Estimating amount and spatial distribution of artificial groundwater infiltration in a highly complex environment based on different tracers

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Motivation

Artificial Groundwater Recharge

- **Artificial groundwater recharge** is typically used to achieve
  - Sufficient water supply
  - Protect drinking water production sites

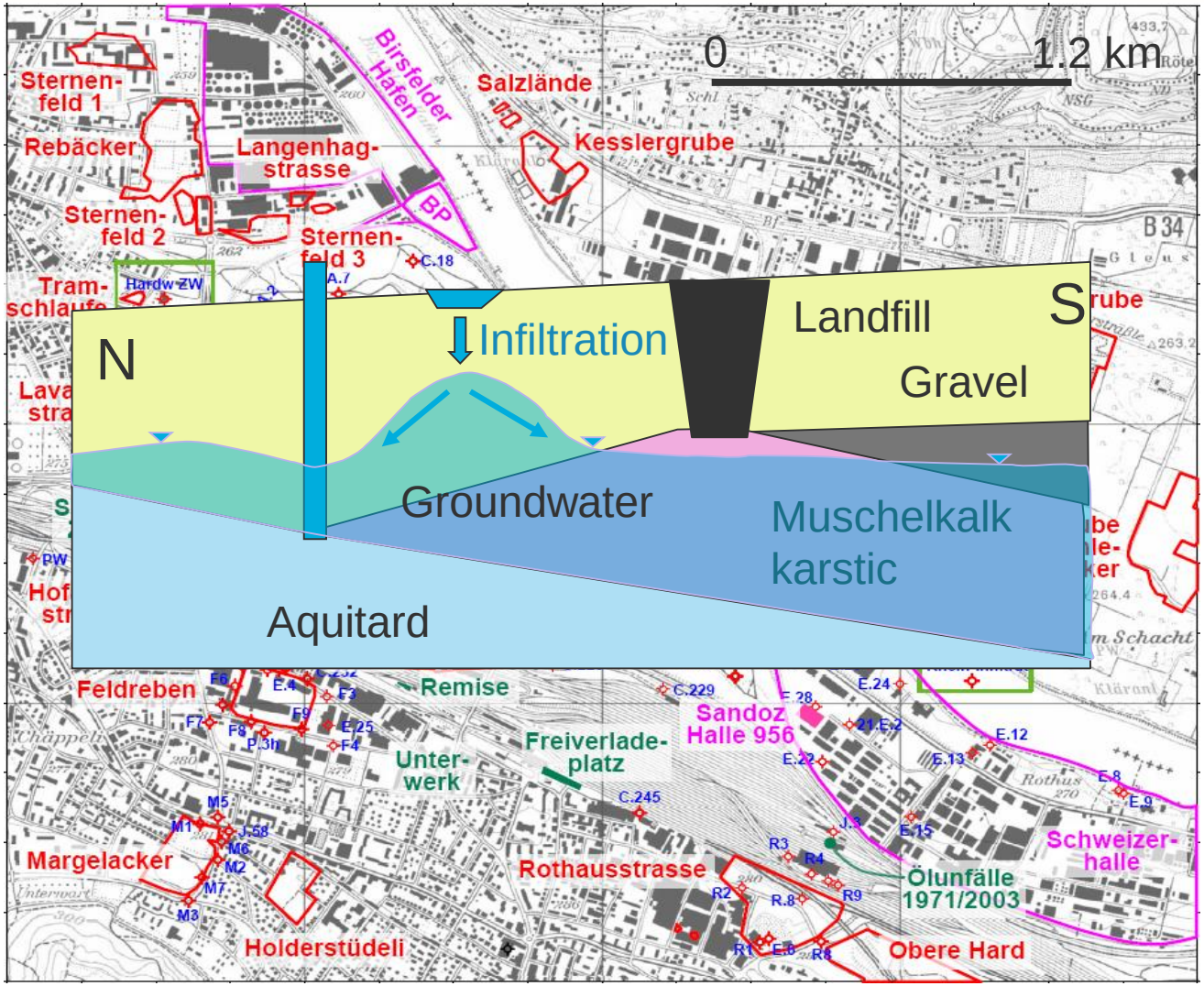
- Sustainable groundwater management requires knowledge about…
  - **residence times**
  - **flow paths**
  - **involved processes** e.g. **mixing** of different water types

- **Multiple tracers** are used to gain information about subsurface processes
  - Dye and heat tracers
  - Anorganic hydrochemistry
  - Persistent artificial sweeteners (e.g. Acesulfame)
  - Stable water isotopes (^{18}O und ^{2}H)
  - Tritium ages
  - On-sites measured dissolved noble gases (e.g. He, Kr, Ar, etc.)
  - Organic micropollutants

Study Area

Urban area

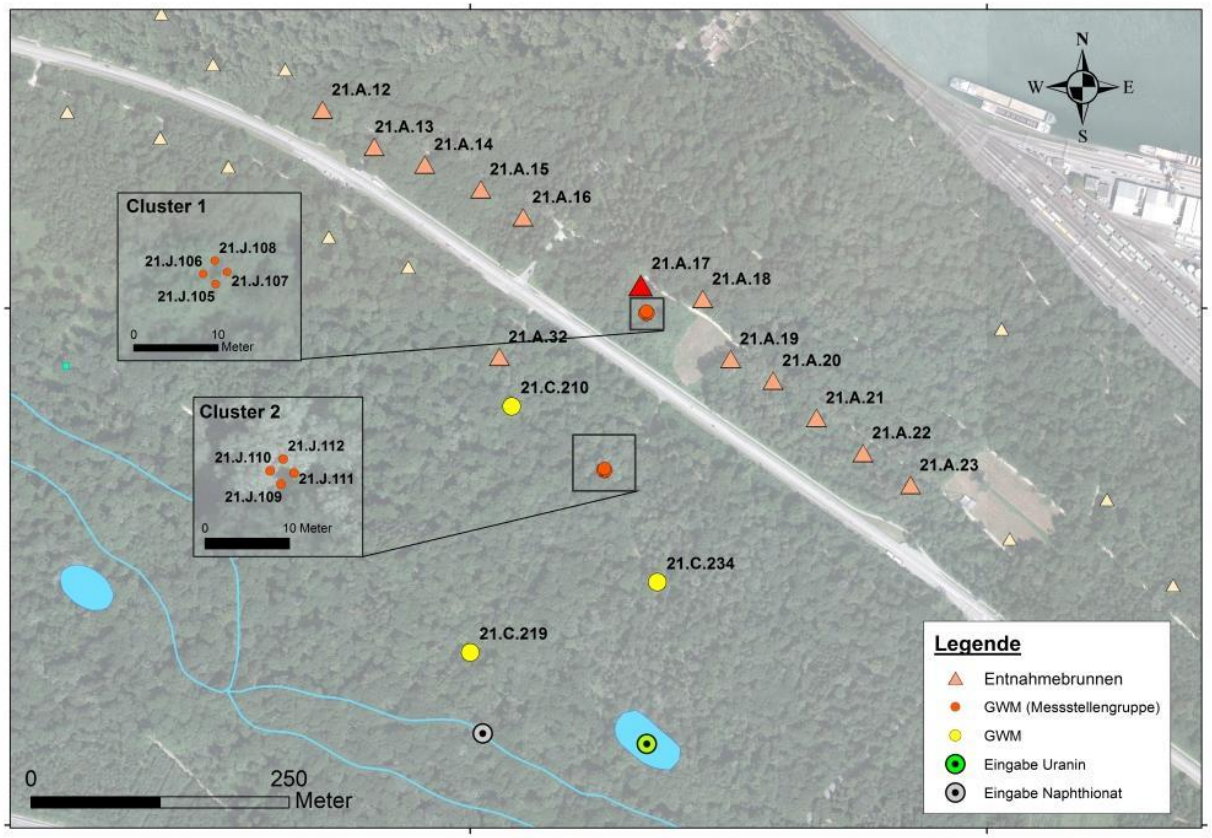
- Important water supply infrastructure
- Drinking water supply combined with artificial infiltration
  - Artificial Infiltration 90.000 ($m^3\ d^{-1}$)
  - Pumping rates 40.000 ($m^3\ d^{-1}$)
- Study Site History
  - Changing boundary conditions
  - Contaminated areas
  - Potential risk for drinking water
- Goal: Avoiding non-infiltration water

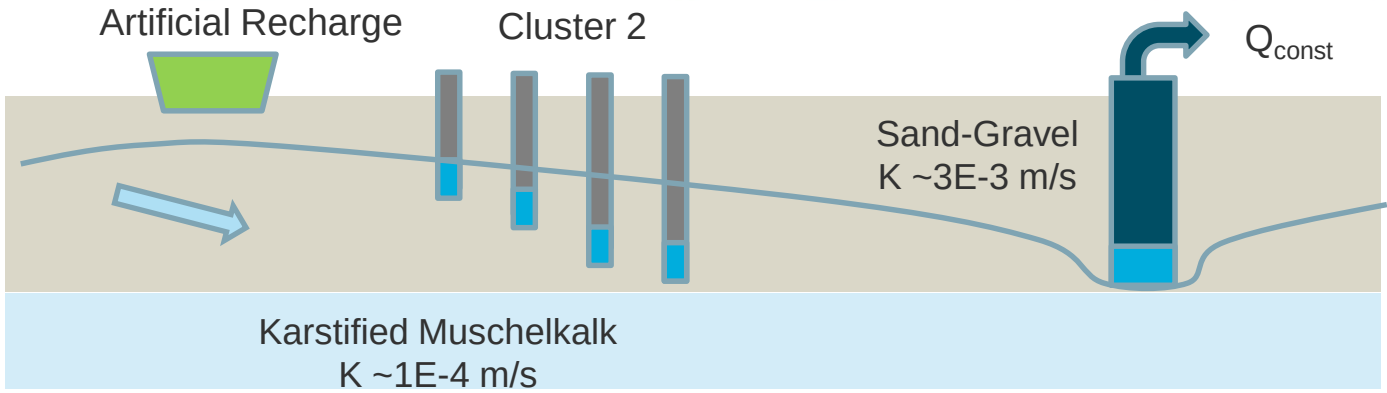


Pumping experiment

Framework

- 21.A.17 constant pumping rate (3 weeks)
- Switch off of wells in the direct vicinity (21.A.16, 21.A.18, 21.A.19 & 21.A.32
- Drilling of 2 nested (cluster) piezometers → Cluster 1 and Cluster 2 covering the whole sand gravel aquifer
- Dye tracer injection & data sampling

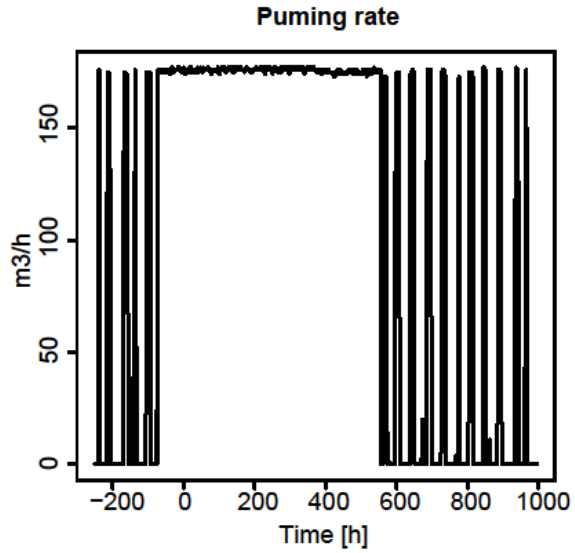


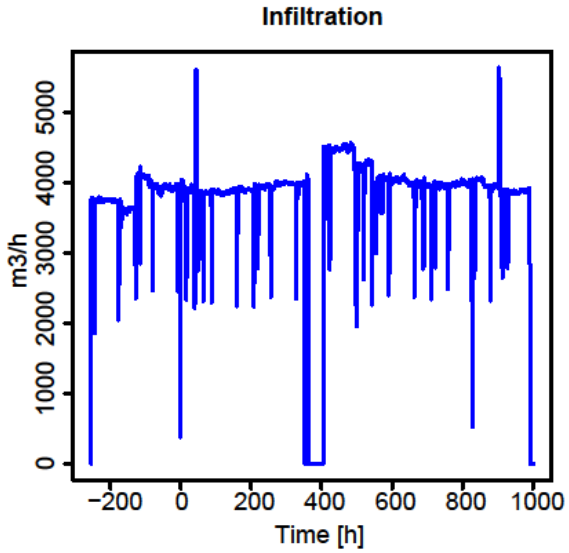


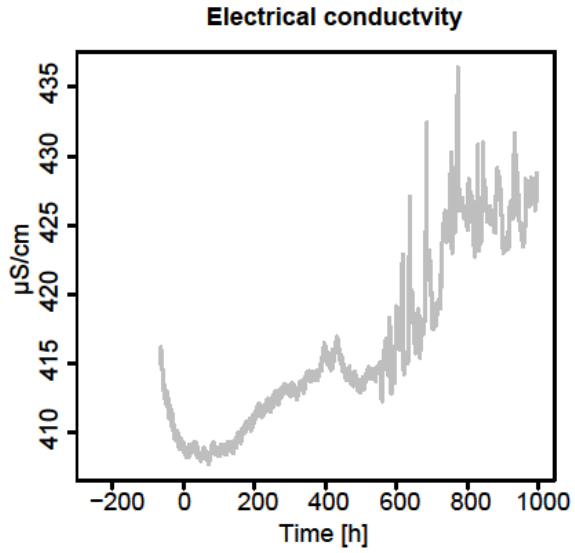
Fluxes and Rates

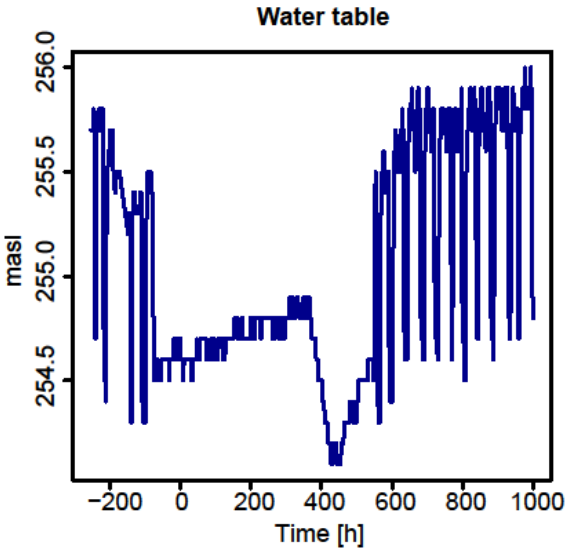
Pumping test stages

- **Pre-Condition**
  - Variable pumping
  - Const. infiltration
- **During pumping test**
  - Const. BC
- **Infiltration stop**
  - Const. pumping
  - Stop infiltration (42 h)









Residence times and flow paths

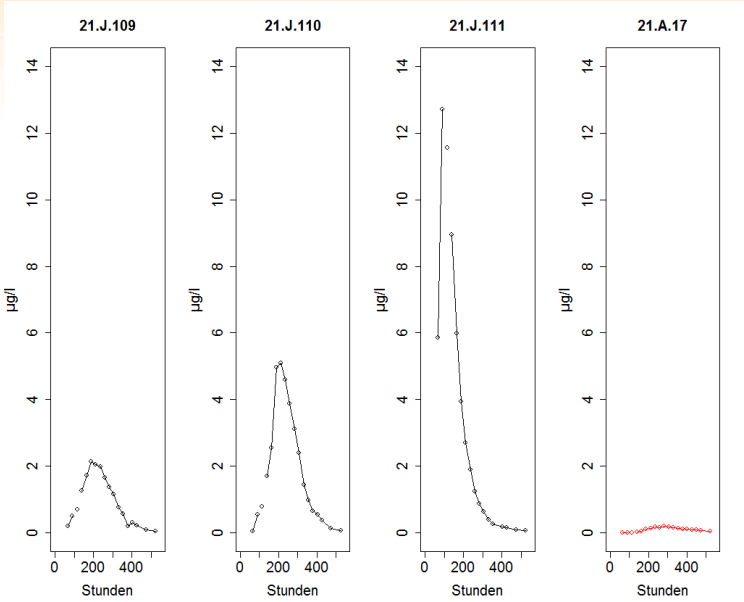
Dye and Heat Tracers

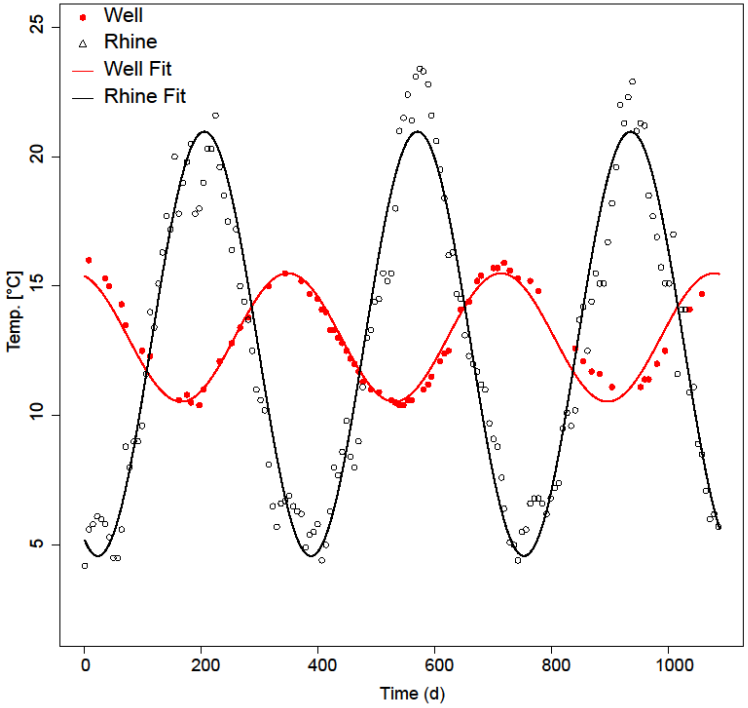
- Residence time from infiltration to pumping well
- **Dye Tracer**
  - Model TRAC for fitting

    First arrival 7 days

    Peak maximum **28** days
- **Heat**
  - Time shift approach (Hoehn and Cirpka, 2006)
  - $R_T = \frac{n_e \rho_w C_w + (1-n_e)\rho_s C_s}{n_e \rho_w C_w}$

    Peak maximum **32** days

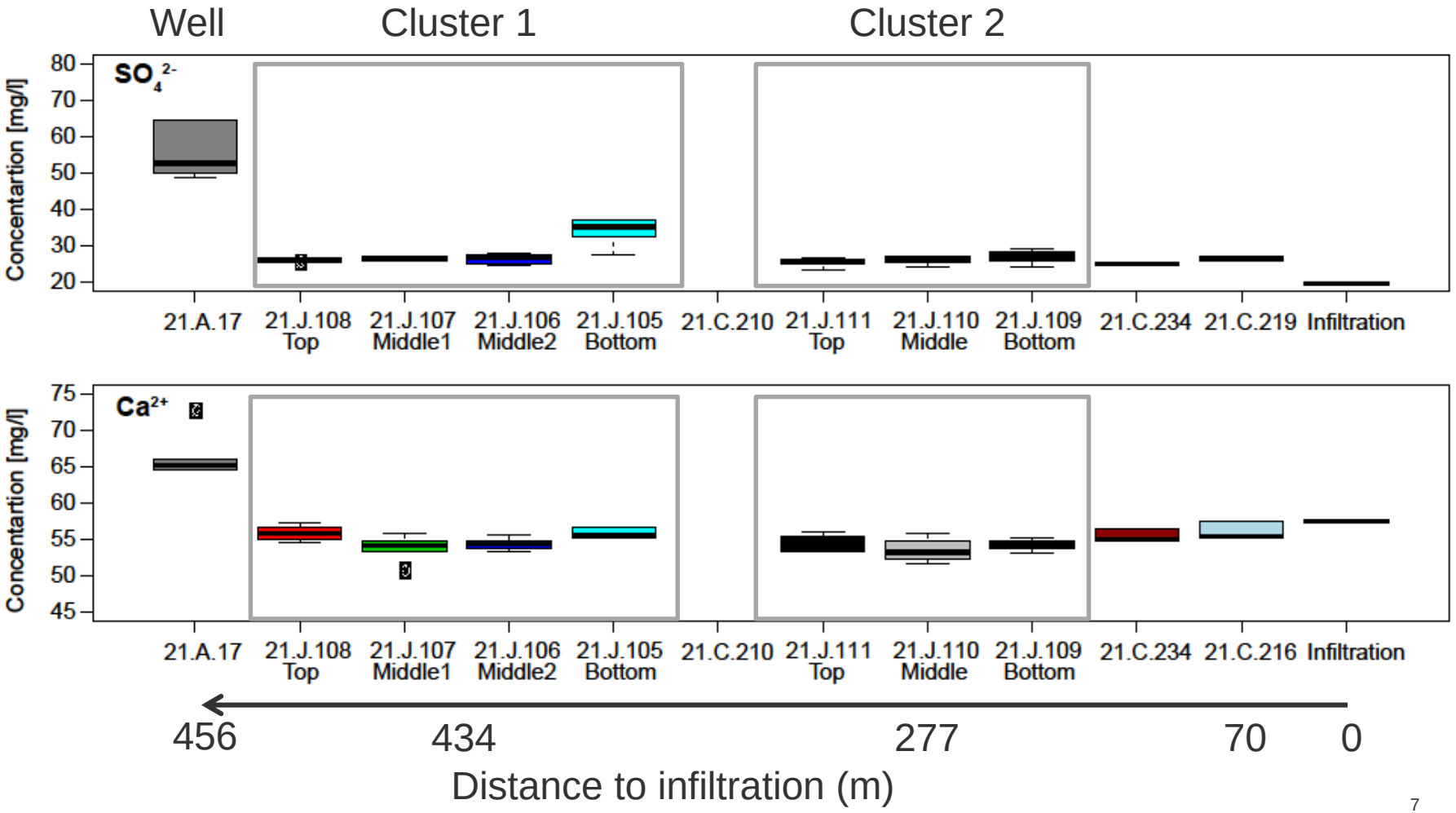




Hydrochemistry classification

Cat- and Anions

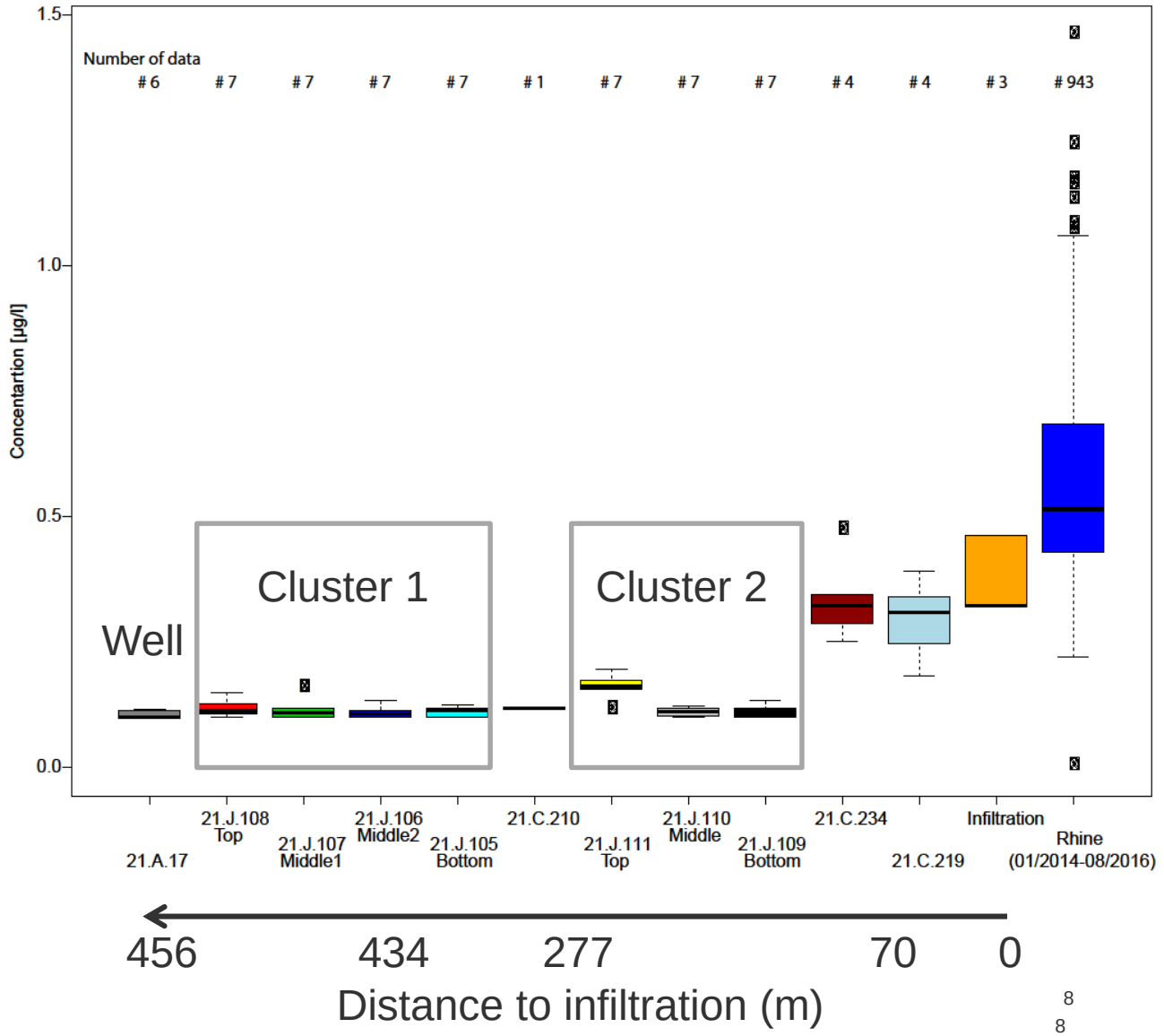
- Different cat- and anion concentration at pumping well



Mixing

Artificial Sweetener: Acesulfame

- Persistent conservative behaviour
- Higher concertation in surface water
- Decreasing trend with increasing distance to infiltration
- Indicating mixing of at least two different water types



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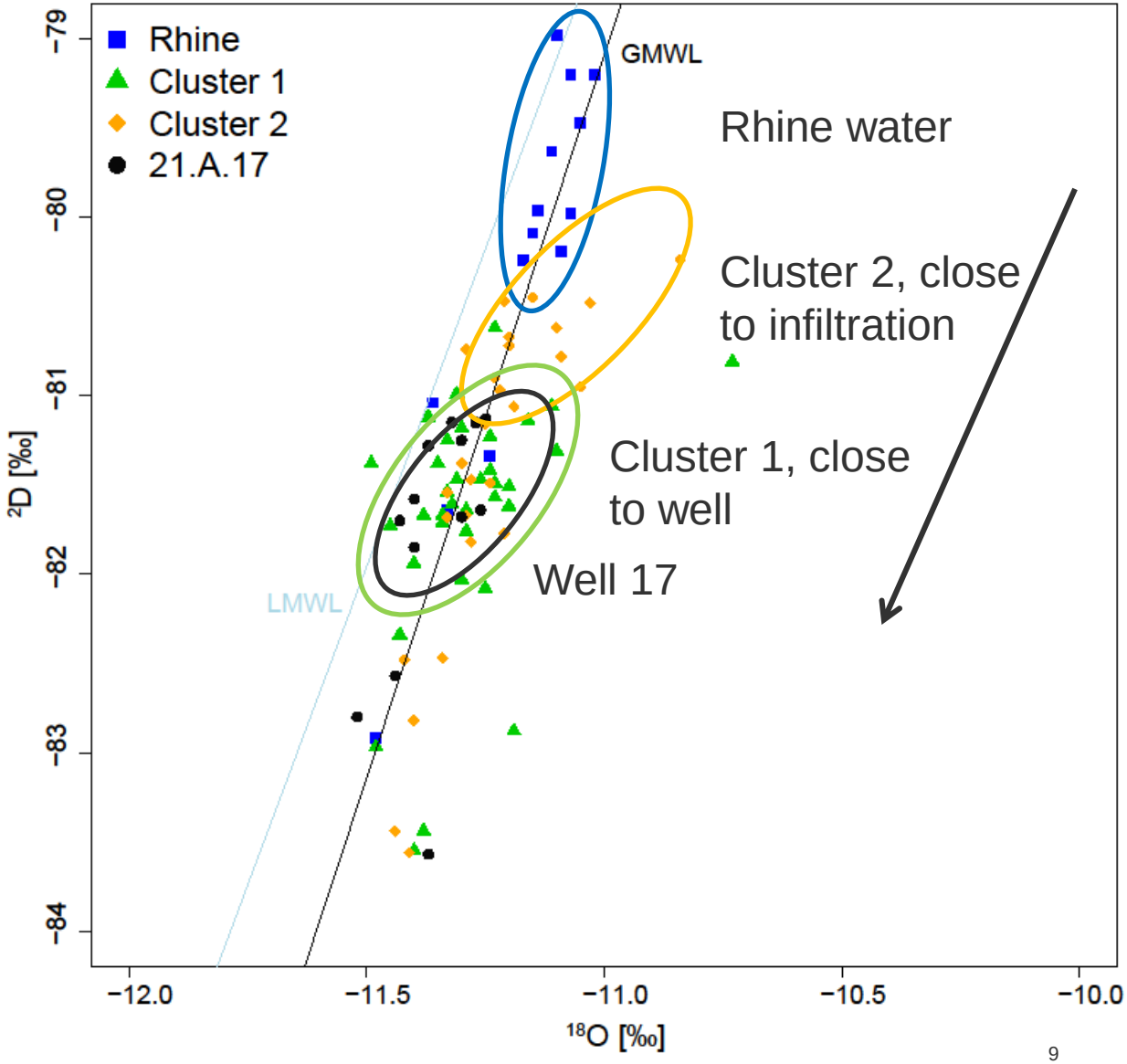
Mixing

Stable water isotopes (^{18}O und ^{2}H)

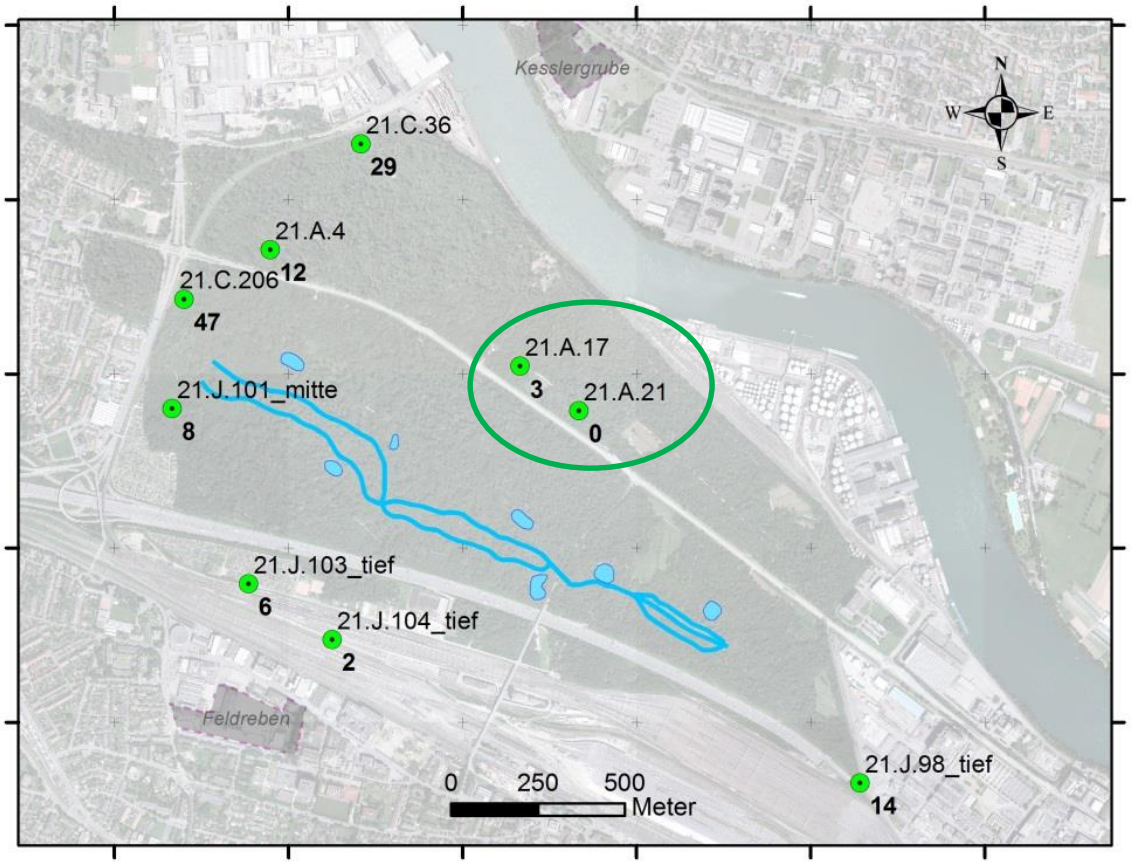
- Trend in isotope signature
- Change from infiltrated water to pumping water
- Indicating mixing of at least two different water types



Water Age

Tritium samples

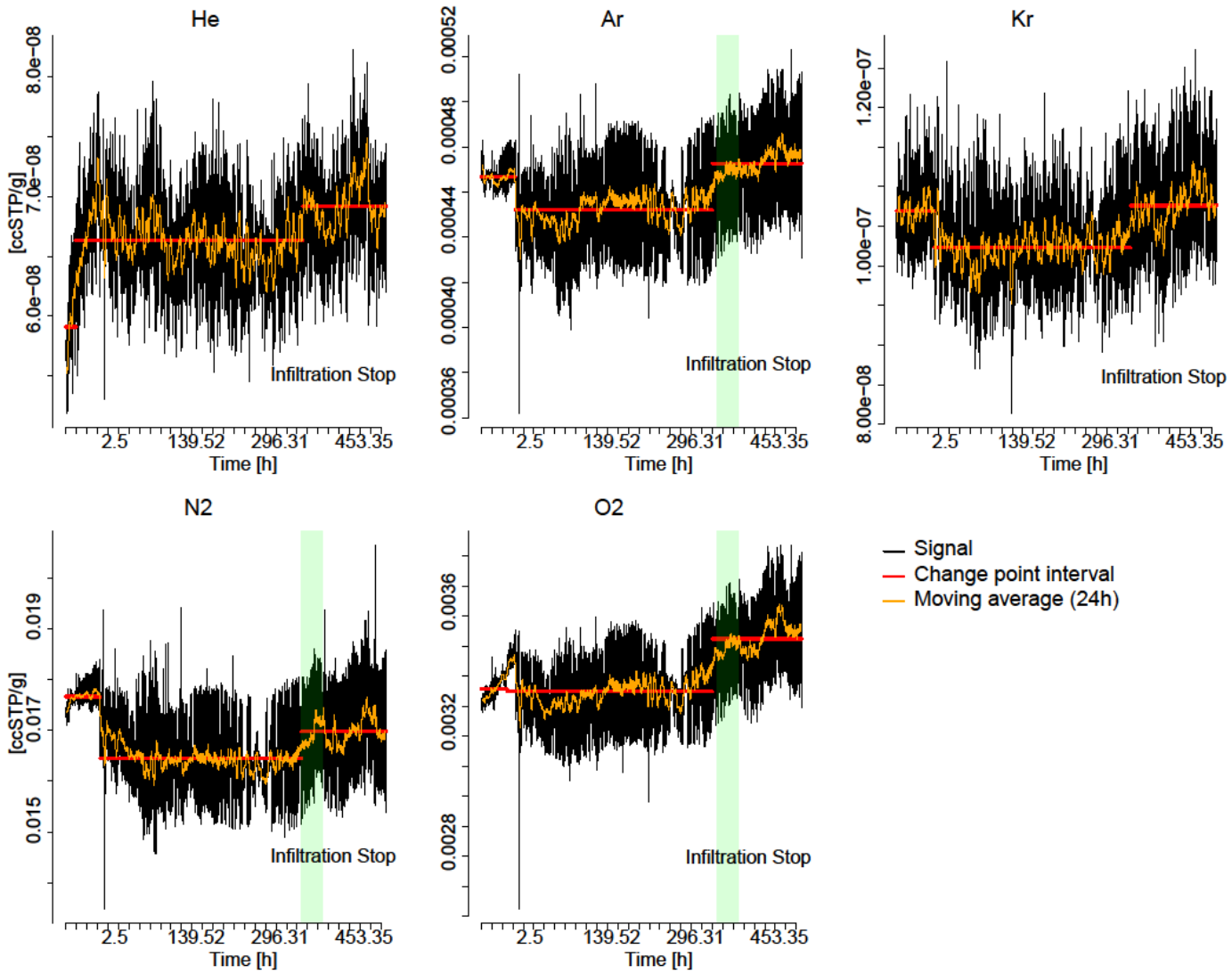
- Dissolved gas samples
- Western border oldest water (12-47 a)
- In areas where artificial infiltration is less pronounced larger ages
- Pumping wells (21.A.17 & 21.A.21) show differences although the distance between them is less than 150 m



Sensitivity to changing boundary conditions

Time series of dissolved gases concentrations

- On-site stand-alone system based on a membrane inlet mass spectrometer (MIMS)
- Time resolution 6 min
- Change-point analysis
- Detection of three stages related to boundary changes

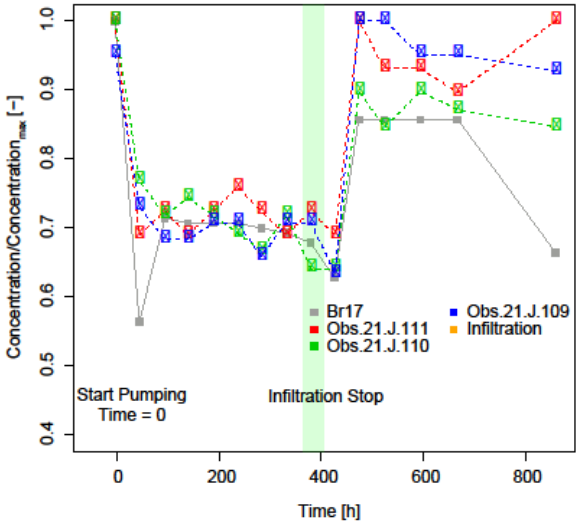


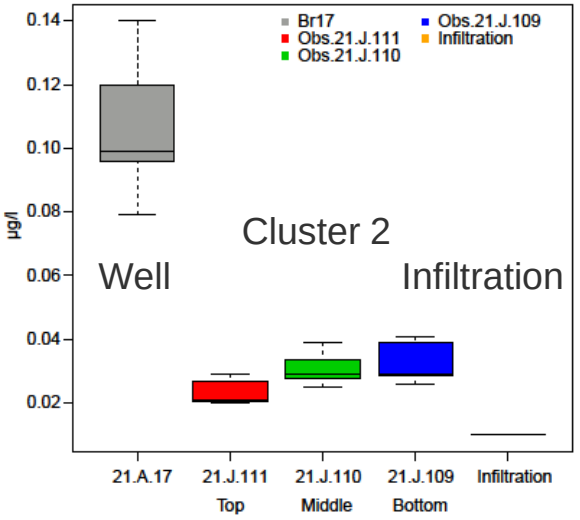
Changing boundary conditions & contaminates

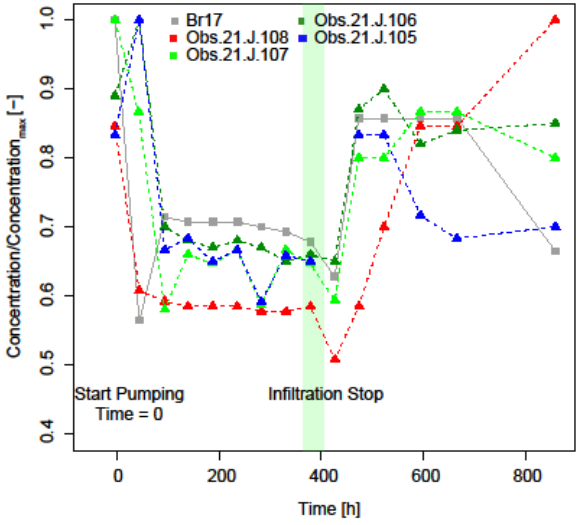
Organic micropollutions

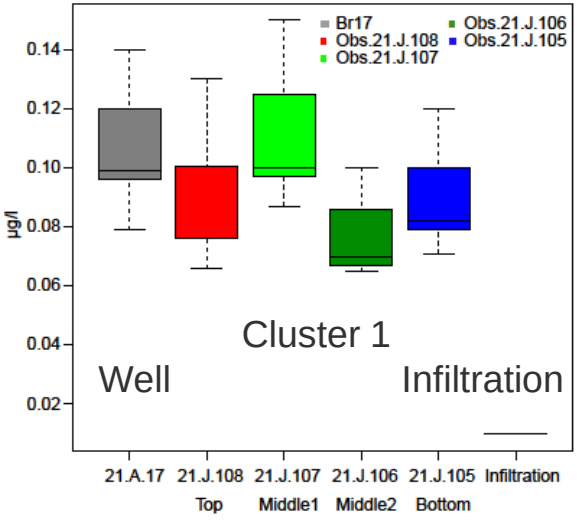
- Tetrachloroethylene (PCE)
- Density PCE > Density water
- Three stages can be identified for well and clusters
- Concentrations higher than in surface water

PCE









Summary and Conclusions

- Estimated residence times based on dye and heat tracers were comparable
- Artificial recharge is spatially variable along the transect
- Pumping well water contains not only artificial infiltrated surface water → Mixing
- Changing boundary conditions have a strong impact on mixing ratios and contaminant concentrations
- High temporal resolution data were required to observe system sensitivity to changing boundary conditions

Gained information about residence time and process understanding from multiple tracers offered more insight than from a single tracer test

Thank you for your attention