Millifluidic tracer experiments to investigate the signature of saline diffusion on effective electrical conductivity

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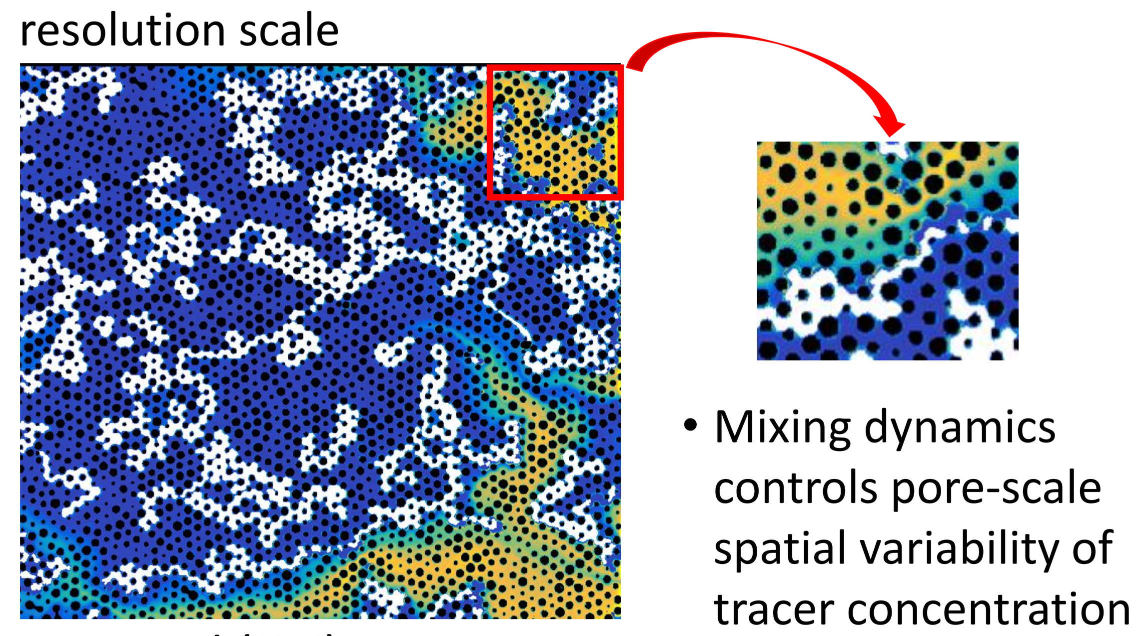
1. Introduction

When monitoring saline tracer tests, standard post-processing of inversion results obtained by time-lapse Electrical Resistivity Tomography (ERT) often fail to accurately predict the temporal evolution of the spatial moments of the solute mass. At least partly, this is a consequence of unaccounted spatial heterogeneity of the tracer distribution below the model resolution of the tomogram. Hence, sub-resolution tracer heterogeneity currently leads to unpredictable effects on inferred upscaled tracer properties obtained by ERT monitoring.

Here, we present preliminary tests towards a series of electrically monitored milifluidic tracer experiments. The general goal of these experiments is to support the development of upscaling methods to predict the impact of spreading and mixing processes on effective electrical conductivity at the ERT resolution scale. In turn, it is hoped that the framework produced can serve to infer statistical properties of spreading and mixing dynamics from effective electrical properties at large scales.

Heterogeneous solute concentration field at the ERT resolution scale



Jougnot et al. (2018)

- Mixing dynamics controls pore-scale spatial variability of tracer concentration

$\Delta C(t, \vec{x})$ → $\Delta\sigma_{eff}(t)$

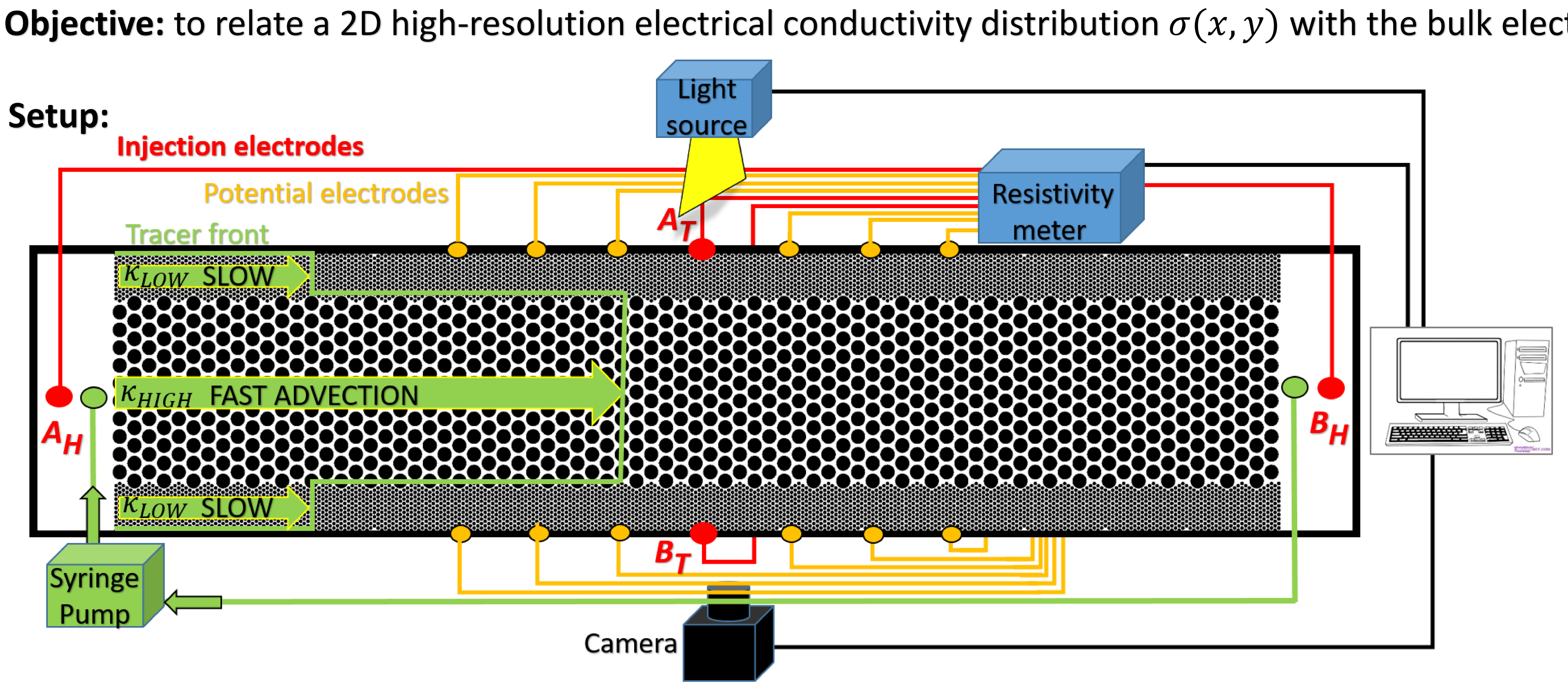
(solute concentration field) (effective electrical conductivity)

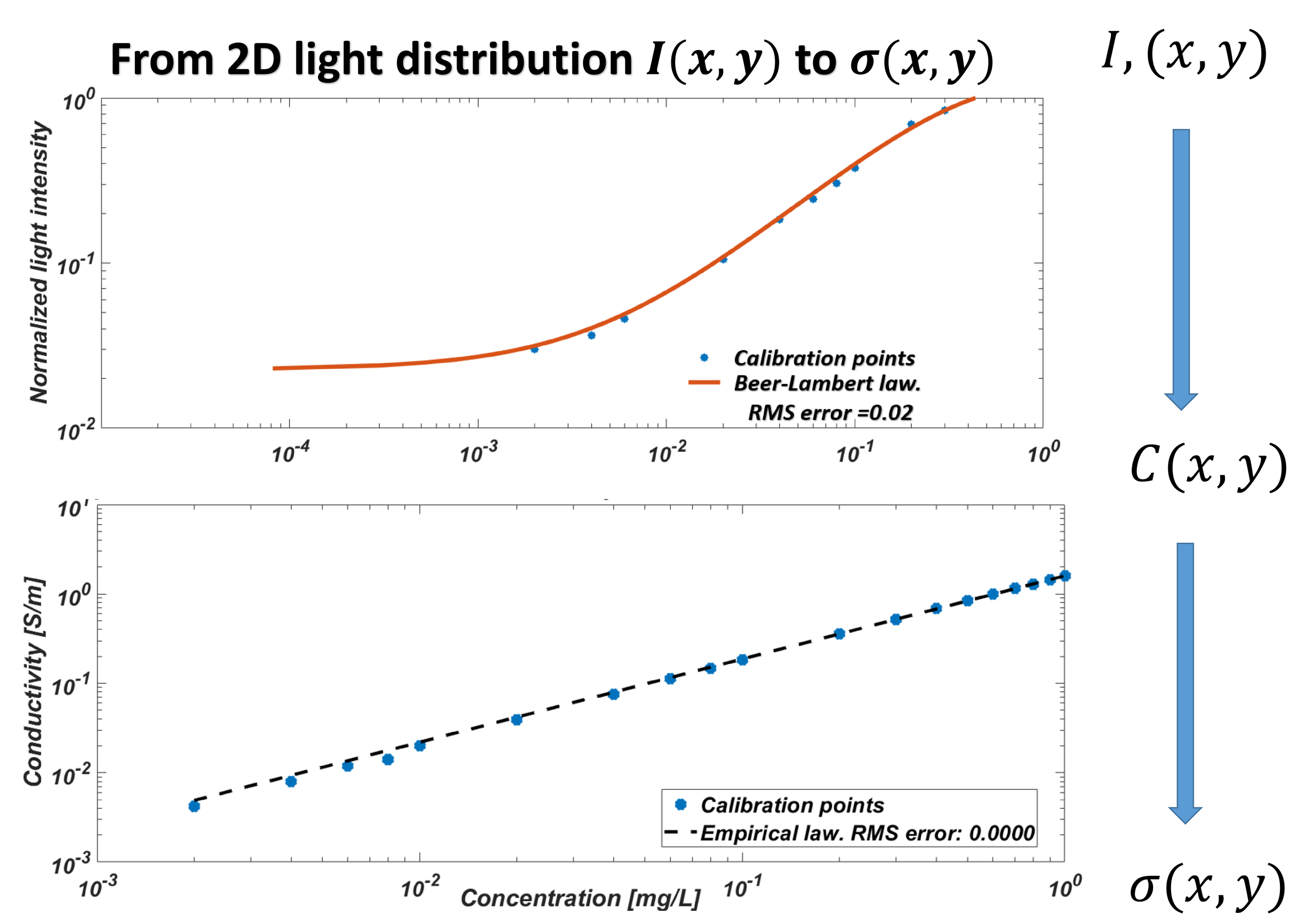
2. Experiment: tracer test in a 2D layered medium

Overview: using a ***Syringe pump***, a fluorescent and electrically-conductive tracer is injected in a decimetric (62 x 8 cm) Hele-Shaw cell, confining an artificial ***Porous medium*** which consists of 0.4 mm-thick cylindrical silicon (polydimethylsiloxane, PDMS) pillars. The tracer is excited with a ***Light source*** placed above the cell, and the light emitted from the sample is recorded over time with a ***Camera*** placed below, which allows to monitor the 2D field of tracer concentration. Concurrently, electrical current is injected in two alternating modes, horizontally and transversally, from the two pairs of ***Injection electrodes*** $A_H - B_H$ and $A_T - B_T$, respectively. The apparent resistivity, related to the effective electrical conductivity σ_{eff}, is monitored from 12 ***Potential electrodes*** for each of the injection modes.

Objective: to relate a 2D high-resolution electrical conductivity distribution $\sigma(x, y)$ with the bulk electrical conductivity σ_{eff}

Setup:



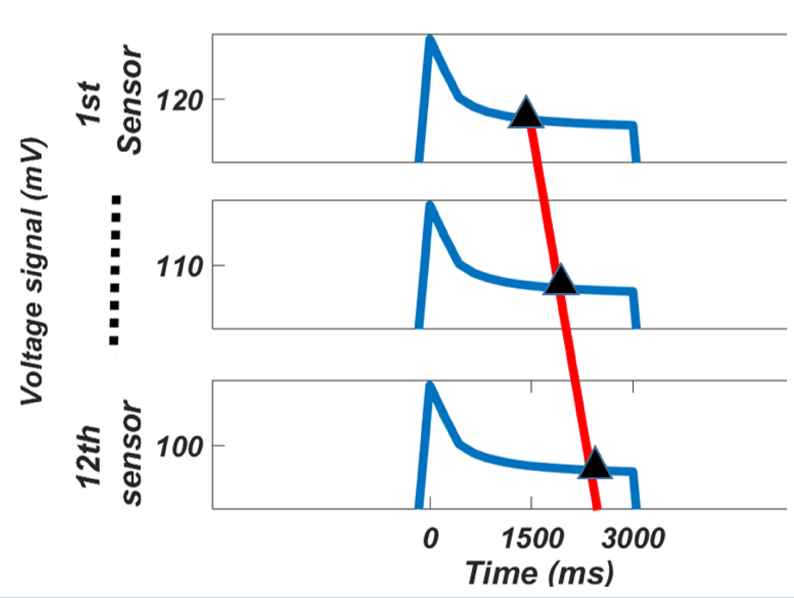


Idea behind layered design: the electrical signature of the conductive tracer invading the medium is separated in time in two parts: first, the ''advective'' signal, caused by rapid horizontal invasion along the high permeability channel ($\kappa_{HIGH} = 16\kappa_{LOW}$) and, second, after the injection has been stopped, the ''diffusive'' signal, caused by slow, transversal invasion through diffusion.

3. Technical challenges

Electrical monitoring

The sampled voltage signal vary over time, but due to the functioning of the Resistivity meter, the samples cannot be taken simultaneously but are taken with some delay between each other.

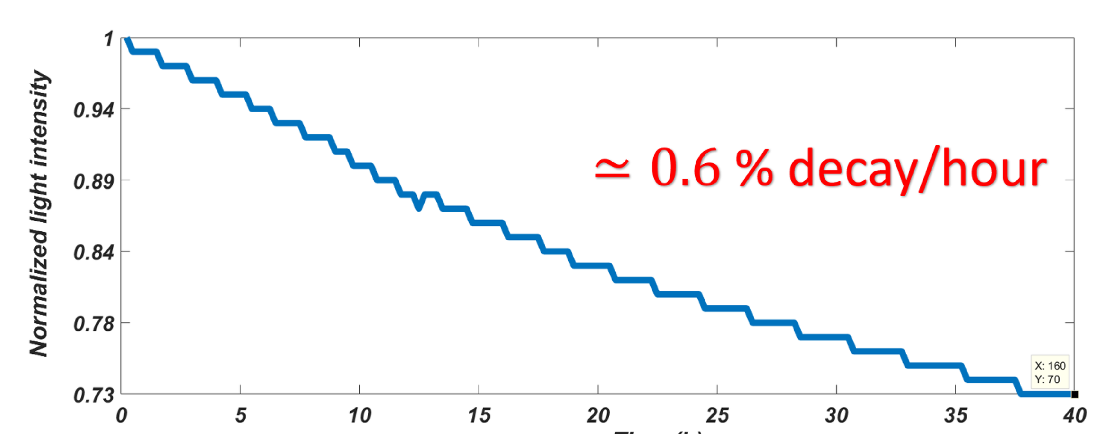


Minimum time shift between first and last measurements: ≃ 0.65 s

Expected error: ≃ 0.6 %

Fluorimetric illumination system

The intensity of the light emitted by the fluorescent tracer decays naturally over time as the electrons present in the substance relaxes to their energy ground state after the excitation. Exposing the tracer to an uninterrupted light source, the decay is consistently observed:



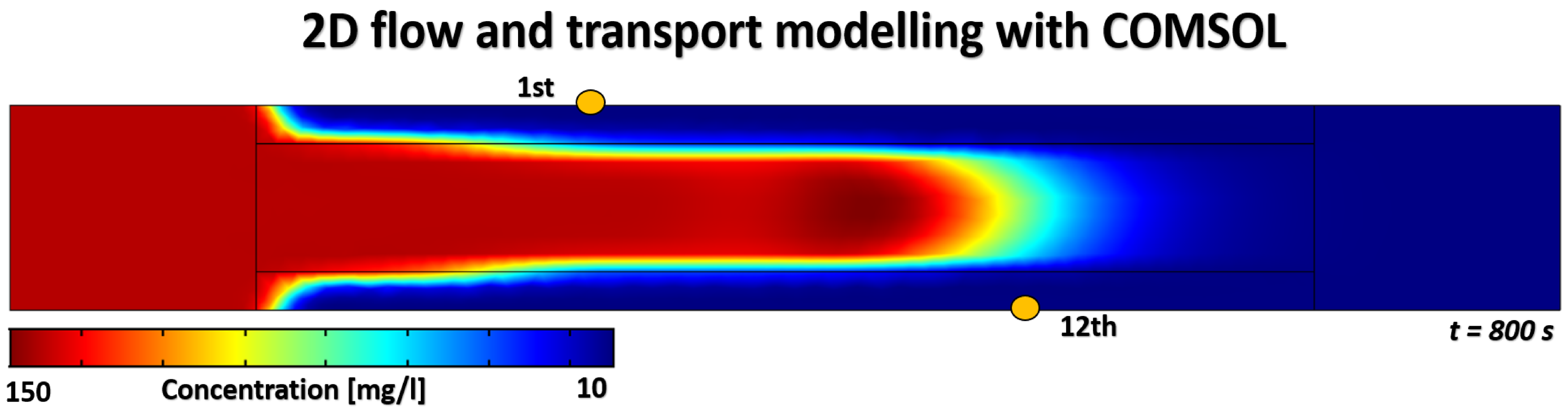
Solved using a light flash synchronized with the ***Camera***: the tracer is excited only at the time of the photography

Flow system

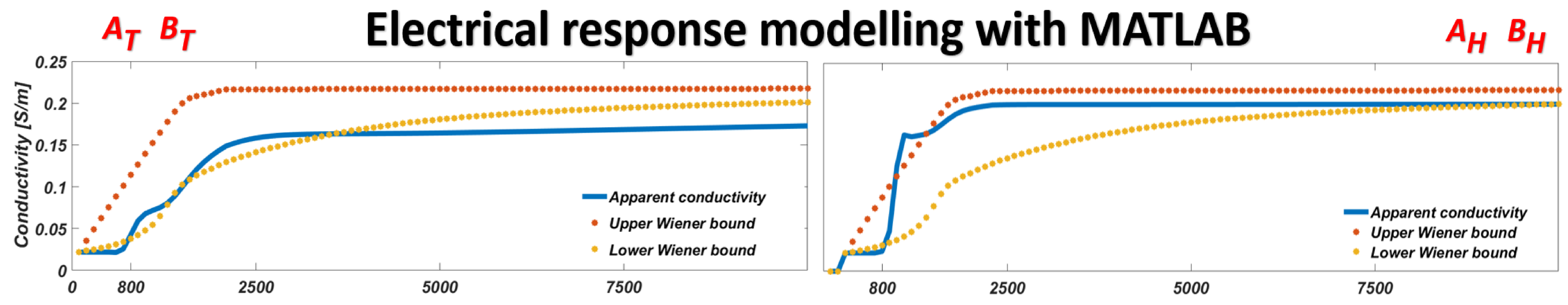
A current problem is that that the PDMS cylindrical pillars are not always well attached to the Hele-Shaw cell, causing undesired flow beneath them. This is currently being solved by adhering the PDMS medium to a thin PDMS film.

4. Numerical simulations

2D flow and transport modelling with COMSOL



Electrical response modelling with MATLAB



Used models

Flow: Stokes flow

Transport: Advection-dispersion equation

Electric potential: Poisson's equation

5. Perspectives

(i) Completion of the experiment series in the layered medium.
(ii) Experiment series in a Dual Domain medium (e.g . Swanson et al., 2012).
(iii) From (i) and (ii) test and develop upscaling approaches.

6. References

[1] Anna, P. de, et al. "Mixing and reaction kinetics in porous media: an experimental pore scale quantification." Environmental science & technology 48.1 (2013): 508-516.
[2] Jougnot, D., et al. "Impact of small-scale saline tracer heterogeneity on electrical resistivity monitoring in fully and partially saturated porous media: insights from geoelectrical milli-fluidic experiments." Advances in Water Resources (2018).
[3] Singha, K., and Steven M. Gorelick. "Saline tracer visualized with three-dimensional electrical resistivity tomography: Field-scale spatial moment analysis." Water Resources Research 41.5 (2005).
[4] Cushman, J. H., and D. M. Tartakovsky, eds. The Handbook of Groundwater Engineering. CRC Press, 2016.
[5] Swanson, R. D., et al. "Direct geoelectrical evidence of mass transfer at the laboratory scale." Water Resources Research 48.10 (2012).

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