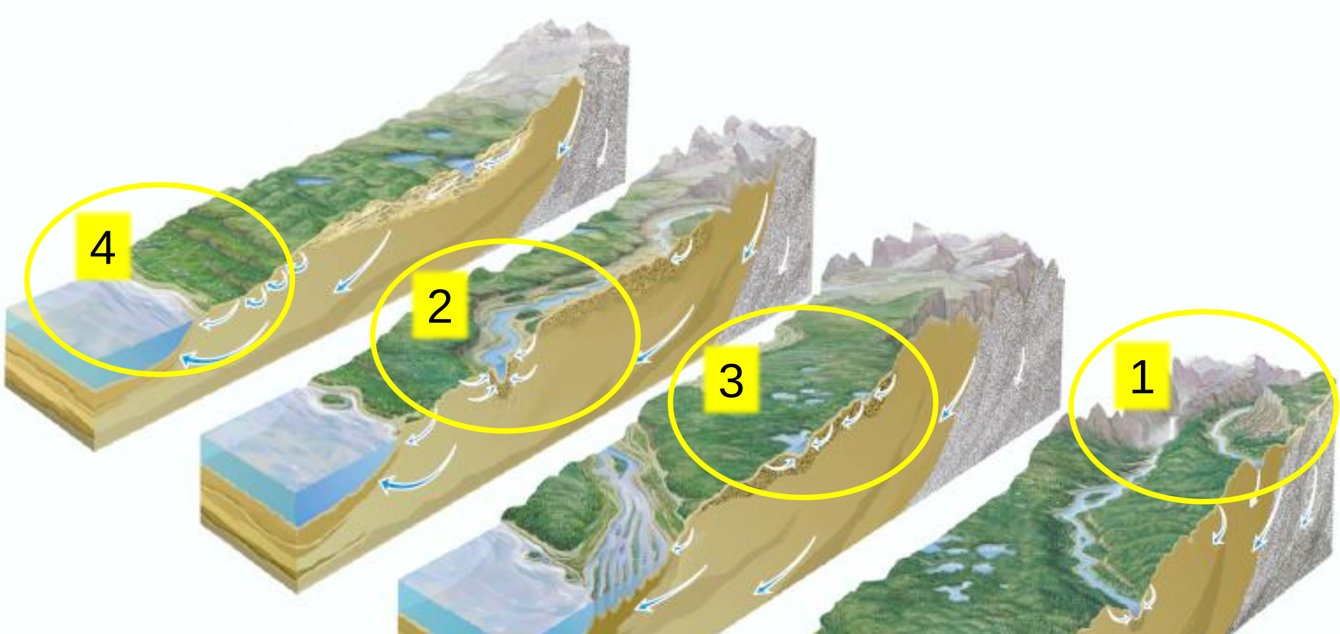
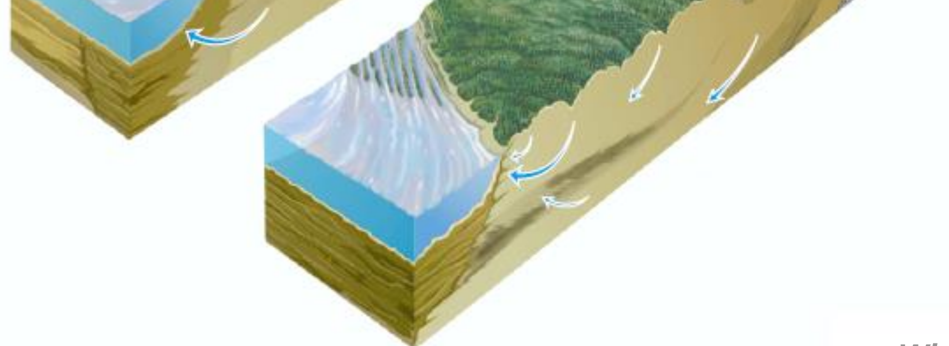
Dynamic interfaces and their influence on groundwater biogeochemistry

Gudrun Massmann & Janek Greskowiak

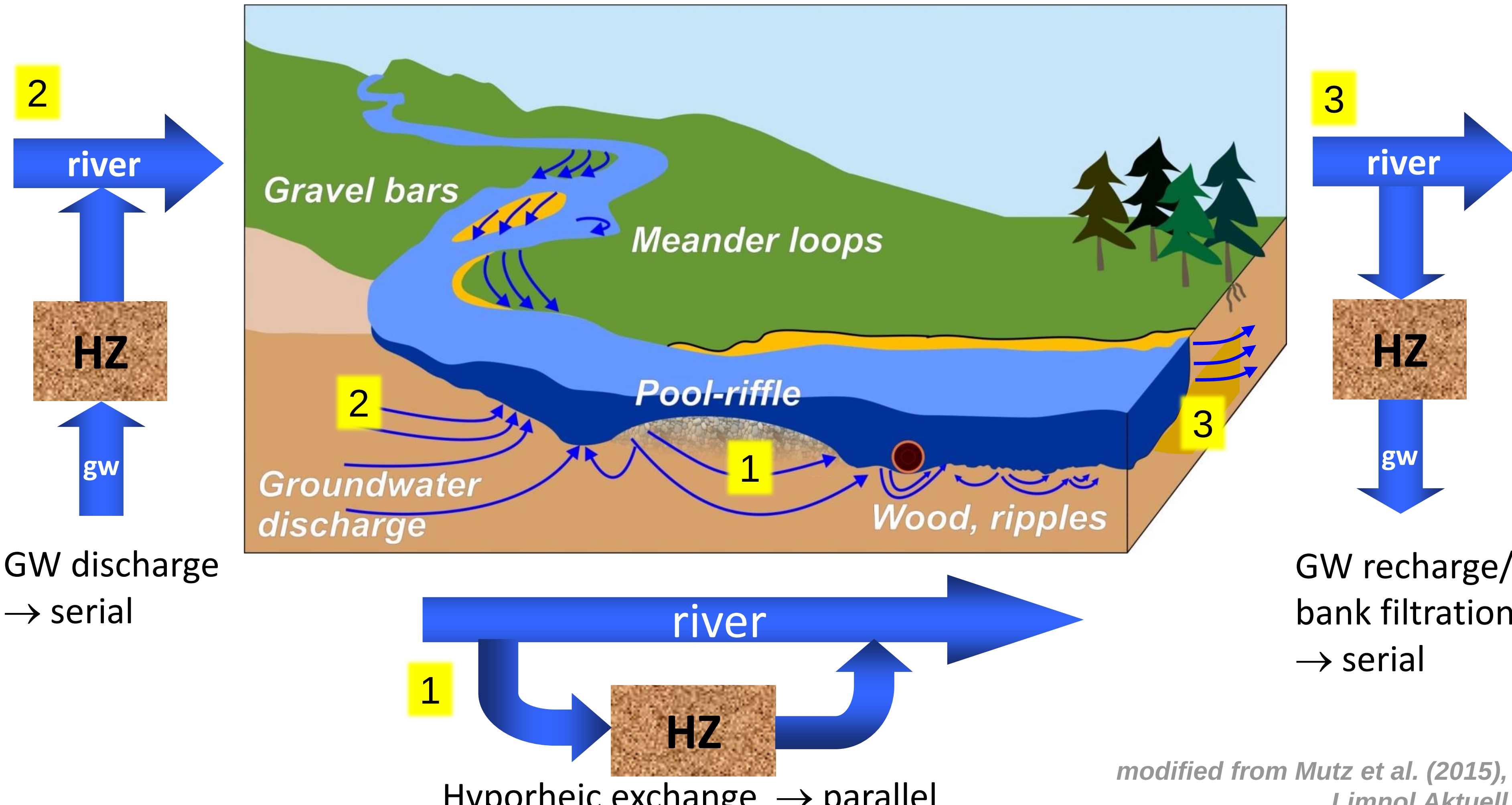
Hydrogeology & Landscape Hydrology

Surface water – groundwater exchange

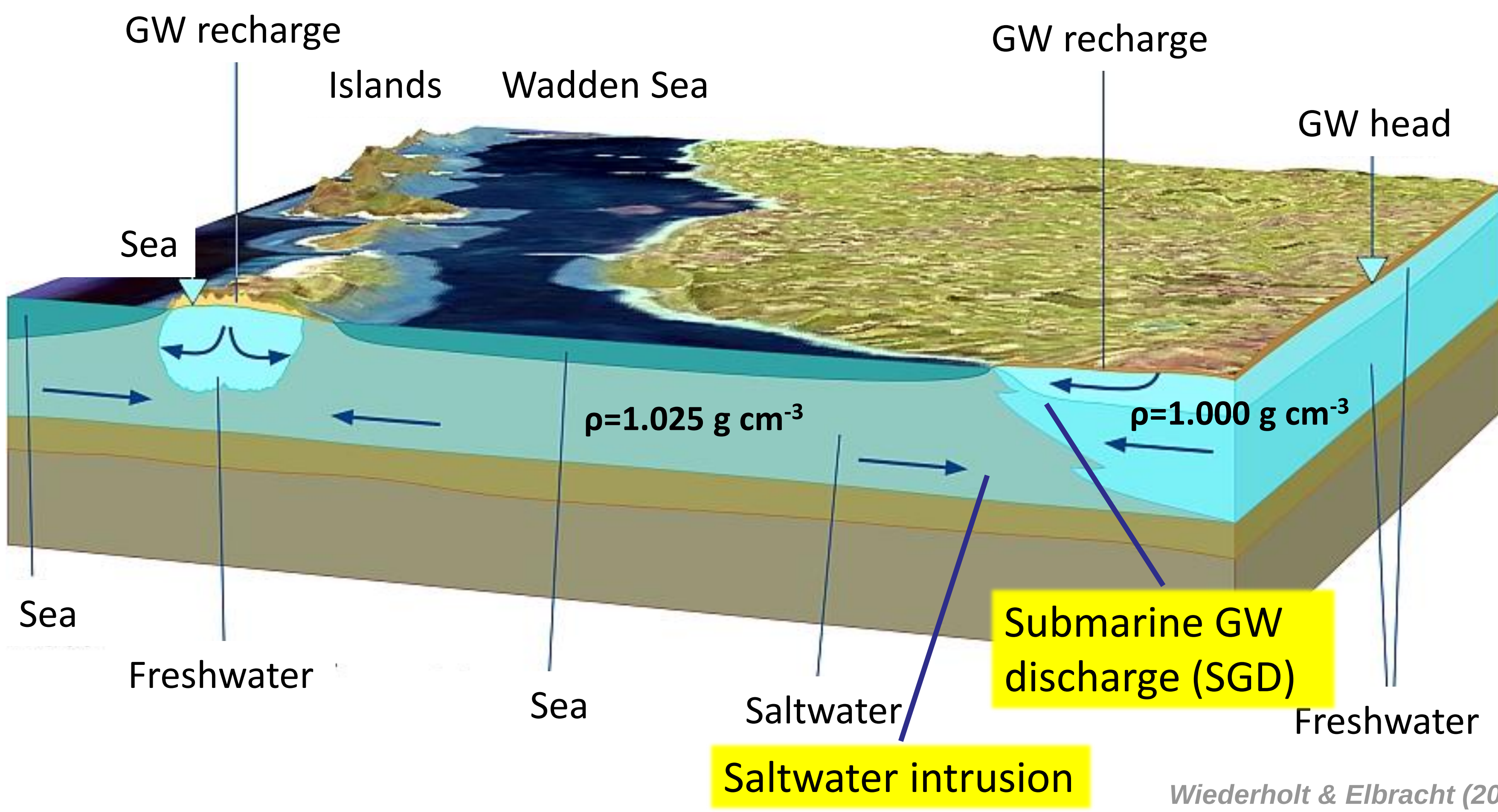
Winter et al. (1998), USGS Circular

Hyporheic exchange versus serial exchange



modified from Mutz et al. (2015), Limnol Aktuell

SW-GW exchange at the coast

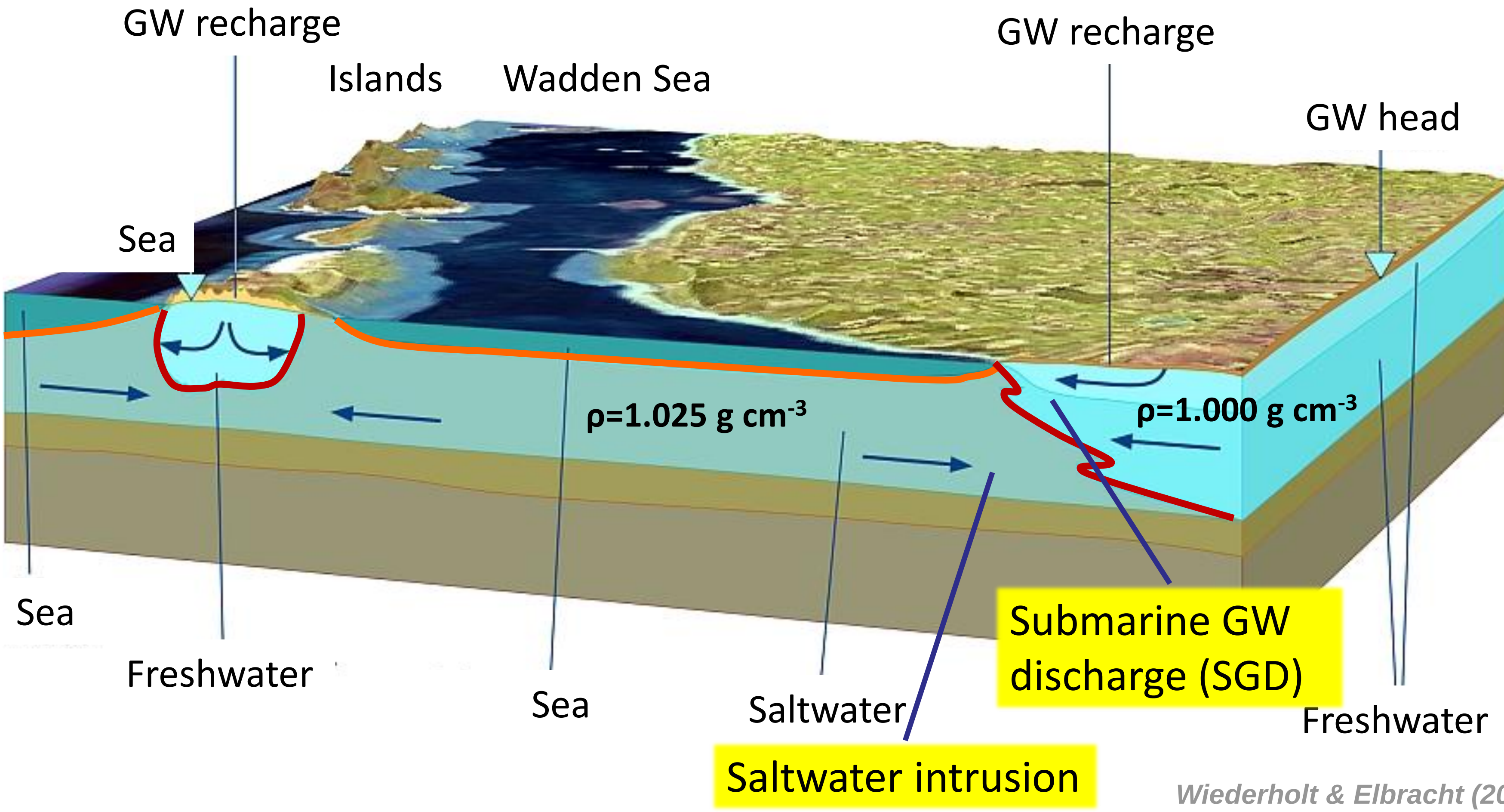


Wiederholt & Elbracht (2013)

Different "interfaces"

SW–GW interface

Interface between chemically different water bodies



Wiederholt & Elbracht (2013)

Characteristics of the SW-GW exchange zone

- Mixing zone of waters with distinctly different water chemistry
- Strong gradients (hydraulics, temperatures, density, biogeochemistry)
- High microbial activity
- (Variable) input of organic matter and electron acceptors
- Often very dynamic (hydraulics, temperatures, biogeochemistry)

→ **Effective bioreactors**

Objectives

- To give two distinctly different examples for dynamic SW-GW exchange and its effect on groundwater quality:

  1. Effect of transient pumping and SW temperatures on redox conditions (and trace organic compounds) during bank filtration in Berlin (urban environment)
  2. Effect of tides, morphodynamics and storm floods on geochemical patterns below a (pristine) high-energy beach

Bank filtration in Berlin

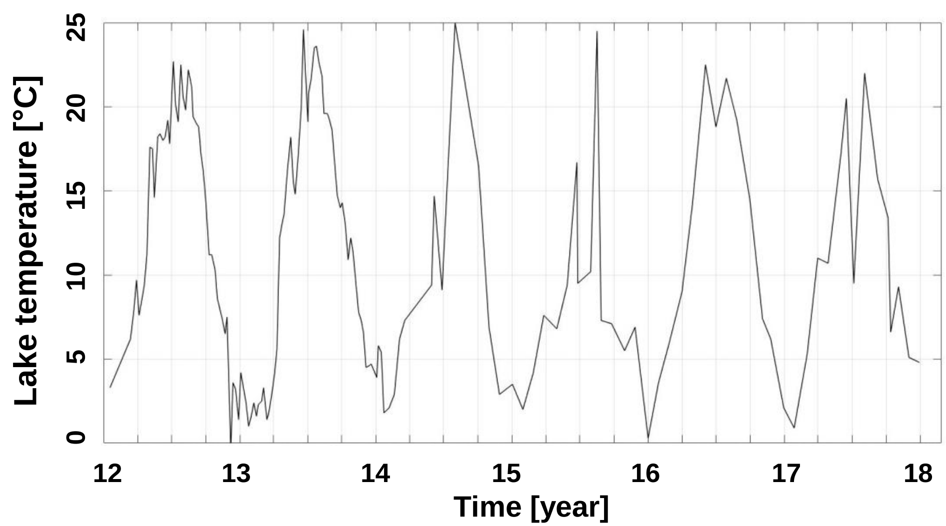
- **N**atural and **A**rtificial **S**ystems for **R**echarge and **I**nfiltration (NASRI, 2002-2005)
- Redox sensitivity and long-term persistence of organic trace pollutants in groundwater: Wastewater-bound compounds (DFG project, 2010-2014)
- Development of operating strategies for an improved removal of organic micropollutants during the process of bank filtration (2015-2016)
- Operation strategies and technologies for water reuse to support drinking water supply in urban areas (TrinkWave, 2016-2020)

Objective and motivation

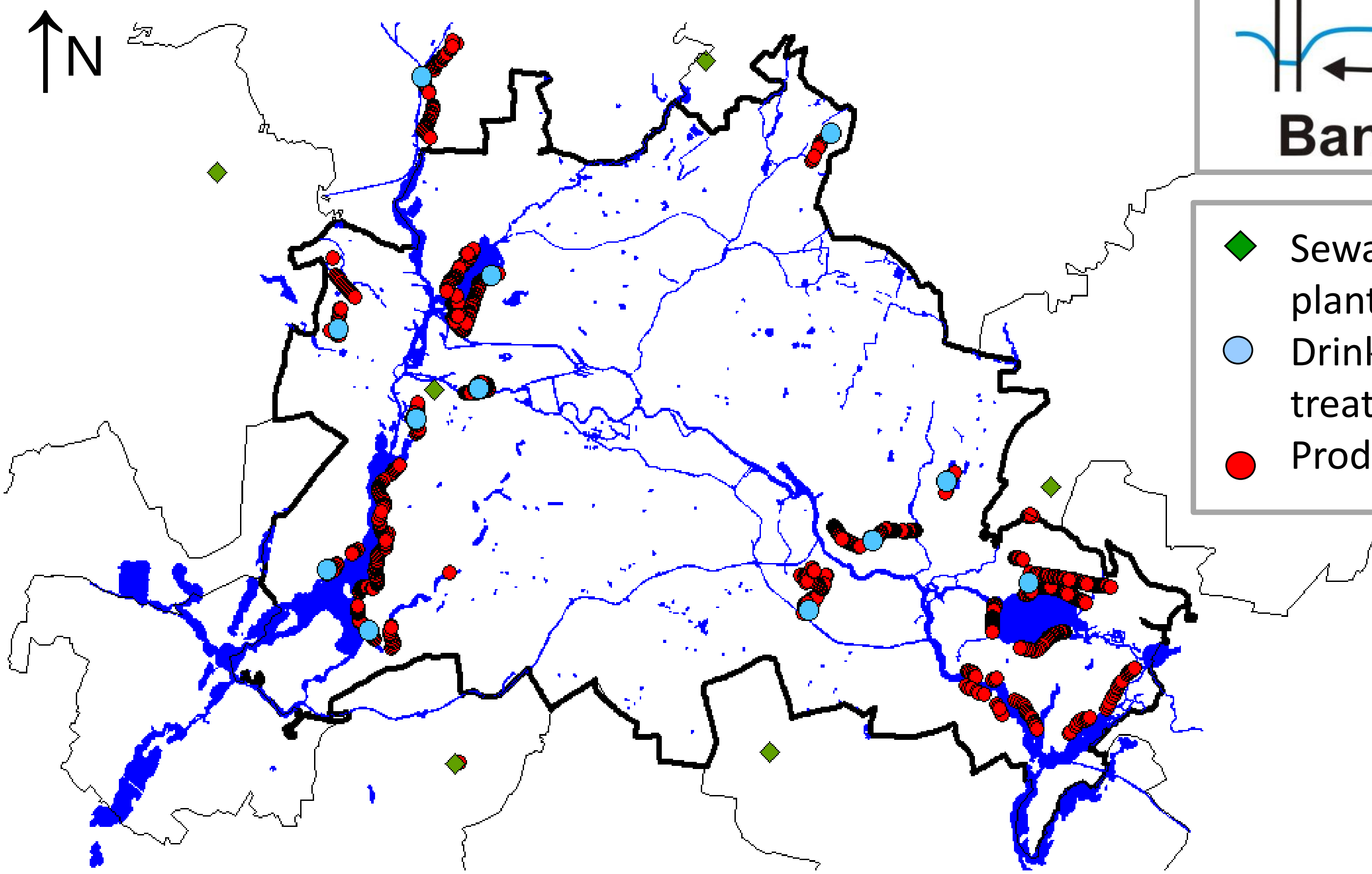
- To elucidate behaviour of trace organic compounds (TOrCs) during bank filtration in a partially-closed urban water cycle
- Motivated by the fact that managed aquifer recharge (MAR) can help ease water stress and improve water quality (and provides drinking water for Berlin)

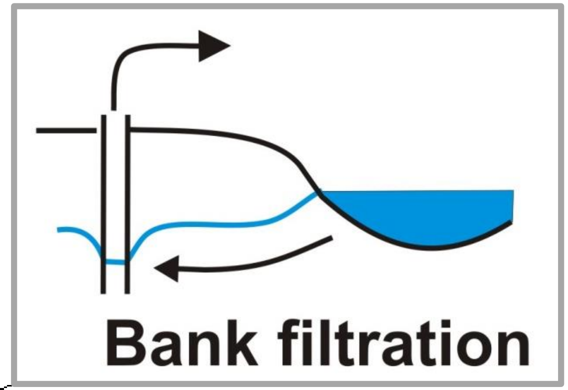
Study site Berlin

- “Lakes” with strong seasonal temperature fluctuations
- Locally high proportion of treated WW →TOrCs



Partially closed water-cycle





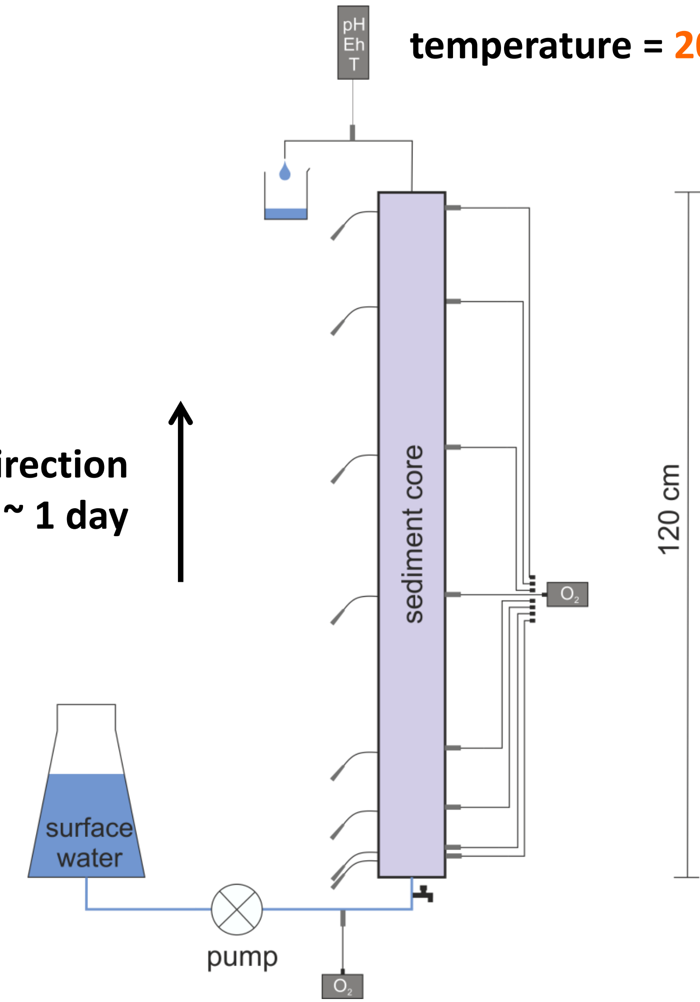
- Sewage treatment plants
- Drinking water treatment plants
- Production wells

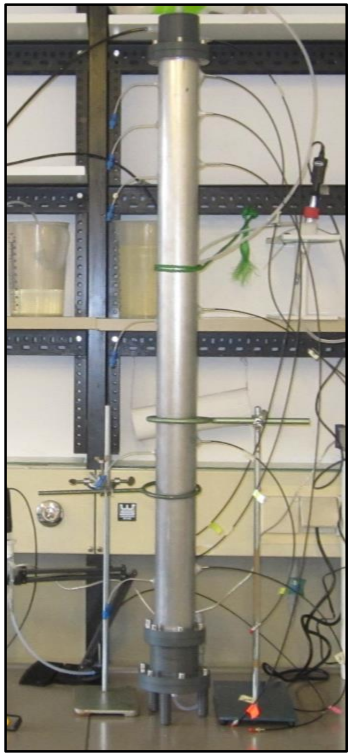
adapted from Dillon et al. (2005) & Berlin Water Company

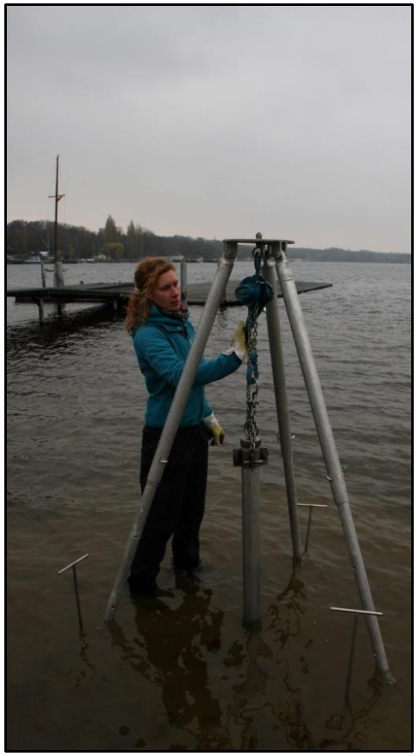
Column experiments on seasonal TOrC attenuation

temperature = 20°C / 6 °C

flow direction
residence time ~ 1 day



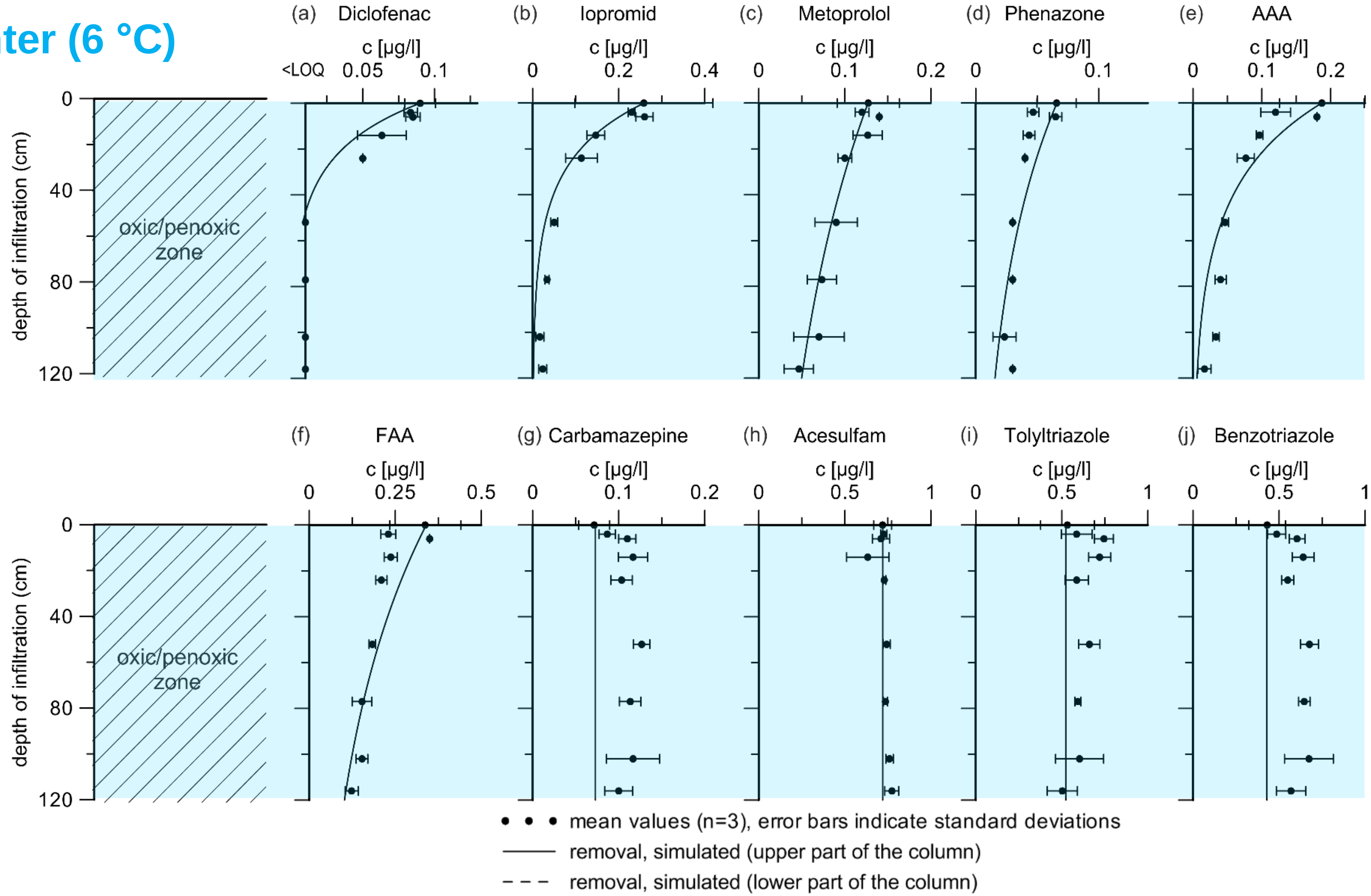




Burke et al. (2014), STOTEN

TOrC attenuation is function of temp. & redox conditions

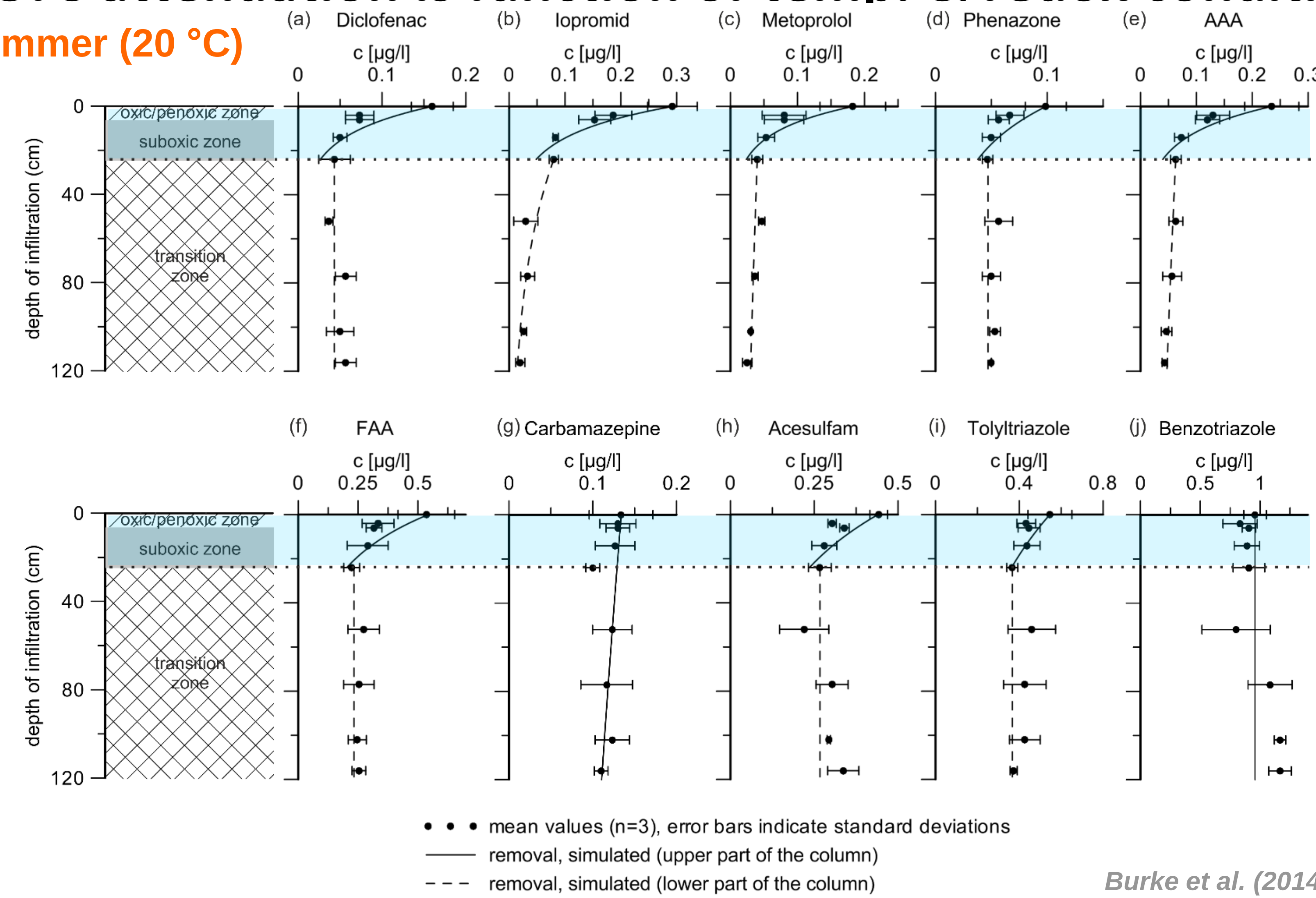
Winter (6 °C)



Burke et al. (2014), STOTEN

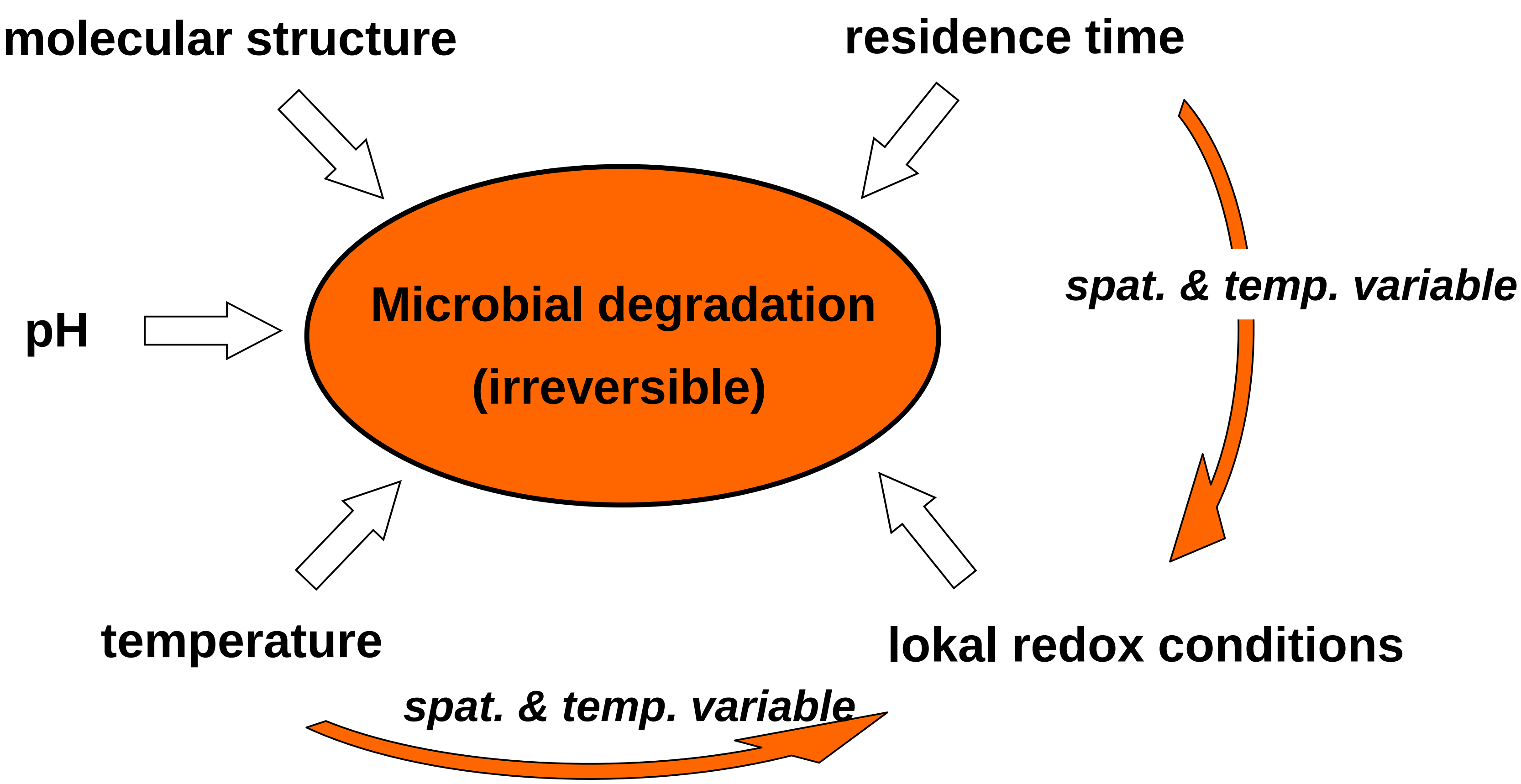
TOrC attenuation is function of temp. & redox conditions

Summer (20 °C)

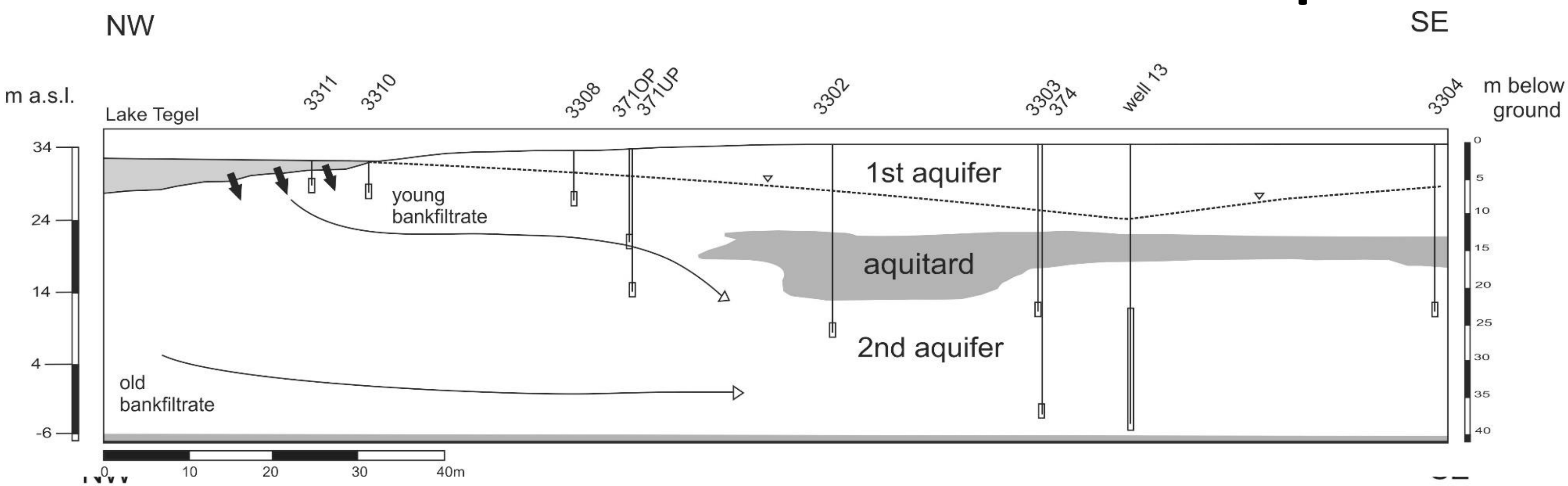


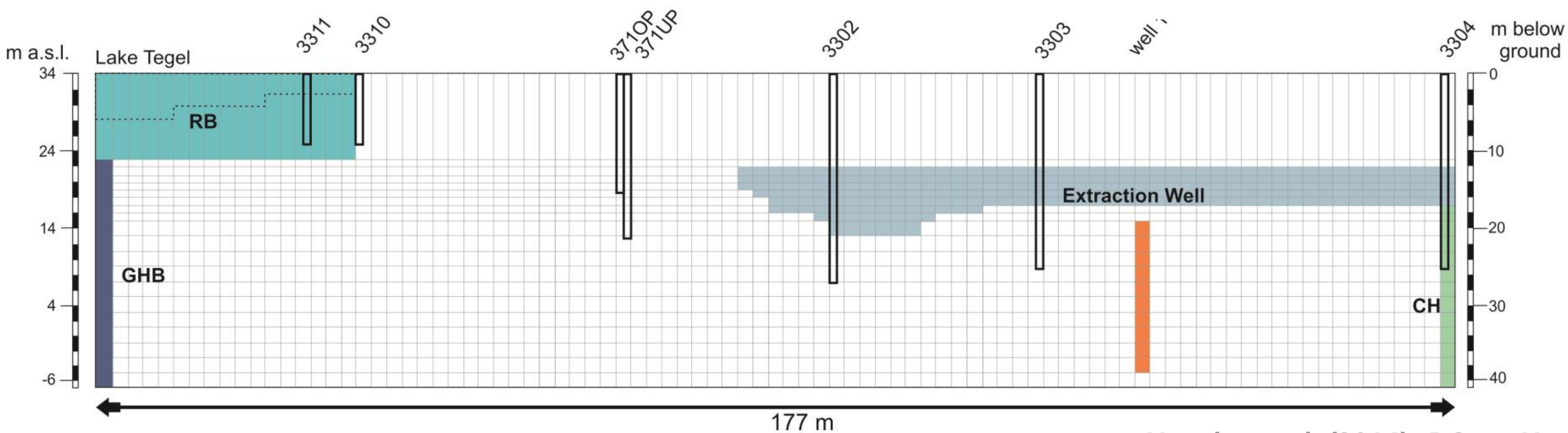
Burke et al. (2014), STOTEN

Factors influencing primary degradation



Research transect and numerical reactive transport model





Henzler et al. (2014), J Cont Hydrol

Temperature dependent reaction kinetics

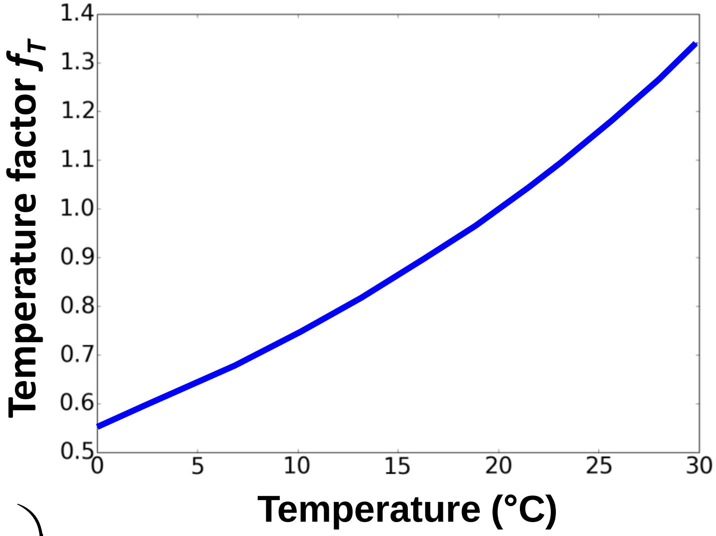
Oxygen reduction

$$r_{ox} = \boxed{f_T} k_{ox} \left(\frac{C_{ox}}{K_{ox} + C_{ox}} \right)$$

Nitrate reduction

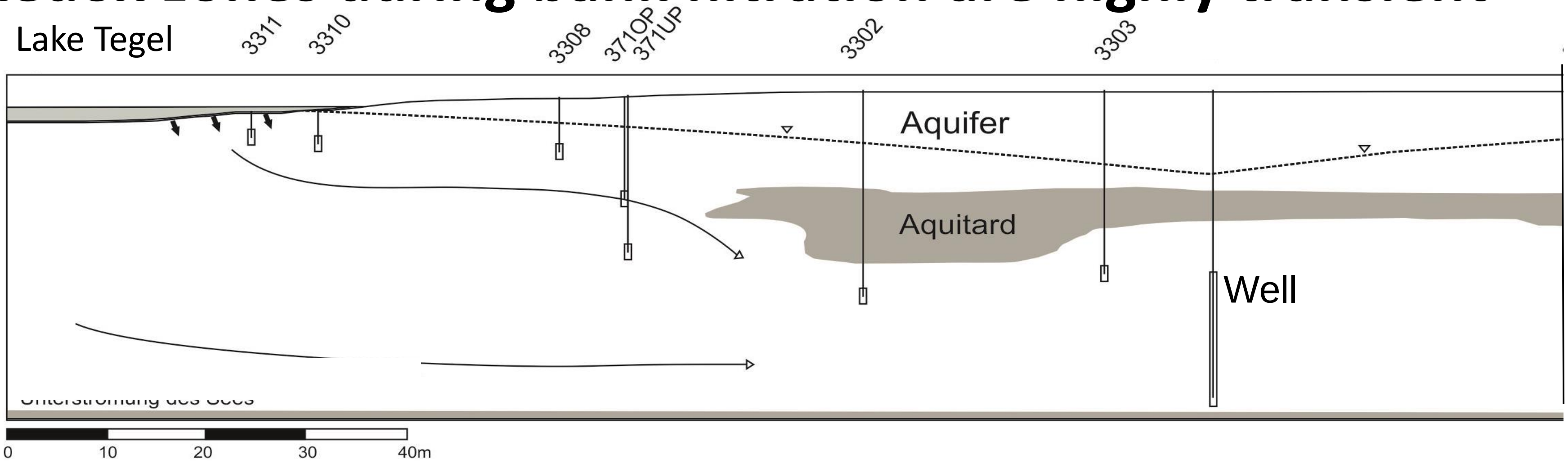
$$r_{nitr} = \boxed{f_T} k_{nitr} \left(\frac{C_{nitr}}{K_{nitr} + C_{nitr}} \right) \left(\frac{K_{ox\_inh}}{K_{ox\_inh} + C_{ox}} \right)$$

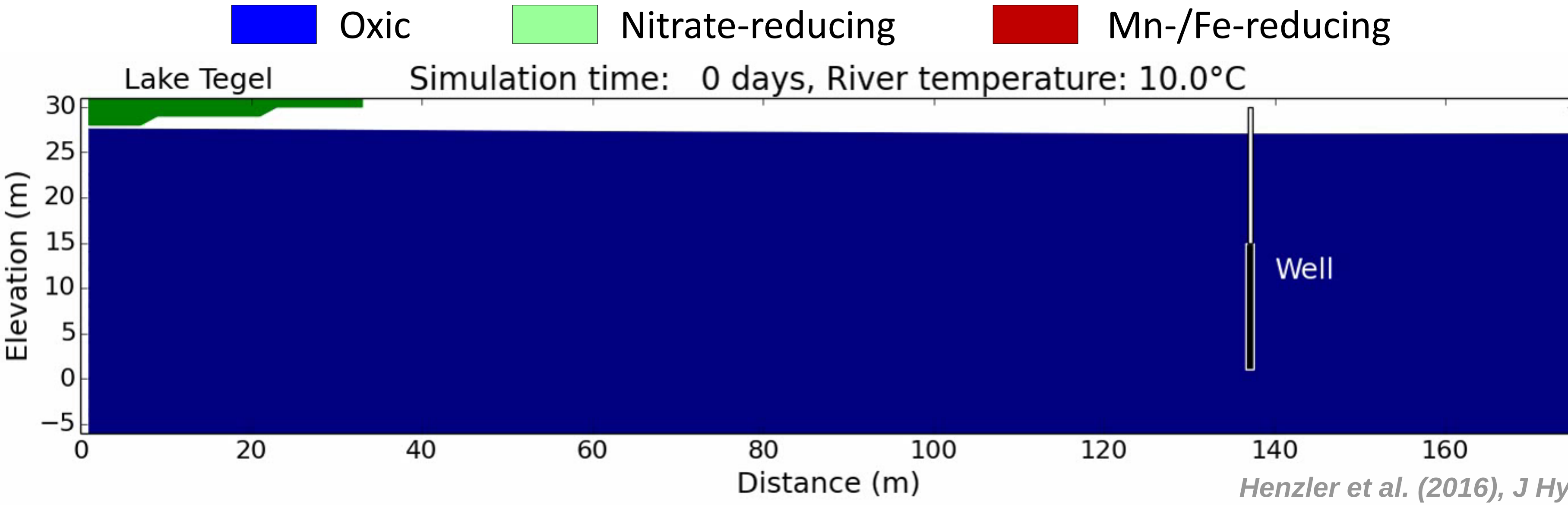
$$\boxed{f_T} = e^{\left(\alpha + \beta T \left((1 - 0.5 \frac{T}{T_{opt}}) \right) \right)}$$



Empirical fomulae after O' Connell (1990), Kirschbaum (1995, 2000)

Redox zones during bank filtration are highly transient





Henzler et al. (2016), J Hydrol

SW-GW exchange in the subterranean estuary

- Formation, Characterization and Groundwater Flow Patterns of a Barrier Island Freshwater Lens (Spiekeroog, Northwest Germany)
  (Dissertation project Tania Röper 2014)
- Assessment of ground- and porewater-derived nutrient fluxes into the German North Sea – Is there a „**B**arrier **I**sland **M**ass **E**ffect“?
  (BIME 2016-2020)

ICBM

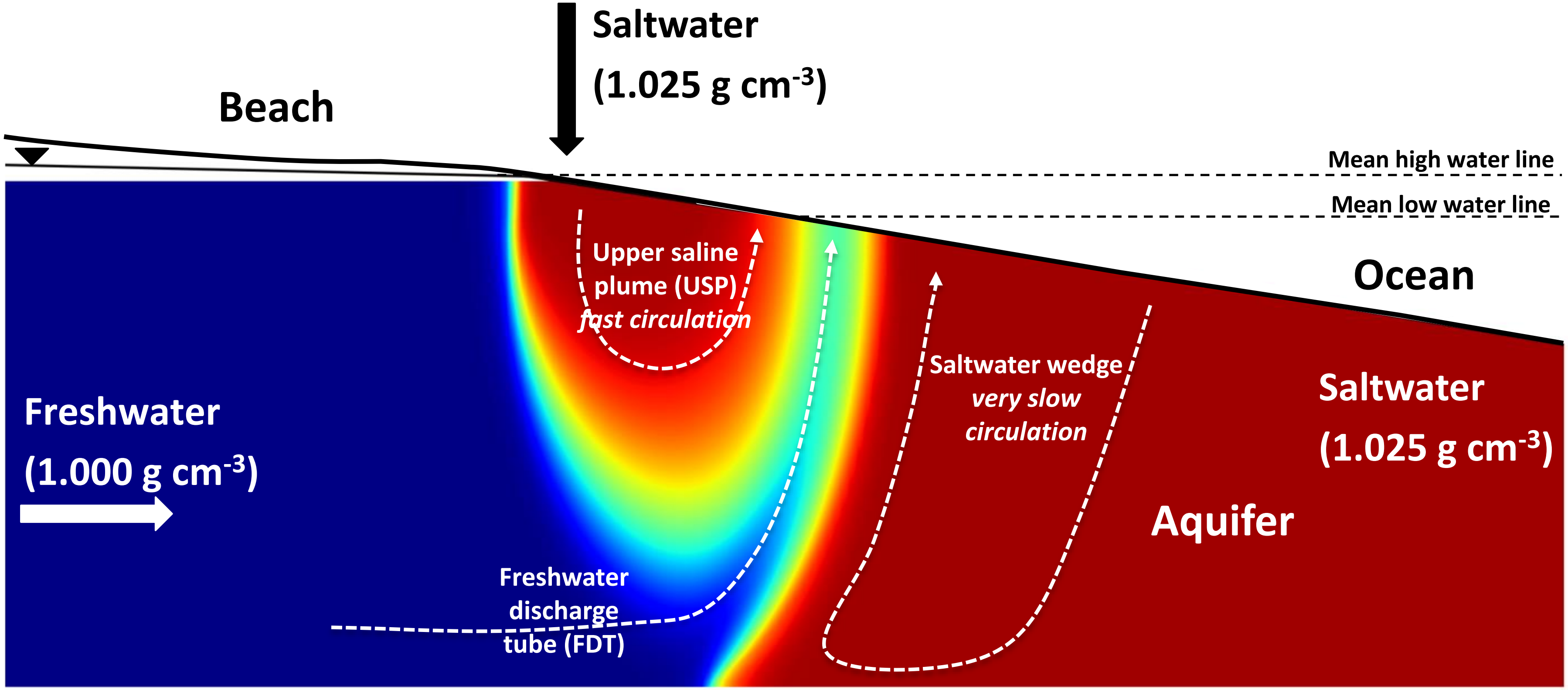
Max Planck Institute for Marine Microbiology

Niedersächsisches Ministerium für Wissenschaft und Kultur

Objectives and motivation

- To elucidate coupled flow and biogeochemical processes in the subterranean estuary to understand its role with regard to elemental fluxes to the sea
- Motivated by the fact that SGD fluxes affect coastal ecosystems

The subterranean estuary under tidal influence

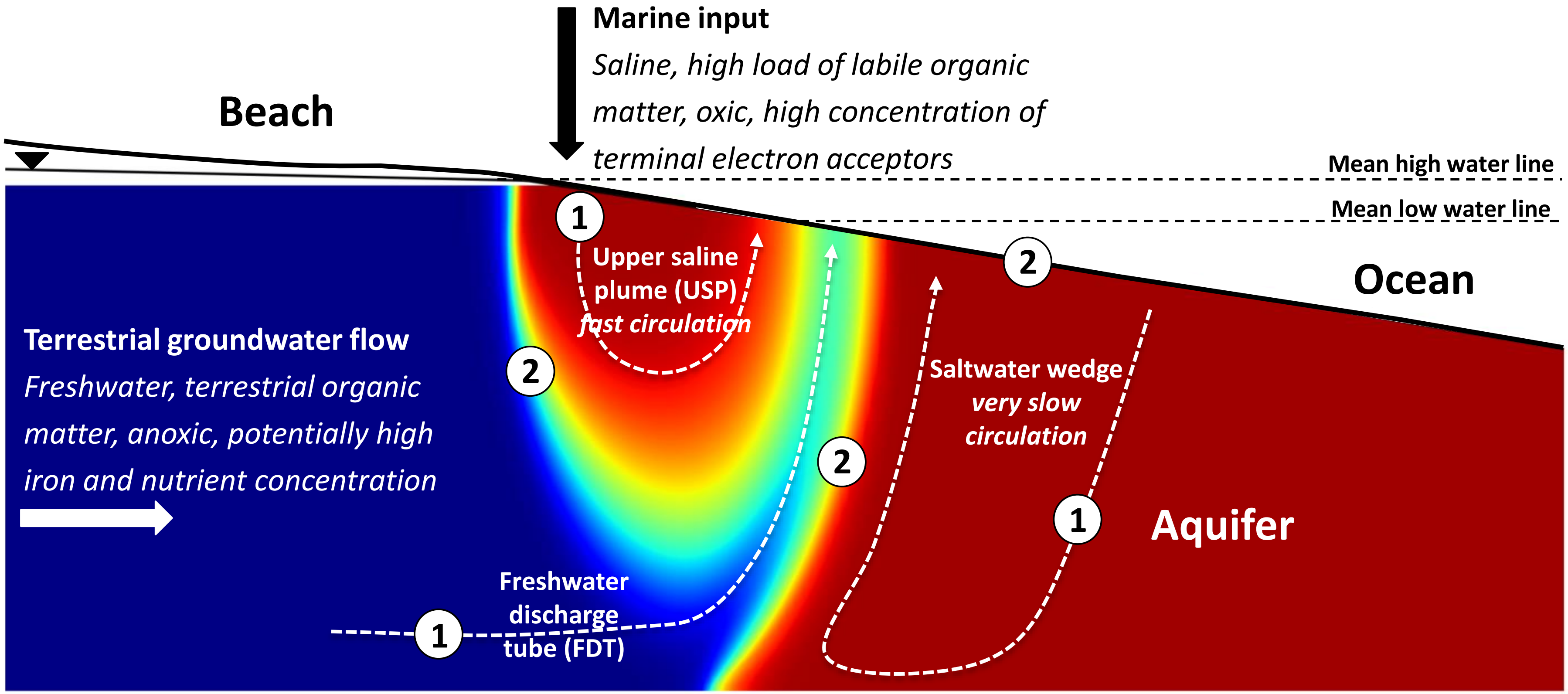


e.g. after Michael et al. (2005), Nature Letters

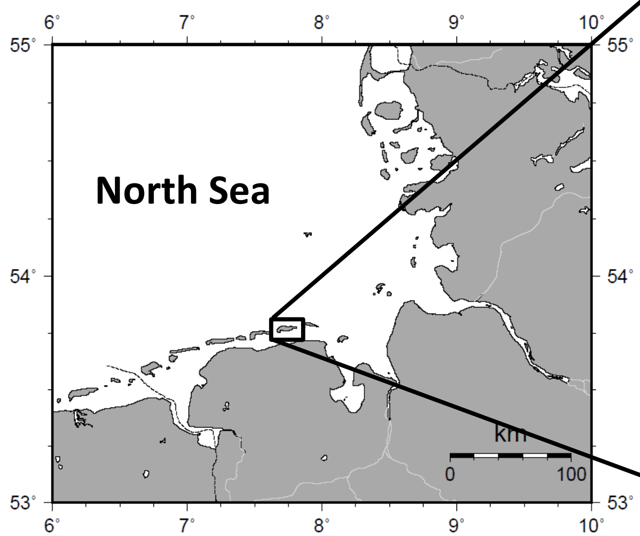
The subterranean estuary under tidal influence

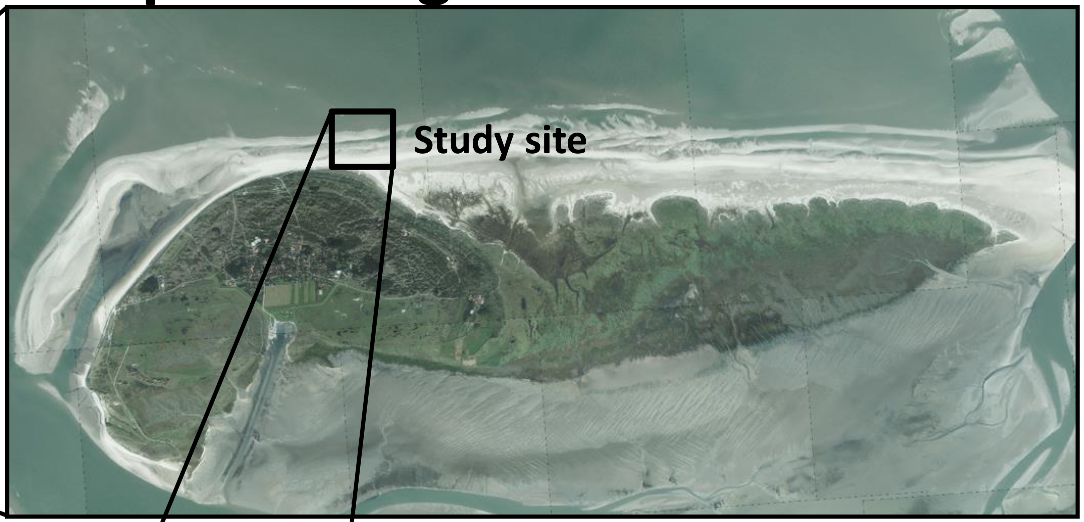
1 Biogeochemical processes along flow paths

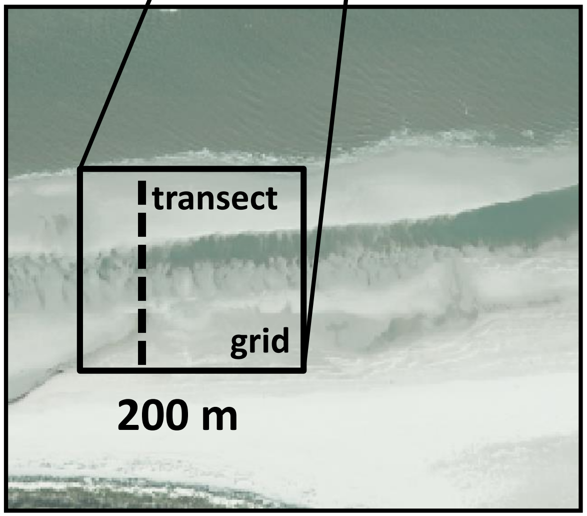
2 Mixing and biogeochemical reactions across interfaces



Field site on barrier island Spiekeroog

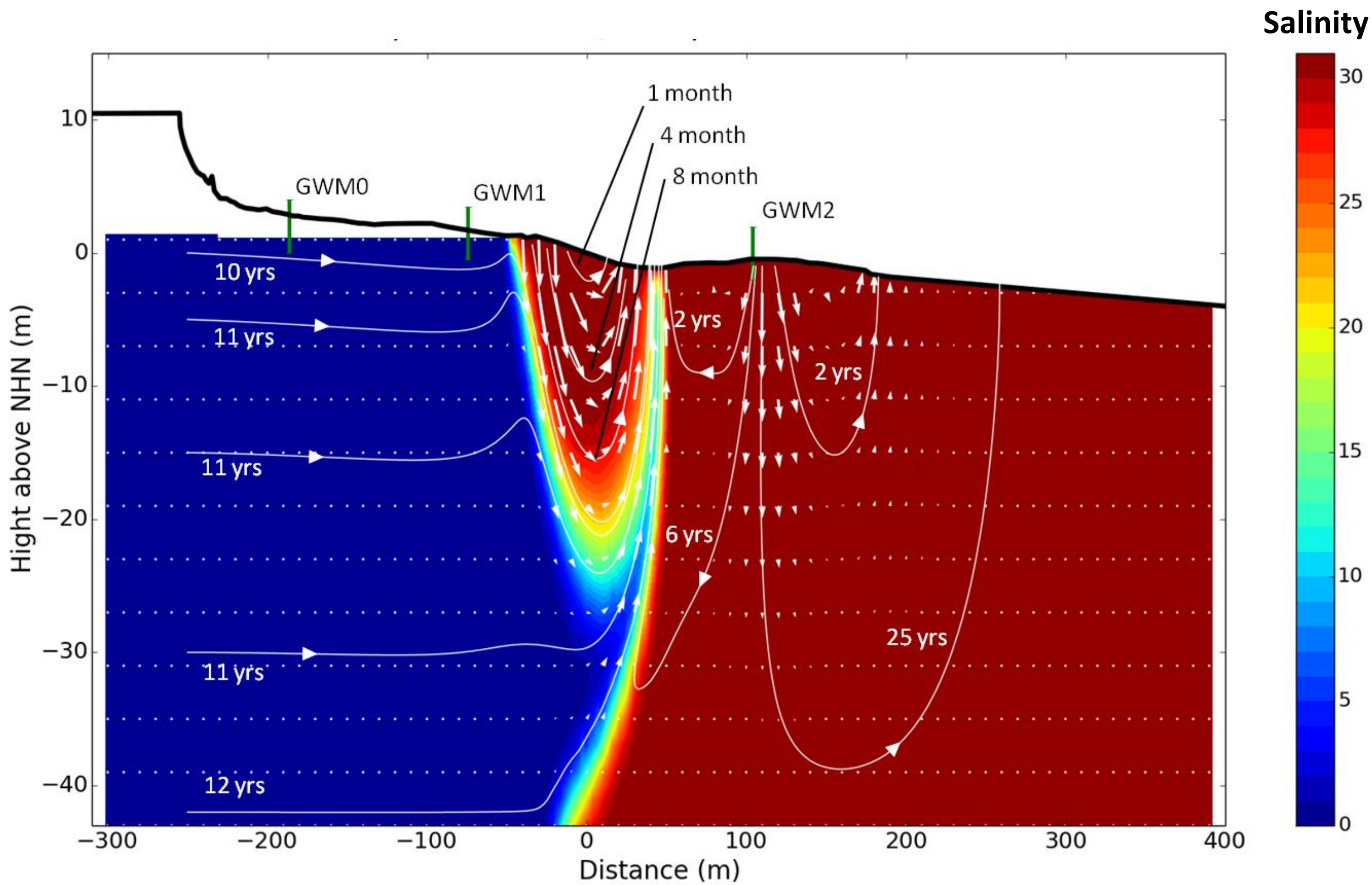






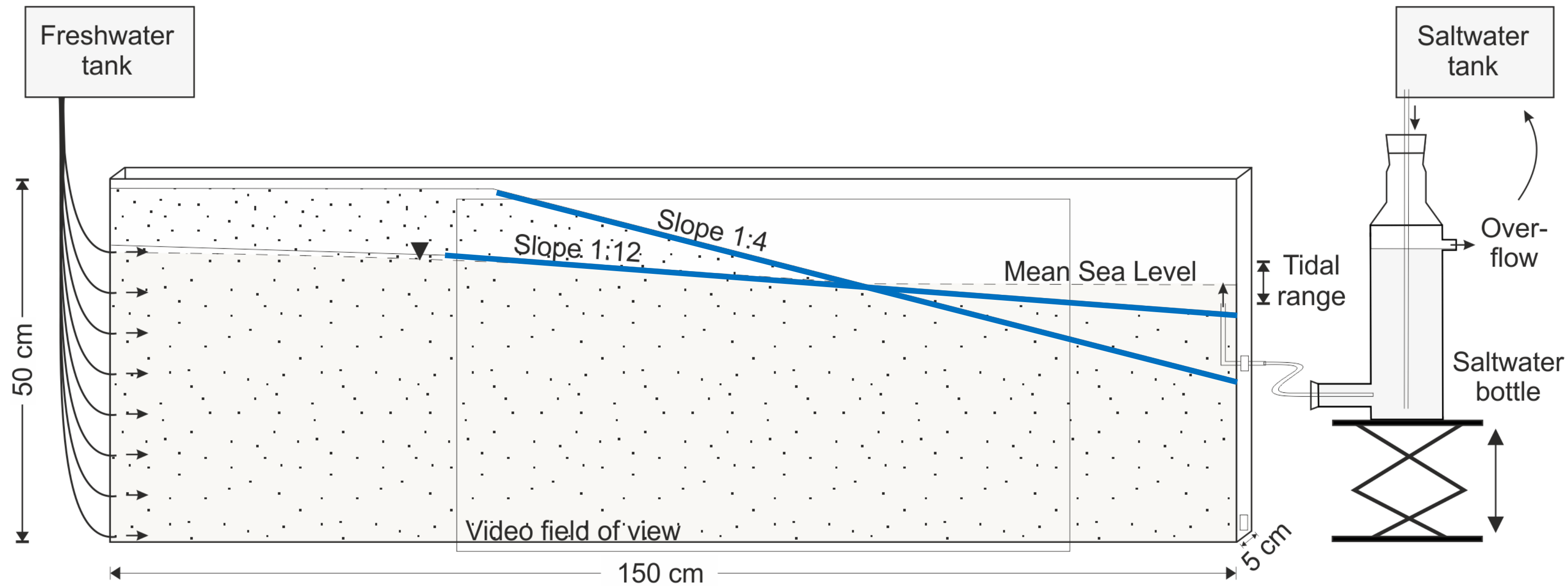
- High energy beach
- Mean significant wave height 1.4 m
- Tidal range 2.7 m
- Runnel and ridge system

First model confirms "classic" salinity distribution



Beck et al. (2017), Marine Chem

Tank experiments on flow stability

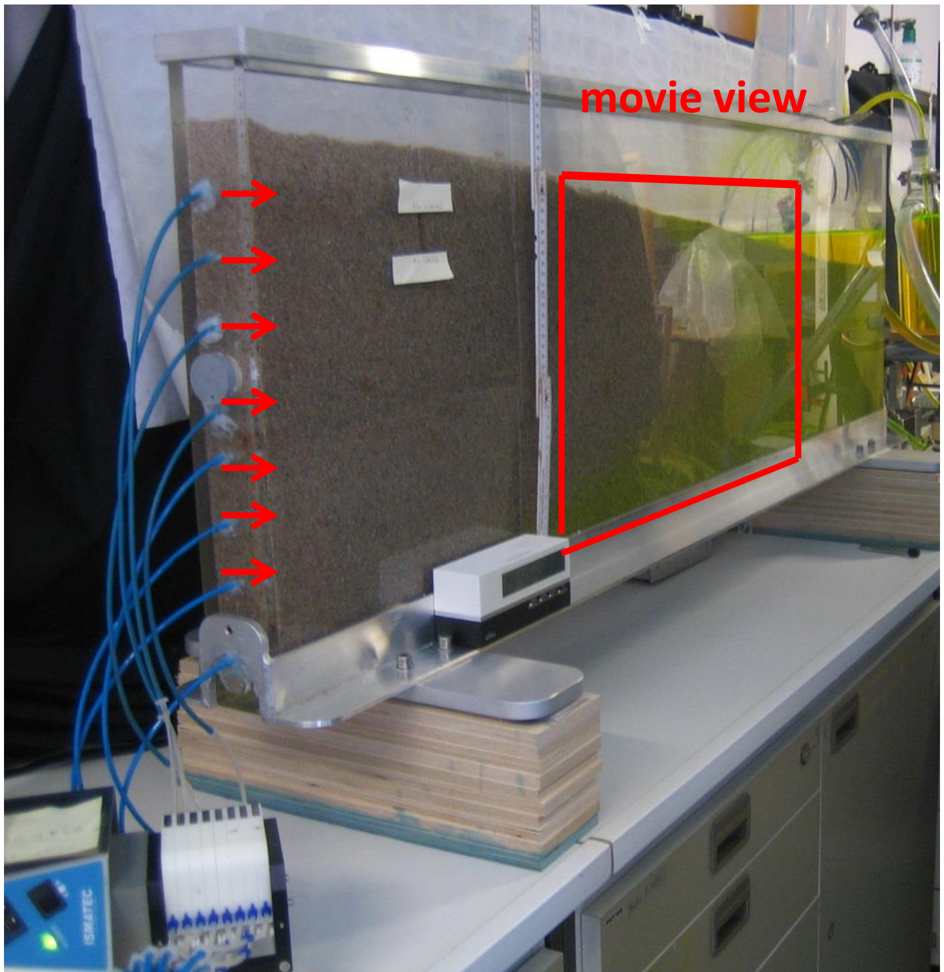


- grain size sand: 0,71–1,4 mm
- hydraulic conductivity (m/s):
  - $8{,}5*0^{-3}$ (sieving)
  - $1{,}38*10^{-2}$ (numerical model)
- SGD rate: 1,2 l/h

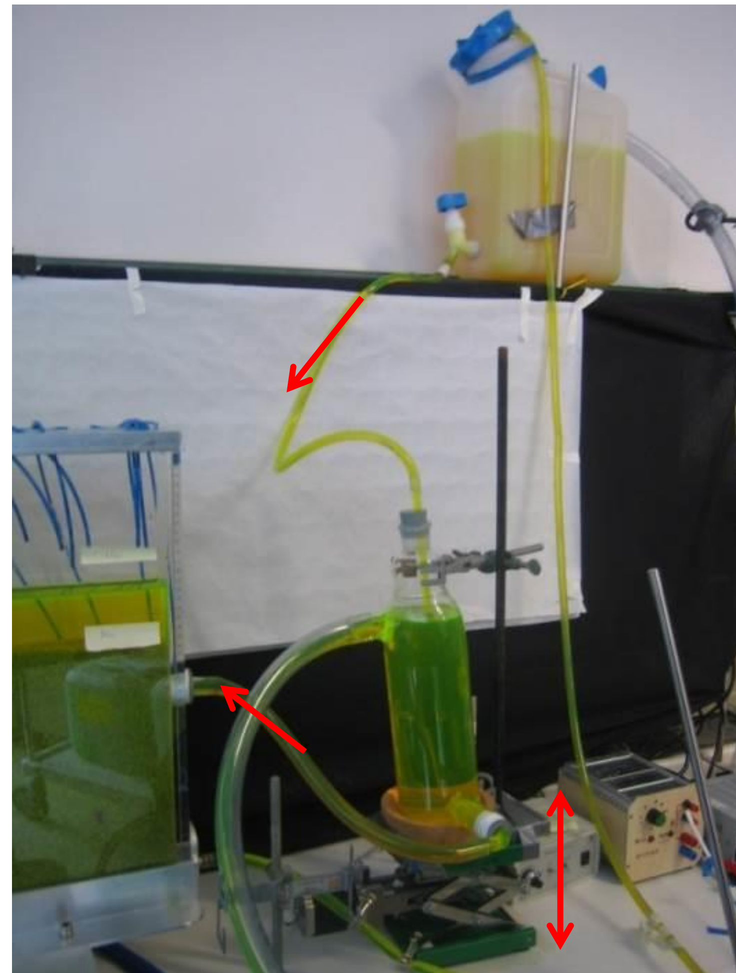
- tidal amplitude: 5 cm
- period length: 2 min
- saltwater density: 35 g/l
- Tracer uranine: 1 g/l

Röper et al. (2014), Limnol Oceanogr

Tank experiments on flow stability



Freshwater inflow



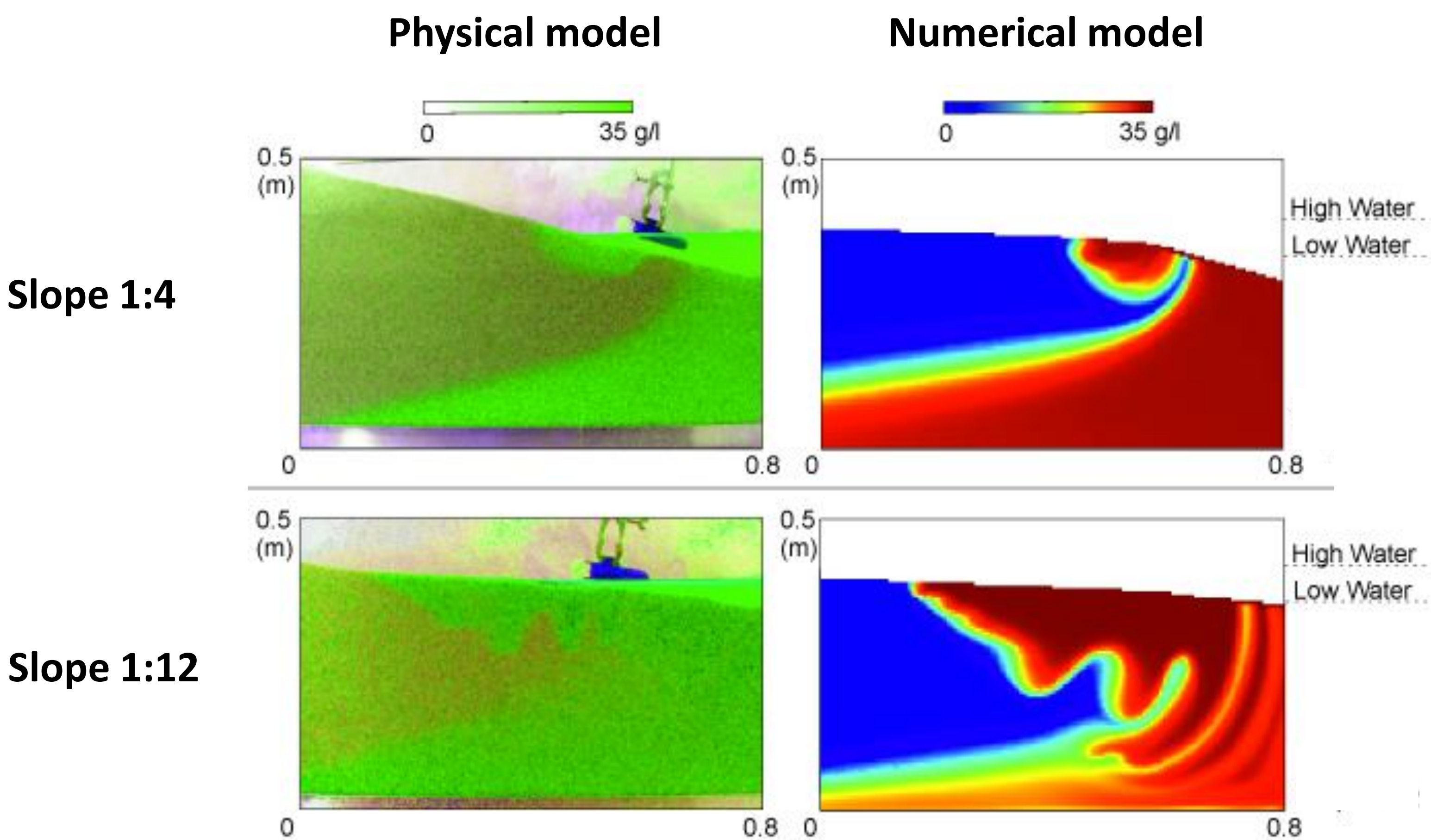
Saltwater inflow

Tidal amplitude

Instabilities appear at flat slopes (1:12)

Röper et al. (2014), Limnol Oceanogr

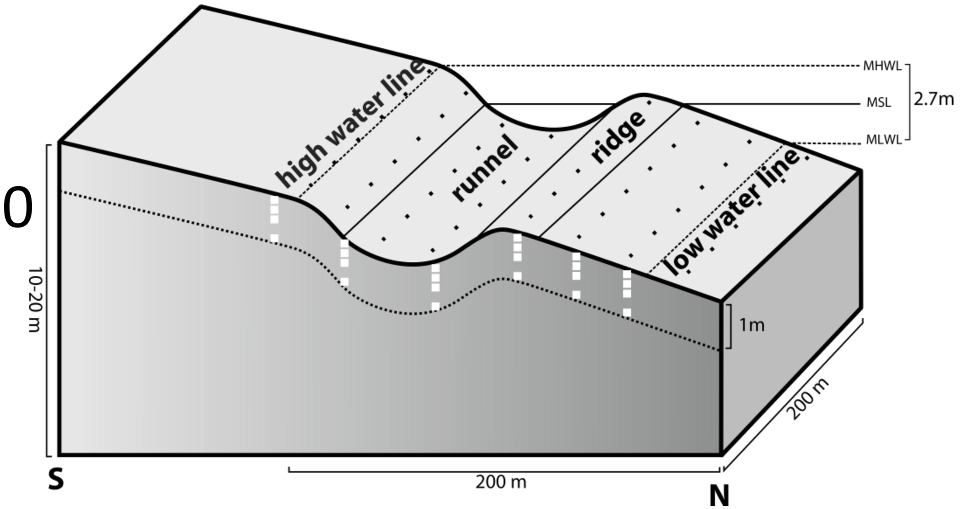
Stable versus instable flow as function of beach slope

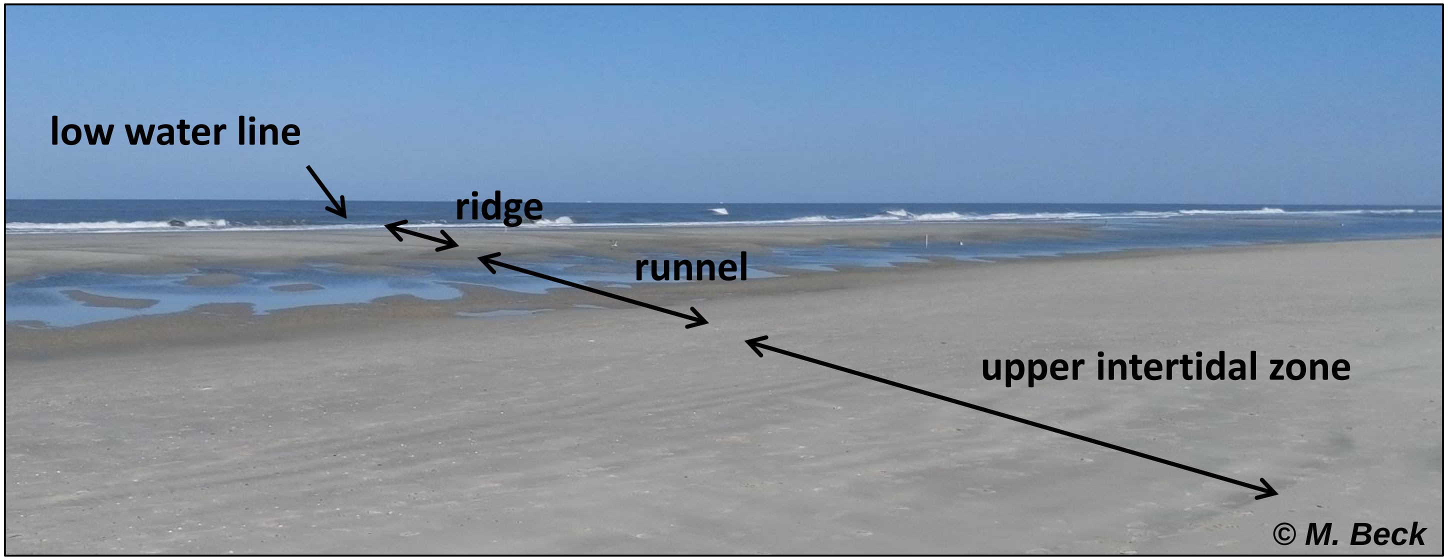


Röper et al. (2014), Limnol Oceanogr

Field data from grid sampling campaign (BIME project)

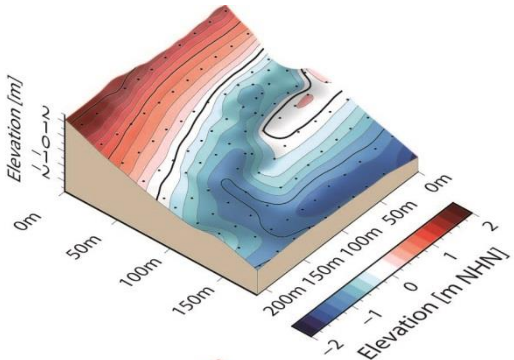
- Seasonal near-surface porewater sampling (50 & 100 cm depth) of the intertidal zone (200*200m grid)



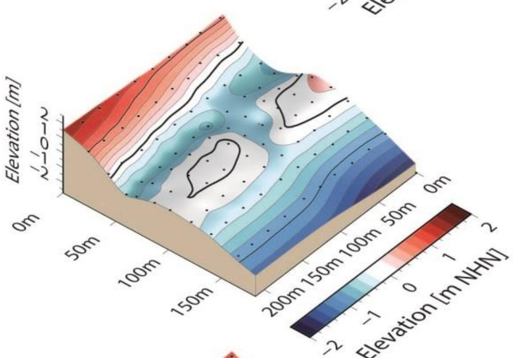


Subsurface flow is function of (highly variable) topography

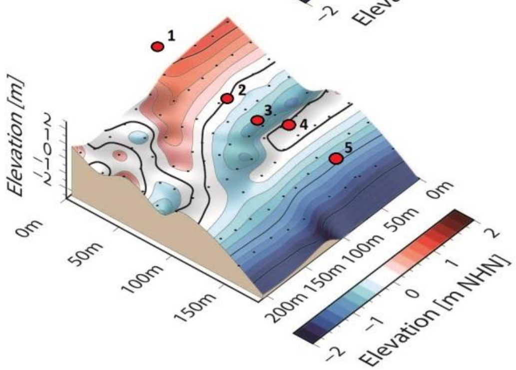
October 2016



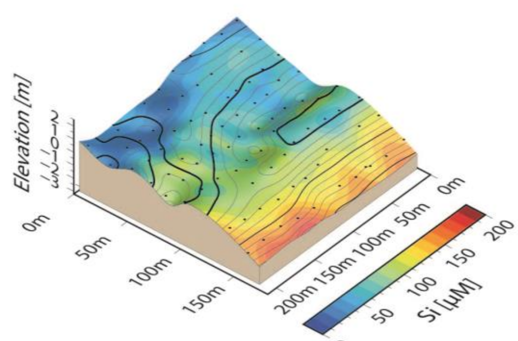
March 2017

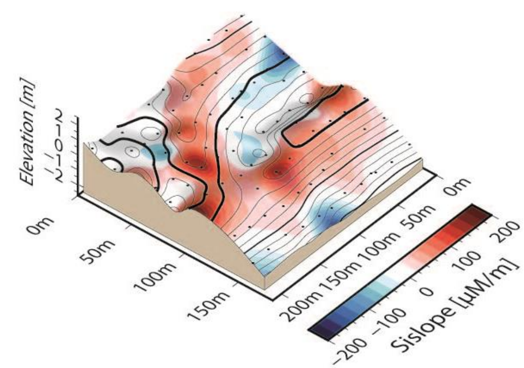


August 2017



- Si concentrations increase with residance time → elevated at discharge locations
- Si gradients ($conc_{100cm}$ - $conc_{50\ cm}$) reveal recharge (red) and discharge (blue) locations following topography





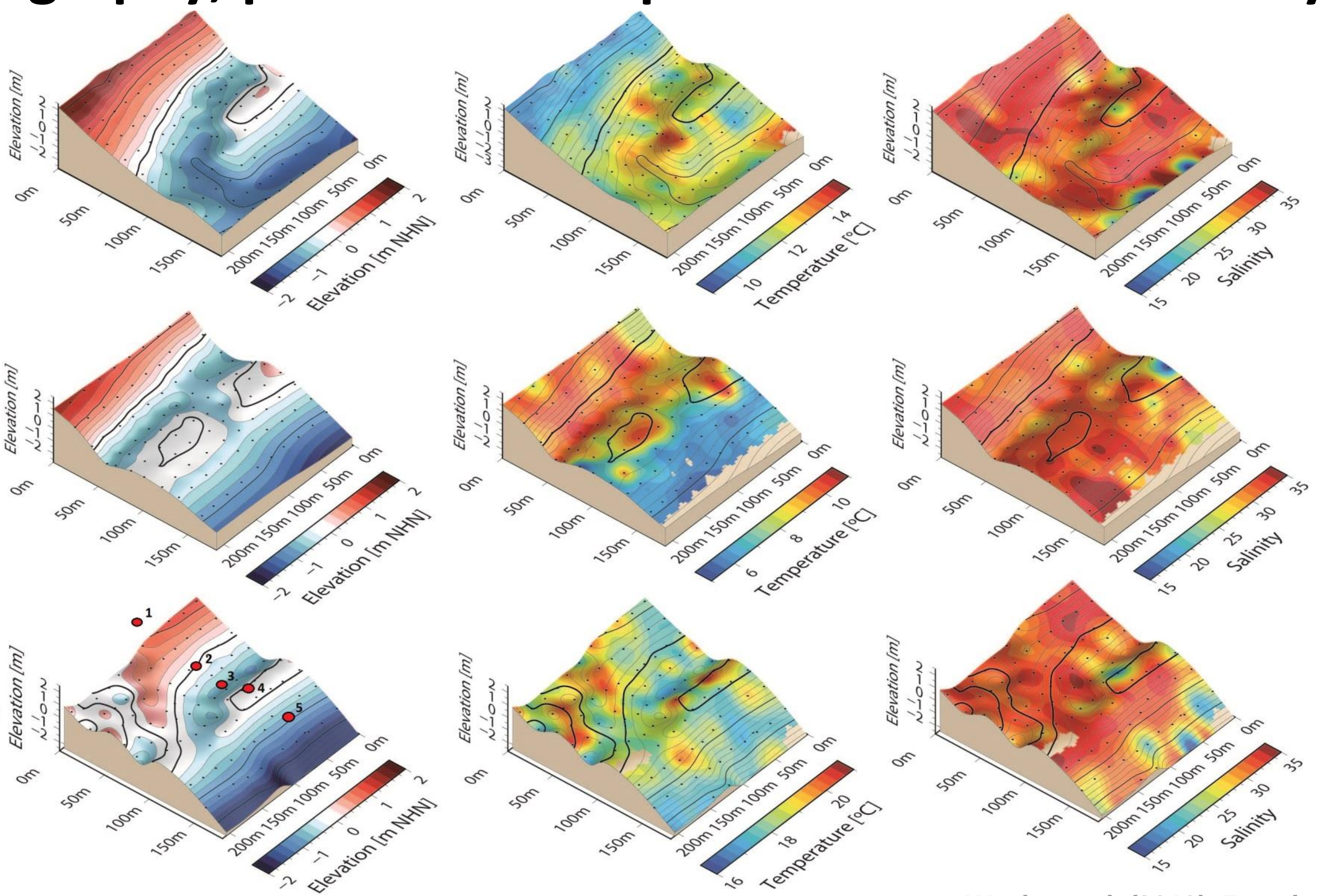
Waska et al. (2019), Frontiers Mar Sci

Topography, porewater temperatures & salinities vary

October 2016

March 2017

August 2017



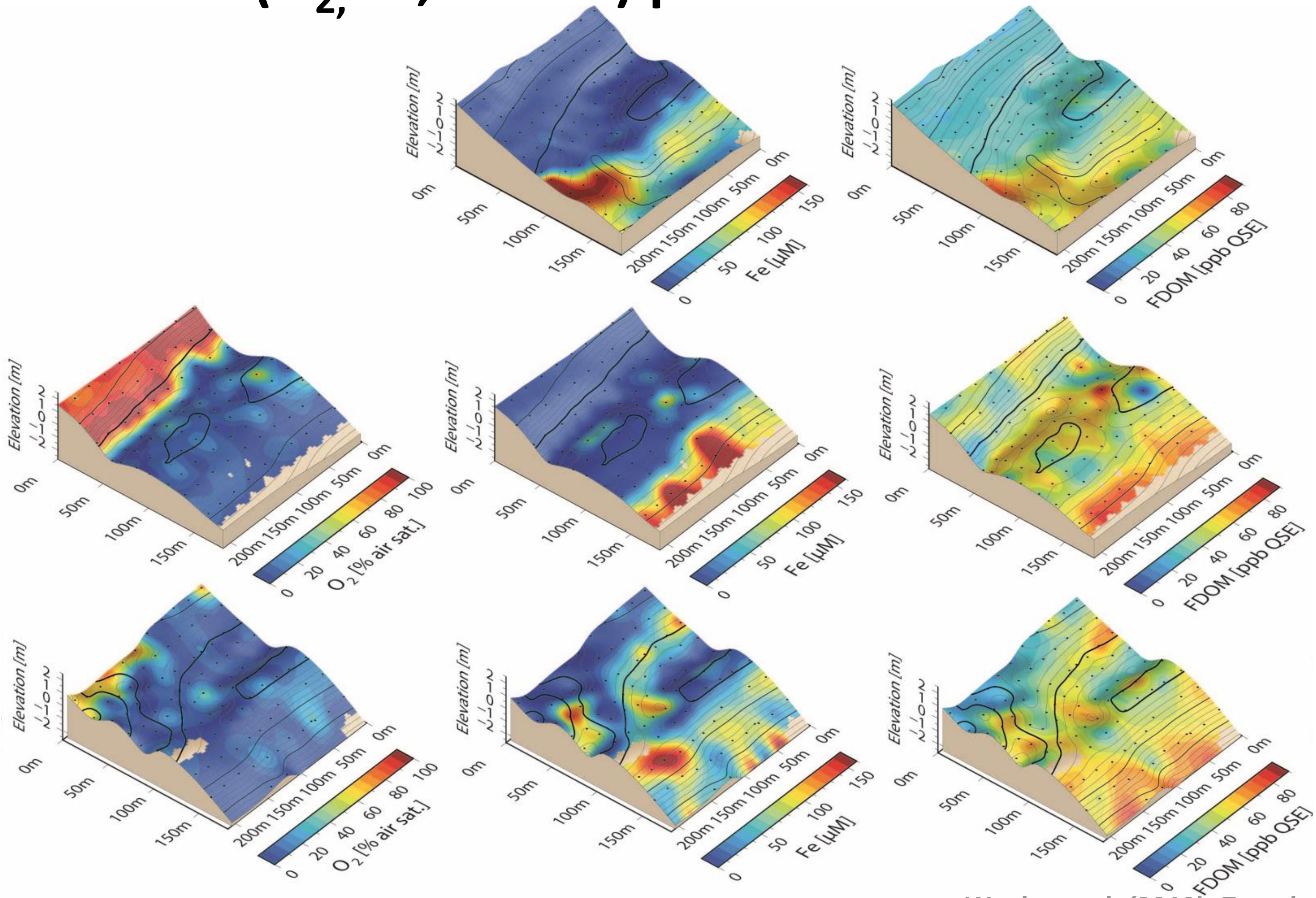
Waska et al. (2019), Frontiers Mar Sci

Geochemical (O_2, Fe, FDOM) patterns are transient

October 2016

March 2017

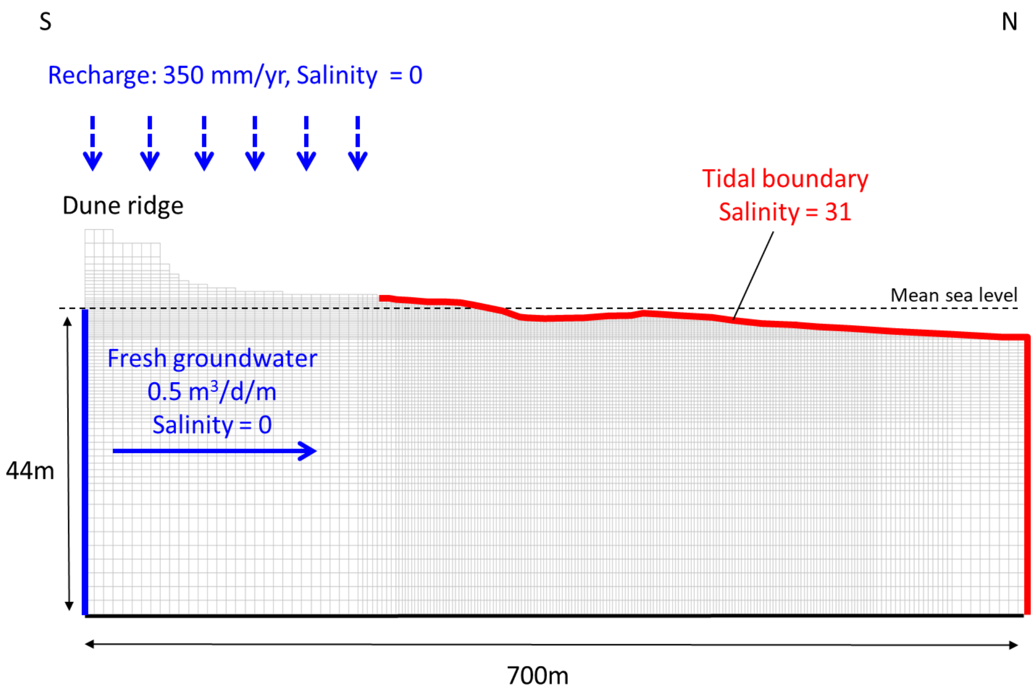
August 2017



Waska et al. (2019), Frontiers Mar Sci

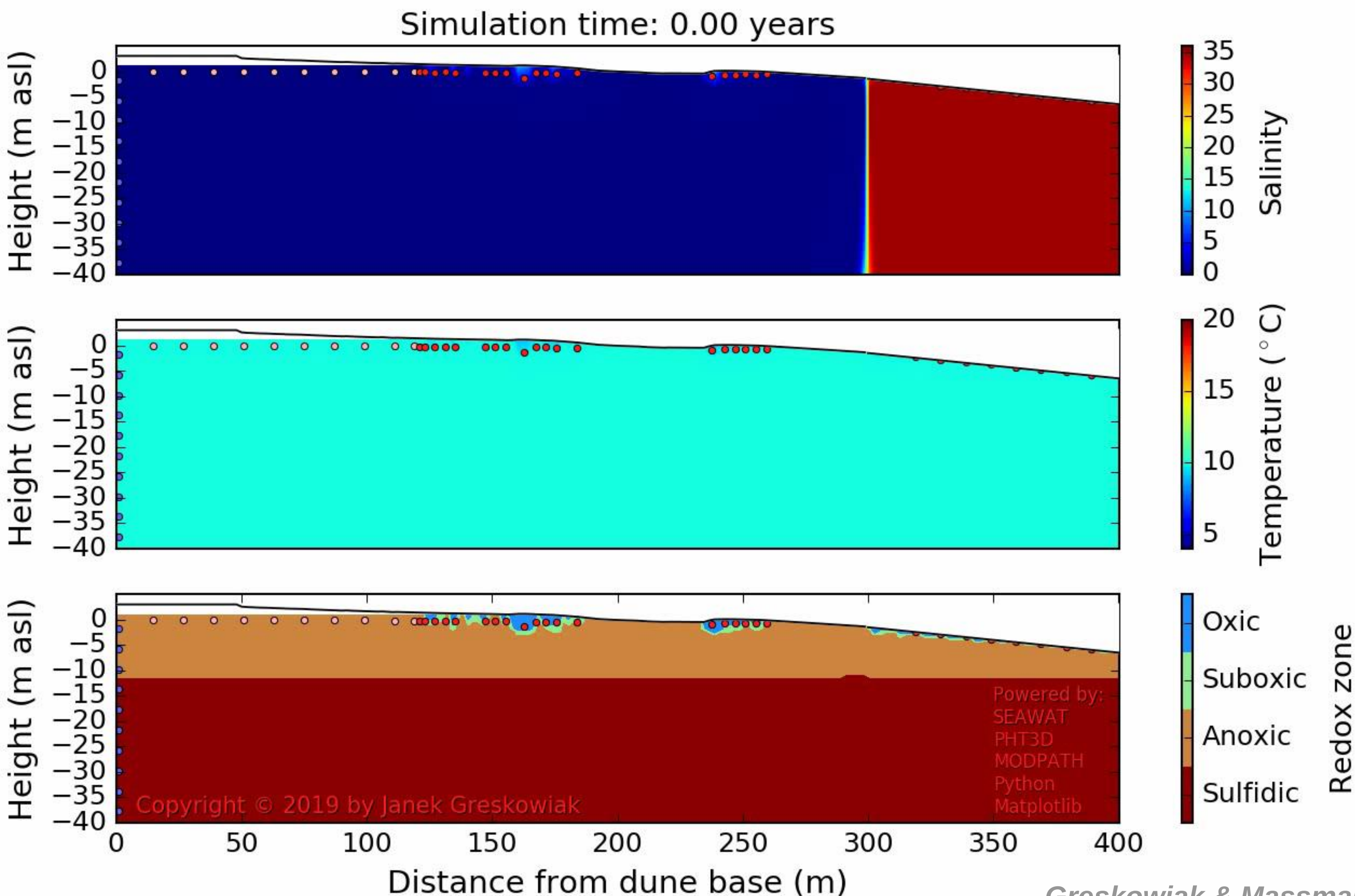
Semi-generic reactive transport model

- SEAWAT/PHT3D model resembling Spiekeroog beach
- Time-variant 3rd type flow boundary at top to (indirectly) account for variable topography
- Three storm-floods per year
- Temperature dependent kinetic redox reactions
- Seasonal oxygen and nitrate input
- No calibration with field data



Beck et al. (2017), Marine Chem

Salinities, temperatures & redox zones highly dynamic



Greskowiak & Massmann (in prep.)

Summary & conclusions

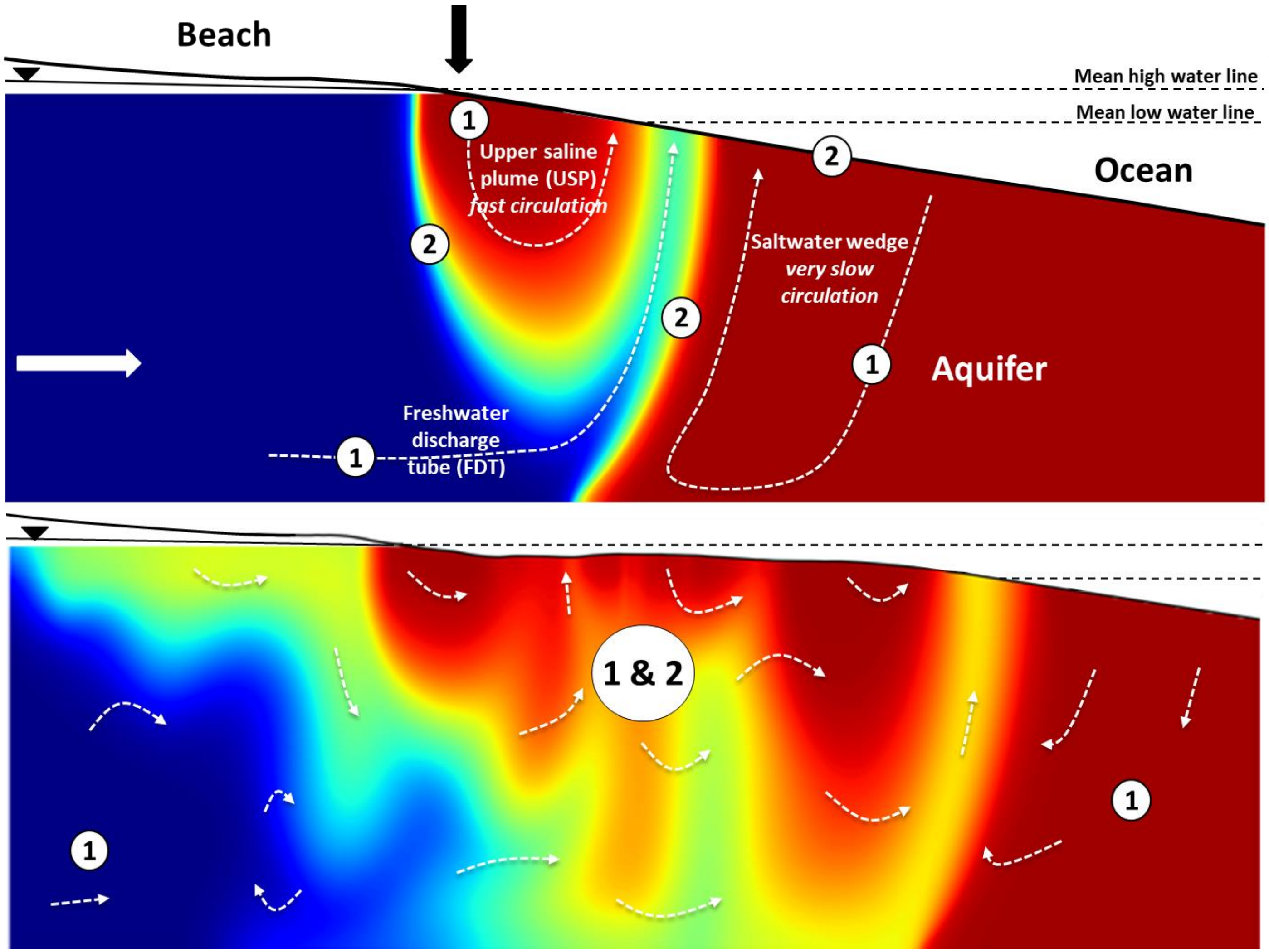
- Seasonal SW temperatures (electron acceptors & DOC input, pumping) cause highly transient subsurface redox conditions during bank filtration → TOrCs affected
- Flow conditions below high-energy beaches most likely highly dynamic, as are geochemical patterns and fluxes
- More high-resolution sampling (time and space) needed to resolve SW-GW exchange processes
- Reactive transport models necessary as transience and interdependencies between morphodynamics, densities, temperatures, redox conditions, attenuation of pollutants cause complex (often non-intuitive) patterns

Thank you to all co-authors of studies cited

- **Berlin:** T. Asmuß, V. Burke, R. Bremermann, U. Dünnbier, J. Greskowiak, A. Sperlich, T. Taute
- **Spiekeroog:** J. Ahrens, Ahmerkamp, M. Beck, T. Birner (Röper), S. P. Böning, H. J. Brumsack, J. Degenhardt, T. Dittmar, C. Ehlert, B. Engelen, J. Greskowiak, N. Grünenbaum, M. Holtappels, K. Pahnke, H. K. Marchant, D. Meier, B. Schnetger, K. Schwalfenberg, H. Simon, V. Vandieken, H. Waska, O. Zielinski

- … and many more

Transient interfaces throughout subterranean estuary



O_2 reduction (oxic)

$$r_{ox} = -k_{ox}\left(\frac{C_{ox}}{K_{ox}+C_{ox}}\right)f_T$$

Nitrate reduction (suboxic)

$$r_{nitr} = -k_{nitr}\left(\frac{C_{nitr}}{K_{nitr}+C_{nitr}}\right)\left(\frac{K_{ox\_inh}}{K_{ox\_inh}+C_{ox}}\right)f_T$$

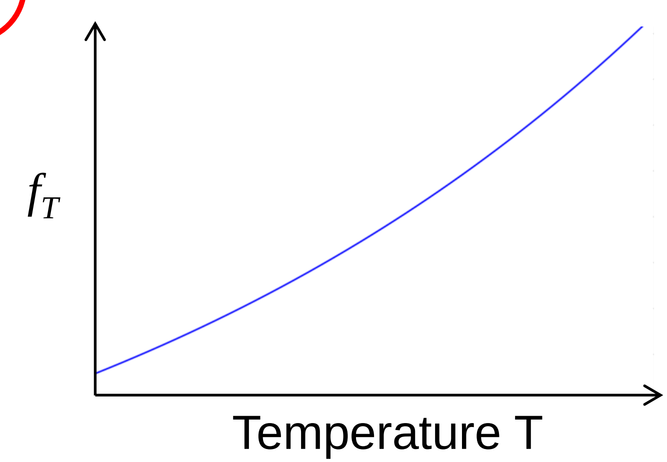
Iron/Sulfate reduction (anoxic/sulfidic) if O_2 and Nitrate are gone

$$r_{fe} = k_{fe}\, f_T \qquad r_{HS} = -r_{SO_4} = k_{SO_4}\, f_T$$

If C_{HS} > 10 µmol/L → sulfidic conditions

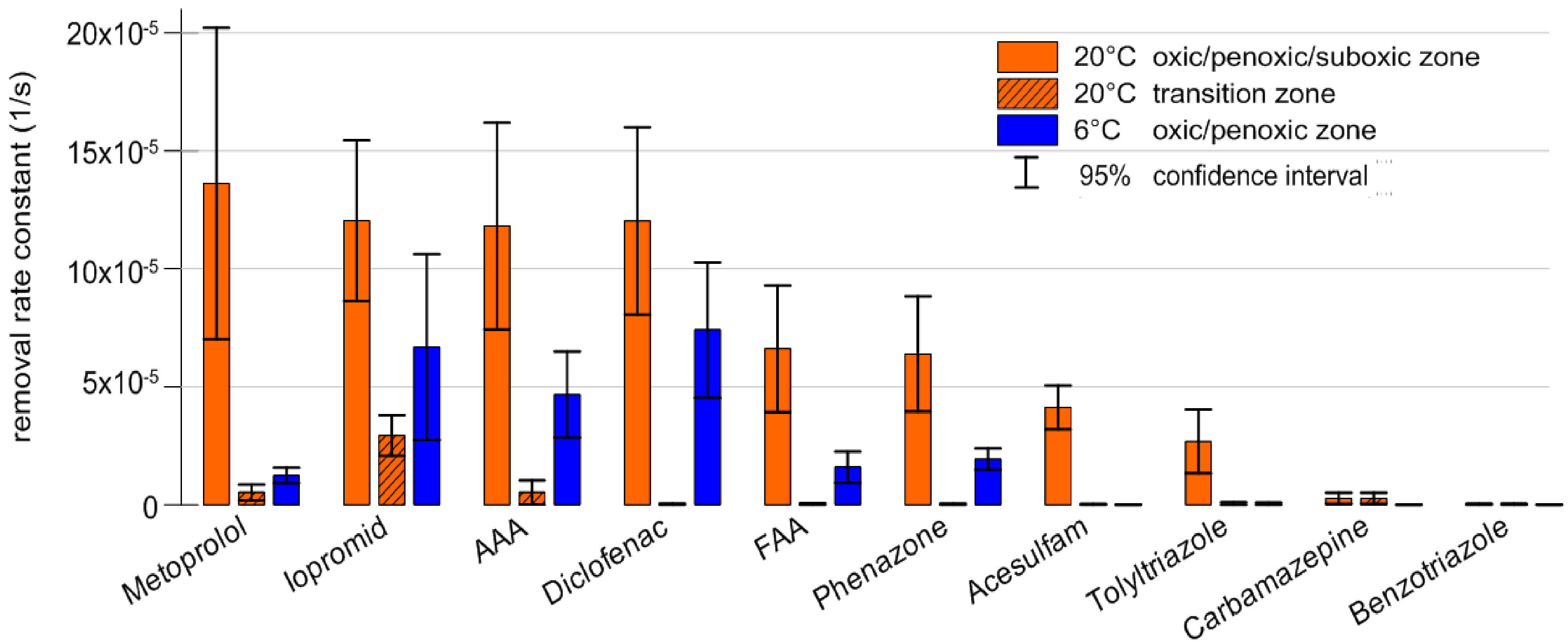
$$f_T = e^{\left(\alpha+\beta T\left((1-0.5\frac{T}{T_{opt}})\right)\right)}$$

(O' Connell, 1990)



TOrC attenuation is function of temp. & redox conditions

$$c = c_o * e^{-\lambda t} \qquad t_{1/2} = ln(2)/\lambda$$



→ warm/oxic > cold/oxic > warm/transition zone (=Mn-reducing)

Burke et al. (2014), STOTEN

TOrC attenuation is function of temp. & redox conditions

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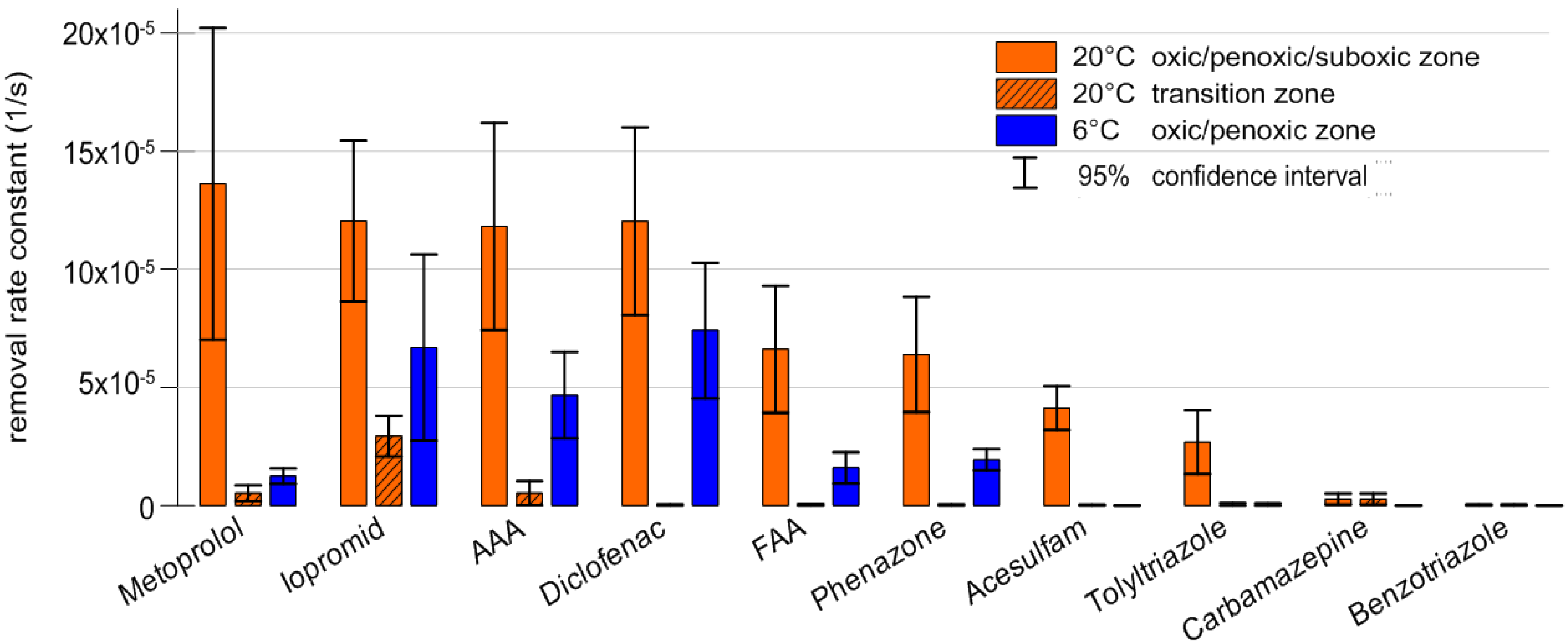

→ **warm/oxic > cold/oxic > warm/transition zone (=Mn-reducing)**

Burke et al. (2014), STOTEN