Cargèse Summer School
June 25th to July 6th, 2018

Hydrogeology
UFZ Leipzig

Photo: André Künzelmann, UFZ

Groundwater (GW) -Surface Water (SW) Interactions and Hyporheic Zone Processes

J.H. Fleckenstein

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Outline

- Main types of GW-SW interactions
- Why care about GW-SW interactions?
- Some methods to quantify GW-SW exchange fluxes
- Simulation of flow and transport in the hyporheic zone (HZ)
- Effects of sediment heterogeneity on HZ flow and transport
- Take home messages

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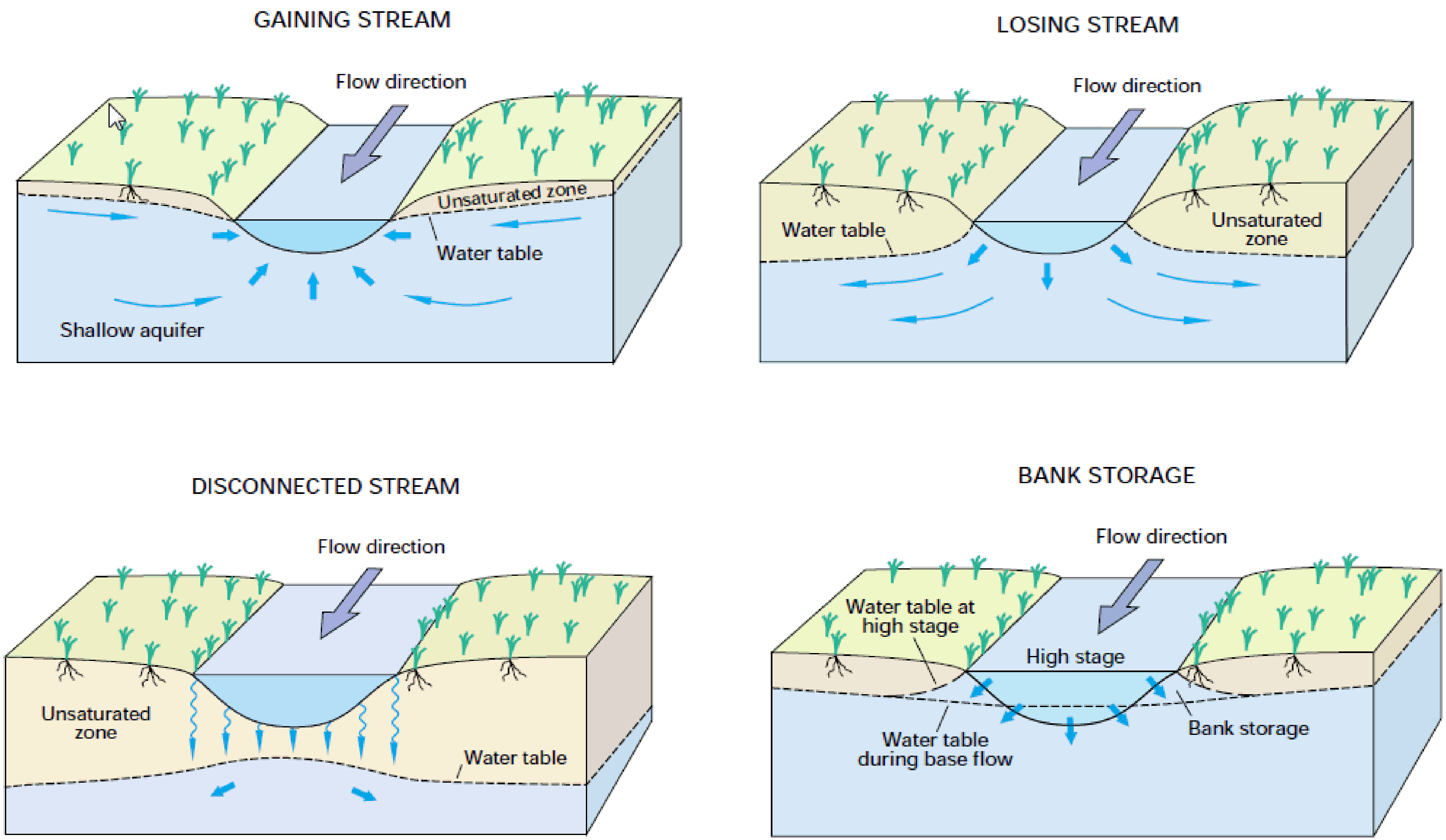
Main types of river-GW interactions



from USGS Circular 1139

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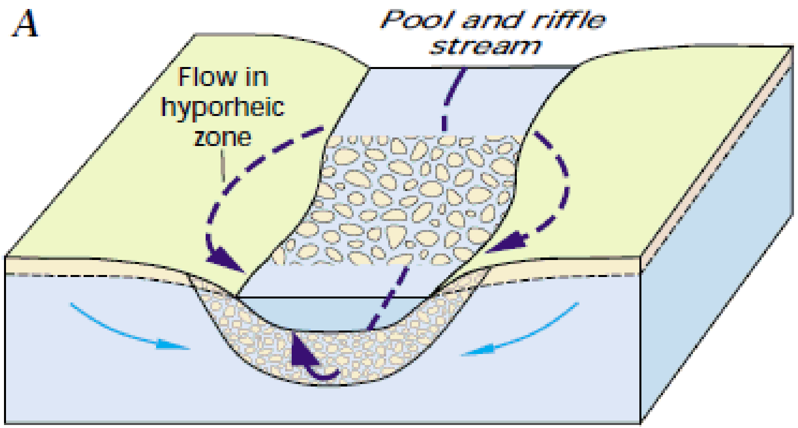
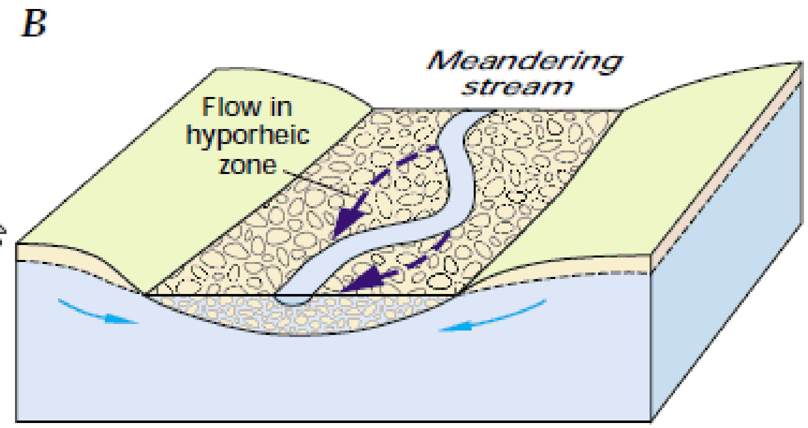
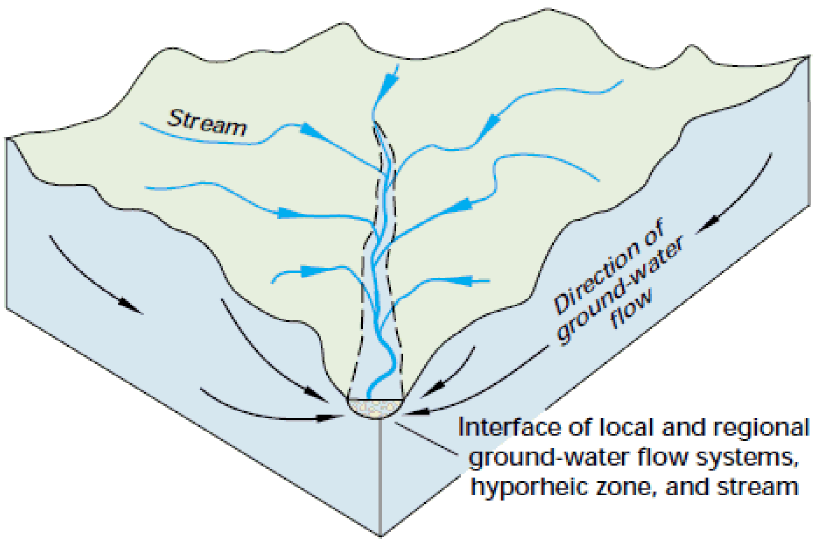
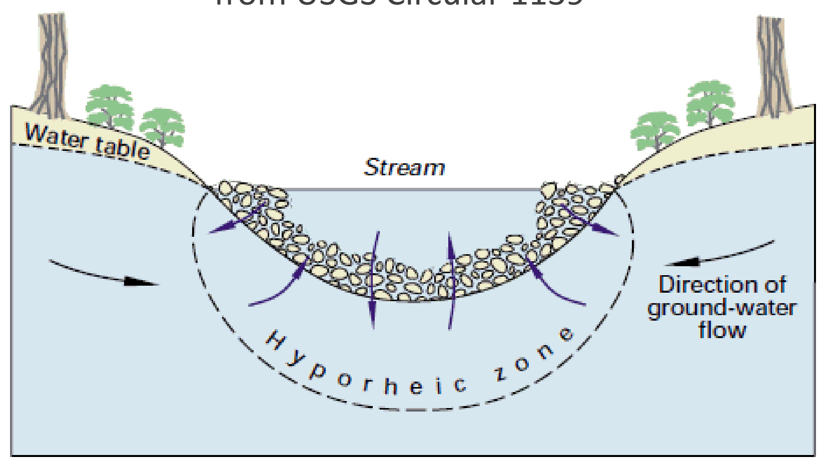
The GW-SW interface and the hyporheic zone







from USGS Circular 1139



USGS Cicular 1139, p. 17: "Streambeds and banks are unique environments because they are where ground water that drains much of the subsurface of landscapes interacts with surface water that drains much of the surface of landscapes."

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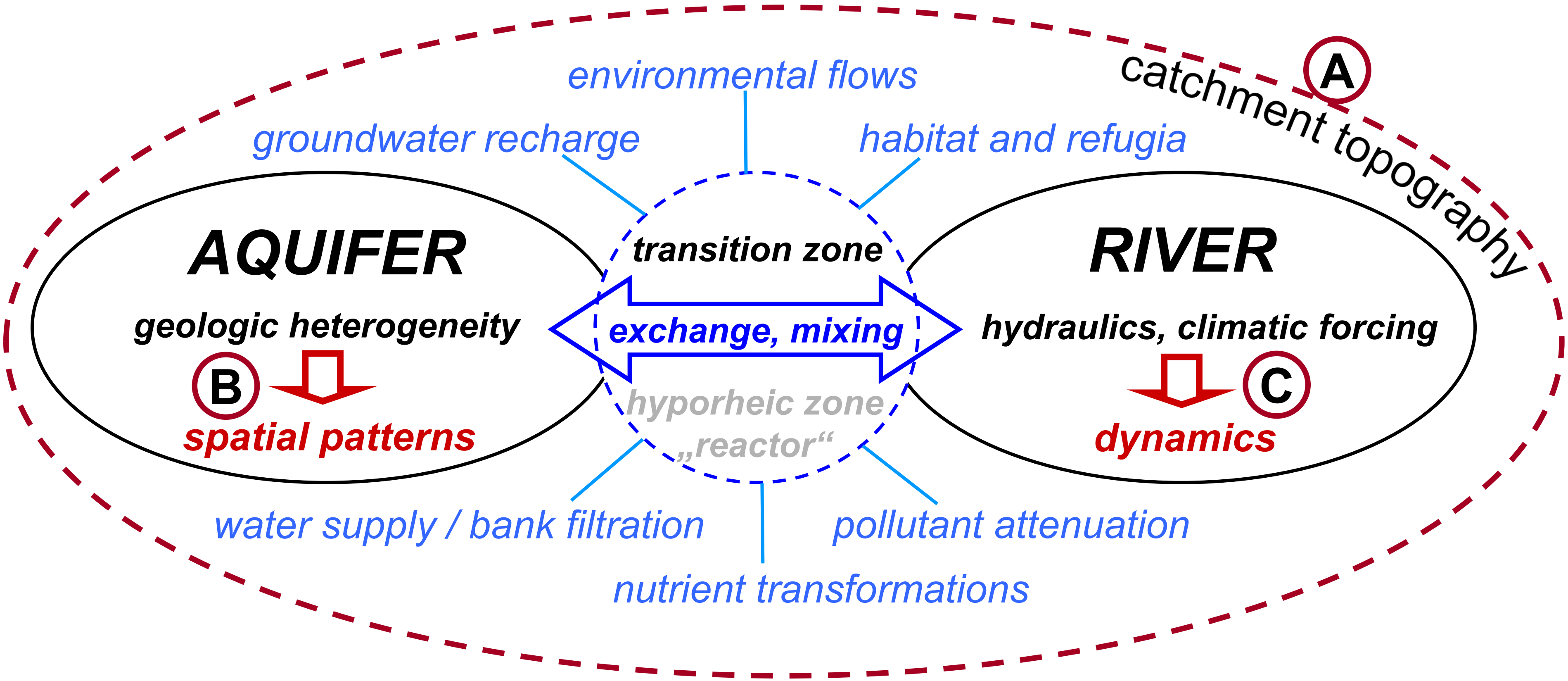
The GW-SW interface – hyporheic zone



A: Primary regional controls → catchment topography, regional geology

B: Secondary local controls → streambed and aquifer heterogeneity

C: Dynamic controls → variability in boundary conditions

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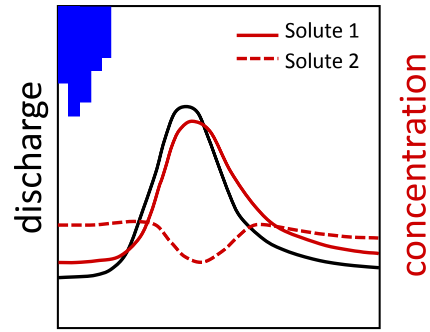
GW-SW interactions → catchment-scale solute dynamics

Two main controls via:

A) runoff generation processes and catchment-scale mixing



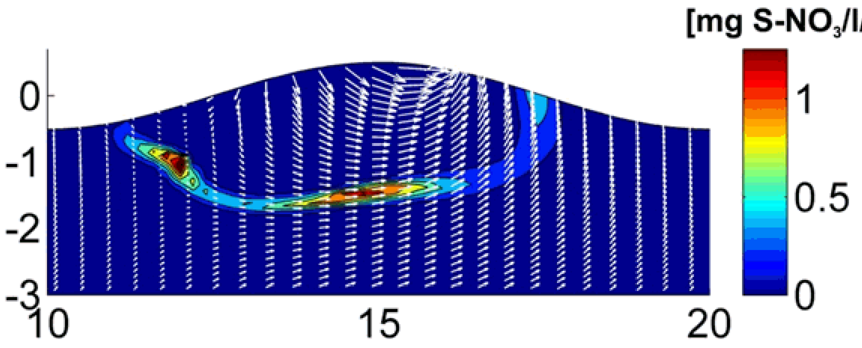
- Connectivity between runoff generating and solute source zones
- Mobilization & transport dynamics (temporal evolution, thresholds)

  → e.g. dilution versus accretion regimes, river network effects

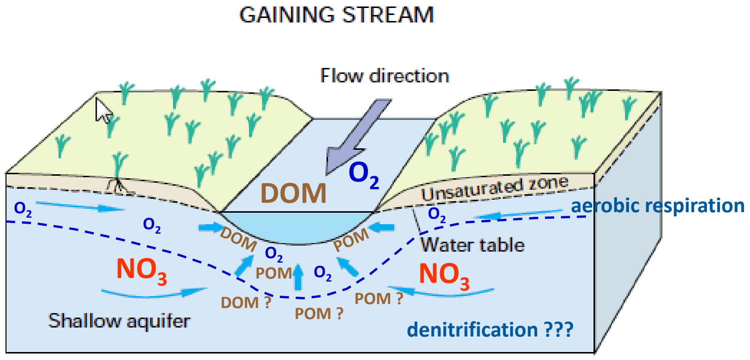
B) Attenuation processes in the transition zone between GW & SW

- Riparian buffering → attenuation of groundwater borne solutes
- Hyporheic exchange & bank storage → instream attenuation

  → uptake & transformation in hyporheic sediments

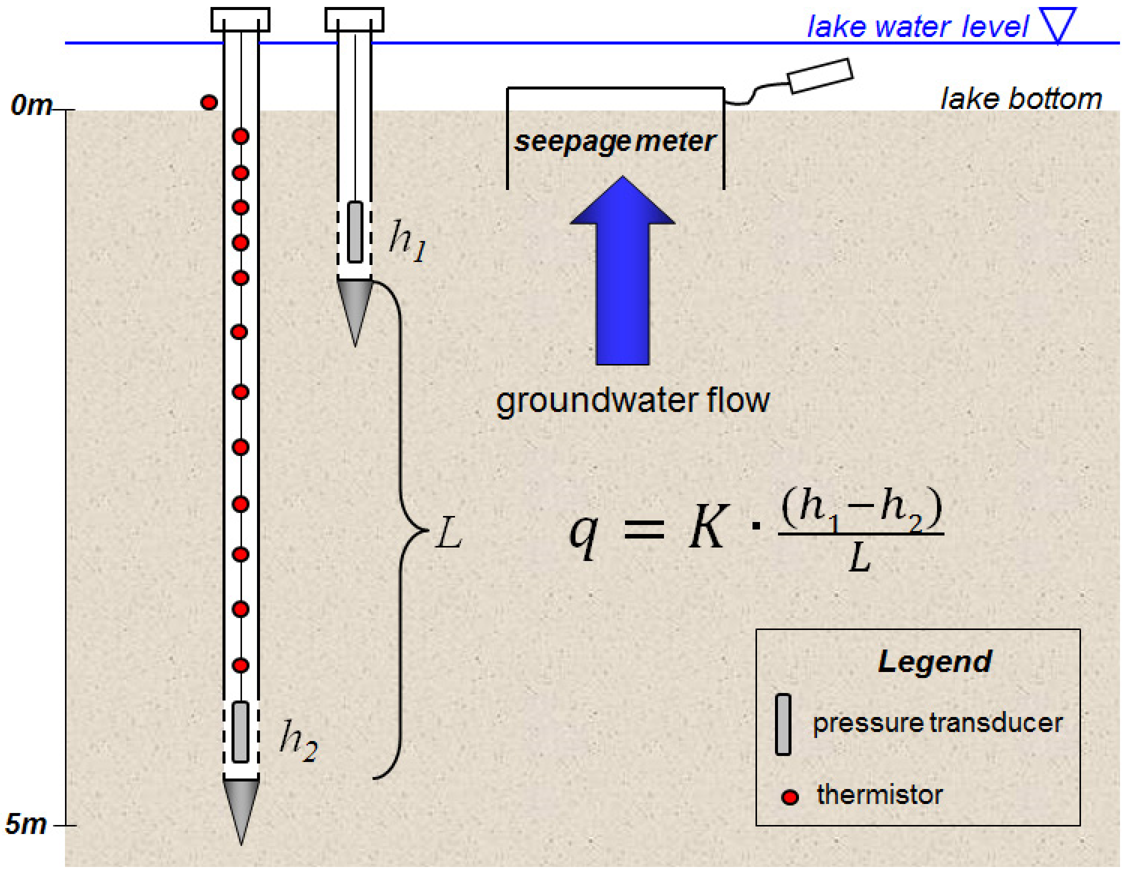


denitrification of surface water borne NO_3 in a riffle



denitrification of groundwater borne NO_3

Point methods: direct (seepage meter), indirect (Darcy- or T-based)



Darcy-based:

- mini-piezometer s → vertical head gradients
- plus K-values (e.g from slug test) → Darcy flux

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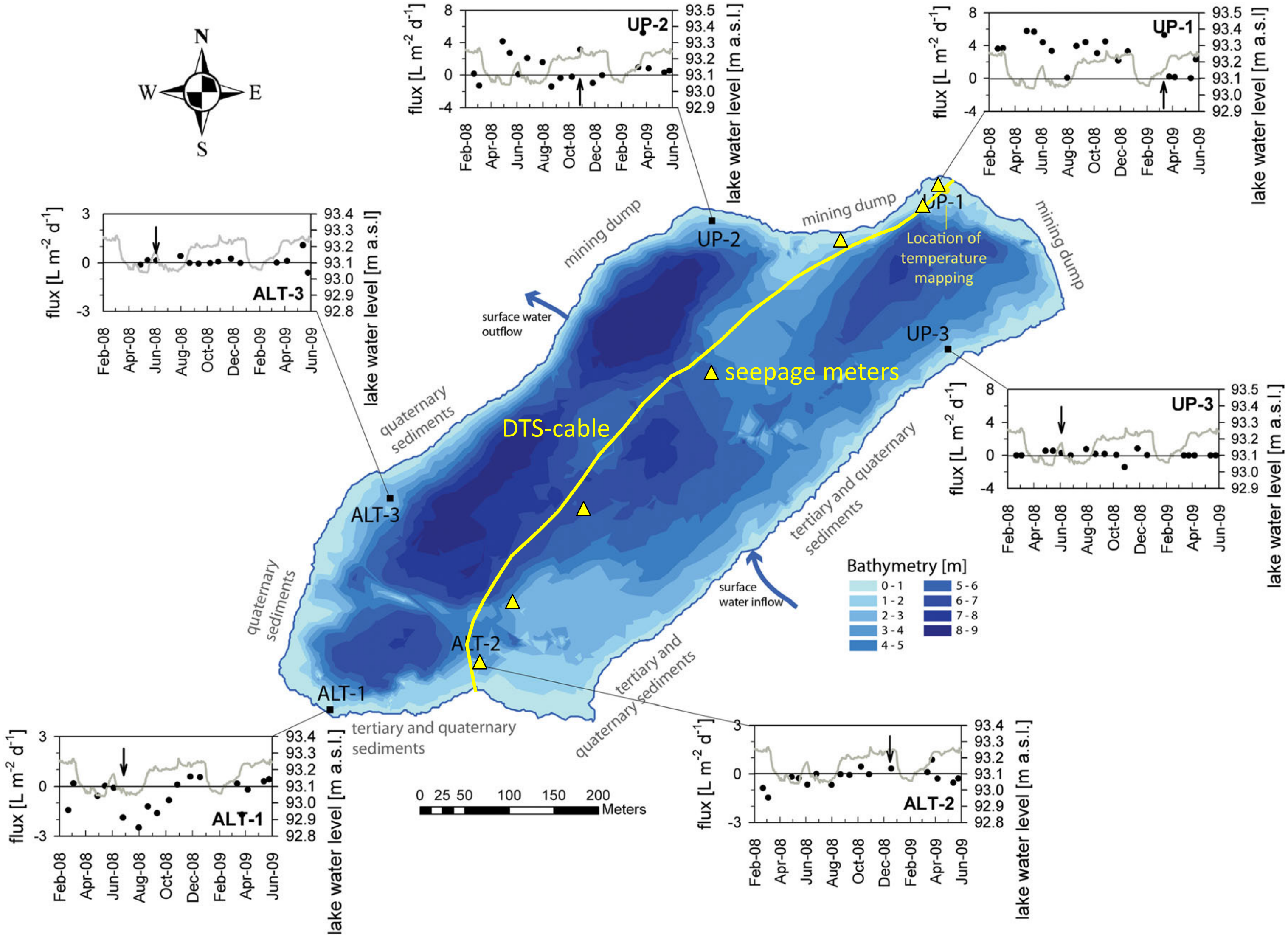
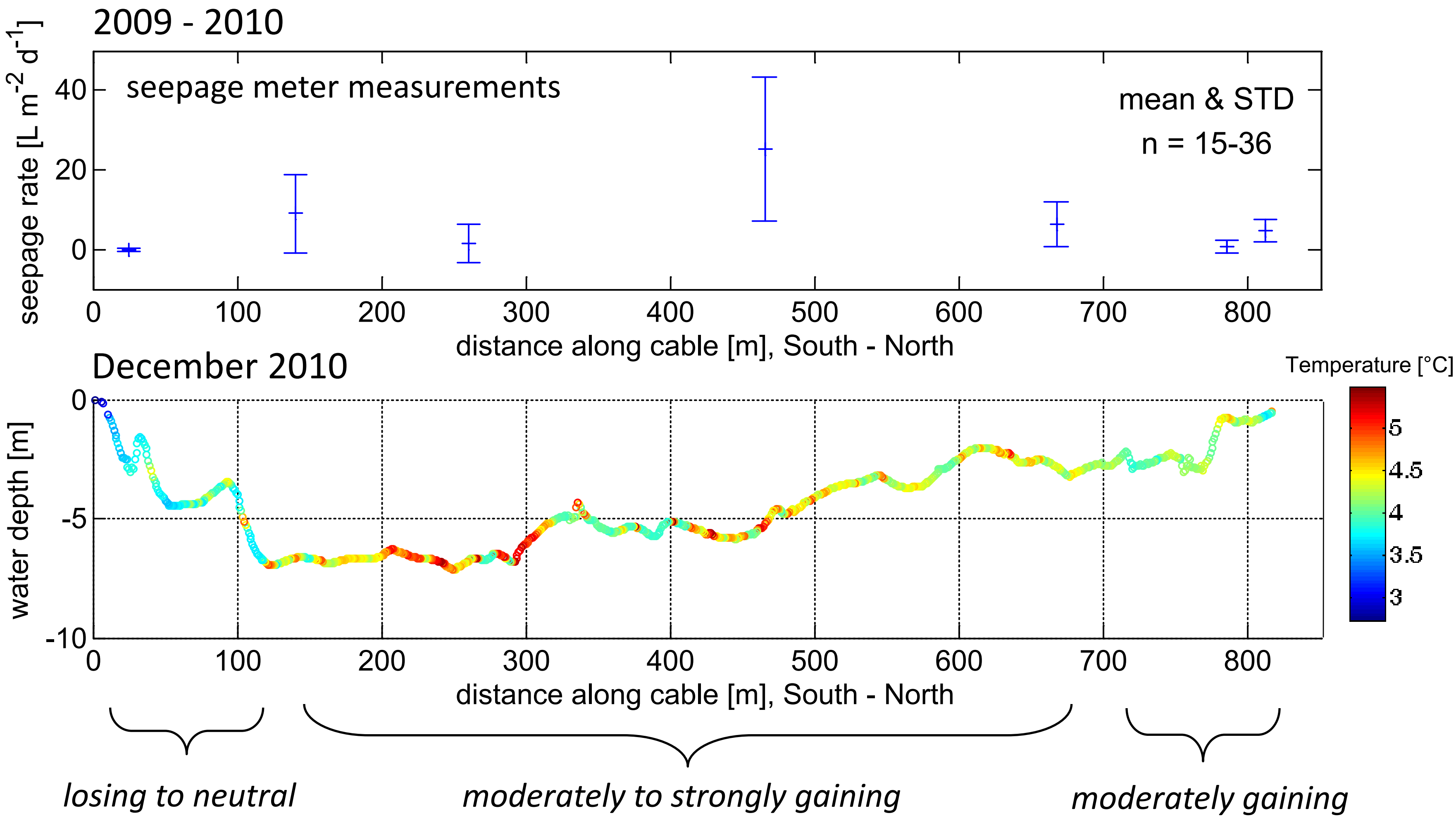
Seepage meter measurements of GW-exchange with a lake

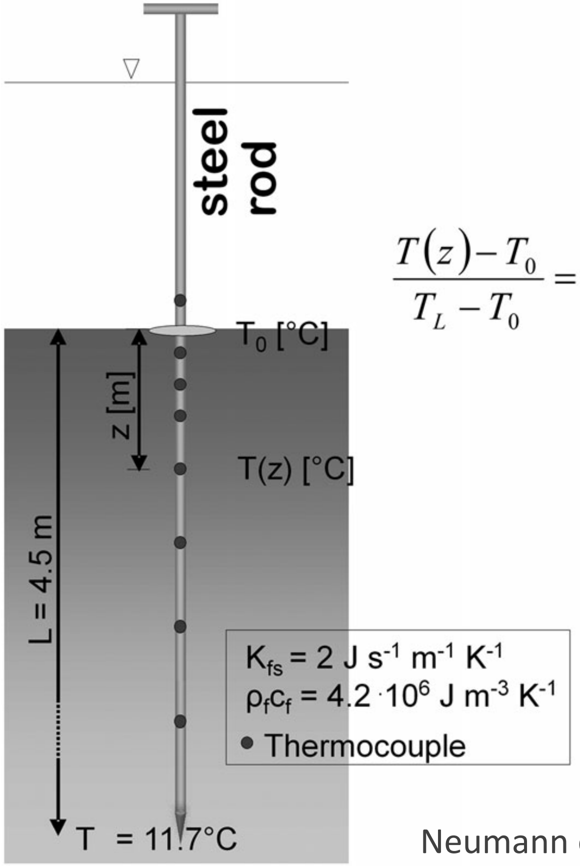


Neumann, Beer, Blodau, Peiffer, Fleckenstein, (2013) Hydrological Processes, 47:3240-3253

DTS-based localization of GW-exchange hotspots in a lake

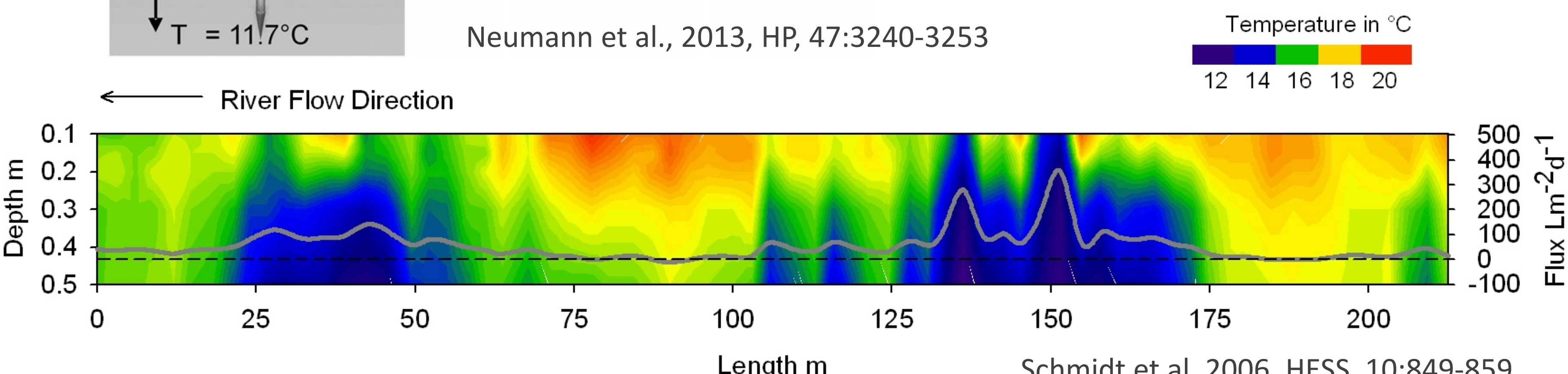


Temperture-based methods – vertical profiles



$$\frac{T(z)-T_0}{T_L-T_0}=\frac{\exp\left(\frac{q_z\rho_f c_f}{K_{fs}}z\right)-1}{\exp\left(\frac{q_z\rho_f c_f}{K_{fs}}L\right)-1}$$

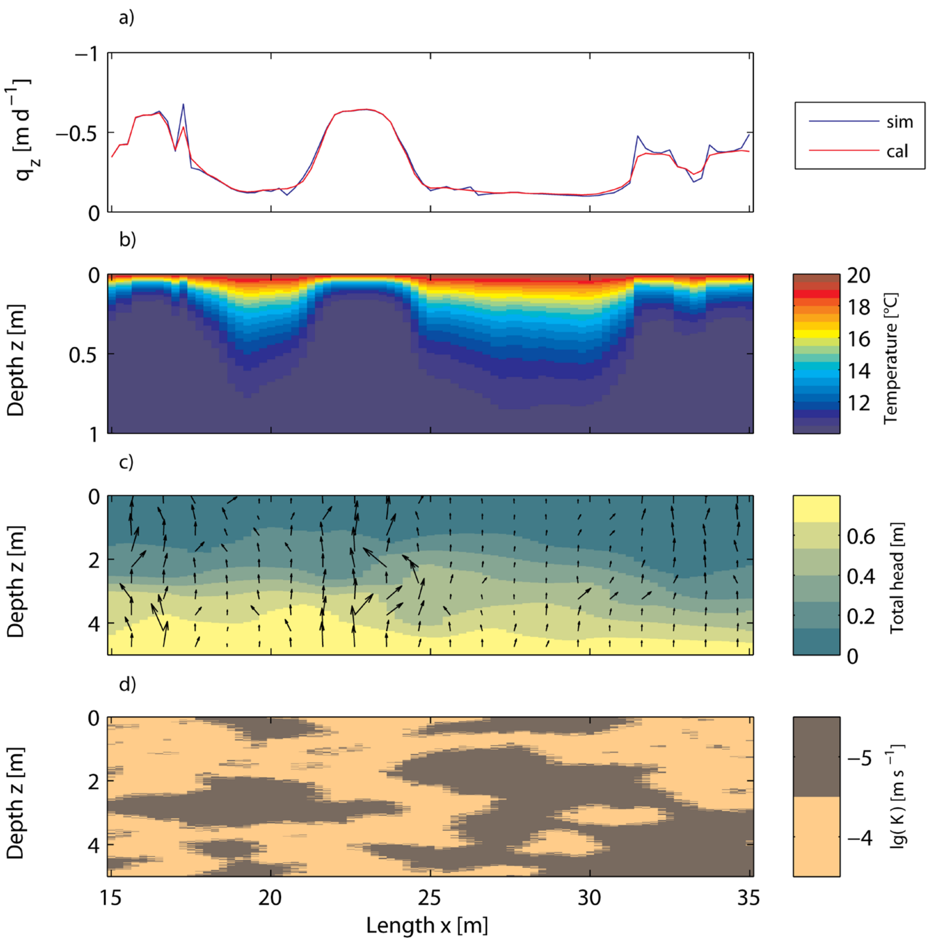
Neumann et al., 2013, HP, 47:3240-3253



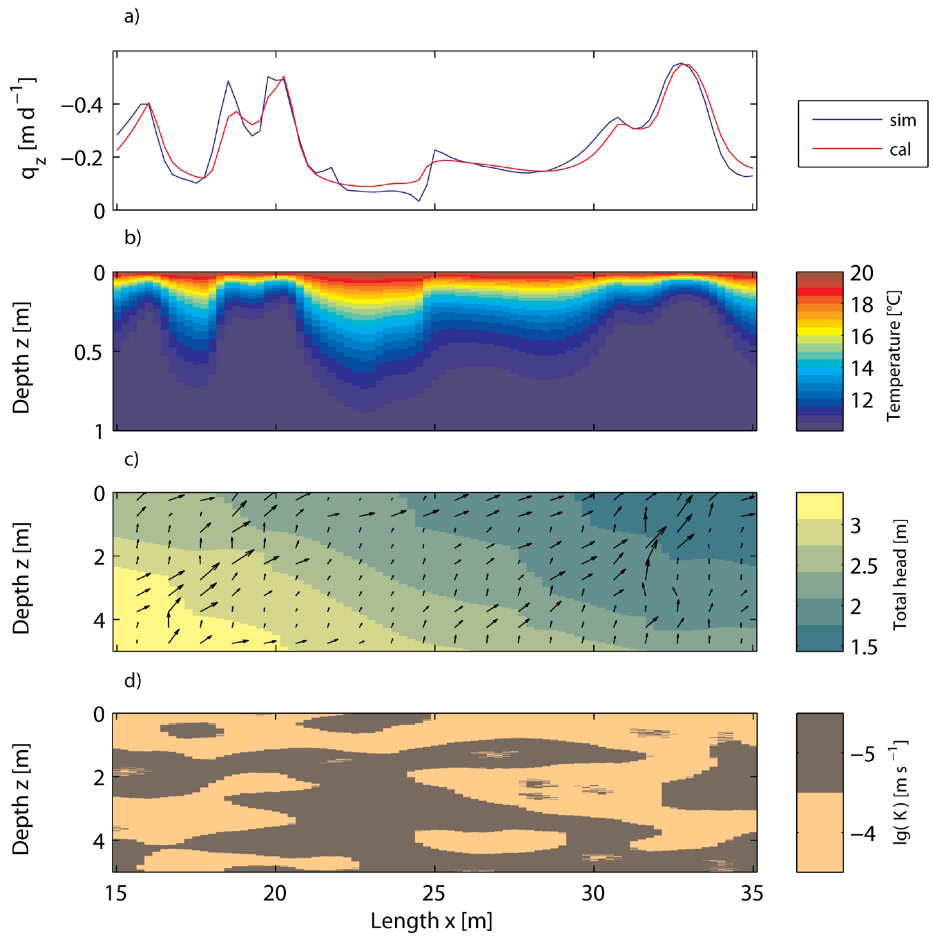
Schmidt et al. 2006, HESS, 10:849-859

Effects of non-ideal conditions – non-vertical flow

vertical flow ($\alpha = 0°$)



diagonal flow ($\alpha = 30°$)



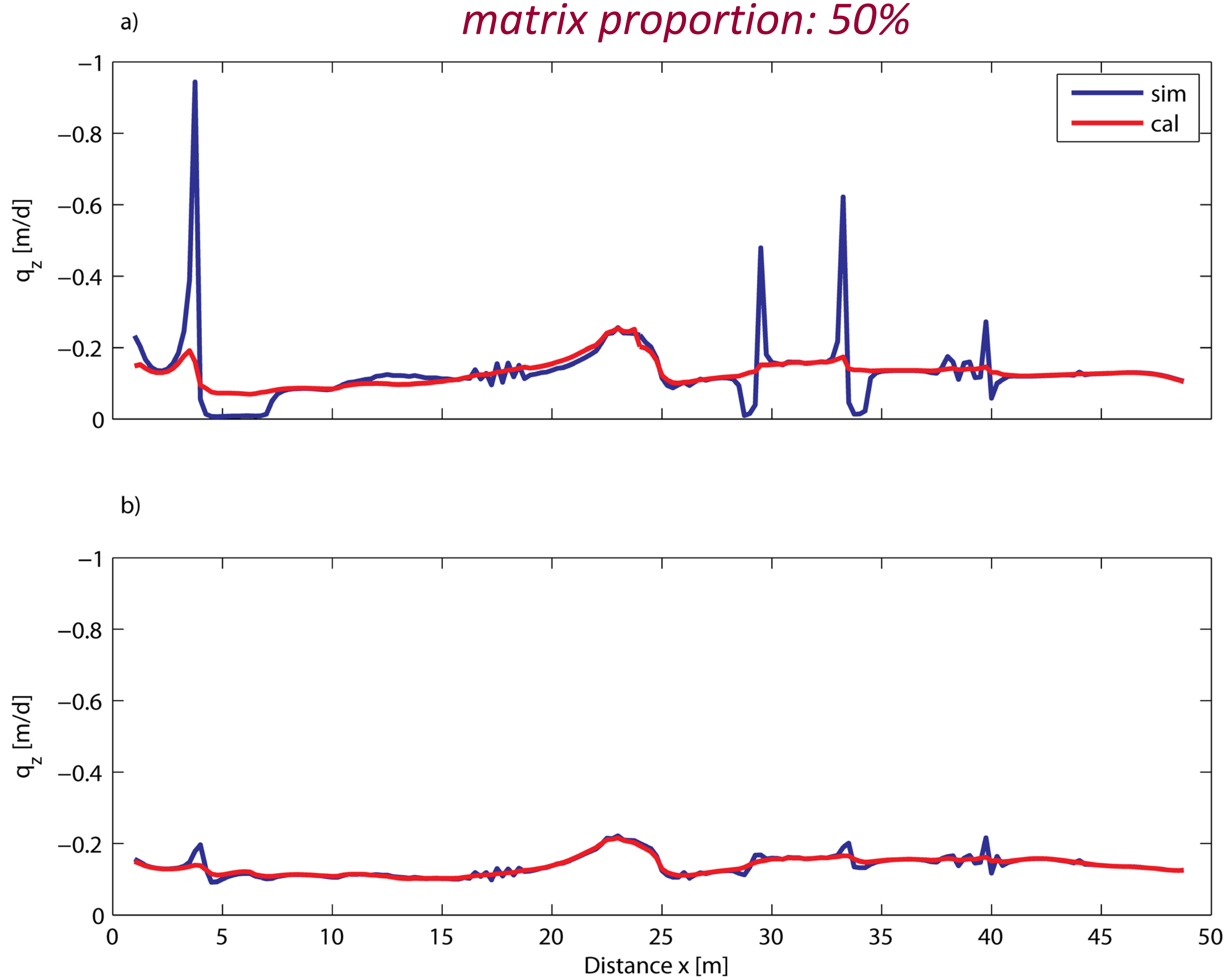
Schornberg, Schmidt, Kalbus, Fleckenstein (2010) Advances in Water Resources, 33:1309–1319

Effects of non-ideal conditions – geologic heterogeneity

matrix proportion: 50%

$K_1/K_2 = 10^3$

$K_1/K_2 = 10^1$



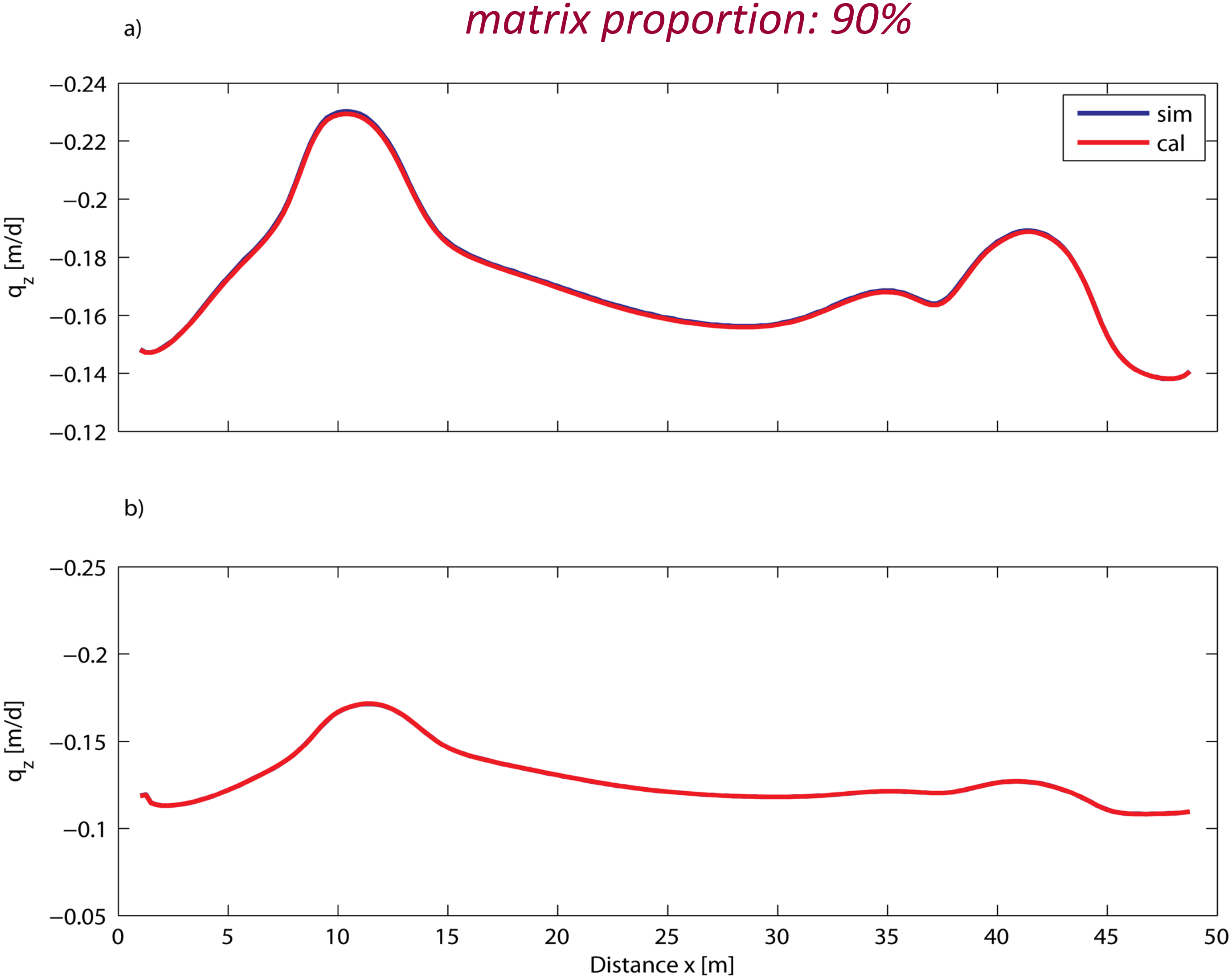
Schornberg, Schmidt, Kalbus, Fleckenstein (2010) Advances in Water Resources, 33:1309–1319

Effects of non-ideal conditions – geologic heterogeneity

matrix proportion: 90%

$K_1/K_2 = 10^3$

$K_1/K_2 = 10^1$

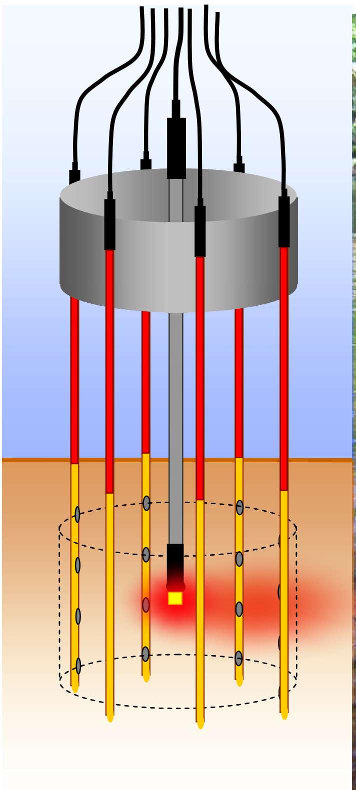


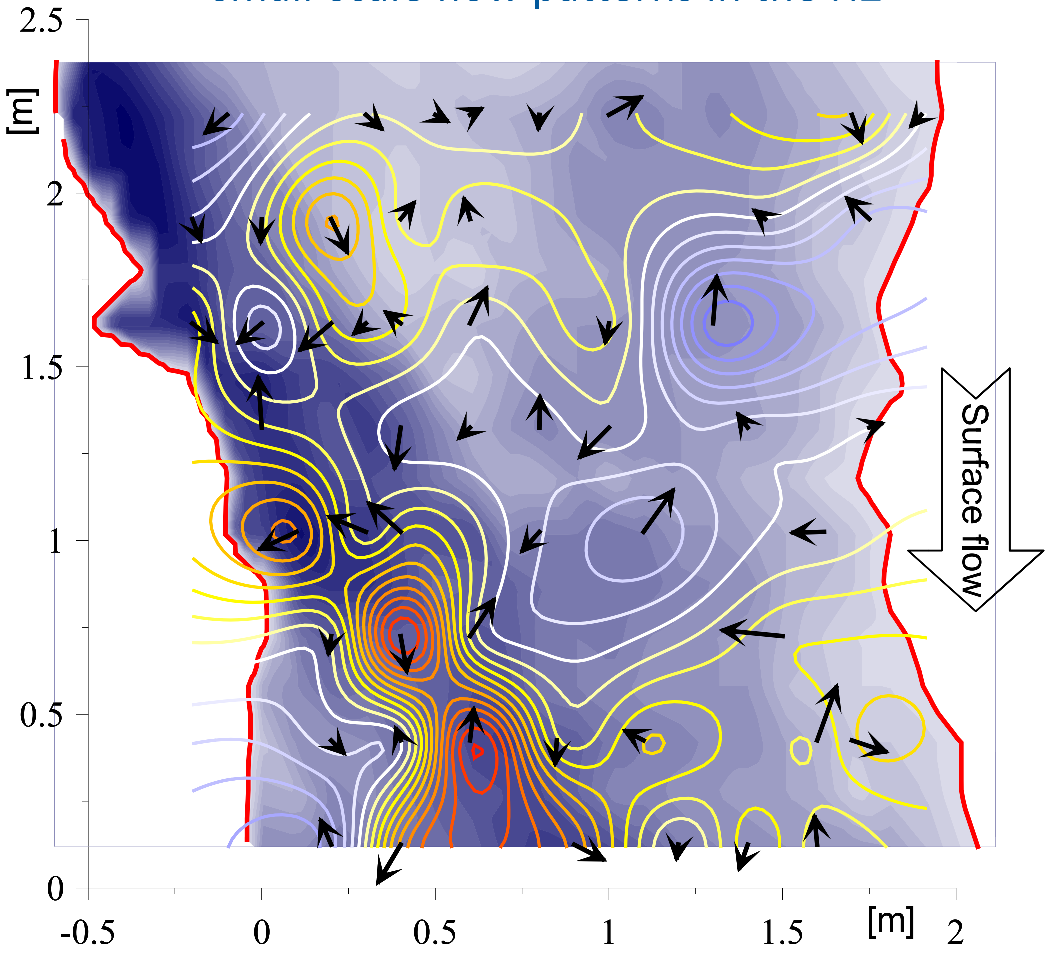
Schornberg, Schmidt, Kalbus, Fleckenstein (2010) Advances in Water Resources, 33:1309–1319

Heat-pulse methods → small-scale patterns of HZ flows

IGB Berlin

UNIVERSITÄT BAYREUTH





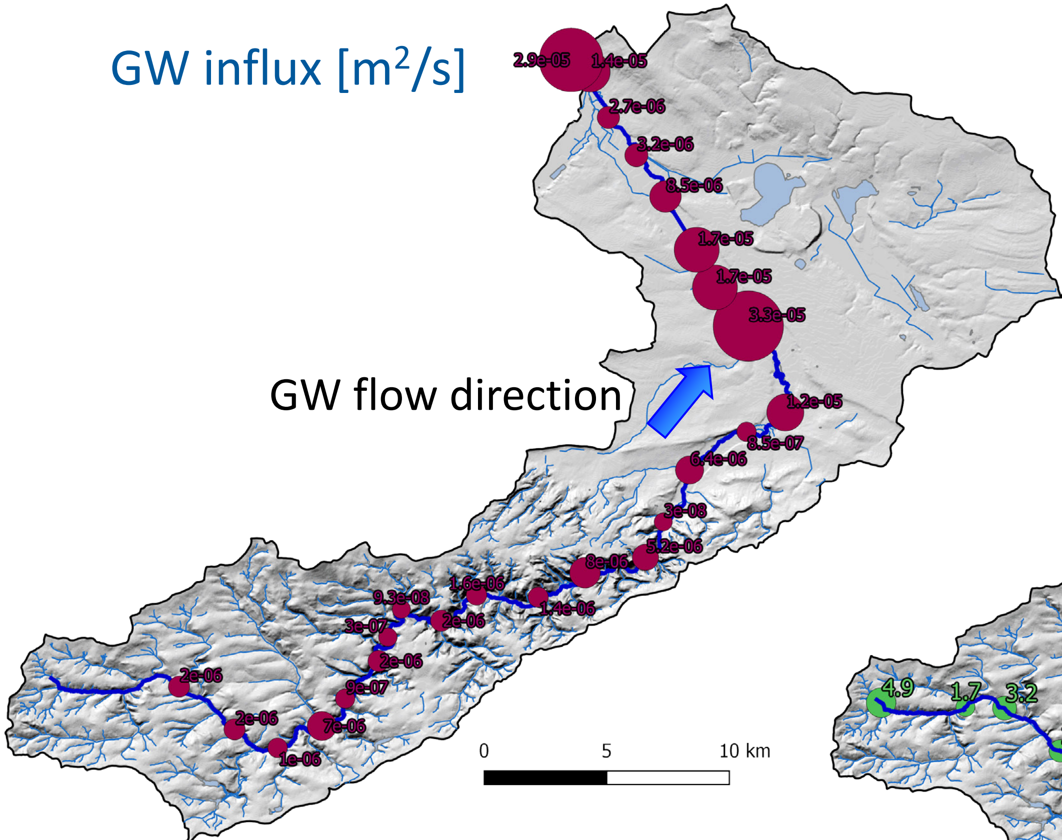
Lewandowski, Angermann, Nützmann & Fleckenstein (2011) Hydrological Processes, 25:3244–3255

Radon (Rn^{222}) as a natural tracer → net groundwater gains

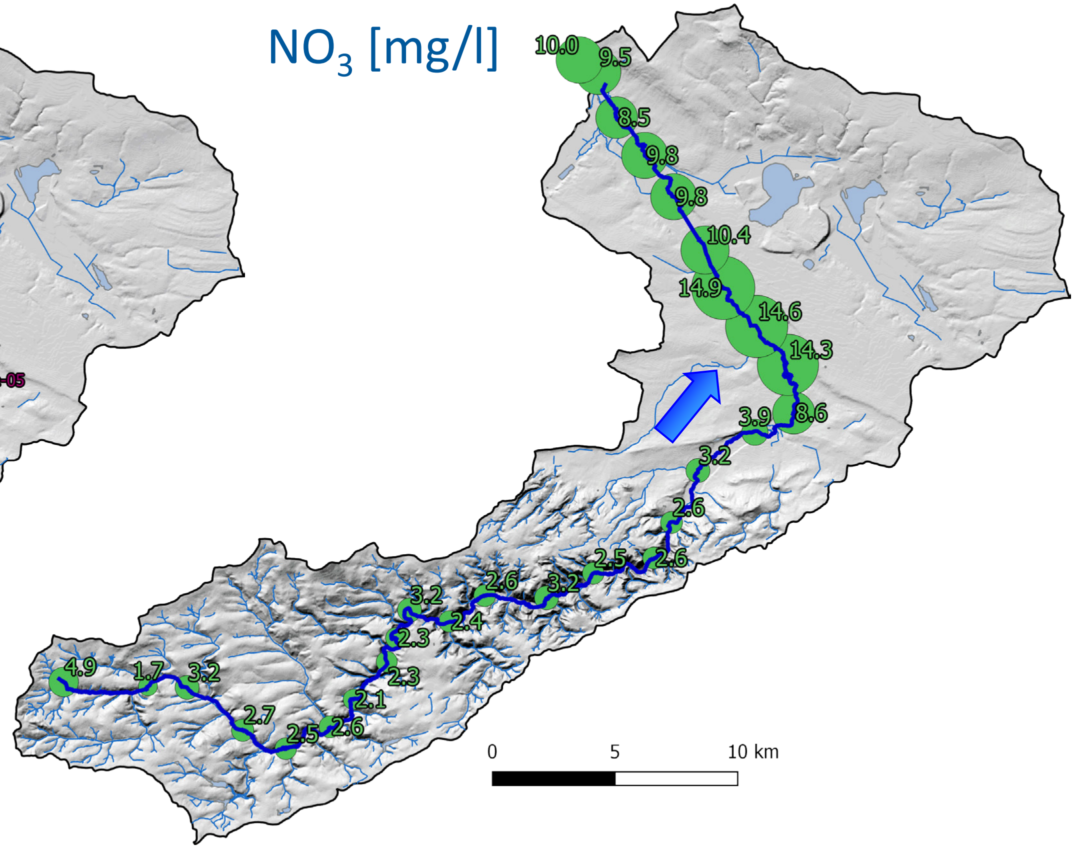
$$Q_S \frac{dc}{dx} = I(c_{gw} - c) - kwc - dw\lambda c + \frac{\gamma h w \theta}{1 + \lambda t_h} - \frac{\lambda h w \theta}{1 + \lambda t_h} c + \frac{Q_r}{R_L}(c_r - c)$$

GW influx | degasing | decay | hyporheic exchange | tributary inflows

GW influx [m^2/s]

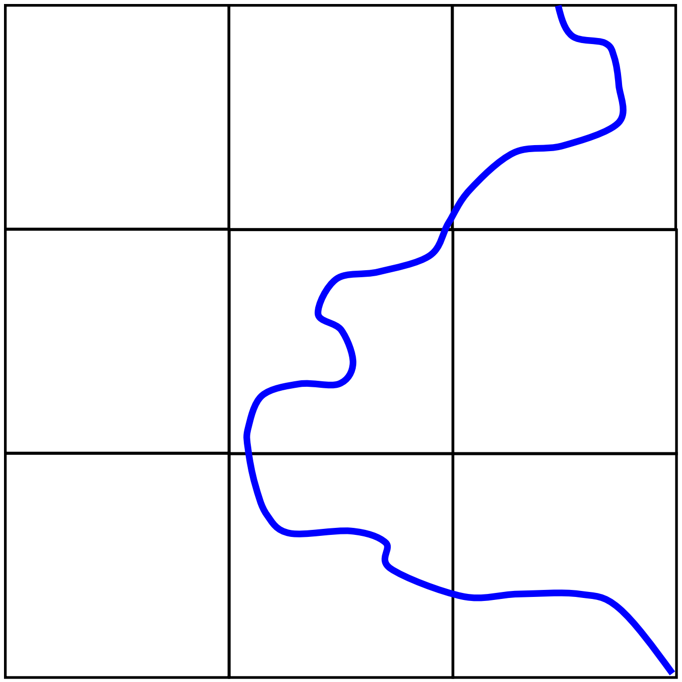


NO_3 [mg/l]

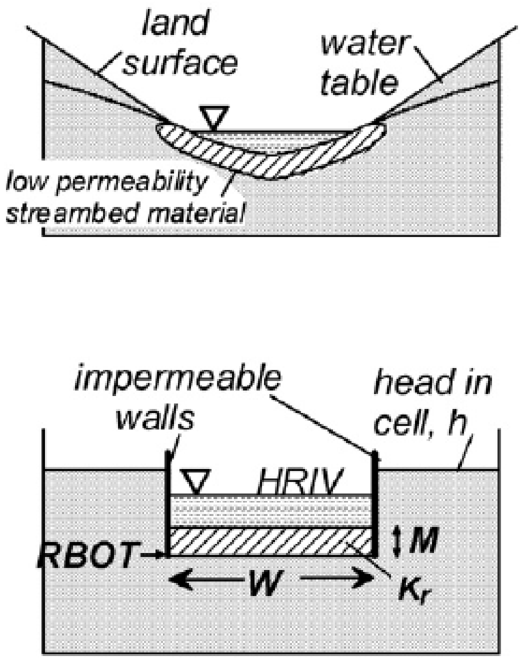


GW-SW interactions in groundwater models – large scale

coarse numerical grids



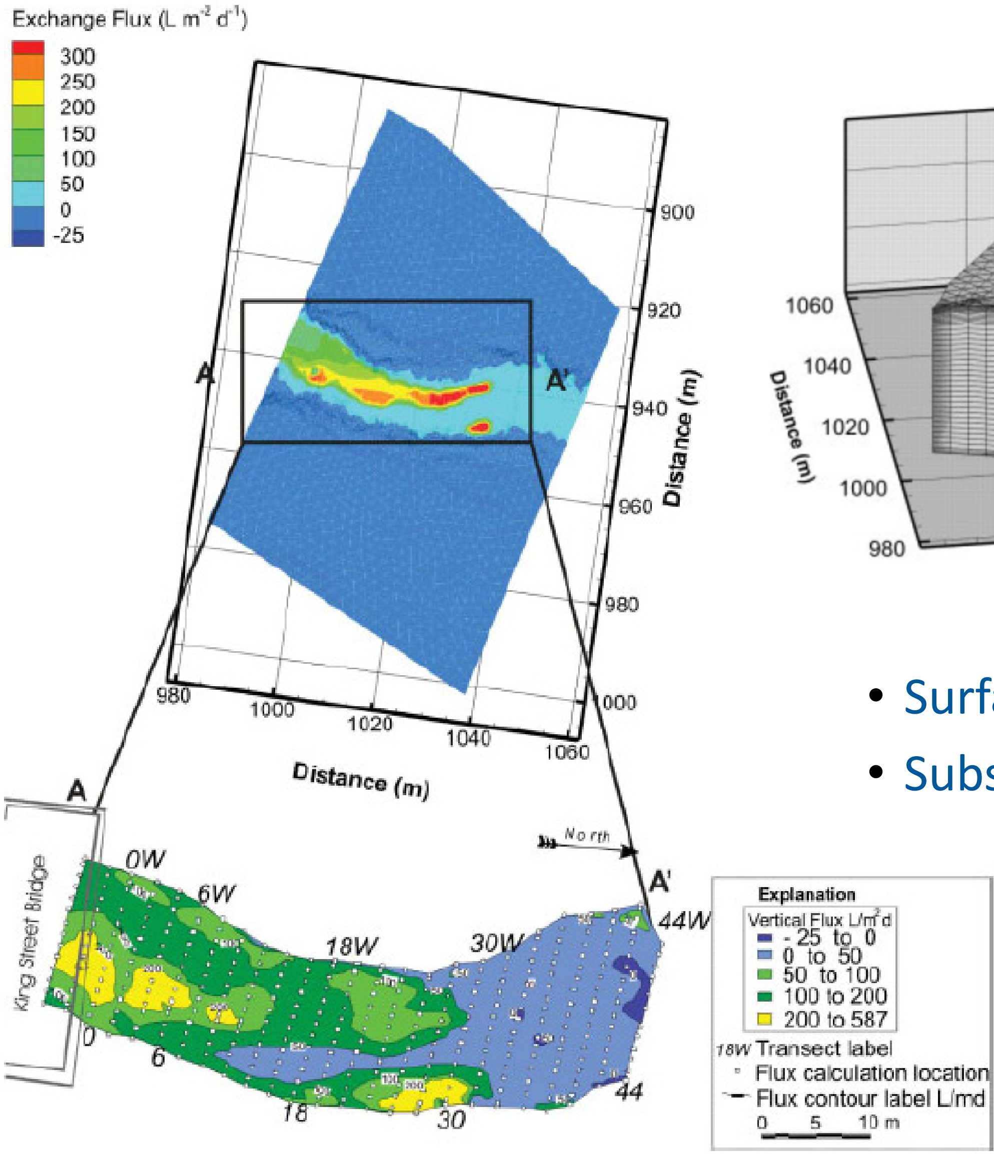
simplified GW-SW-interface (e.g. MODFLOW)

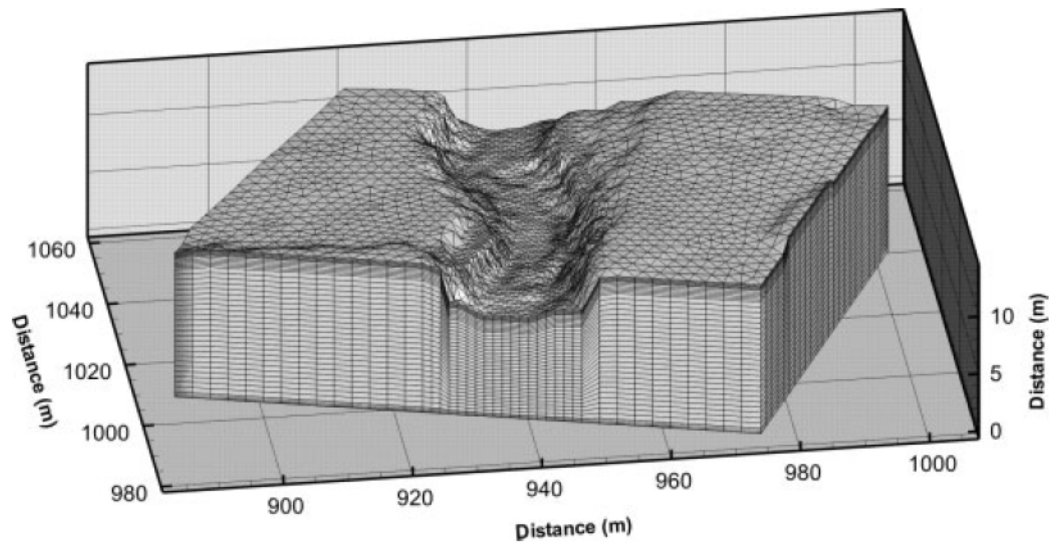


Rusthon, J.of Hydrology., 334, 2007

Problem: coarse spatial resolution, small-scale patterns can not be resolved

Integrated surface-subsurface simulation – finer scale





- Surface flow: St. Venant or approximations
- Subsurface flow: 3D Richards

Brookfield et al. 2009, Hydrological Processes, 23,(15)

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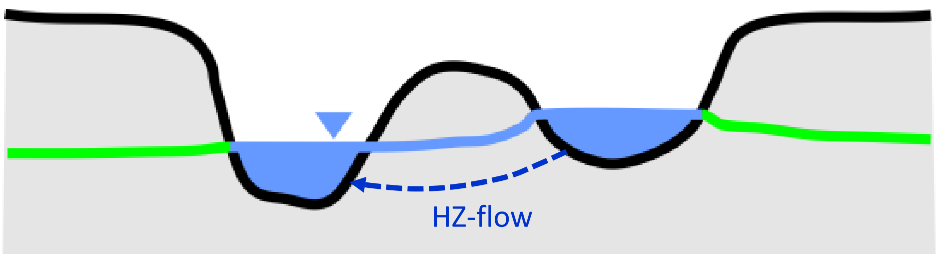
Submerged features (e.g. riffles) → dynamic pressures

non-submerged features

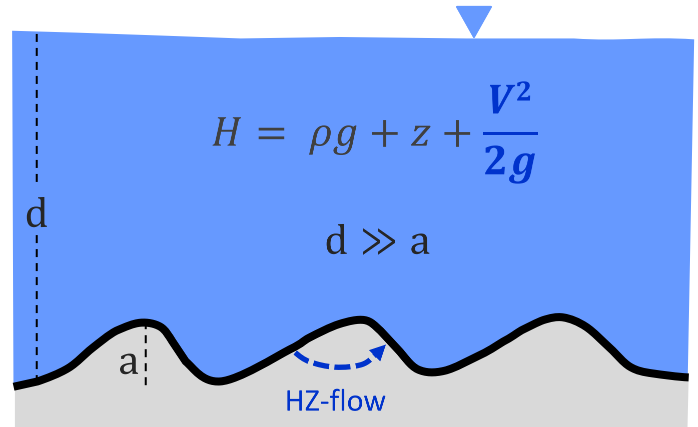
hydrostatic pressure dominates HZ flow

$$H = \boldsymbol{\rho g} + \boldsymbol{z} + \frac{V^2}{2g}$$



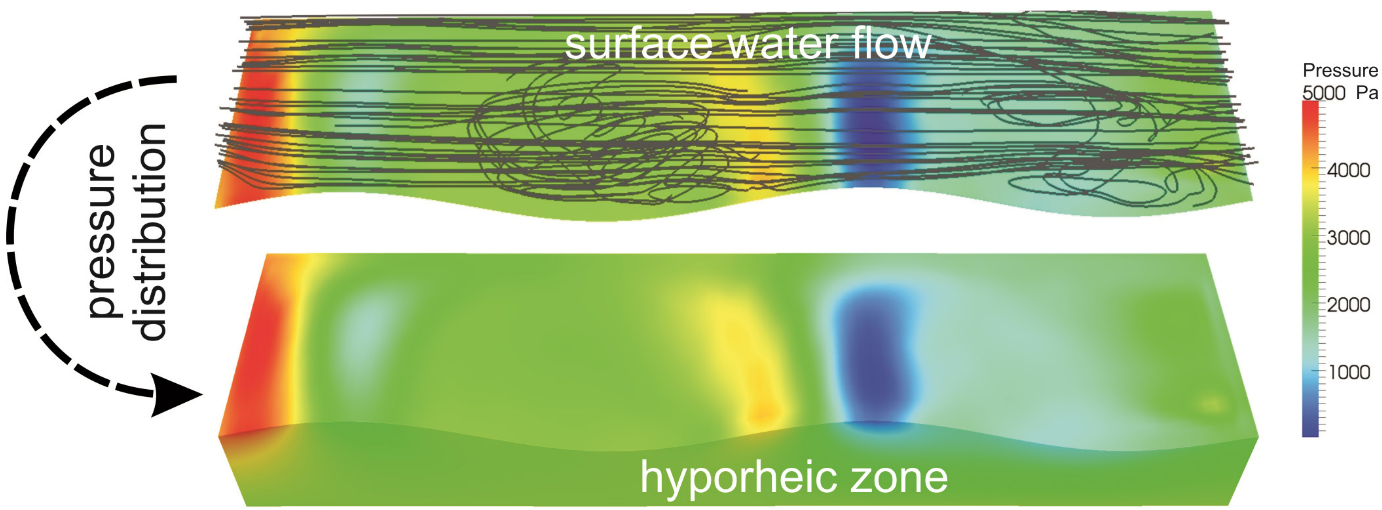
submerged features

dynamic pressure dominates HZ flow



Navier-Stokes Model,

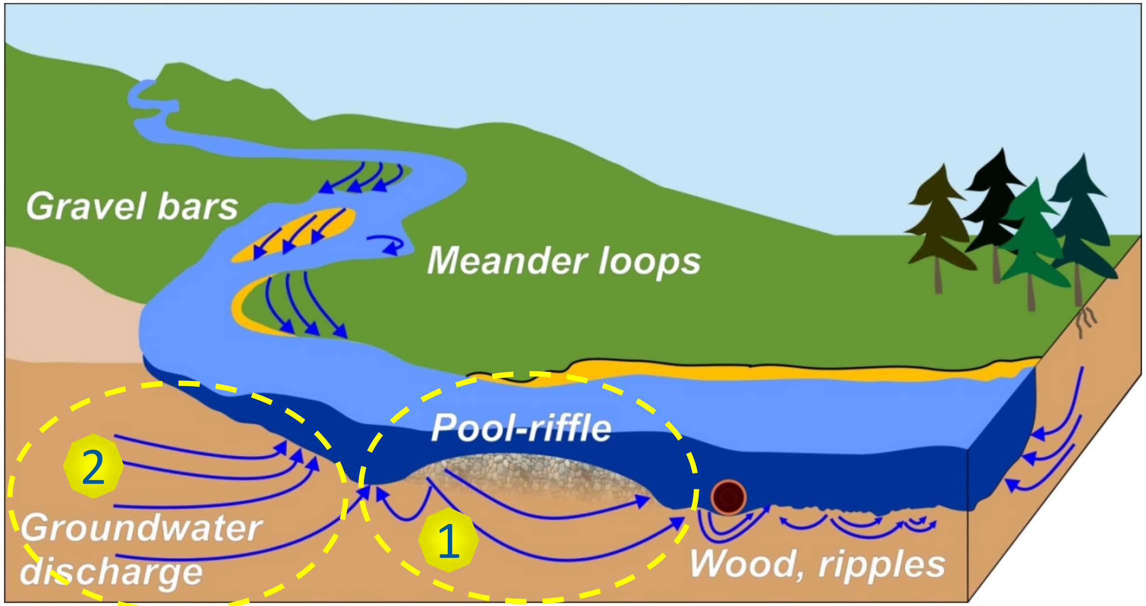
e.g. OpenFOAM



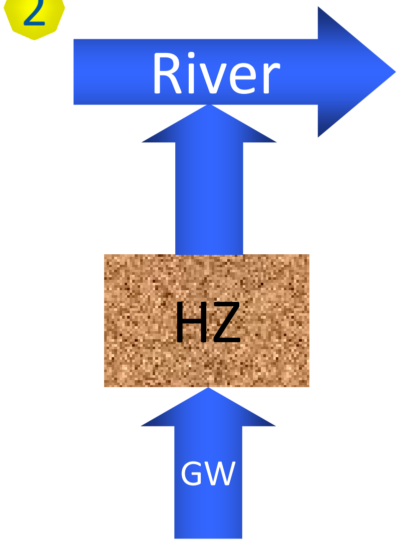
The hyporheic zone as a biogeochemical reactor/barrier ?

„A River's liver", Fischer et al. 2005

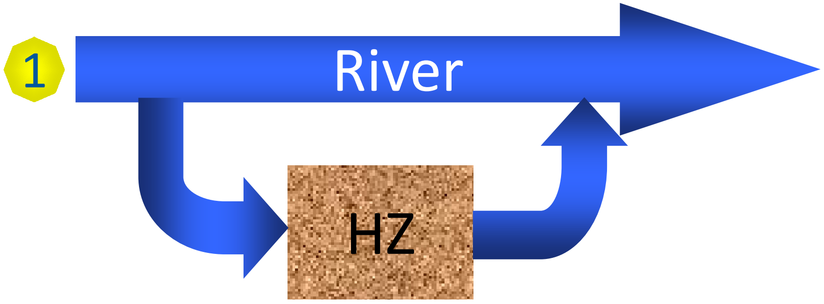
- mixing of chemically different waters
- pronounced gradients
- enhanced microbial activity
- increased residence times
- input of OM as electron-donor
- temporally variable redox conditions



from: Mutz, Schmidt & Fleckenstein, Limnologie Aktuell Vol.14, 2015



GW-discharge → in series



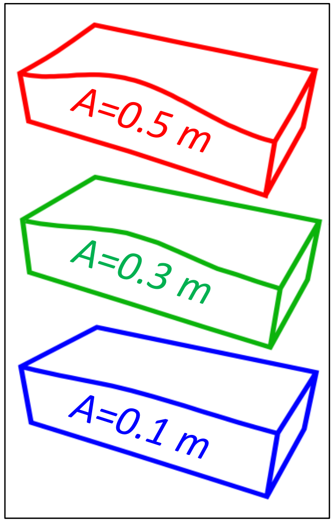
hyporheic exchange → in parallel

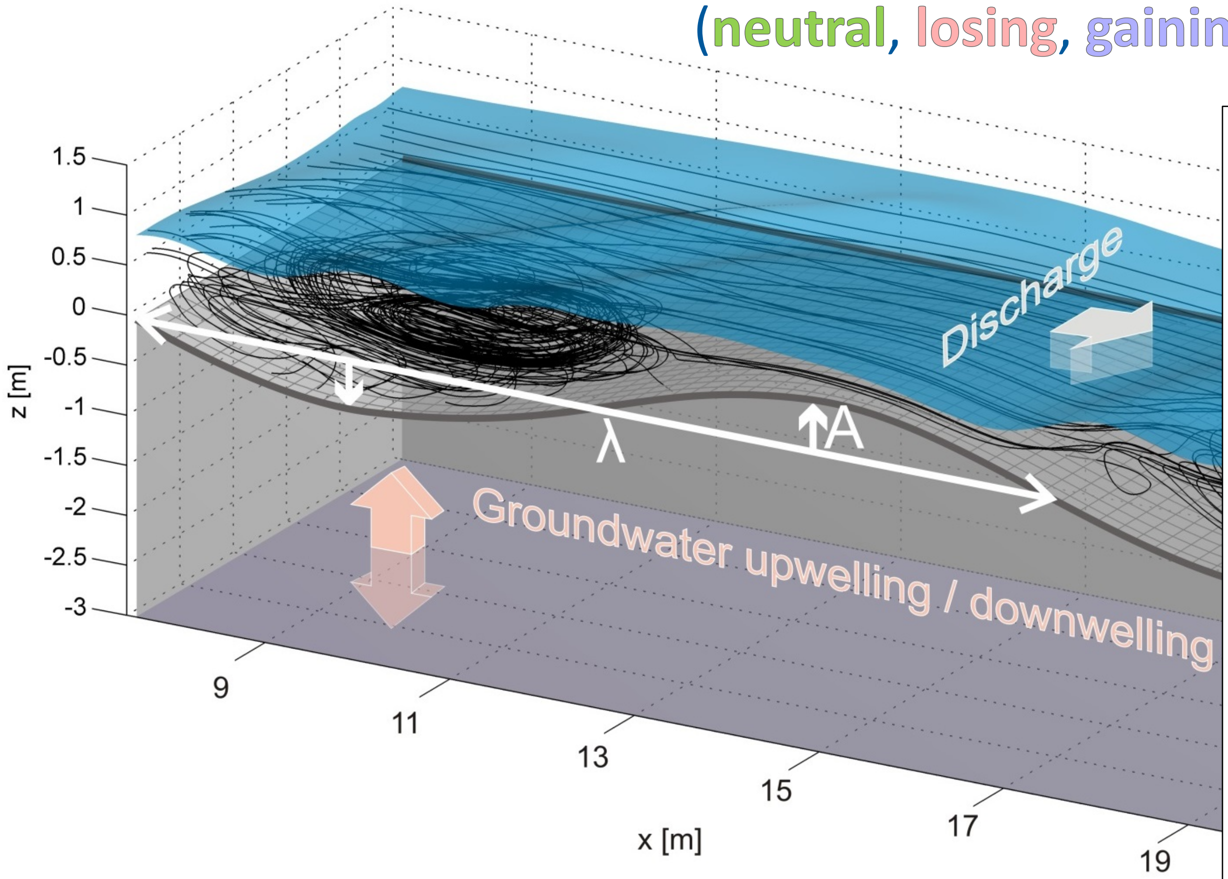
→ hyporheic exchange length

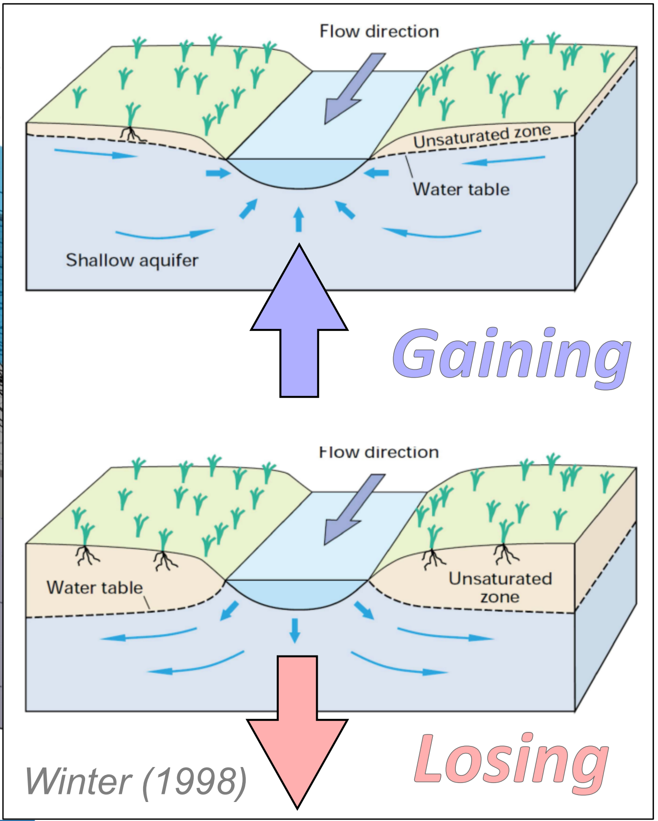
Model set-up – water flow

- Morphology: Pool-riffles with various amplitudes
- Variation of stream discharge (Q_{surf})
- Variation of ambient groundwater flow

(neutral, losing, gaining conditions)



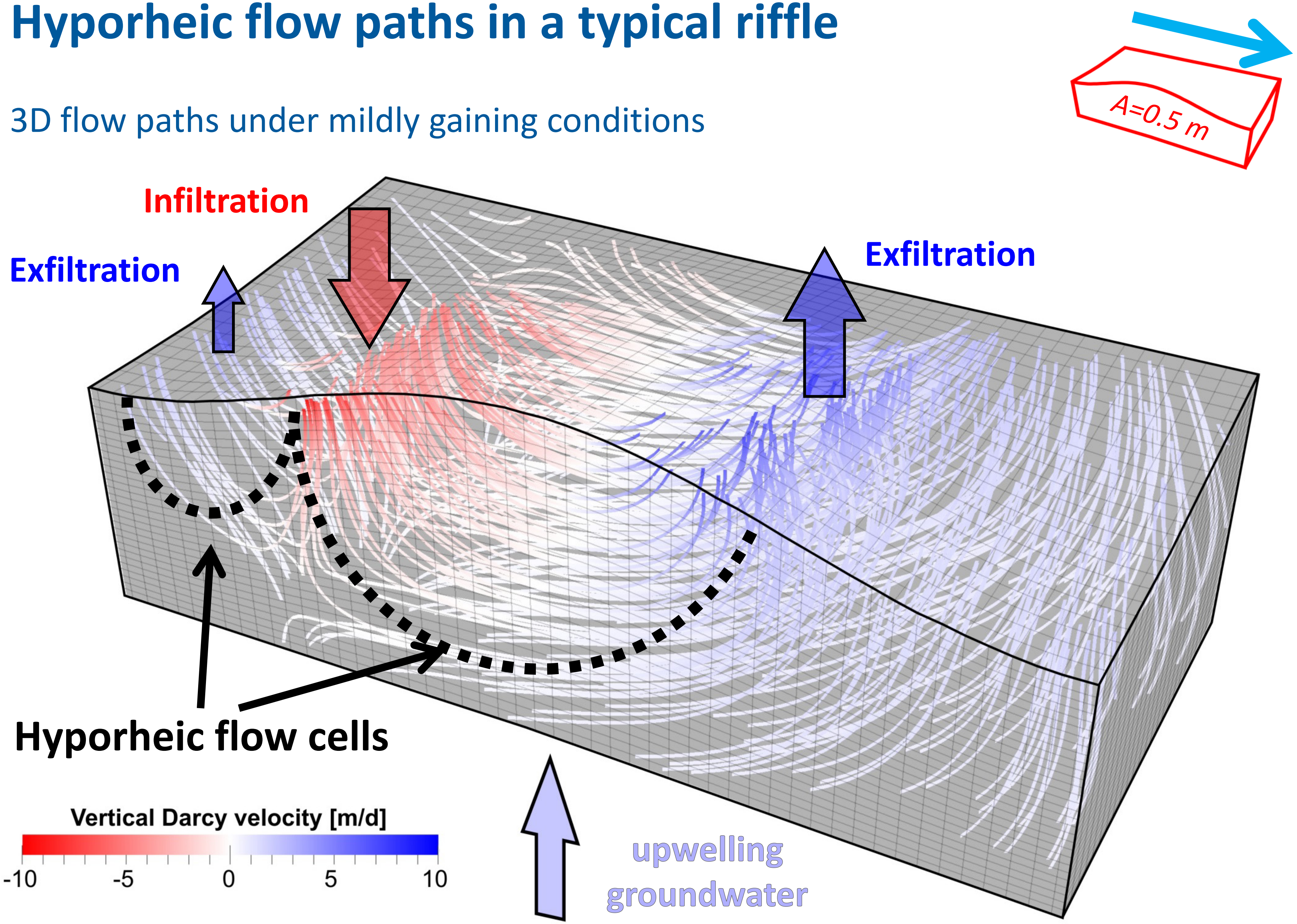




Trauth, Schmidt, Maier, Vieweg, Fleckenstein (2013) WRR, 49:1-17

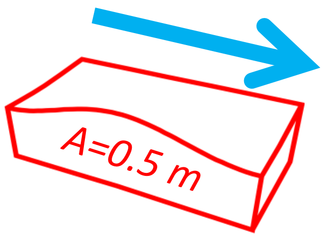
Hyporheic flow paths in a typical riffle

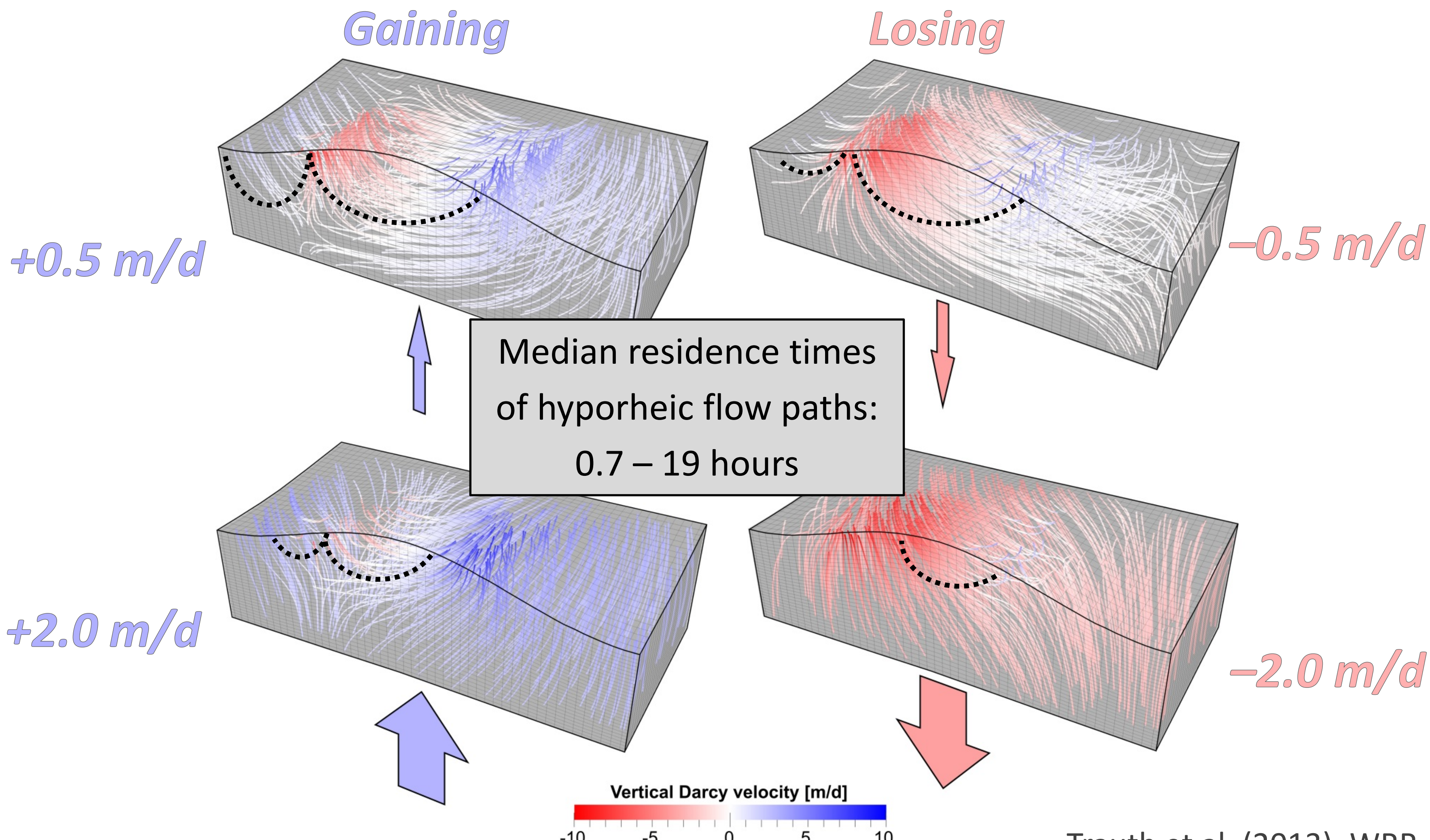
3D flow paths under mildly gaining conditions



Hyporheic flow paths – gaining vs. losing

Effects of gaining and losing conditions



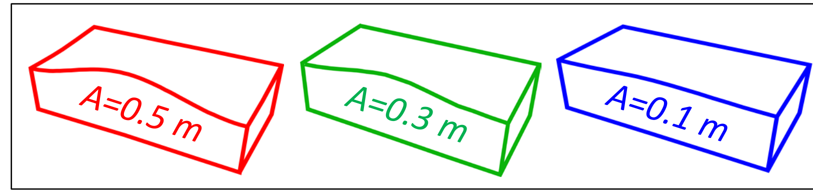


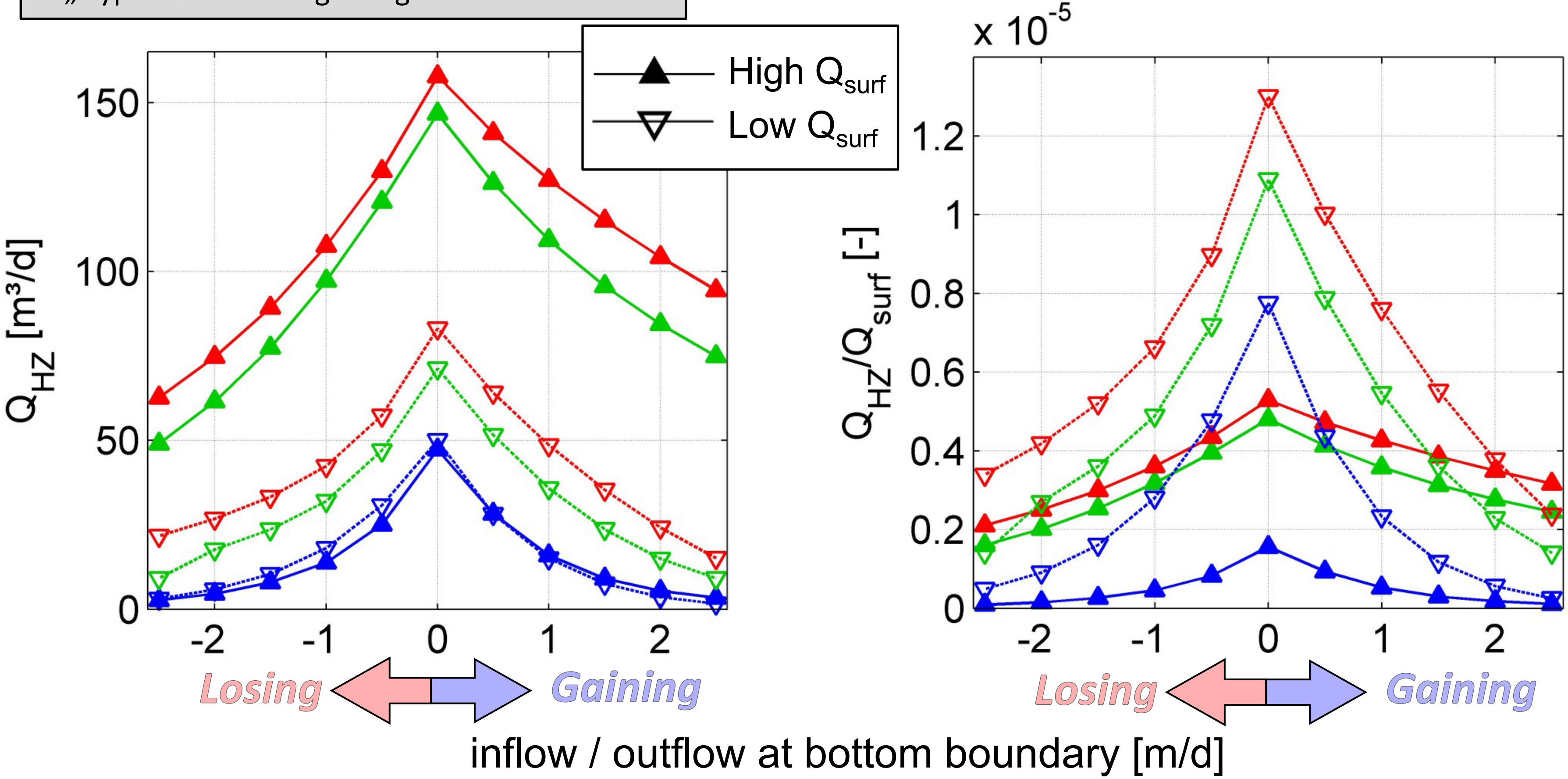
Trauth et al. (2013), WRR

Magnitude of the hyporheic exchange flux (Q_{HZ})

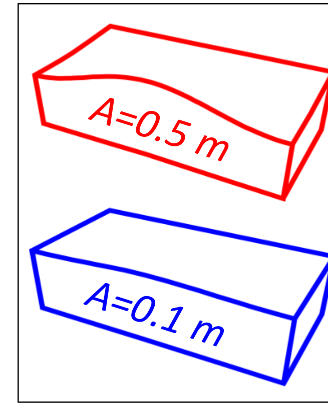
Effects of gaining versus losing conditions

fraction of streamwater
pumped through the hyporheic zone:
Q_{HZ}/Q_{surf} = 1:10.000 to 1:100.000
„Hyporheic exchange length“: 10 to 100 km



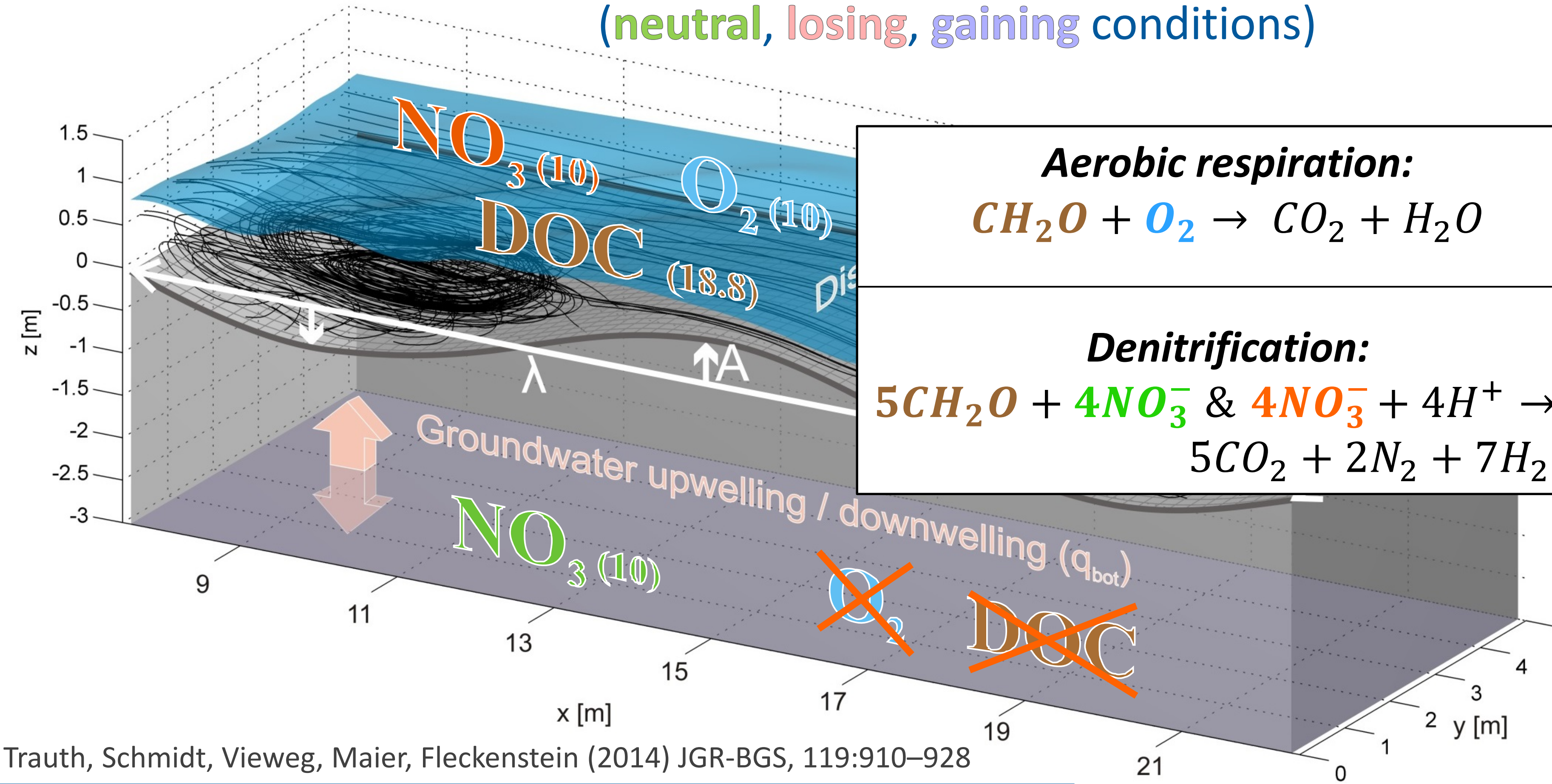


Model set-up – reactive transport



- Morphology: Pool-riffles with various amplitudes
- Variation of stream discharge (Q_{surf})
- Variation of ambient groundwater flow

(neutral, losing, gaining conditions)



Aerobic respiration:

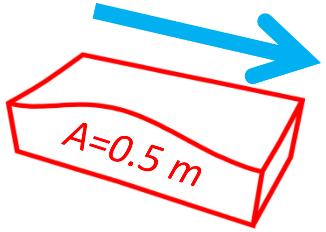
$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

Denitrification:

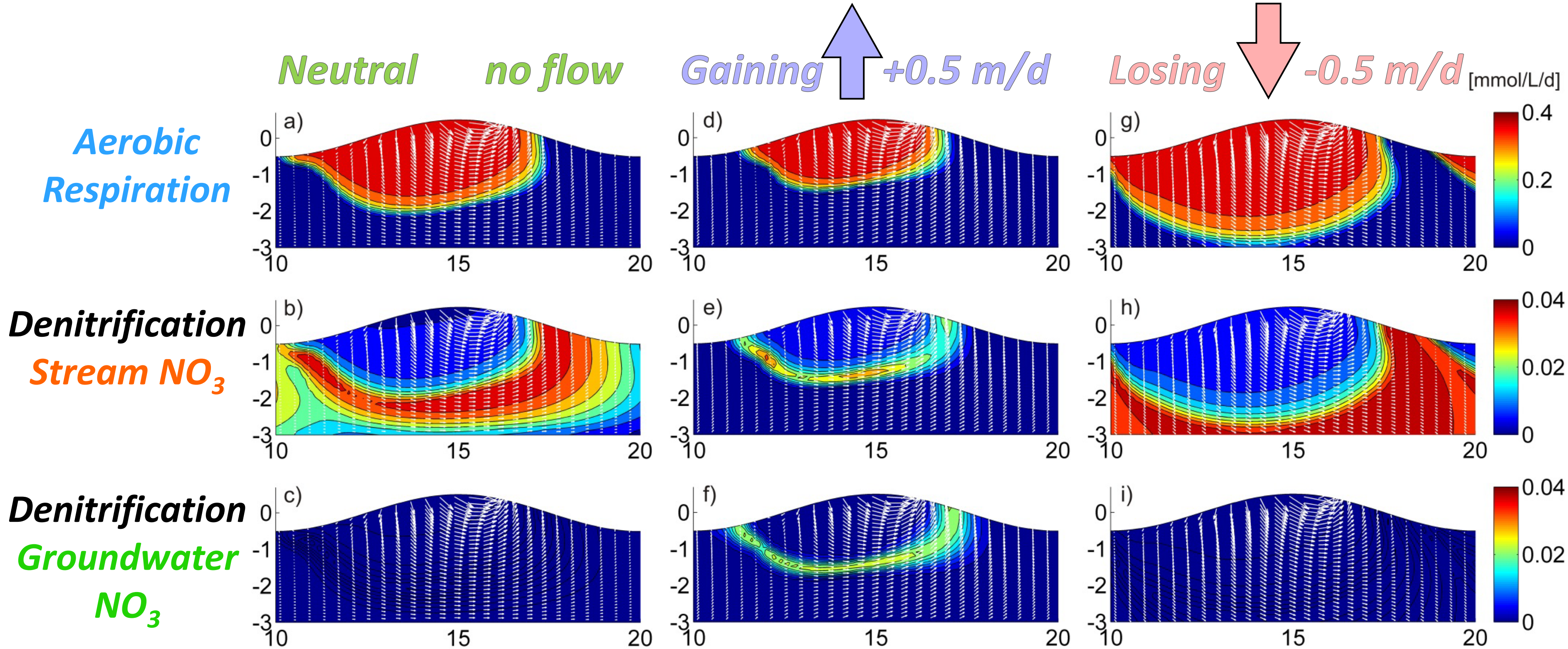
$$5CH_2O + 4NO_3^- \;\&\; 4NO_3^- + 4H^+ \rightarrow 5CO_2 + 2N_2 + 7H_2O$$

Trauth, Schmidt, Vieweg, Maier, Fleckenstein (2014) JGR-BGS, 119:910–928

Reactions & turn over – pool-riffle sequence



2D - spatial distribution of consumption rates



Trauth et al. (2014) JGR-BGS

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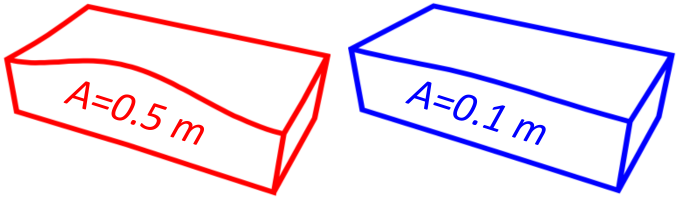
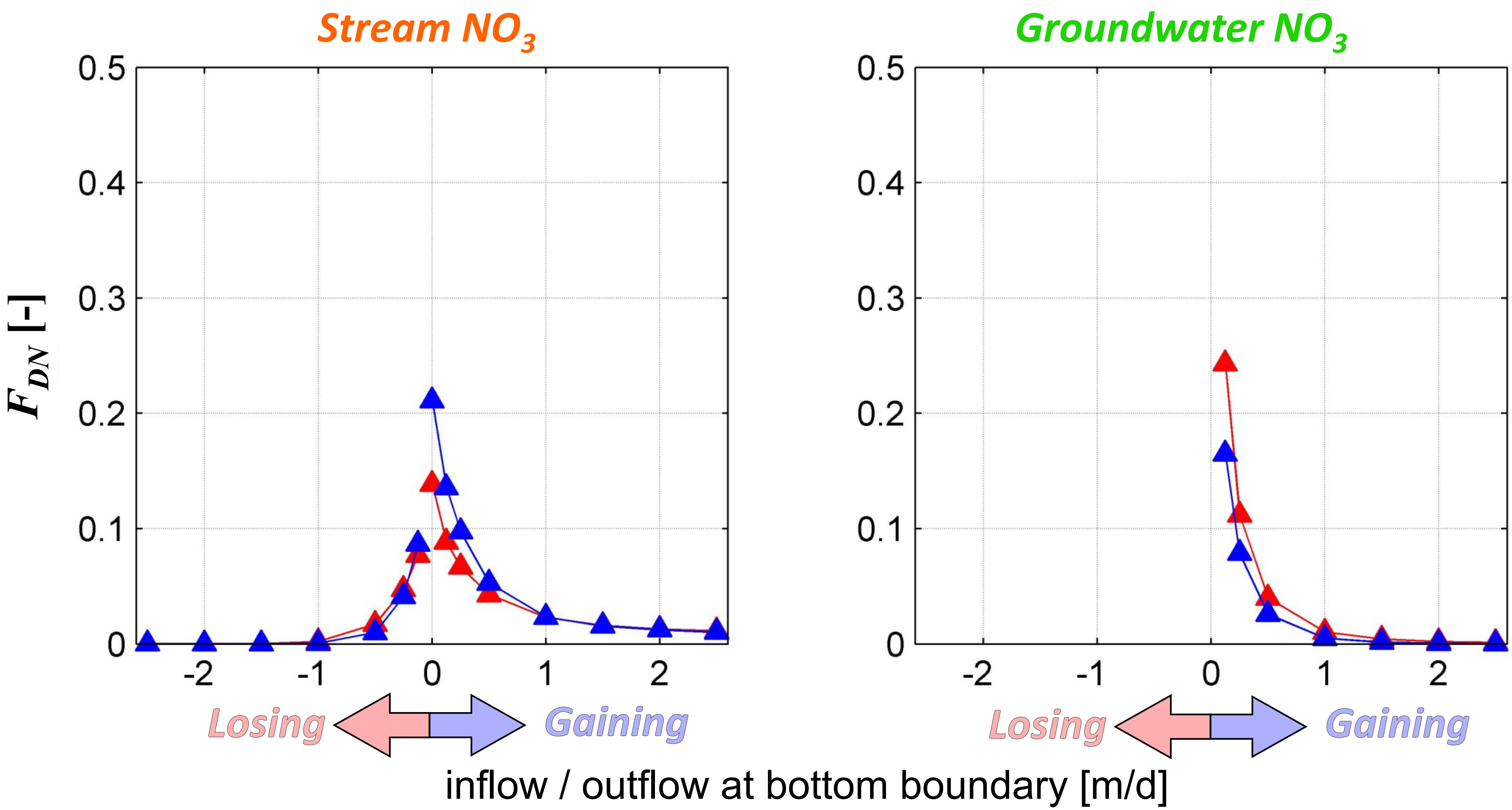
Denitrification efficiency – pool-riffle sequence

Efficiency: $F_{DN} = \frac{NO_3 Consumption}{NO_3 Influx}$

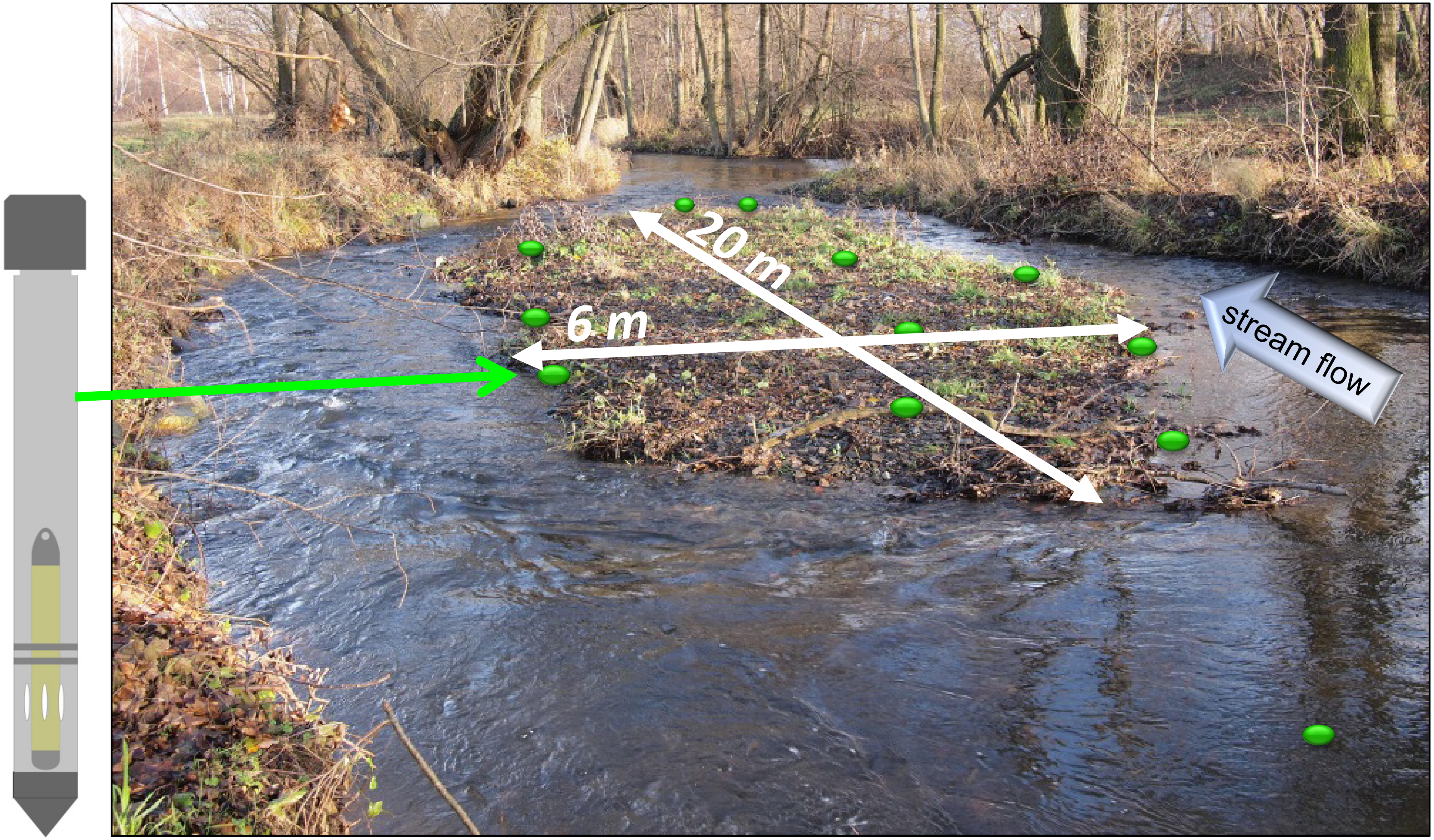




Trauth et al. (2014) JGR-BGS

Instream gravel bar – field site

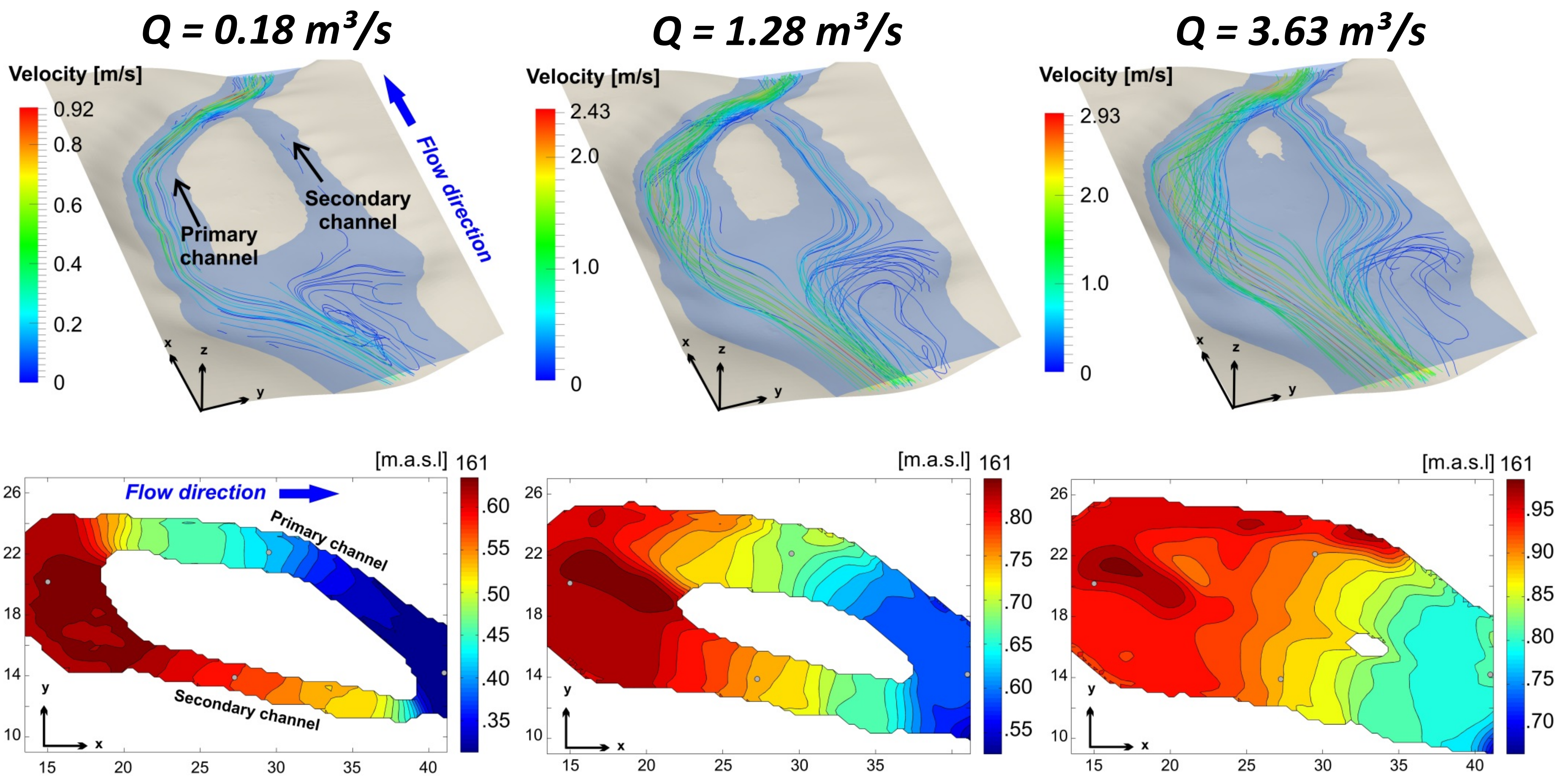
- In-stream gravel bar at the river Selke, central Germany
- Field data: stream discharge, water level, electrical conductivity



Trauth et al. (2015), WRR

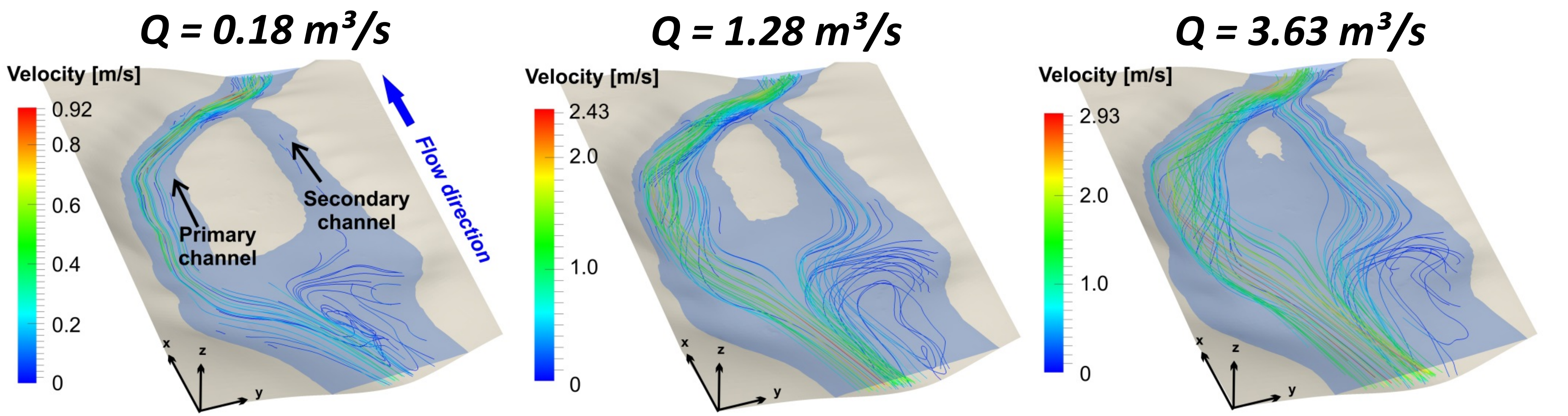
Instream gravel bar – model set-up

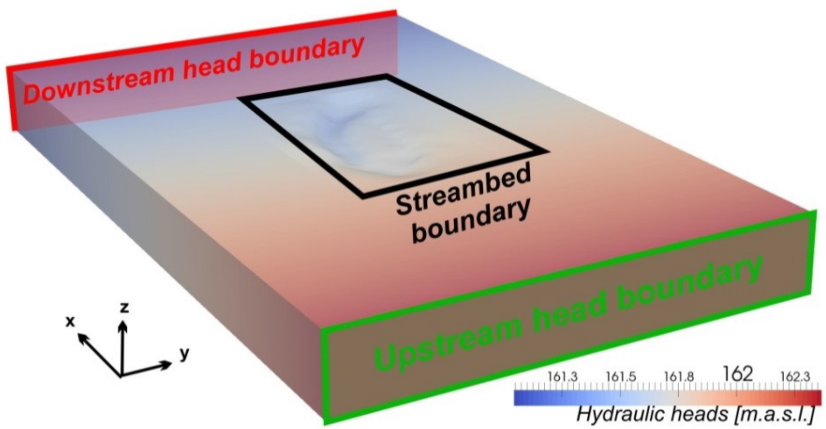
- CFD code: Stream discharges ranging from 0.18 to 5.0 m³/s



Instream gravel bar – model set-up

- CFD code: Stream discharges ranging from 0.18 to 5.0 m³/s
- Groundwater model: Range of ambient groundwater heads inducing neutral, losing, gaining conditions





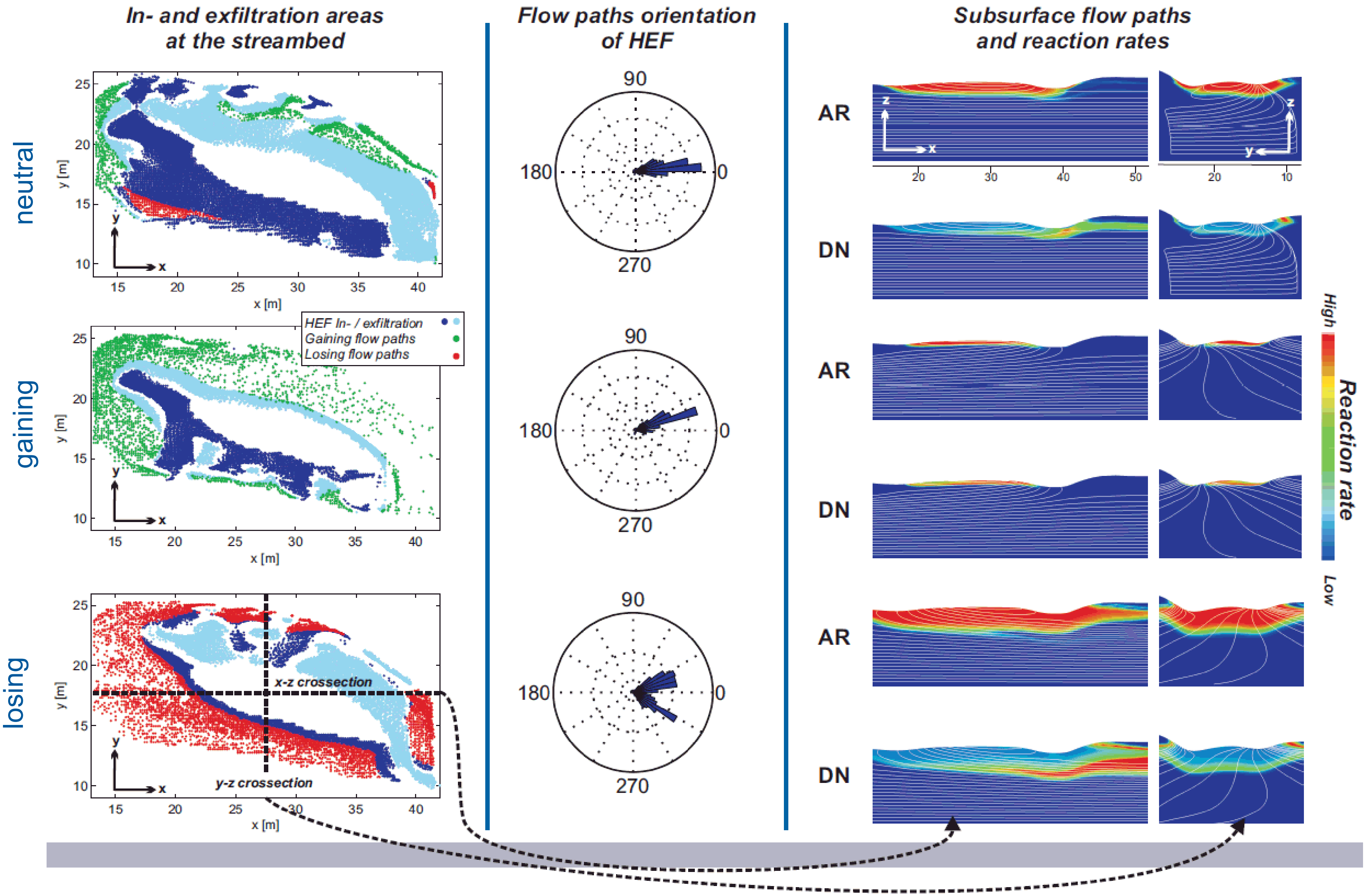
Aerobic respiration:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

Denitrification:

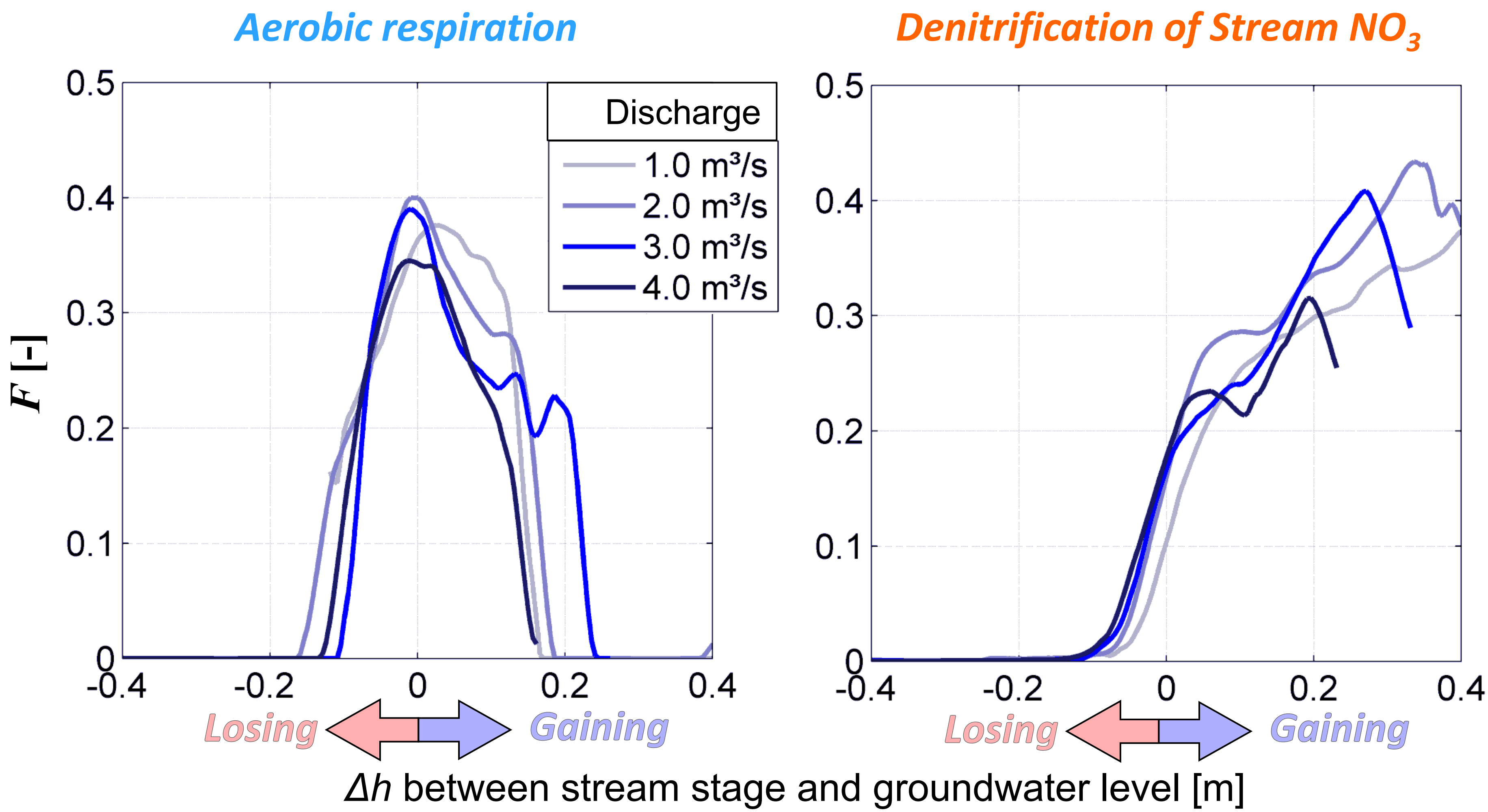
$$5CH_2O + 4NO_3^- + 4H^+ \rightarrow 5CO_2 + 2N_2 + 7H_2O$$

Instream gravel bar – flow patterns and reactions

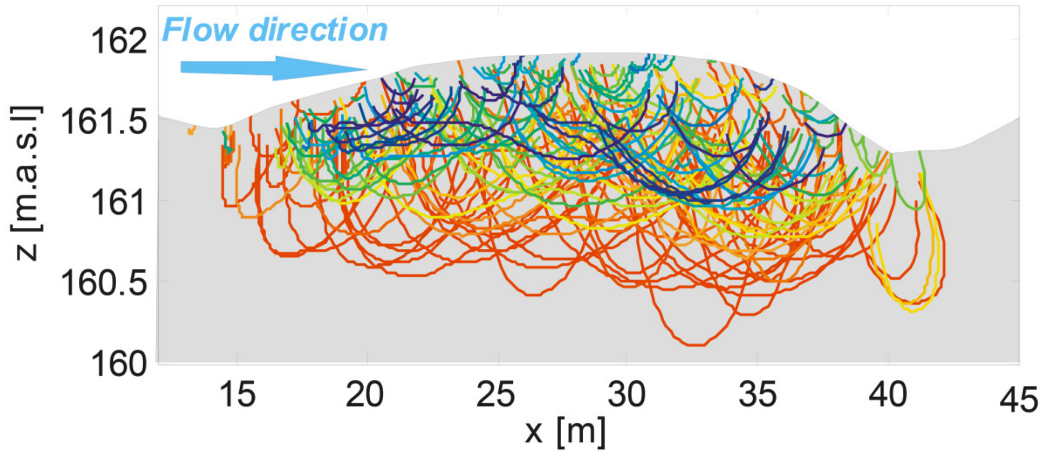


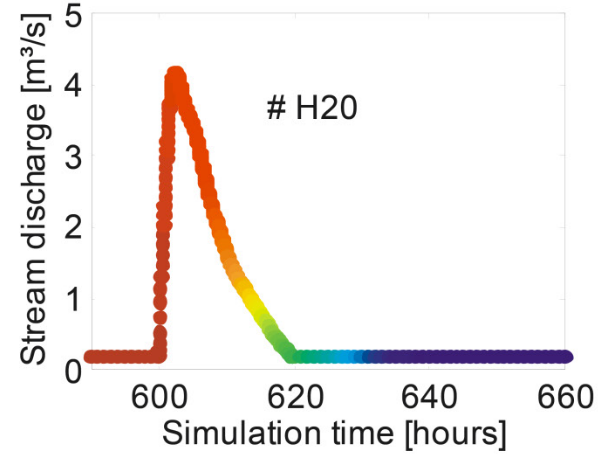
Instream gravel bar – reactive efficiency

Efficiency of reactions **within** the hyporheic flow cell: $F = \frac{Solute\ Consumption}{Solute\ Influx}$



Instream gravel bar – transient stream flow (events)

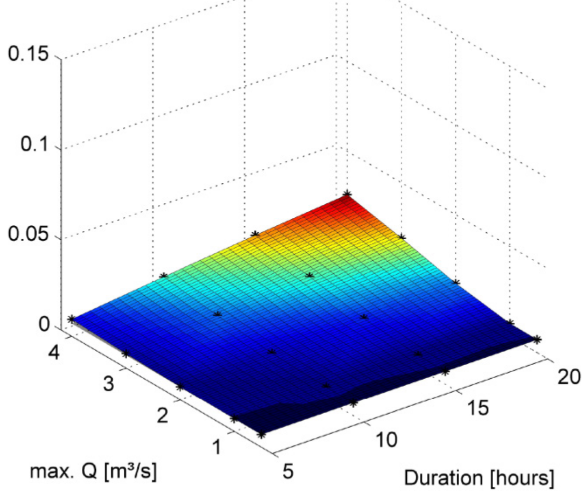


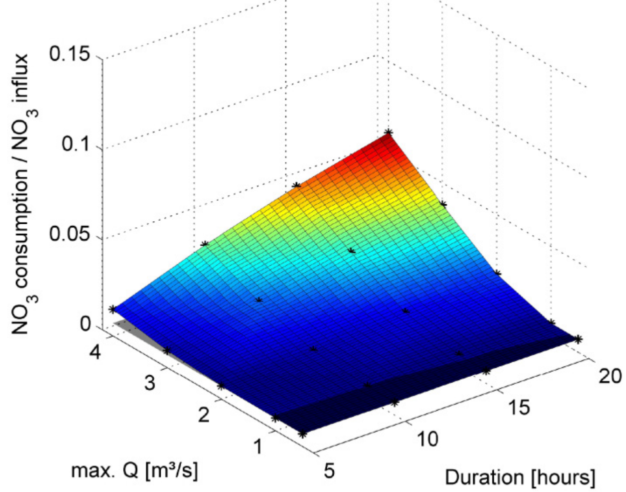


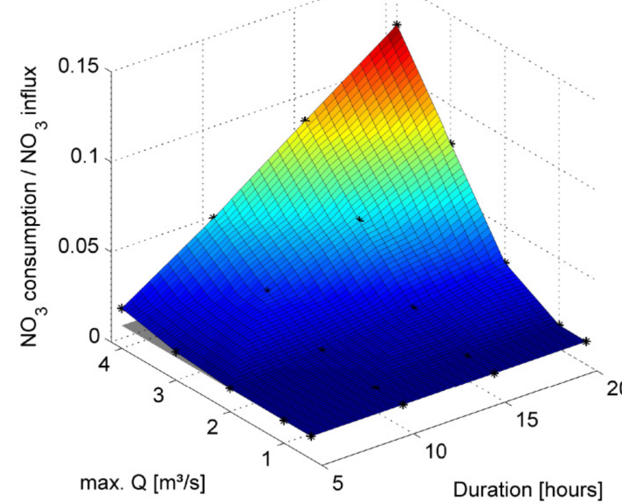
 # C1: DOC and NO_3 equal to base flow conditions (pure effects of hydraulic conditions)

 # C2: DOC and NO_3 increase with Q

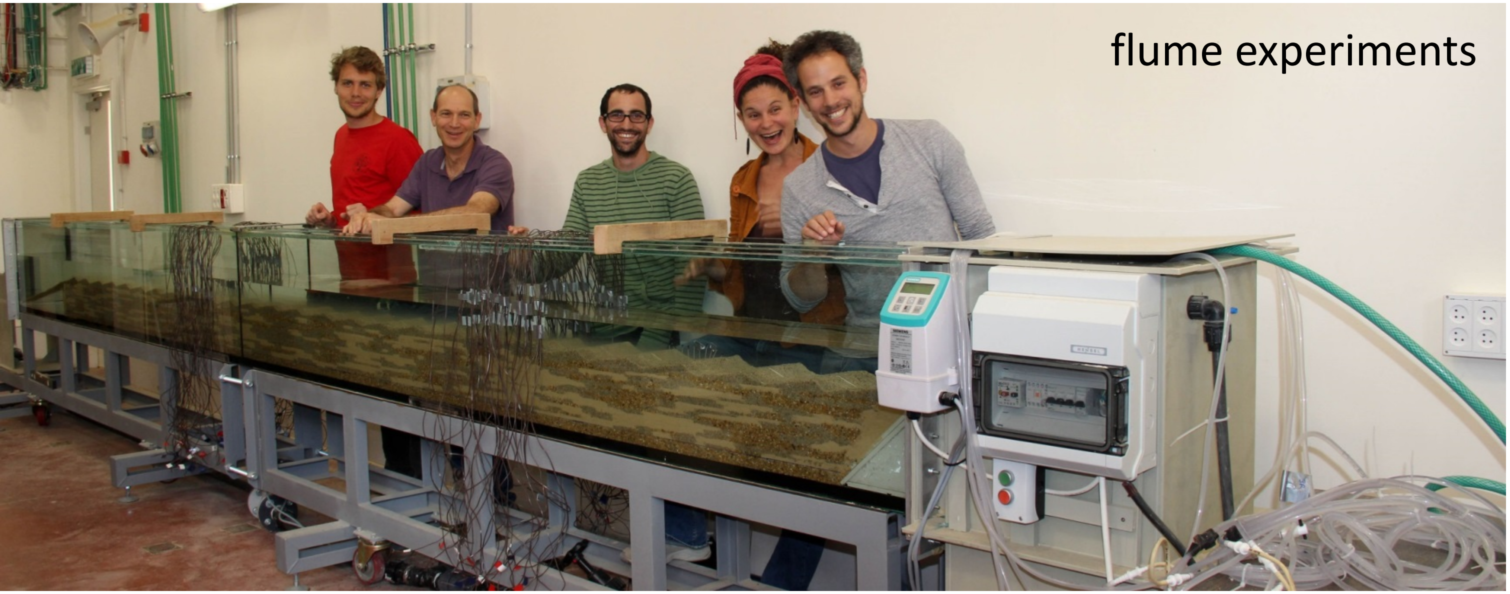
 # C3: unlimited DOC, NO_3 increases with Q







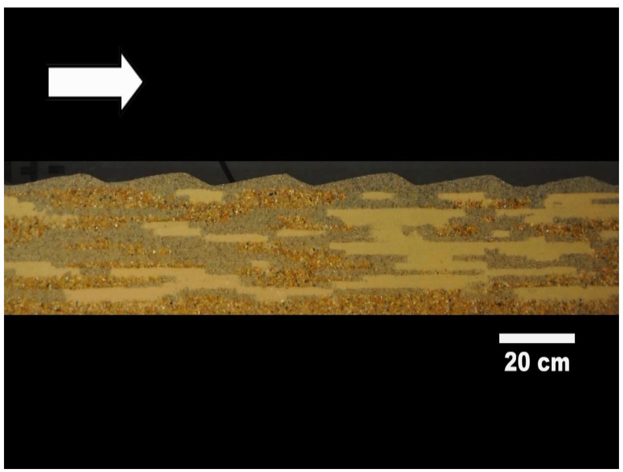
Trauth and Fleckenstein (2017) WRR, 53:779–798



group: Dr. Shai Arnon

project funded by German Israeli Foundation - GIF

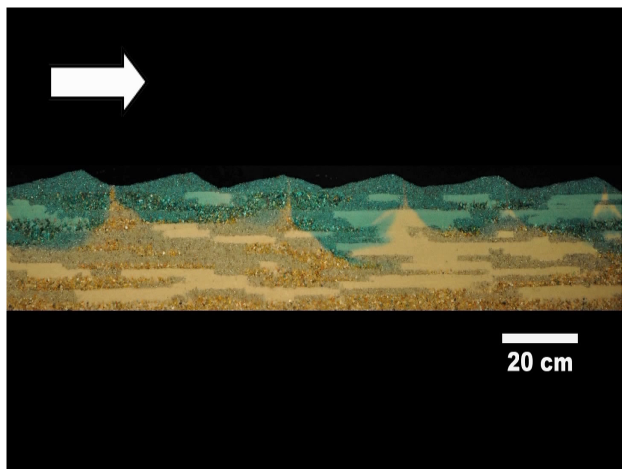
gaining



V_{stream}= 15 cm/s

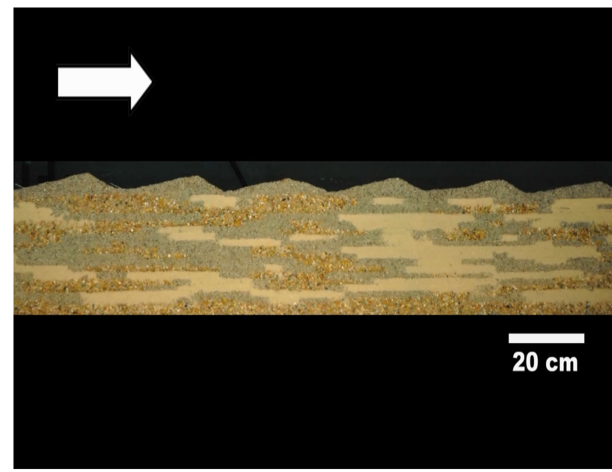
q_{down}= 50 cm/d

neutral



V_{stream}= 15 cm/s

losing

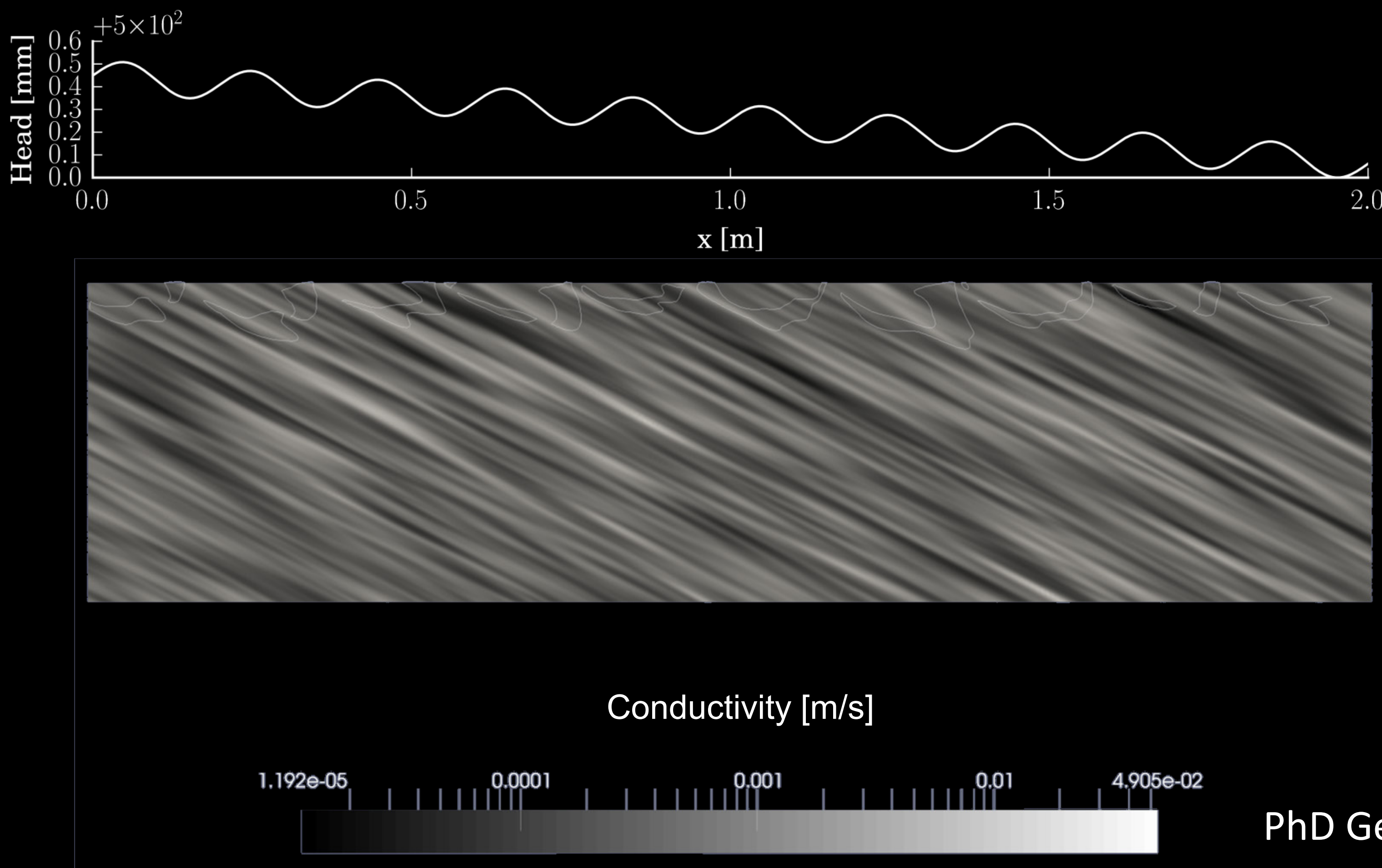


V_{stream}= 15 cm/s

q_{up}= 50 cm/d

Effects of sediment heterogeneity on flow and reactions

- geostatisctical simulation of random, multi-gaussian and indicator fields
- 10000 realizations + evaluation of effects of different correlation lengths & angles
- Sinusoidal streambed pressure (Elliot & Brooks) → simulation of flow & reactive transport



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Physical effects of sediment heterogeneity

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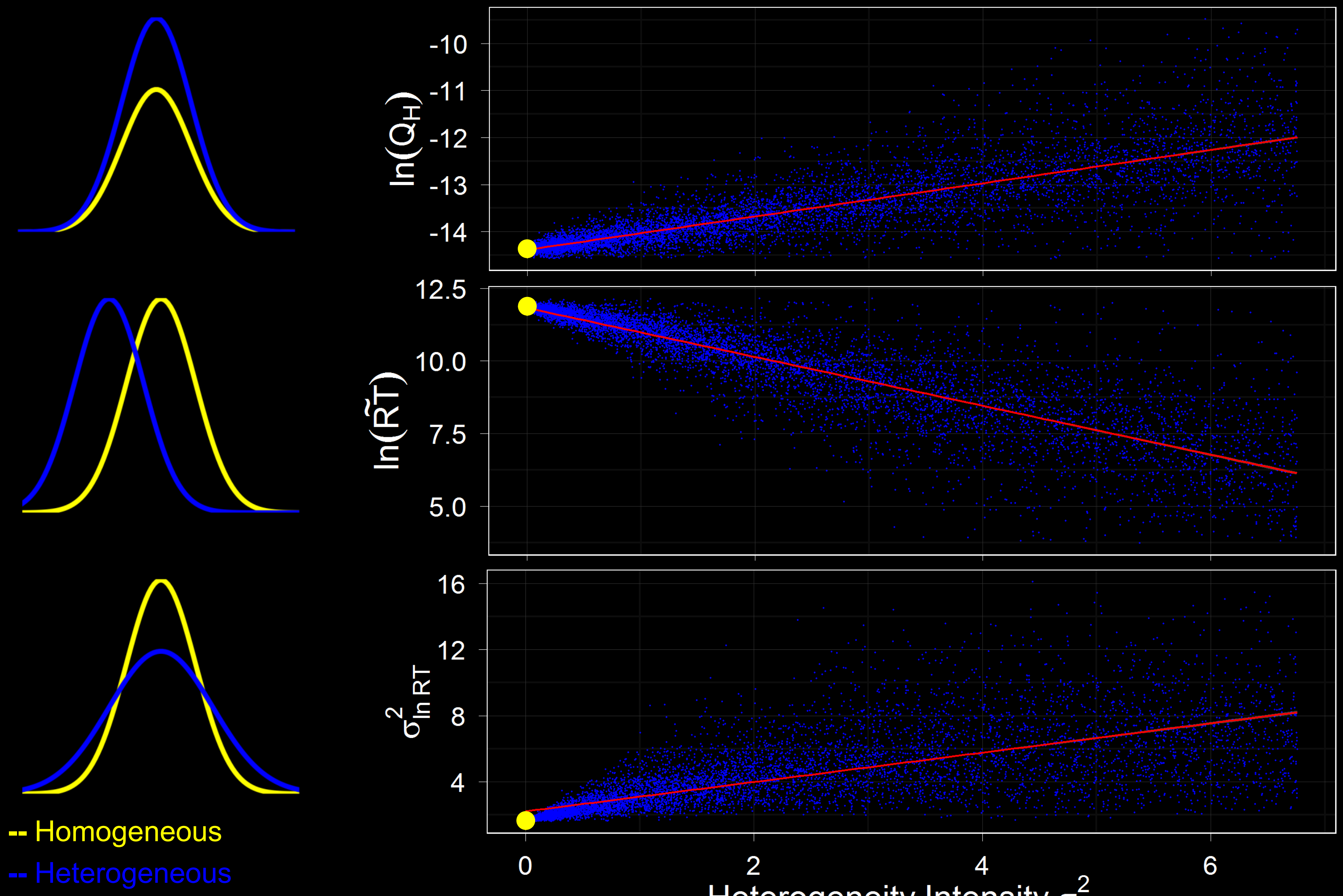

Reactions → denitrification, homogeneous case

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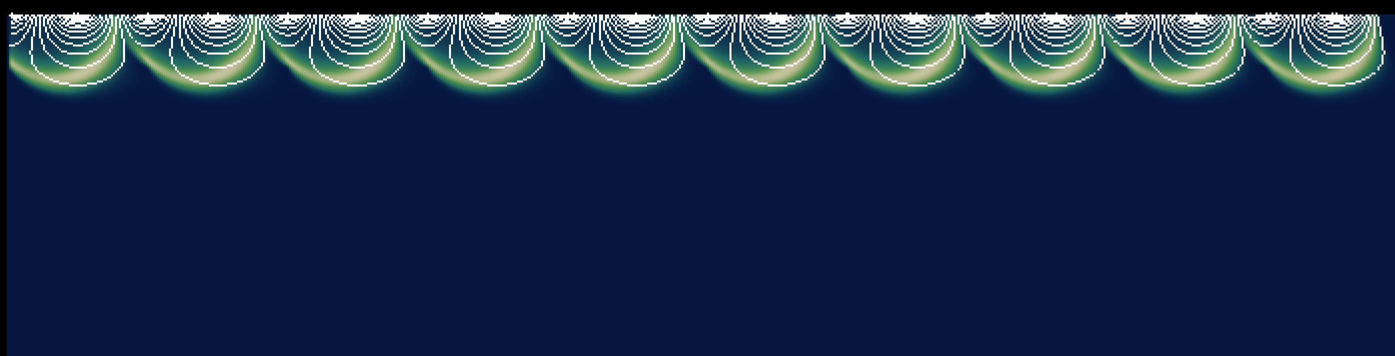
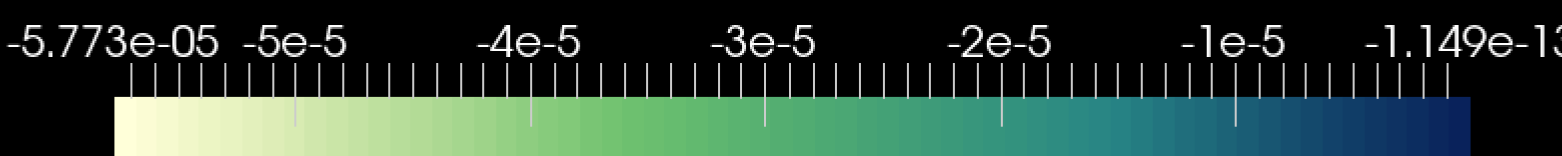
reactive fringe with denitrification, like in Trauth et al. 2014

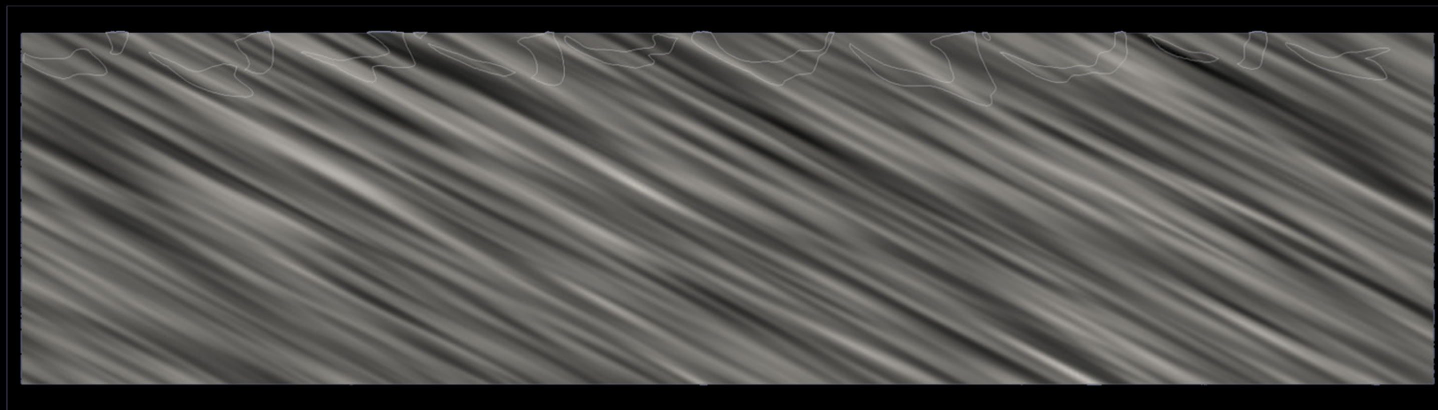


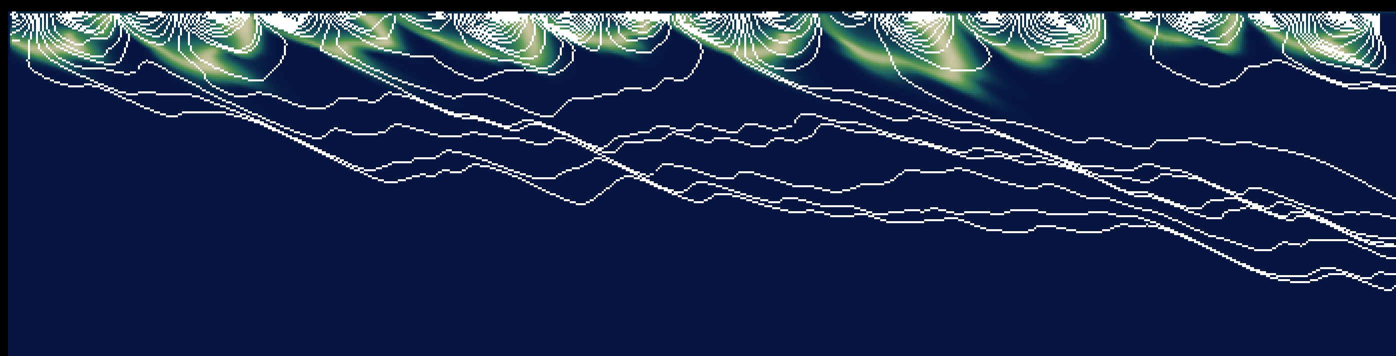
Denitrification [mol/l/d]



Reactions → denitrification, effects of heterogeneity

non-uniform distribution of denitrification hot spots





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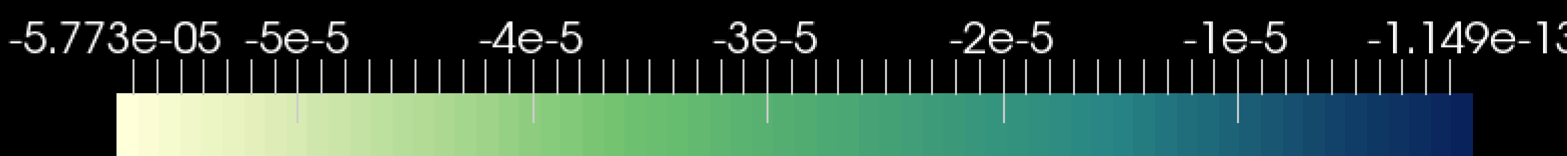
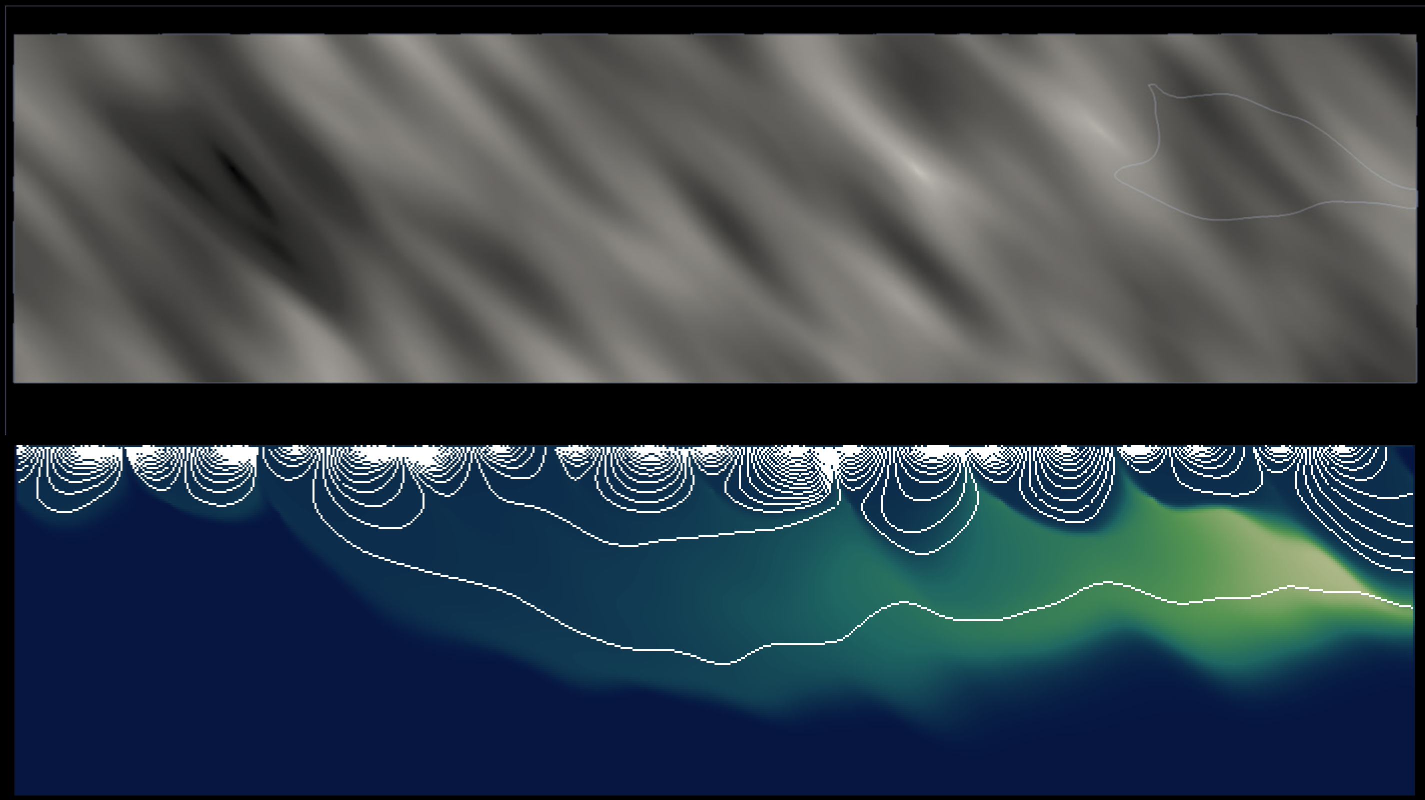
Denitrification [mol/l/d]



Reactions → denitrification, effects of heterogeneity

denitrification in deeper parts of the hyporheic zone



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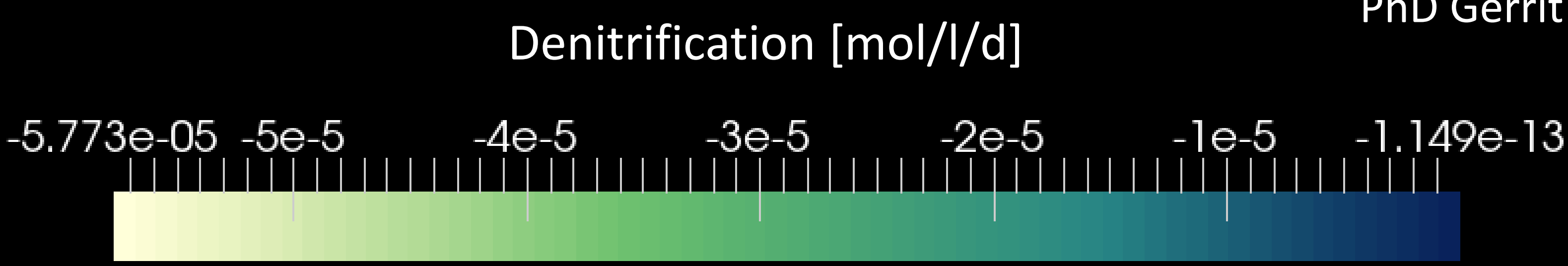

Take home messages

- GW-SW exchange takes place at nested scales
- Exchange fluxes can be quantified using various direct or indirect methods
- Pressure variations at the streambed → primary driver of HZ-flow
- Losing and gaining conditions work against the primary driver, diminishing hyporheic exchange flux, extent, residence times
- Reactive potential controlled by the extent of the reactive areas within the hyporheic flow cells and the associated hyporheic residence times
- Modeling suggests: Up to 8% of the nitrate load in stream water can be consumed along 1 km stream section
- Events temporarily increase removal efficiency for NO_3 by up to 3.6-times
- Streambed heterogeneity increases Q_{hz} & the width of the RTD, but decreases mean hyporheic RT
- Heterogeneity decreases denitrification potential in shallow HZ, but promotes denitrification in deeper HZ

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Thank you for your attention – Fin !

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