Hot Spots and Hot Moments of Biogeochemical Cycling at Aquifer-River Interfaces

Stefan Krause

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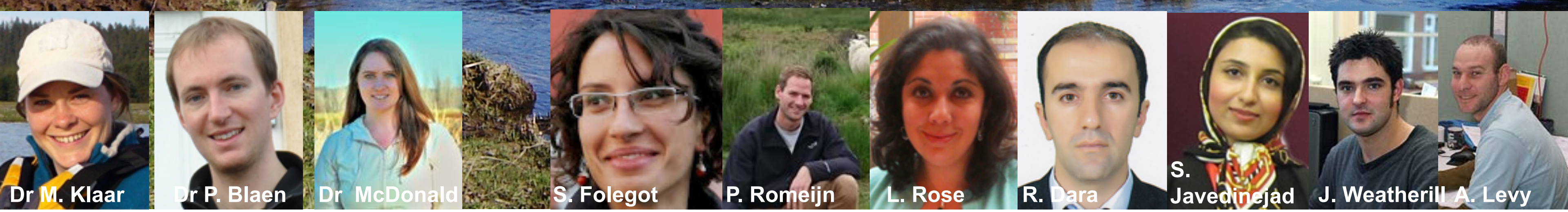

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TERENO
TERRESTRIAL ENVIRONMENTAL OBSERVATORIES

Functional Significance of Aquifer-River Interfaces

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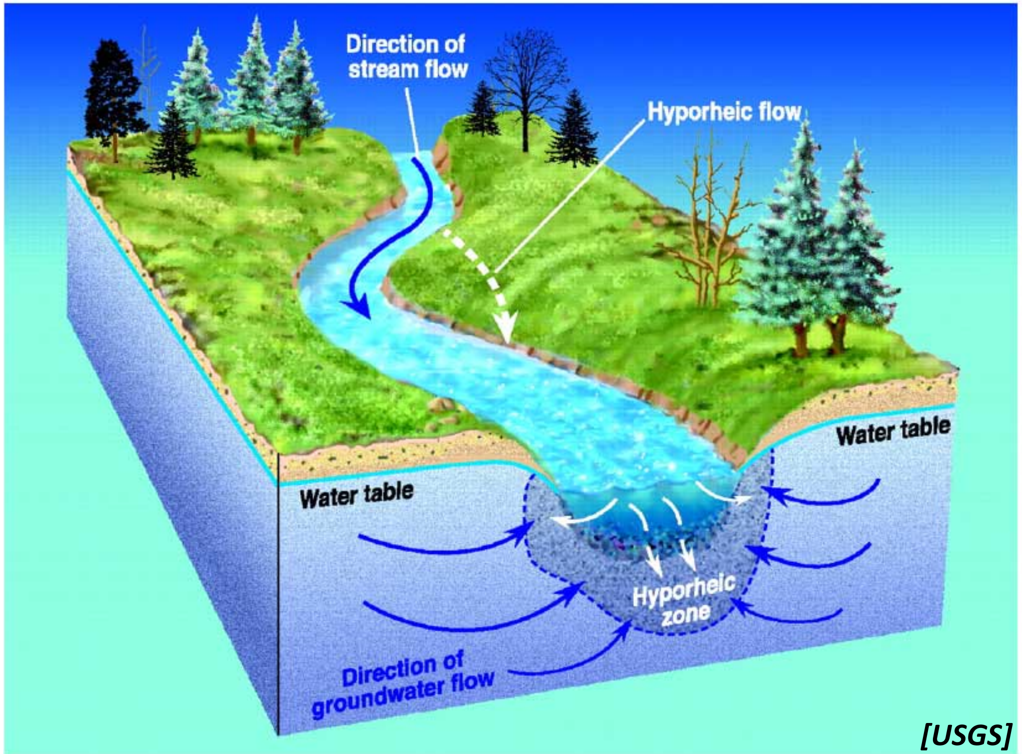
Biogeochemical Reactor

Dynamic Habitat

Flow / T - Control



Habitat and refugia for a range of organisms:

- *moderation of extremes in temperatures, water stress and chemical status*

Zone of enhanced biogeochemical cycling of nutrients and contaminants:

- *Organic rich hyporheic + riparian sediments, local anoxia*
- *Limited understanding of spatial patterns and scales, temporal dynamics*

Aquifer-River Interfaces as Biogeochemical Hotspots

Ecosystems (2003) 6: 301–312
DOI: 10.1007/s10021-003-0161-9
ECOSYSTEMS
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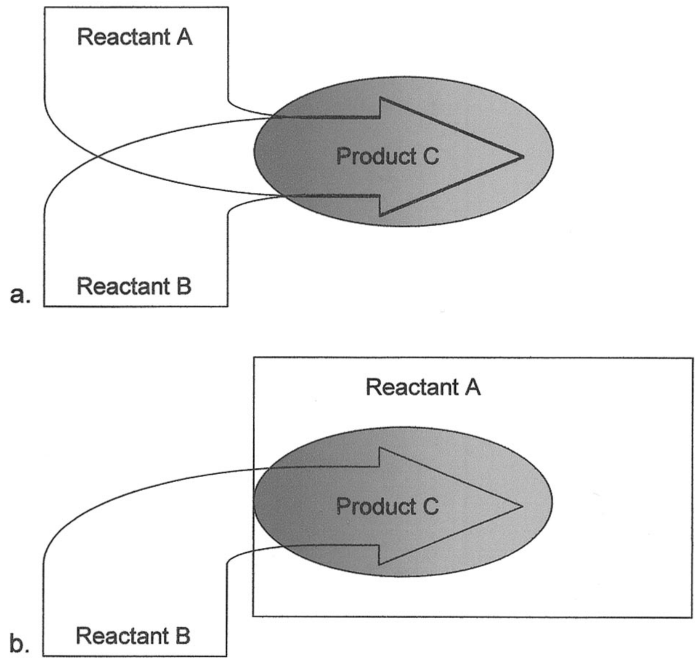
COMMENTARY

Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems

Michael E. McClain,[1*] Elizabeth W. Boyer,[2] C. Lisa Dent,[3] Sarah E. Gergel,[4] Nancy B. Grimm,[5] Peter M. Groffman,[6] Stephen C. Hart,[7] Judson W. Harvey,[8] Carol A. Johnston,[9] Emilio Mayorga,[10] William H. McDowell,[11] and Gilles Pinay[12]



Biogeochemical hotspot:

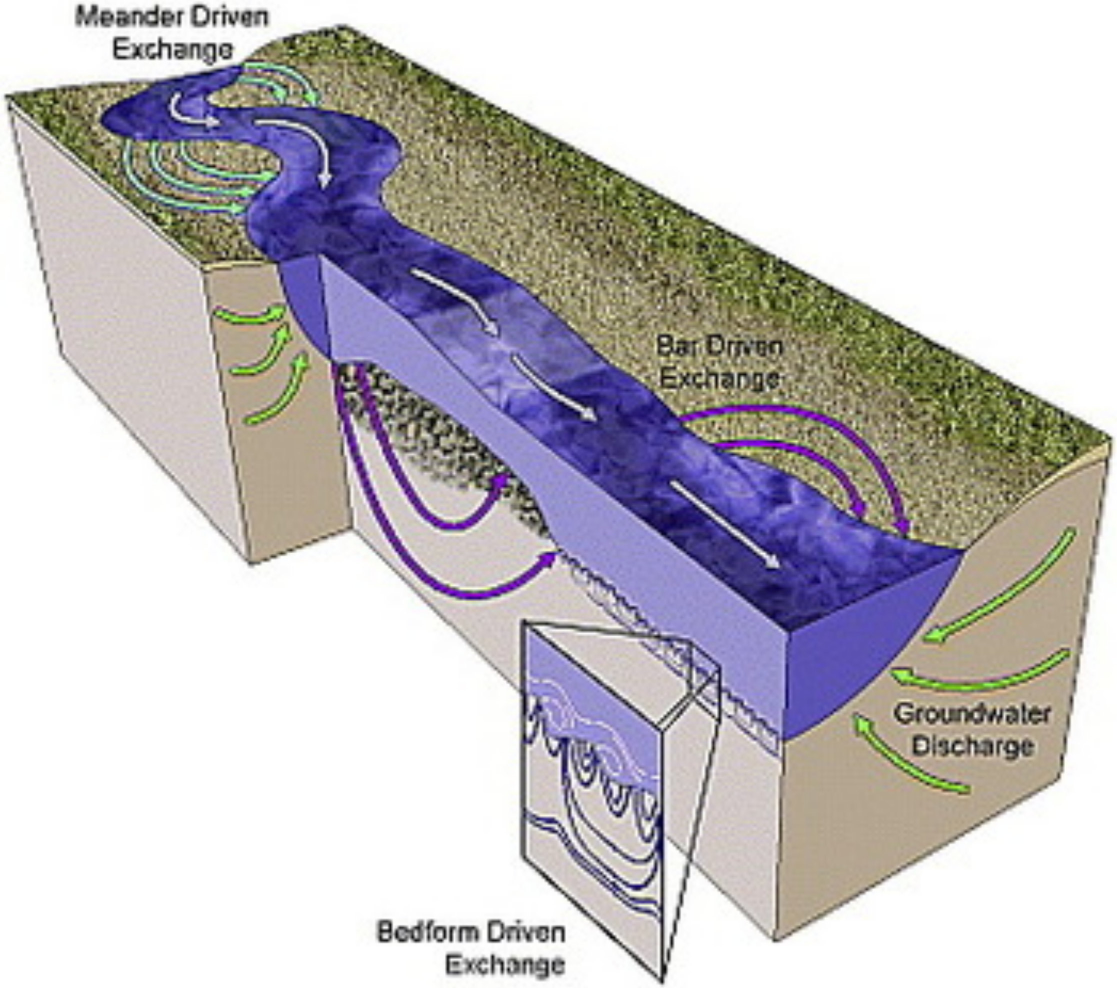
(a) convergence of hydrologic flowpaths carrying complementary reactants

(b) flowpath carries reactant A into a substrate containing reactant B

So hyporheic zones are cleaning our rivers and groundwater?

Drivers and Controls of Hyporheic Exchange Flow (HEF)

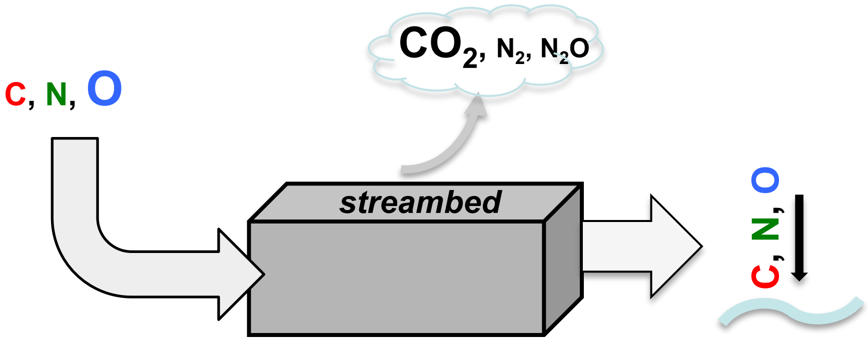
Drivers of HEF at multiple scales



[Stonedahl et al., 2010]

Bardini et al., 2012; Boano et al., 2007; Cardenas et al., 2004, 2008; Endreny & Lautz 2011 a,b, 2012; Kasahara & Wondzell, 2003; Lautz et al., 2010; Stonedahl et al., 2010; Thibodeaux & Boyle, 1987; Tonina & Buffington, 2007....

Headwaters to mid-stream sections:



A

Challenging Current Concepts of Hyporheic Biogeochemical Cycling

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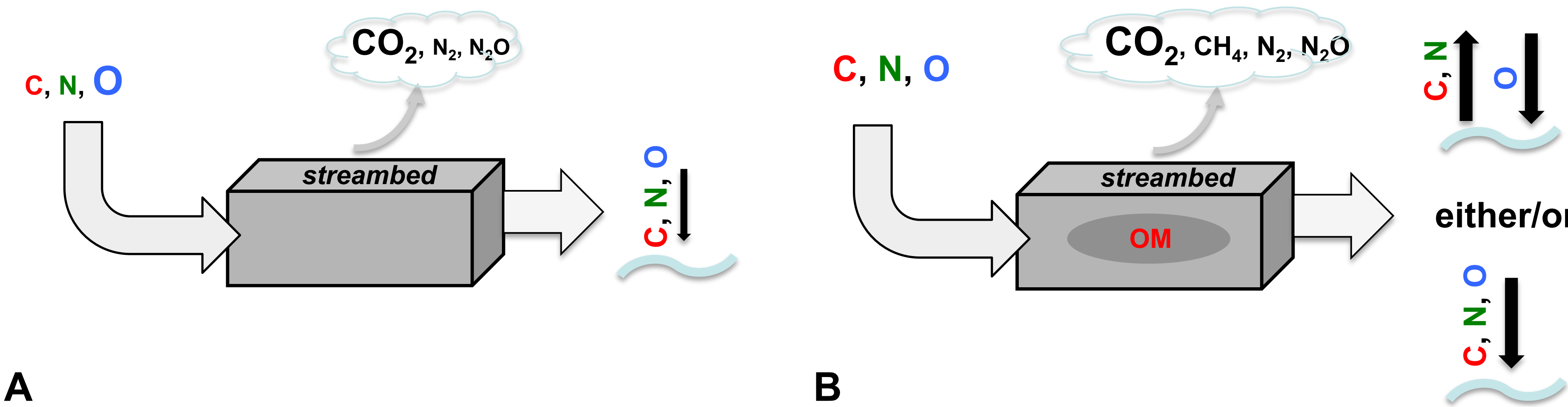
Headwaters to mid-stream sections:



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Challenging Current Concepts of Hyporheic Biogeochemical Cycling

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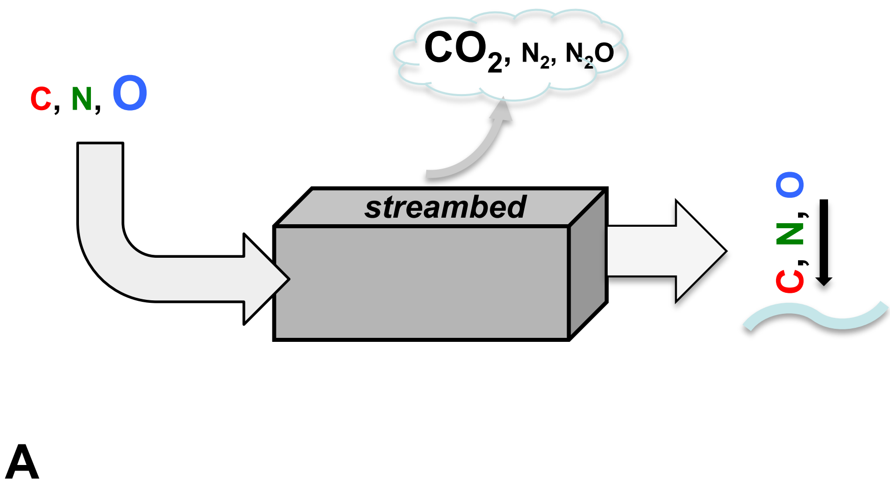
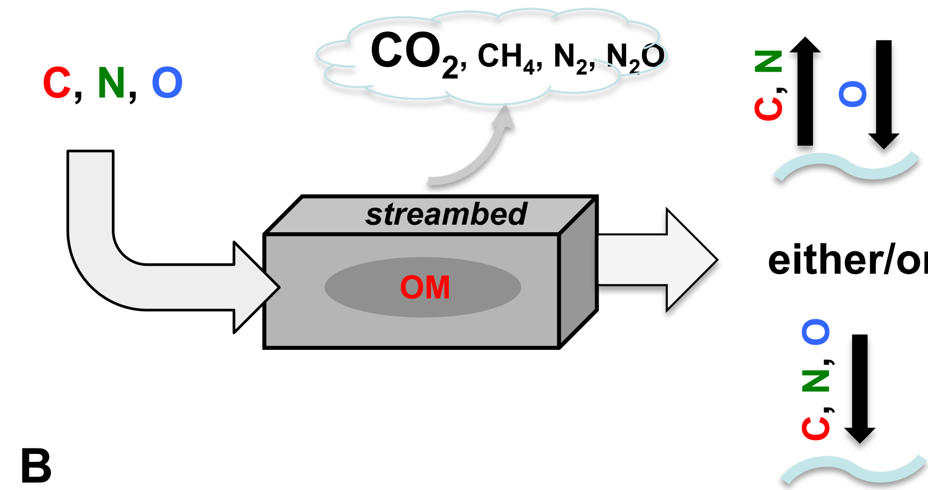
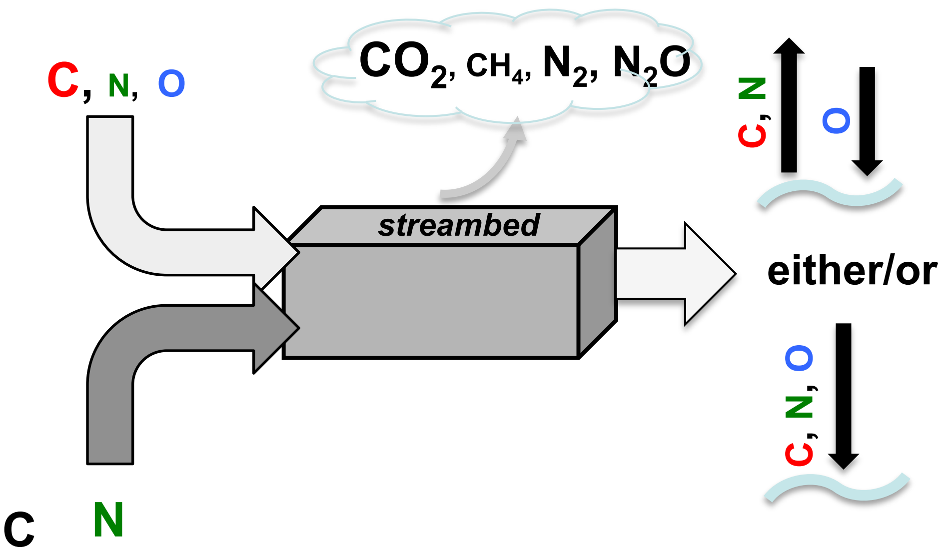




Mid-stream sections to lowland rivers:



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Challenging Current Concepts of Hyporheic Biogeochemical Cycling

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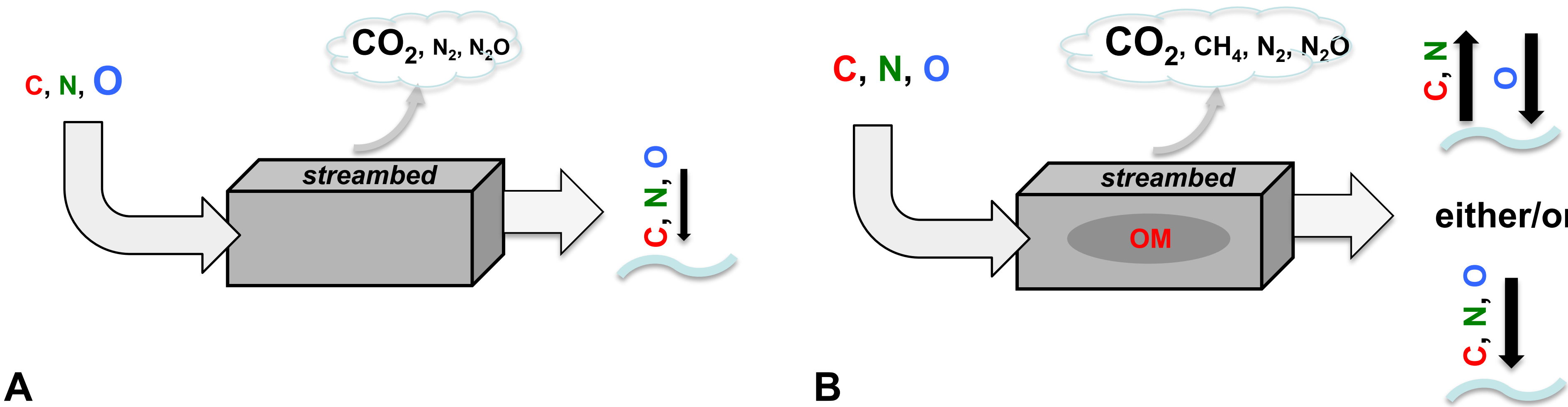

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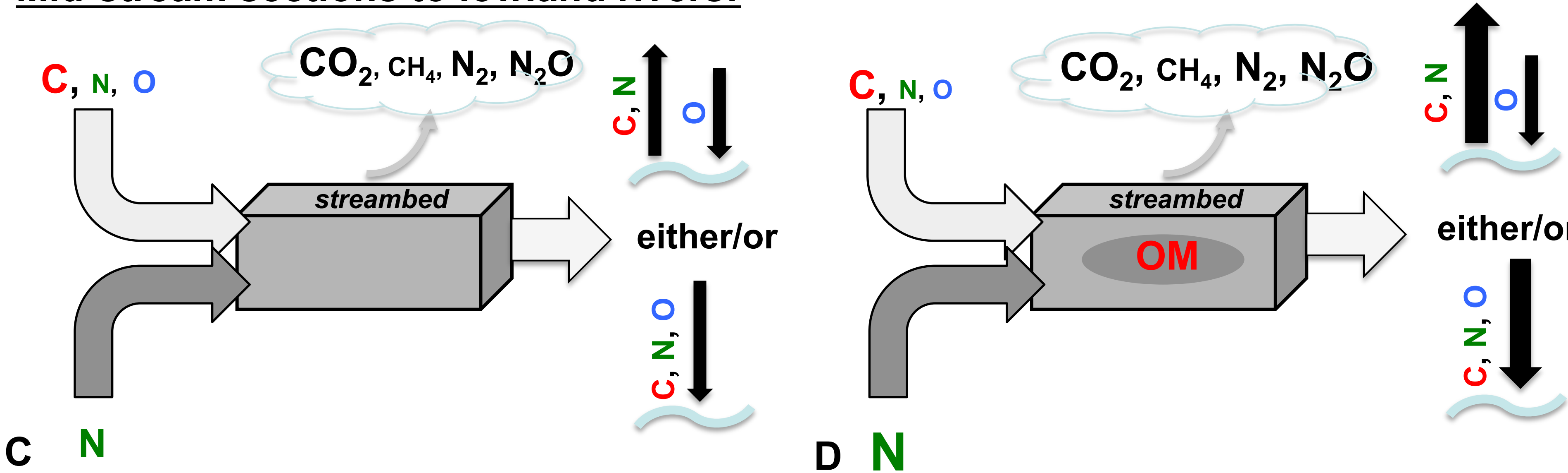

Biogeochemical Cycling in Complex Hypoheic Zones

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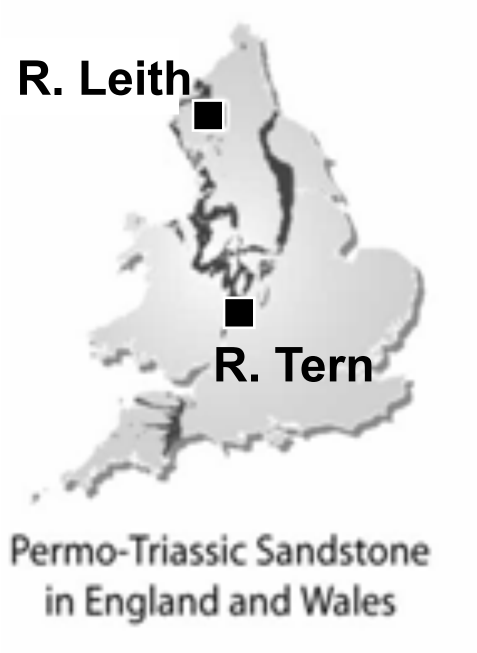
HZ nutrient transformation in up-welling GW



Quantifying the impact of small-scale streambed heterogeneity on hotspots of biogeochemical turnover

Geophysical surveys (ERT, GPR)

Multiple tracer tests (reactive, conservative)

Nested multi-level piezometer, diffuse gel-samplers (passive)

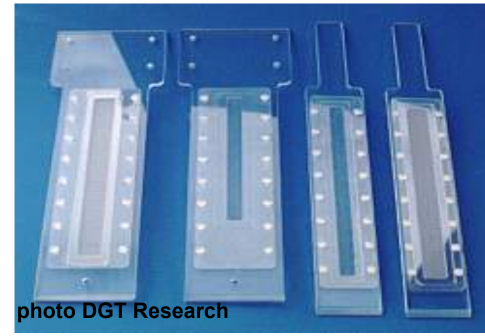
Multi-component reactive transport (TCE, NO_3, NH_4, TN/TON, DO)

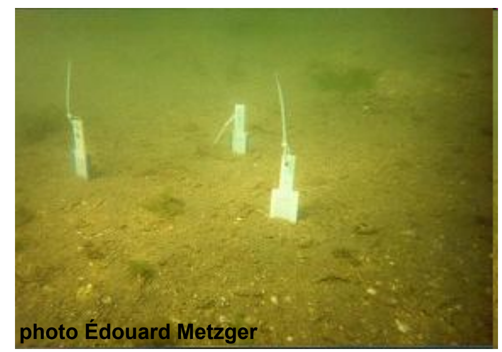
Distributed sensor networks (FO-DTS), Heat Pulse Sensors

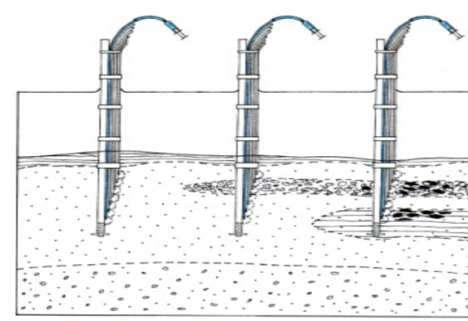
Coupled groundwater-surface water models (stream reach - sub-catchment)

Multi-piezometer sampling – Active heat pulse tracer

Diffuse Equilibrium in Thin films (DET) Passive Gel Samplers







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Biogeochemical Cycling in Complex Hypoheic Zones

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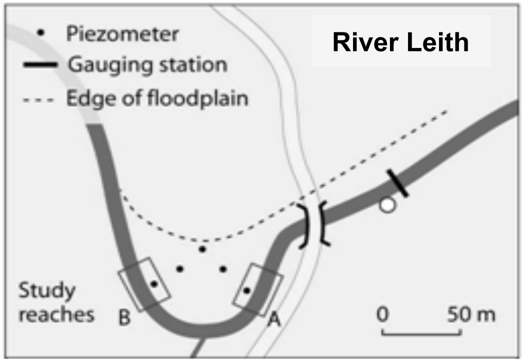
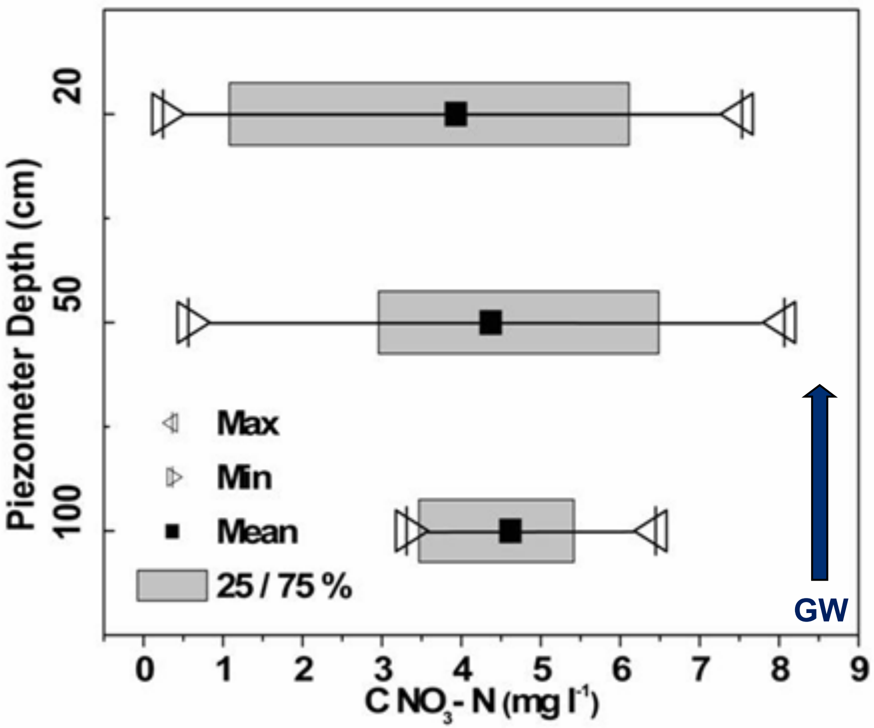
Change of nitrate concentrations in up-welling groundwater

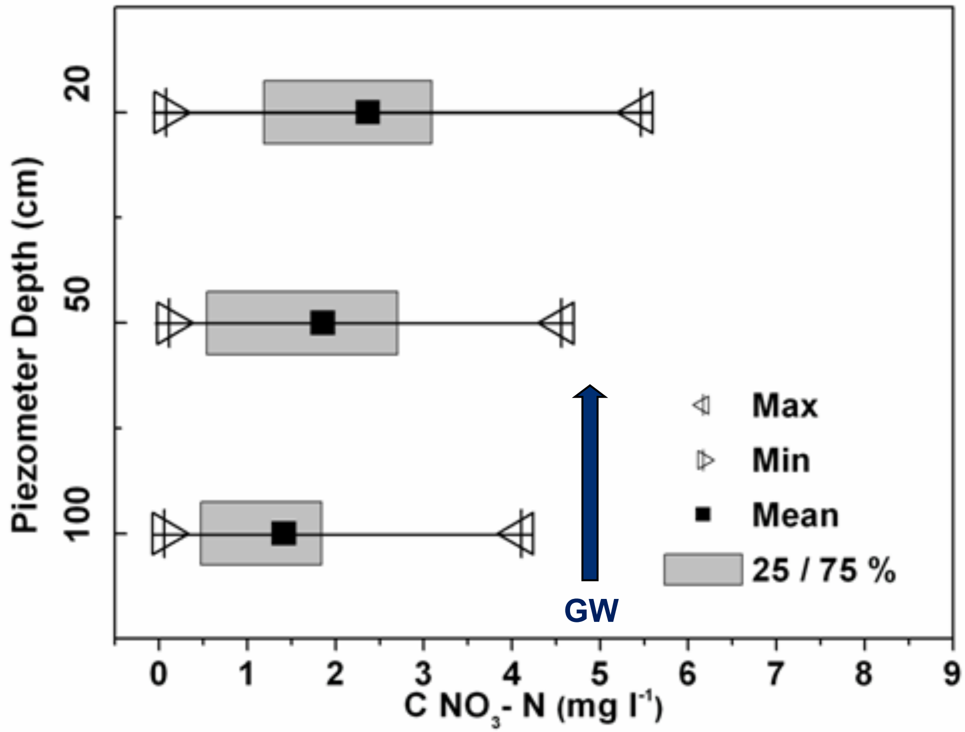
Not just a matter of nitrate attenuation!



Leith A



Leith B



[Krause et al. HP 2009]

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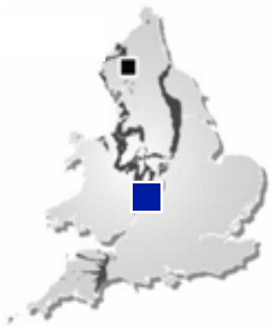
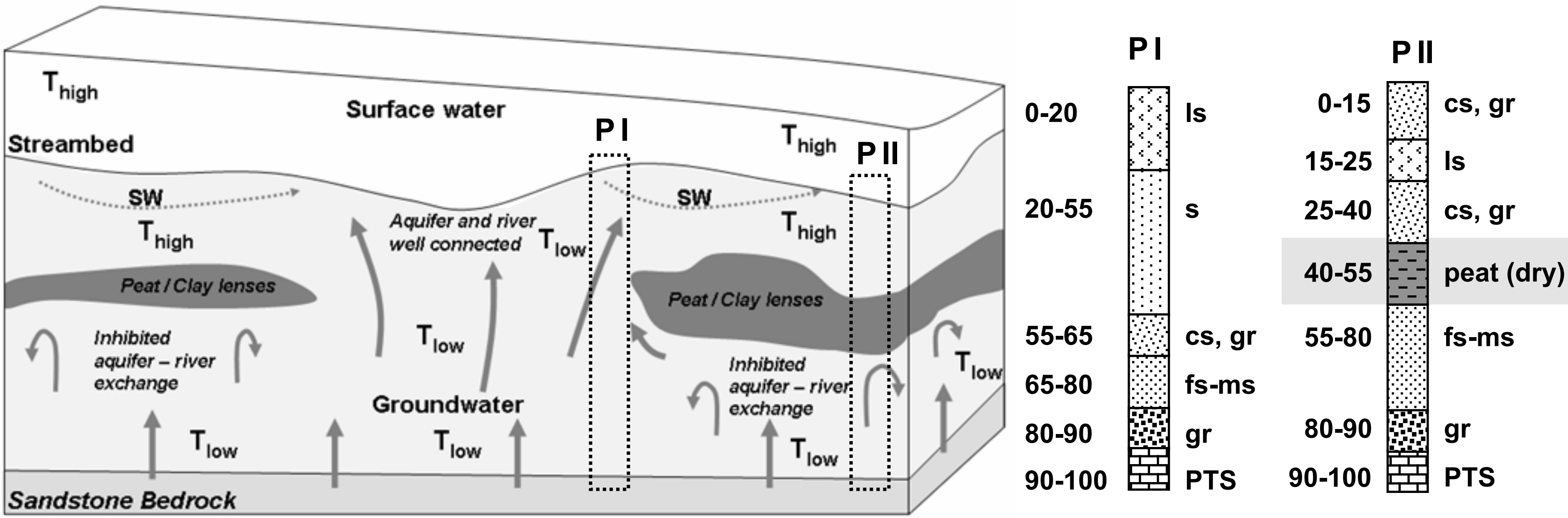
Hot moments and hot spots of HZ reactivity

- Increased reactivity (NO_3, TCE decay) in confined streambed locations
- RTD controls: HEF + heterogeneities in streambed permeability



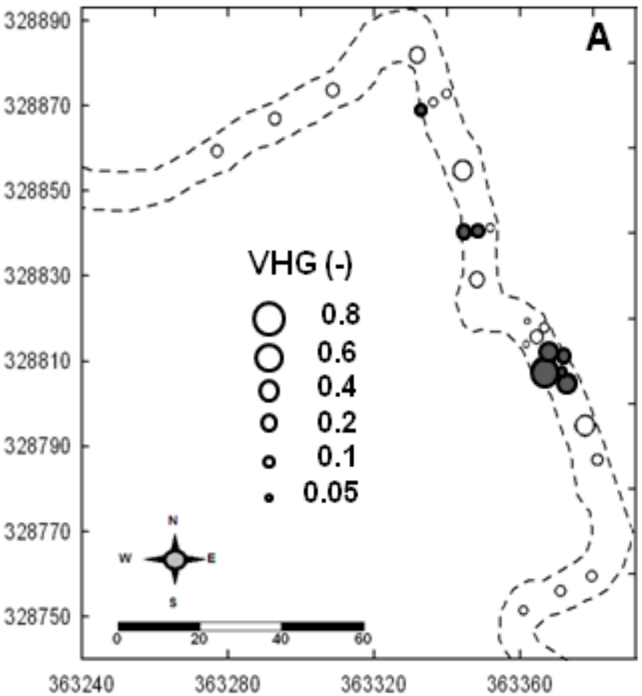


Long GW-residence times in anoxic sediments with increased C_{org} availability

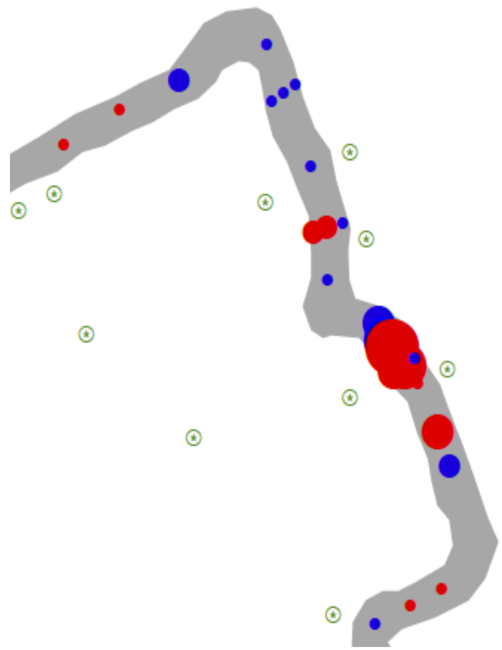
[Krause et al. HESS, 2012; JGR-Biogeosciences, 2013; Krause & Blume, WRR, 2013]

Organisational Principles of Hyporheic Nutrient Cycling

Vertical hydraulic gradients



Nitrogen turnover



Diffuse Equilibrium in Thin films (DET) Passive Gel Samplers


photo DGT Research

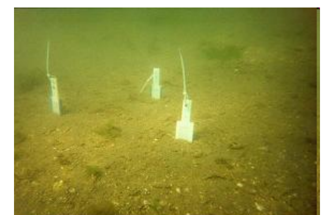
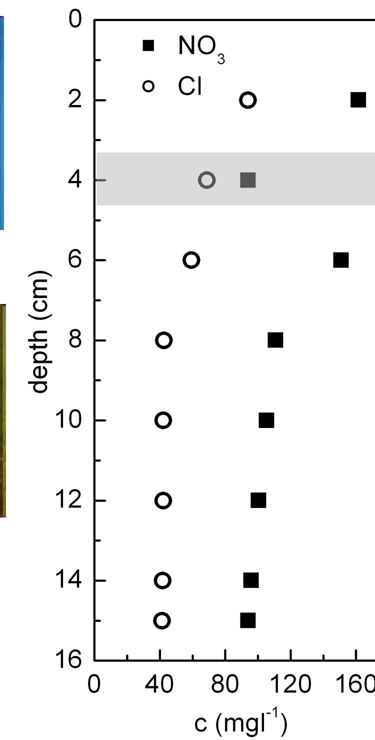


photo Édouard Metzger



Hotspots of nutrient turnover in association to low conductivity strata

GW up-welling indicated by positive VHG throughout observation period

[Krause et al. HESS, 2012; Krause & Blume, WRR 2013; Krause et al., WRR 2014]

How Important is Small Scale Interface Heterogeneity?

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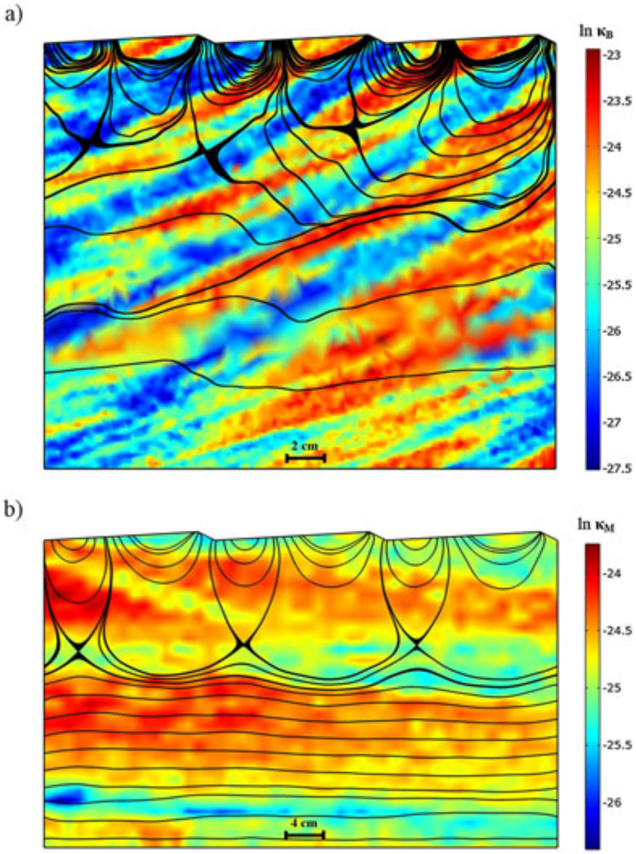
Small-scale permeability heterogeneity has negligible effects on nutrient cycling in streambeds

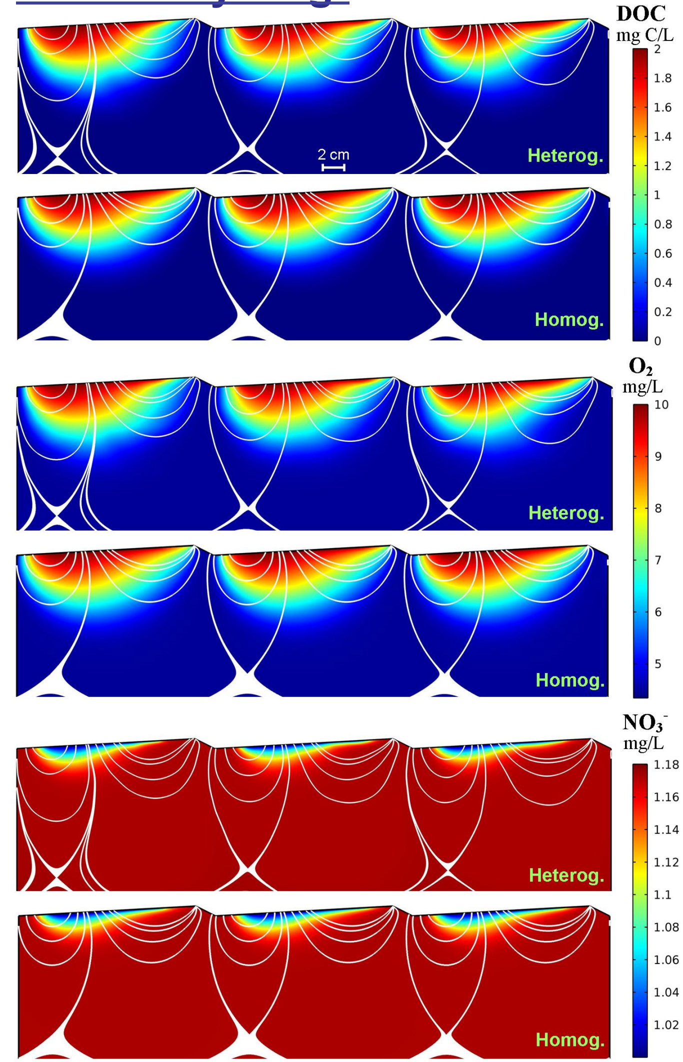
L. Bardini,[1] F. Boano,[1] M. B. Cardenas,[2] A. H. Sawyer,[3] R. Revelli,[1] and L. Ridolfi[1]

Bedform driven HEF:



[Bardini et al., GRL, 2013]

Streambed structural impact on nutrient cycling:



Dynamic Interactions of Point-source and Diffuse Pollution

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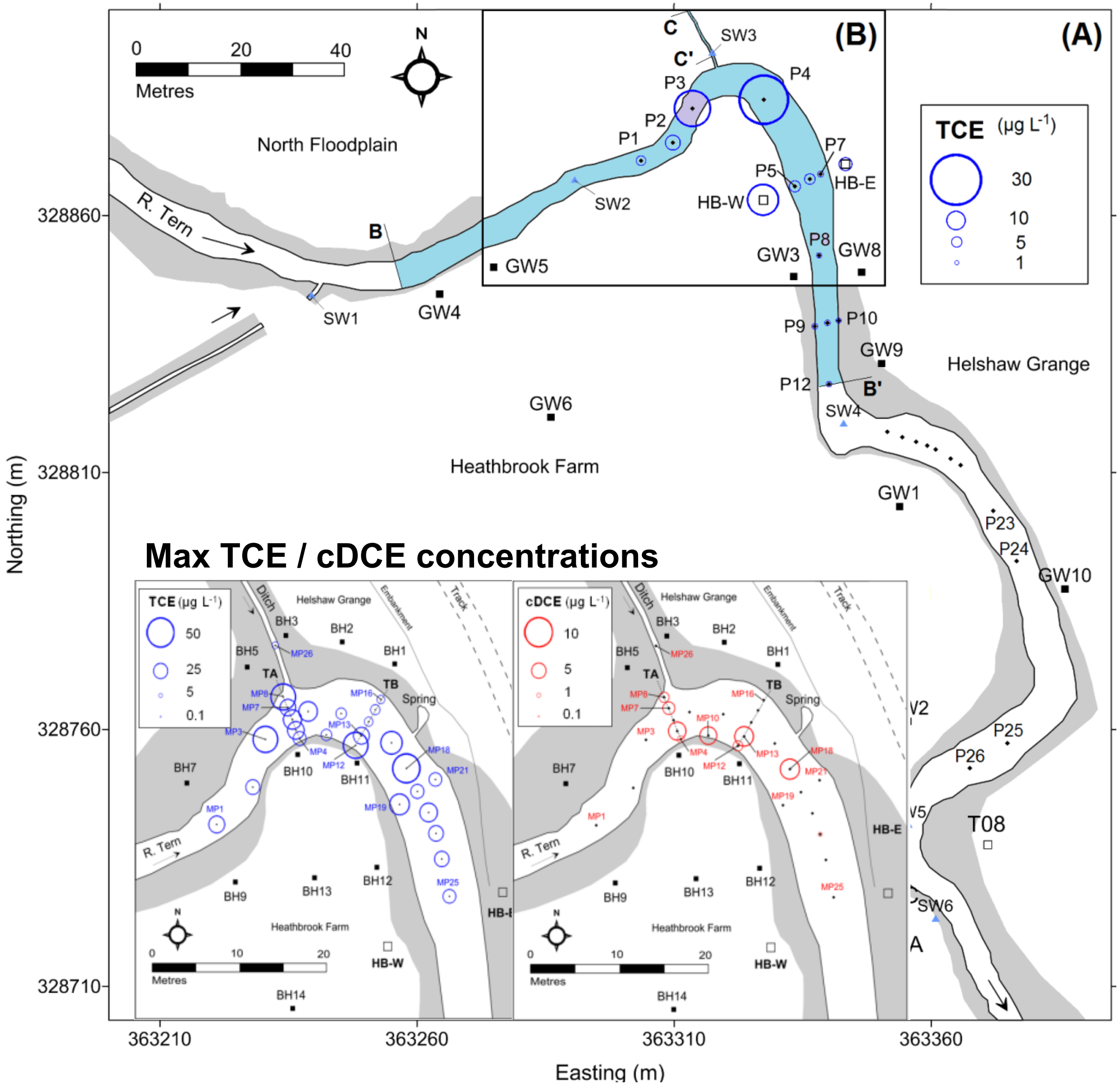
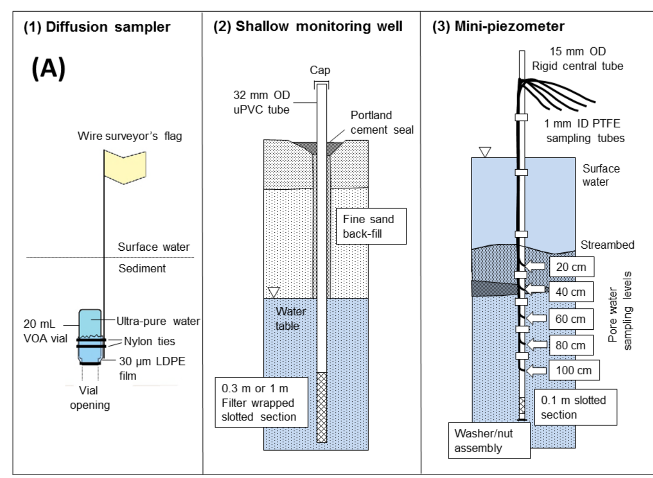


Coincidence of diffuse nitrate and point source TCE

Competition for DOC as electron donor

Controlled by spatial patterns/temporal dynamics of HEF



[Weatherill et al., J. Cont. Hydrol., 2014]

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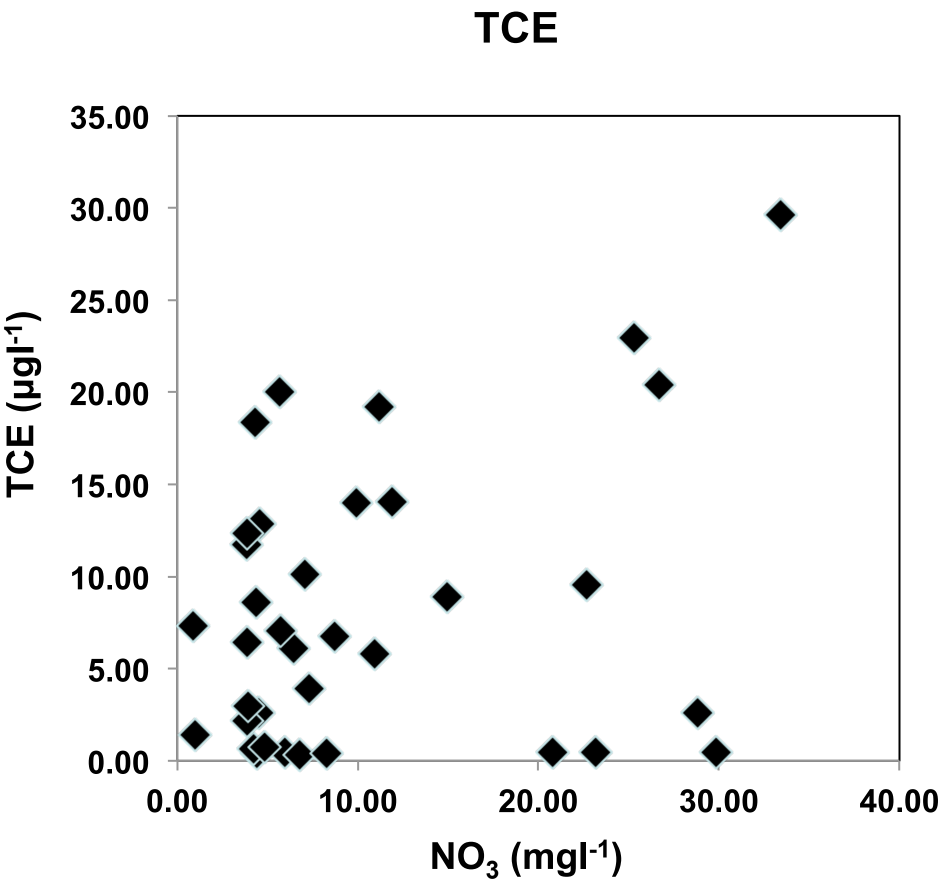
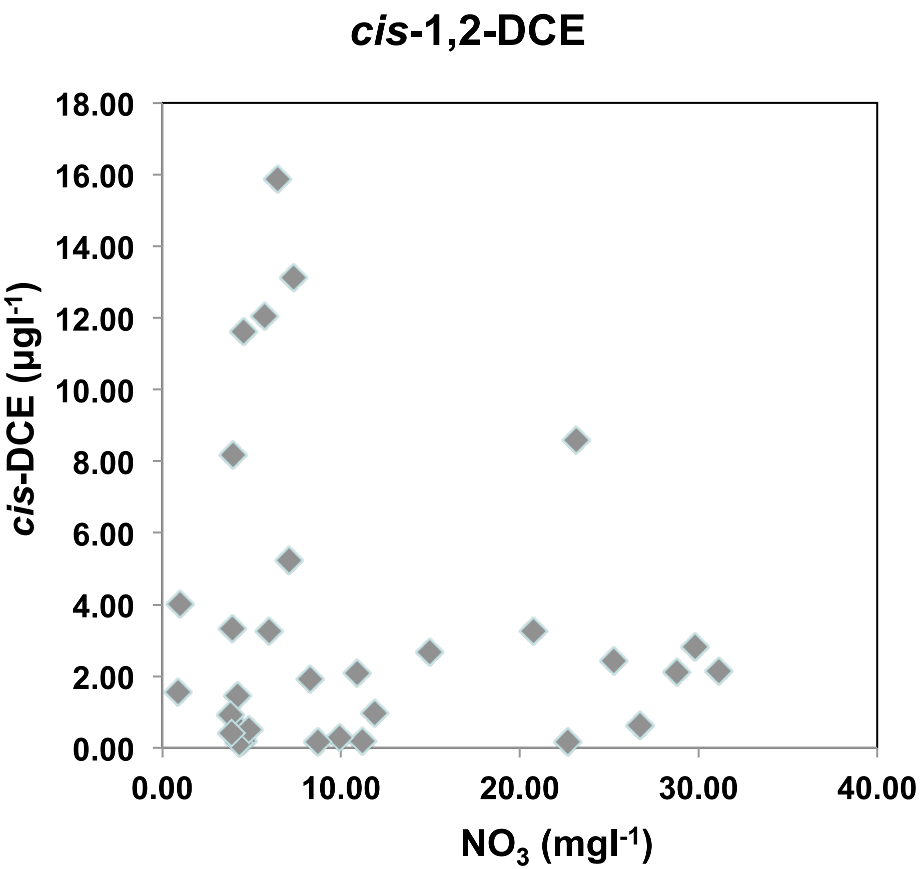
Enhanced NO_3 concentrations effectively inhibit TCE breakdown!





[Weatherill et al., J. Cont. Hydrol., 2014]

Summary:
Organisational principles of HEF + biogeochemical turnover

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Small scale structural variability matters:

Increased nitrogen turnover in streambed environment (attenuation and enhancement), driven by bedform induced HEF and streambed permeability

Hotspots of nitrate turnover – controlled by GW up-welling and small-scale (DOC rich) low conductivity structures

Diffuse and point source pollution interact (compete):

Enhanced nitrate concentrations inhibit TCE breakdown (apart from streambed hotspots of increased denitrification)

Identifying Hotspots of HZ Biogeochemical Turnover

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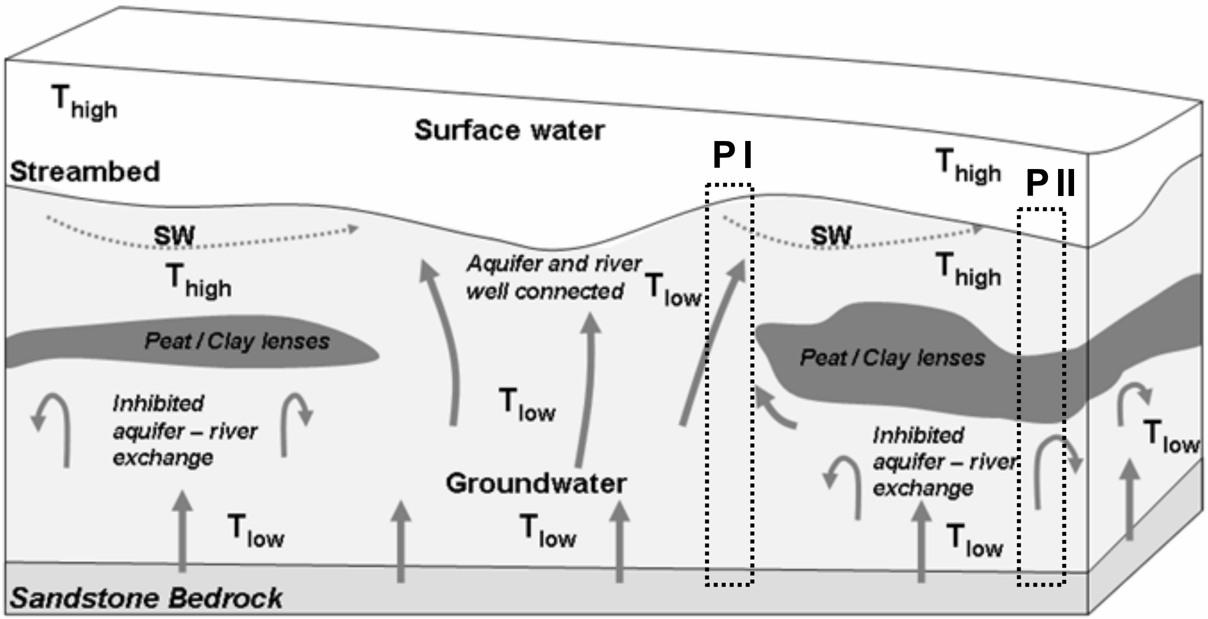
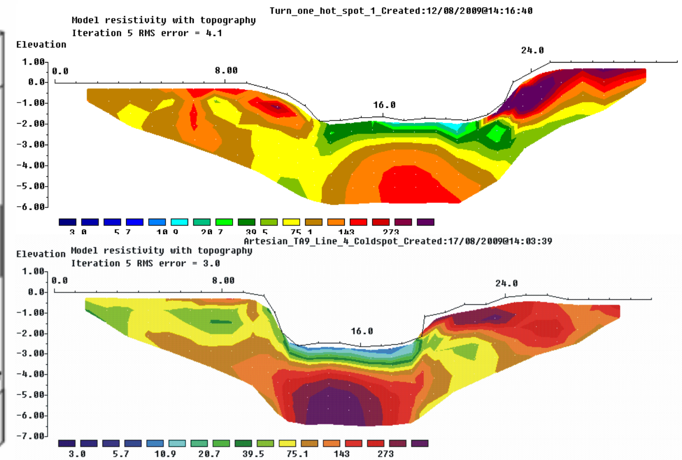
Detecting Hot moments and hot spots of HZ reactivity

Increased reactivity (NO_3, TCE decay) in confined streambed locations





Electric Resistivity Tomography -ERT

Ground Penetrating Radar - GPR

AIM:

Detection of low conductivity hotspots + their dynamic impact on streambed metabolism

[Weatherill et al. in prep.]

Identifying Hotspots of HZ Biogeochemical Turnover

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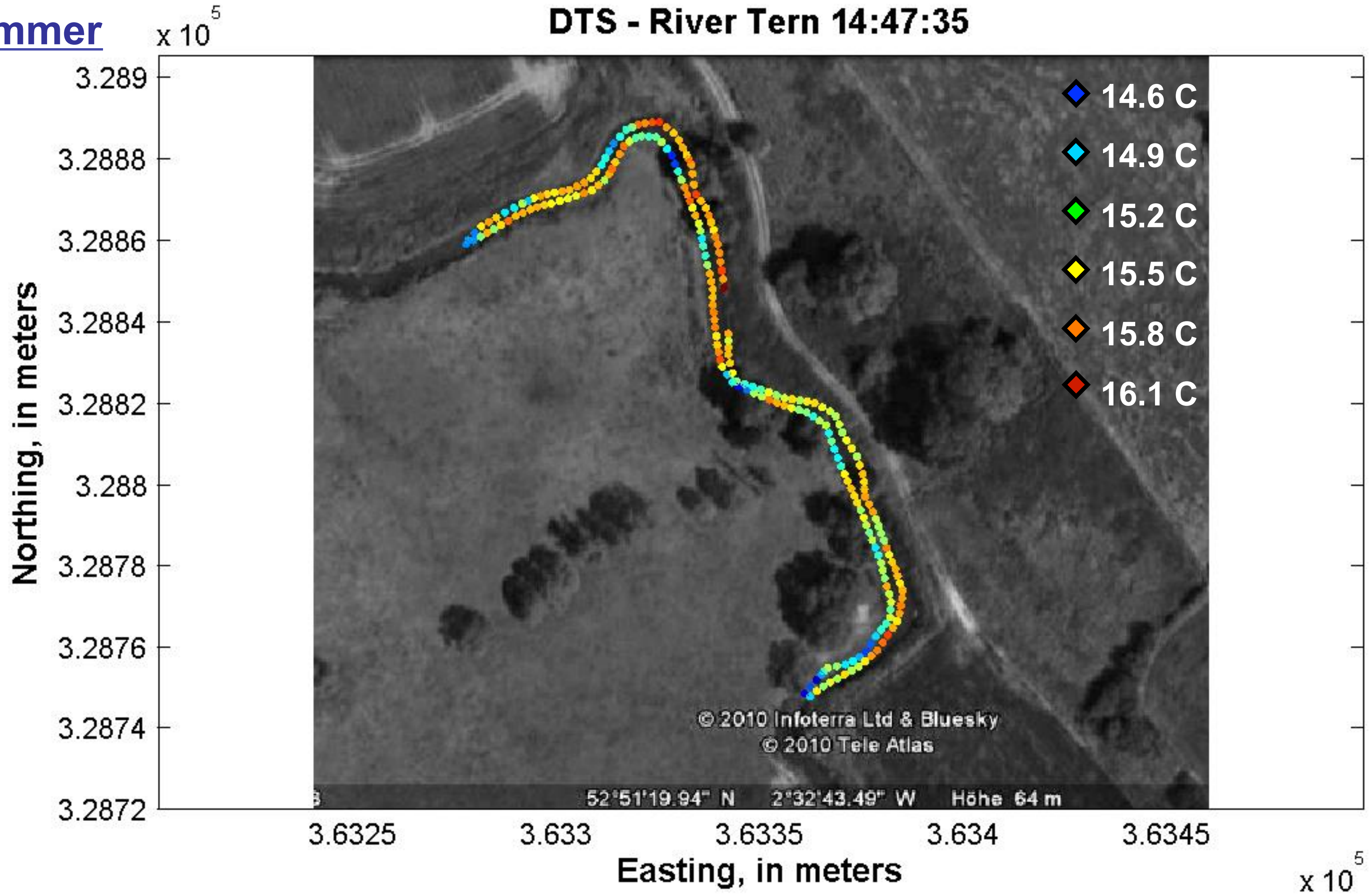
Summer



[Krause et al., 2012, HESS]

Identifying Hotspots of HZ Biogeochemical Turnover

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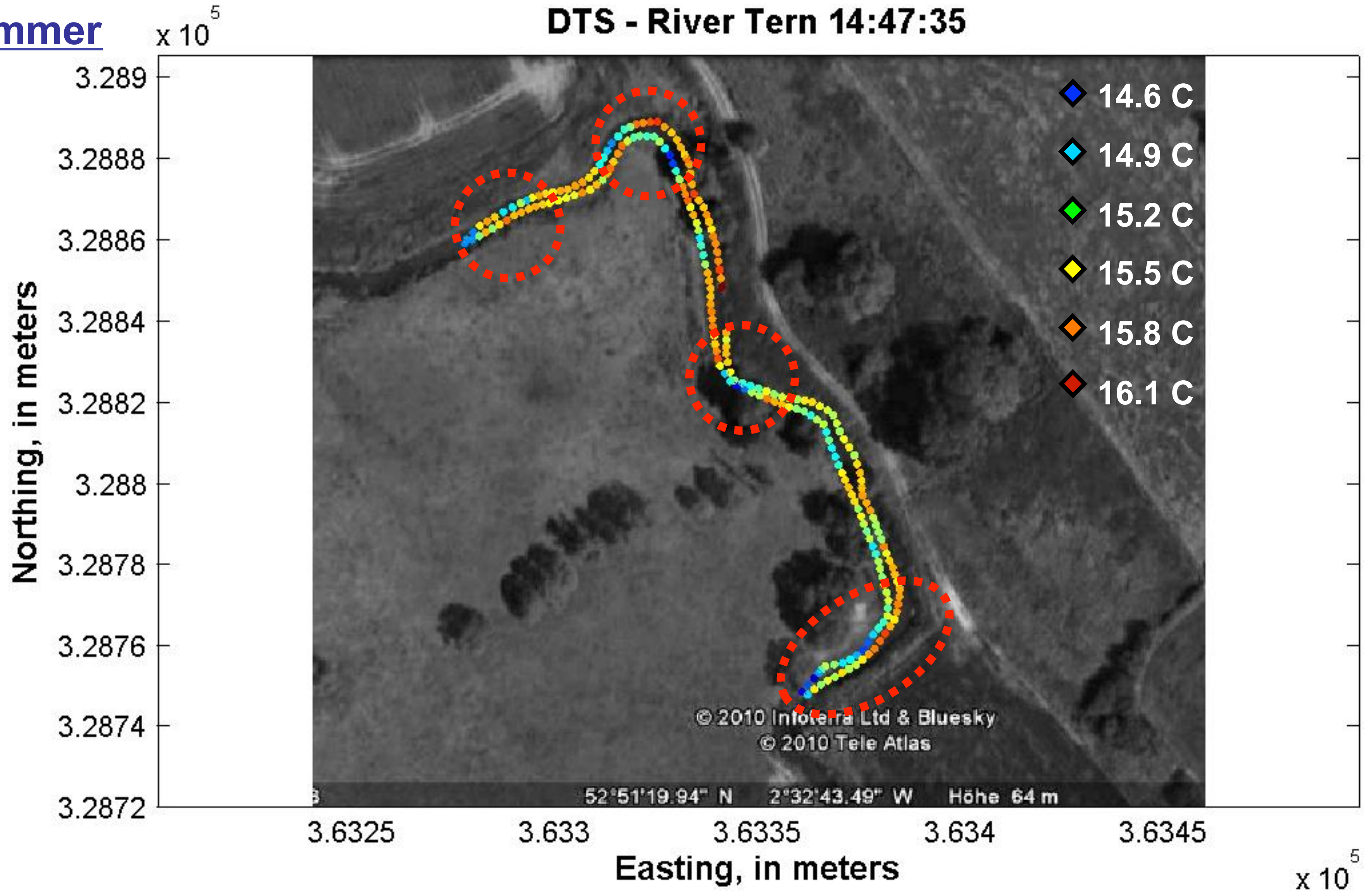
Summer



[Krause et al., 2012, HESS]

Identifying Hotspots of HZ Biogeochemical Turnover

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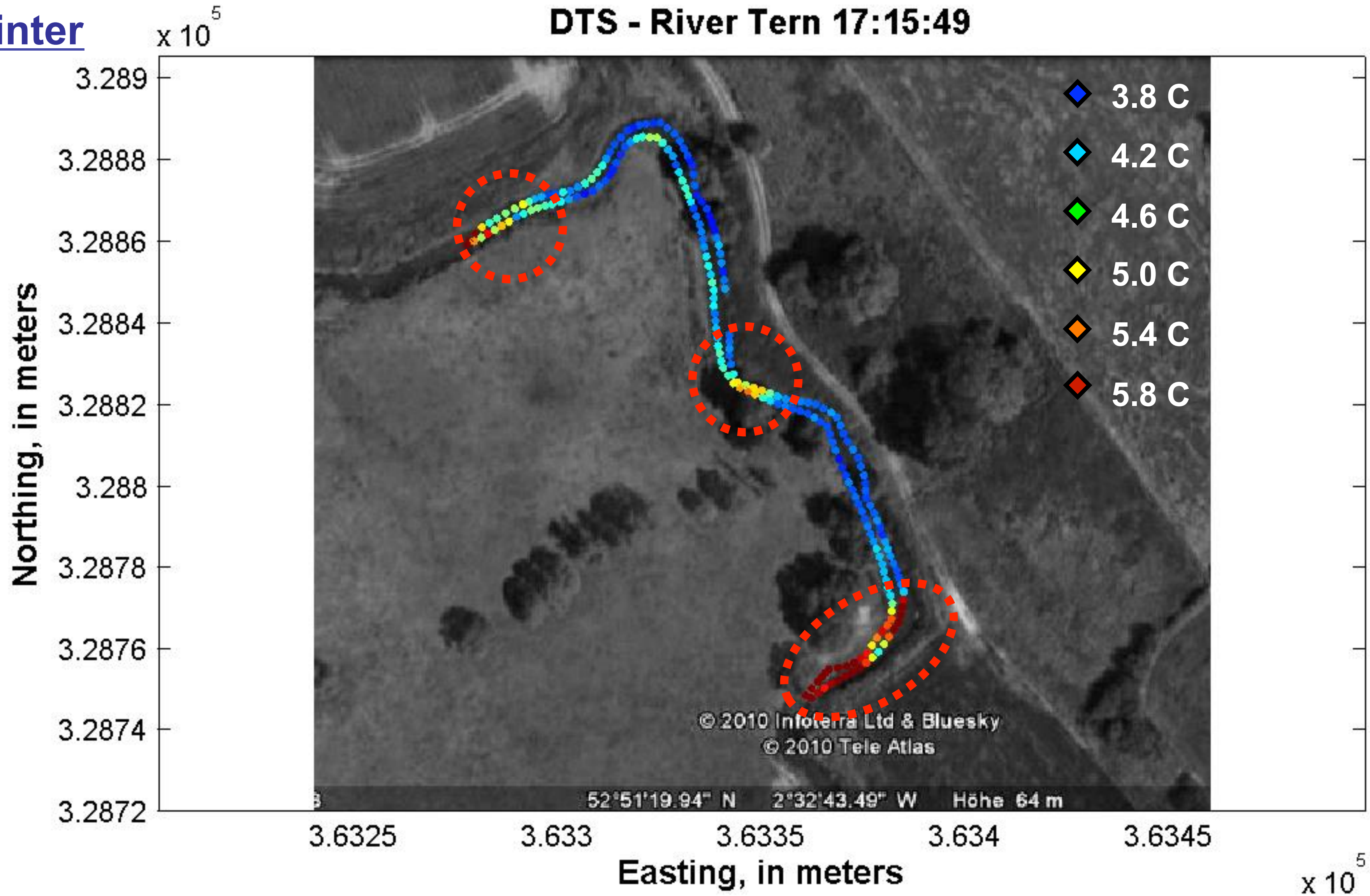
Winter



[Krause et al., 2012, HESS]

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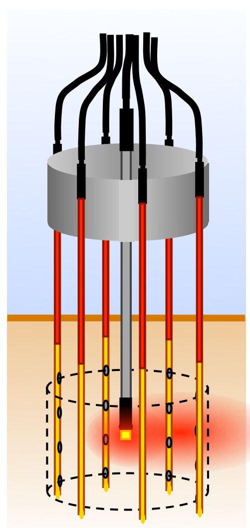
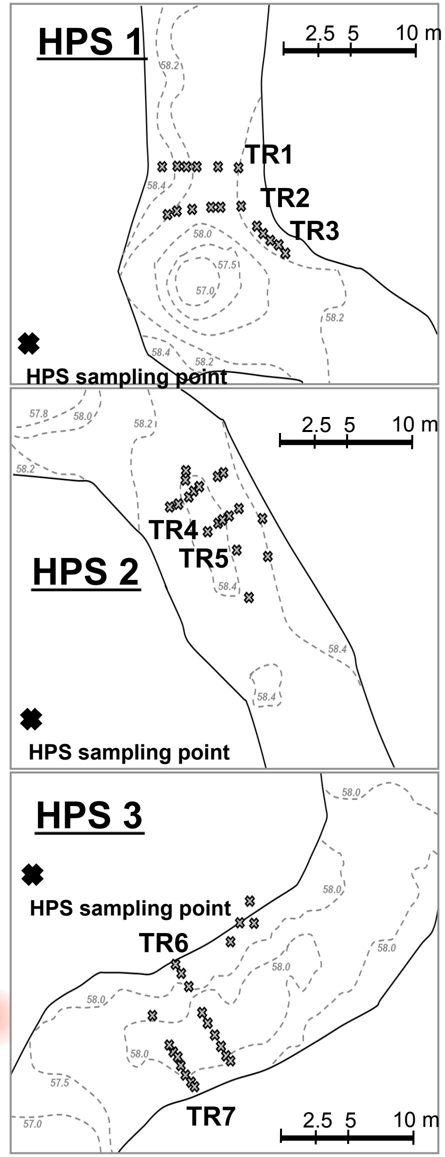
HPS Heat Pulse Sensor (Active Injection)

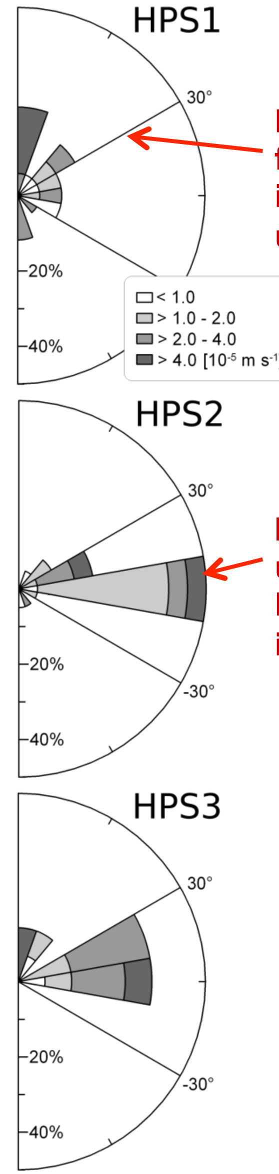
FO-DTS – selected sites

Detailed, 3-D flow field analysis (small scale)



[Angermann et al., WRR, 2012]





Hydrodynamic forcing super-imposed by GW up-welling

Inhibited GW up-welling leads to increased HEF

Summary:
Organisational principles of HEF + biogeochemical turnover

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Small scale structural variability matters:

Increased nitrogen turnover in streambed environment, driven by GW-upwelling patterns instead of bedform induced HEF

Hotspots of nitrate turnover – controlled by GW up-welling and small-scale (DOC rich) low conductivity structures

Diffuse and point source pollution interact (compete):

Enhanced nitrate concentrations inhibit TCE breakdown in streambed (apart from streambed hotspots of increased denitrification)

Hot spots and hot moments can be identified:

Hot spots of biogeochemical turnover (DOC rich low conductivity structures) can be effectively identified by FO-DTS

Generalising Principles of Aquifer-River Exchange

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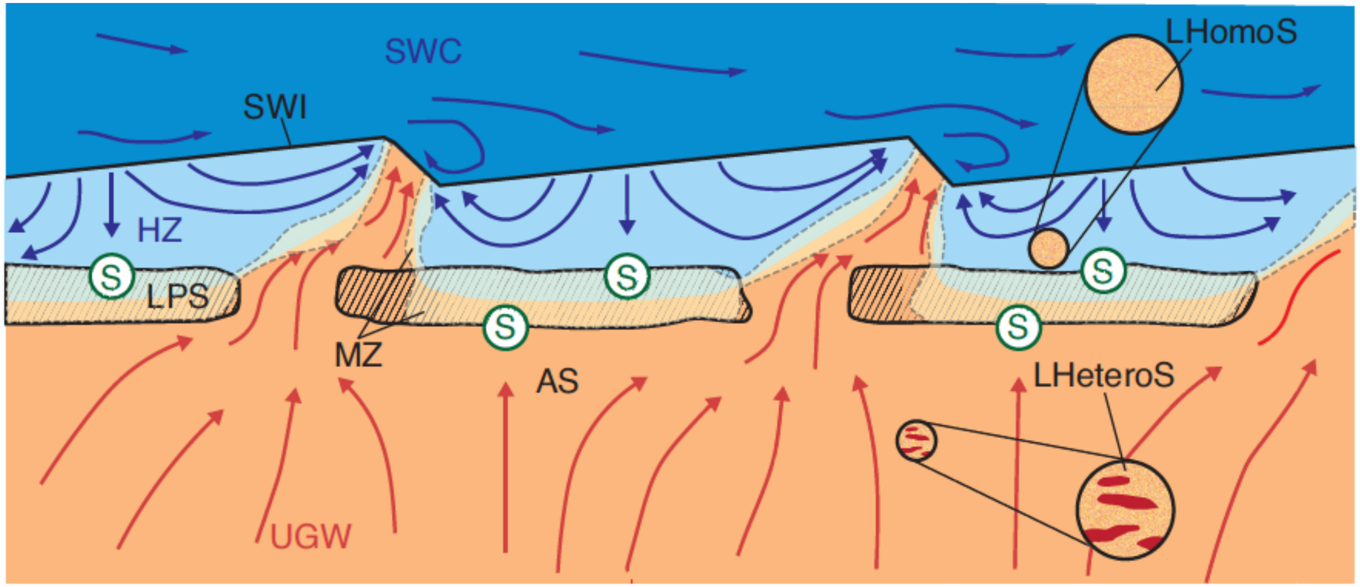

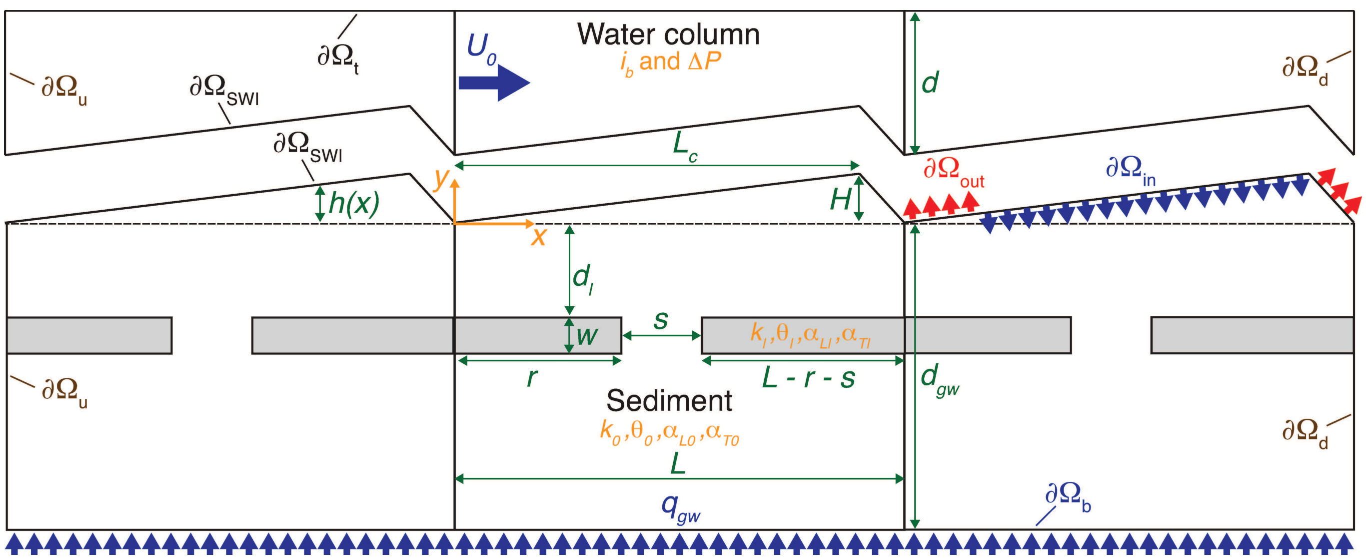

<u>Two-dimensional alluvial system:</u>

- **asymmetrical dunes repeated periodically downstream**
- **turbulent flow in water column by steady-state Reynolds-averaged Navier-Stokes (RANS)**
- **Dirichlet boundary to describe pressure distribution at sediment water interface**
- **uniform groundwater upwelling along the bottom boundary**

[Gomez, et al., WRR, 2014]

Generalising Principles of Aquifer-River Exchange

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Sensitivity of HEF metrics

Net hyporheic flux:

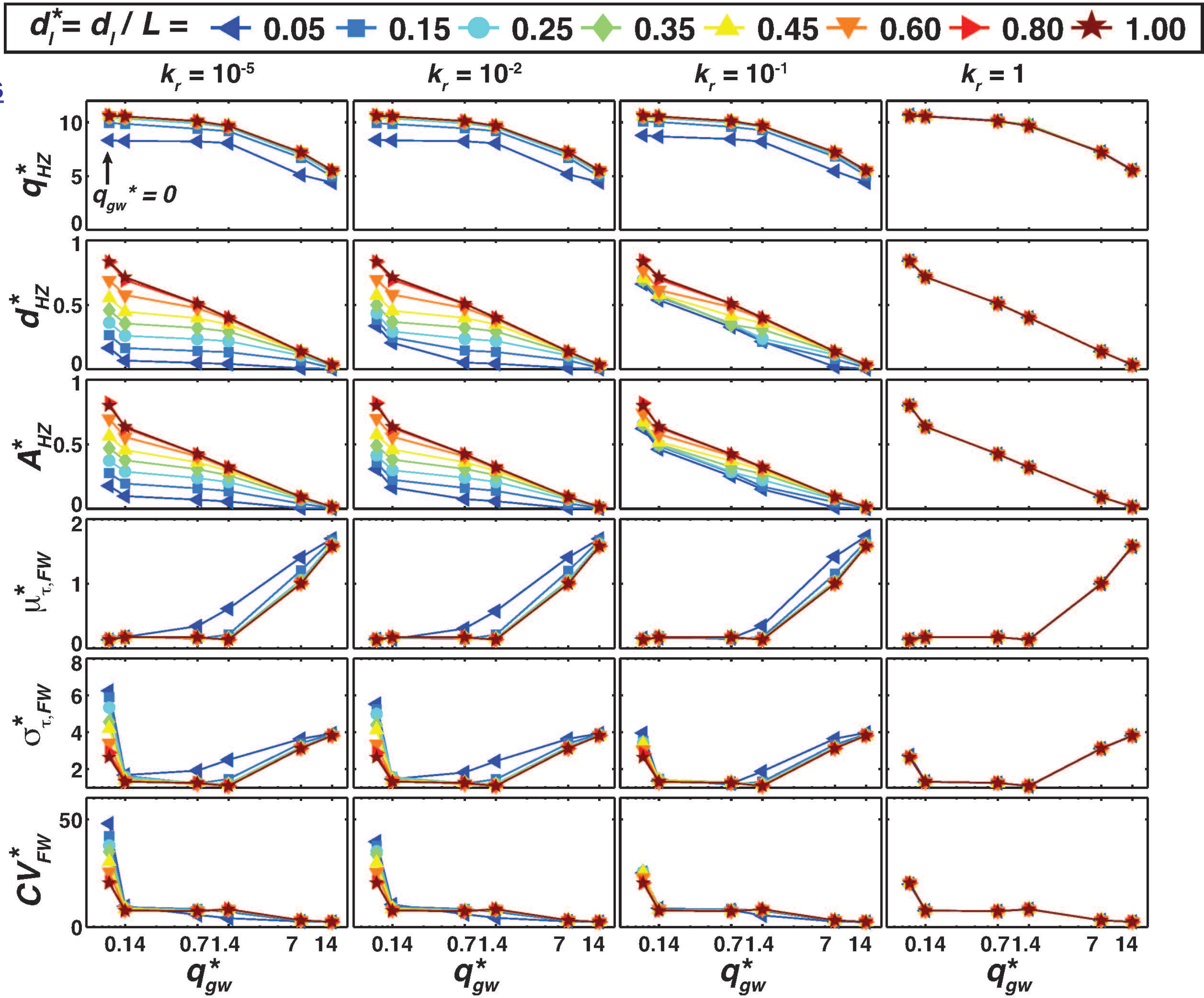
Maximum depth of the HZ:

Area of the HZ:

Flux-weighted mean RT:

Flux-weighted standard deviation RT:

Flux-weighted coefficient of variation:



[Gomez, et al., WRR, 2014]

Generalising Principles of Aquifer-River Exchange

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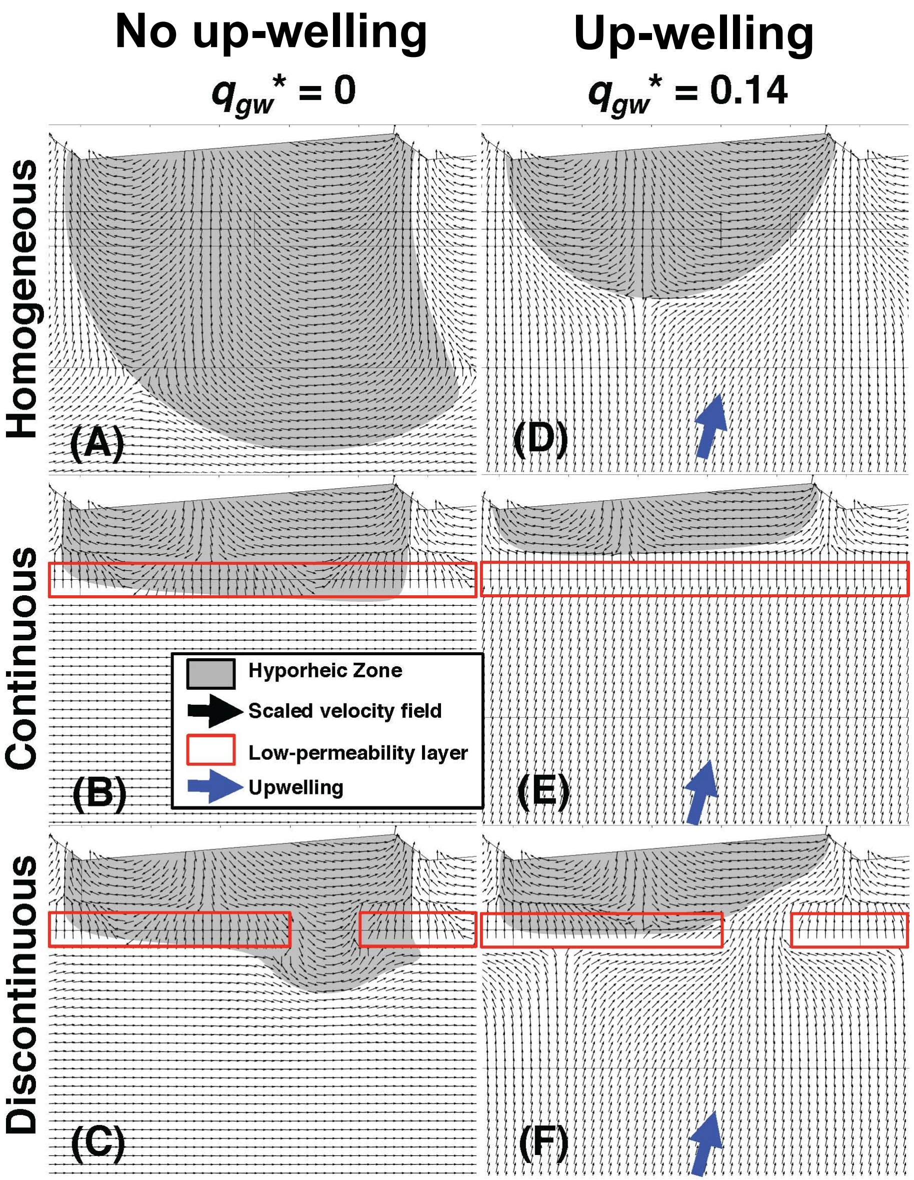

Example scenarios

Flow fields (arrows) and spatial extent of HZ (>50 % surface water) for different flow / conductivity scenarios

[Gomez, et al., WRR, 2014]

Summary:
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Diffuse and point source pollution interact (compete):

Enhanced nitrate concentrations inhibit TCE breakdown in streambed (apart from streambed hotspots of increased denitrification)

Hot spots and hot moments can be identified / predicted:

Hot spots of biogeochemical turnover (DOC rich low conductivity structures) can be effectively identified by FO-DTS

The theoretical impact of hot spots and hot moments of enhanced RTD and biogeochemical turnover can be quantified

The challenge remains:
What are the large scale implications of small scale hotspots and hot moments?

Outlook

Large(r) Scale Implications of Streambed Biogeochemical Cycling

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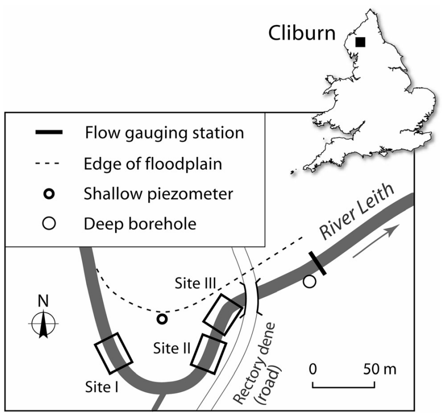
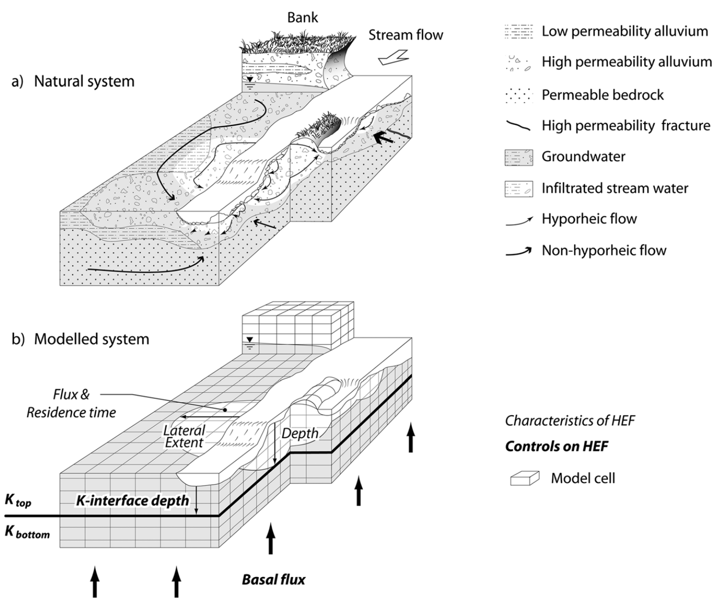
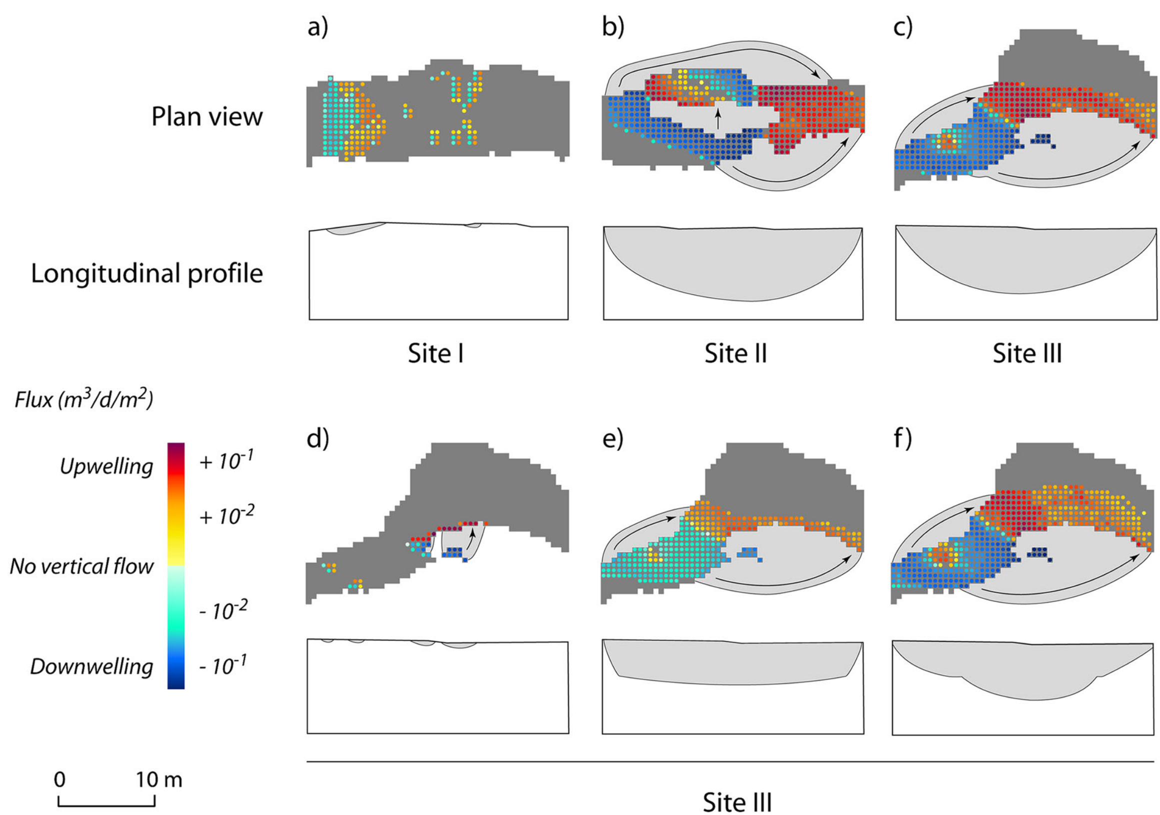


Up-scaling to 3-D deterministic HEF modelling

Improved spatial/temporal discretisation





[Kaeser, et al., HP, 2014; Munz et al., HP 2011] interfaces

INTERFACES – Ecohydrological interfaces as critical hotspots for transformations of ecosystem exchange fluxes

This project has received funding from the European Union's 7th Framework Programme for research, technological development and demonstration under grant agreement no. 607150.

The Leverhulme Trust

The International Hyporheic Zone Research Network: Where rivers, groundwater and disciplines meet

Thank You

MARIE CURIE ACTIONS
SEVENTH FRAMEWORK PROGRAMME

INTERFACES - Ecohydrological interfaces as critical hotspots for transformations of ecosystem exchange fluxes and biogeochemical cycling. FP7-PEOPLE-2013-ITN, 2013-2017

NERC SCIENCE OF THE ENVIRONMENT

- *Large woody debris - A river restoration panacea for nitrate attenuation?* NERC-NE/L004437/1, 2014-1017
- *Groundwater flooding: Community recovery following extreme recharge.* NERC-NE/M005151/1, 2014-2015
- *Active DTS for high-resolution fluid-flow monitoring in boreholes.* NE/L012715/1, 2014-2015
- *Smart tracers and distributed sensor networks for quantifying the metabolic activity in streambed reactivity hotspots.* NERC-NE/I016120/1, 2011-2013

The Leverhulme Trust

Where rivers, groundwater and disciplines meet: a hyporheic research network. 2014-2017

Environment Agency

Risk assessment and potential for attenuation of TCE in hyporheic sediments, 2010-2014

C-KIC: Prediction of drought impacts on thermal and water quality extremes, 2014-2017

FO-DTS for identifying GW-SW exchange flow in Icelandic lakes 2012-2013

eit Knowledge & Innovation Community Climate-KIC

IGB Leibniz-Institute of Freshwater Ecology and Inland Fisheries
Research for the future of our freshwaters

Special thanks to:

- D.M. Hannah, L. Rose, L. McMillan, S. Milner (University of Birmingham)
- J. Lewandowski, K. Meinikmann (IGB-Berlin)
- A. Binley, L. A. Heathwaite, P. Keenan (Lancaster University)
- V. Bense, T. Read (University of East Anglia)
- T. Blume, L. Angermann, C. Tecklenburg (GFZ-Potsdam)
- J. P. Zarnetske (University of Michigan)
- J.H. Fleckenstein, C. Schmidt (UFZ-Leipzig)
- F. Day-Lewis, J. Gomez, (USGS)
- J. Weatherill, S. Ullah, N.J. Cassidy, (University of Keele)
- M. Munz (University of Potsdam)
- D. Kaeser (Uni Neuchatel)

Leibnitz IGB-Berlin for hosting Senior Visiting Fellowship

Organisational principles of HEF along the hillslope continuum (incl. GW)

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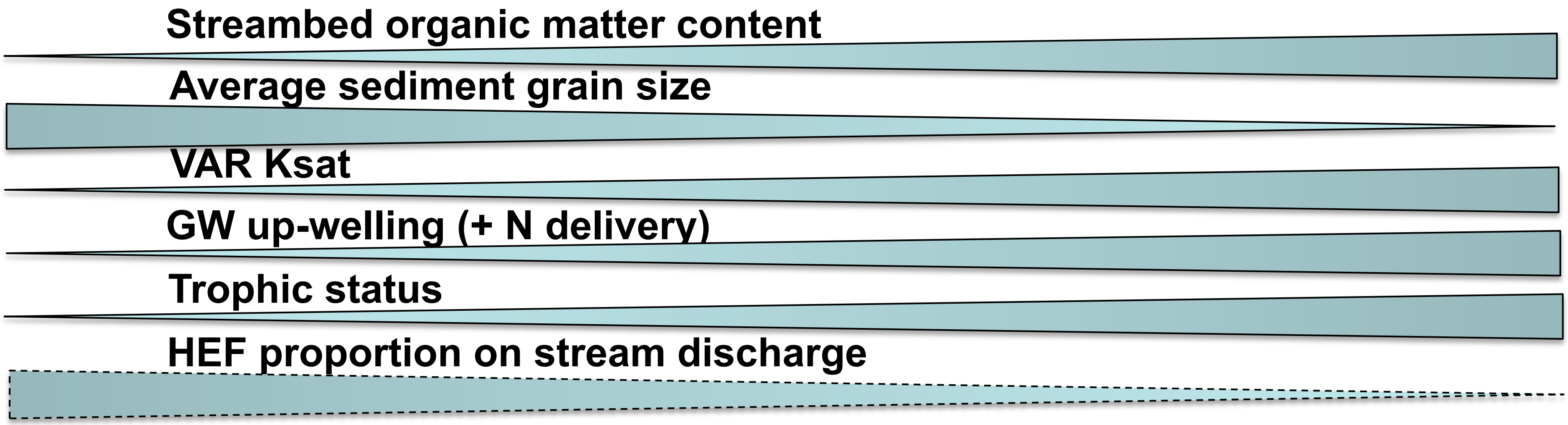

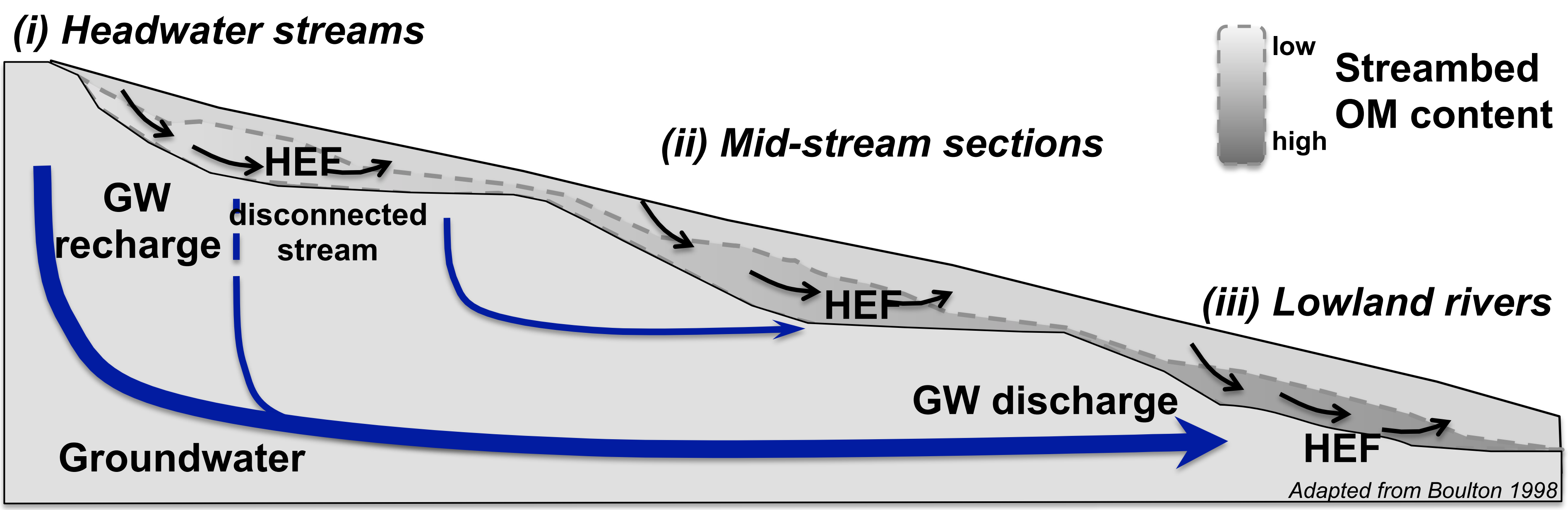

Motivation - a groundwater nitrate time bomb?

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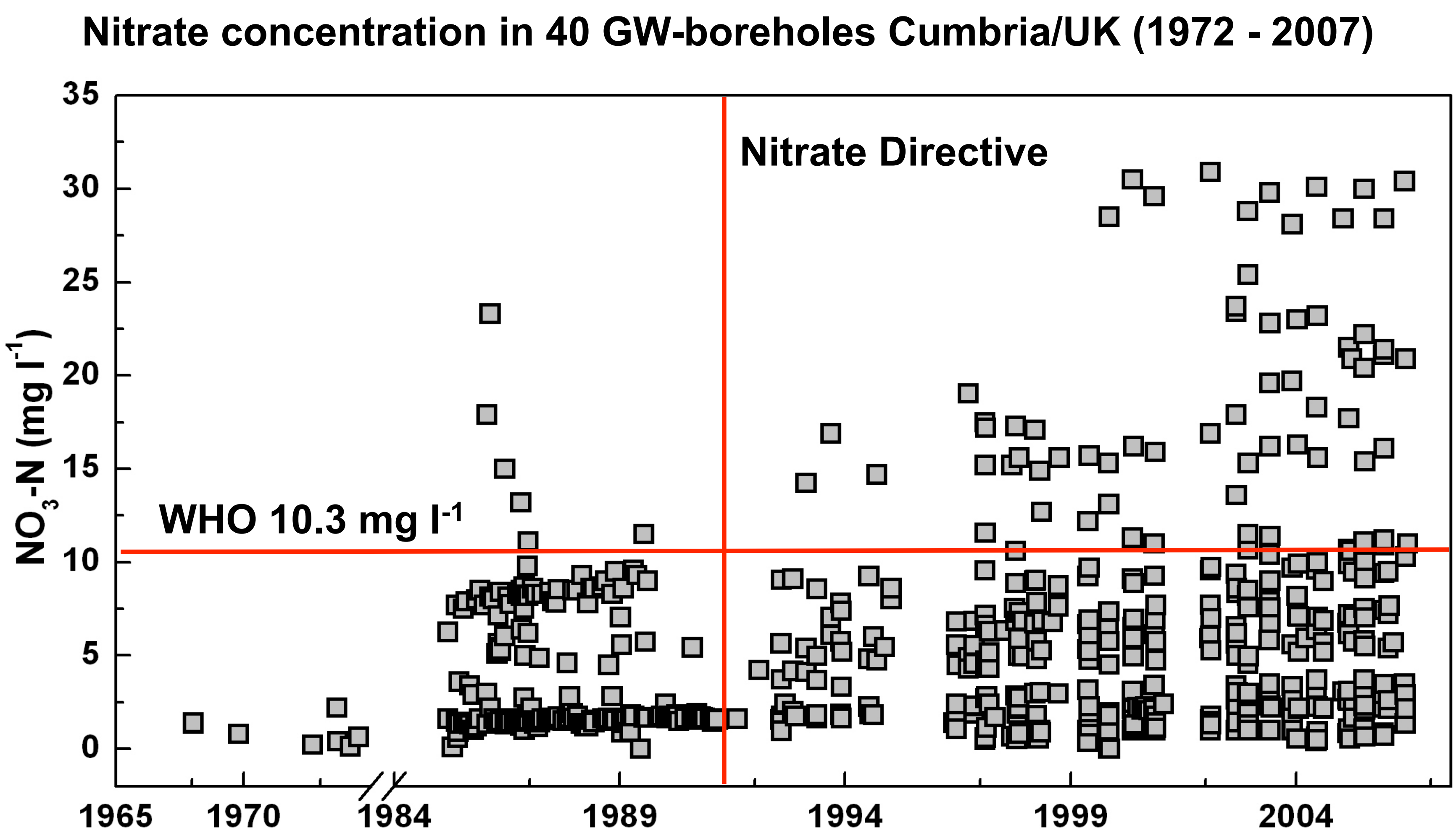

Decay = f (aquifer reactivity, residence time)