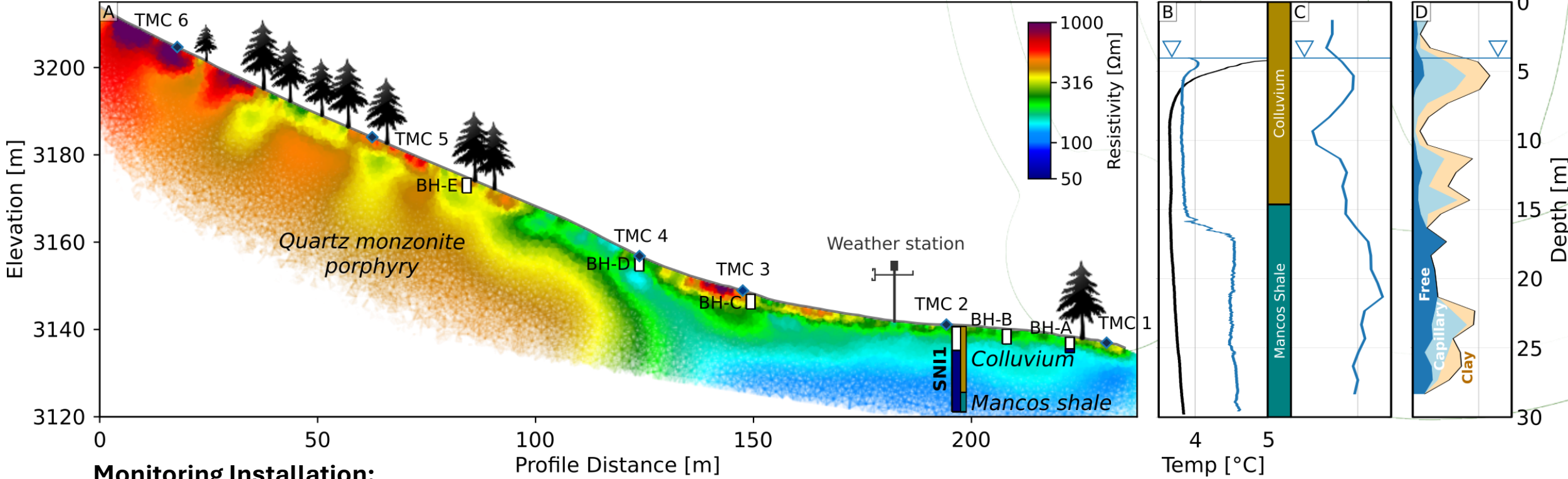


Uhlemann et al. (2024), *Bedrock and vegetation gradients modulate subsurface water flow dynamics of a mountainous hillslope*. *Water Resources Research*

Subsurface resistivities highlight strong gradient

Transect divided into bedrock and sediments

EC [$\mu\text{S/cm}$] K_{est} [m/s] Water cont [%]
 100 125 10^{-10} 10^{-4} 0 20

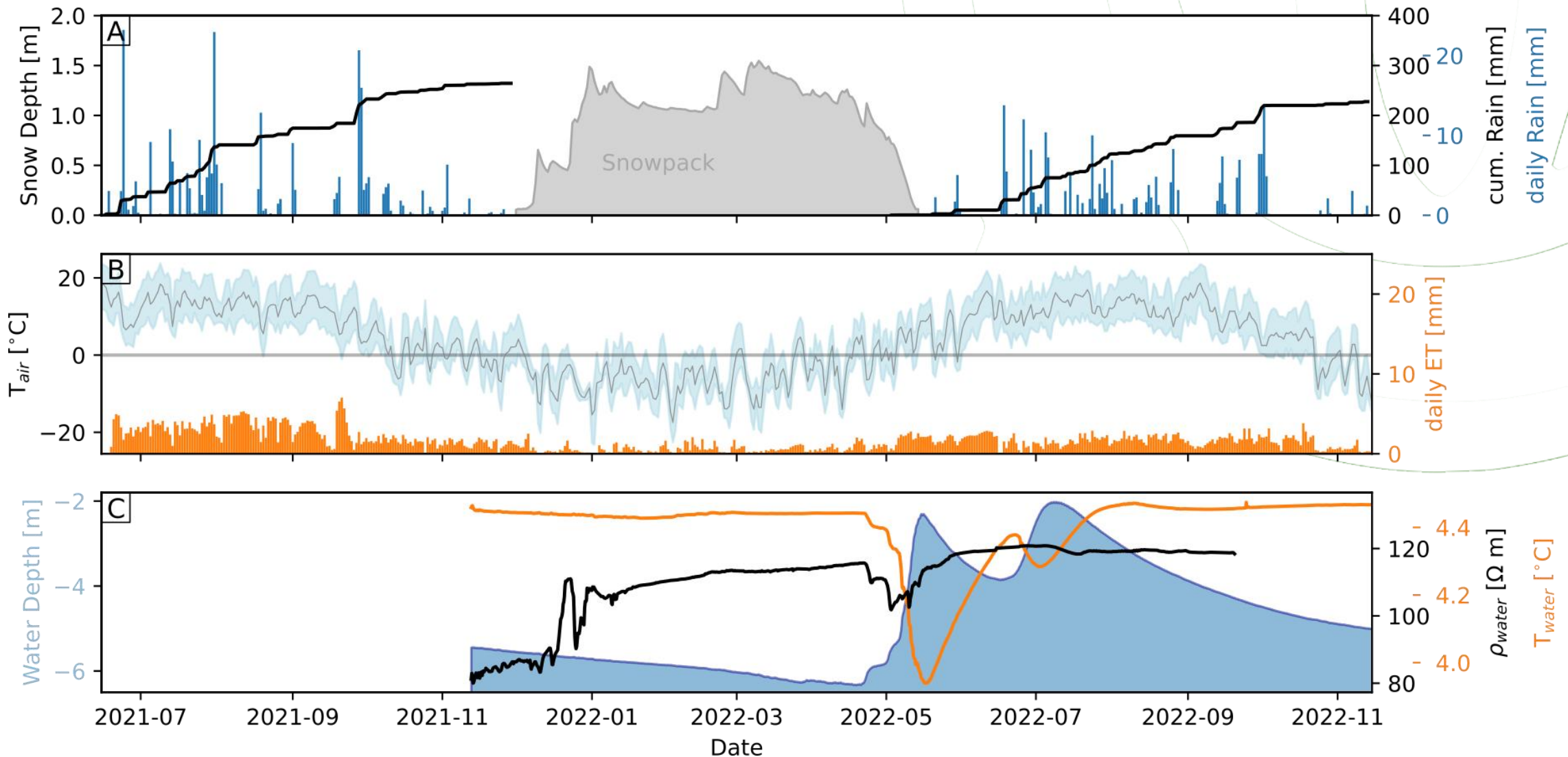


Monitoring Installation:

- ERT measurements (1 to 6 times per day)
- 1 deep + 5 shallow piezometers
- Soil moisture, temperature and snow temperature at 6 locations
- Weather station
- ERT, soil temperature, and deep piezometer data transmitted in **near real-time**
- **Electrical resistivity sensitive to changes in moisture content**

Environmental monitoring shows strong influence of snowmelt

Summer rainfall only leads to water-limited conditions



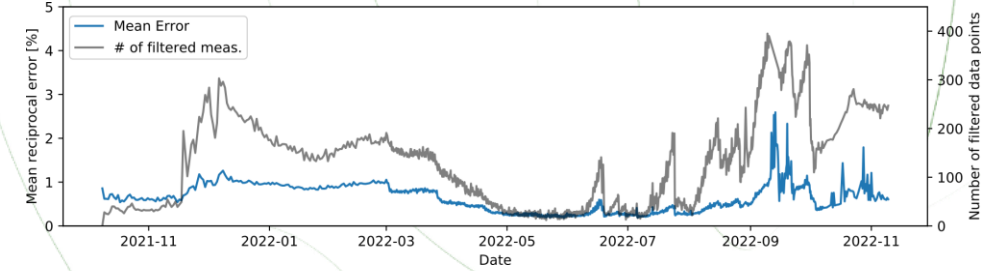
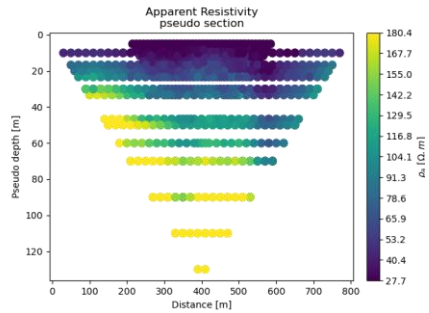
Long-term ERT monitoring workflow

Data collection and processing

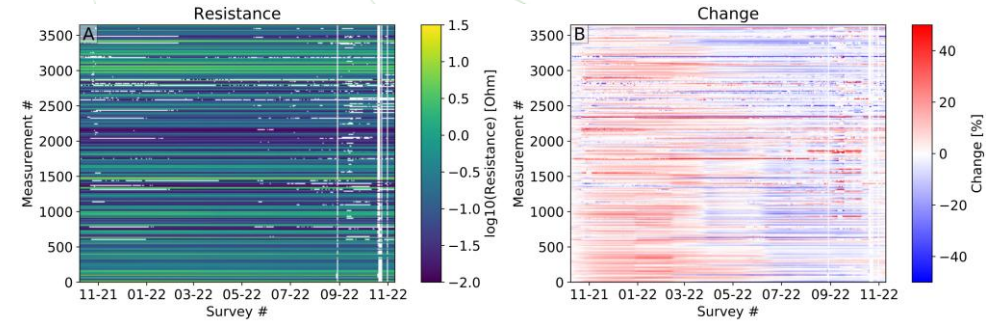
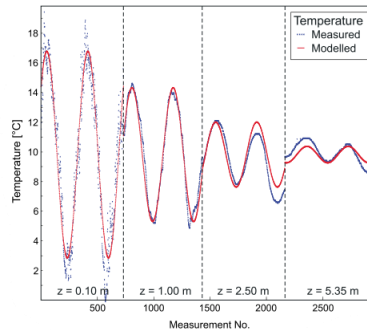
Monitoring data (up to 6/day)

Data QA, storage

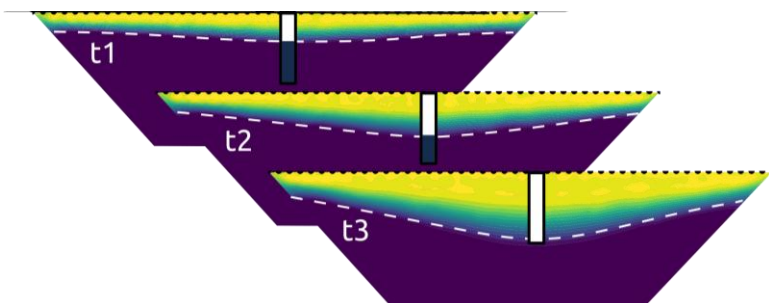
Time-lapse data processing → Creating a consistent data set



Solar powered, 10W system



Temperature correction



Inversion



Windowed 4D

Sequential
Time-lapse



Approach:

1. Filtering of data with large (>20%) reciprocal error
2. Fitting of linear error model
3. Inverse-distance weighted interpolation → temporally consistent data set
4. Assignment of large error to interpolated data

Long-term ERT monitoring requires correction of temp. variation

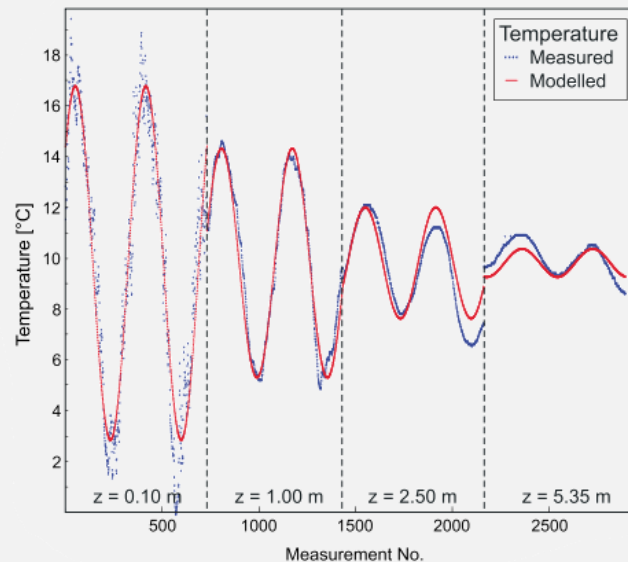
Workflow and limitations

Aim: Correction of **seasonal temperature variation**

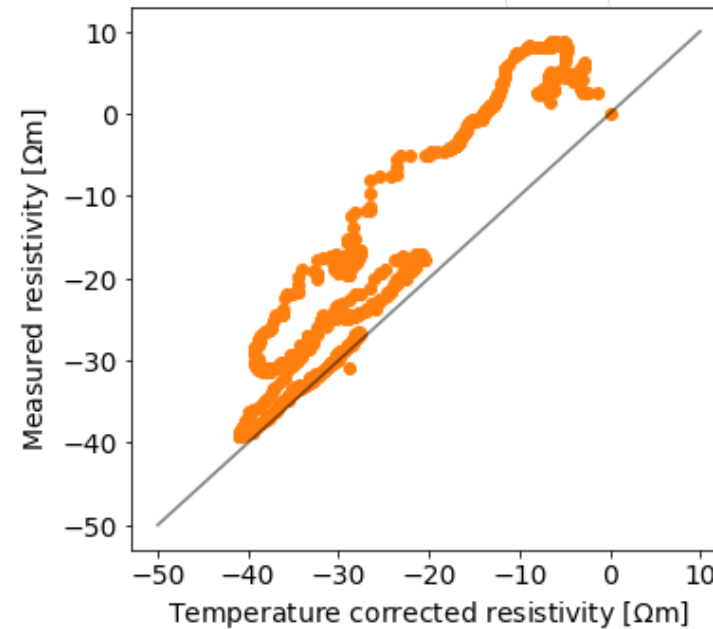
1. Fit heat equation to measured temperatures
2. Apply ratio model to correct resistivity

$$T_{\text{model}}(z, t) = T_{\text{mean}} + \frac{\Delta T}{2} \exp\left(-\frac{z}{d}\right) \sin\left(\frac{2\pi}{365}t + \phi - \frac{z}{d}\right)$$

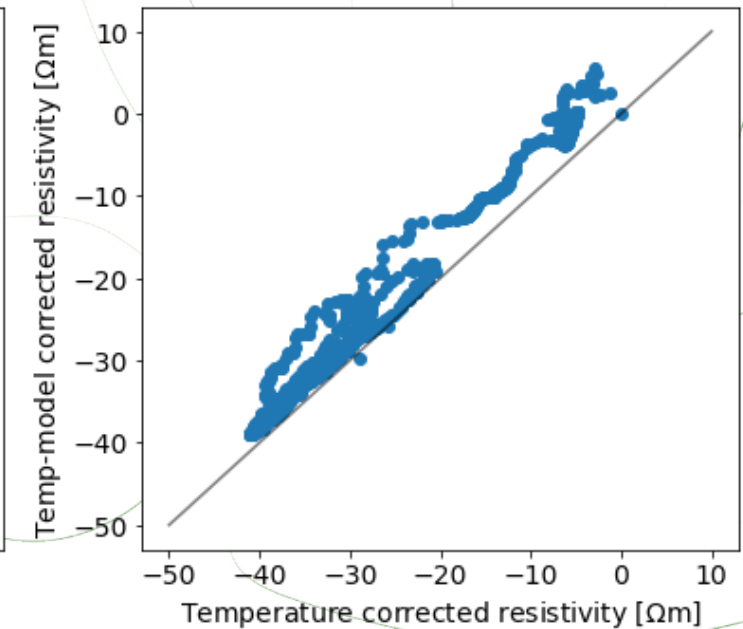
$$\rho_{\text{cor}} = \rho \left[1 + \frac{tc}{100} (T_{\text{standard}} - T_{\text{model}}) \right]$$



Corrected vs. uncorrected



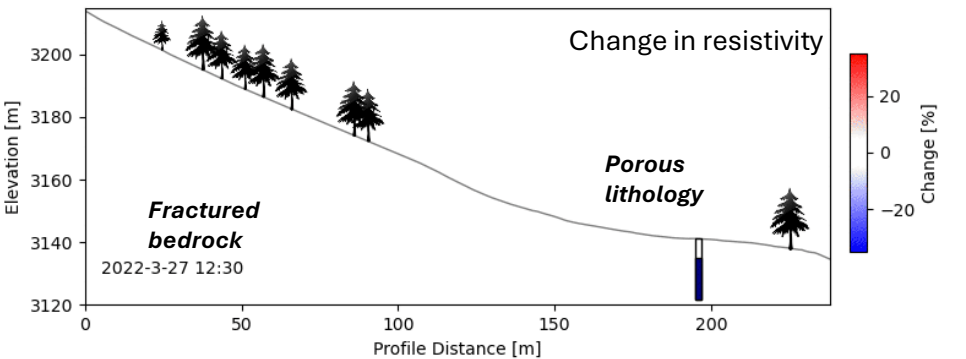
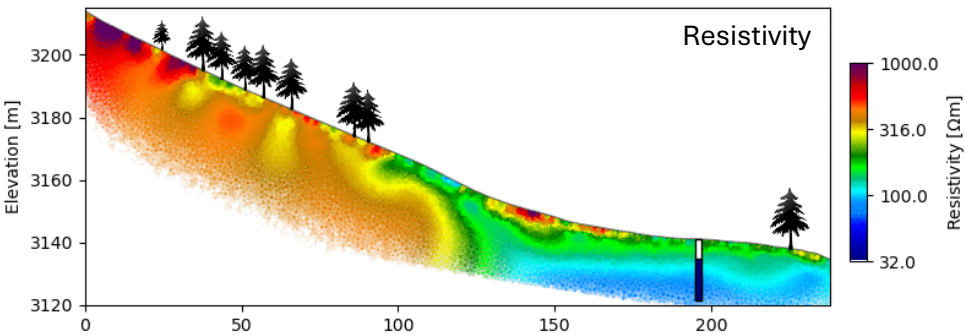
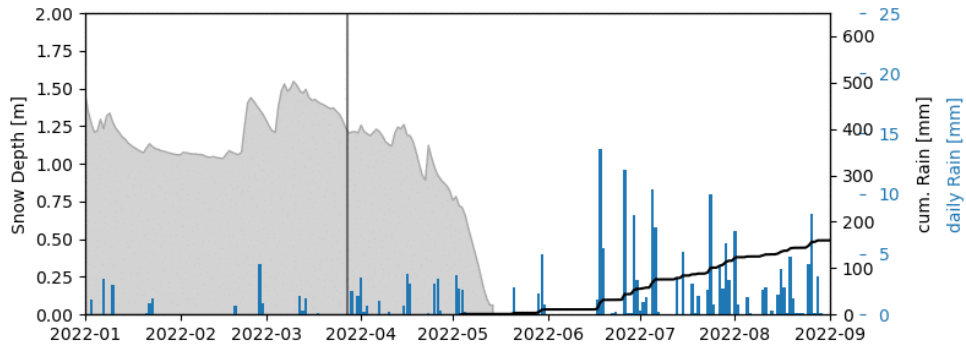
Measured vs. modelled Temp



- Diffusive heat equation assumes a sinusoidal annual temperature variation
- In snow-dominated environments that is not the case
- Error within 10% - modelled temperatures are sufficient to predict and correct resistivity data

Snowmelt provides large, heterogeneous water input to the system

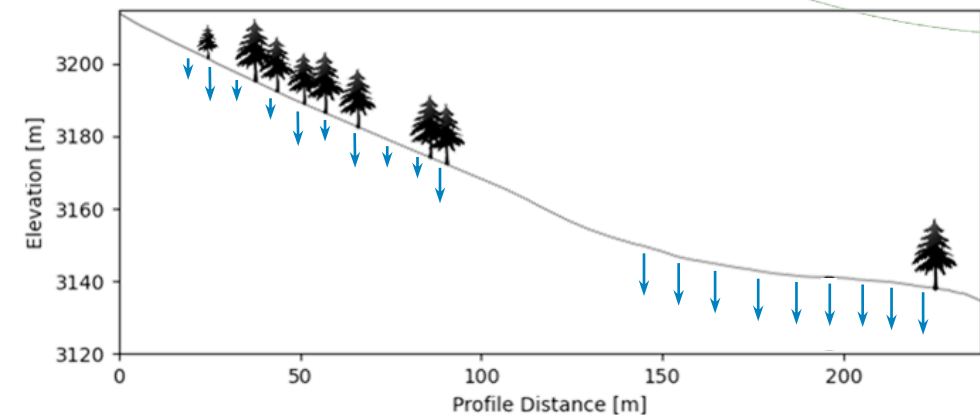
Small changes in upper, large changes in lower part



Monitoring of snowmelt of 2022 – measurements twice per day

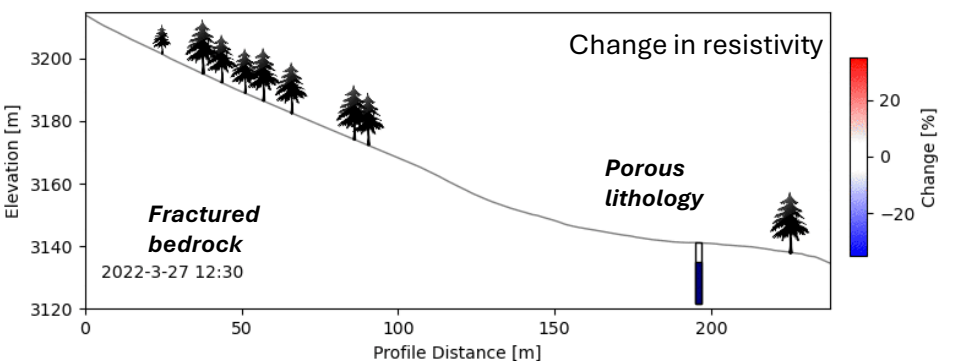
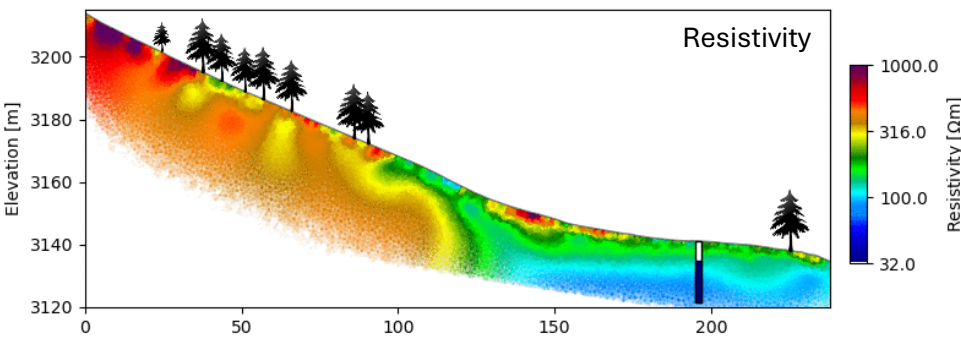
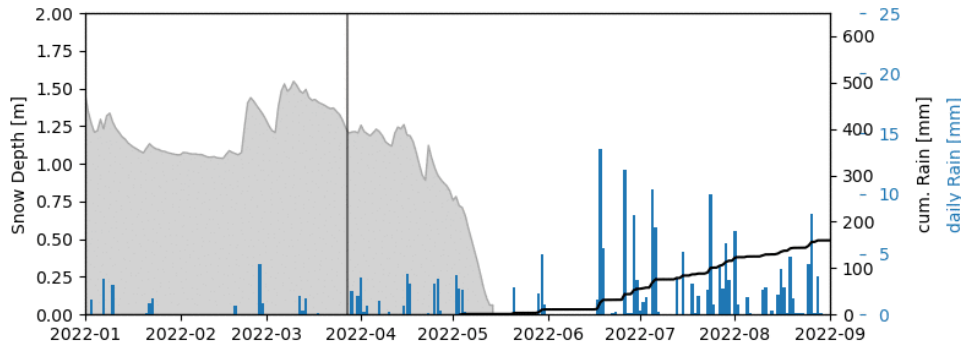
Main Observations:

- No notable change during the first weeks
- Snowmelt leads to decrease in resistivity
 - First in lower, gentle part
 - Later in upper, steep part
- Horizontal feature coincides with large changes in groundwater level



Snowmelt provides large, heterogeneous water input to the system

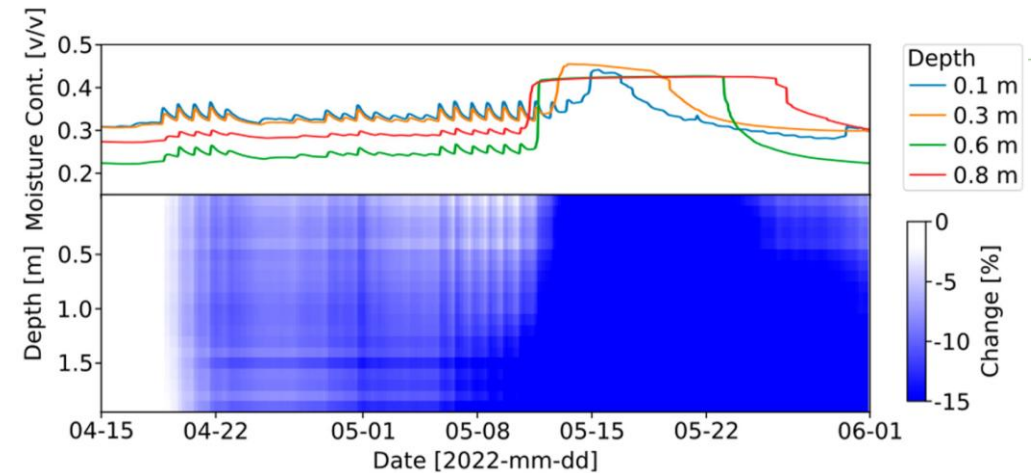
Small changes in upper, large changes in lower part



Monitoring of snowmelt of 2022 – measurements twice per day

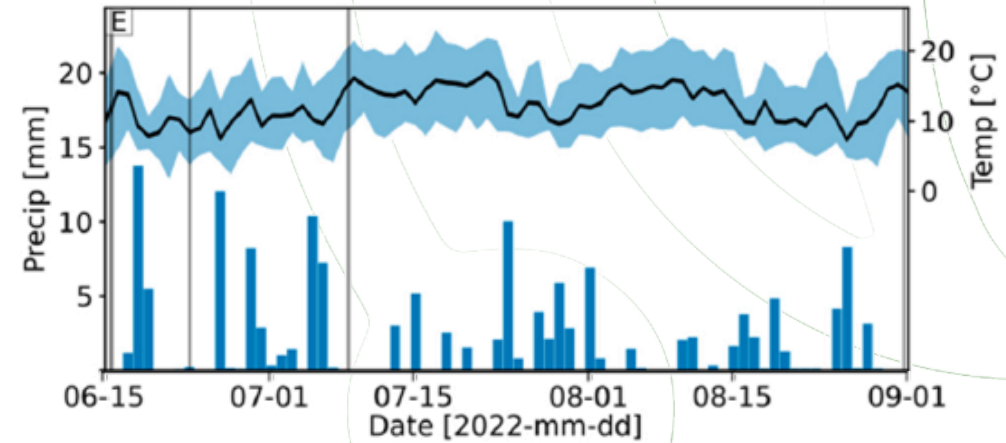
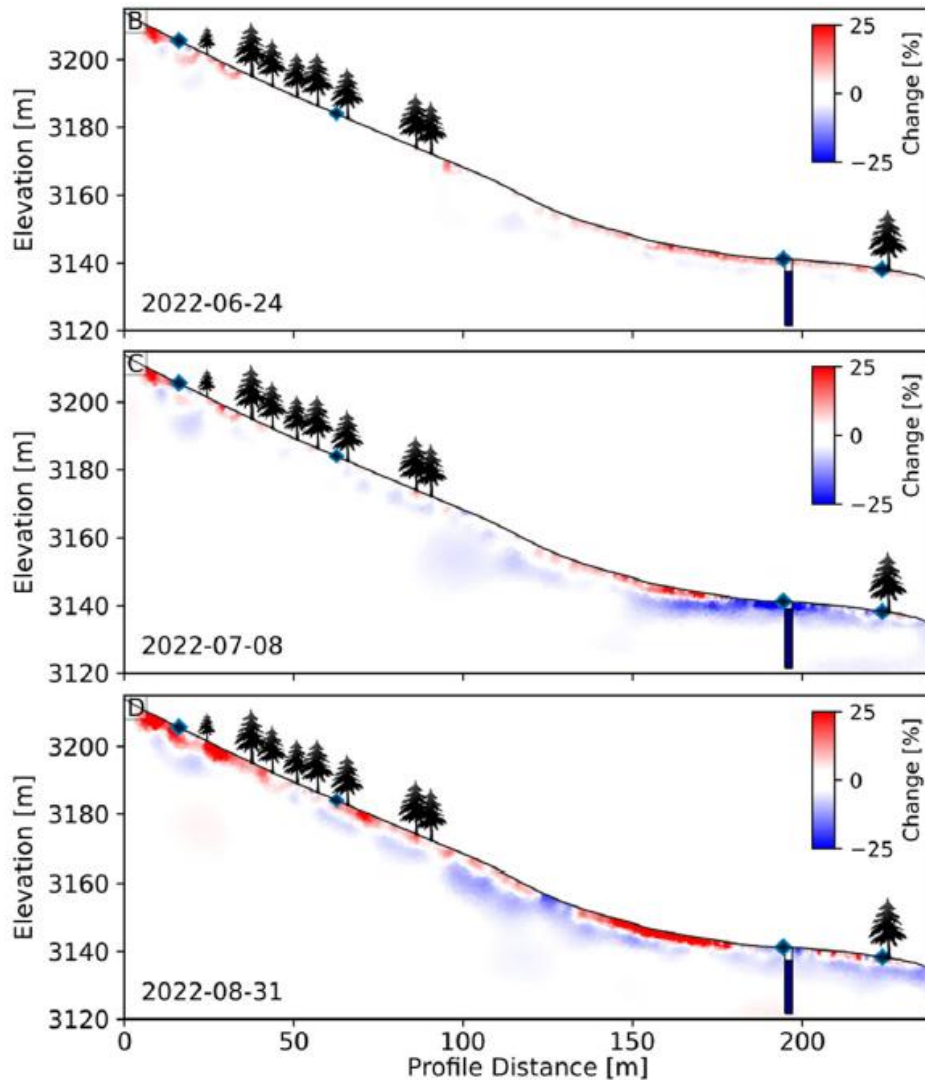
Main Observations:

- No notable change during the first weeks
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 - First in lower, gentle part
 - Later in upper, steep part
- Horizontal feature coincides with large changes in groundwater level



Summer monsoon is not providing significant water input

Evapotranspiration larger than recharge leading to drying of surficial soil layer



Despite frequent rain events (>10 mm/day) surface layers are becoming more resistive

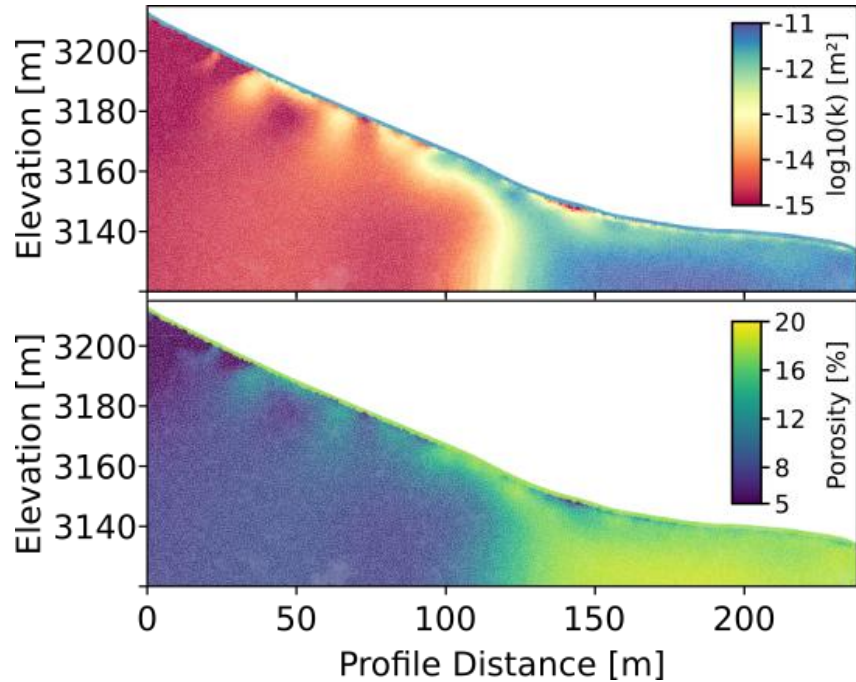
Main Observations:

- Mostly increasing resistivity in shallow soil layers
 - First in lower part, later in upper part
 - Delay suggests that litter and canopy reduce evaporation
- Decreasing resistivity in lower part related to second groundwater peak = upwelling
- Location of upwelling = location of veratrum

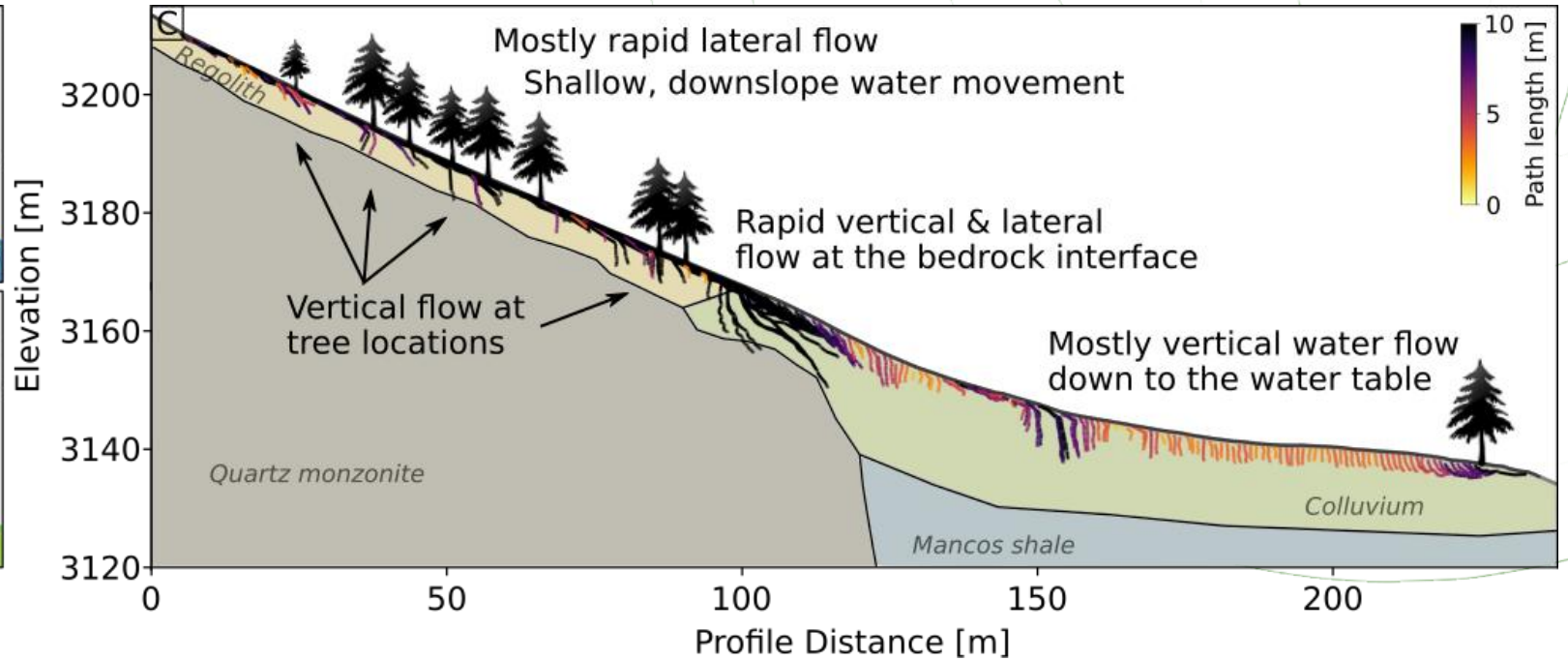
Modelling subsurface flow pattern

Model confirms the observations and provides details into recharge pattern

Model Parameterization



Simplified Ground Model & Modelling result

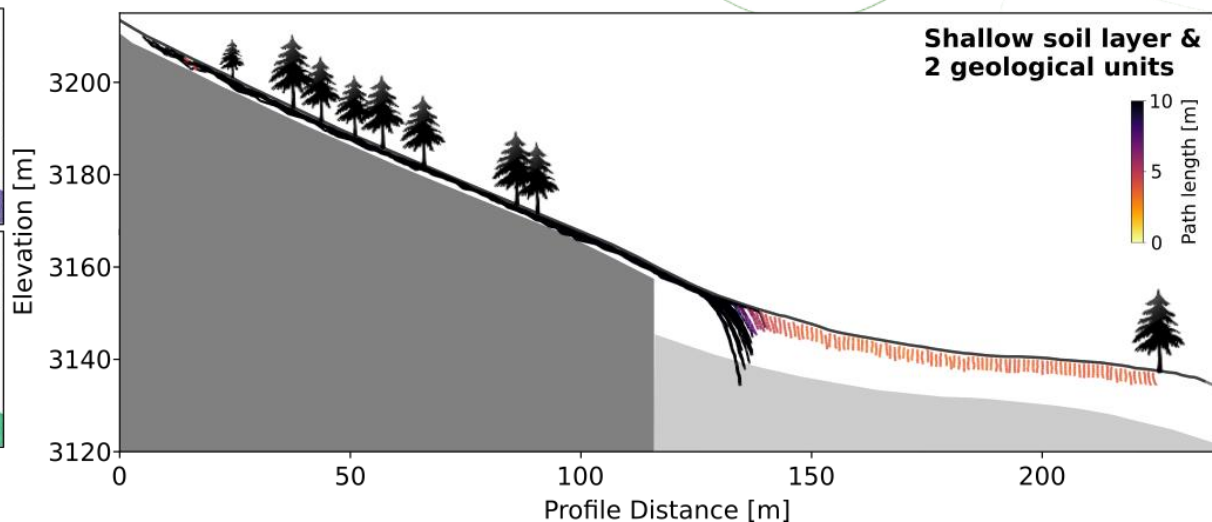
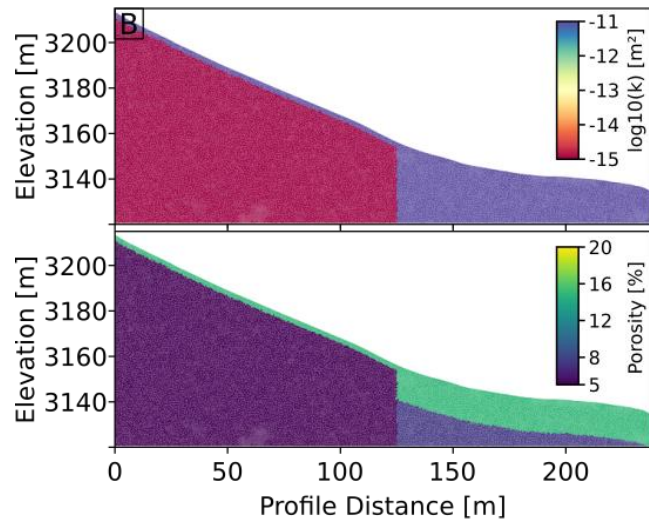
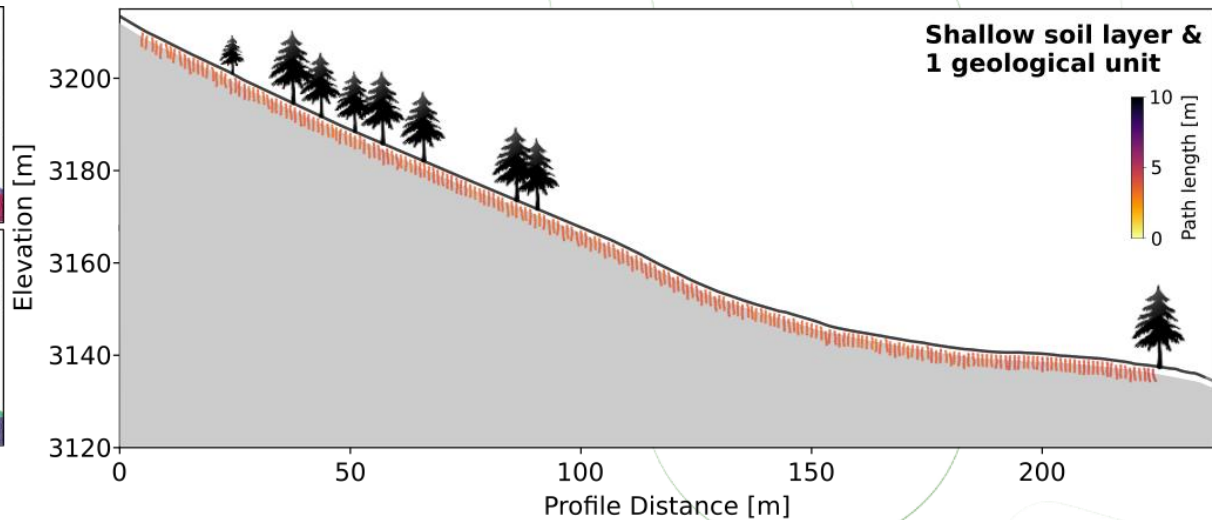
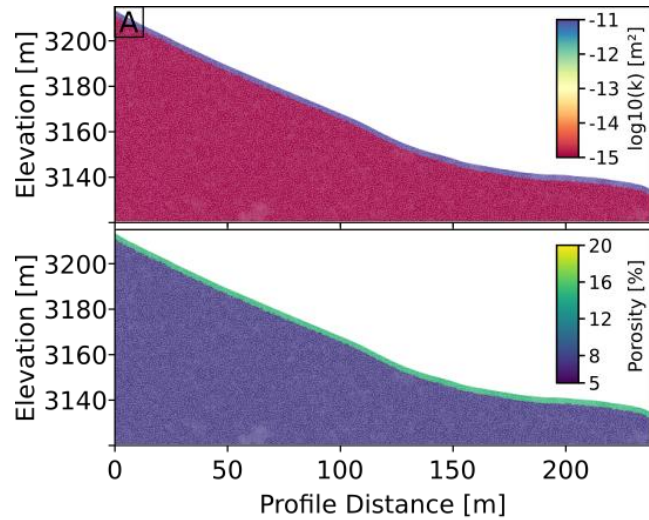


Main observations:

- Shallow lateral flow characterizes steep, shallow bedrock
- Deeper flow at tree locations
- Vertical up and downward flow prevails at gentle slope underlain by colluvium

Modelling subsurface flow pattern

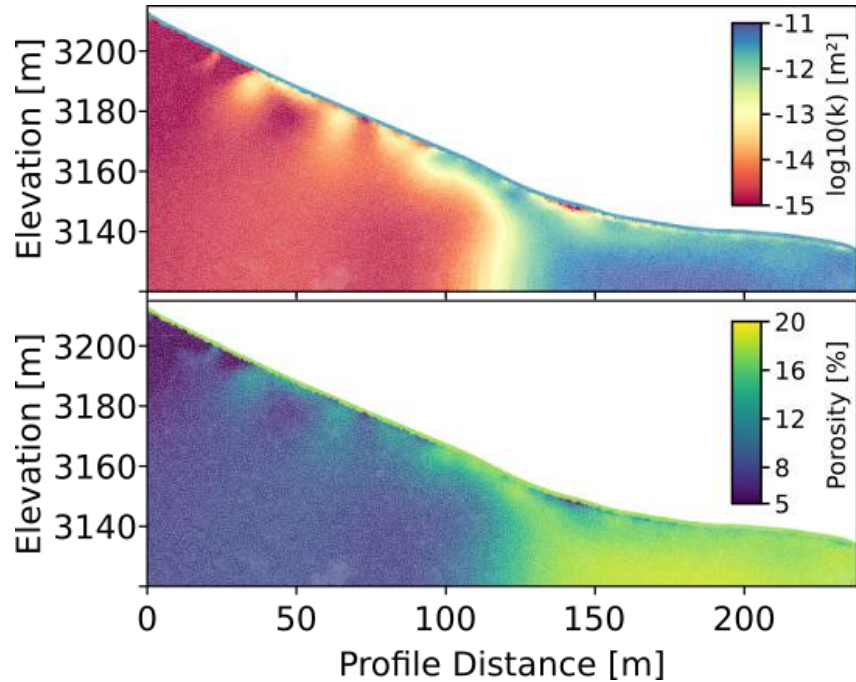
Simplified models show topographic control of some observations



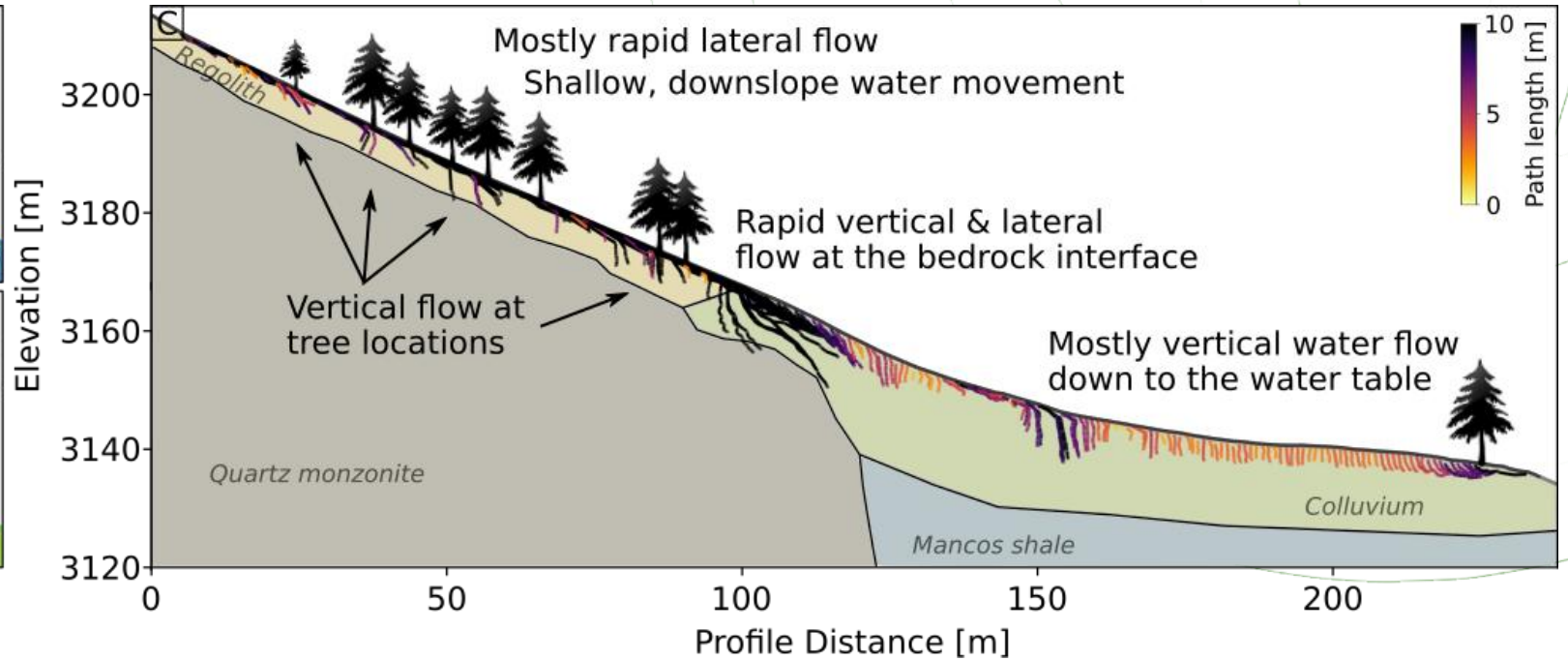
Modelling subsurface flow pattern

Model confirms the observations and provides details into recharge pattern

Model Parameterization



Simplified Ground Model & Modelling result





Conclusions

- Snowmelt provides critical input into hydrological cycle at this site
- Vegetation, bedrock and topographic characteristics define hydrological dynamics
- Shallow lateral flow characterizes steep, shallow bedrock, interrupted by more vertical flow at tree locations
- Vertical up and downward flow prevails at gentle slope underlain by colluvium
- High resolution, integrated ERT monitoring shows detailed hydrological dynamics

Methodological Developments

- Novel processing scheme for long-term, high-resolution ERT data
- Spatially variable temperature correction

Quantifying groundwater recharge through 4D geoelectrical monitoring



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Geosyntec
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RECLAMATION

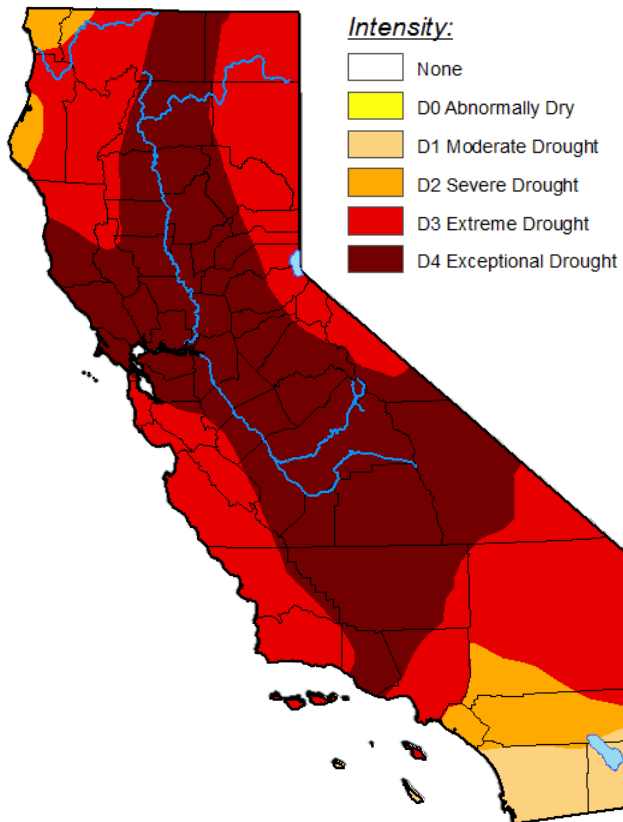


Public Works
LOS ANGELES COUNTY

Assessing Performance of Sustainable Urban Drainage Systems

Groundwater recharge to ease urban groundwater stress

U.S. Drought Monitor California

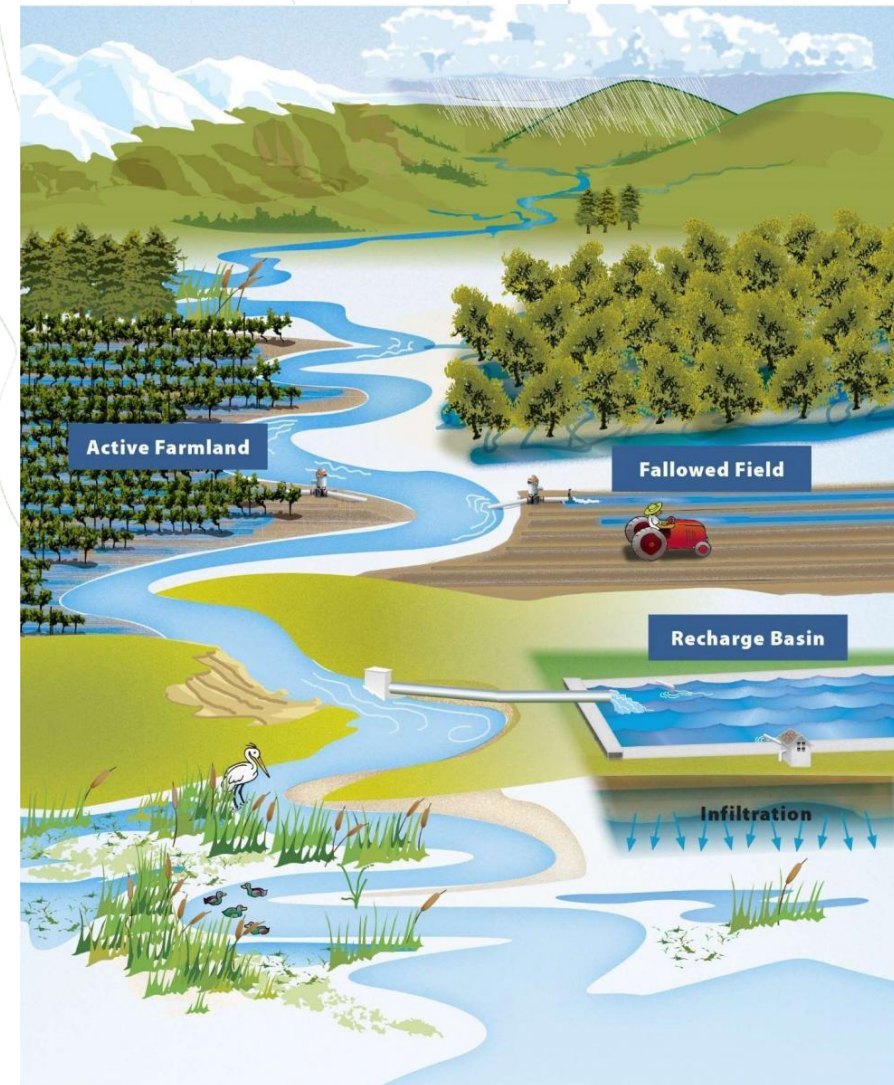


California is prone to droughts

“Solution”: Managed aquifer recharge

1. Provide more **stable water supplies** during drought
2. **Supplement the quantity** of groundwater available
3. **Conserve** and dispose of **runoff and floodwaters**

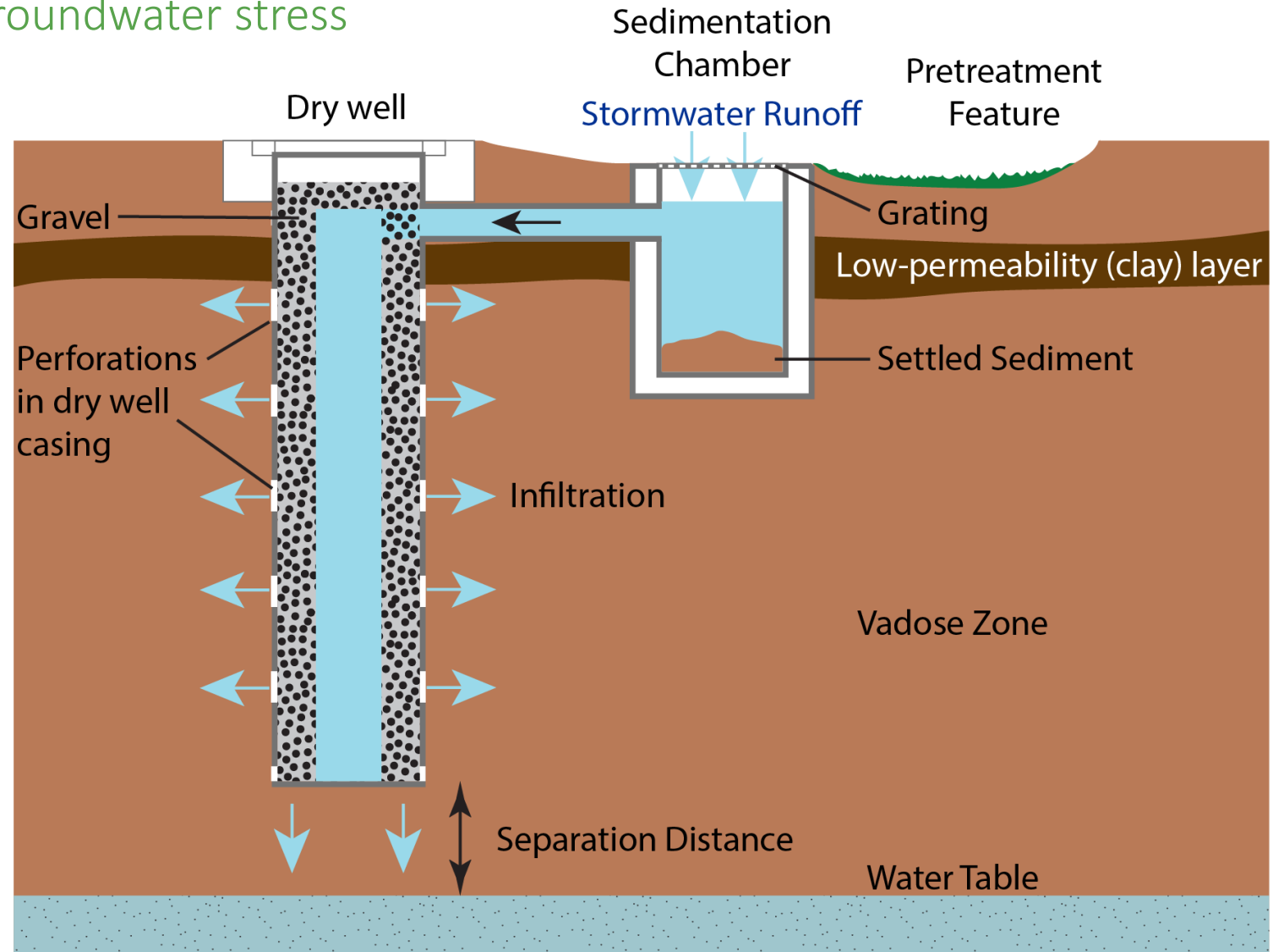
How do you quantify and control these effects?



Assessing Performance of Sustainable Urban Drainage Systems

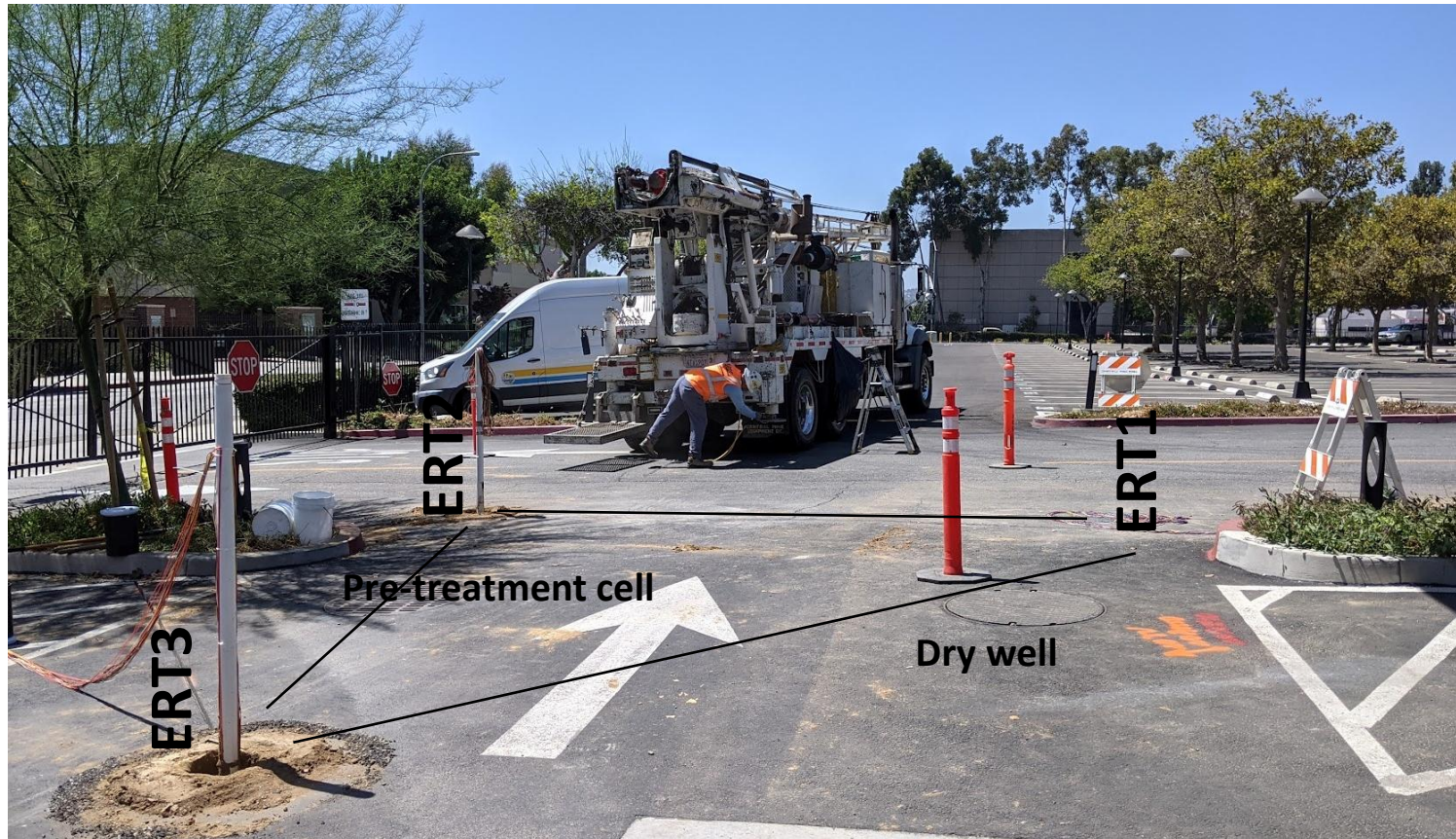
Groundwater recharge to ease urban groundwater stress

- **SUDS are designed for storm water control**
 - LA annual rainfall: 508 mm @ 35 days
 - Precipitation mostly linked to storm events
- SUDS come in many different types
- **Actual infiltration patterns are poorly understood**
- **What is the contribution of SUDS to urban groundwater recharge?**



Assessing Performance of Sustainable Urban Drainage Systems

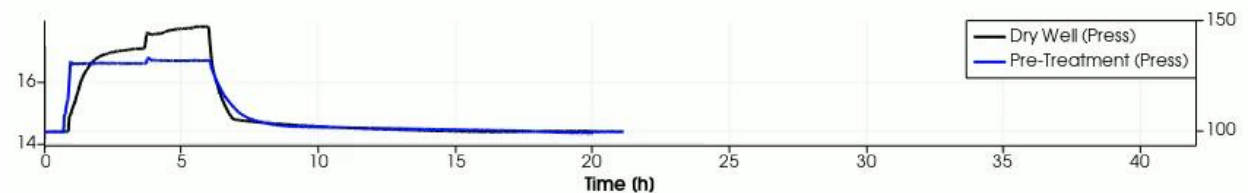
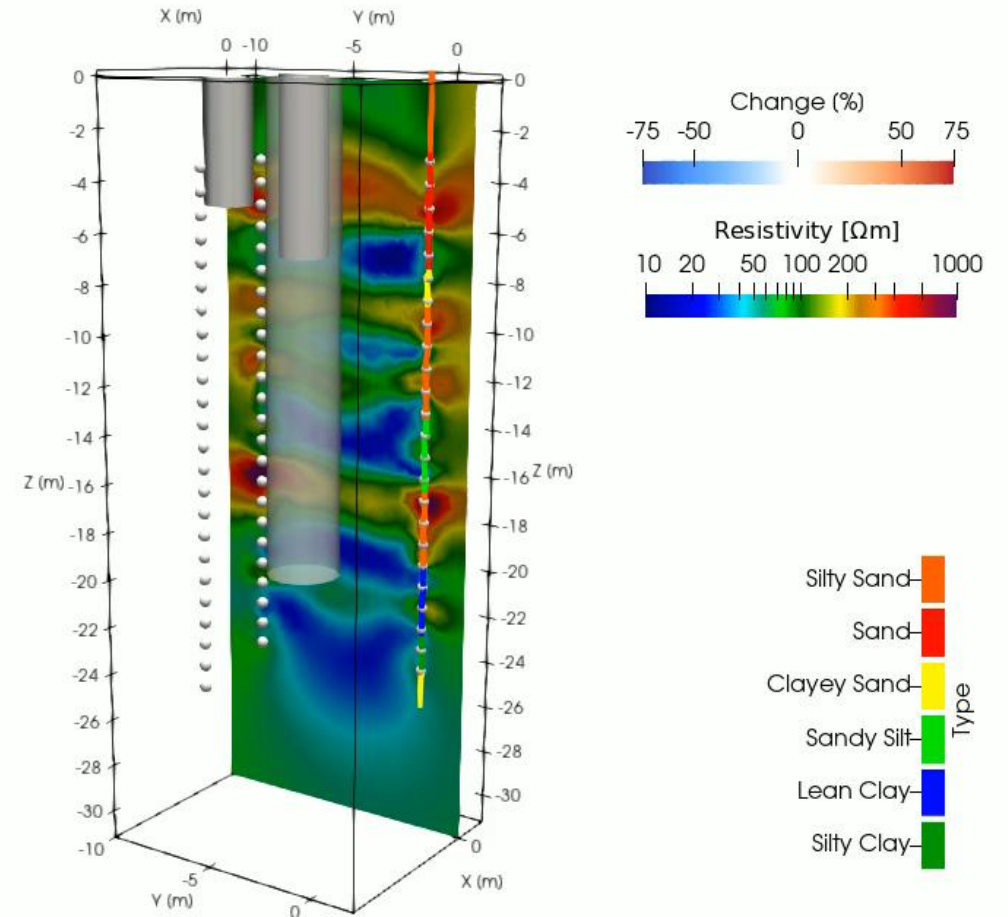
Installation of ERT monitoring system at LA County Public Works dry well



Assessing Performance of Sustainable Urban Drainage Systems

Results of controlled recharge experiment

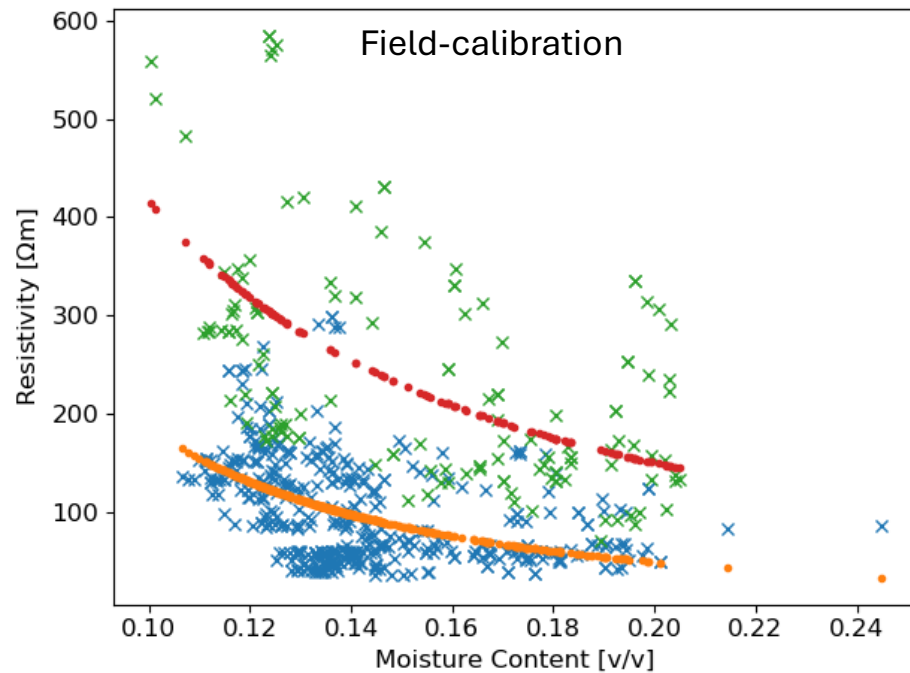
- **Soil sampling and background resistivity show alternating clayey and sandy layers**
- **Simulated rainfall event**
 - 98 m³ in 5.5 h
 - Simulating a typical rainfall event for Southern California
- Water moves mostly laterally, occupying more resistive layers
- **Rapid drawdown in the wells → system not saturated**



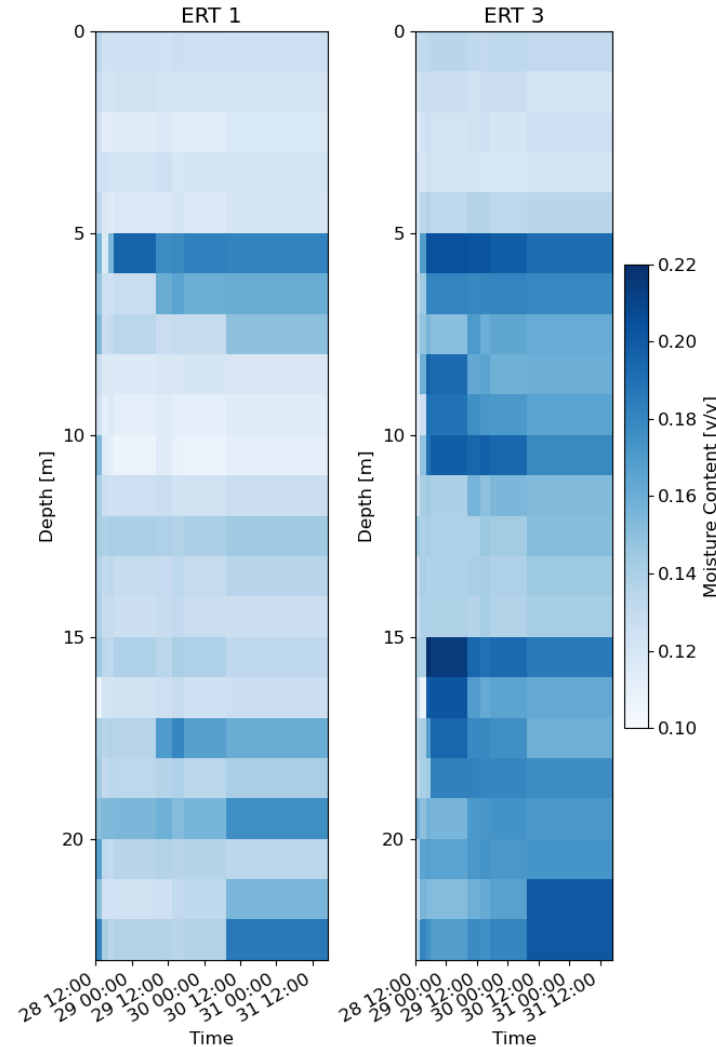
Assessing Performance of Sustainable Urban Drainage Systems

Enabling quantitative assessment

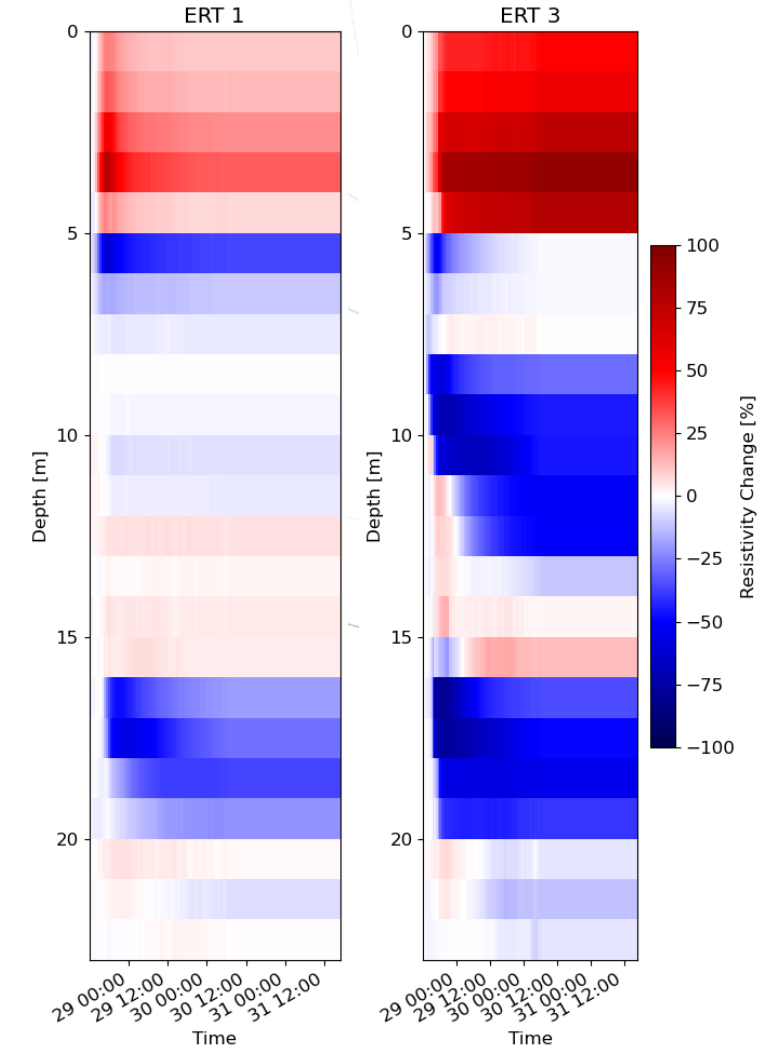
- **Changes in resistivity correlate with soil moisture data**
- In-field calibration of resistivity monitoring data to obtain models of moisture content



Direct measurements of moisture content



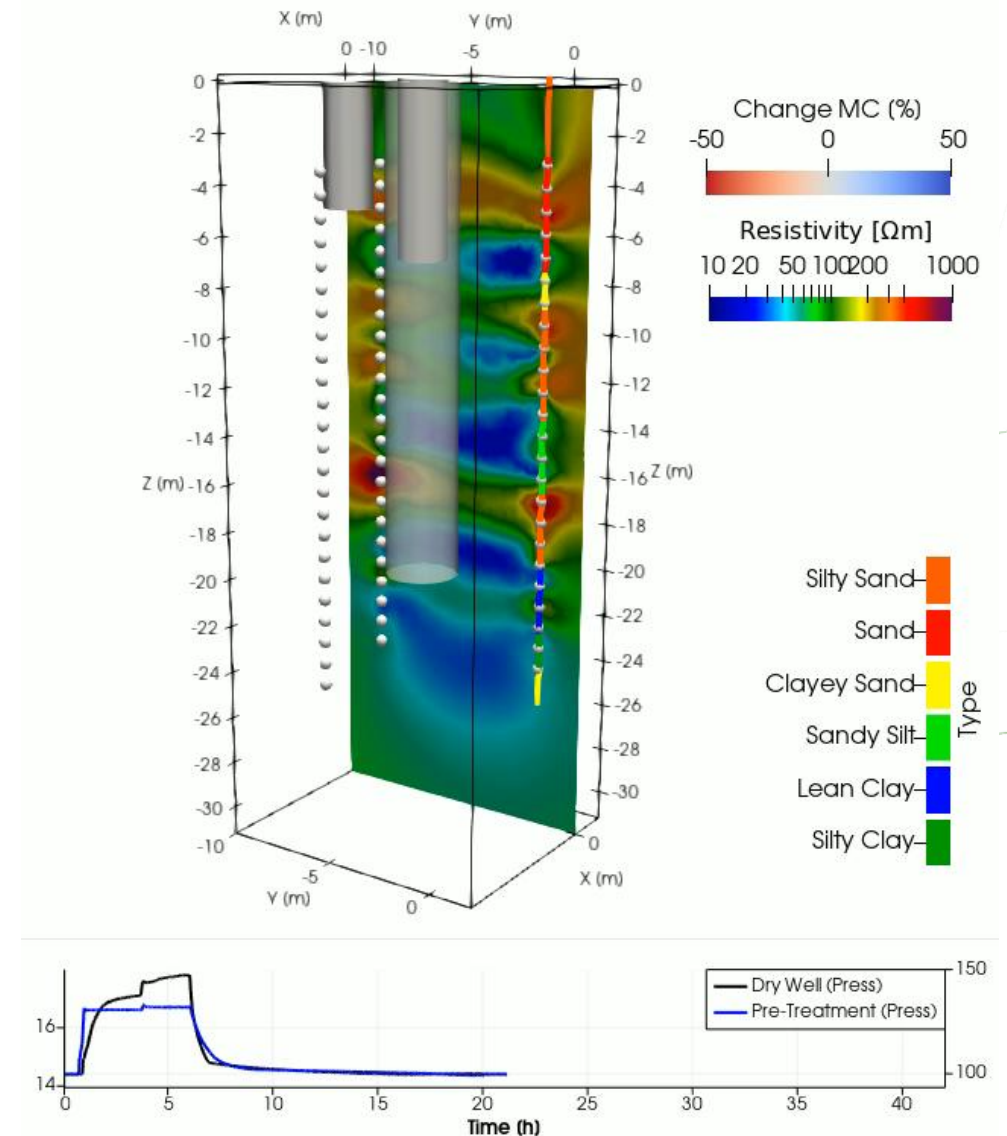
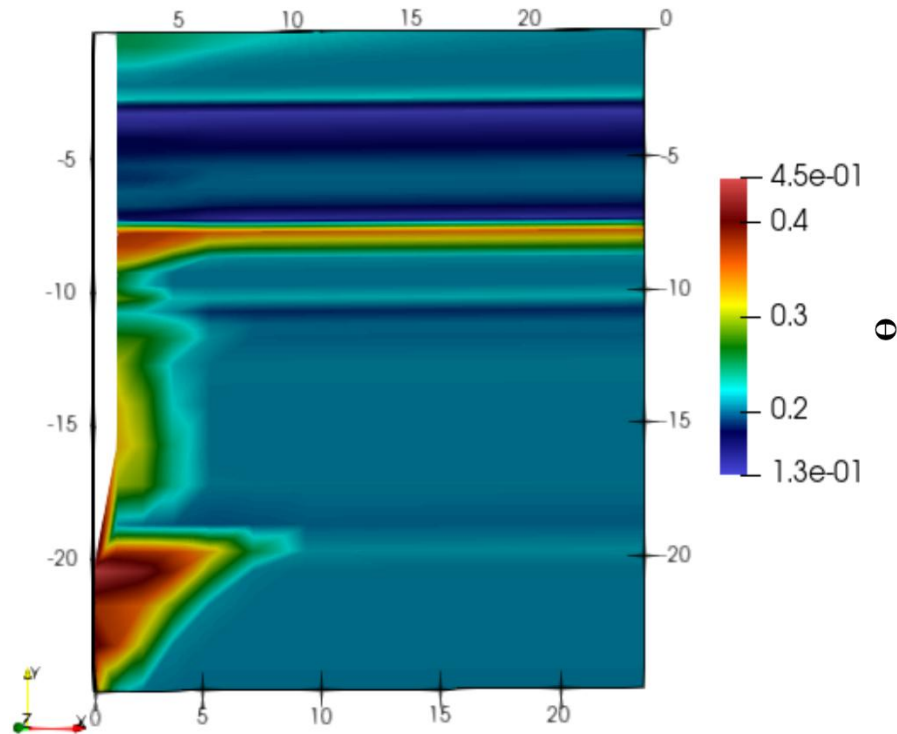
Electrical resistivity time series



Assessing Performance of Sustainable Urban Drainage Systems

Enabling quantitative assessment

- Petrophysical transfer function translates resistivity into water content
- Water occupies drywell and feeds into the aquifer
- Input for 3D hydrological model calibration





ERT monitoring sheds light on urban infrastructure

- Changes in electrical resistivity linked to changes in soil moisture content
- Resistivity monitoring can be used to assess groundwater recharge processes
 - Drywell setup provides direct input to local aquifer
 - Other SUDS types not as effective

Outlook

- Linking observations with hydrological models to quantify the contribution of SUDS to groundwater recharge
- Extension of monitoring network to assess different SUDS designs



THANKS!

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-
Mission 4 “Education and Research” - Component 2: “From research to business” - Investment
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

