HelmholtzZentrum münchen
German Research Center for Environmental Health

Importance of immobile water for transport in porous aquifers

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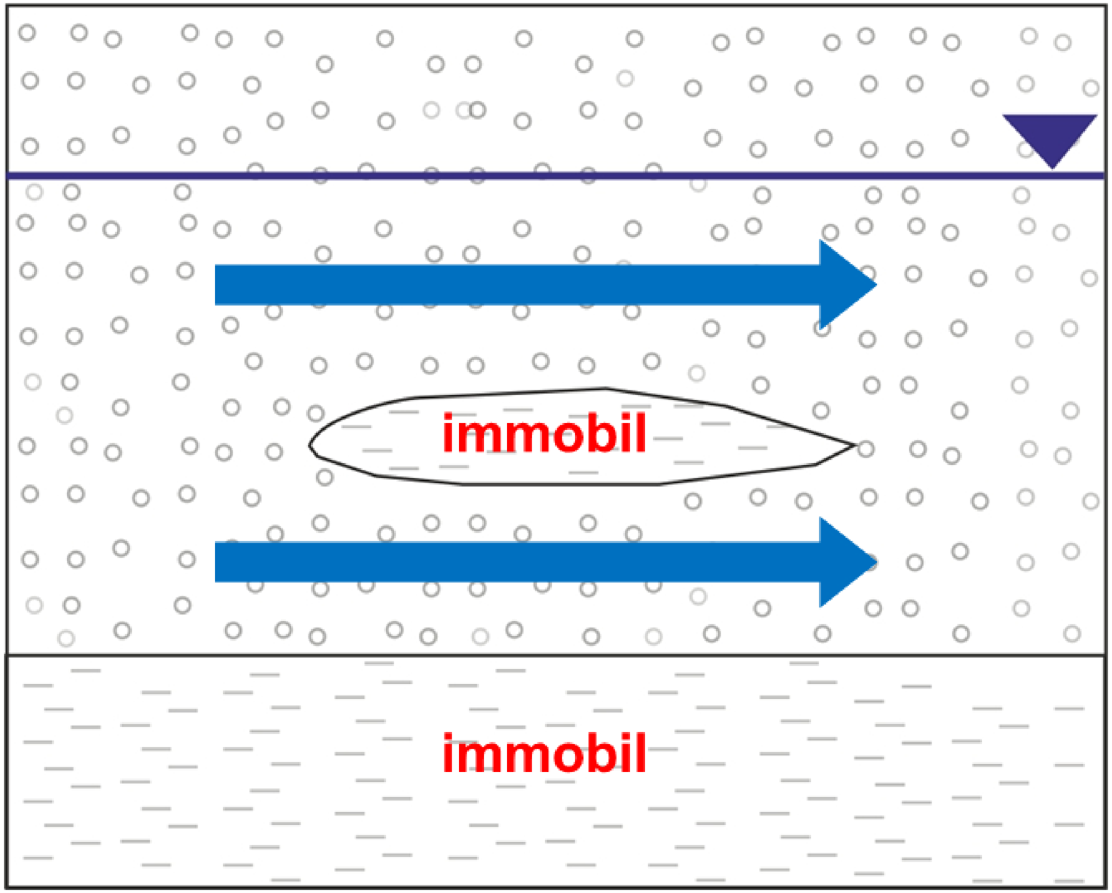
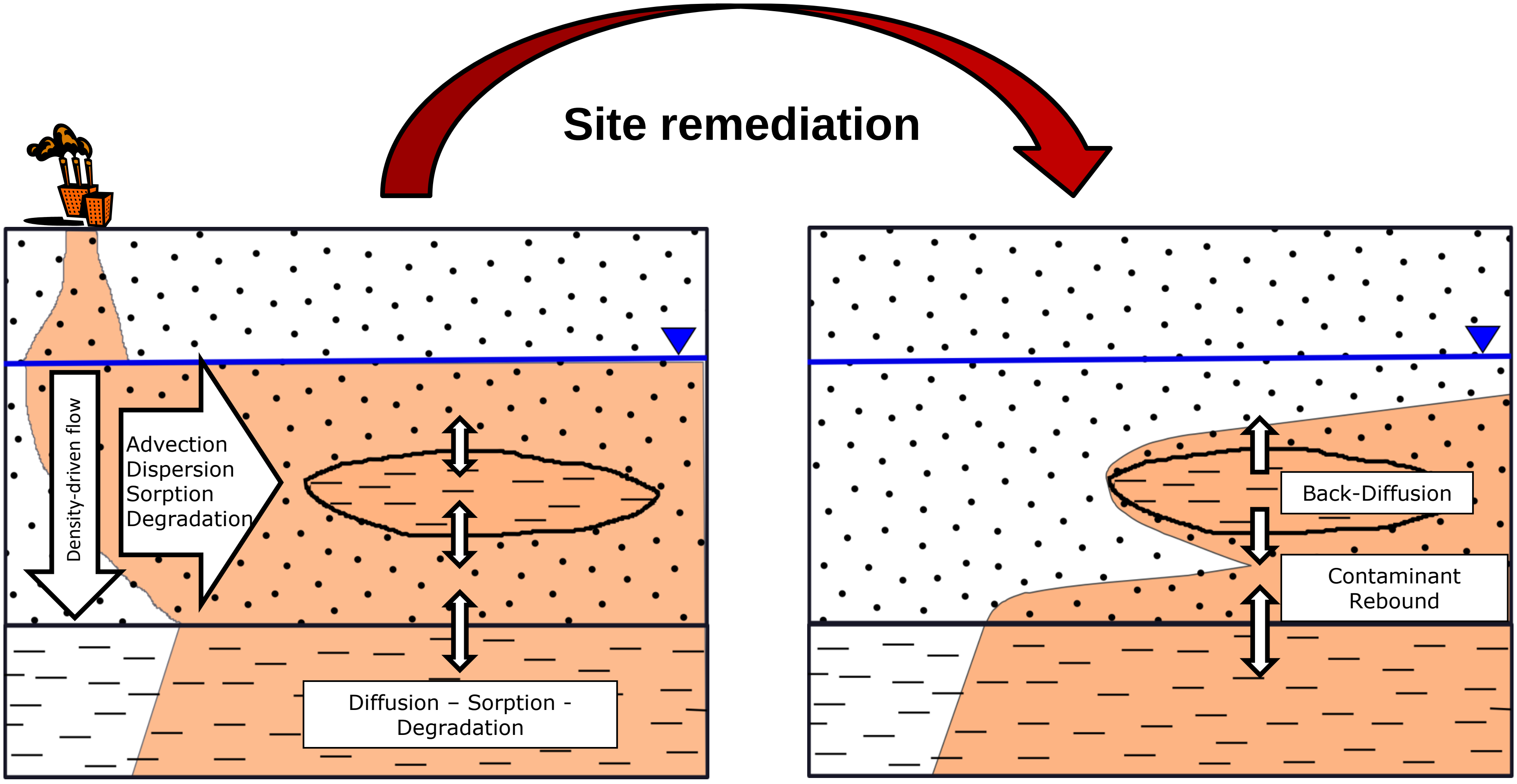
IAH, 28.09.2016, Montpellier

Aquifers are heterogeneous containing less permeable layers



Impact of immobile water on transport



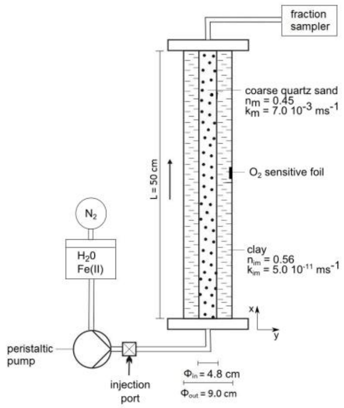
Research gaps

I Properties and spatial distribution of immobile water regions unknown
→ tracer and model approaches

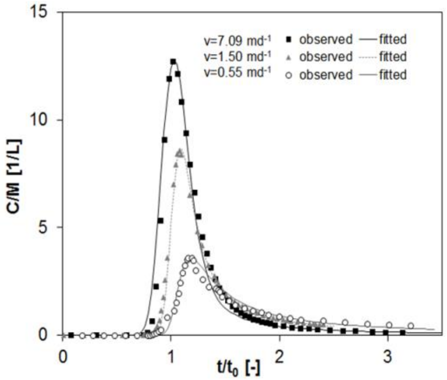
II Quantification of influence of immobile water regions on reactive transport
→ process understanding and model approaches

III Contaminant transport often effected by density-driven flow
→ influence of immobile water regions on contaminant transport and density-driven flow

Objectives

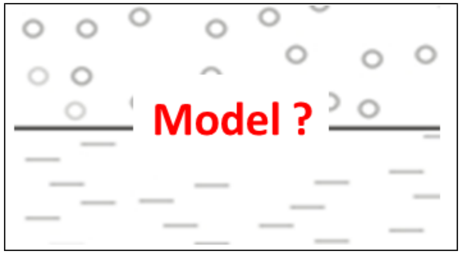


1) develop experimental methods to study specific transport processes in dual-porosity systems

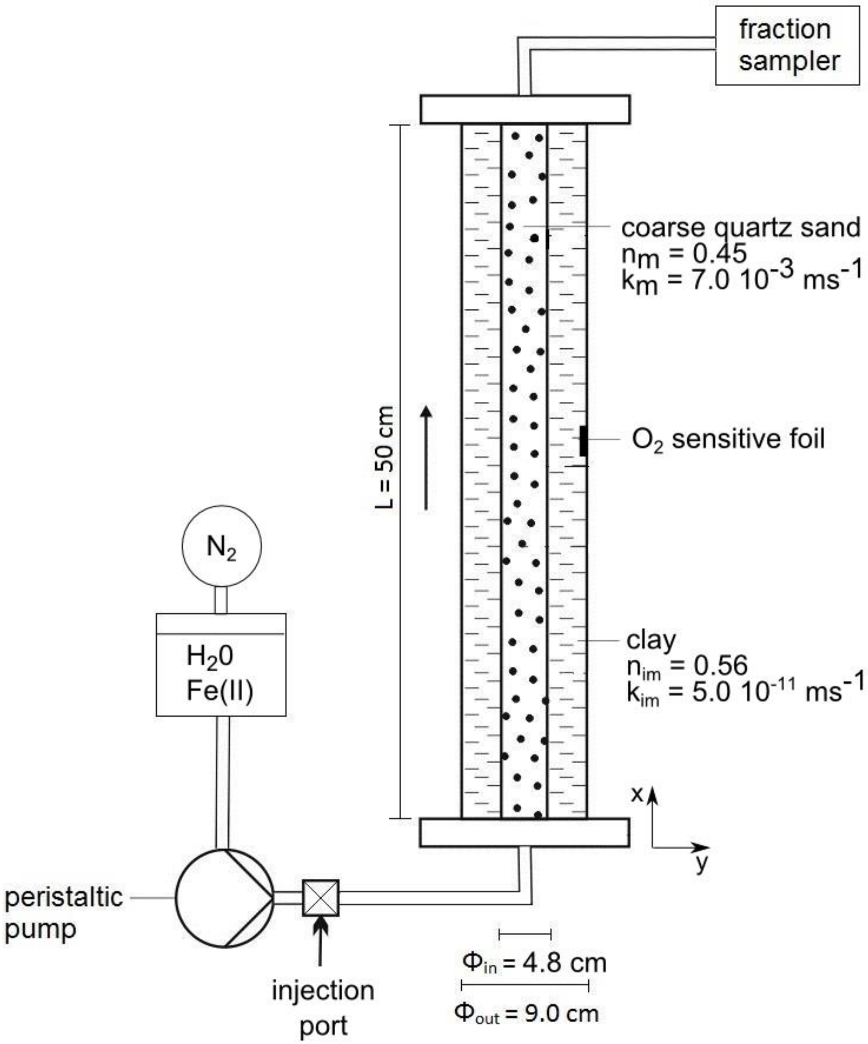


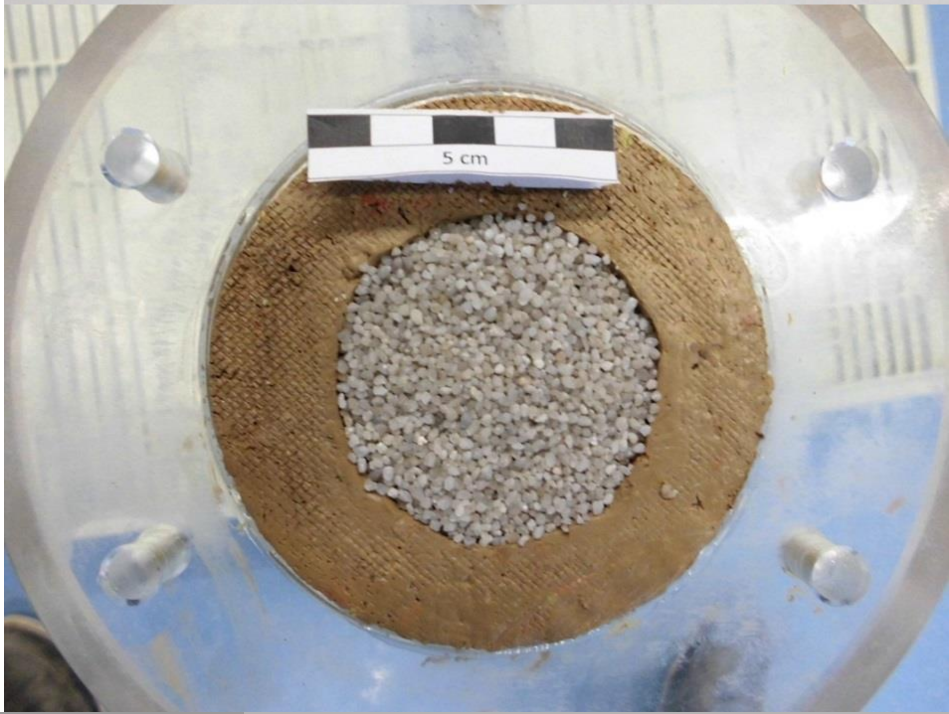
2) identify impact of immobile water on transport processes in dual-porosity systems

3) improve mathematical models for reactive transport modelling in dual-porosity systems

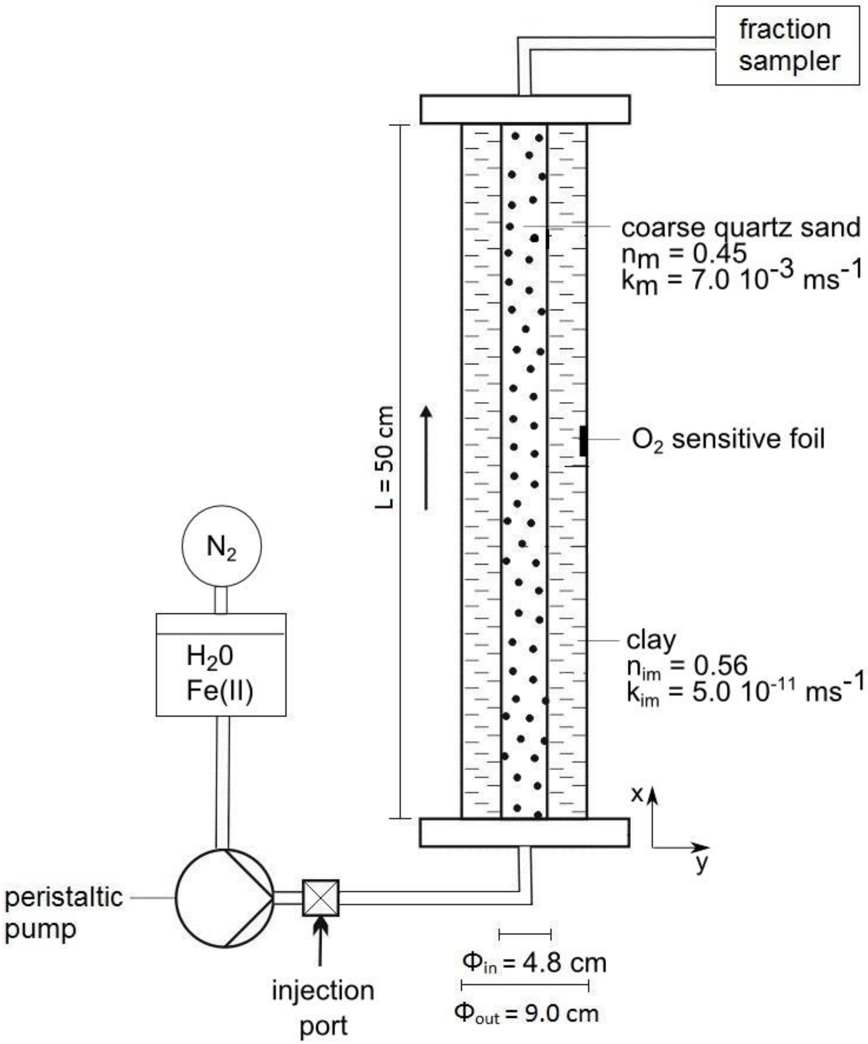


Experimental Setup





Experimental Setup

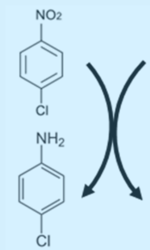


1) conservative transport

$D_{uranine}$ < $D_{bromide}$ < $D_{deuterium}$

2a) reactive transport

4-Cl-nitrobenzene



4-Cl-nitroaniline

Fe(II)

Structural or surface-bound species

Fe(III)

Source: Hofstetter et al. (1999), Elsner et al. (2004)

2b) reactive transport

^{134}Cesium

3) density driven flow

Methanol

0 > -0.0036 > -0.0071

Mathematical Modelling

Single Fissure Dispersion Model (SFDM) including sorption and degradation/decay:

$$\frac{\partial C_m}{\partial t} + v\frac{\partial C_m}{\partial x} - D\frac{\partial^2 C_m}{\partial x^2} - \frac{n_{im}D_{im}}{2b}\frac{\partial C_{im}}{\partial y}\bigg|_{y=\frac{\phi_{in}}{2}} = 0 \qquad \text{for} \qquad 0 \le y < \frac{\phi_{in}}{2}$$

$$\frac{\partial C_{im}}{\partial t} + R_{im}\frac{\partial C_{im}}{\partial t} - D_{im}\frac{\partial^2 C_{im}}{\partial y^2} + kC_{im} = 0 \qquad \text{for} \qquad \frac{\phi_{in}}{2} \le y < \infty$$

Analytical Solution

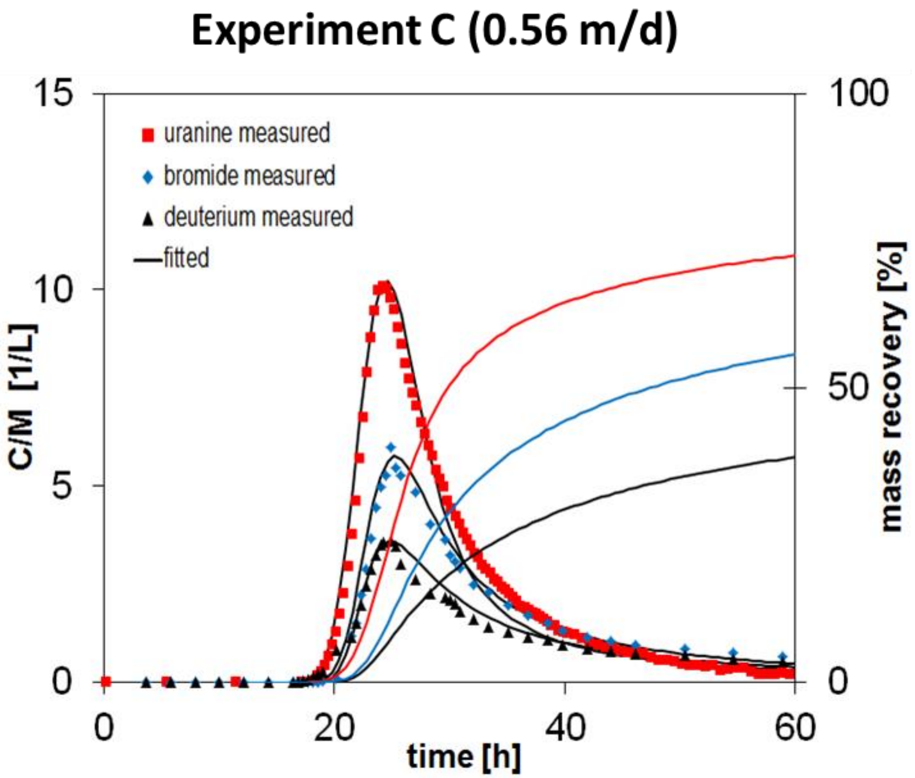
Source: Maloszewski and Zuber (1985, 1990)

$$C_m(t) = \frac{M\,a\sqrt{R_{im}}}{2\pi Q}\sqrt{\frac{t_0}{P_D}}\int_0^t exp\left[-\frac{(t_0-u)^2}{4P_D u t_0} - \frac{(a\sqrt{R_{im}})^2u^2}{t-u} - \frac{k_{degr}}{R_{im}}(t-u)\right]\frac{du}{\sqrt{u(t-u)^3}}$$

Fitting Parameter:

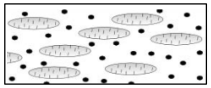
transit time of water	diffusion parameter	dispersion parameter	retardation factor	first-order rate
$t_0 = \frac{V_m}{Q}$	$a = \frac{n_p\sqrt{D_p}}{2b}$	$P_D = \frac{\alpha_L}{L}$	$R_{im} = 1 + \frac{\rho_b}{n_p}K_d$	k_{degr}

Results – conservative transport

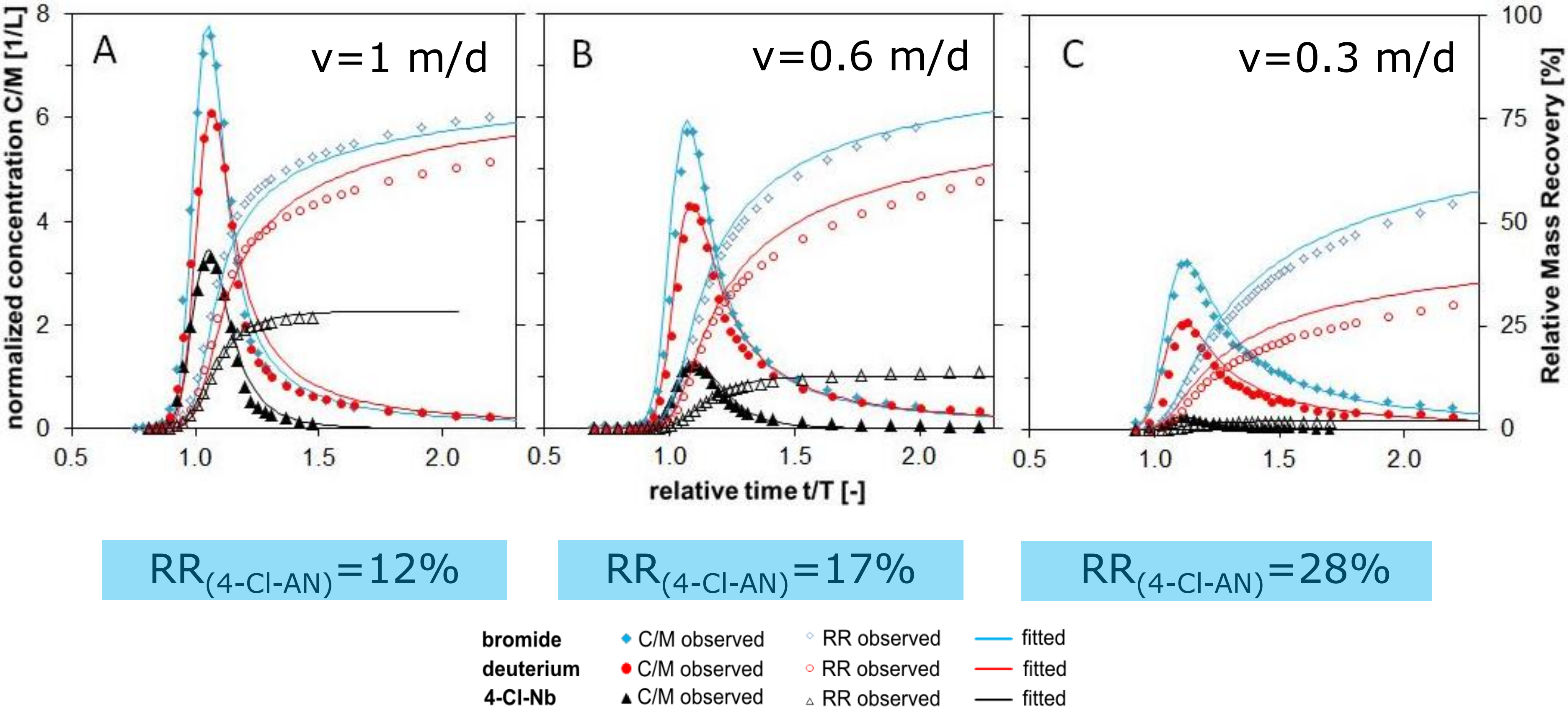


(Knorr et al. Hydrological Processes, 2016)

→ fit parameter in agreement with measurements ($n_{mob} + n_{immob}$)

→ also applicable for randomly distributed immobile water regions 

Results – reactive transport: 4Cl-Nitrobenzene



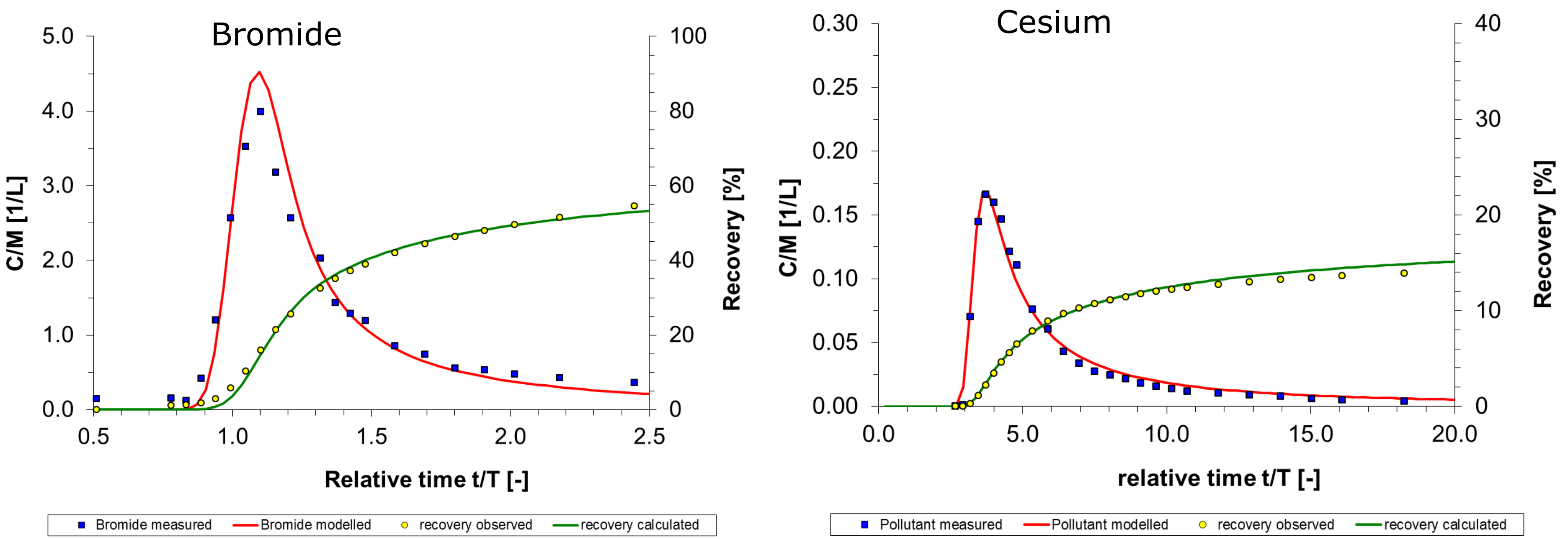
$RR_{(4\text{-Cl-AN})}=12\%$ $RR_{(4\text{-Cl-AN})}=17\%$ $RR_{(4\text{-Cl-AN})}=28\%$

→ fit parameter in agreement with measurements (n_{mob} + n_{immob})

→ back diffusion limited by transformation

→ transformation independent on flow velocity but on transit time

Results – reactive transport: ^{134}Cs

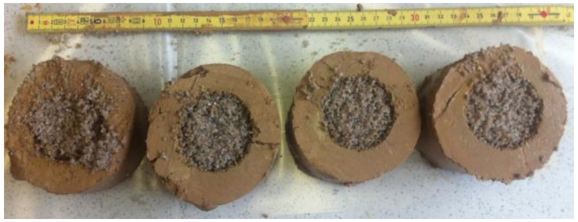


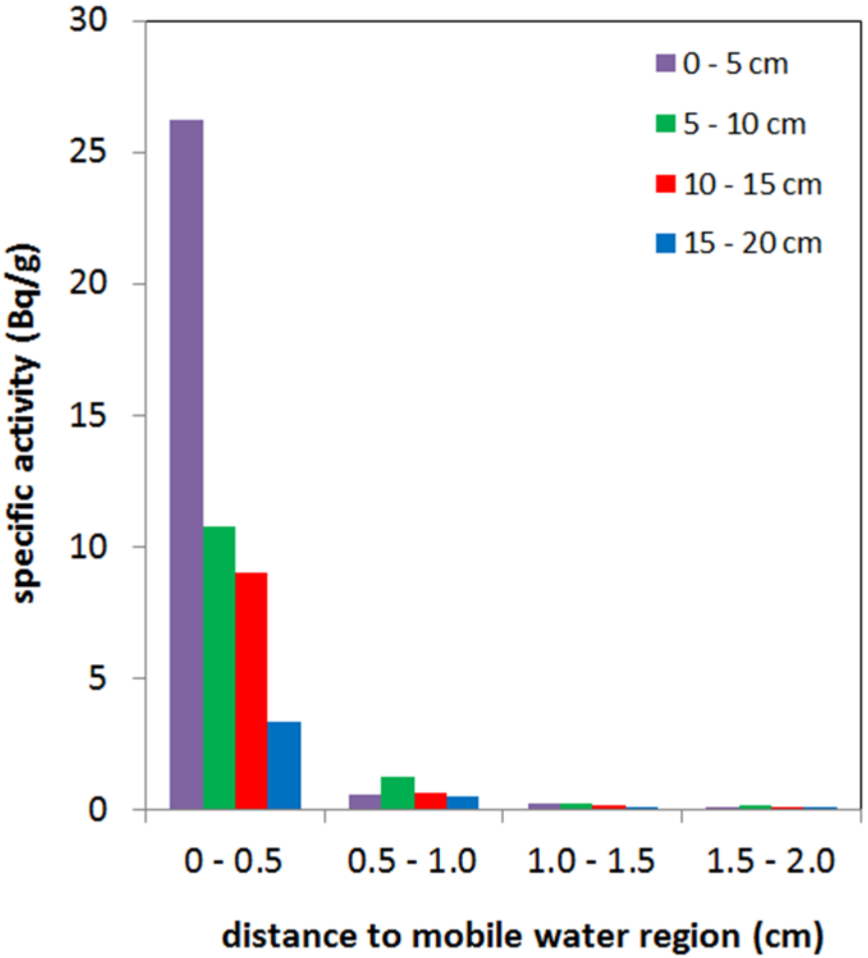
→ strong retardation of 134 Cs (R=3.2)

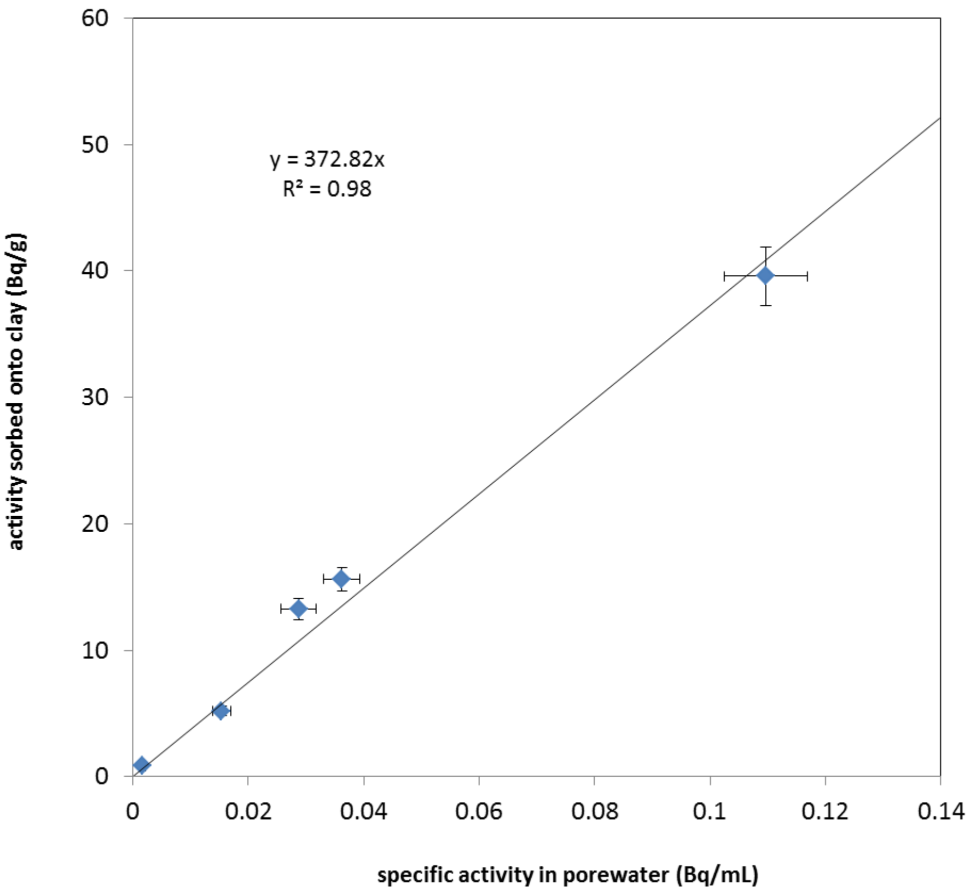
→ impact on diffusion into immobile water

→ same immobile water content for bromide and cesium

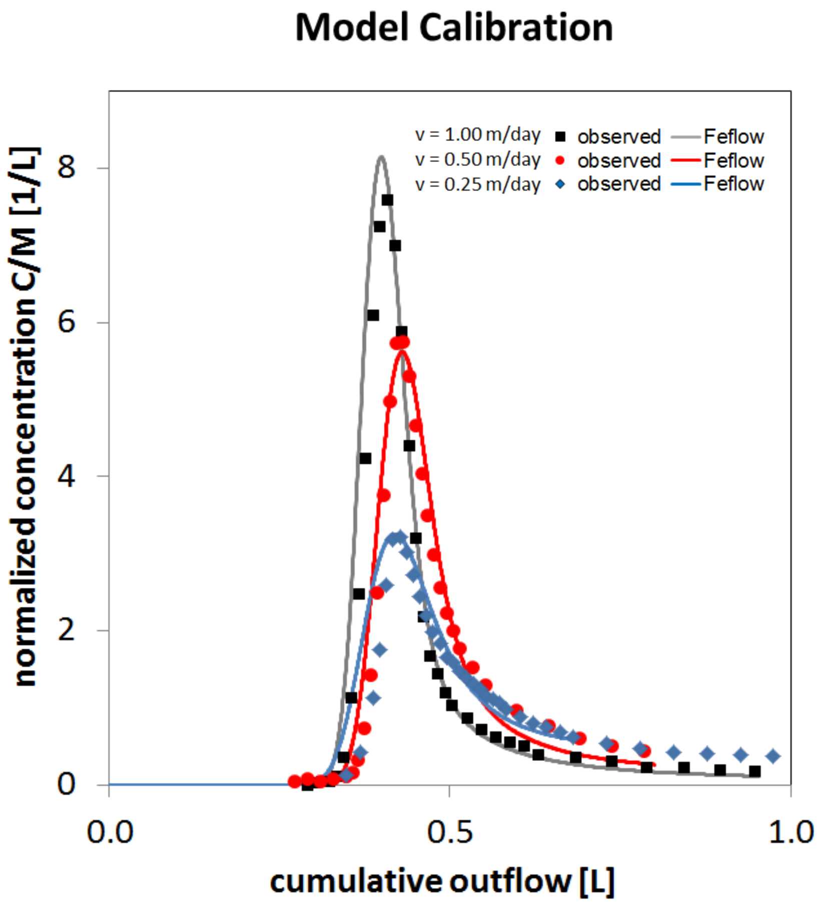
Results – reactive transport: ^{134}Cs

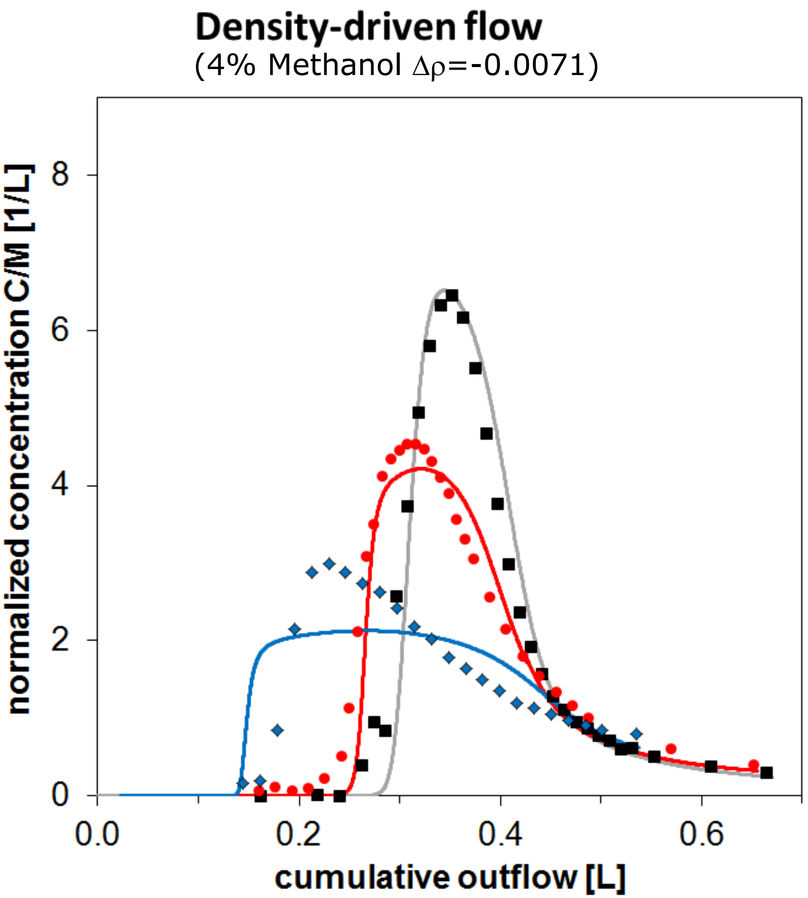






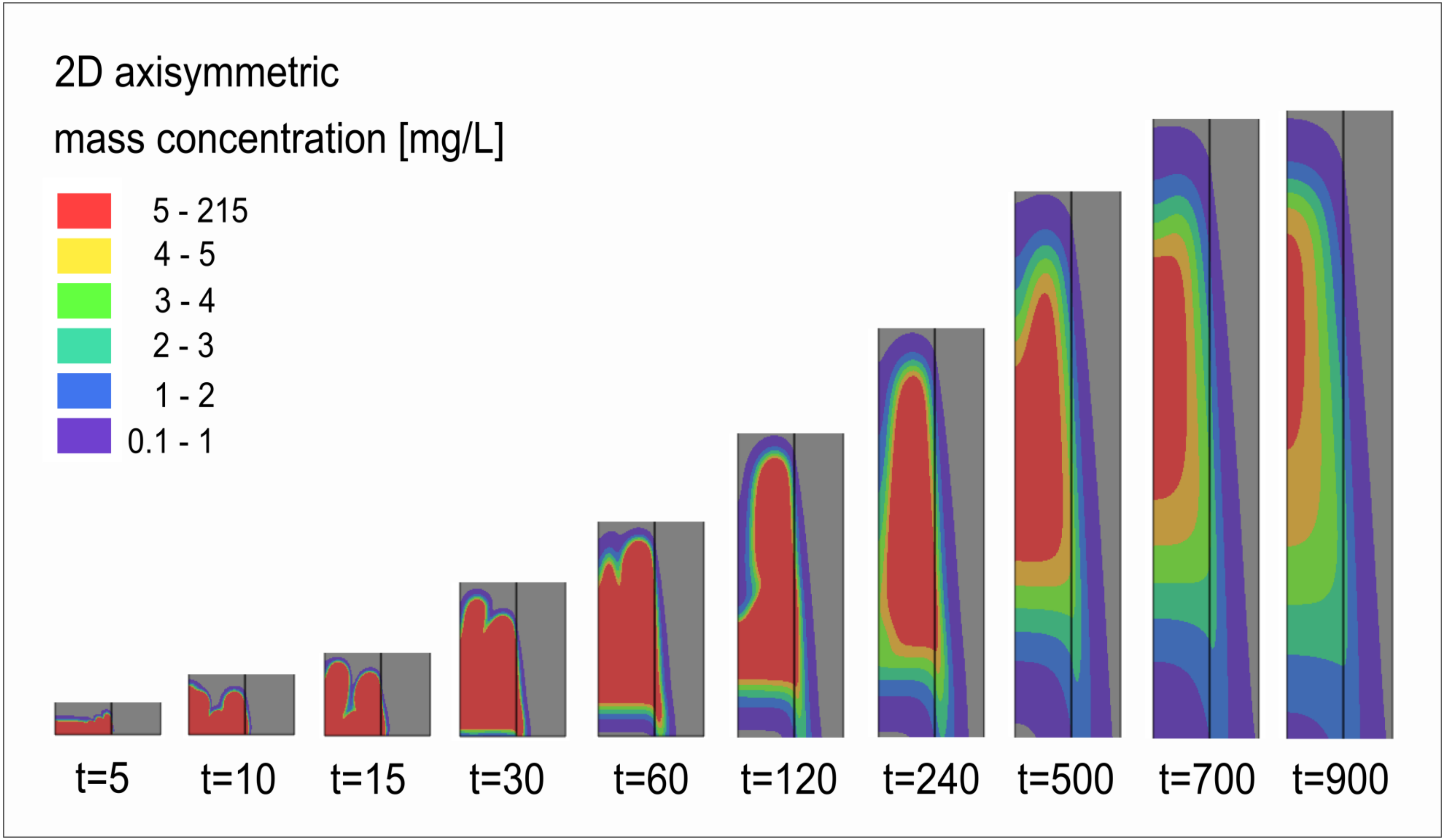
Results – density driven flow





→ very small differences in density caused instabilities
→ increased diffusion due to longer contact times
→ numerical modelling required

Results – density driven flow Feflow simulation



Conclusions

- immobile water region strongly impact transport in heterogeneous aquifers
- mass transfer depends on diffusion coefficient
- multitracer approach
- abiotic reaction reduces mass transfer
- mass transfer enhanced for density driven flow and inhibition of flow instabilities
- SFDM also applicable in porous aquifers for conservative and reactive transport
- numerical modelling required to describe density driven flow