- Hot moments in cold spots - Multi-scale tracing of reactivity hotspots in hyporheic environments

Stefan Krause

T. Blume, D.M Hannah, L. Angermann, E. Naden, N.J. Cassidy, A. Binley, M. Munz, C. Tecklenburg

Research Institute for the Environment, Physical Sciences & Applied Mathematics

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Research Focus: Aquifer-River Interfaces

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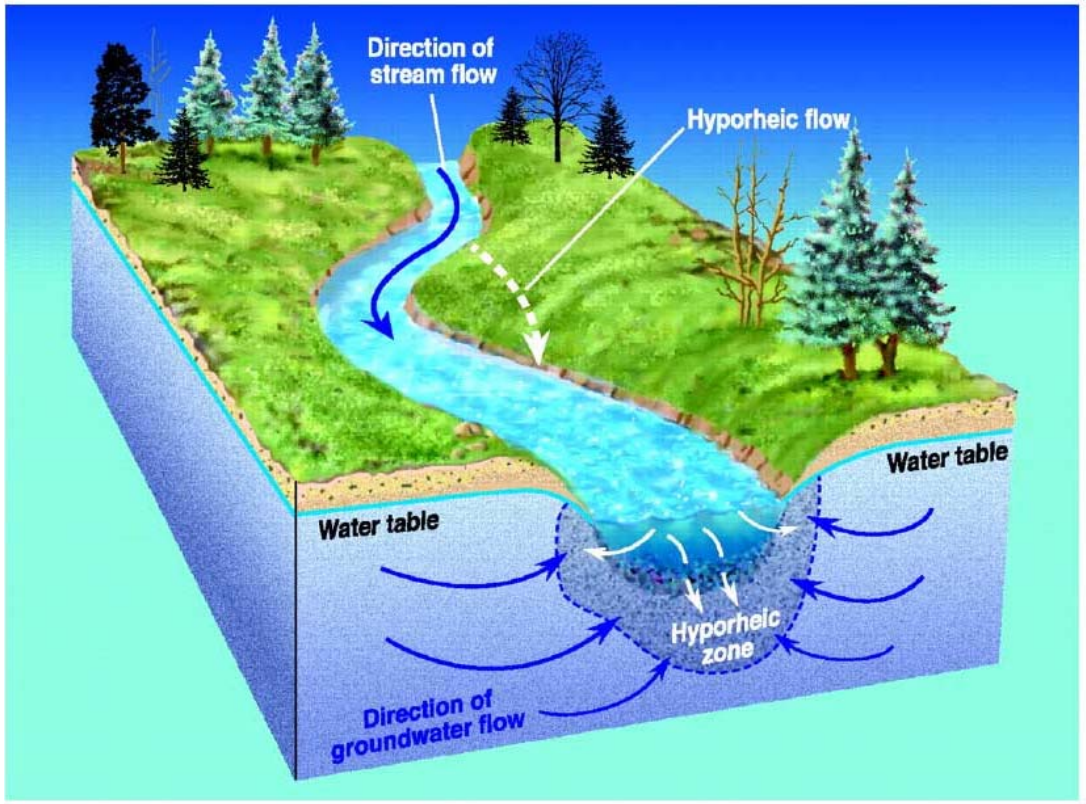
Hyporheic attenuation potential



© USGS

GW + SW Contamination risk

Reactive transport and feedback mechanisms

Motivation: A Nitrate Time Bomb?

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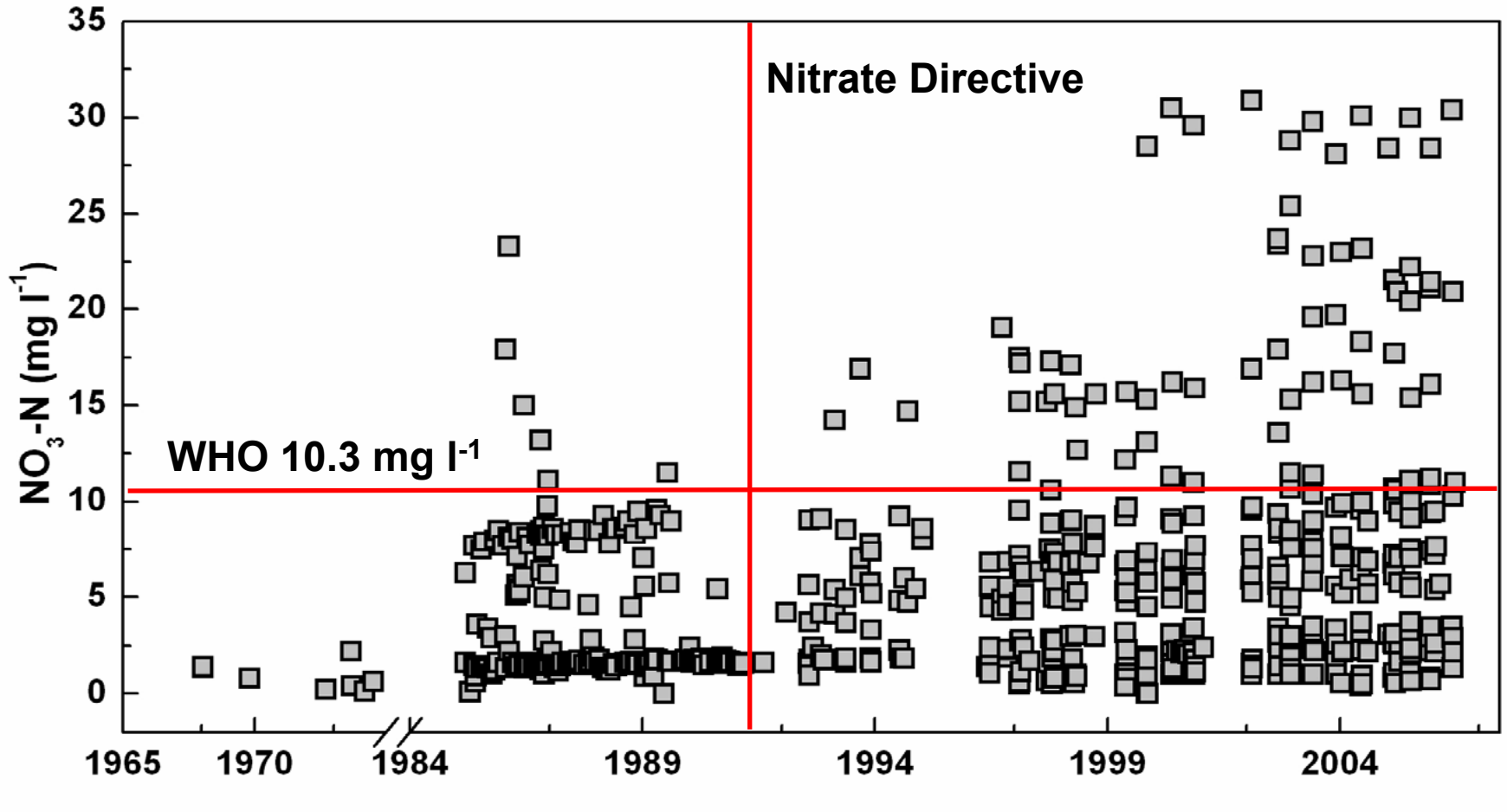
Nitrate concentration in 40 GW-boreholes Cumbria/UK (1972 - 2007)



GW concentrations increasing albeit reduced inputs

Identification of HZ attenuation potential

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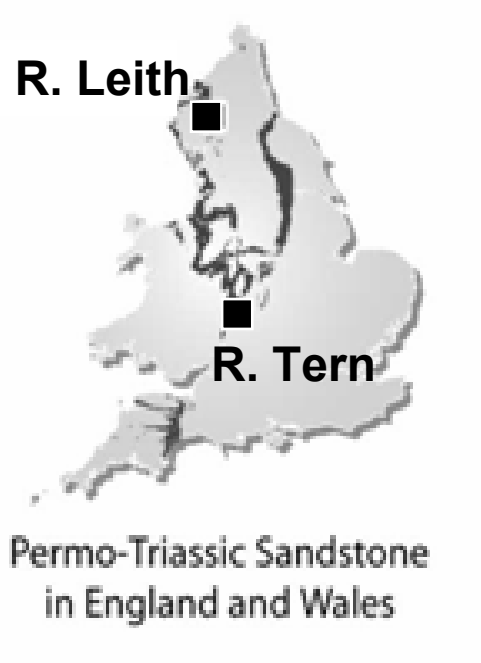
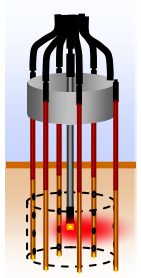
Hyporhceic process dynamics in upland and lowland rivers

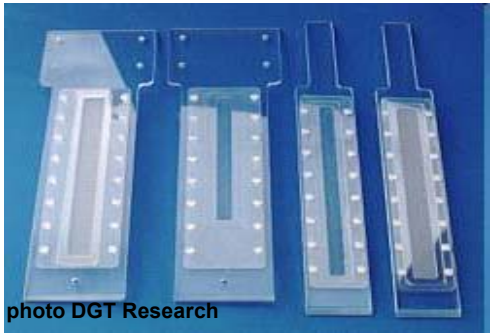


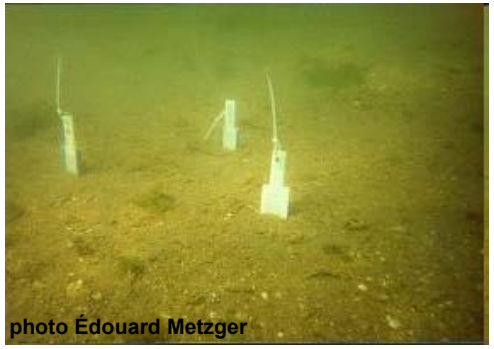
- geophysical underground exploration (ERT, GPR)
- Multiple tracers
- Nested multi-level piezometers, Diffuse gel-samplers
- Multi-component reactive transport (TCE, NO_3, NH_4, TN/TON, DO)
- Distributed sensor networks
- Coupled groundwater - surface water models (stream sections - sub catchments)

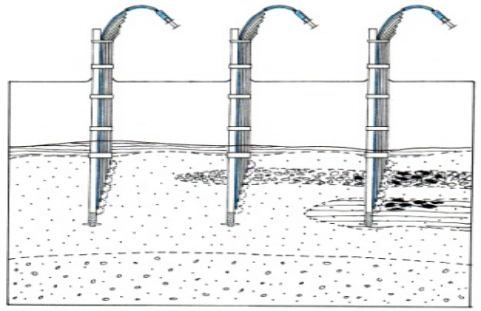


Multi-piezometer sampling – Active heat pulse tracer

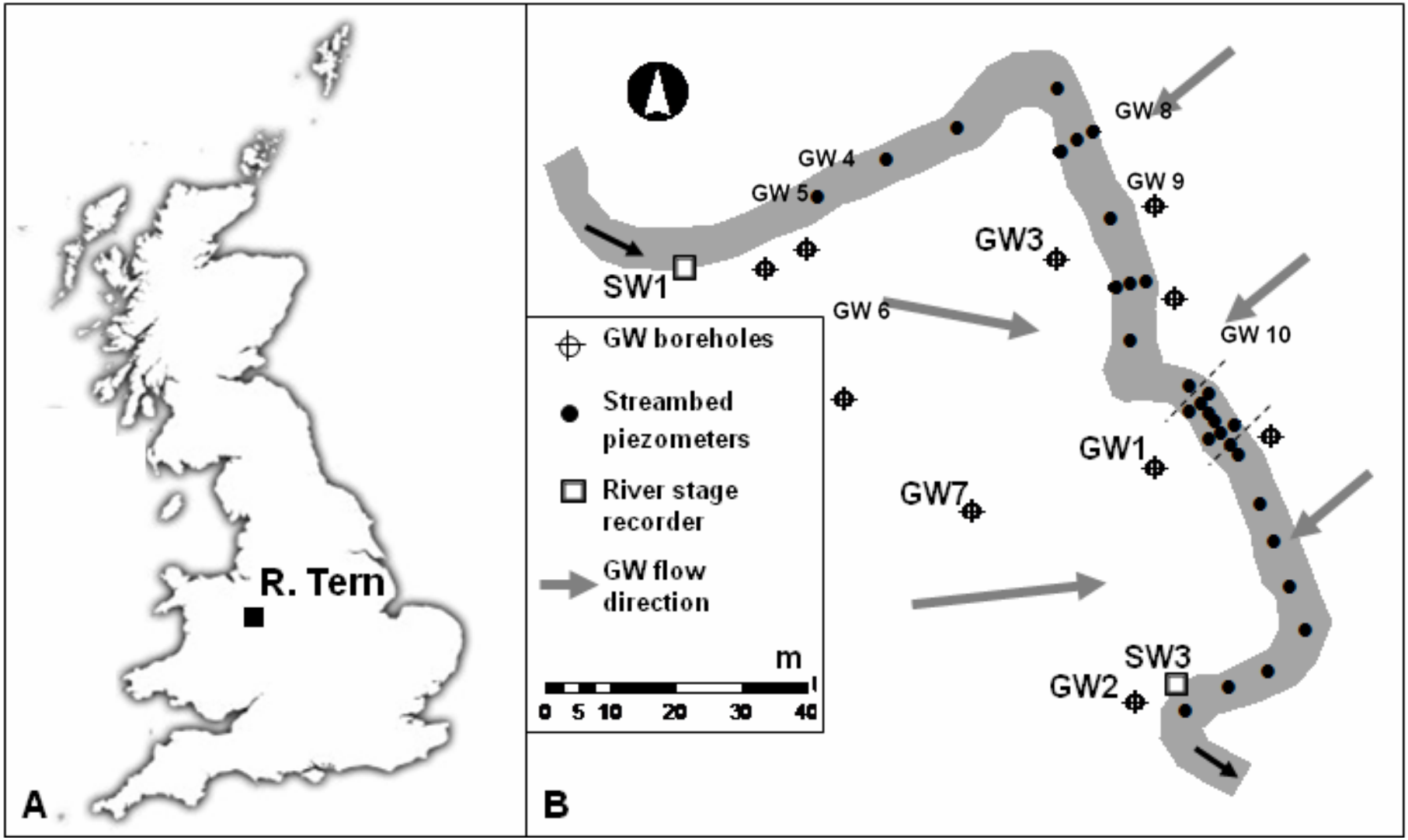
Diffuse Equilibrium in Thin films (DET) Passive Gel Samplers



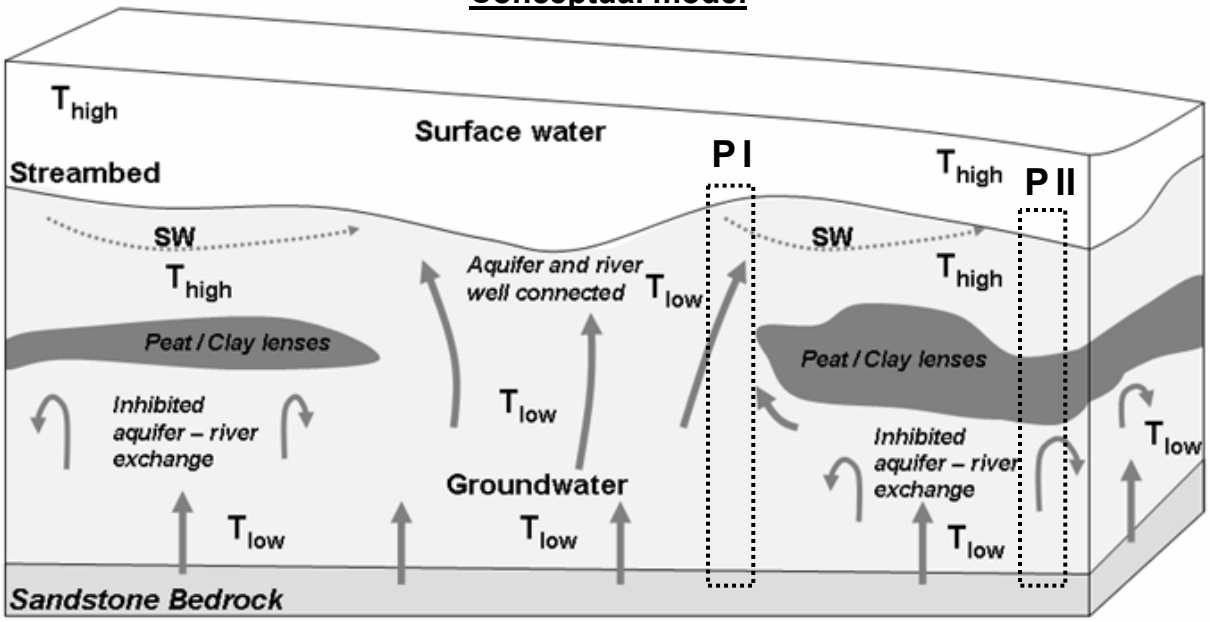




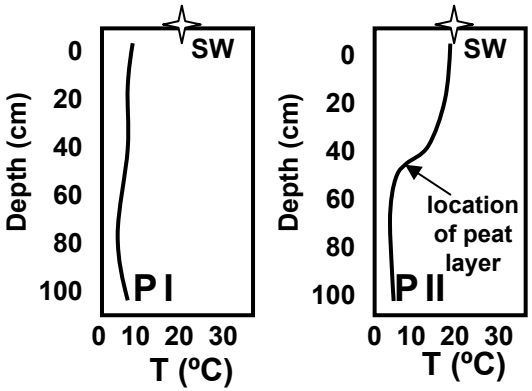
River Tern – Experimental Field Site



Conceptual model



Vertical streambed temperature profiles



High streambed hydraulic conductivity

Low streambed hydraulic conductivity

T_{high}: high summer streambed temperature (15-20°C); T_{low}: low summer streambed temperature (8-10°C); SW: Surface water

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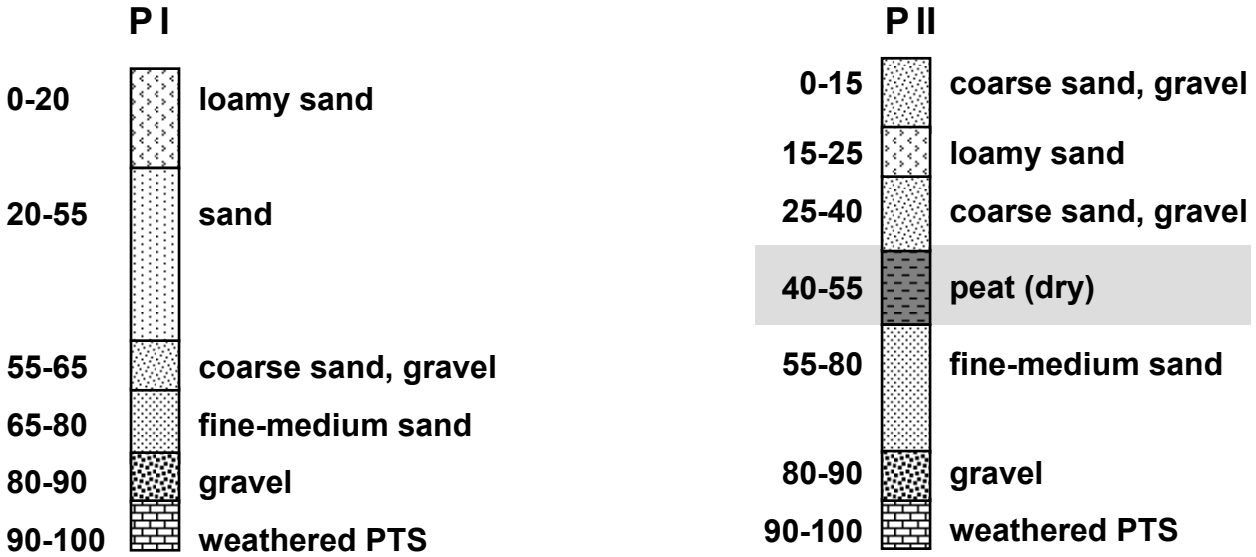
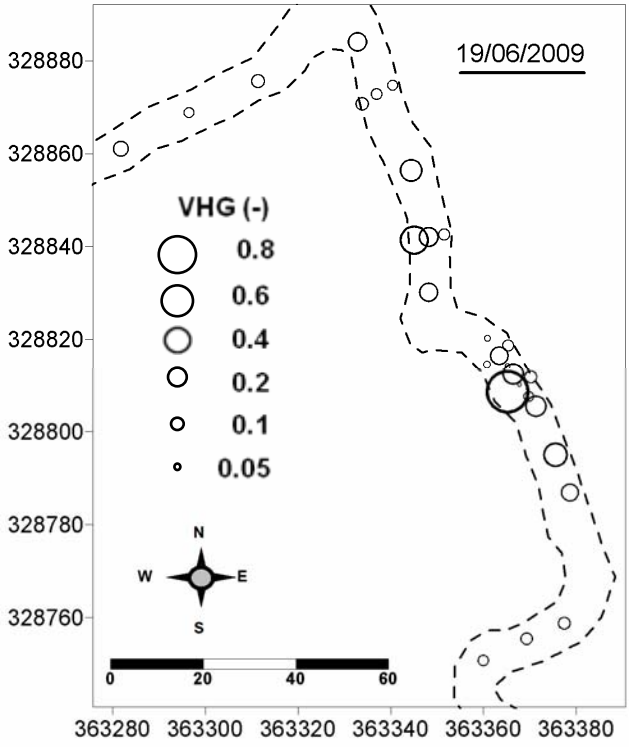
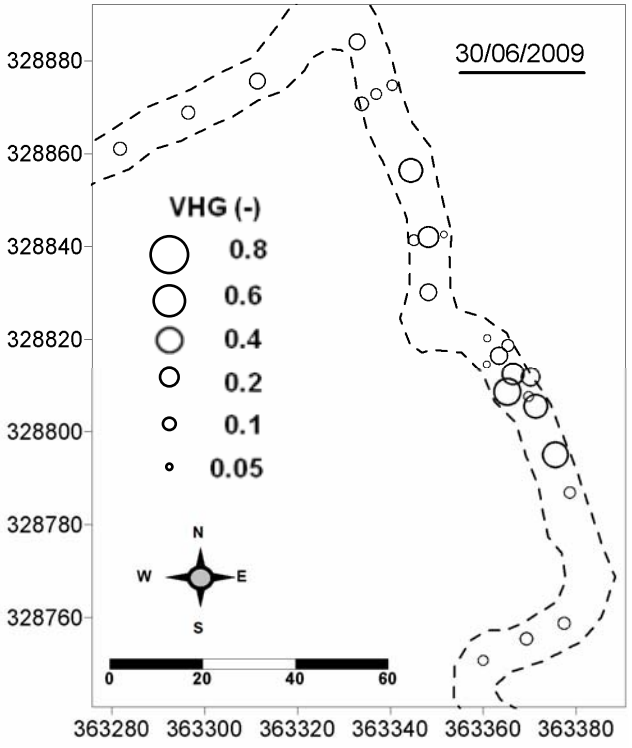
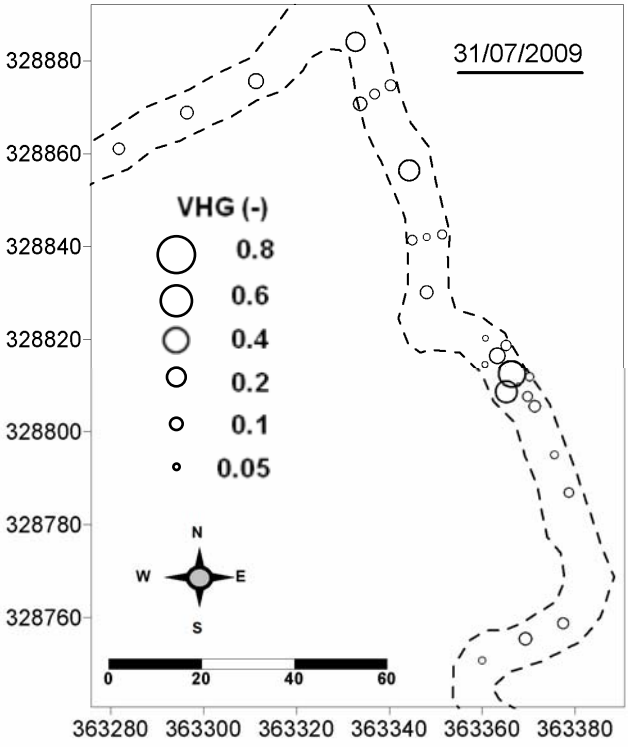
Streambed core profiles:



GW-SW exchange - Vertical hydraulic gradients







GW up-welling indicated by positive VHG throughout observation period

Spatially heterogeneous patterns

River Leith – HZ Nitrate Concentration Ranges

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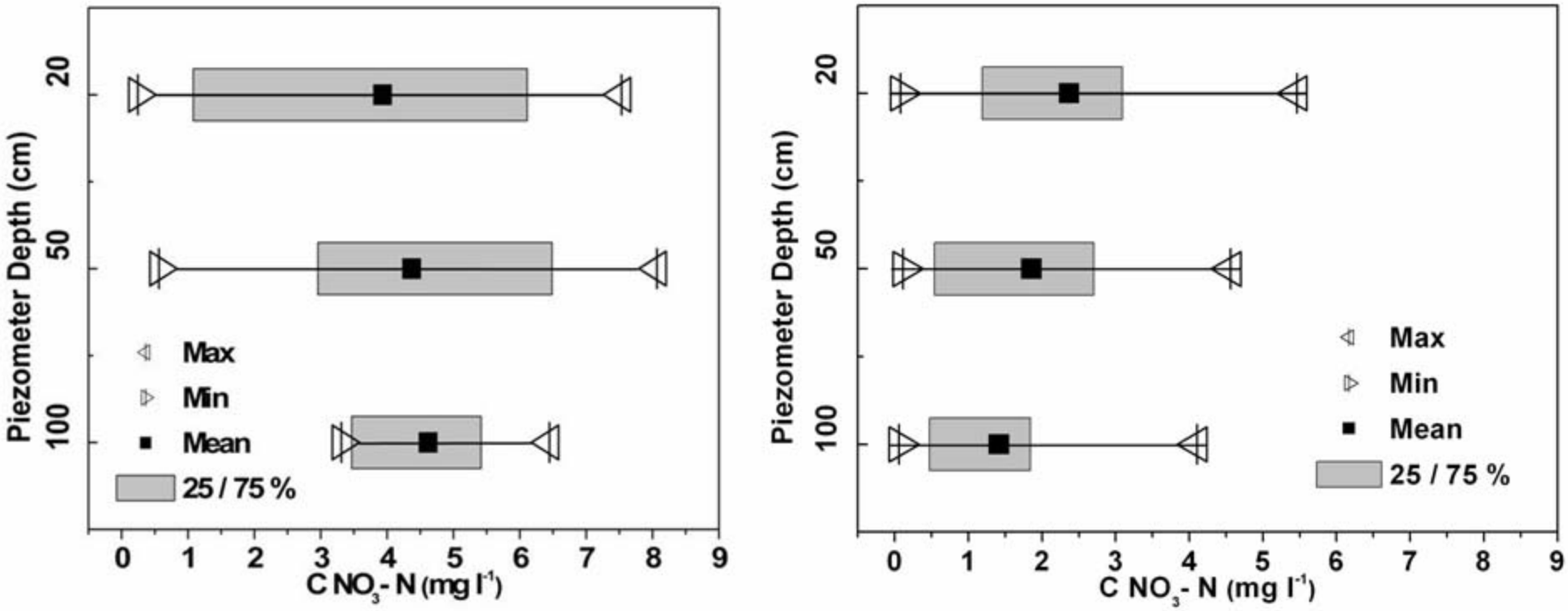
Nitrate concentration ranges in up-welling groundwater



Concentration changes in up-welling GW depend on:

- **Flow paths and hyporheic residence times**
- **Redox potential, dissolved oxygen and org. carbon content**

Krause et al. HP 2009

Redox-reactivity hotspots

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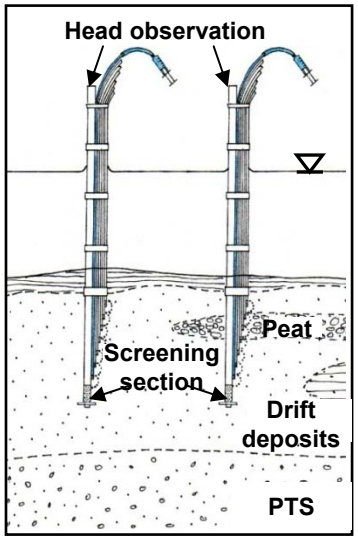
Nitrate concentrations changes (deep to shallow) 24/05/2009

ΔNO_3 (mgl^{-1})

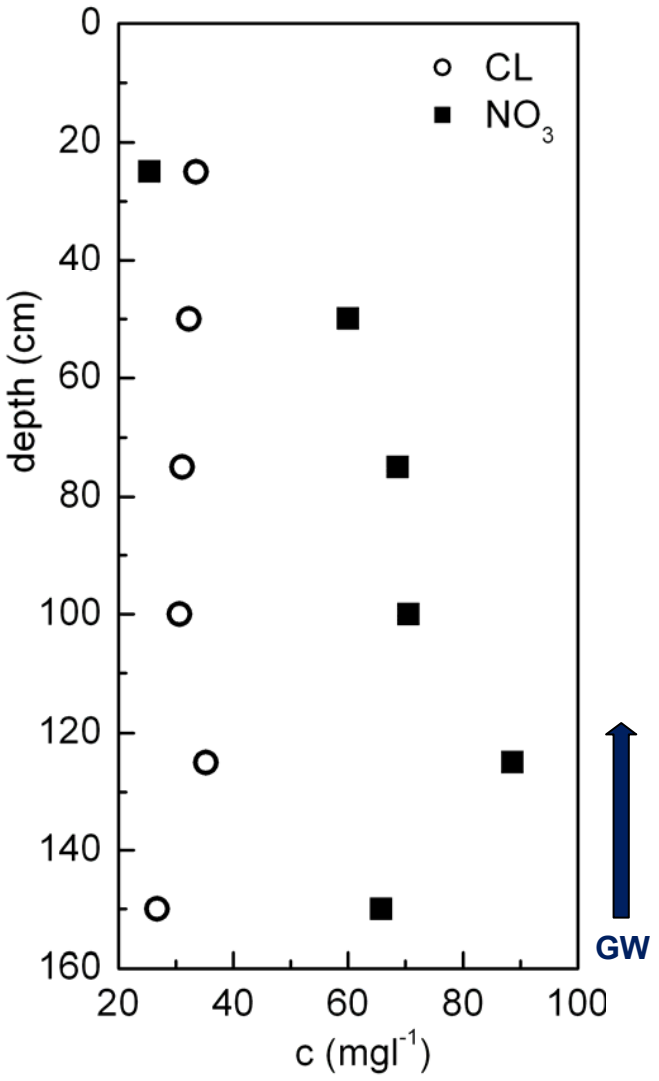
- -100 - -80
- -80 - -60
- -60 - -40
- -40 - -20
- -20 - 0
- 0 - 20
- 20 - 40
- 40 - 60
- 60 - 80
- 80 - 100
- Tern_river

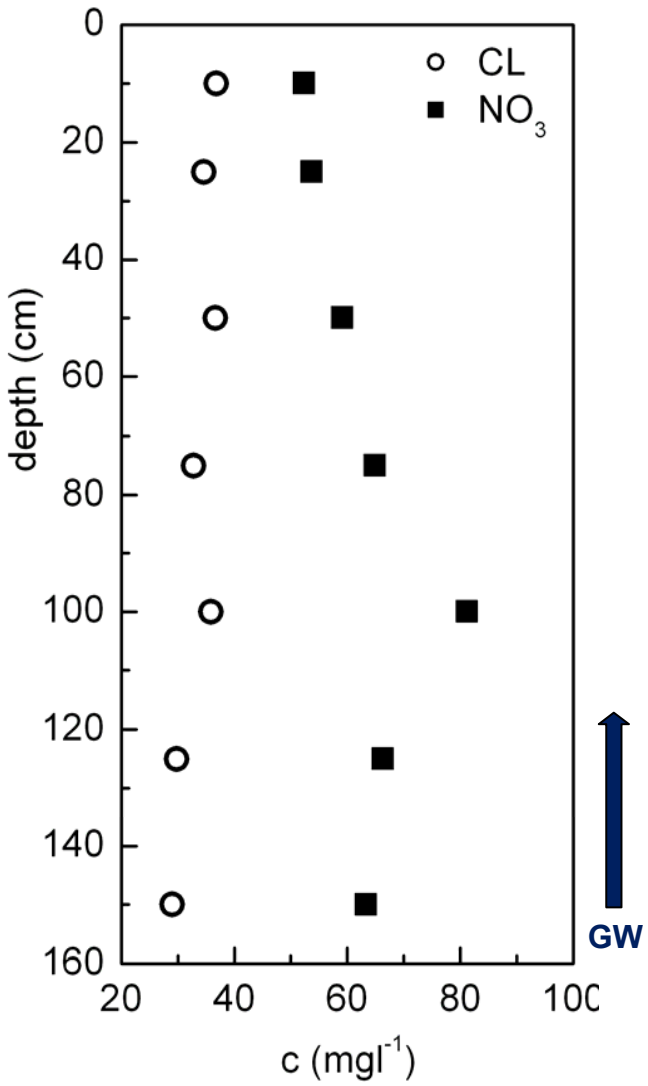


0 5 10 20 30 40

Krause et al. in prep.

Mixing or Chemical Transformation?



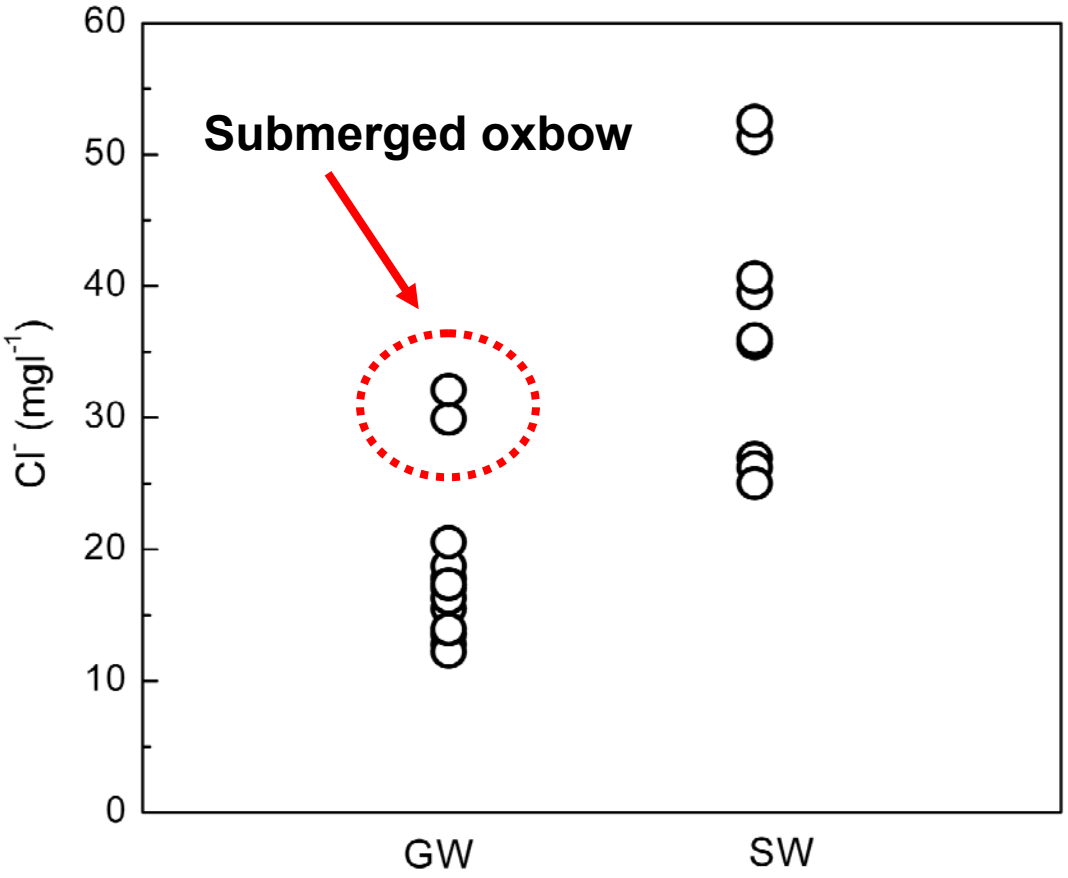


Chloride (Cl) non-reactive (conservative)

Nitrate (NO_3) reactive

Krause & Naden, in prep.

River Tern – mixing vs. chemical transformation

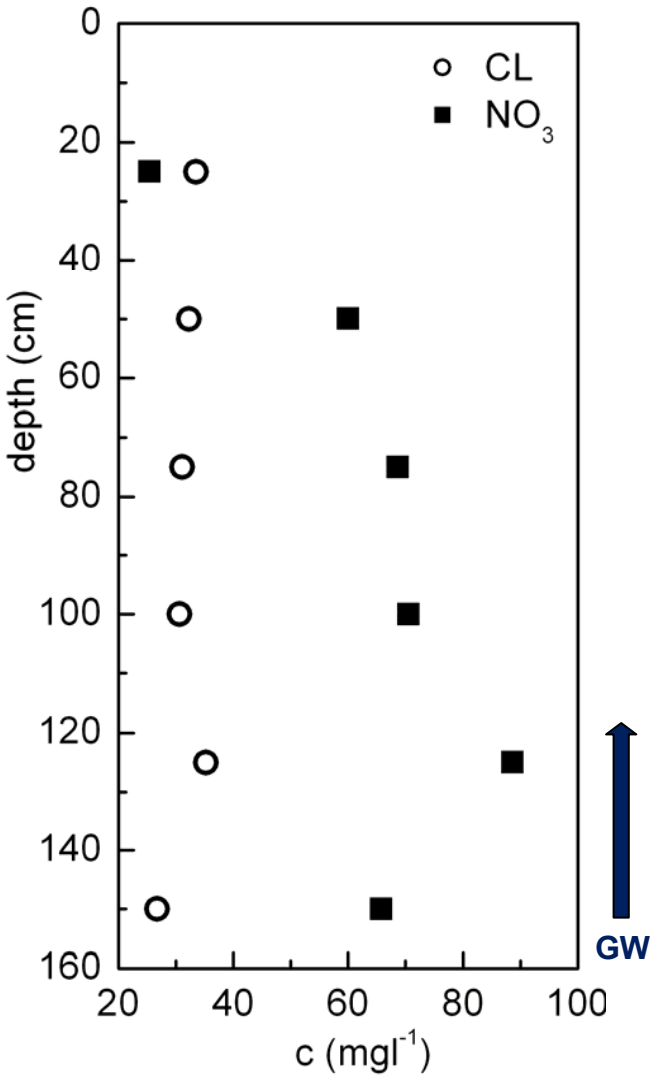


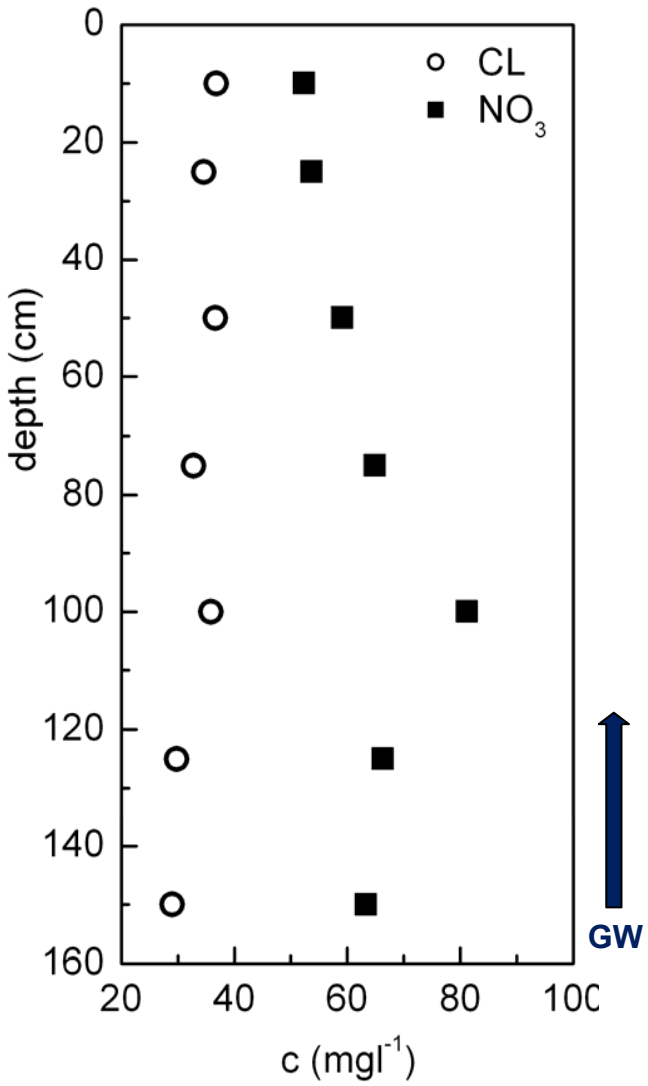
2-component mixing model:

$$\%SW = \frac{(C_{HZ} - C_{GW})}{(C_{SW} - C_{GW})} * 100$$

C_{HZ}	concentration hyporheic zone
C_{GW}	concentration groundwater
C_{SW}	concentration surface water

River Tern – Reactive vs. Non-reactive transport





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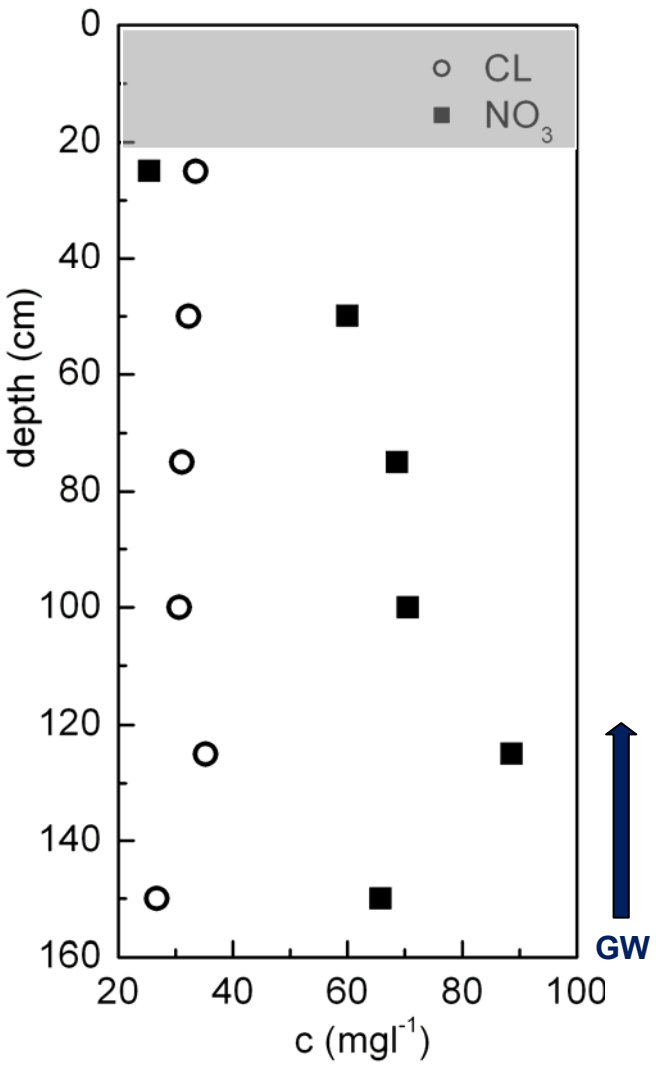
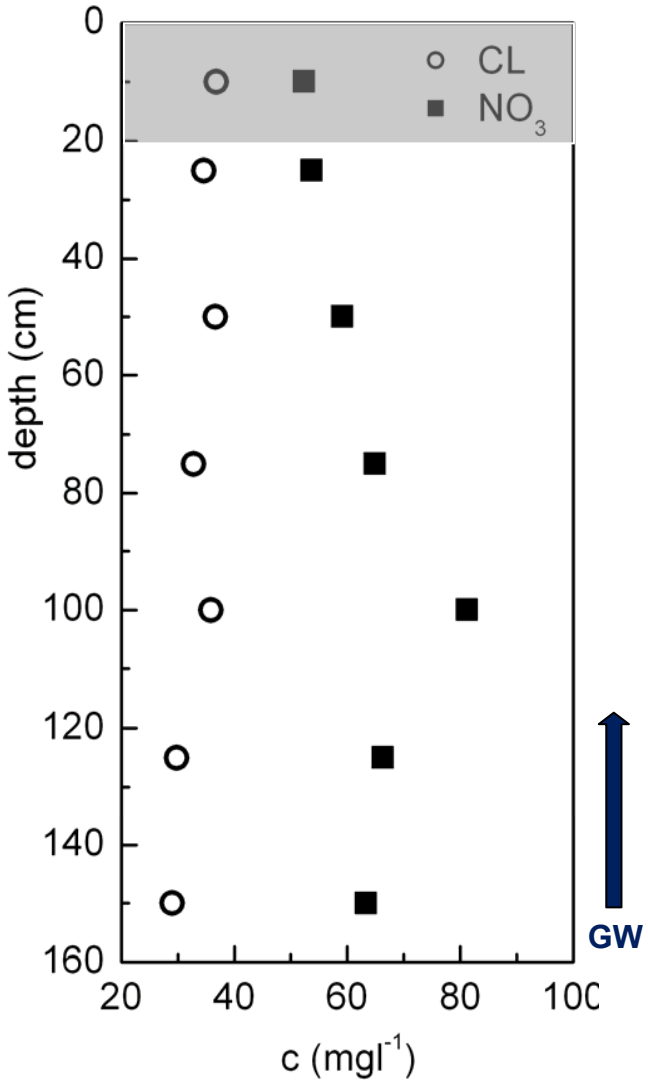
Krause & Naden, in prep.

River Tern – Reactive vs. Non-reactive transport





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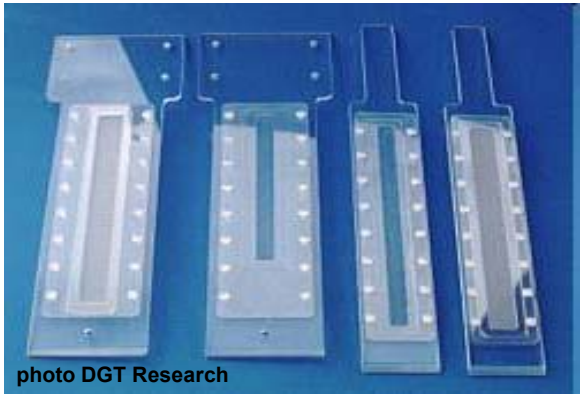
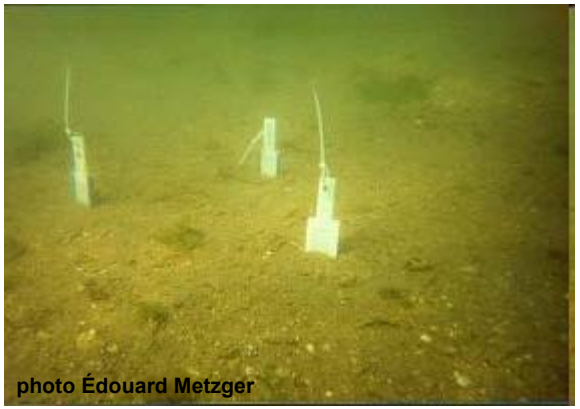
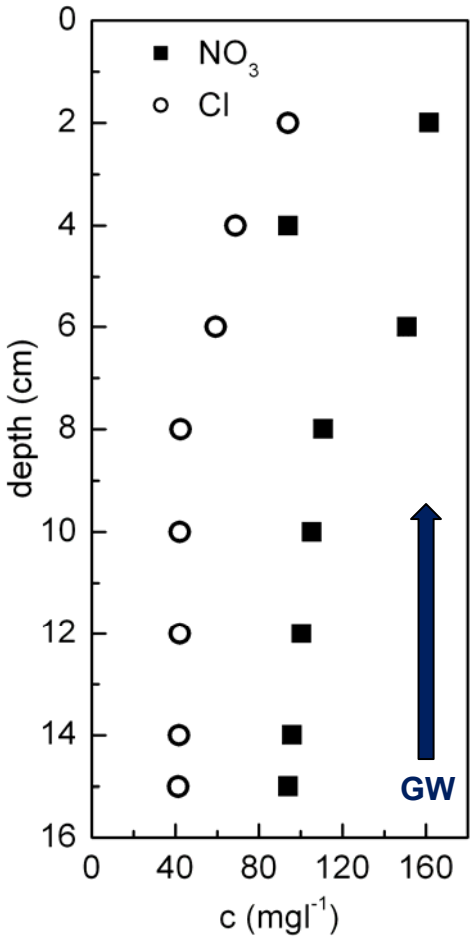
Krause & Naden, in prep.

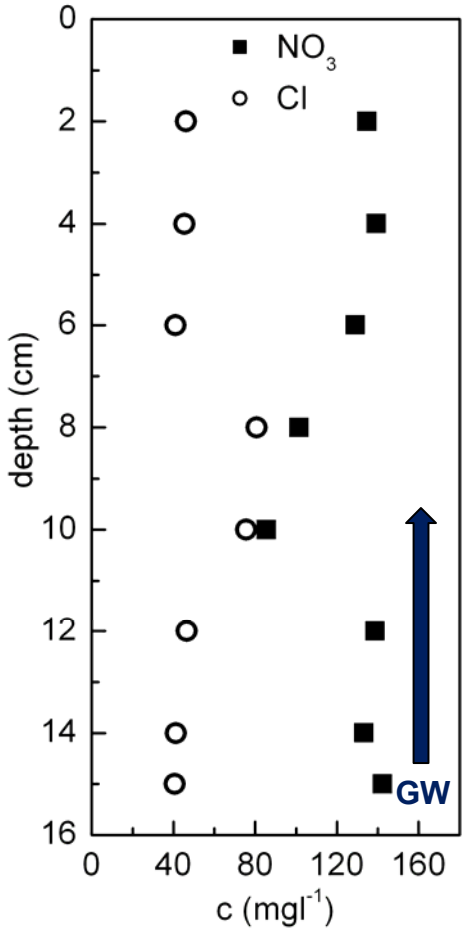
River Tern – Reactive vs. Non-reactive transport

Diffuse Equilibrium in Thin films (DET)
Passive Gel Samplers



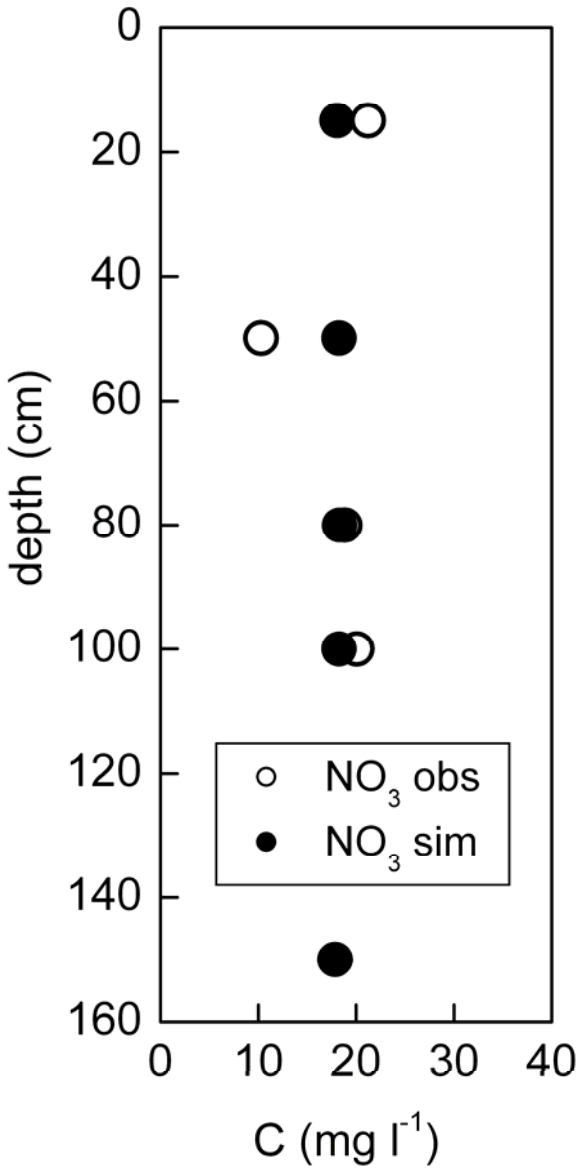


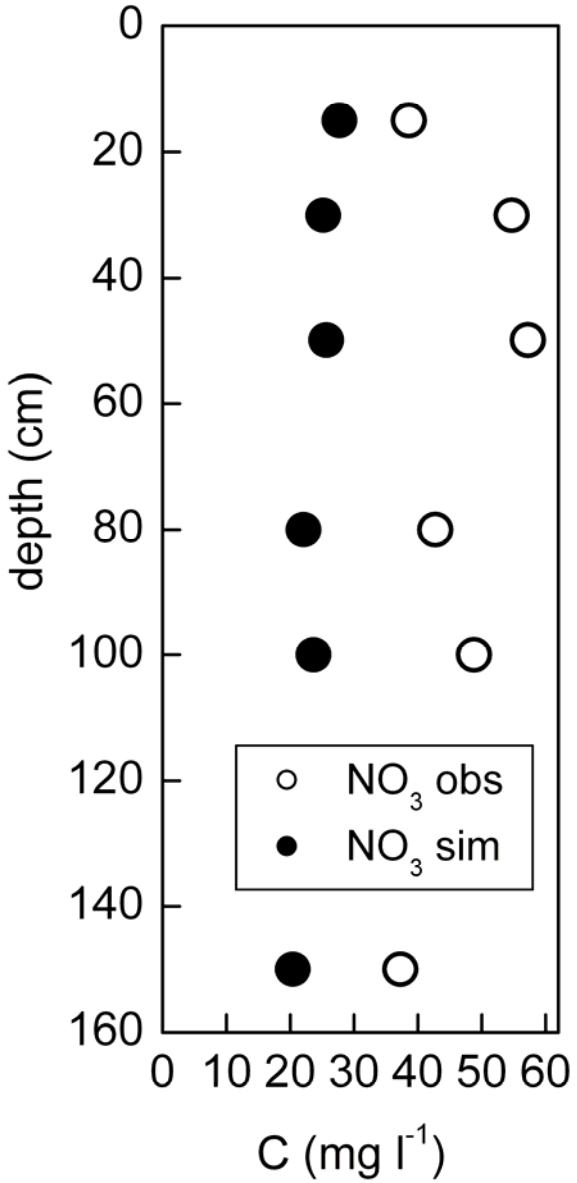




Krause & Naden, in prep.

River Tern – Reactive vs. Non-reactive transport





Krause & Naden, in prep.

Model simulation - GW-SW exchange

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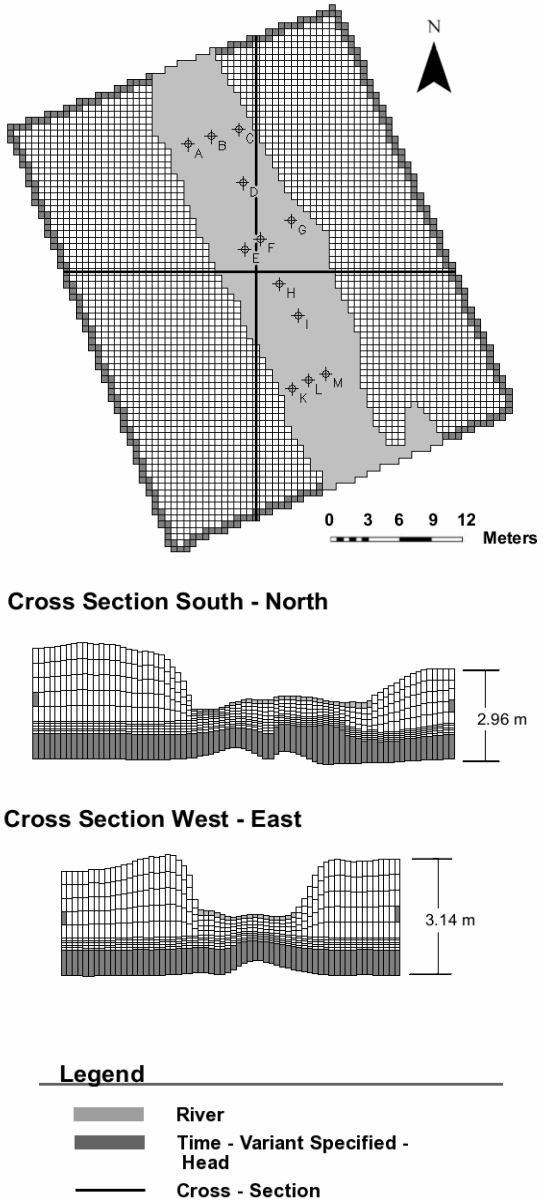
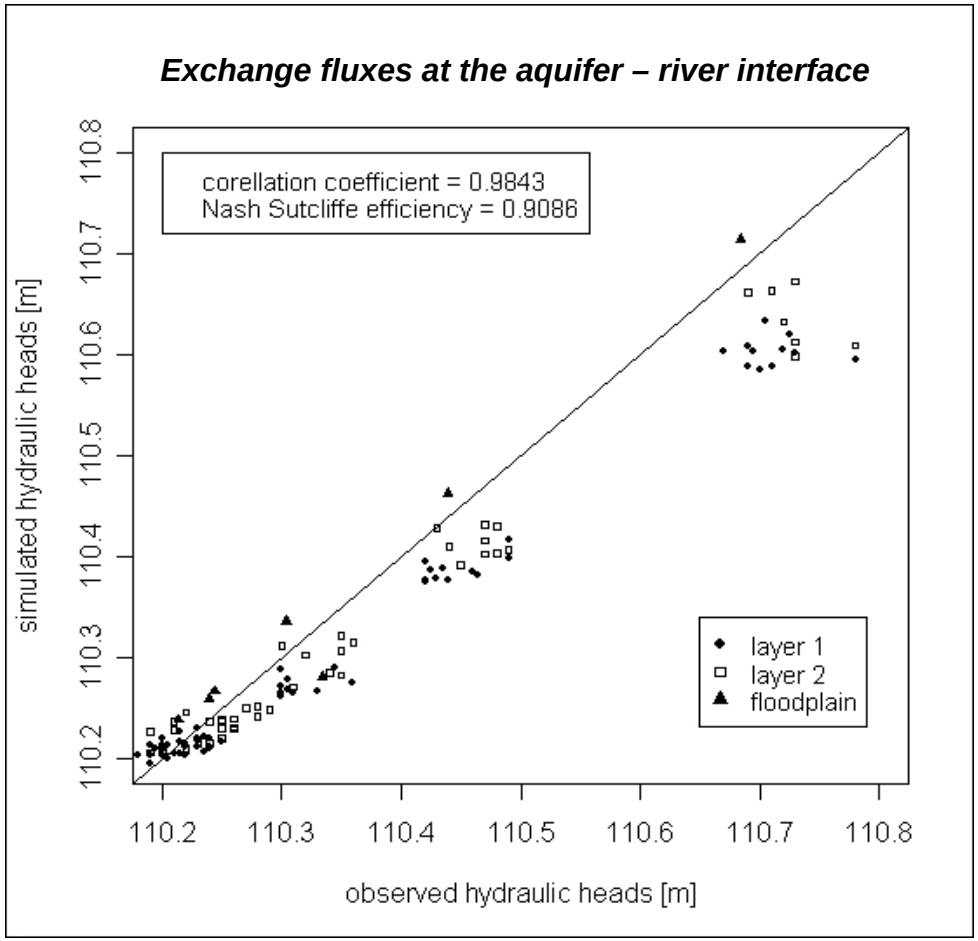


Model-based quantification of GW-SW exchange



(Munz et al. HP 2011)

Model simulation - Reactive nitrate transport

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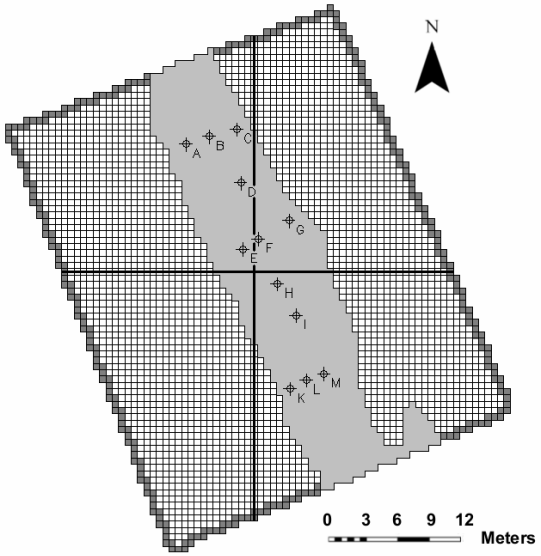
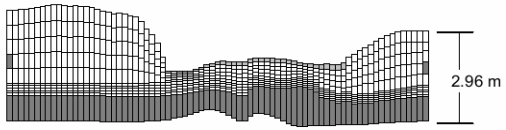
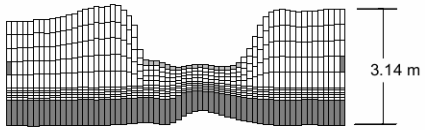


Cross Section South - North



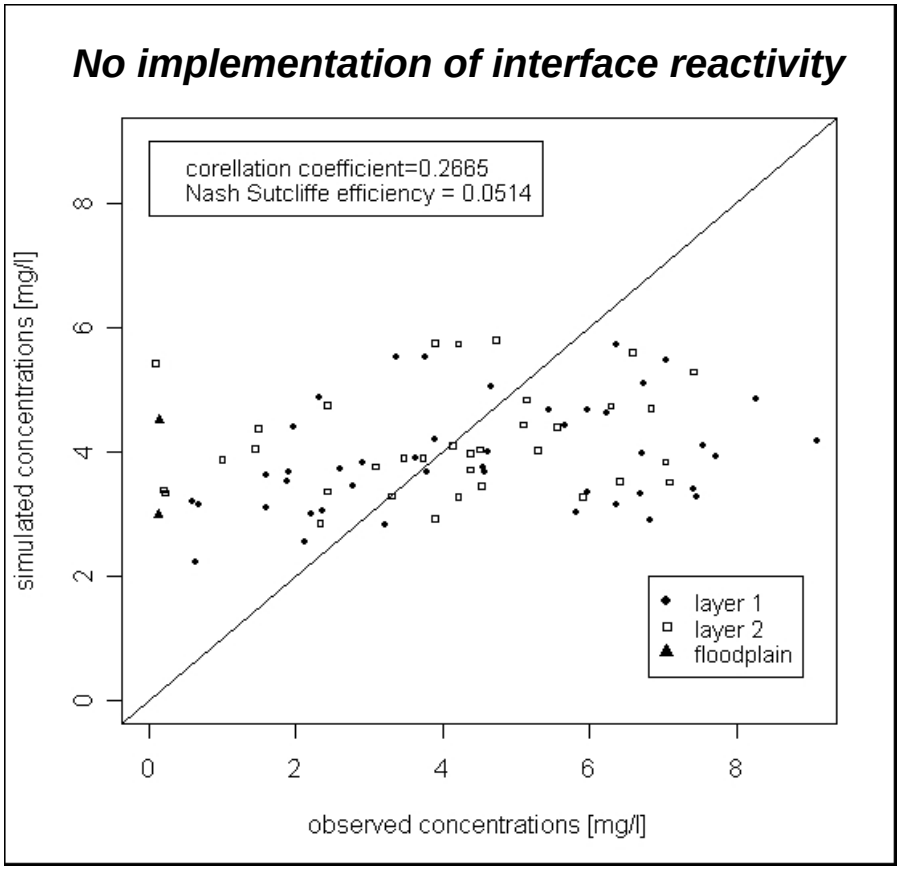
Cross Section West - East



Legend

- River
- Time - Variant Specified - Head
- Cross - Section

Reactive Transport and Transformation (Nitrate)



Strong evidence for increased HZ reactivity !!

(Tecklenburg et al. in prep)

Model simulation - Reactive nitrate transport

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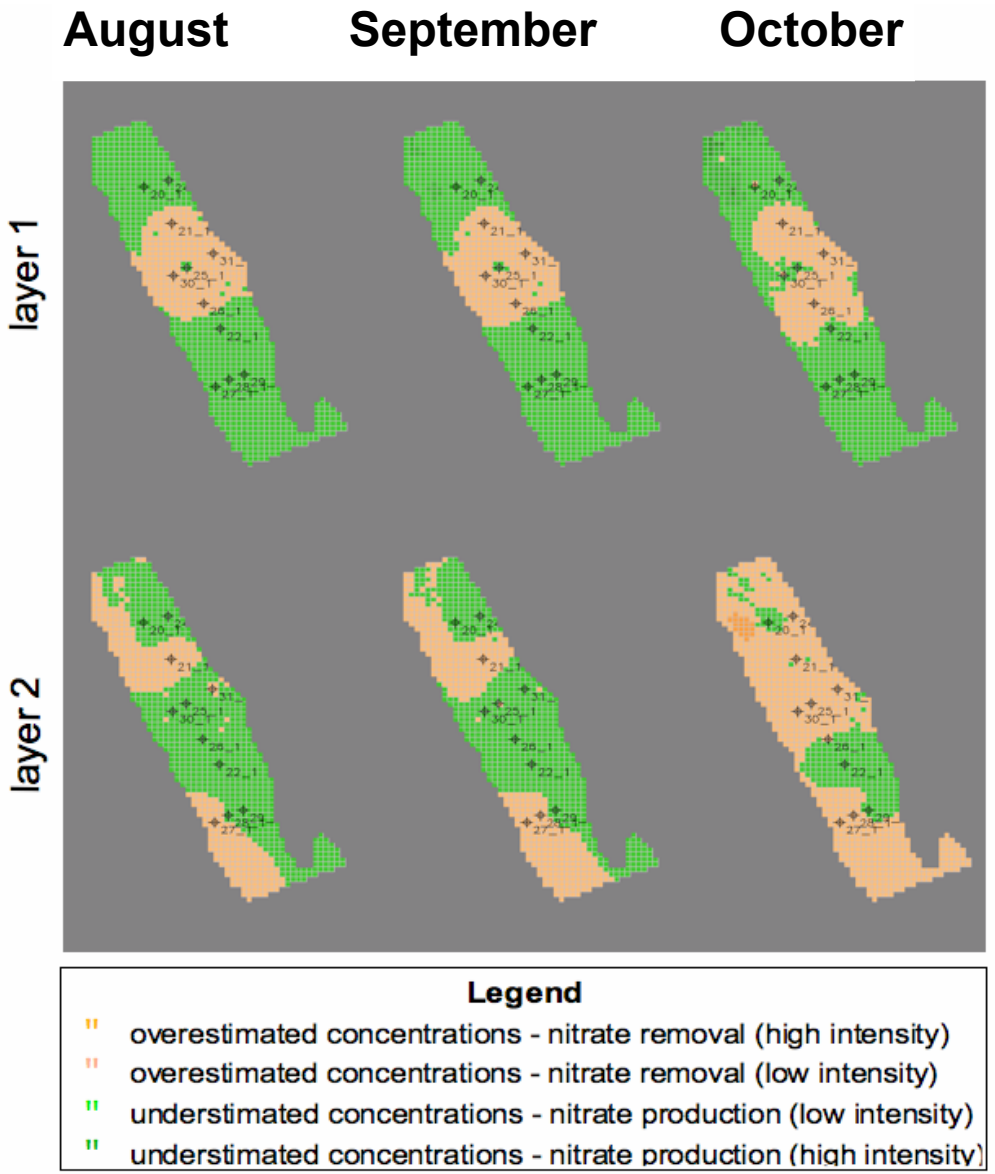
Topographic controls on N - transformation

- **Model over-prediction (high attenuation) in riffle head areas**
- **Model under-estimation (nitrate enrichment) in pool areas and riffle tail**
- **Hyporheic transformation rates of up to +/- 90%**



Tecklenburg et al, JoH in prep.

HZ River Tern - Hot moments in cold spots

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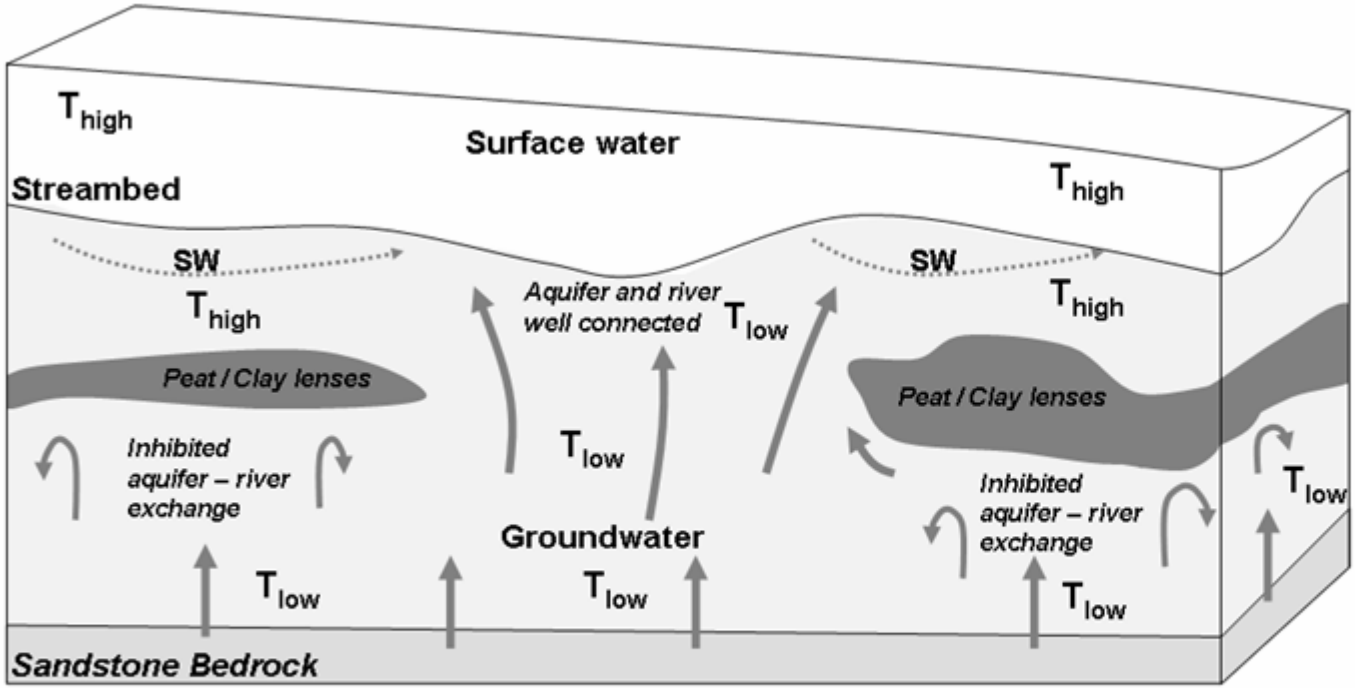
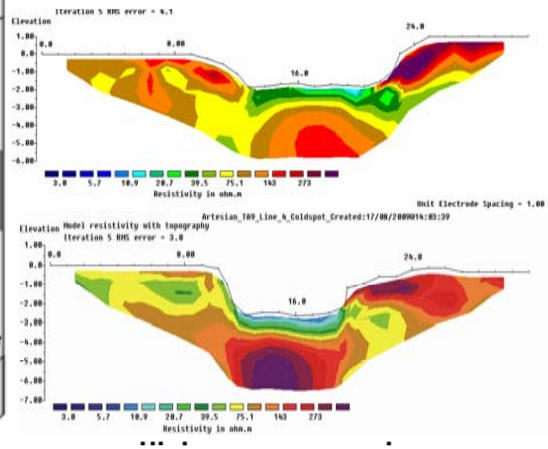
Streambed properties – impact on N - transformation:

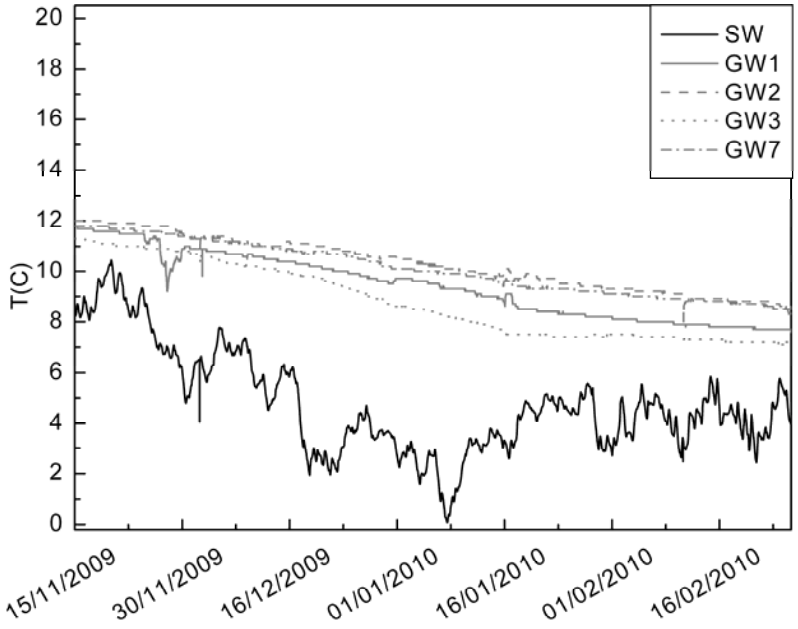
Disconnecting Peat Layers – pockets of semi-confined groundwater

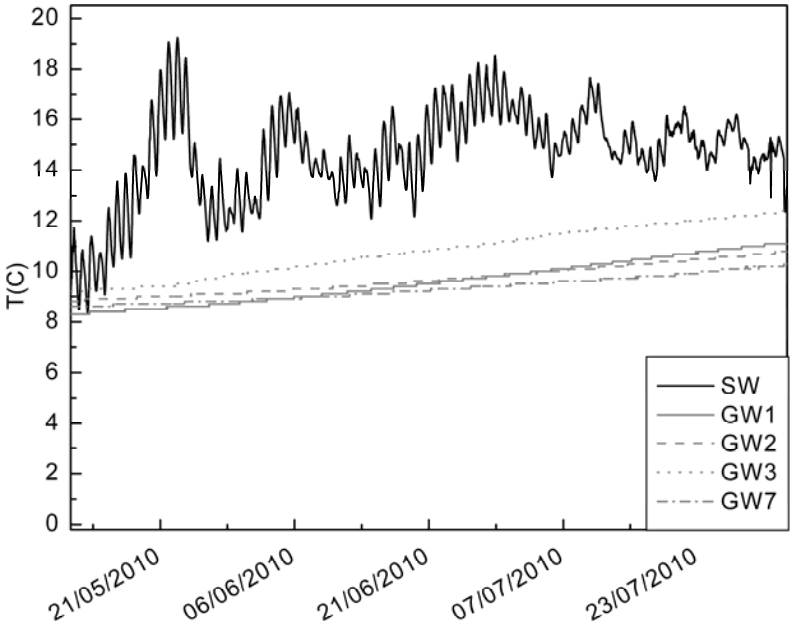


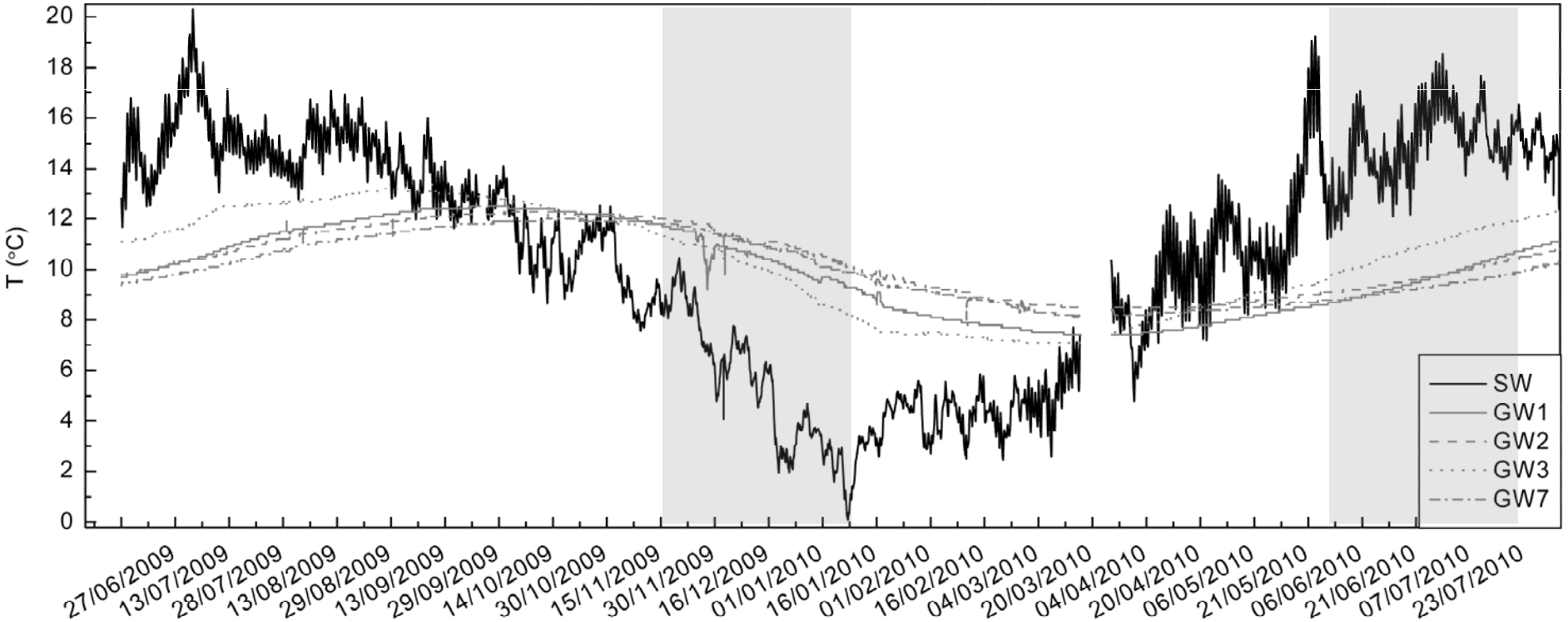
ERT cross-sectional profiles



- **Locations of increased residence times and high chemical reactivity**
- **Nearly complete nitrate removal**


SW
GW1
GW2
GW3
GW7
T(C)
0
2
4
6
8
10
12
14
16
18
20
15/11/2009
30/11/2009
16/12/2009
01/01/2010
16/01/2010
01/02/2010
16/02/2010


SW
GW1
GW2
GW3
GW7
T(C)
0
2
4
6
8
10
12
14
16
18
20
21/05/2010
06/06/2010
21/06/2010
07/07/2010
23/07/2010


SW
GW1
GW2
GW3
GW7
T (°C)
0
2
4
6
8
10
12
14
16
18
20
27/06/2009
13/07/2009
28/07/2009
13/08/2009
29/08/2009
13/09/2009
29/09/2009
14/10/2009
30/10/2009
15/11/2009
30/11/2009
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01/01/2010
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01/02/2010
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04/04/2010
20/04/2010
06/05/2010
21/05/2010
06/06/2010
21/06/2010
07/07/2010
23/07/2010

HZ River Tern - Hot moments in cold spots

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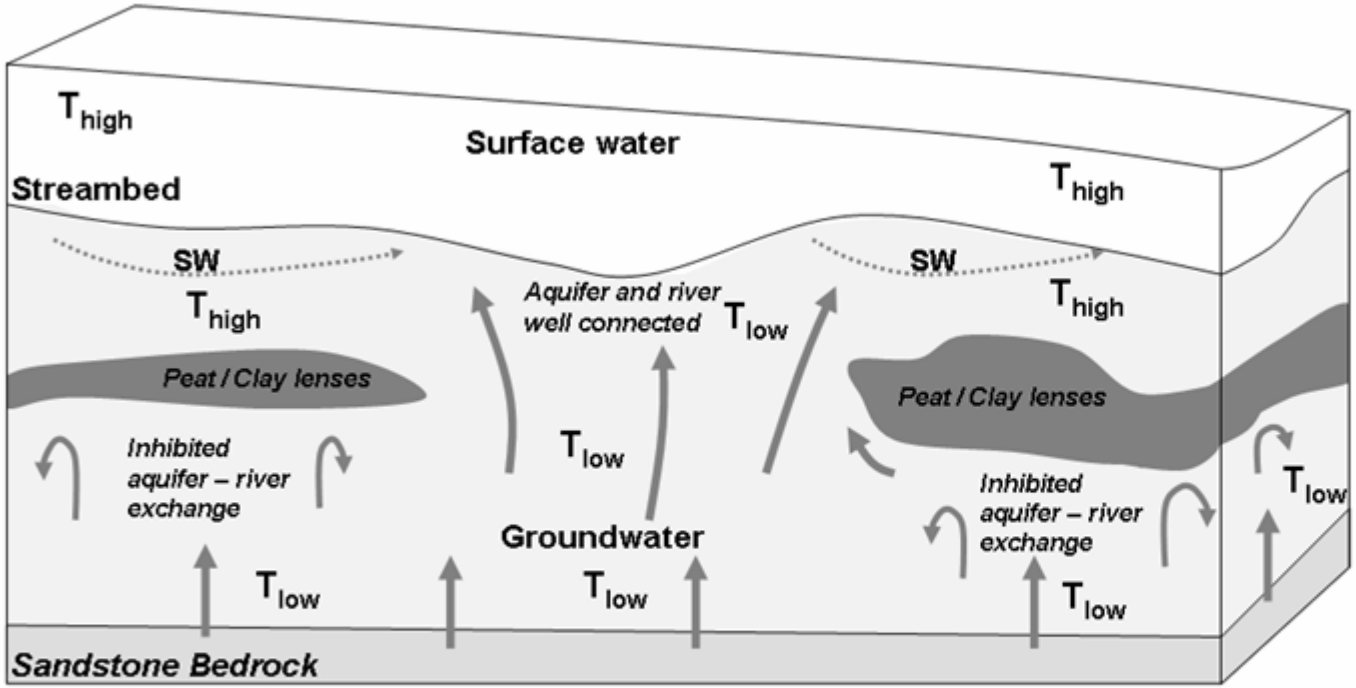
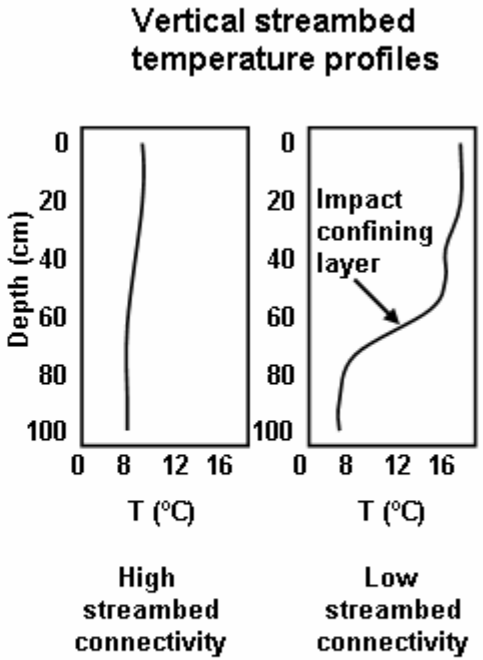
Streambed modulation of interstitial pore water temperature in up-welling GW

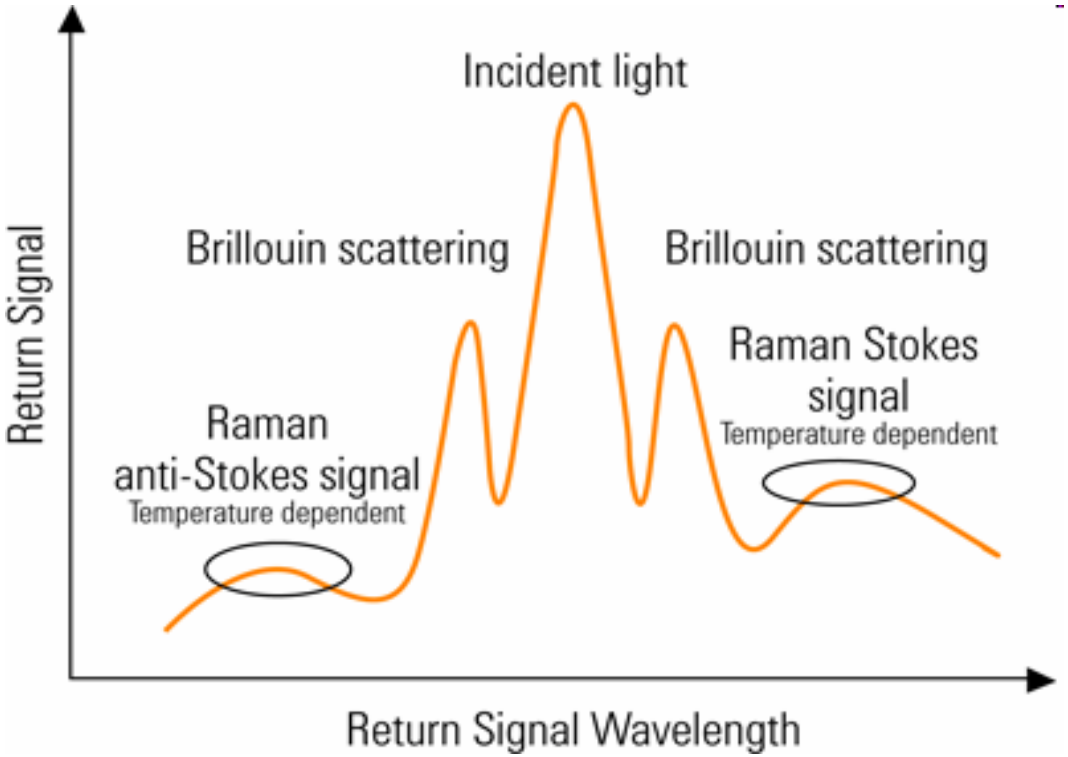
T-anomalies as predictors for GW up-welling patterns + HZ reactivity hotspots





T_{high}: high summer streambed temperature (15-20°C); T_{low}: low summer streambed temperature (8-10°C); SW: Surface water

Heat Tracer Fibre-optic Distributed Temperature Sensing



Raman-Optical Time-Domain-Reflectometry

Back scatter of optical laser pulse

Analysis of Stokes / anti-Stokes signal

Figure courtesy of AP Sensing

Heat Tracer Fibre-optic Distributed Temperature Sensing

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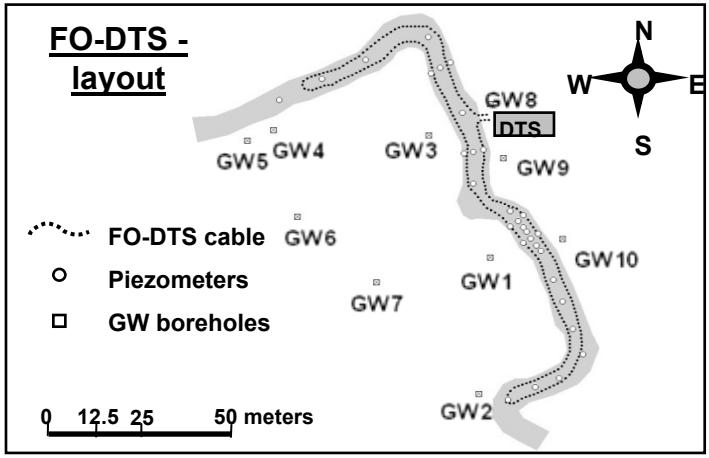
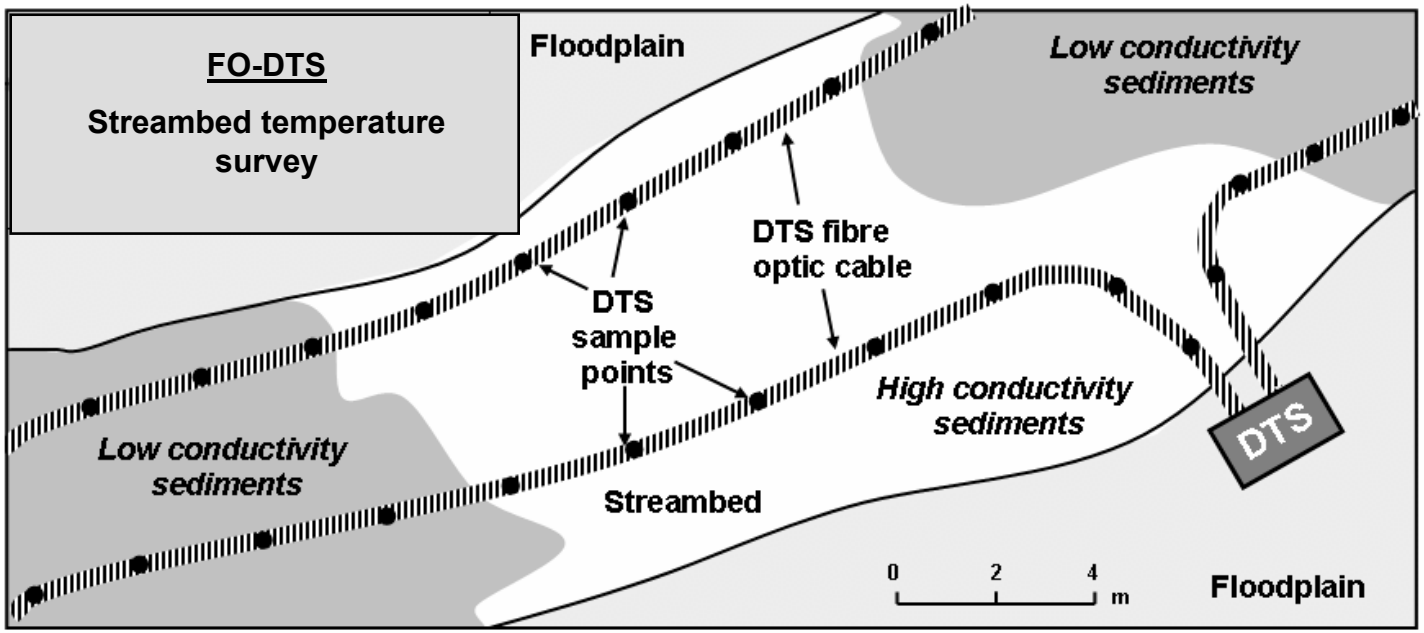


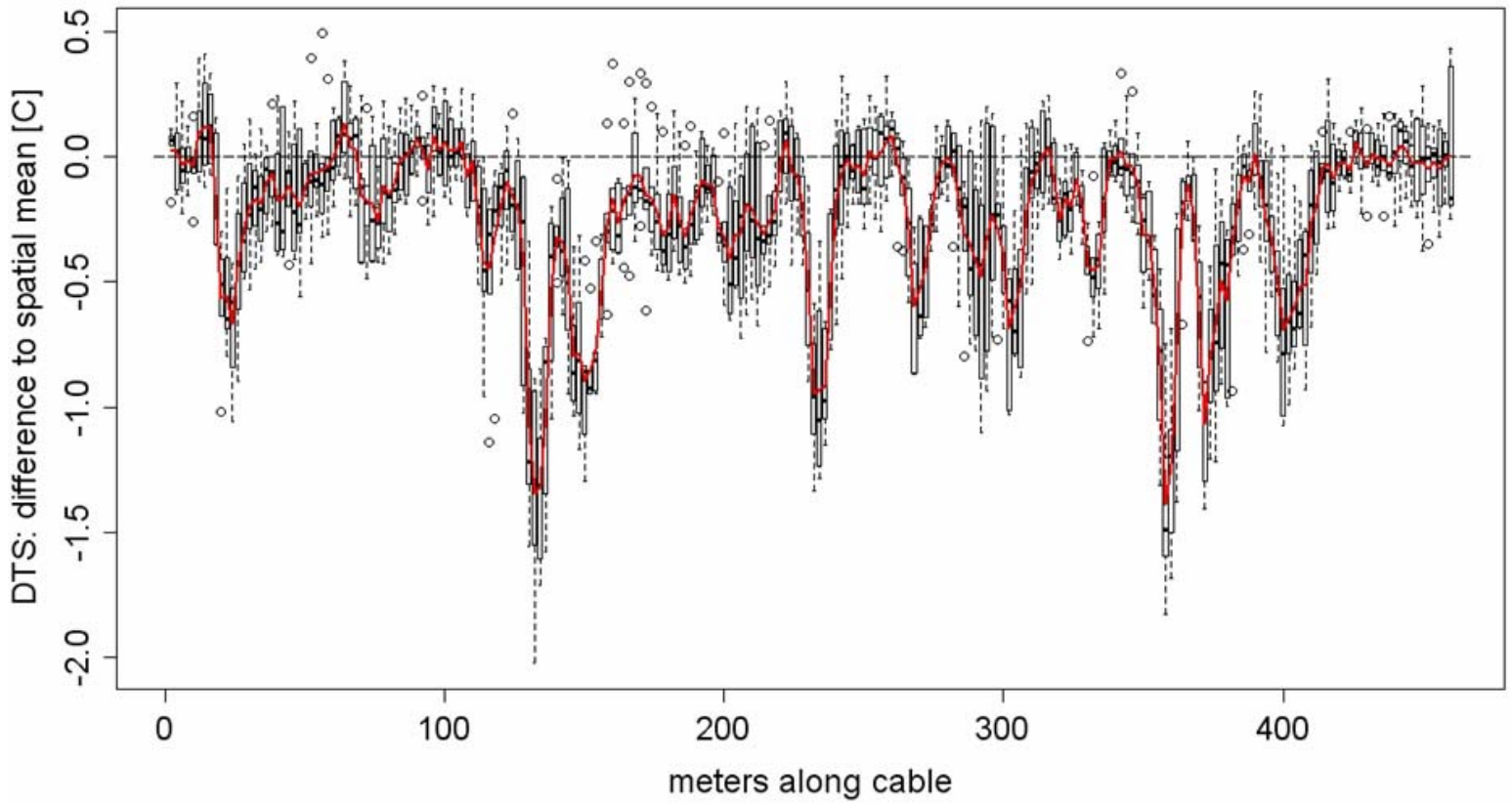


500 m loop along meander bend

2 channels – double ended

Single ended vs. double ended measurements

Heat Tracer Fibre-optic Distributed Temperature Sensing



Heat Tracer Fibre-optic Distributed Temperature Sensing

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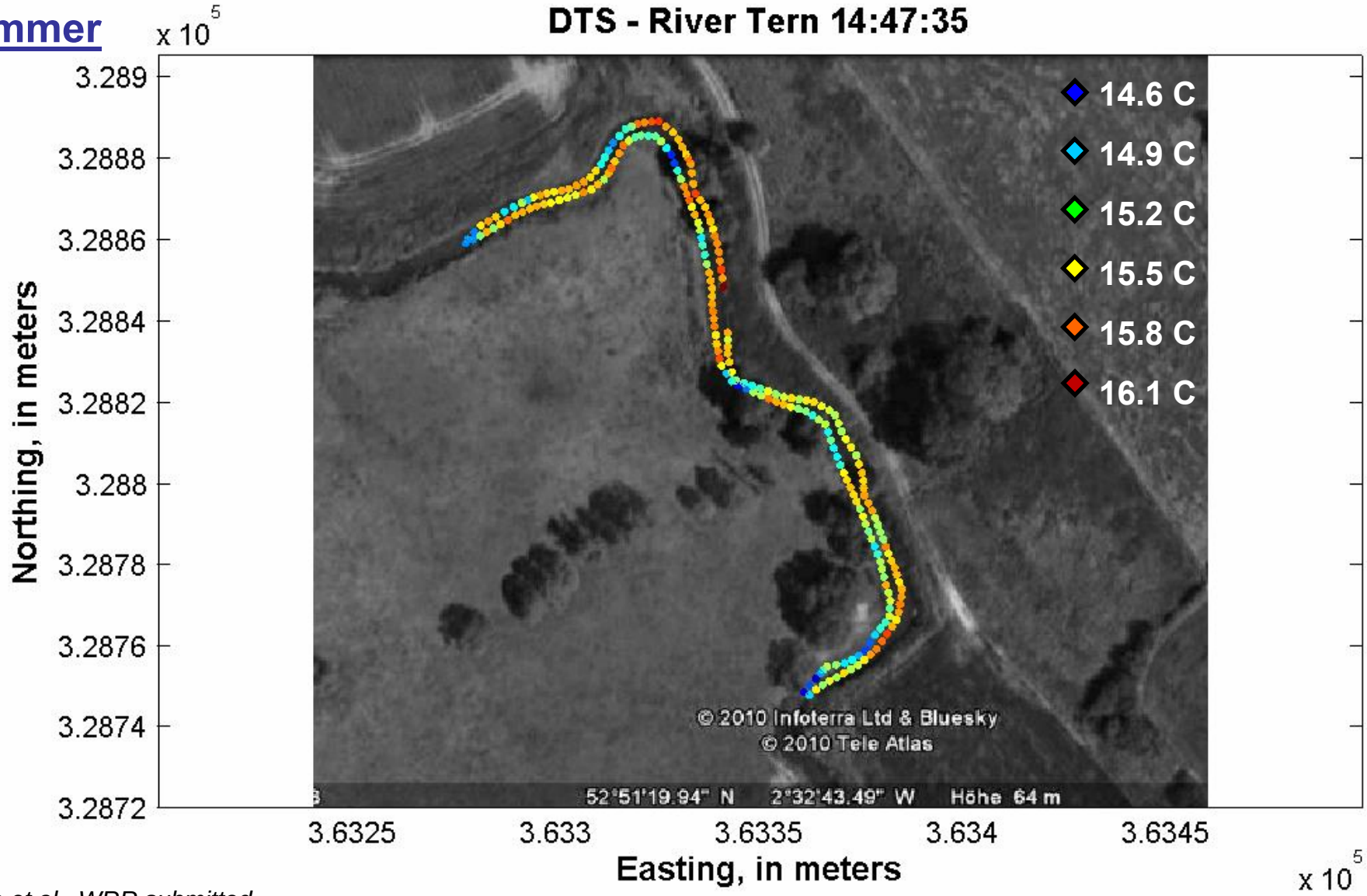
Summer



Krause et al., WRR submitted

Heat Tracer Fibre-optic Distributed Temperature Sensing

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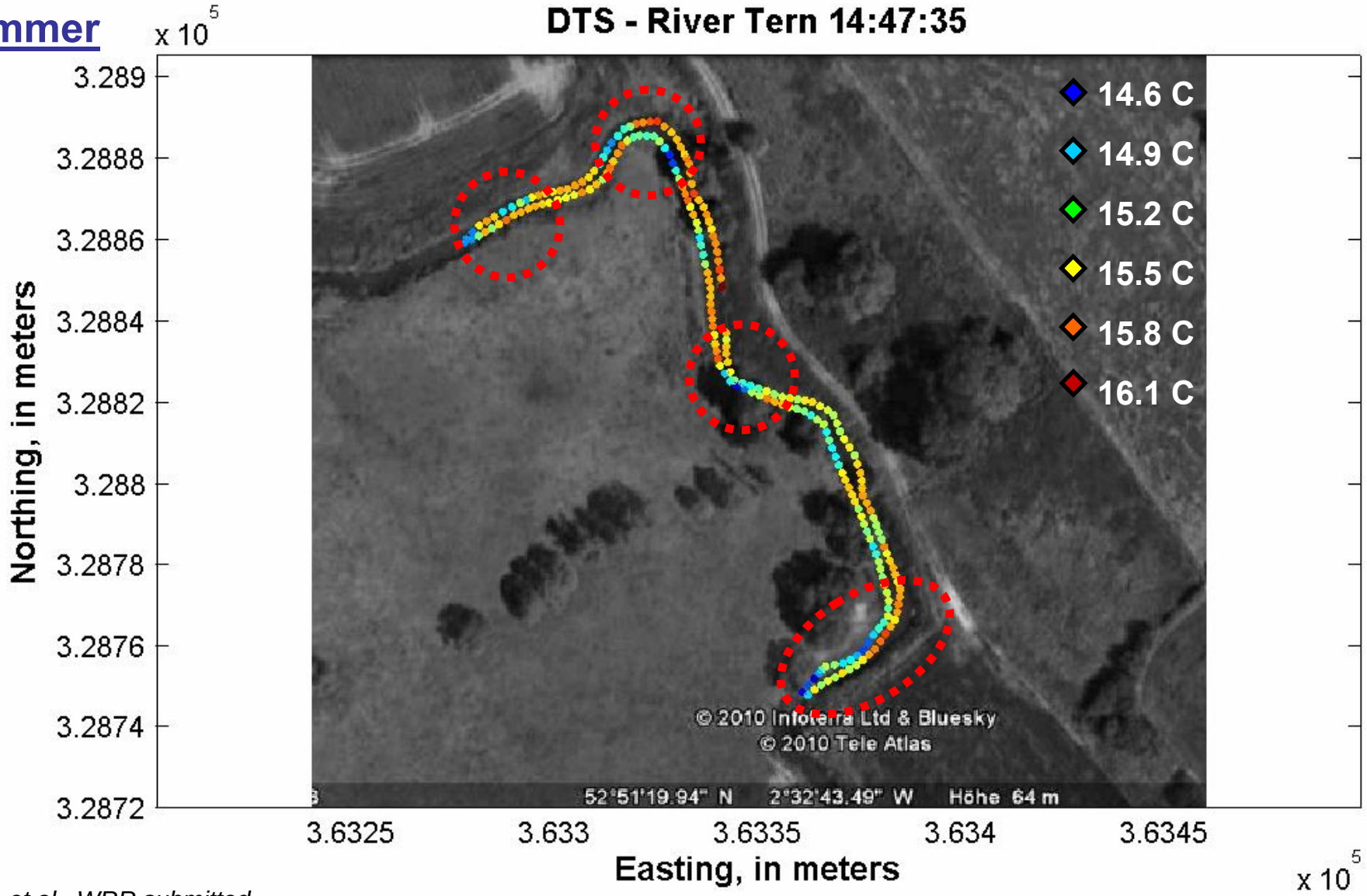
Summer



Krause et al., WRR submitted

Heat Tracer Fibre-optic Distributed Temperature Sensing

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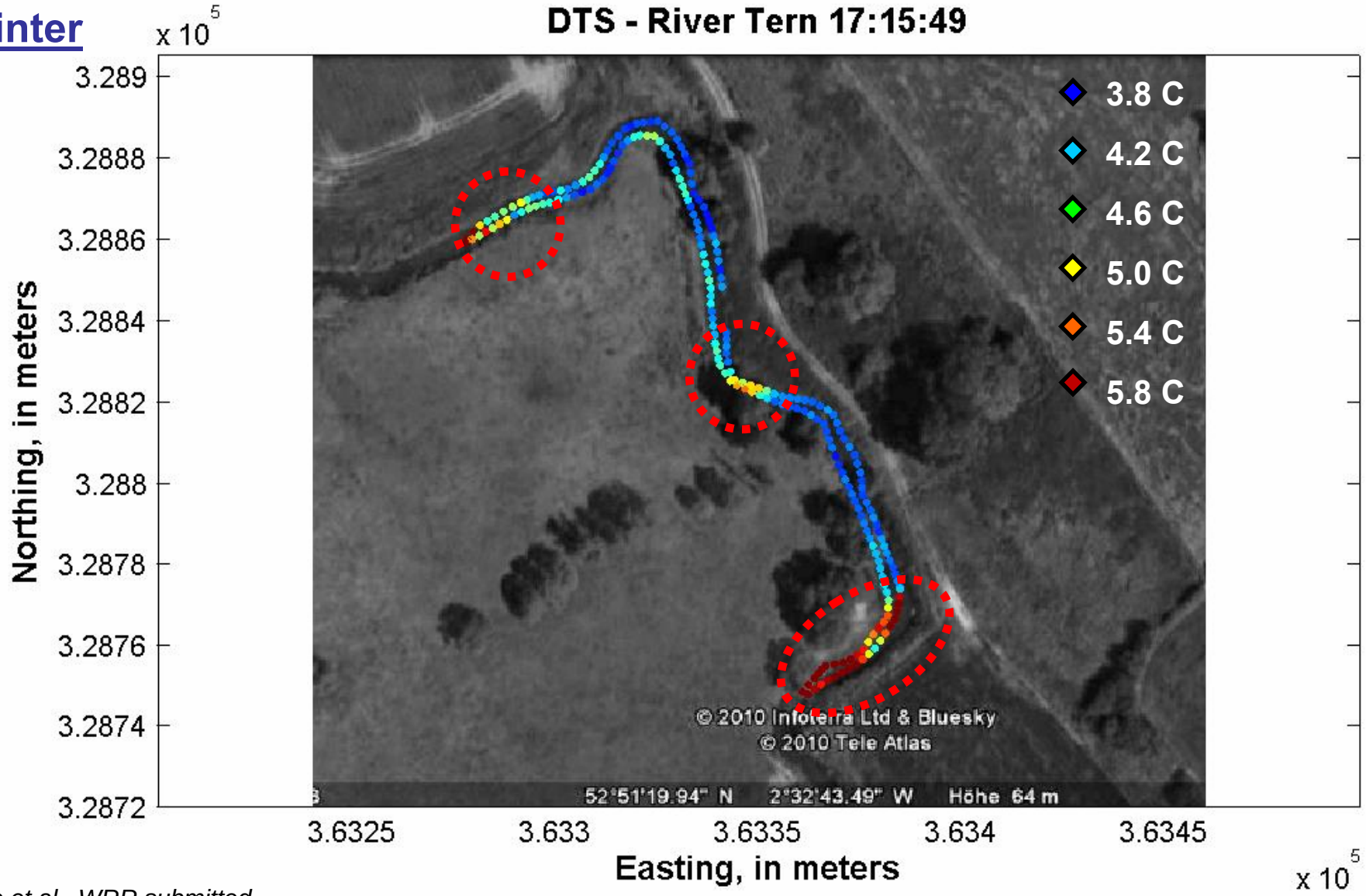
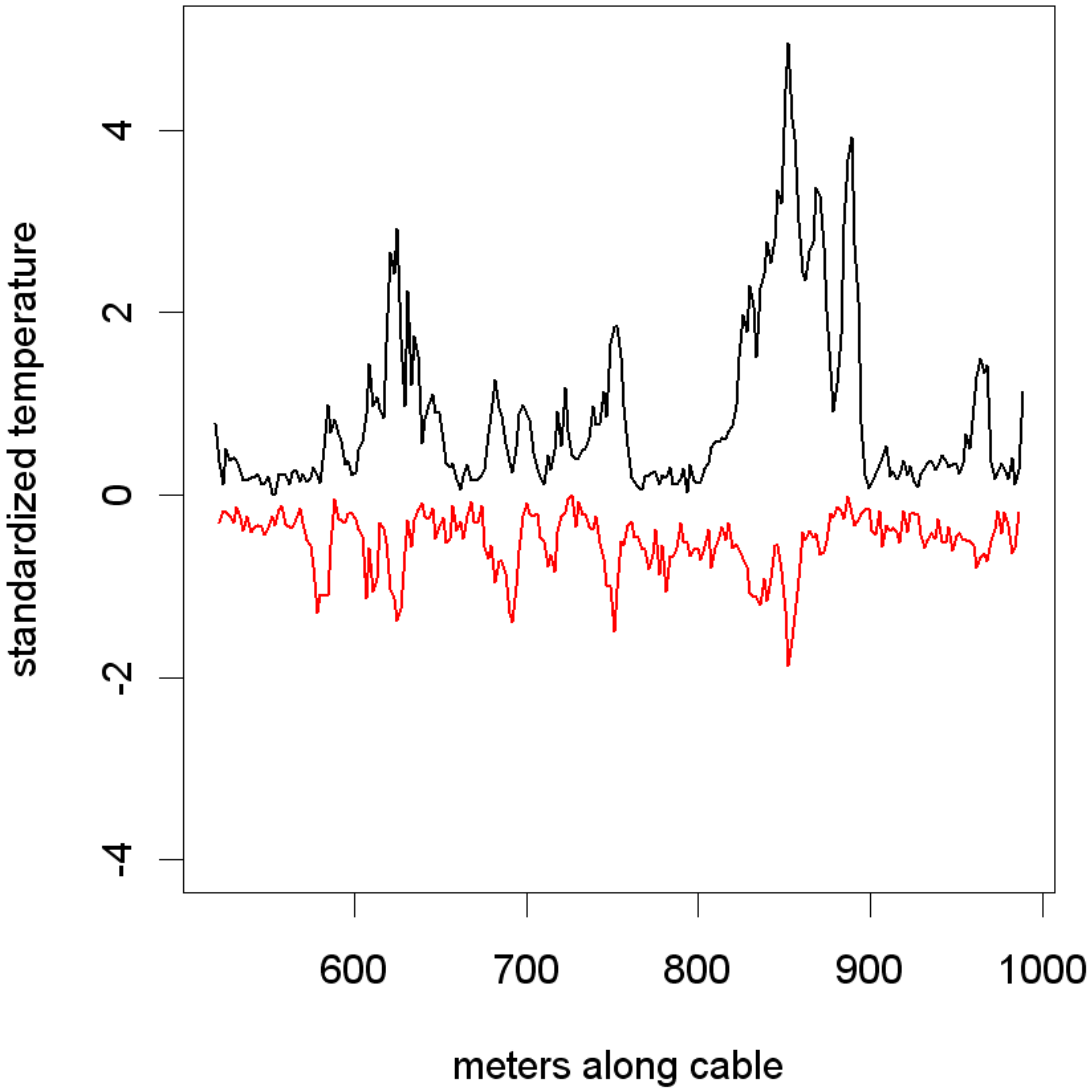
Winter



Krause et al., WRR submitted

Heat Tracer FO-DTS - Summer vs. Winter signal strength



Blume & Krause, in prep.

River Tern – Impact of Advective Pumping

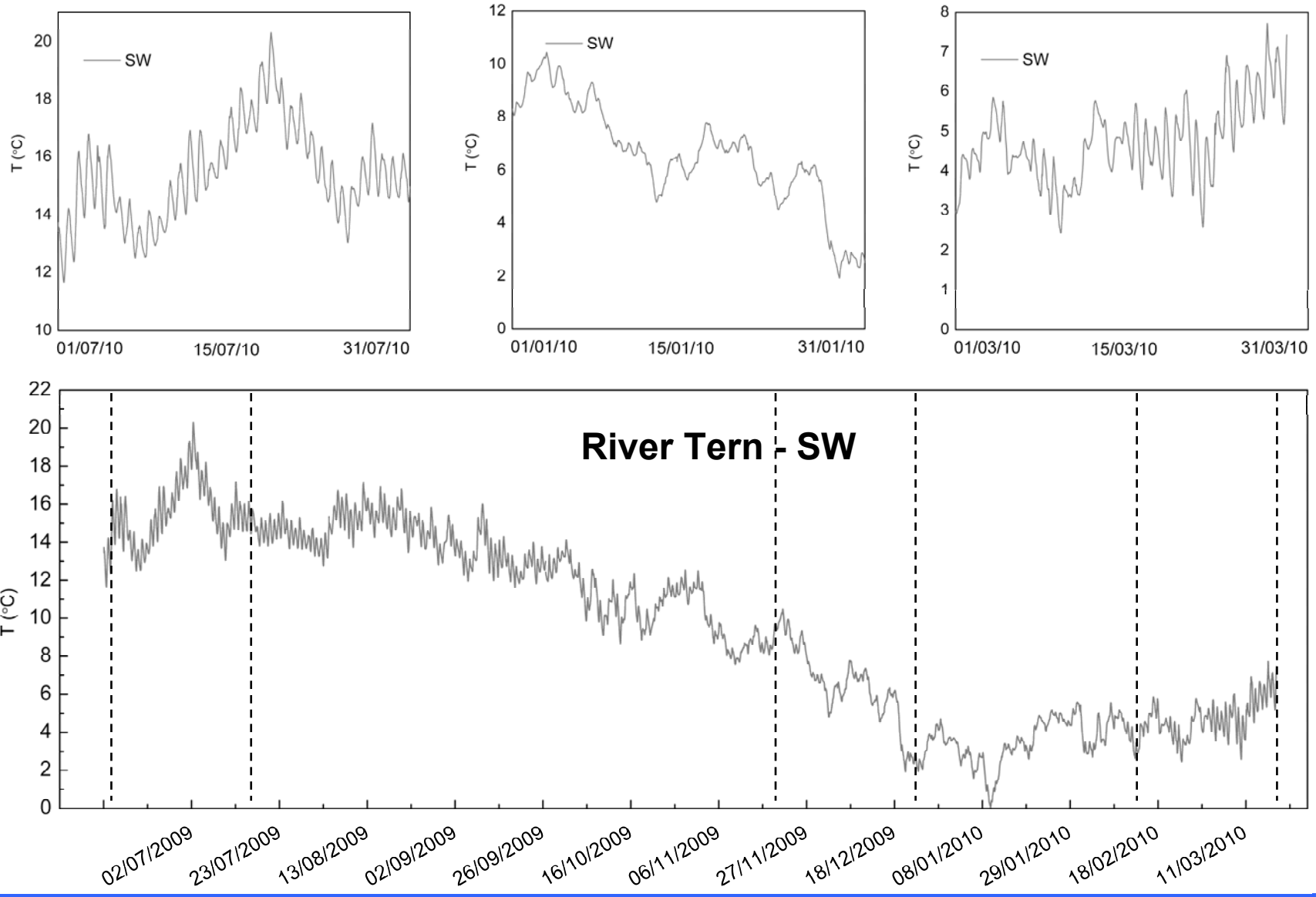
KEELE UNIVERSITY

Does streambed topography induced temperature modulation by advective pumping mask groundwater up-welling hotspots?

VHG observations: **only snap shot sampling, invasive, stage recorder size, expensive**

Alternative signals for determination of GW-SW exchange?

SW Temperature – Diurnal Signal Dynamics



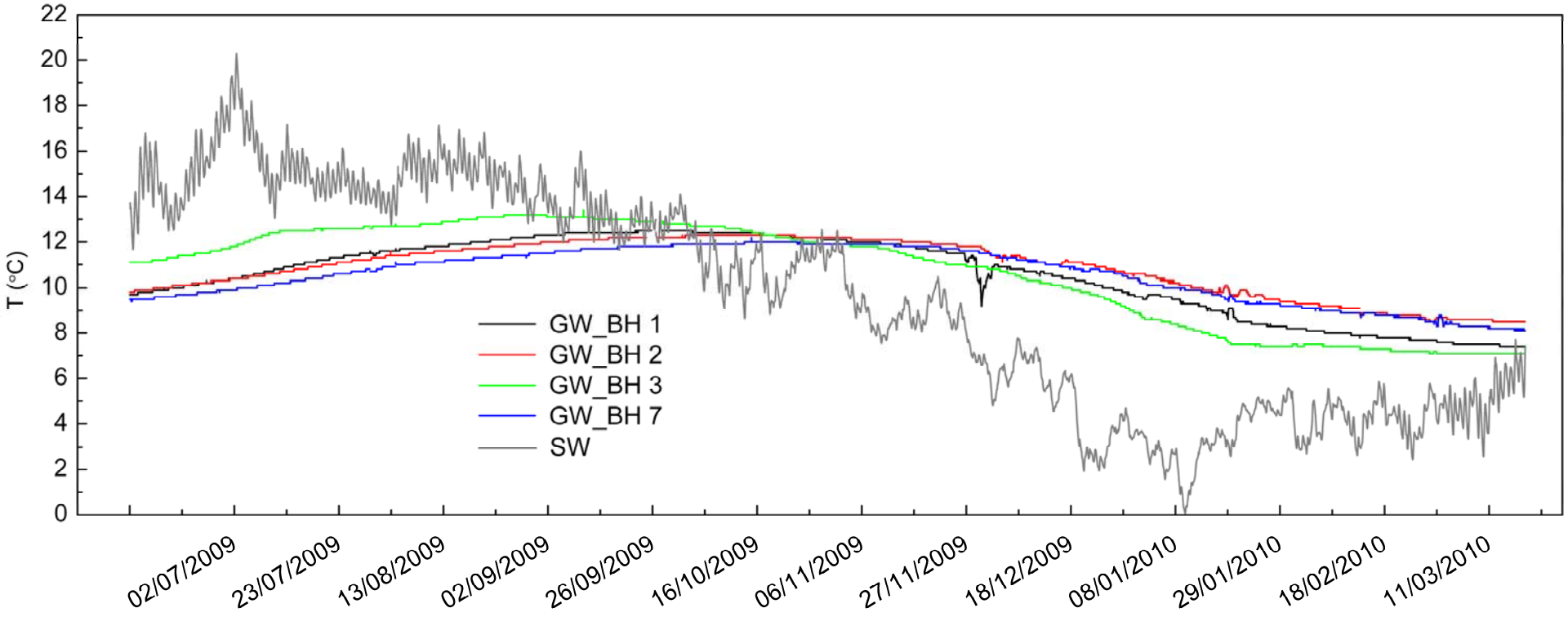
River Tern – SW vs. GW Temperature

KEELE UNIVERSITY

GW (relatively homogeneous) modulates SW diurnal patterns

Spatial variability in SW down-welling should impact streambed T patterns

How much does GW up-welling induced modulation of diurnal T signal vary spatially along prominent pool-riffle-pool feature?



Streambed geomorphology impact on HEF and interstitial temperature patterns

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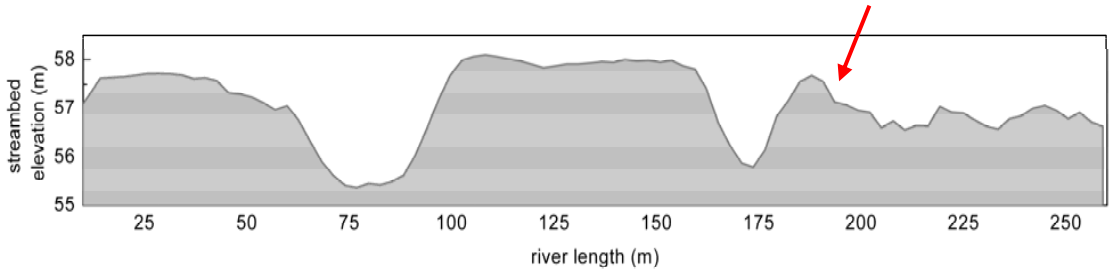
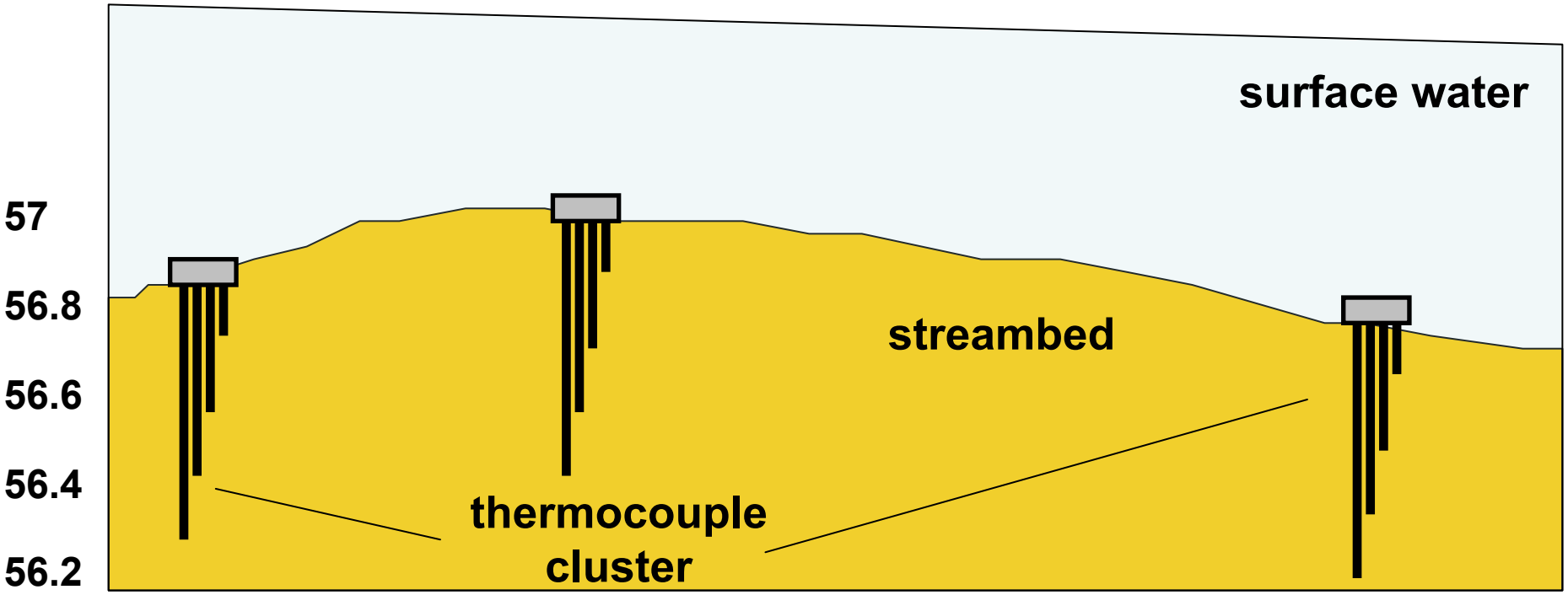
12 m longitudinal pool-riffle section

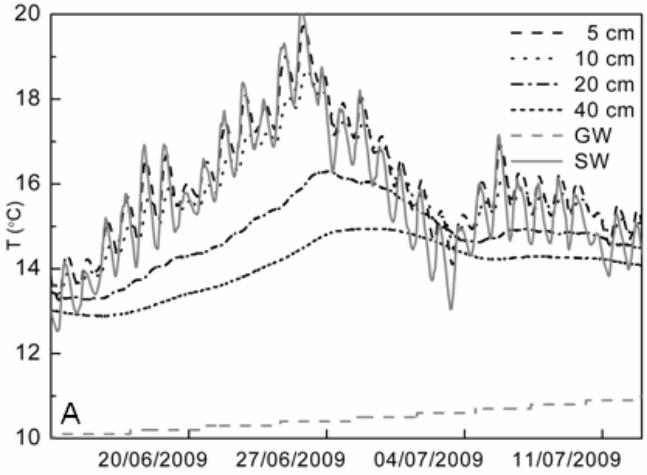
Three thermocouple clusters

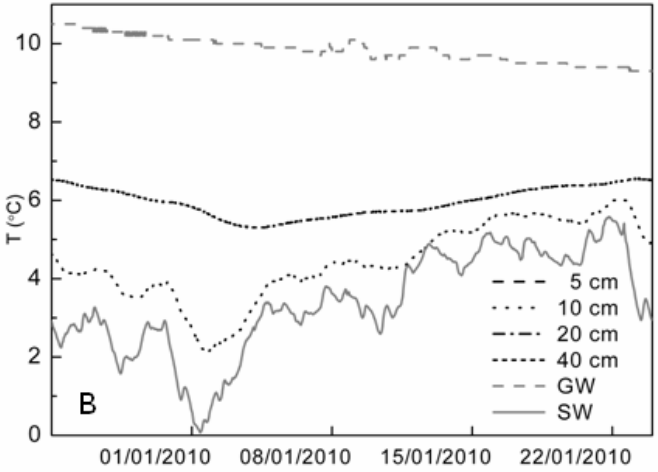
5–40 cm depth, streambed + GW

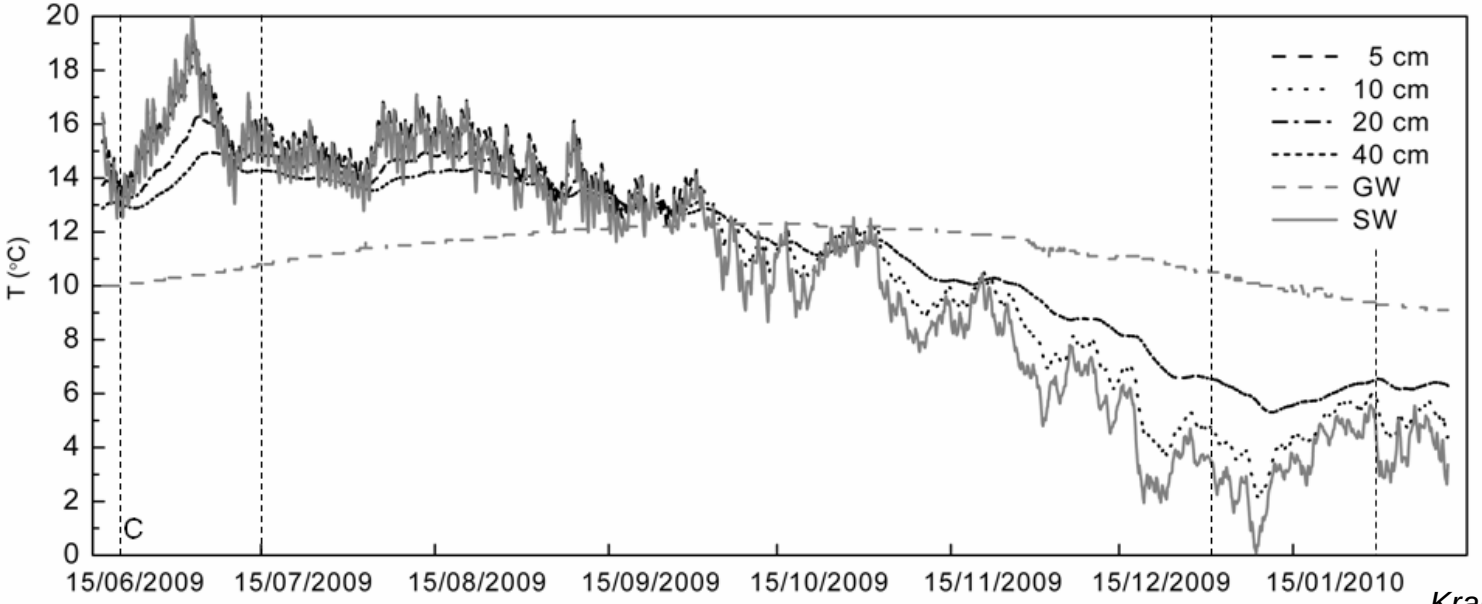




Streambed geomorphology impact on HEF and interstitial temperature patterns







Spatially variable modulation of diurnal T-signal

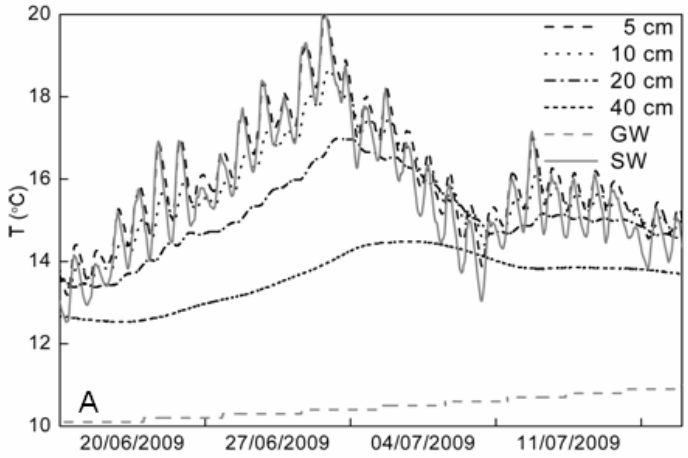
Dampening and offset of T oscillation

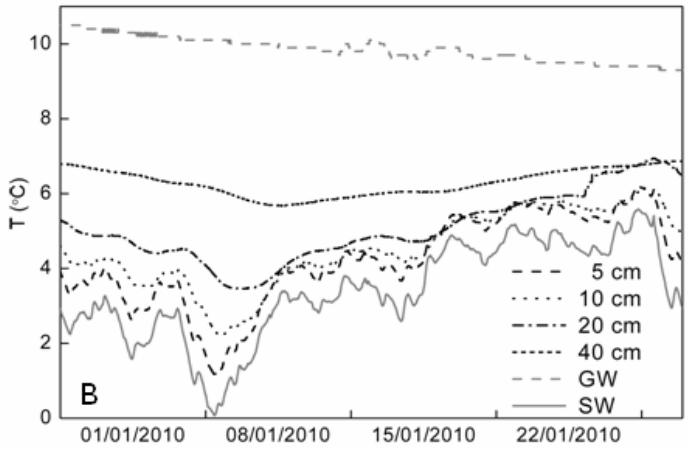
CCF = 4 - 36 hrs depth delay in signal progression

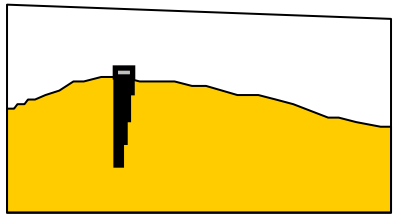
Lateral variability limited

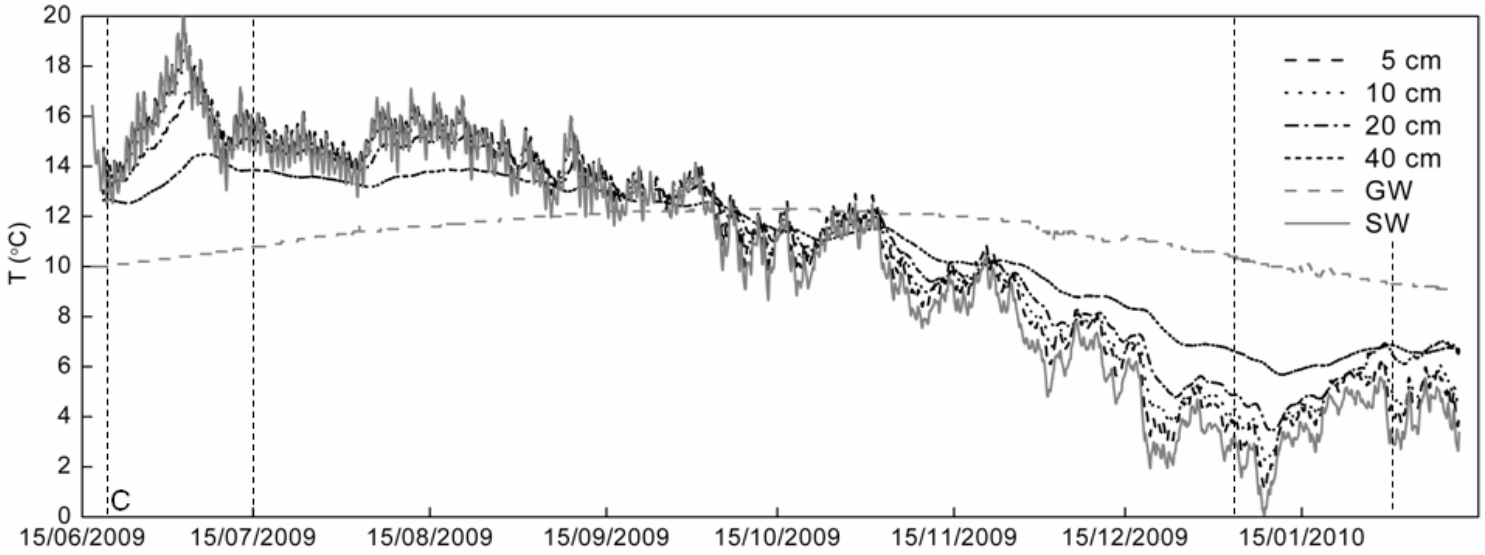
Krause et al. Ecohydrol. J. 2011a

Streambed geomorphology impact on HEF and interstitial temperature patterns









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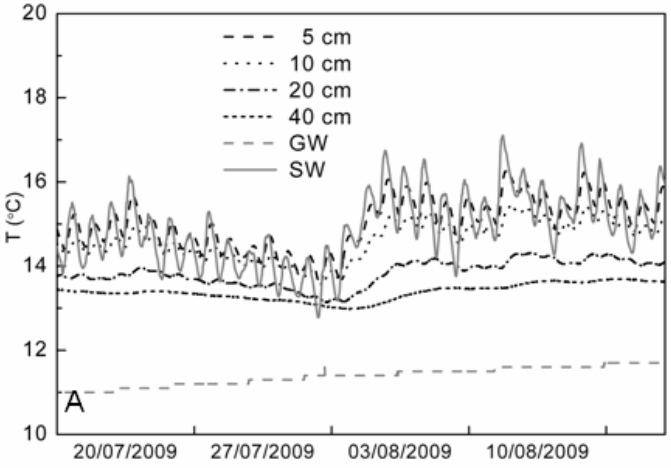

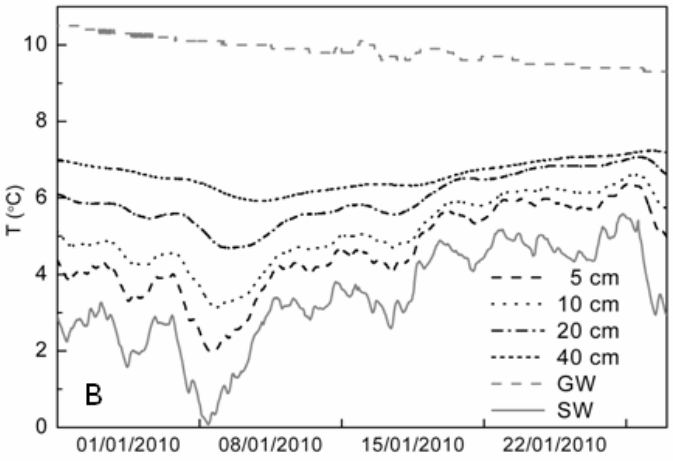

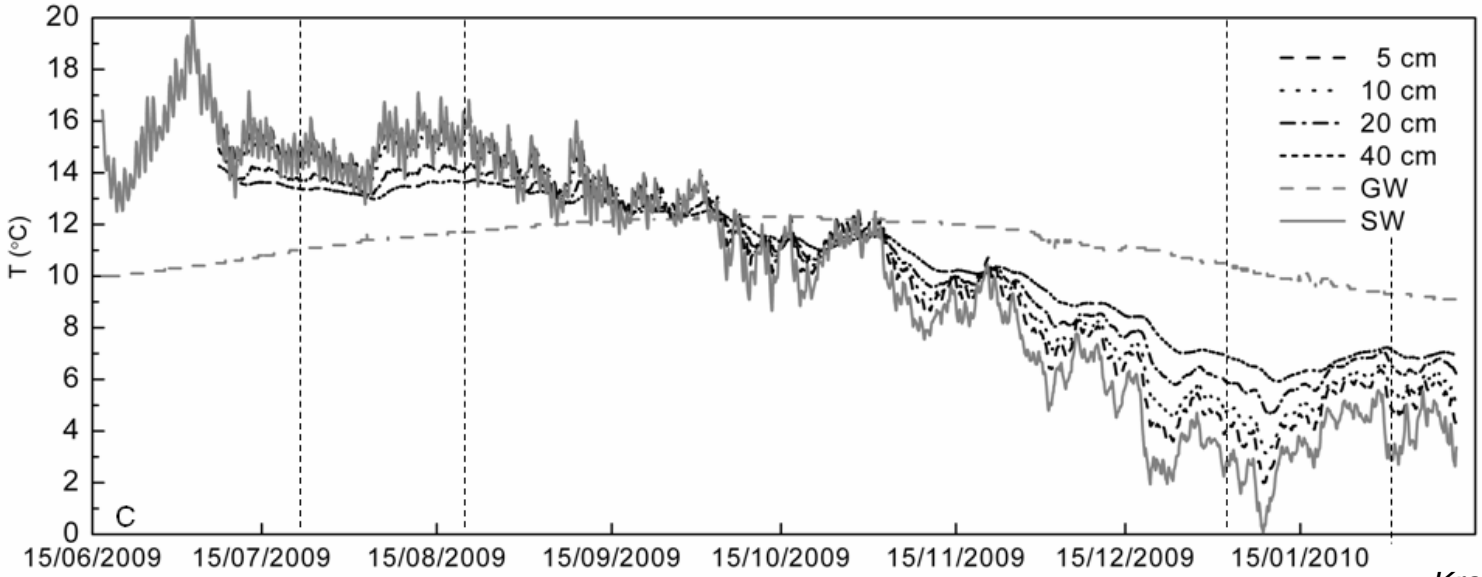

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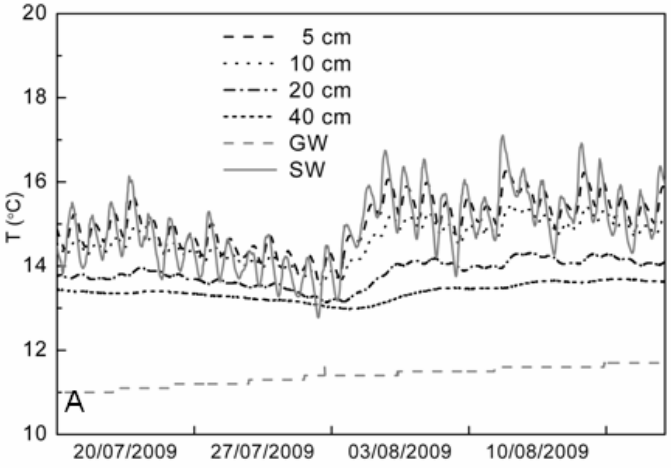
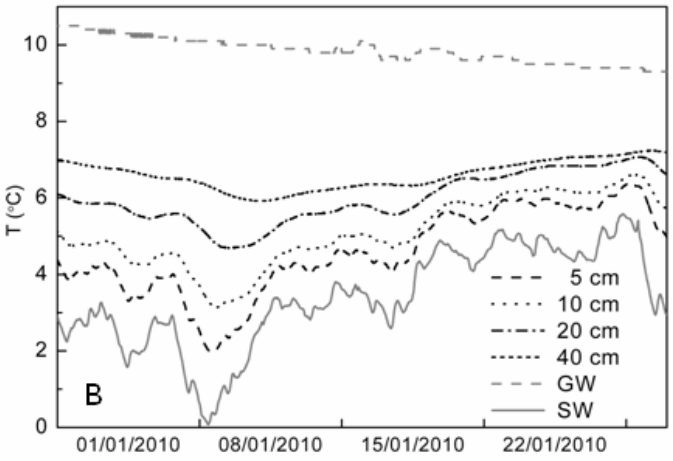
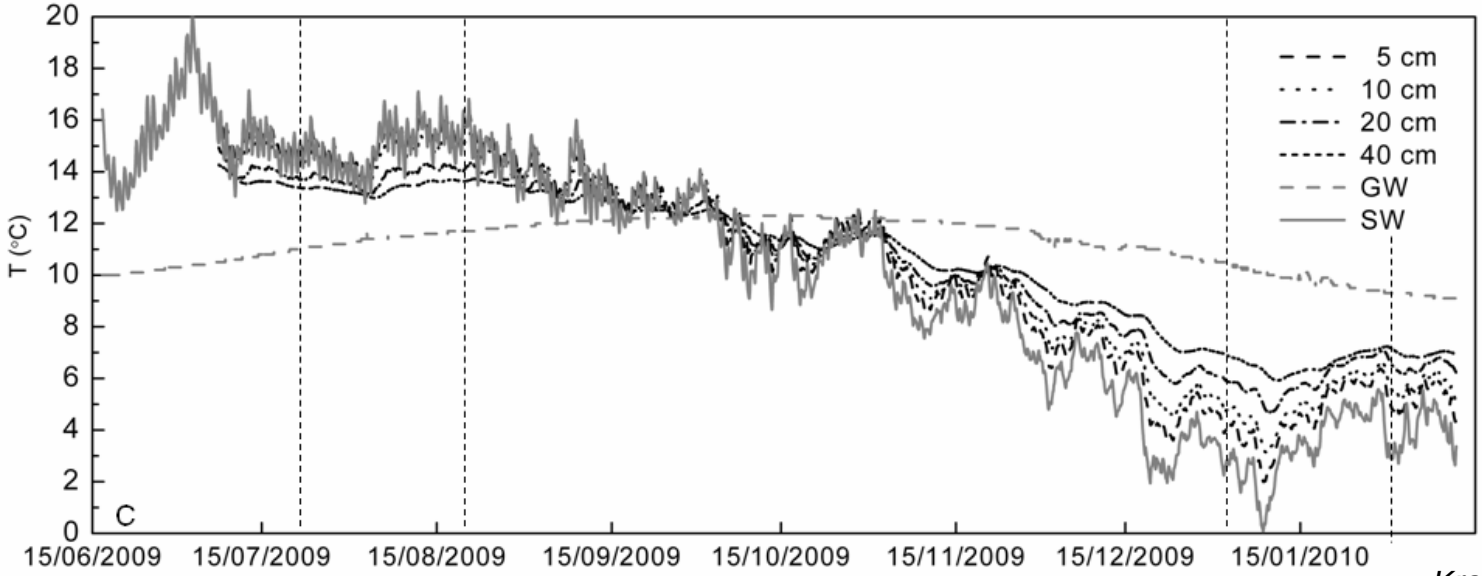






No evidence for advective SW flow > 5 cm

Signal transport by heat conduction from streambed surface – dampened by GW advection

Max lateral T variability < 0.3 °C

Krause et al. Ecohydrol. J. 2011a

Heat Tracers Active Heat Pulse Injection

Lisa Angermann - IGB-Berlin

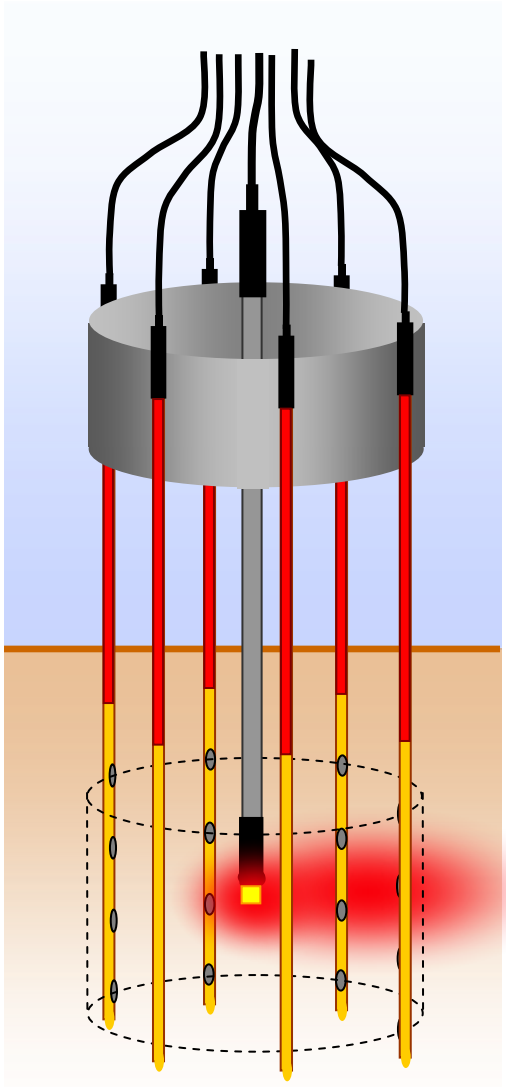
KEELE UNIVERSITY

Near surface hyporheic exchange fluxes:

Increased lateral pore water flow at locations with inhibited GW up-welling?

24 Thermocouples spaced around central heater

Depths up to 25 cm in four focus areas



Heat Tracers Active Heat Pulse Injection

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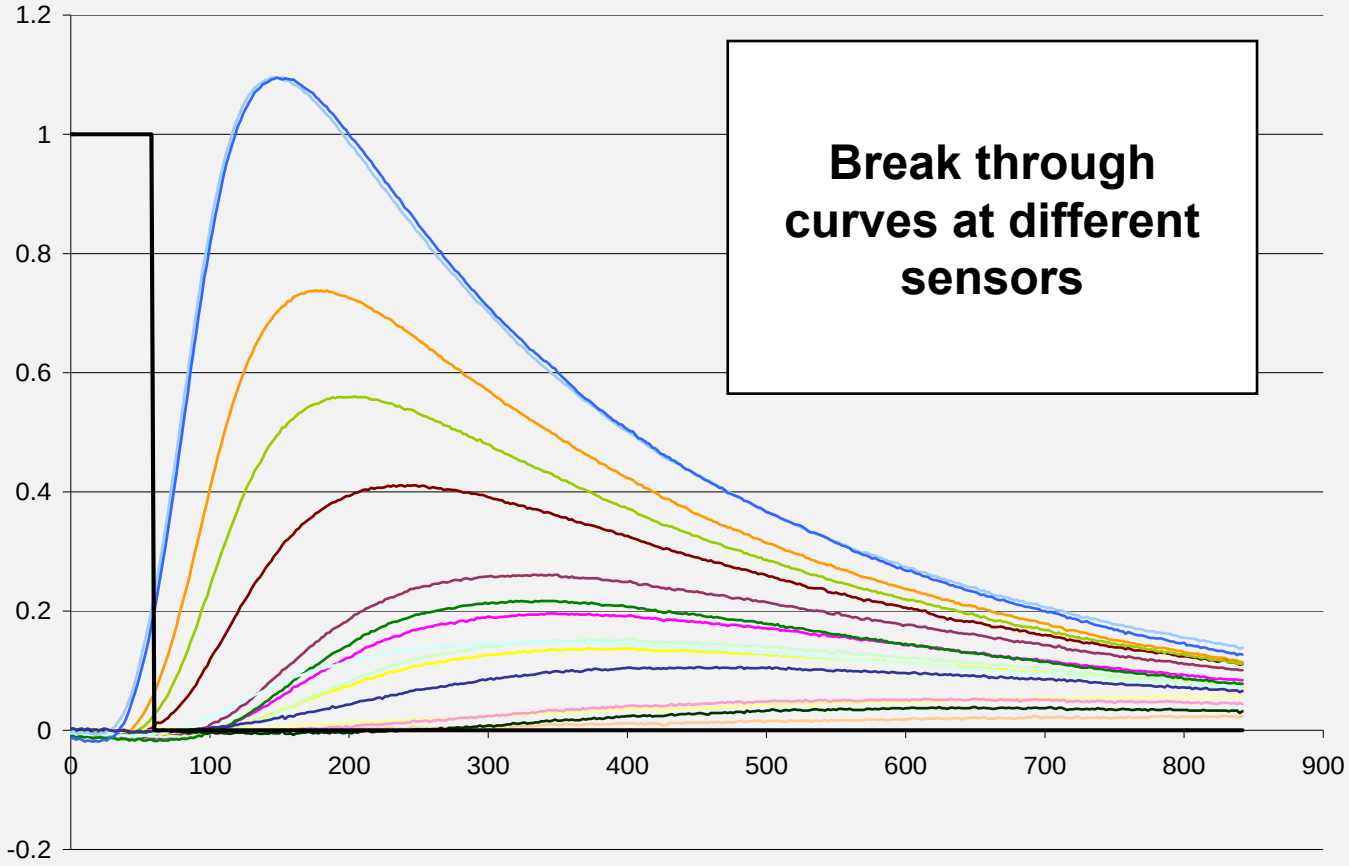
Near surface hyporheic exchange fluxes:

Increased lateral pore water flow at locations with little GW up-welling?



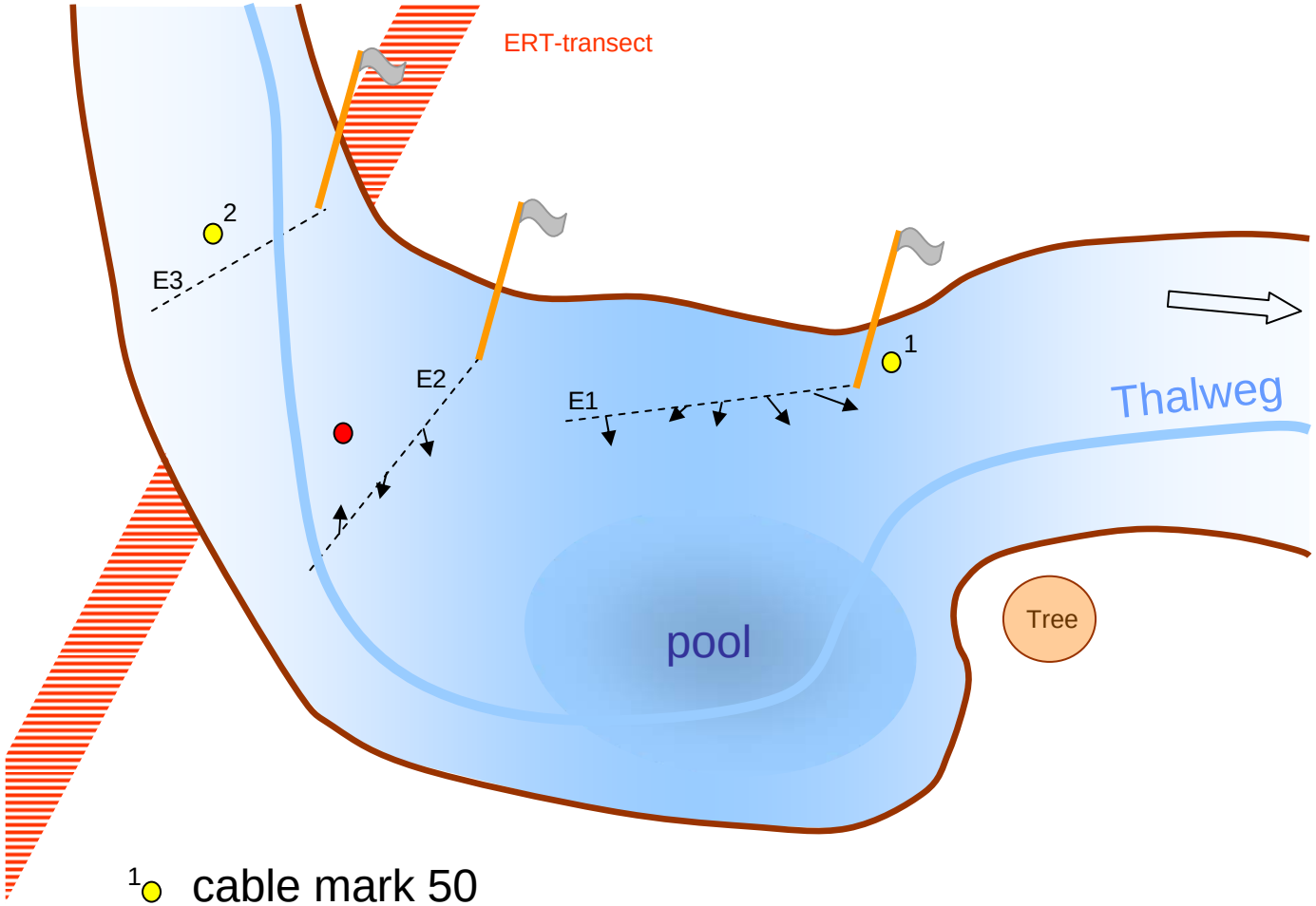
Determination of

- flow direction

- flow velocity

Angermann et al. in prep.

T-race - River Tern - results



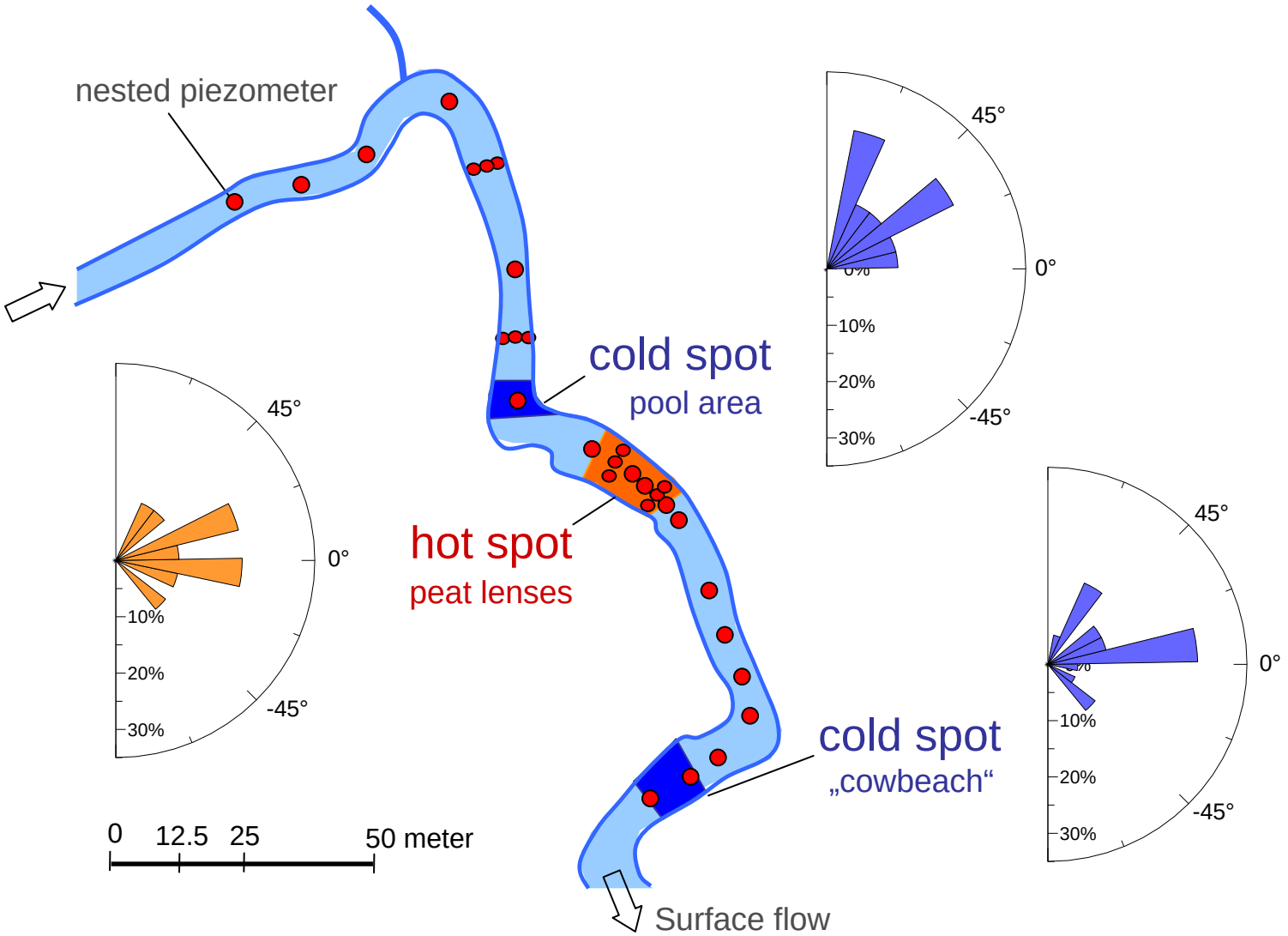
[1] cable mark 50

[2] cable mark 4740

piezometer

Angermann et al. in prep.

T-race - River Tern - results



Angermann et al. in prep.

Heat Tracers Summary

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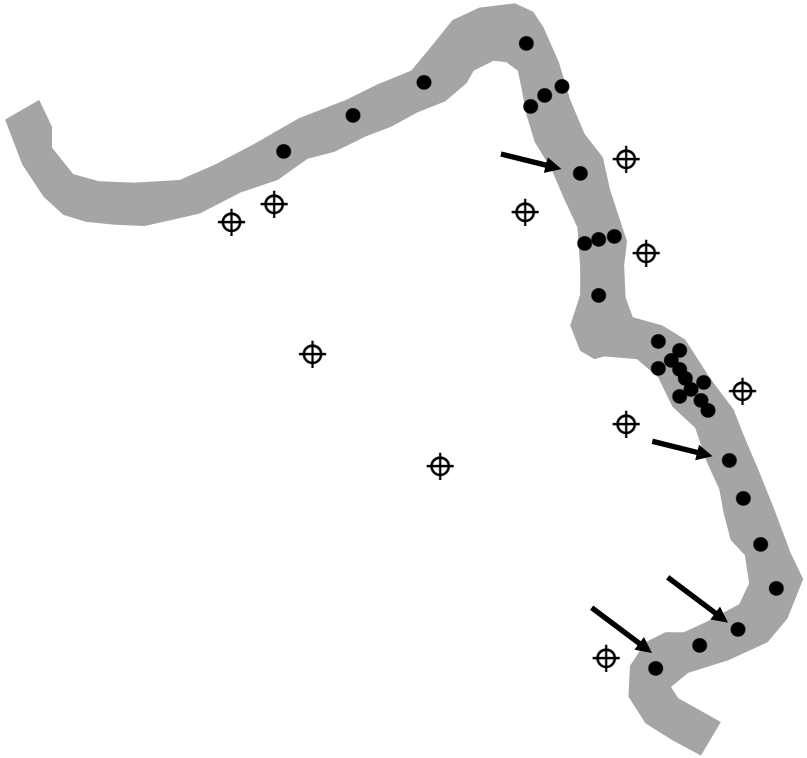
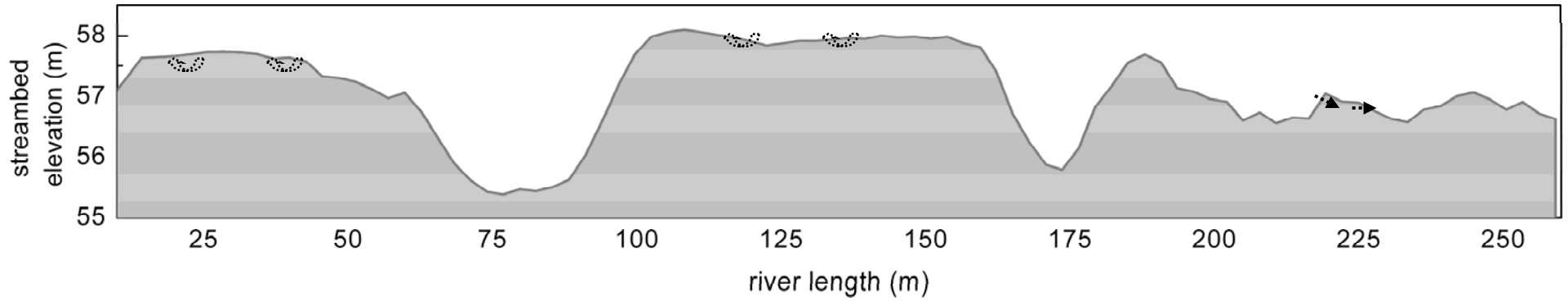
Heat pulse injection:

- **Superficial flow paths**
- **Lateral GW-fluxes**





Heat Tracers Summary

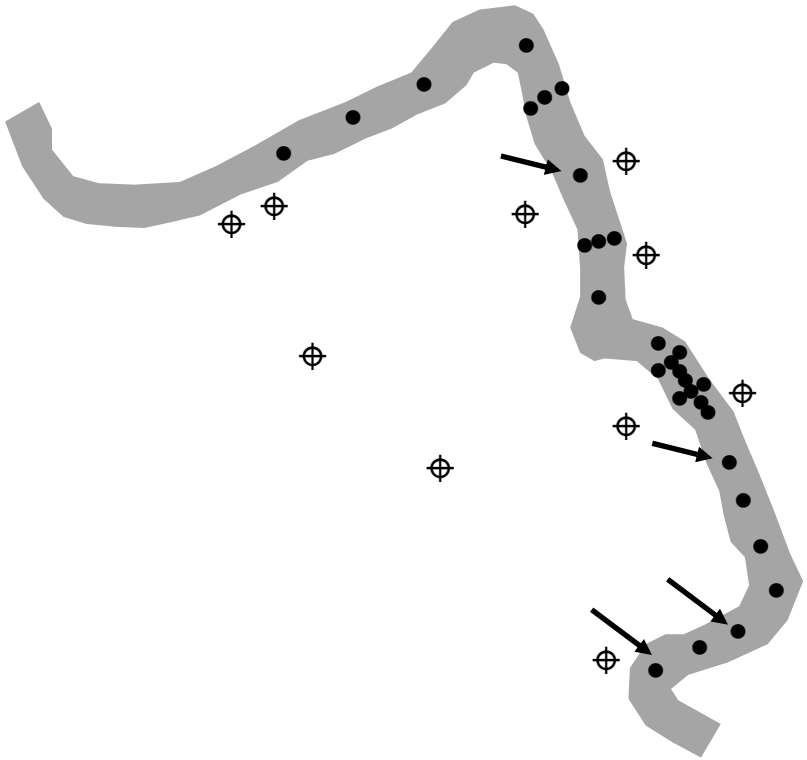
KEELE UNIVERSITY

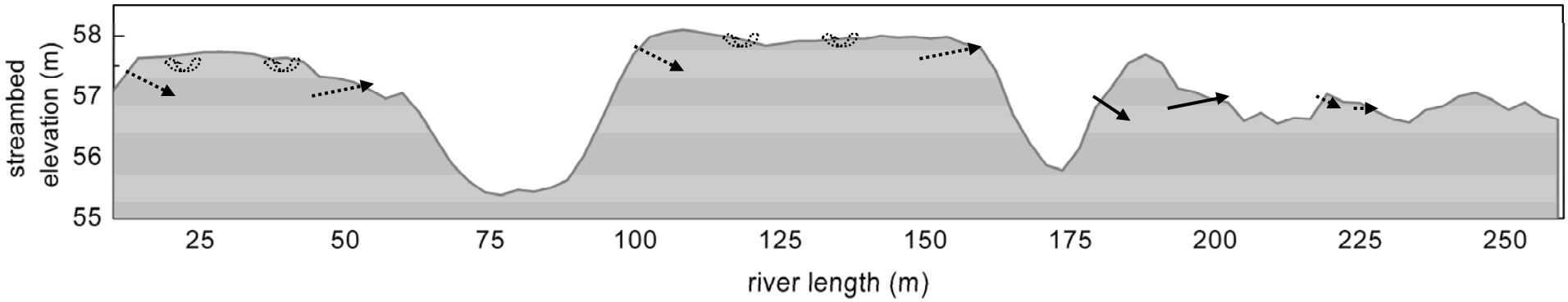
Heat pulse injection:

- **Superficial flow paths**
- **Lateral GW-fluxes**

Thermocouple clusters:

- **HZ-exchange in pool-riffle sequences**
- **Signal dampening + offset for 2-D advective heat flow modelling**





Heat Tracers Summary

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Heat pulse injection:

- Superficial flow paths
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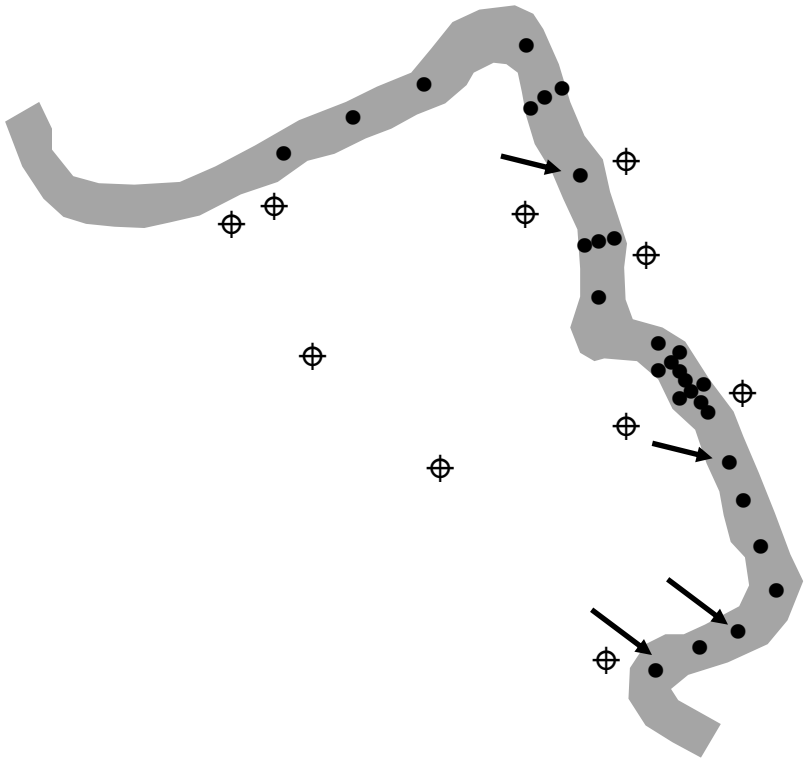
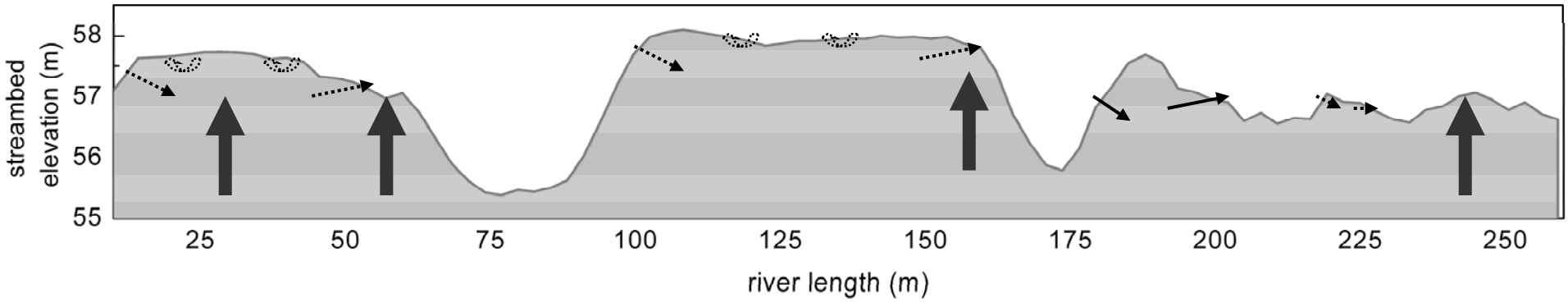


Thermocouple clusters:

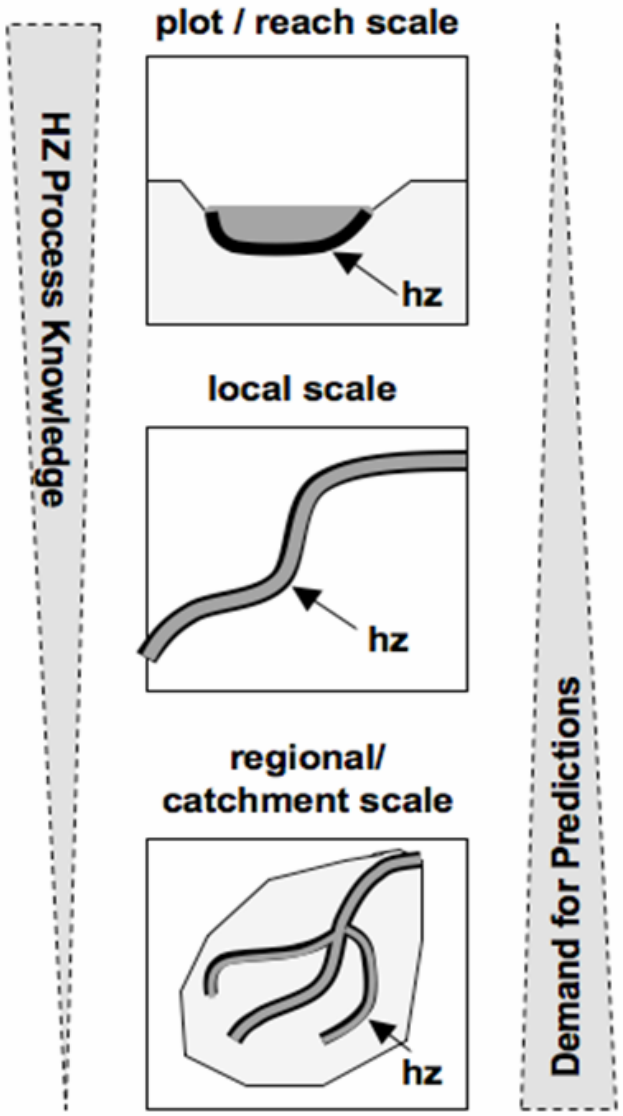
- HZ-exchange in pool-riffle sequences
- Signal dampening + offset for 2-D advective heat flow modelling

FO-DTS:

- Regional GW up-welling
- Spatial/temporal patterns



Future Challenges – Up-scaling HEF



Process Up-scaling

Need to identify the scale dependency of HZ-impacts on aquifer-river exchange and biogeochemical cycling

Quantification of large-scale implications of HZ processes on groundwater and surface water resources

Adaptive Modeling Techniques

Conditioning of stochastic parameterisation approaches for the representation of model boundary conditions and hydro-facies

Conditioned by distributed sensor network information at 'control section'

Krause et al. Ecohydrol. J. 2011

Thank You

Thanks to:

- N. Cassidy, E. Naden, T. Millington, I. Winfield, J. Weatherall (Keele University)
- F. Day-Lewis (USGS)
- A. Binley (Lancaster University)
- T. Blume (GFZ - Helmholtz Research Centre forGeoscience, Potsdam)
- L. Angermann, J. Lewandowski (Inst. f. Freshwater Ecology, Berlin)
- C. Tecklenburg, M. Munz (Potsdam University)
- D.M. Hannah (Birmingham University)
- K. Voyce (Environment Agency)