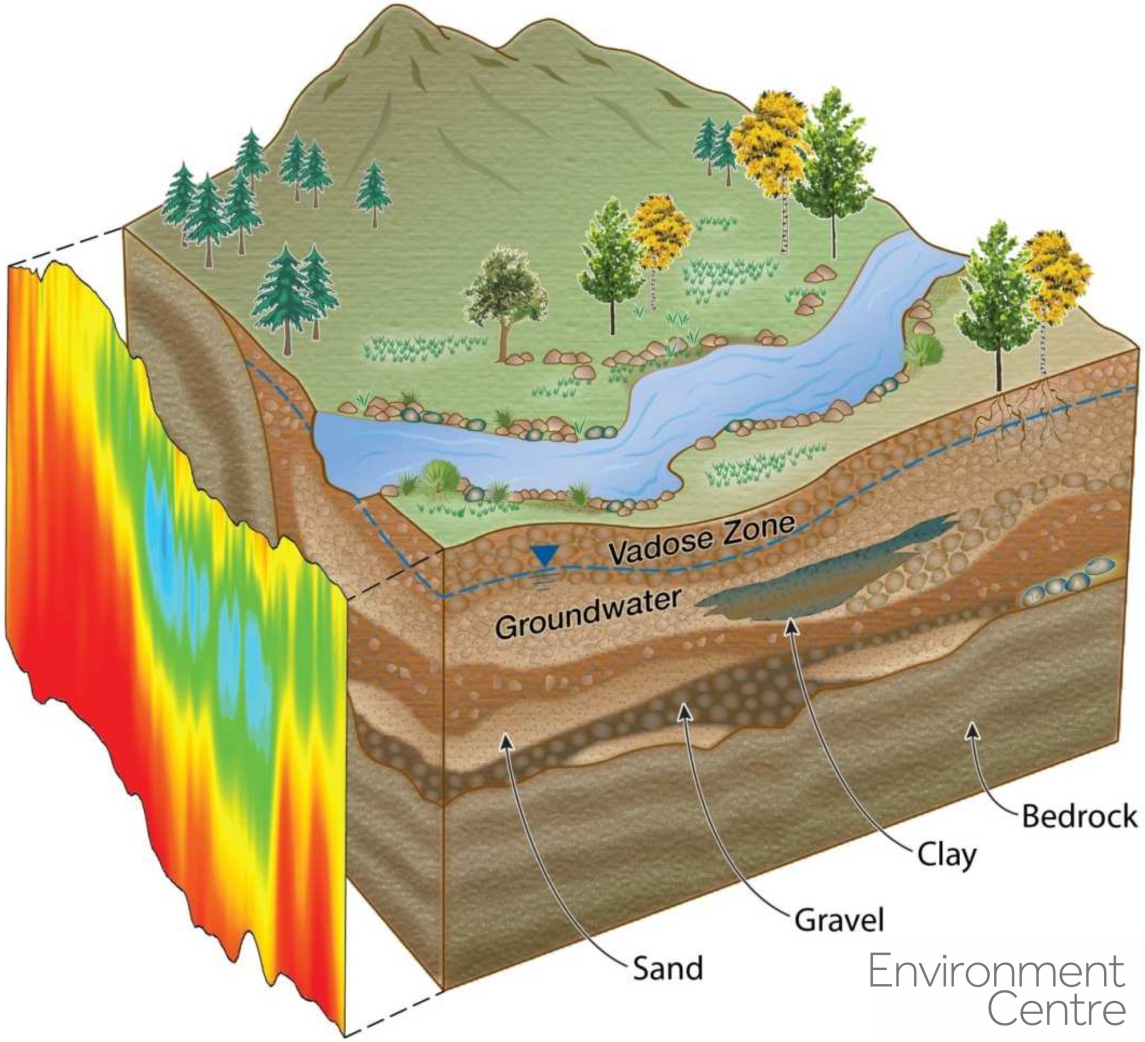
Hydrogeophysics over multiple scales

Andrew Binley

Lancaster Environment Centre, Lancaster University, Lancaster, UK

Email: a.binley@lancaster.ac.uk



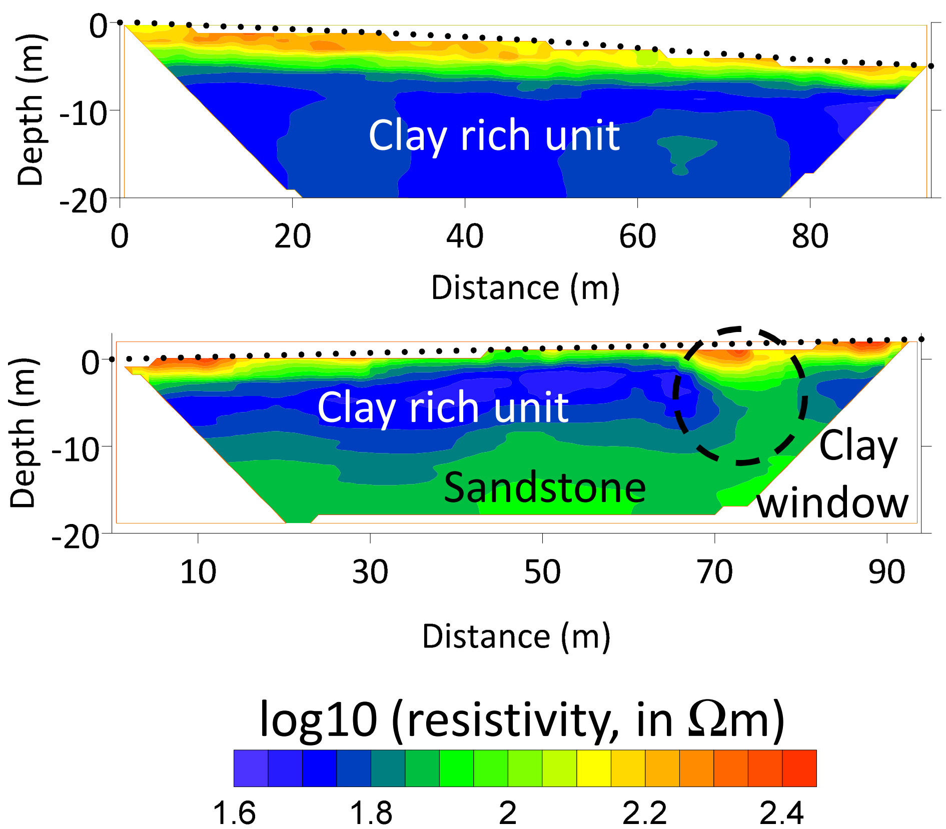
Environment Centre

Lancaster University

Hydrogeophysics – goals

Geophysics has been widely used to support groundwater investigations for many years.

Many of the earlier approaches concentrated on using geophysics to define lithological boundaries and other subsurface structures.

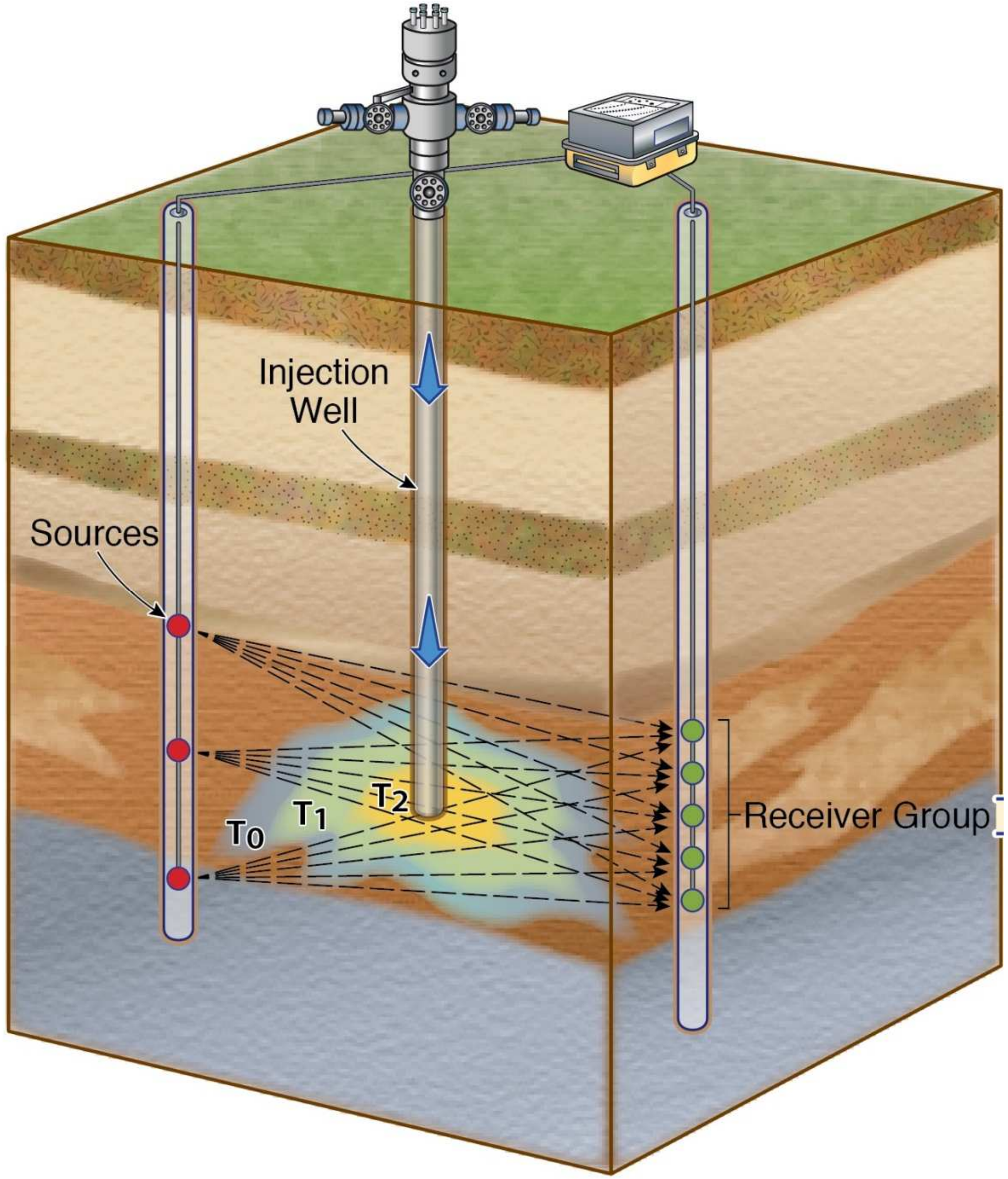


Mejus, PhD thesis Lancaster, 2016

This is still valuable but many attempts are now made to gain quantitative information about the subsurface.

Hydrogeophysics – goals

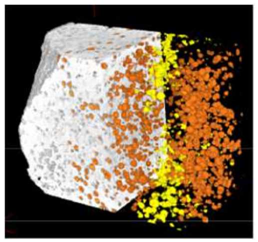
Time-lapse methods have evolved as a means of studying dynamic processes, e.g. related to groundwater clean-up.



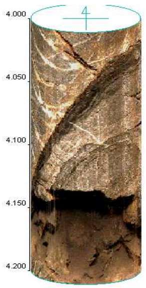
Binley et al., 2015, WRR

Hydrogeophysics – resolution and scale

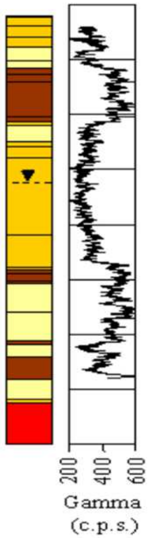
Resolution



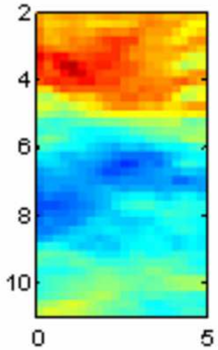
Micro-
structure



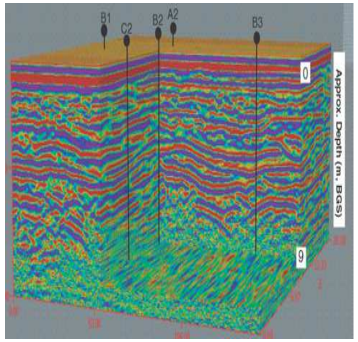
Core
imaging



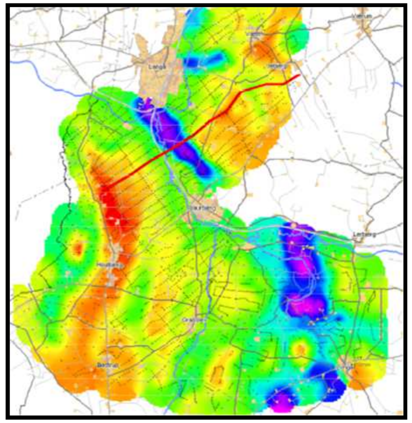
Well logs



Cross-borehole
imaging



Surface imaging

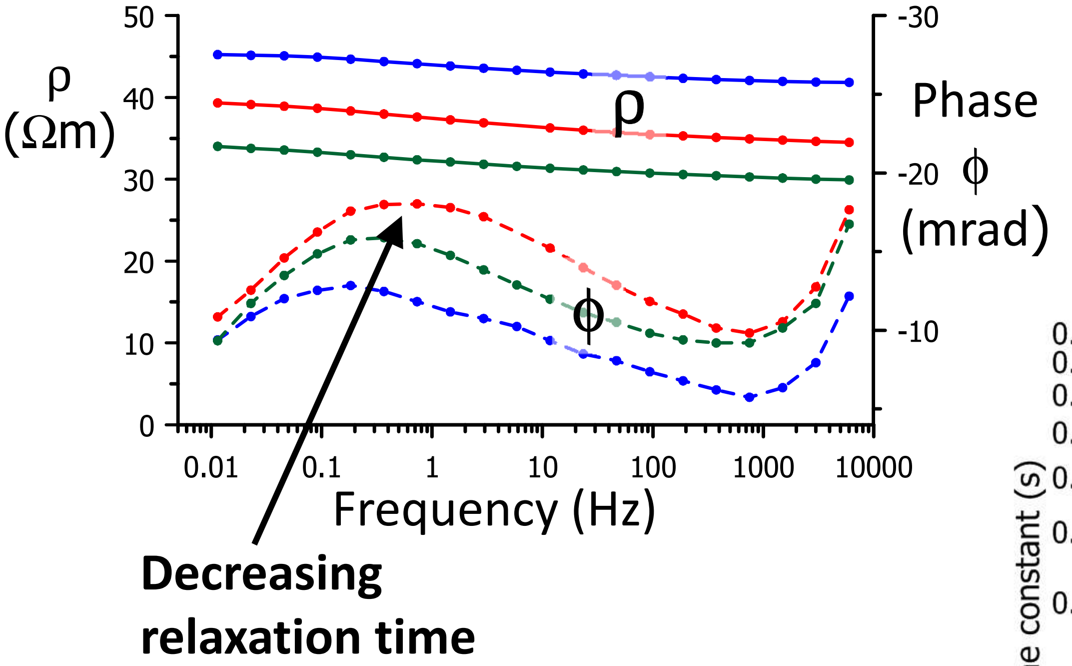


Airborne

Survey scale

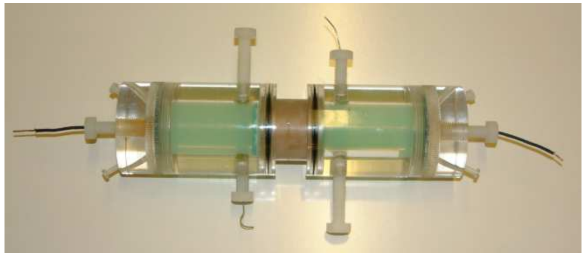
Hydrogeophysics – core scale

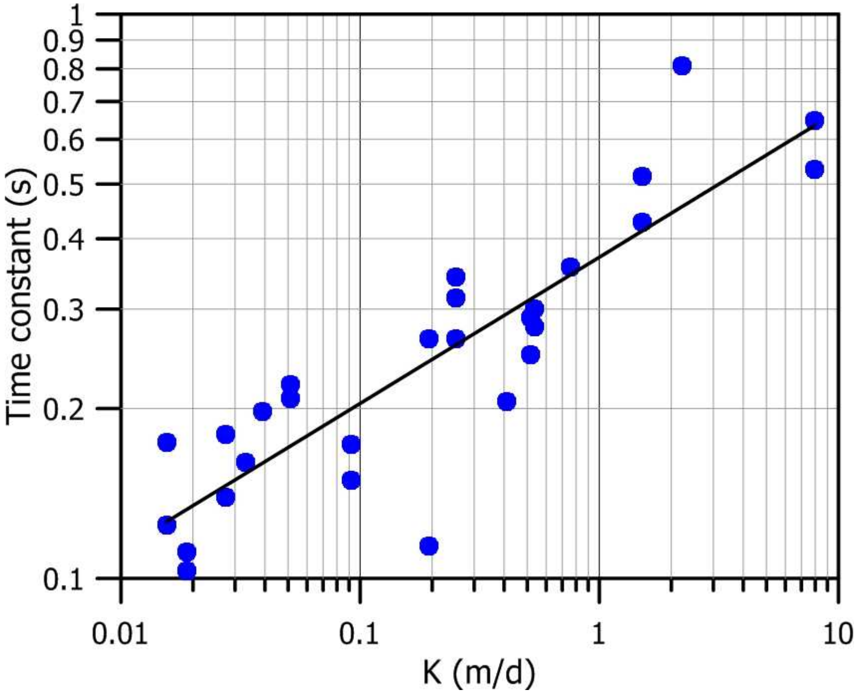
Attempts to link electrical conduction and polarisation to hydraulic properties, e.g. permeability



Longer time scale ≡ larger particles (higher K)

25mm diameter sandstone sample

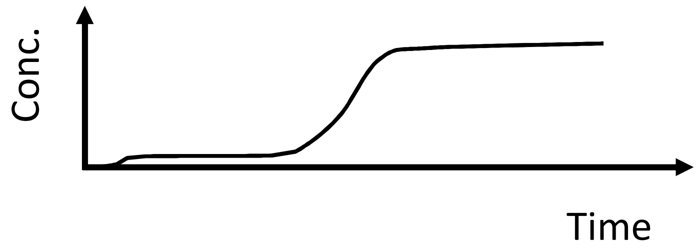


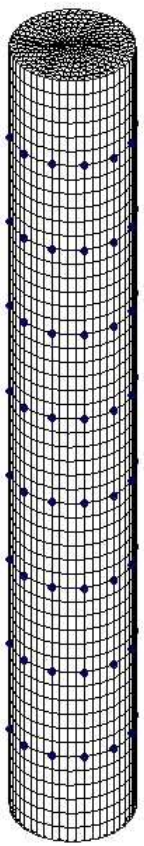


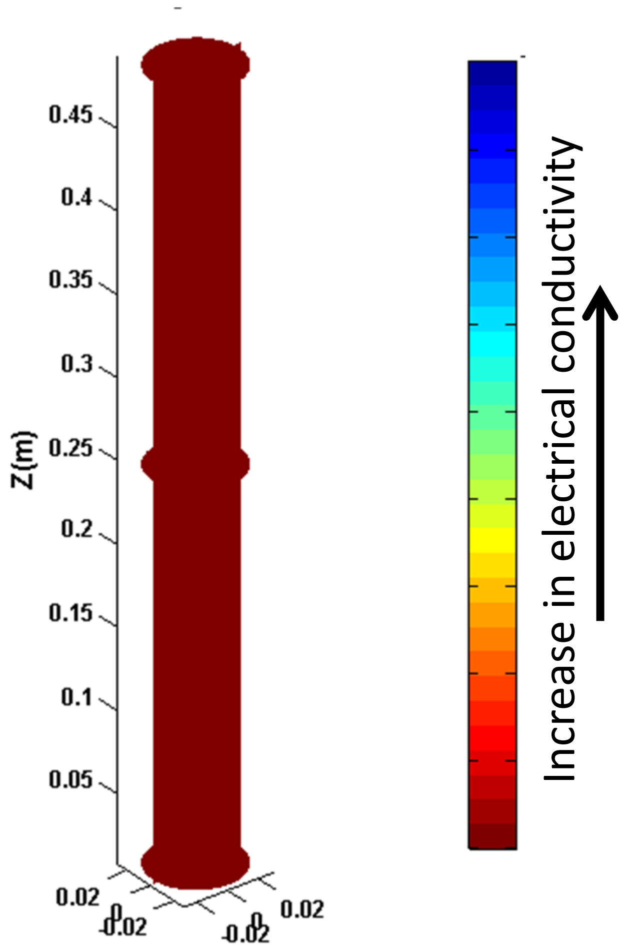
Binley et al., 2005, WRR

Hydrogeophysics – core scale

Tracking breakthrough of a tracer in soil columns







Hydrogeophysics - moving to larger scales

We illustrate results from three application areas where the need is to expand to large scale investigation

Sustainable land management

- Mapping heterogeneity of karst in SW China

Sustainable water resources

- The interaction of groundwater and surface water

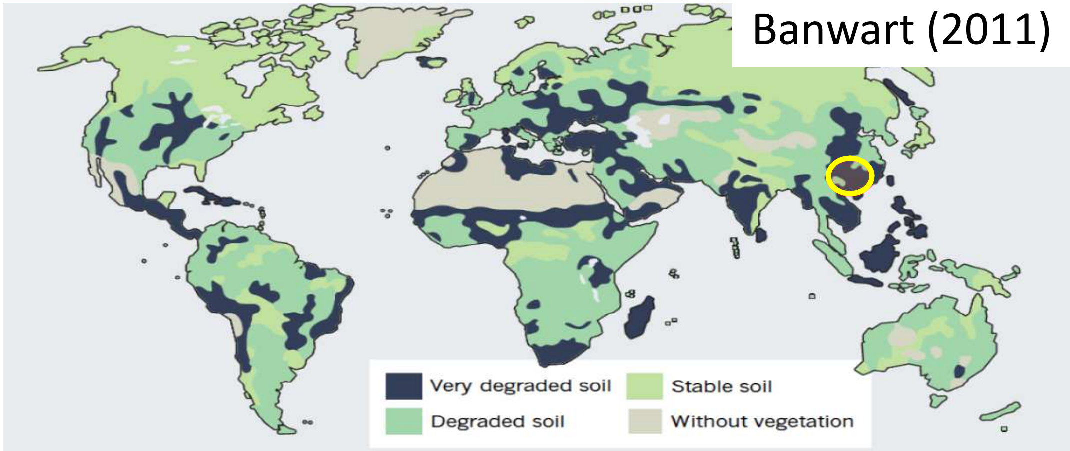
Food security

- Plant-soil-water interactions

Mapping heterogeneity of karst in SW China

Karst:

- 33% of China's land area
- Home for 50 million people



- High heterogeneity
- Significant human activity
- Limited soil quantity
- Special channel structures
- Multi-erosion processes
- Complex lithological structure

Rapid and intensive land use change in one of the poorest regions of China: Guizhou has caused severe ecosystem degradation during the last 50 years.

Work described funded through NERC Grant NE/N007409/1

NERC SCIENCE OF THE ENVIRONMENT

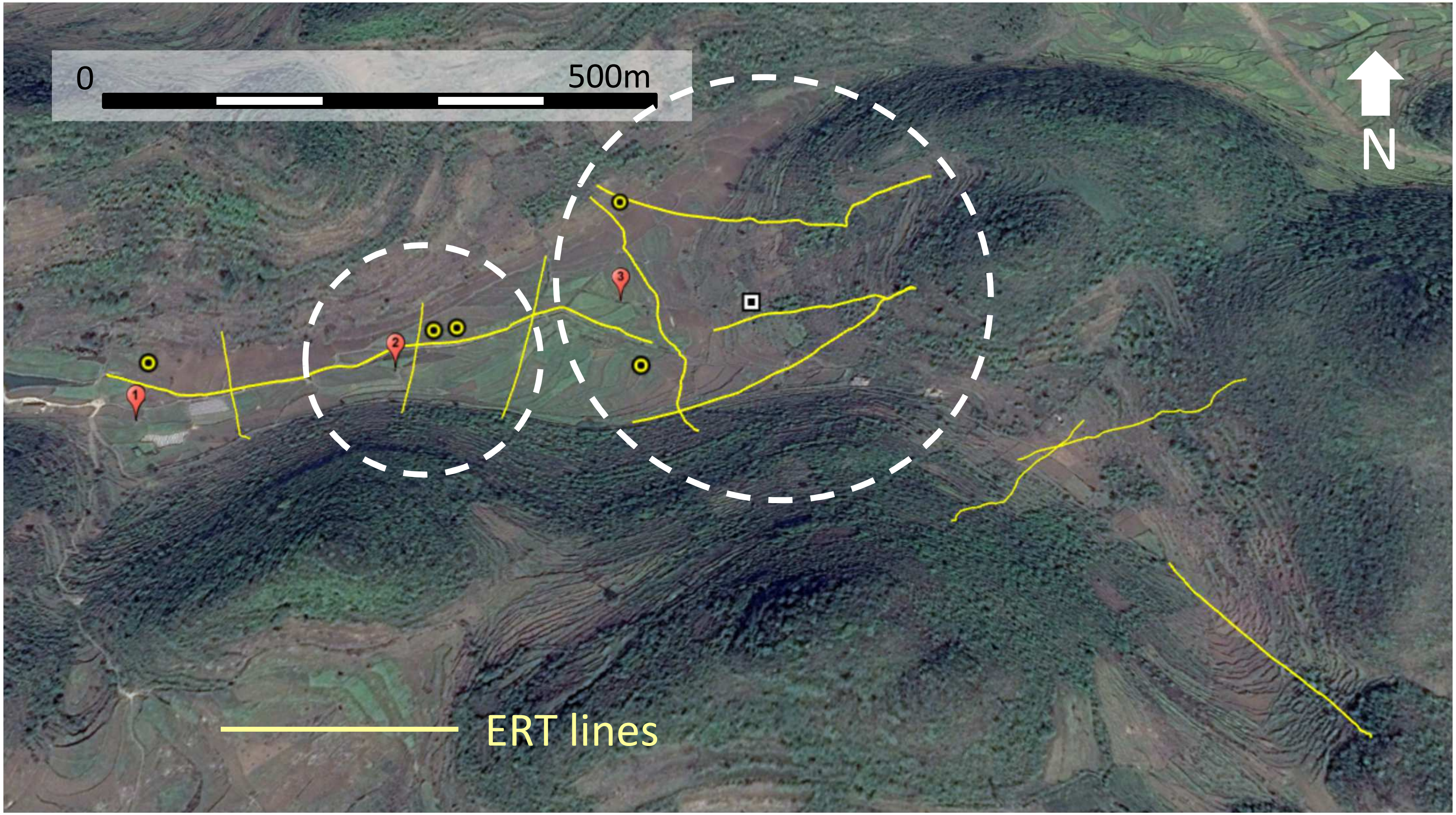
Mapping heterogeneity of karst in SW China

Chenqi study catchment

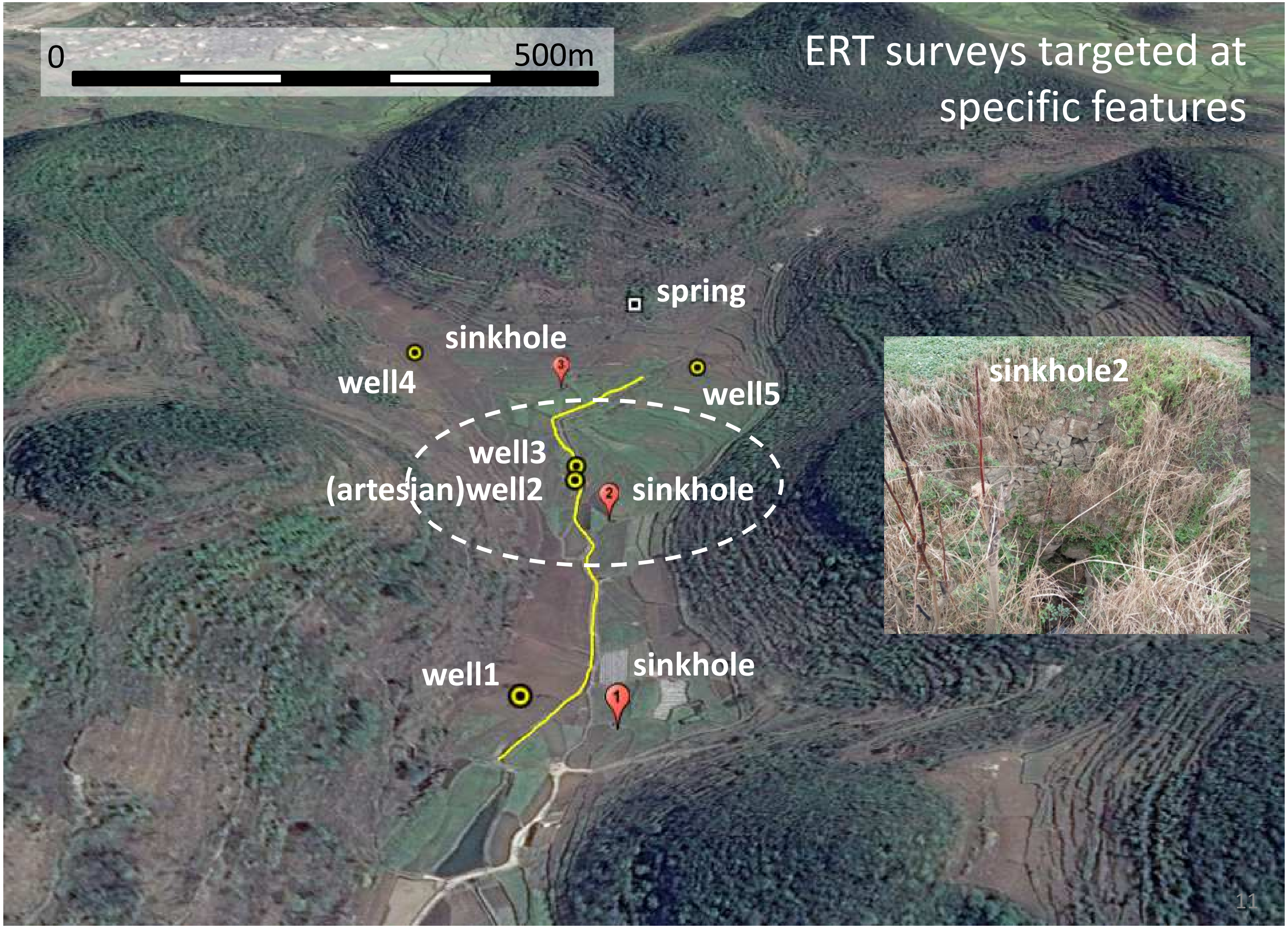
- Area 1.29 km^2 , maximum elevation 1500 masl.
- Climate sub-tropical-monsoonal
- Agriculture fields mainly in the valley but some on lower slopes
- Crops commonly grown: rice, maize, soybeans, peanuts, and rape oil seed in rotation.

Mapping heterogeneity of karst in SW China

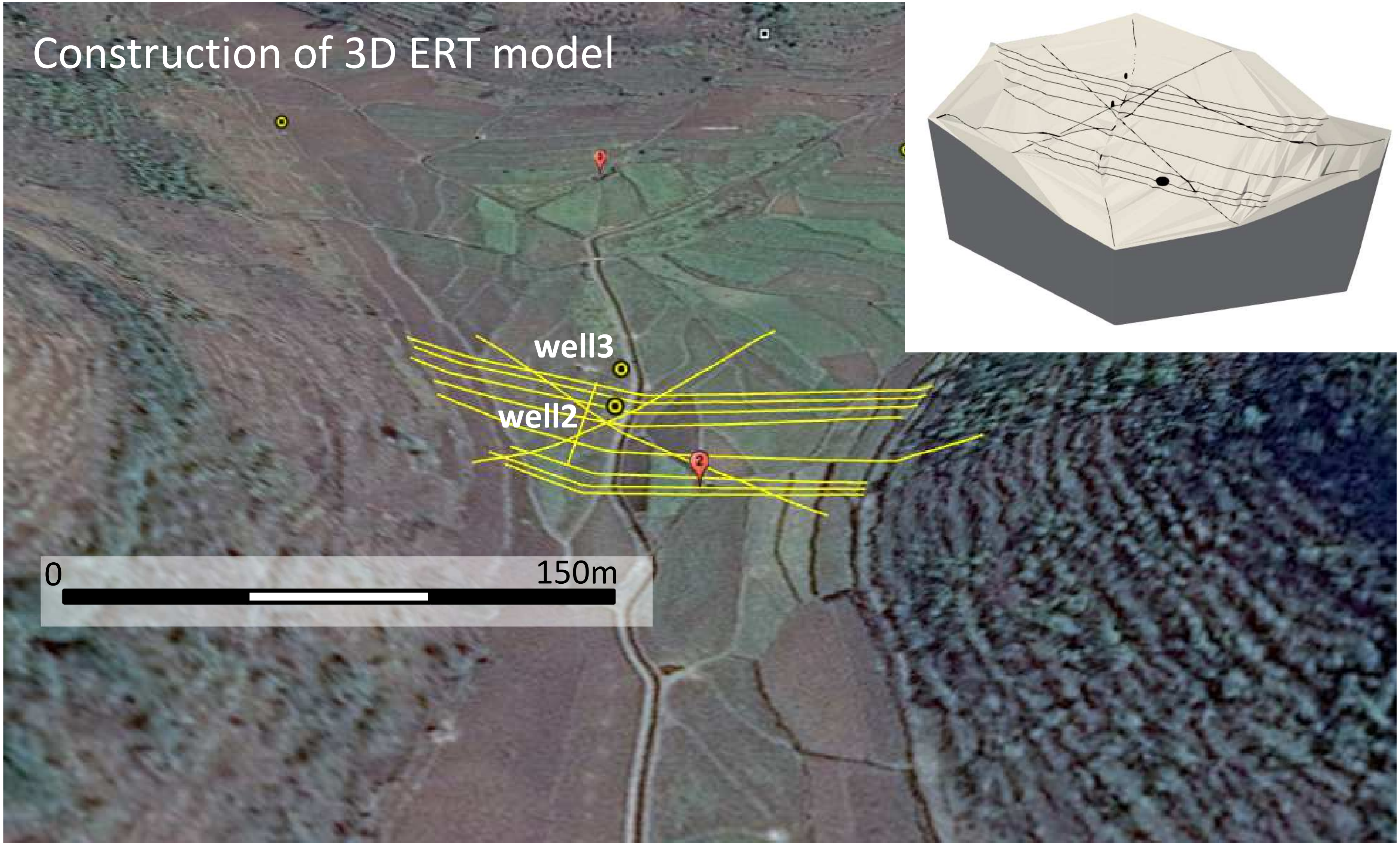
Geophysical campaigns aimed to try help explain hydraulic and hydrochemical responses in existing observational network, ultimately to improve conceptual model of the catchment



Mapping heterogeneity of karst in SW China



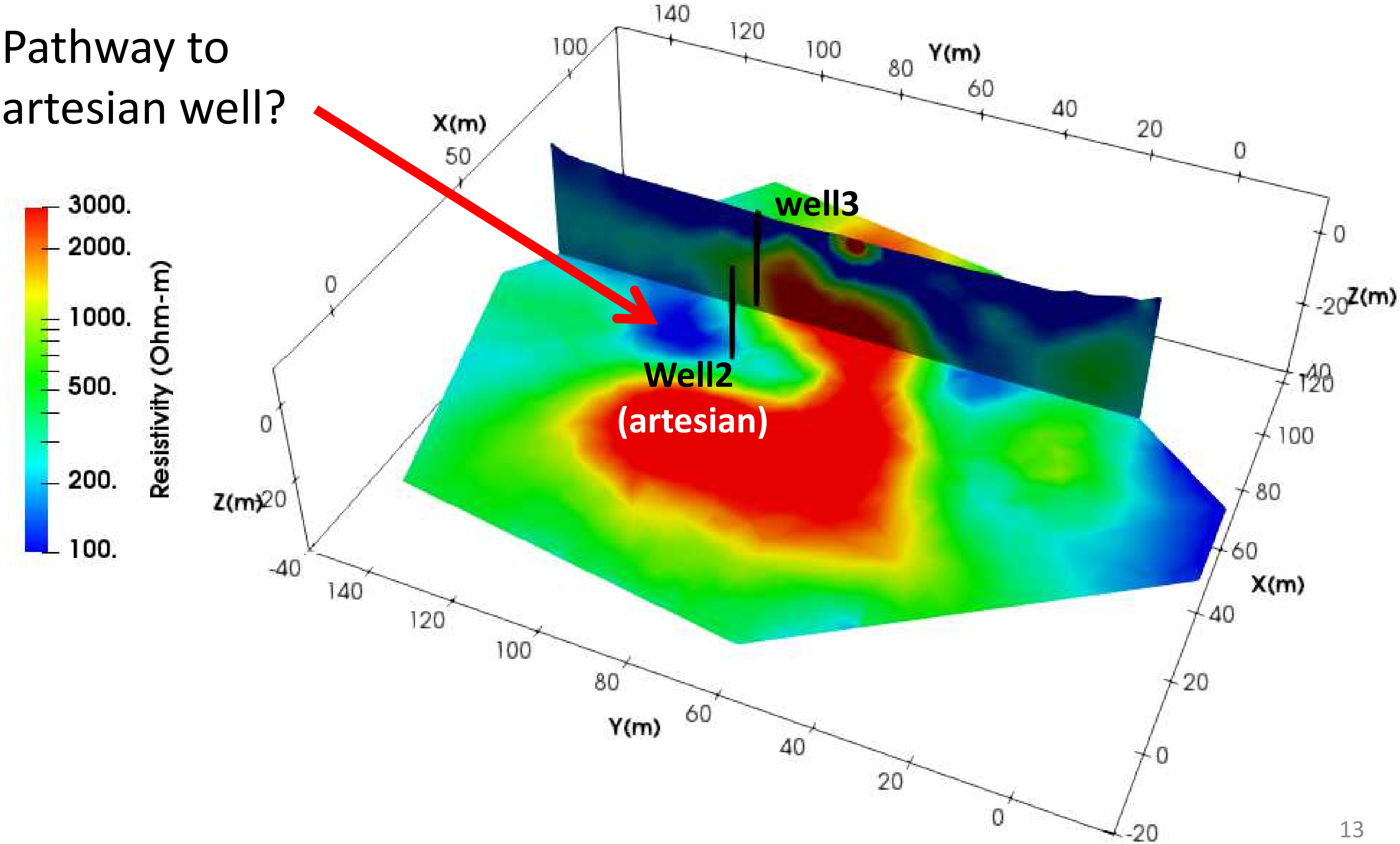
Mapping heterogeneity of karst in SW China



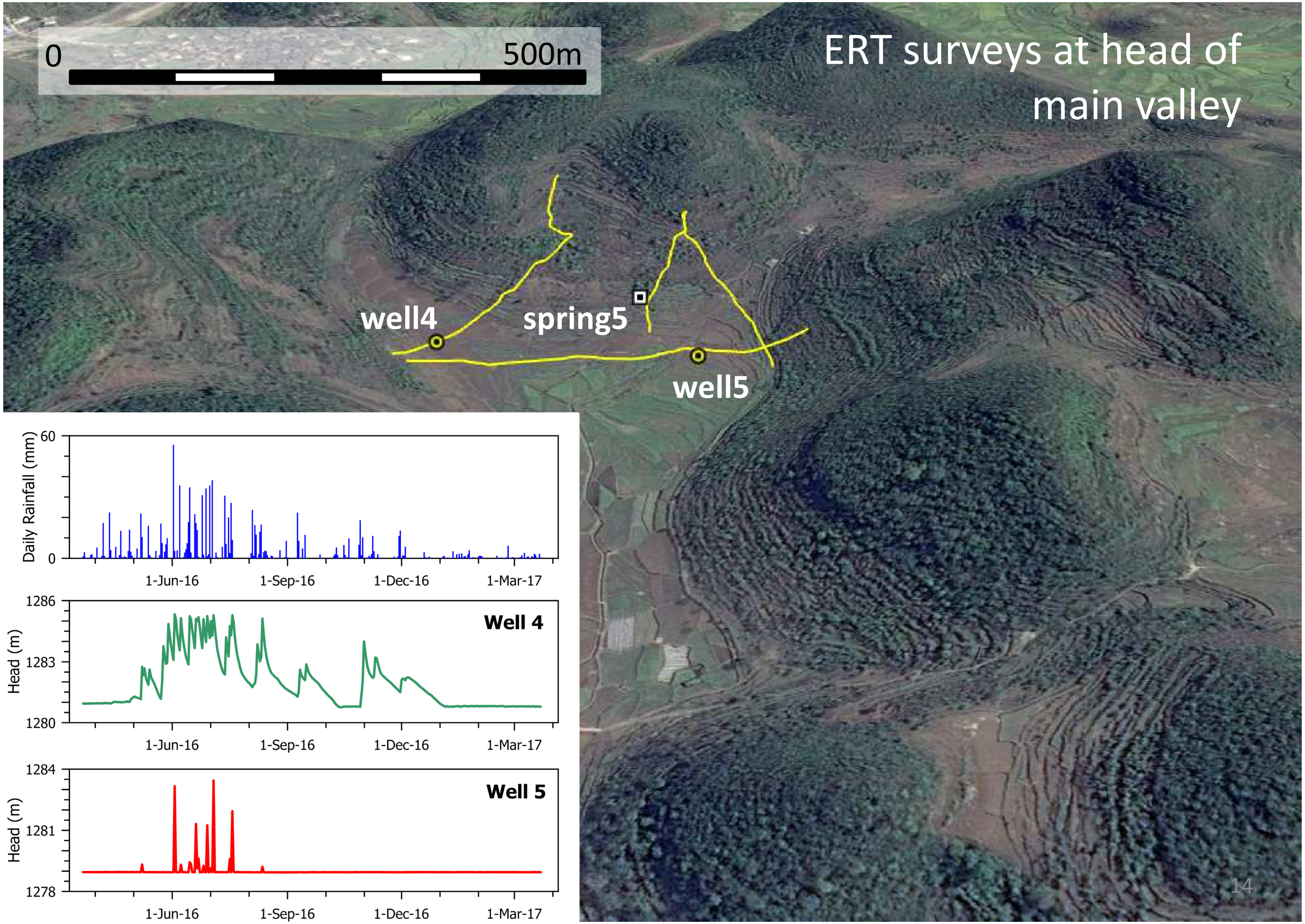
Mapping heterogeneity of karst in SW China

3D ERT provides evidence of local geological contrast that helps explain contrast in well behaviour

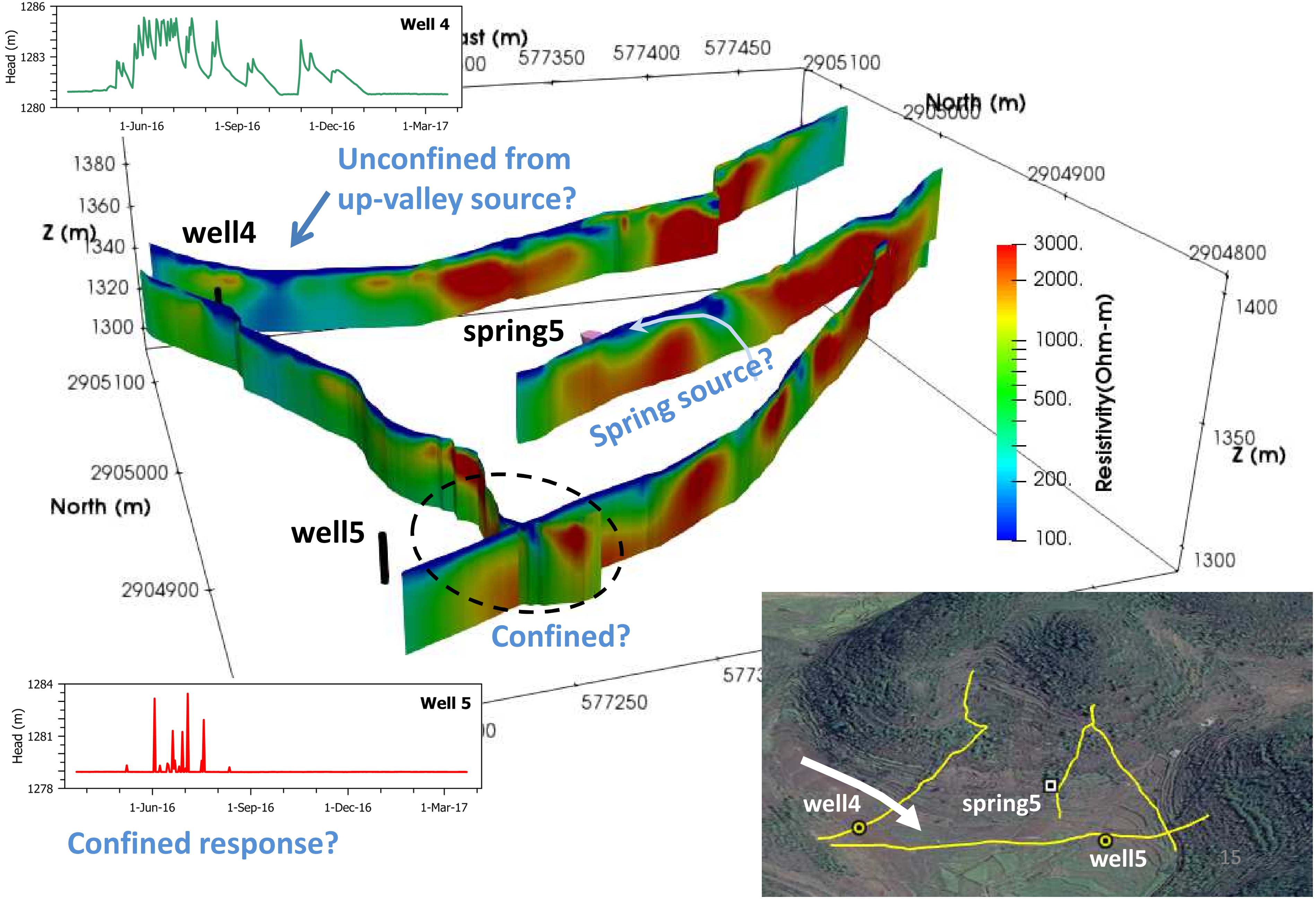
Pathway to artesian well?



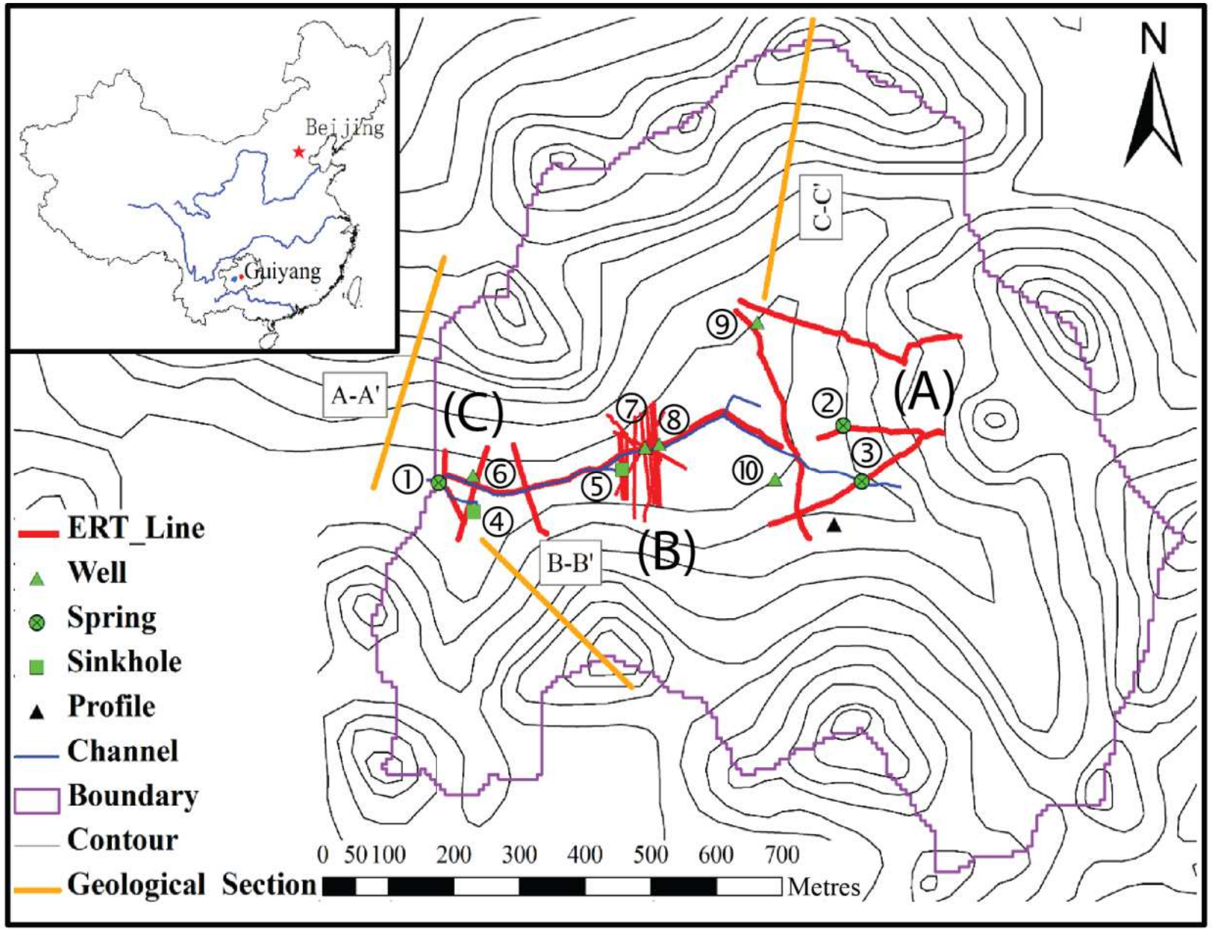
Mapping heterogeneity of karst in SW China

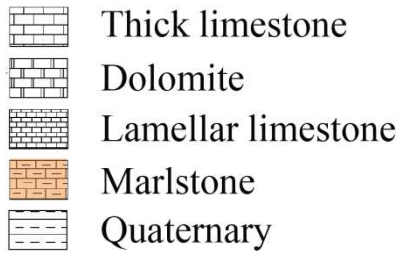


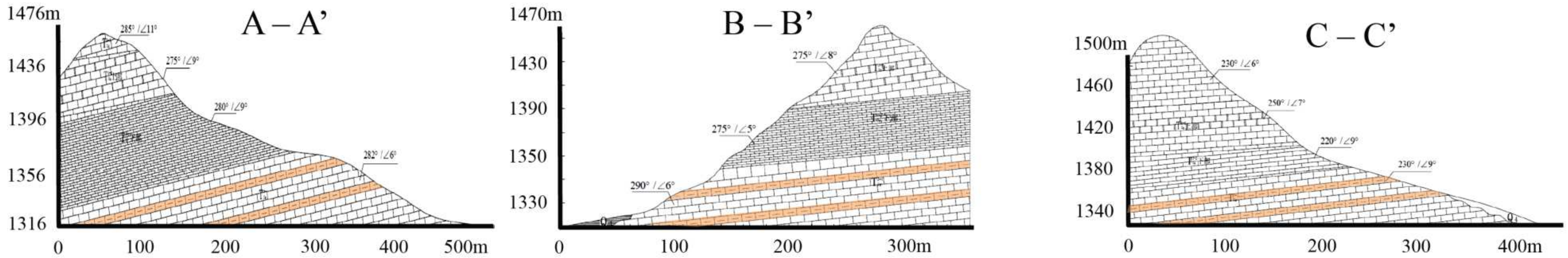
Mapping heterogeneity of karst in SW China



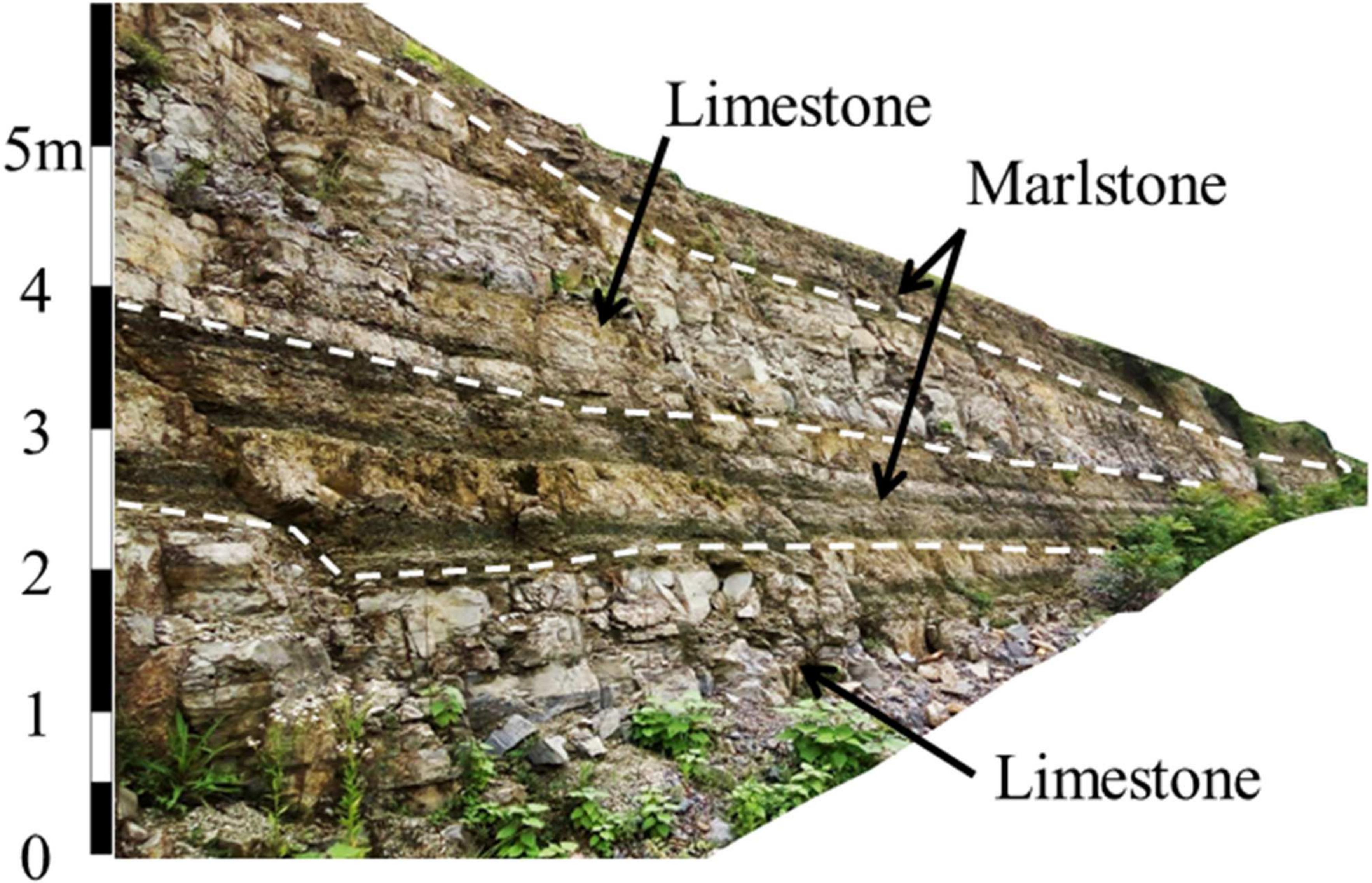
Mapping heterogeneity of karst in SW China





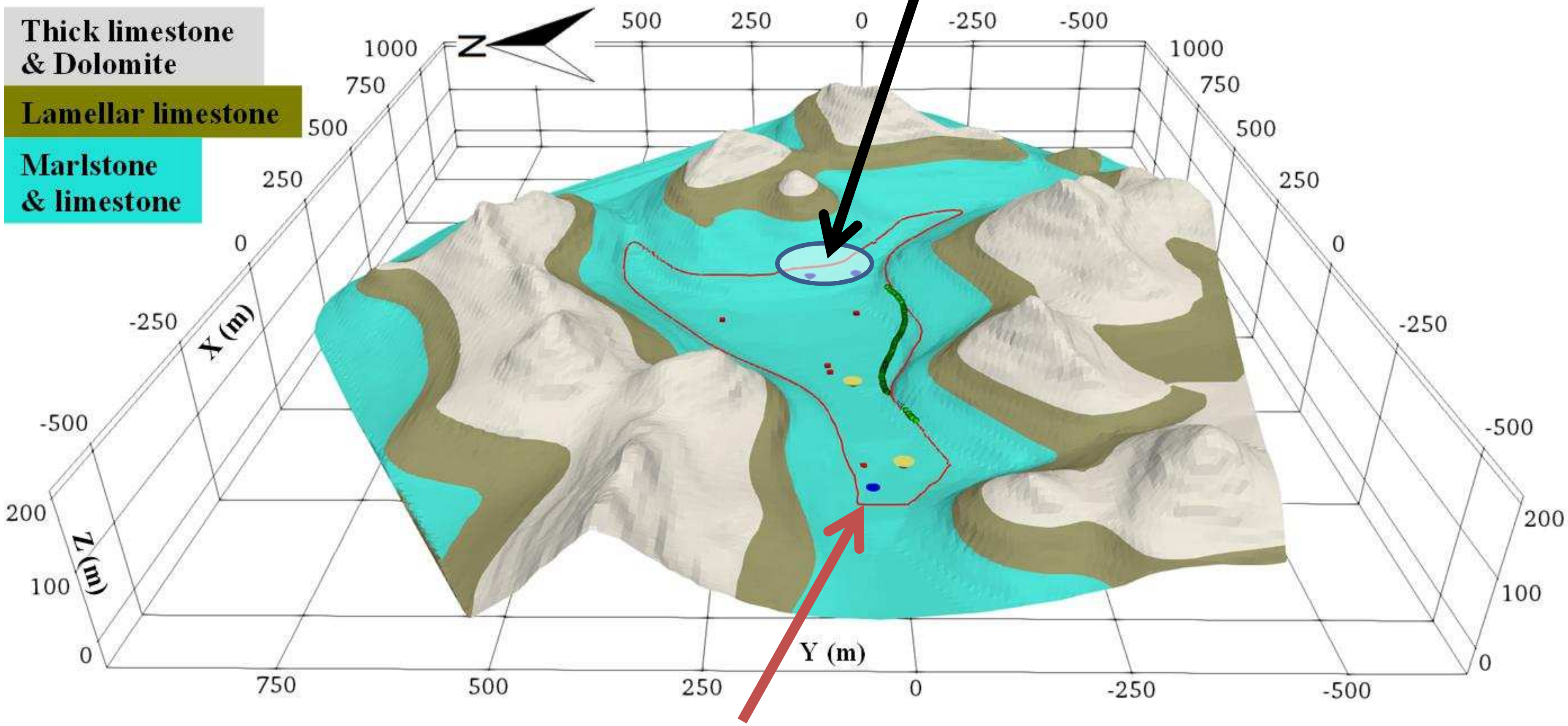


Mapping heterogeneity of karst in SW China



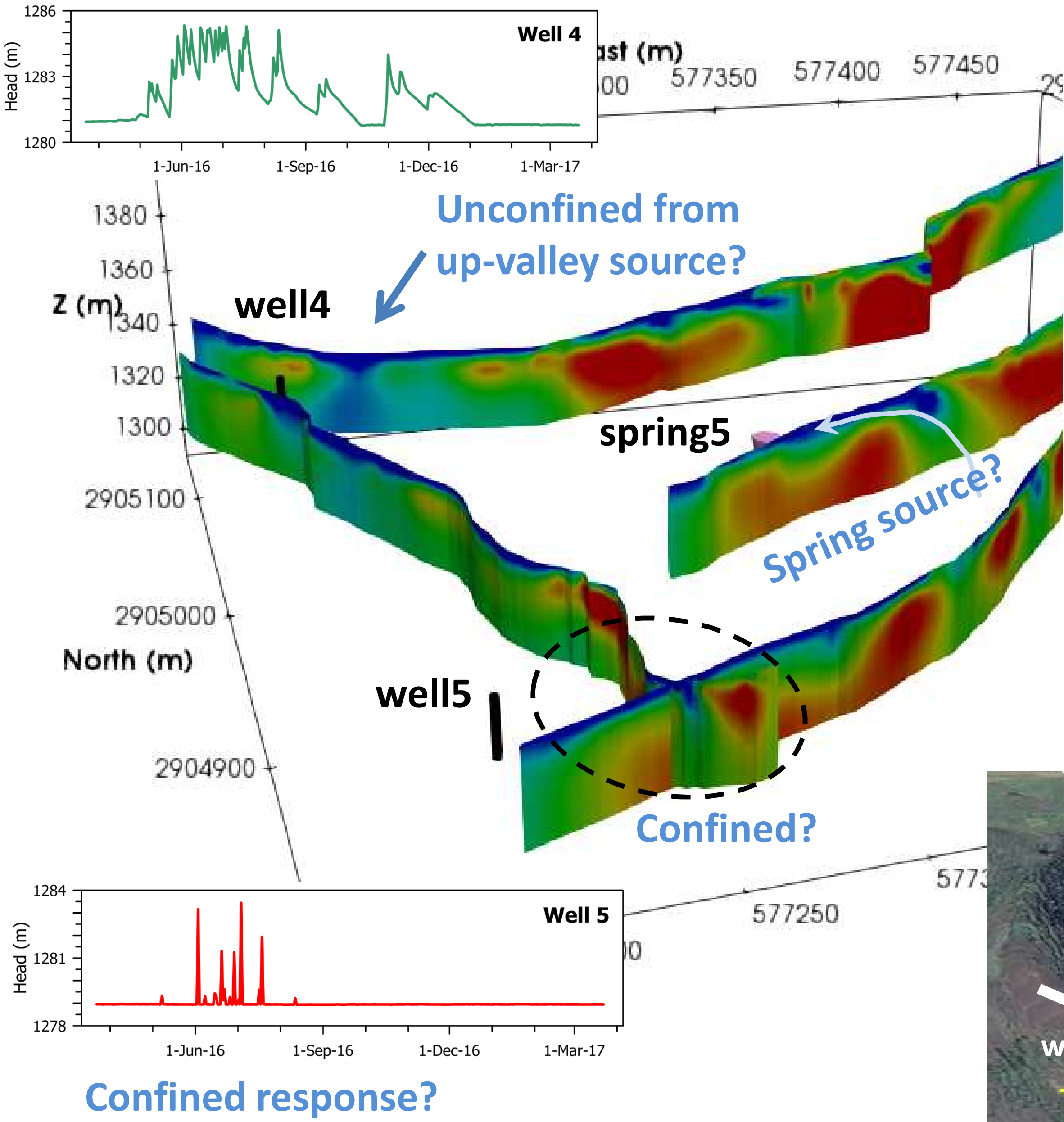
Mapping heterogeneity of karst in SW China

Electrically conductive area from ERT model

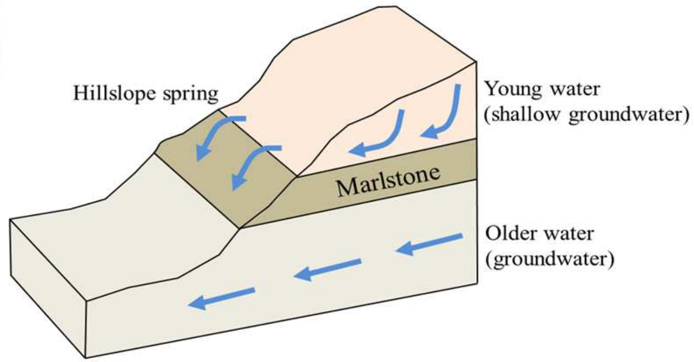


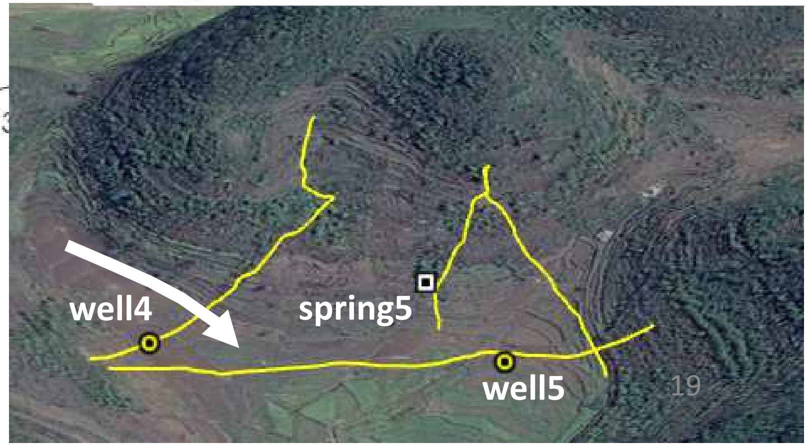
Marlstone outcrop inferred from geological model and digital terrain model

Mapping heterogeneity of karst in SW China



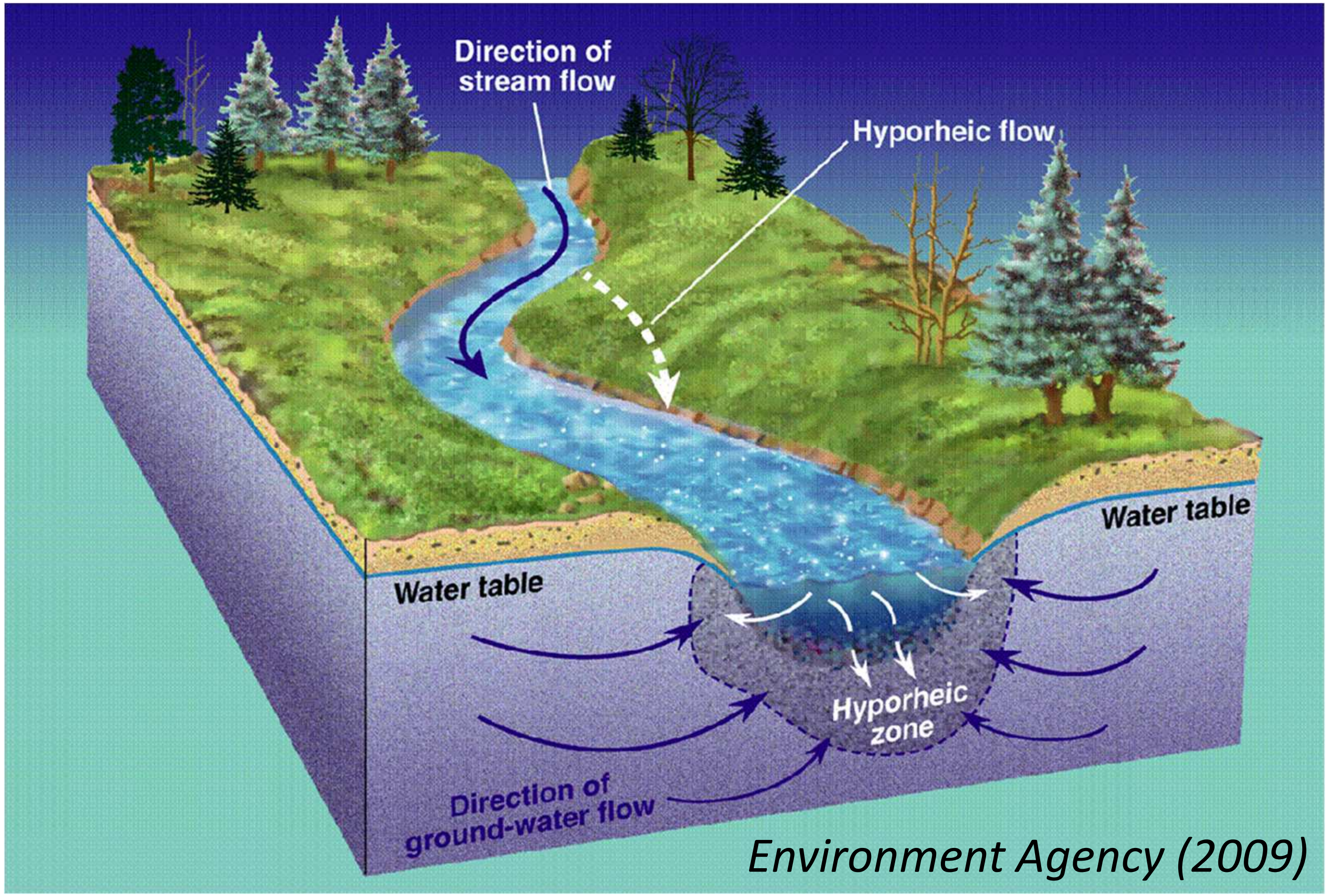
Does marlstone layer control springs (impeding layer) and confined response in wells (confining layer above)?





Groundwater-surface water interactions

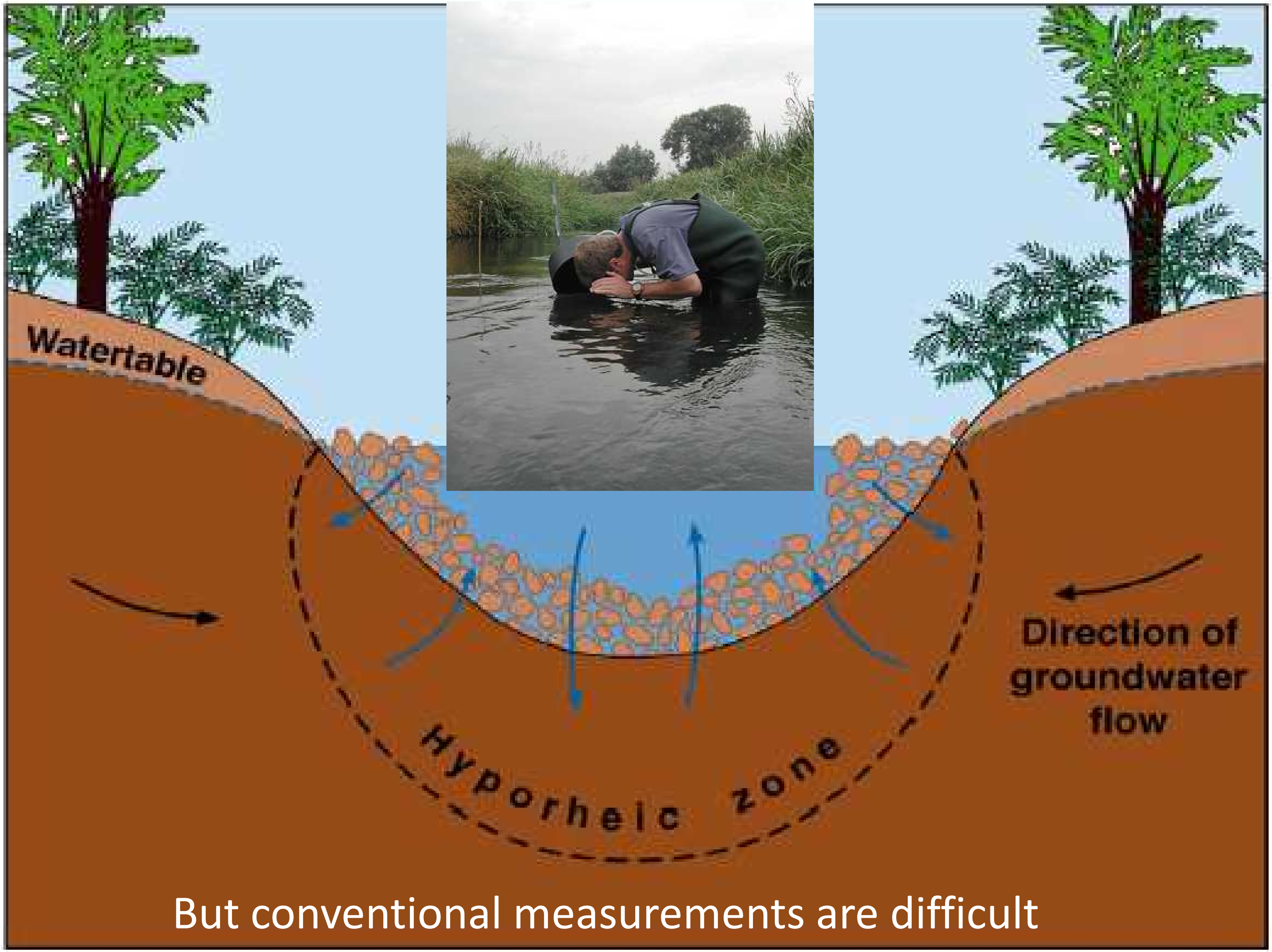
There is a need for improved understanding of hydrological and biogeochemical processes operating at critical interfaces



Environment Agency (2009)

Work described here from UK Natural Environment Research Council (grant NE/F006063/1).

Groundwater-surface water interactions

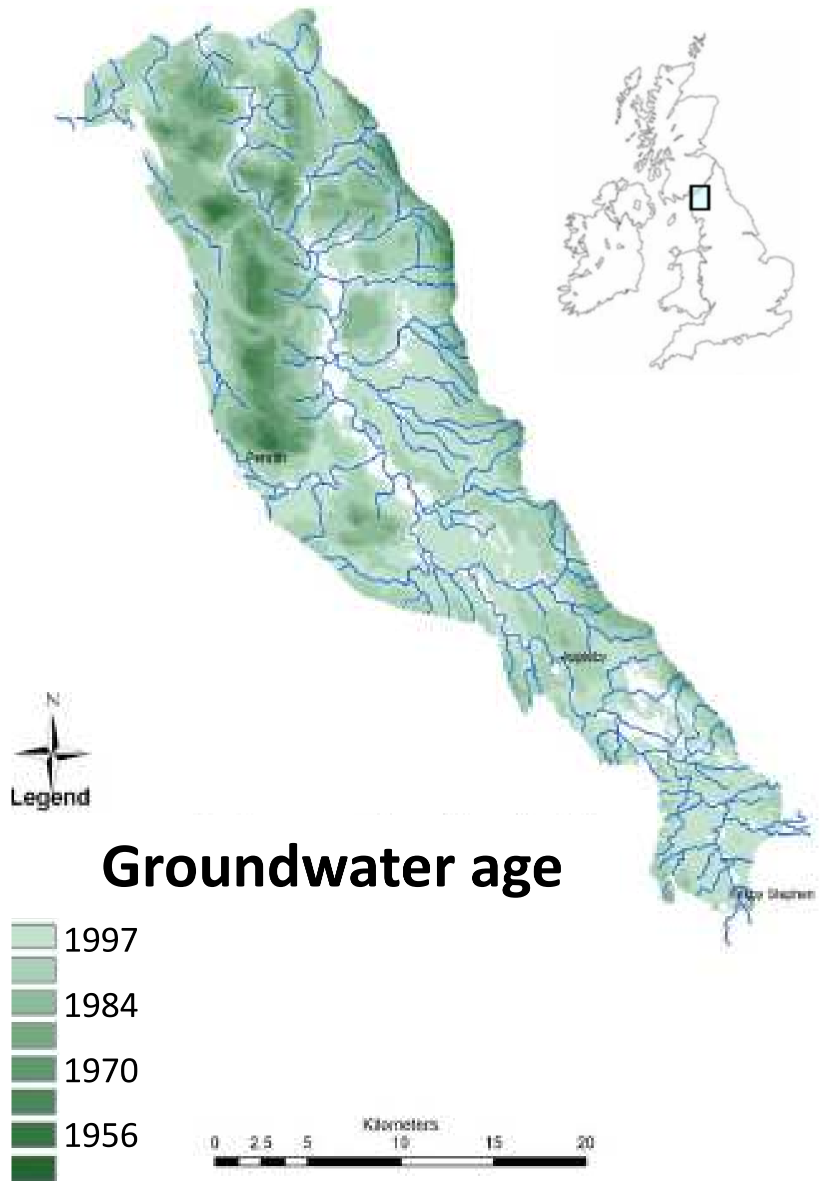


Groundwater-surface water interactions

The Eden Valley

Long unsaturated zone travel times

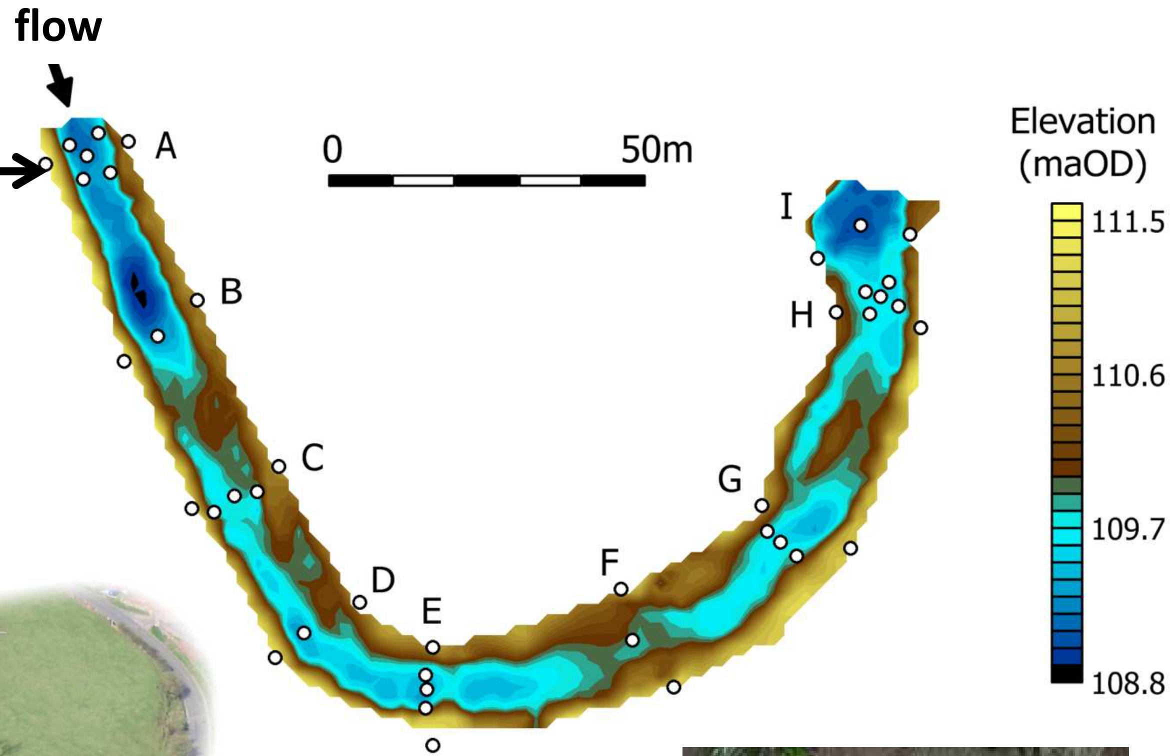
Leads to rising nitrate levels



Butcher et al. (2008)

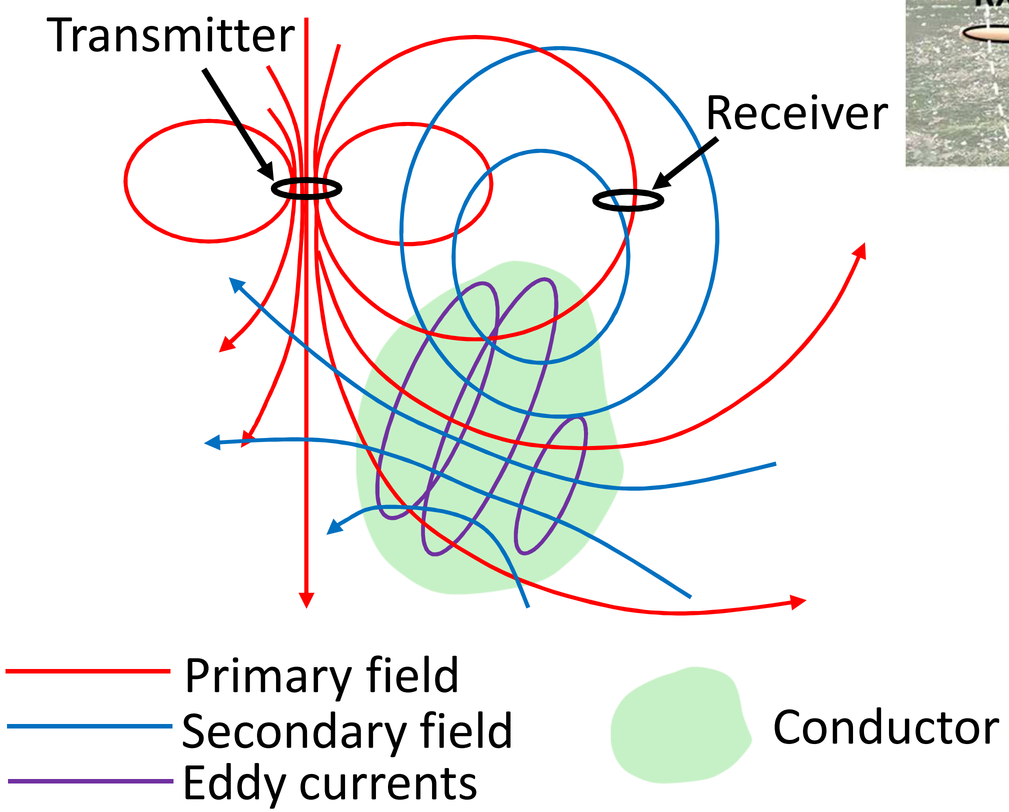
Groundwater-surface water interactions

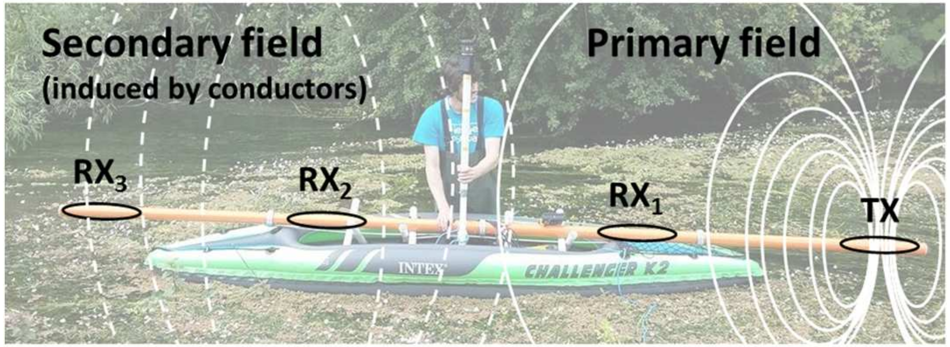
Piezometer cluster



Groundwater-surface water interactions

Characterisation of spatial heterogeneity of river bed sediments using electromagnetic conductivity mapping.

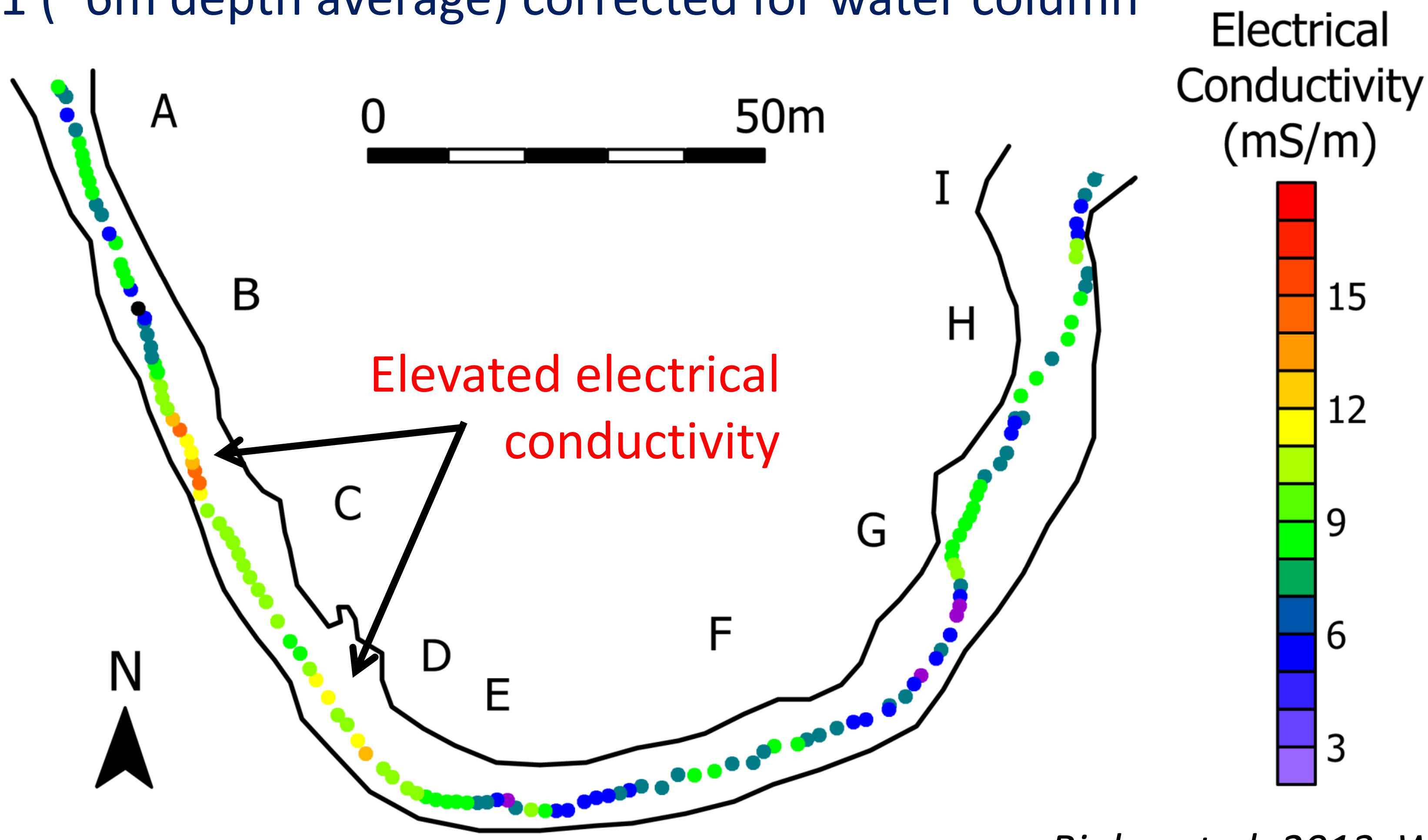




Groundwater-surface water interactions

Electrical conductivity profile along river indicates potential contrasts in either river bed sediments or pore fluid chemistry

EM31 (~6m depth average) corrected for water column

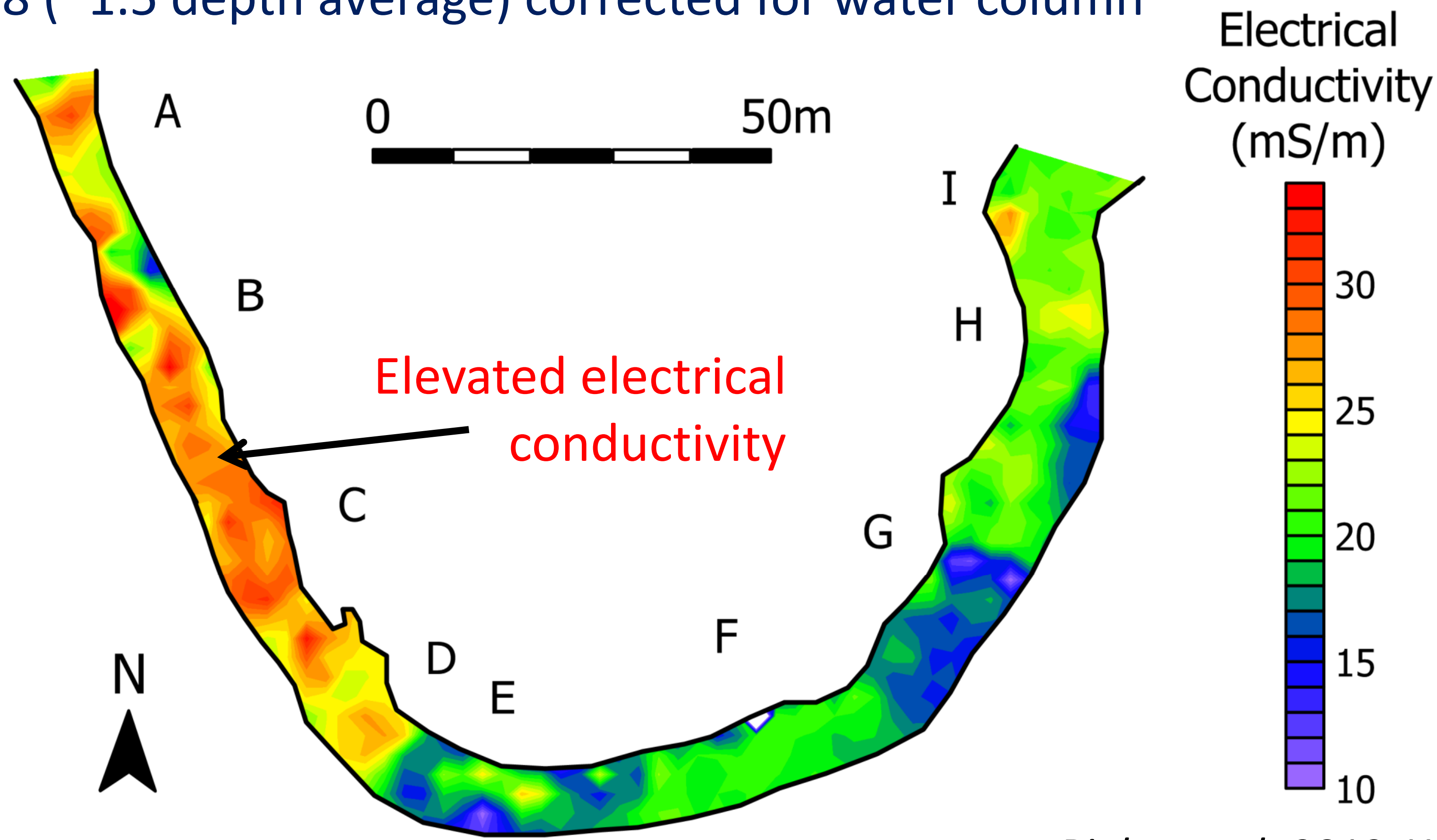


Binley et al.,2013, WRR

Groundwater-surface water interactions

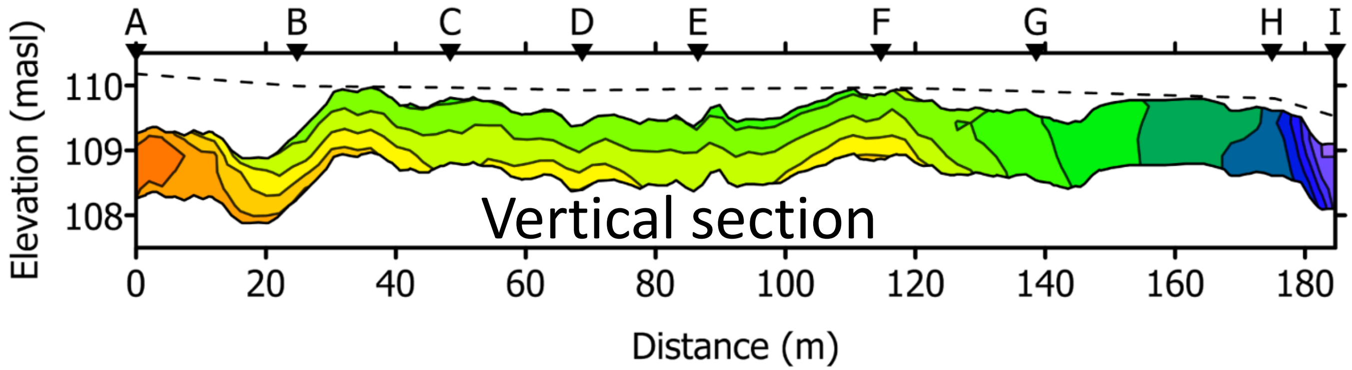
Electrical conductivity profile along river indicates potential contrasts in either river bed sediments or pore fluid chemistry

EM38 (~1.5 depth average) corrected for water column

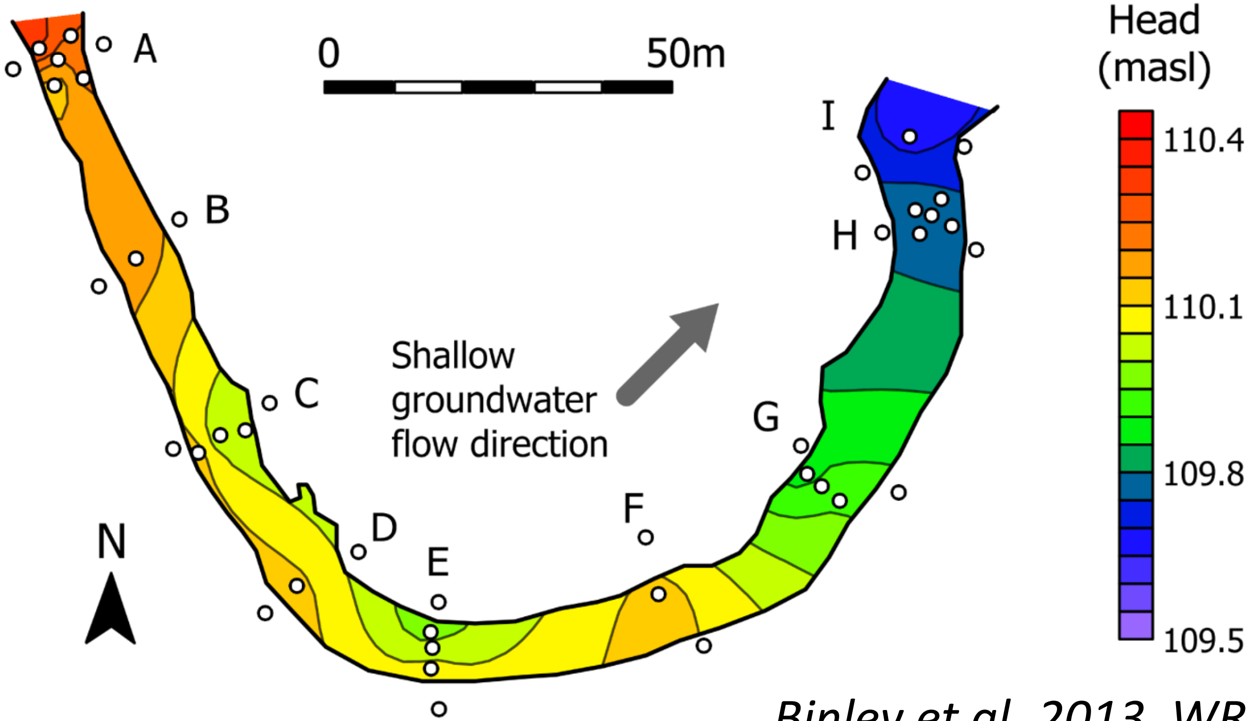


Binley et al.,2013, WRR

Groundwater-surface water interactions



In-stream hydraulic head data reveals transformation from vertical flow to horizontal flow.

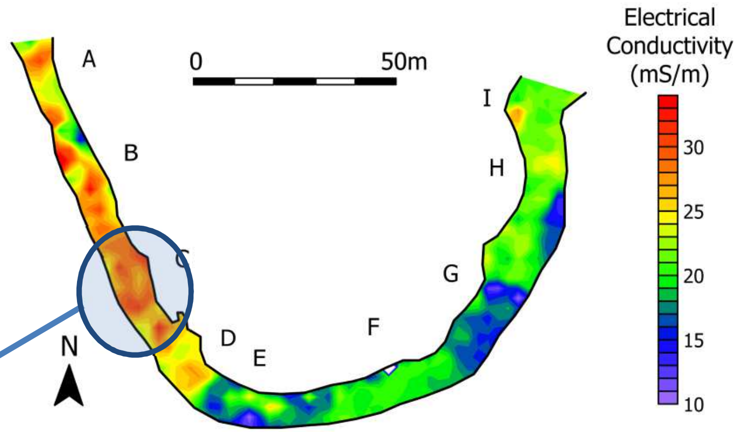


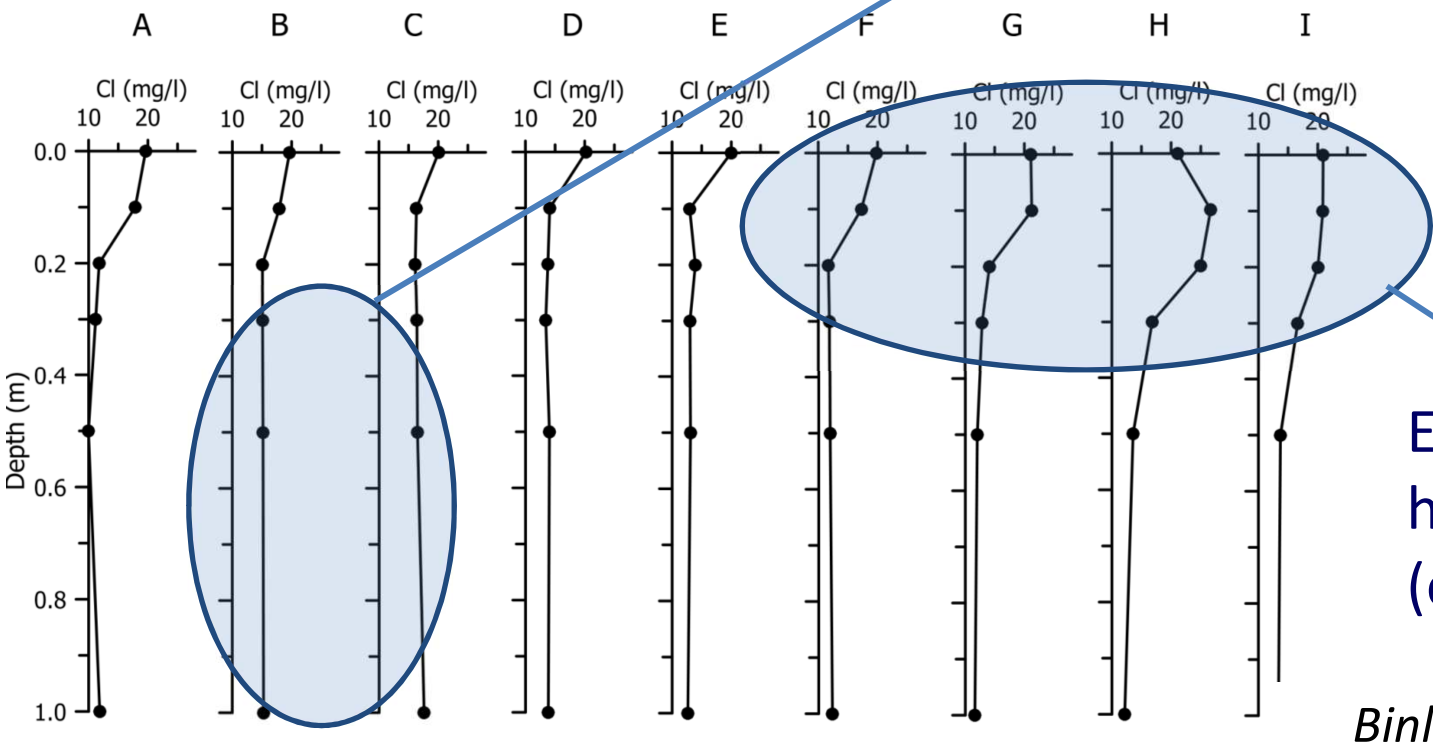
Binley et al.,2013, WRR

Groundwater-surface water interactions

Chloride data from multi-level samplers suggests different groundwater source?

EM conductivity data mirrors chloride response



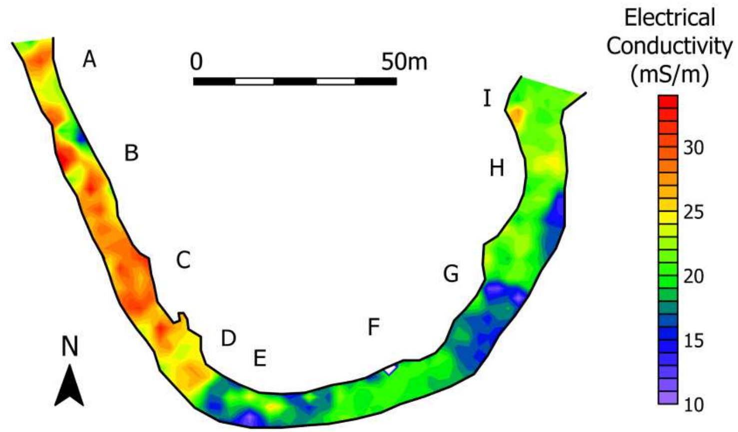


Evidence of horizontal flow (or exchange?)

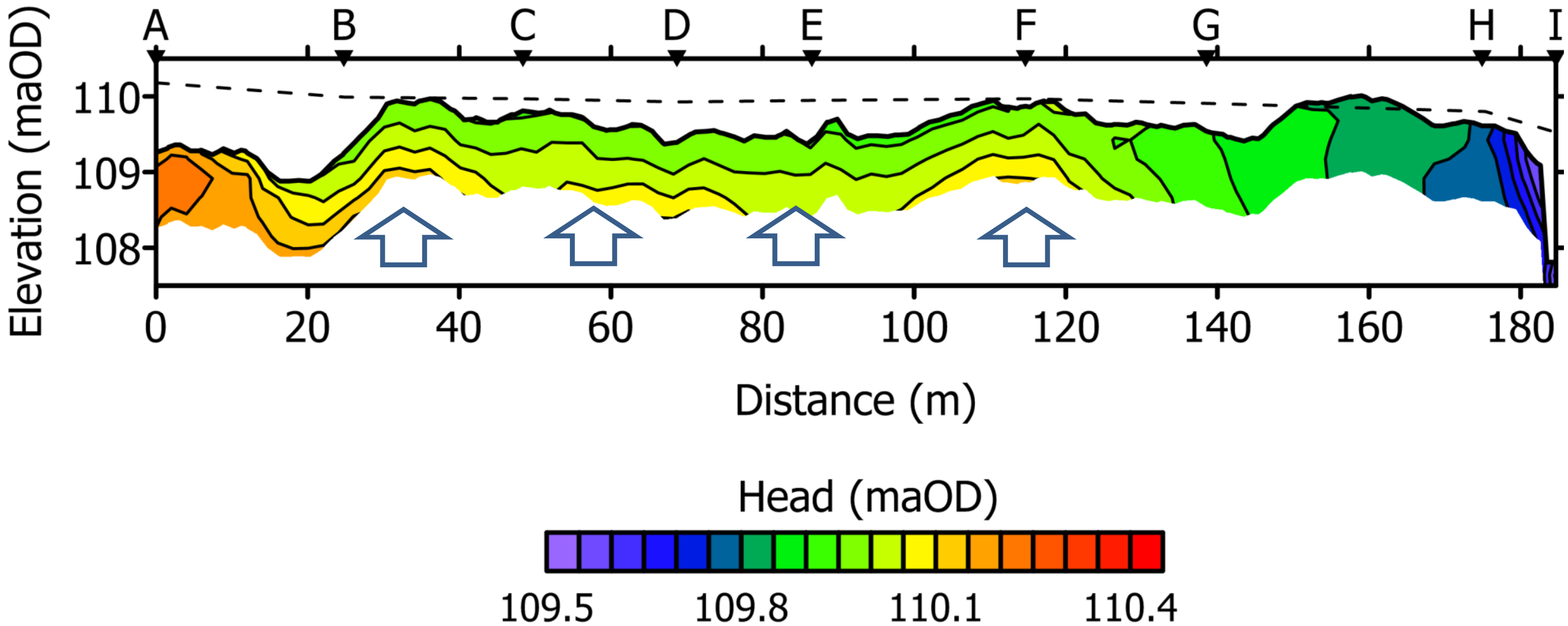
Binley et al.,2013, WRR

Groundwater-surface water interactions

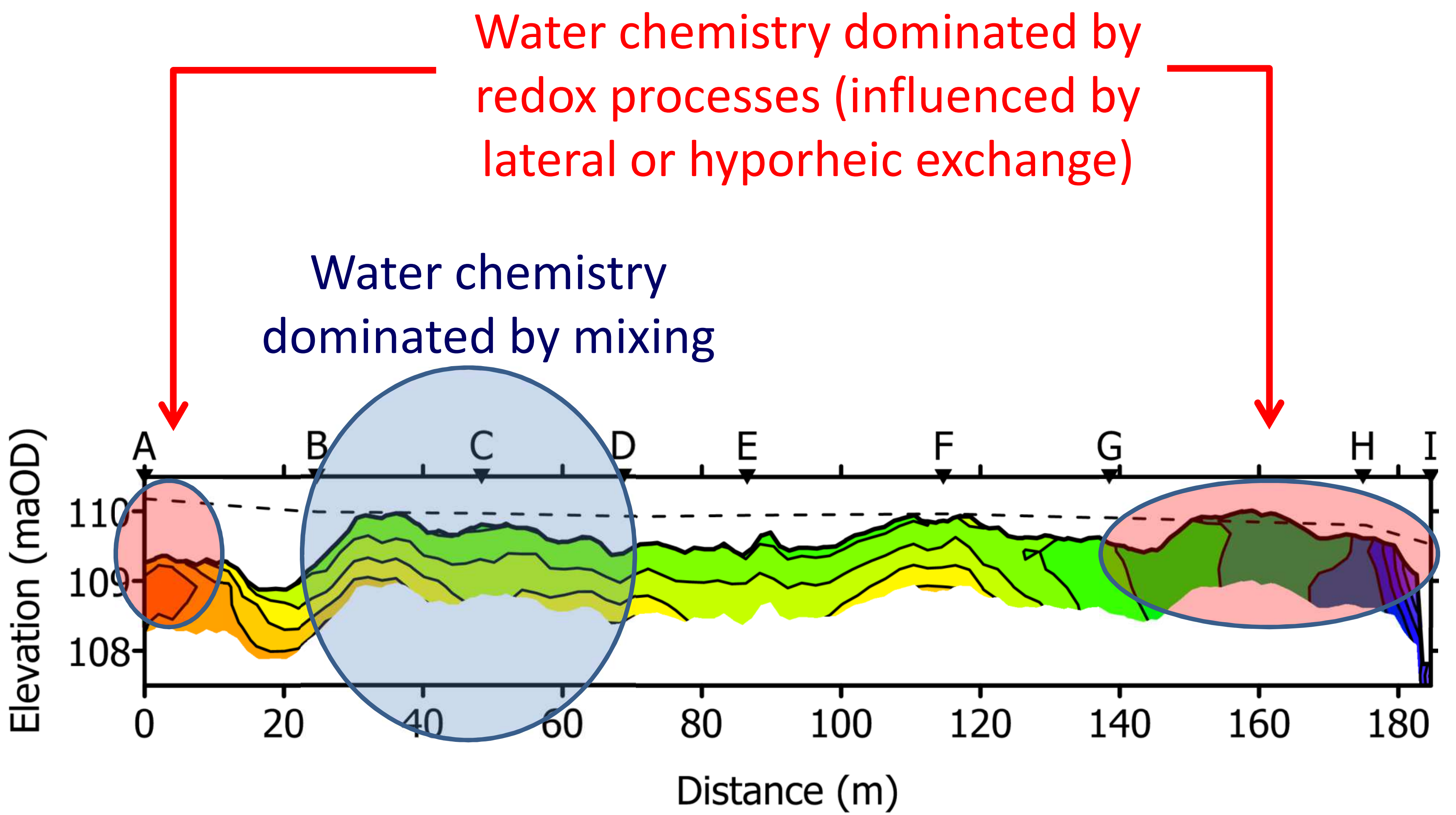
And piezometer head data indicates significant vertical gradients in the upstream section of the reach



Vertical section



Groundwater-surface water interactions



Geophysics played a key part in developing the conceptualisation of the site and helping the targeting of more invasive measurements

Plant-soil-water interactions

We are interested in establishing the value of geophysics for augmenting traditional measurements in order to help plant breeding (in this case phenotyping wheat) and ultimately food security.

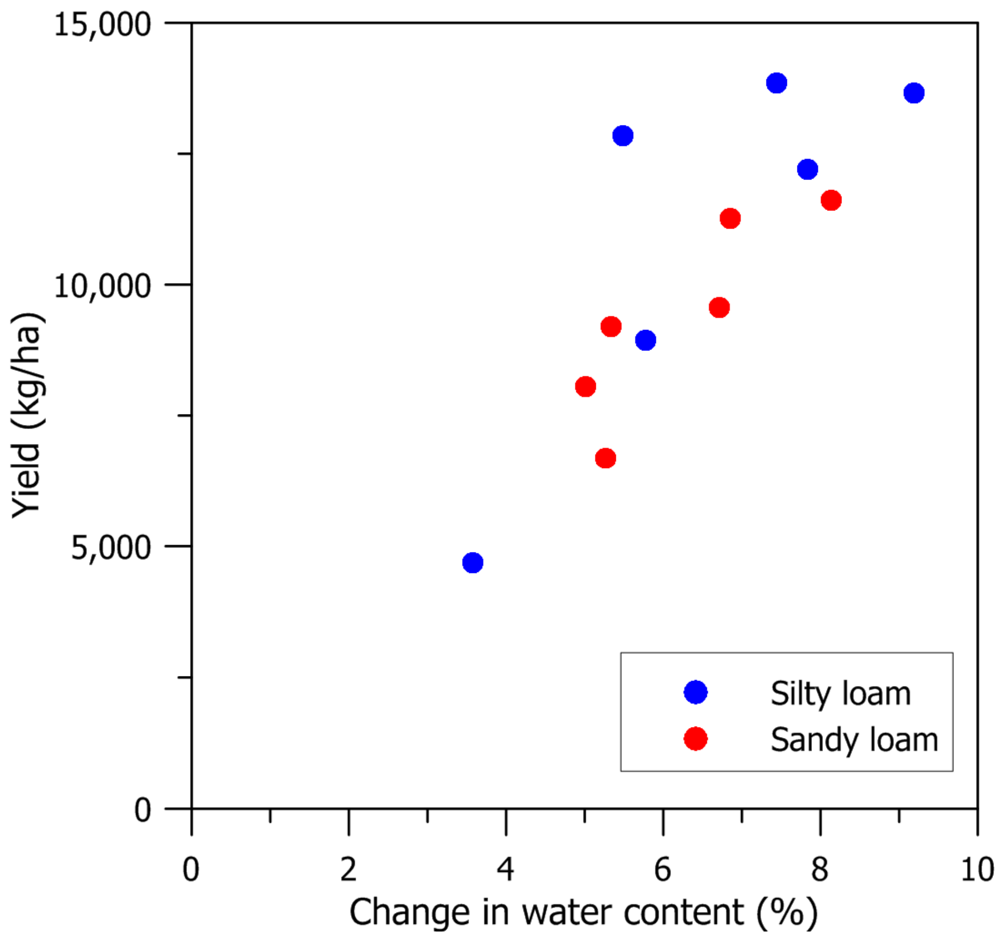
Work described here from UK Biotechnology and Biological Sciences Research Council grant BB/J01950X/1 .

BBSRC bioscience for the future

Plant-soil-water interactions

Assessing water content (and uptake) in soils is important

Wheat grain yield vs water uptake for six wheat varieties in two soils for the 2013 growing season



Plant-soil-water interactions

But most measurement techniques are limited to small support volumes and can be invasive

Plant-soil-water interactions

Electrical conductivity is affected by water content (and several other factors), for example:

Pore water conductivity

particle geometry

Texture/particle size

$$\sigma = \phi^{m} S_{w}^{n} \left(\sigma_{w} + \frac{BQ_{v}}{S} \right)$$

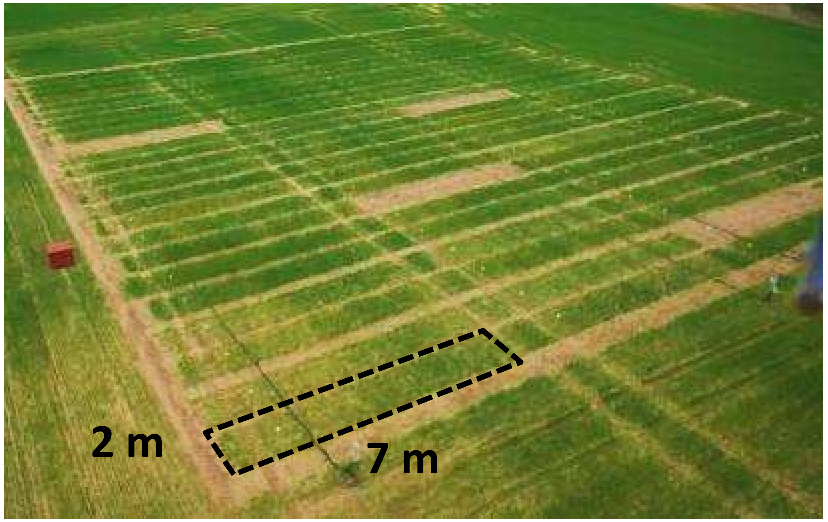
porosity

saturation

Direct estimation of water content may be challenging but **change in electrical conductivity** as a proxy for change in water content may be suitable

Plant-soil-water interactions

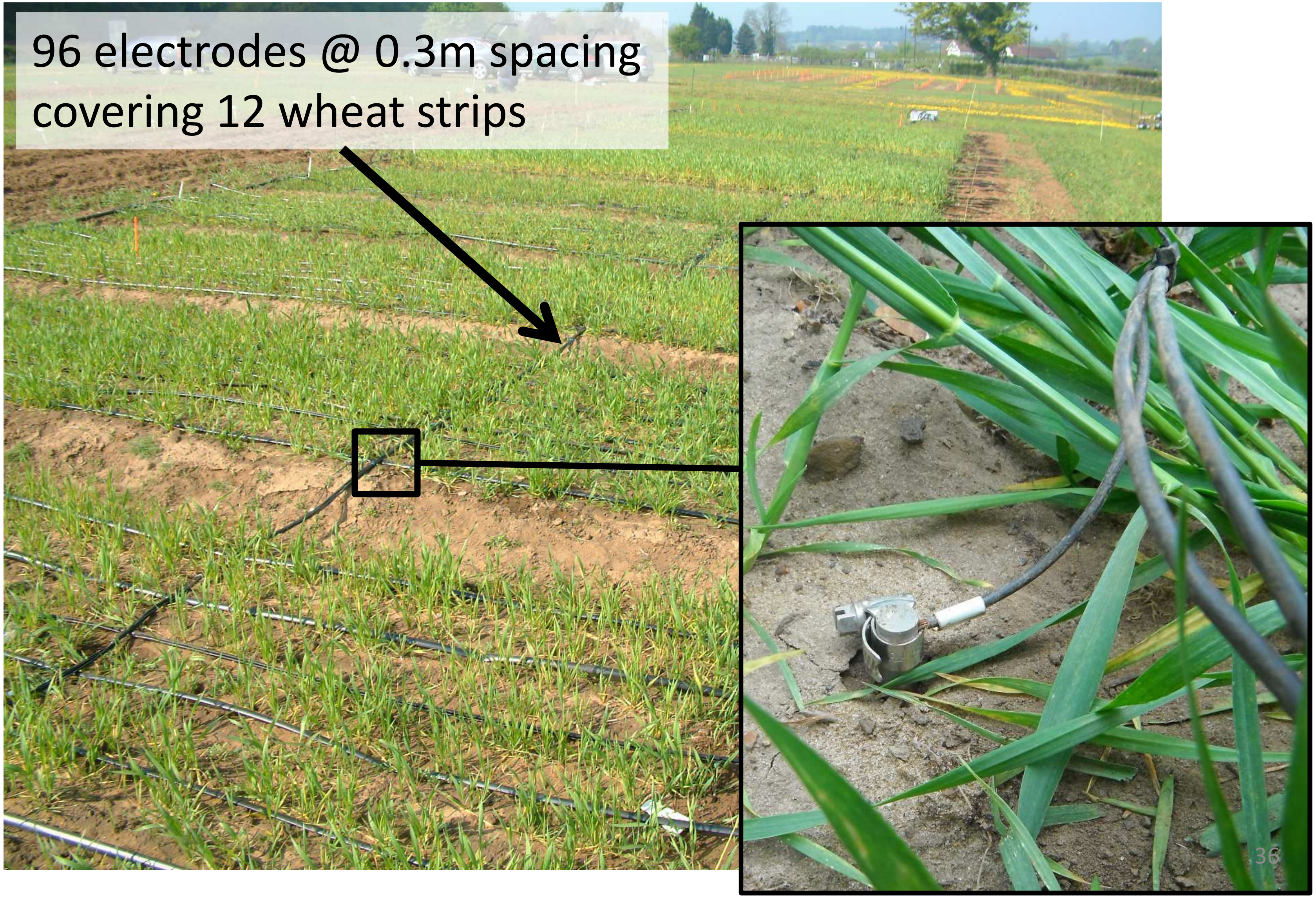
Woburn Experimental Farm



- Mar ‘13 to Aug ’13
- Nov ‘13 to Aug ’14
- Feb ‘15 to Jun ‘15
- Three sites:
  - Butt Close = sandy loam (2013 & 2014)
  - Warren Field = silt-clay loam (2013, 2015 & 2017)
  - Broad Mead = silt-clay loam (2014)
- 24 treatments:
  - 23 winter wheat varieties
  - Control, ‘fallow’
  - **4 replicates in 96 plots**
  - 7 x 2 m plots
  - Random block design

Plant-soil-water interactions

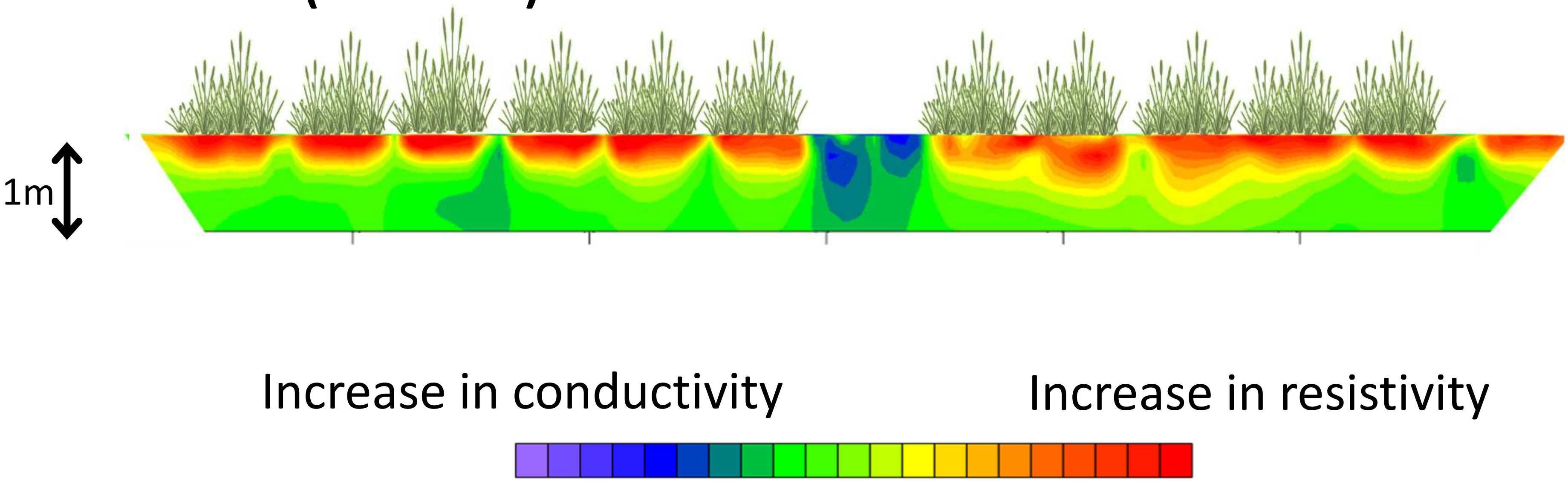
ERT – electrical resistivity tomography



Plant-soil-water interactions

Changes in conductivity over time (2013 season) at the two sites determined from electrical resistivity tomography (ERT)

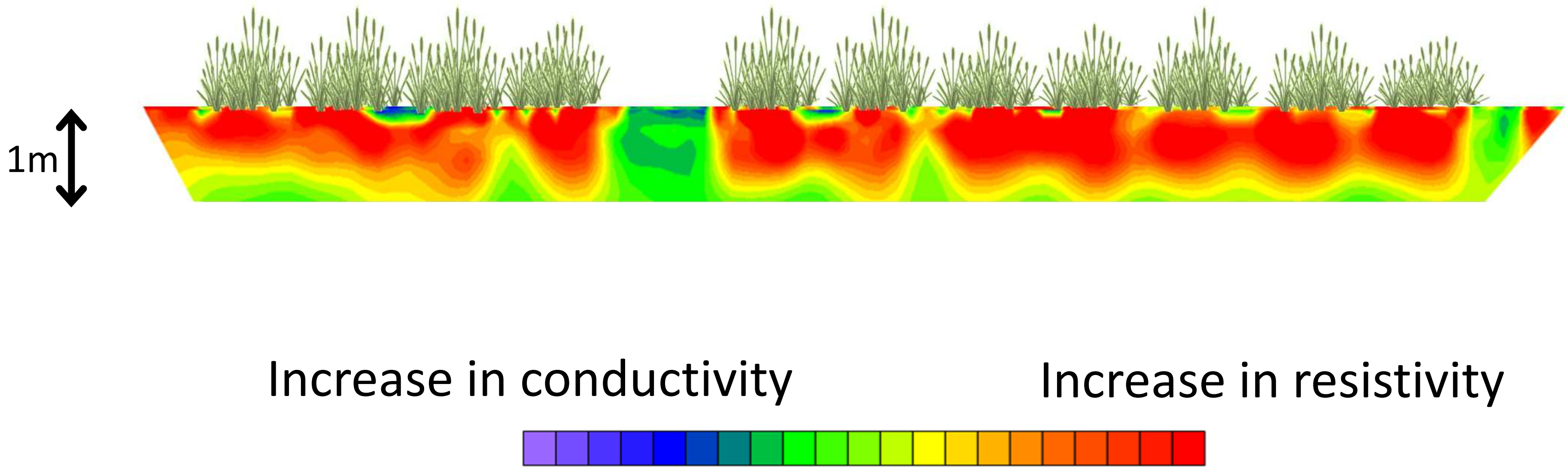
Butt Close (sand rich)



Plant-soil-water interactions

Changes in conductivity over time (2013 season) at the two sites determined from electrical resistivity tomography (ERT)

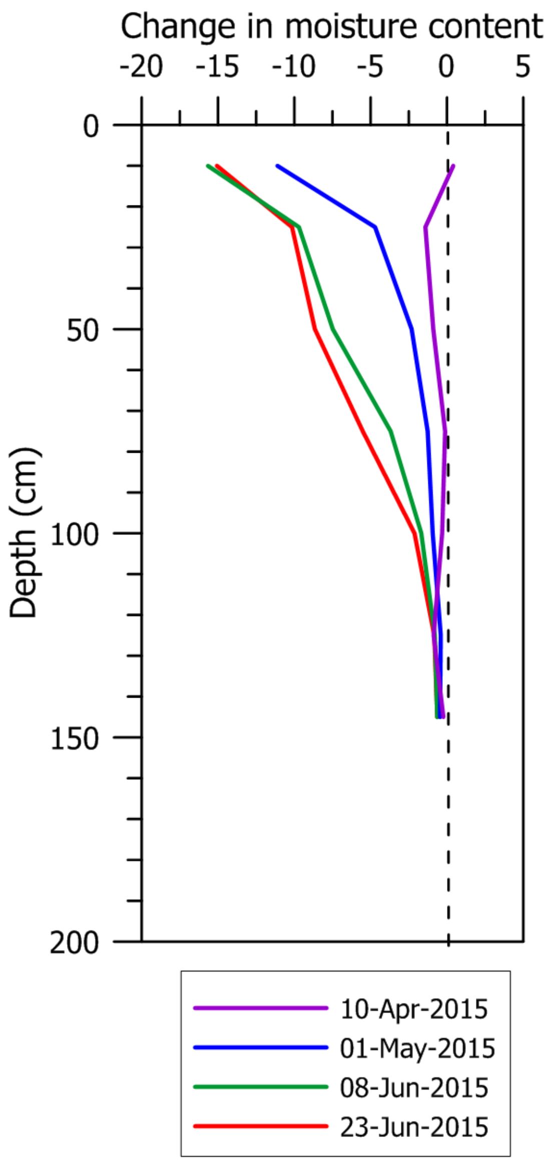
Warren Field (clay rich)



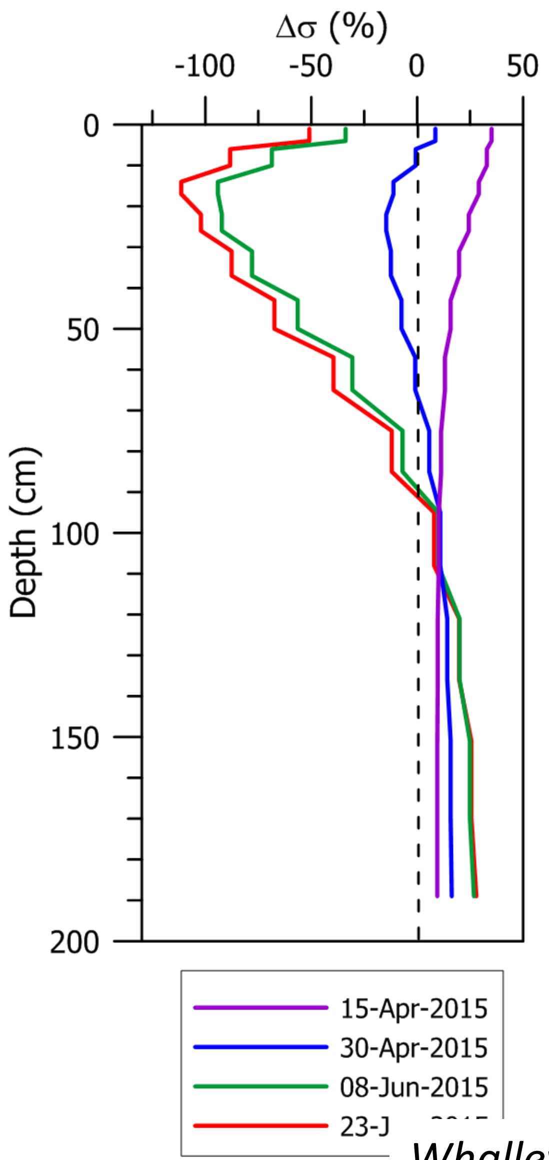
Plant-soil-water interactions

2015

Neutron probe



ERT



Whalley et al., 2017, Plant Soil

Plant-soil-water interactions

There may be scope for coverage of large areas with geophysical methods

(Some) Current challenges

- Credibility across disciplines
- geophysics or geofantasy?
- Moving to a larger scale
- Integration of multiple data types

Improving credibility across disciplines?

Most hydrogeophysical studies lack statistical analysis
- Most are based on n=1 experiments
- Which may be seen as anecdotal in some disciplines
  (can be important for high impact interdisciplinary work)

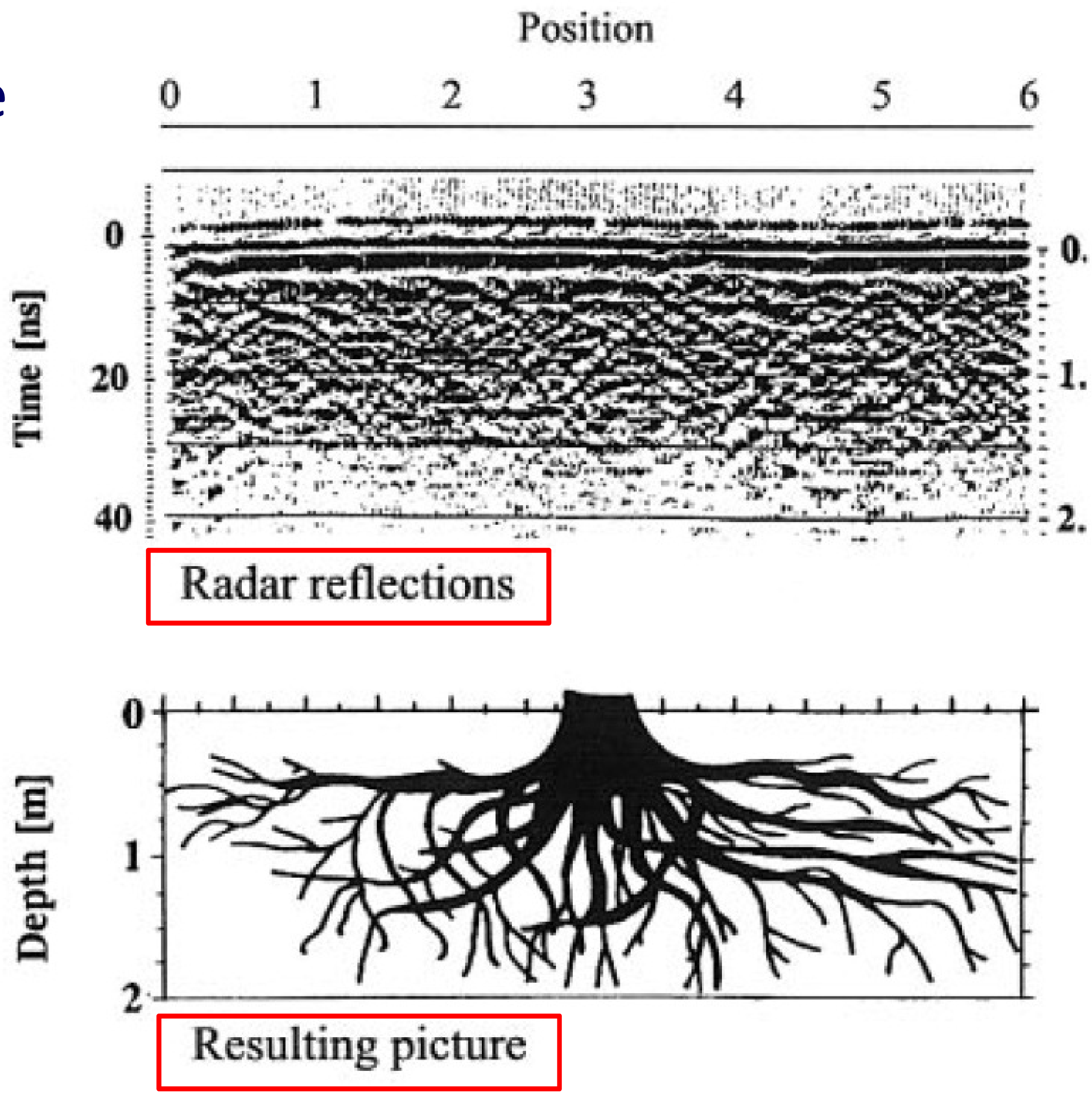
And many ignore quantification of uncertainty

An alternative perspective

"If your experiment needs statistics, you ought to have done a better experiment"
Lord Ernest Rutherford (1871-1937)

Geophysics or geofantasy?

And sometimes the interpretations are a little ambitious?



Nadezhdina & Cermak (2003)

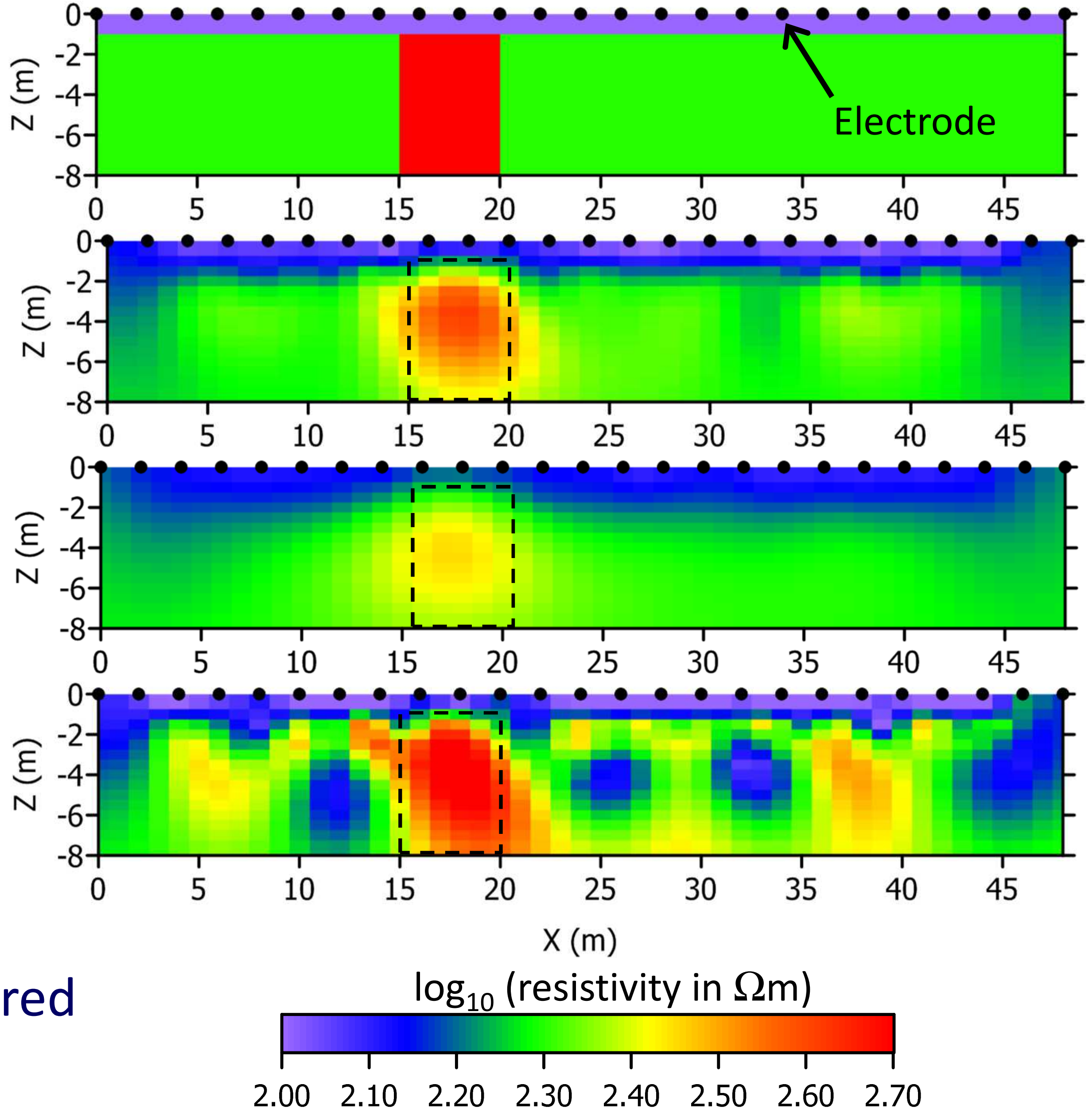
Geophysics or geofantasy?

Synthetic model
(add 5% noise and invert)

Correct noise
Assume 5% noise

The pessimist
Assume 10% noise

The optimist
Assume 2% noise



This could be an even bigger problem in fractured rock applications

Moving to a larger scale

There are numerous examples of geophysical studies of relatively small plot experiments.

But many of the hydrological challenges are at a larger scale

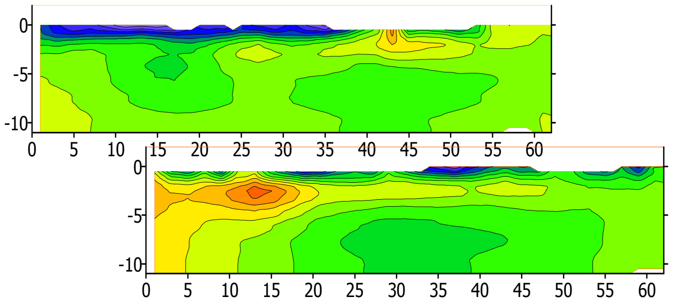
Moving to a larger scale

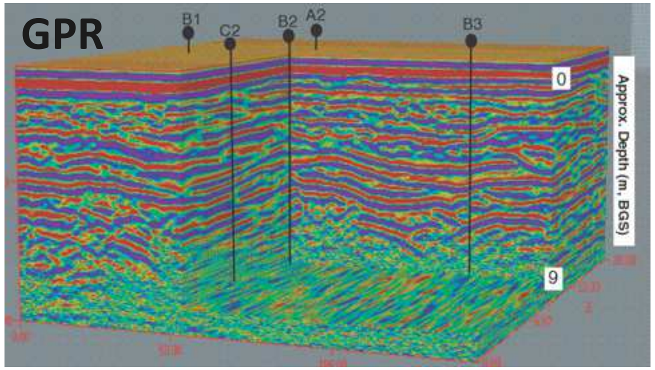
There has been a growth in interest in manned airborne geophysics for hydrological studies, although costs will remain high.

Recent developments in drone technology looks promising

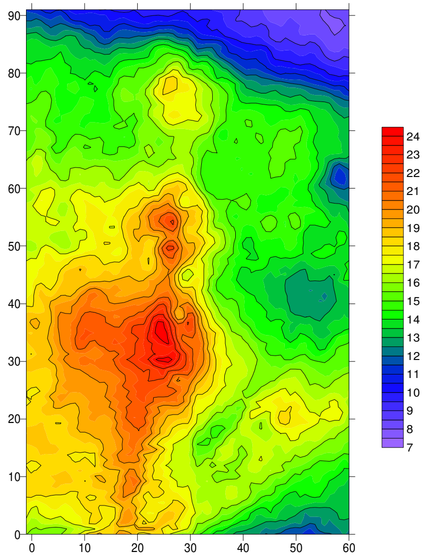
Larger scale integration – data fusion

Resistivity & Induced Polarisation



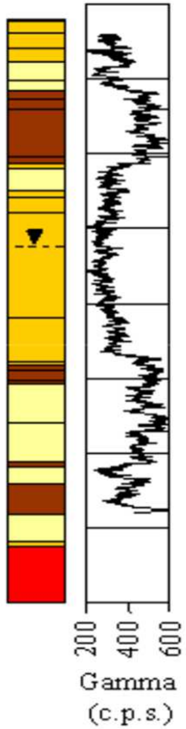


Ground Conductivity



Local sampling and geology

Borehole logs



How do we bring all these data together to form one consistent, improved model of the system?

Summary

- We’ve made significant advances in hydrogeophysics over the past 25 years. Geophysics is now widely integrated into many hydrological programs. Many opportunities in agriculture exist.
- Mapping boundaries of ‘features’ is still a very effective use of geophysics, particularly as we move to larger scale application. (rock physics still important).
- Some statistical rigour in experimental design and analysis of results may also help with future impact, particularly across disciplines.
- We should attempt, where possible to illustrate some measure of uncertainty in our geophysical results.
- In some areas of application we need to move away from plot experiments and develop large scale investigative approaches.


A positive outlook