University of Stuttgart
Institute for Modelling Hydraulic and Environmental Systems

# An adaptive multiphysics model coupling vertical equilibrium and full multidimensions for the simulation of underground gas storage

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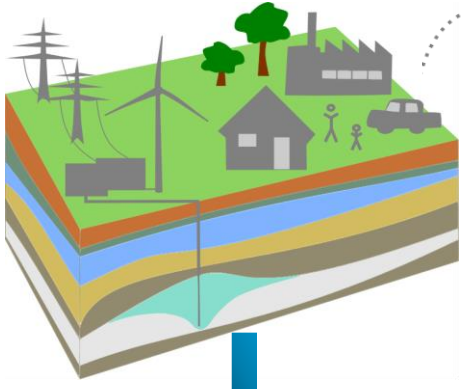
# Underground energy storage



Mobility

Industry

Turbines

Generator

Mechanical

Chemical

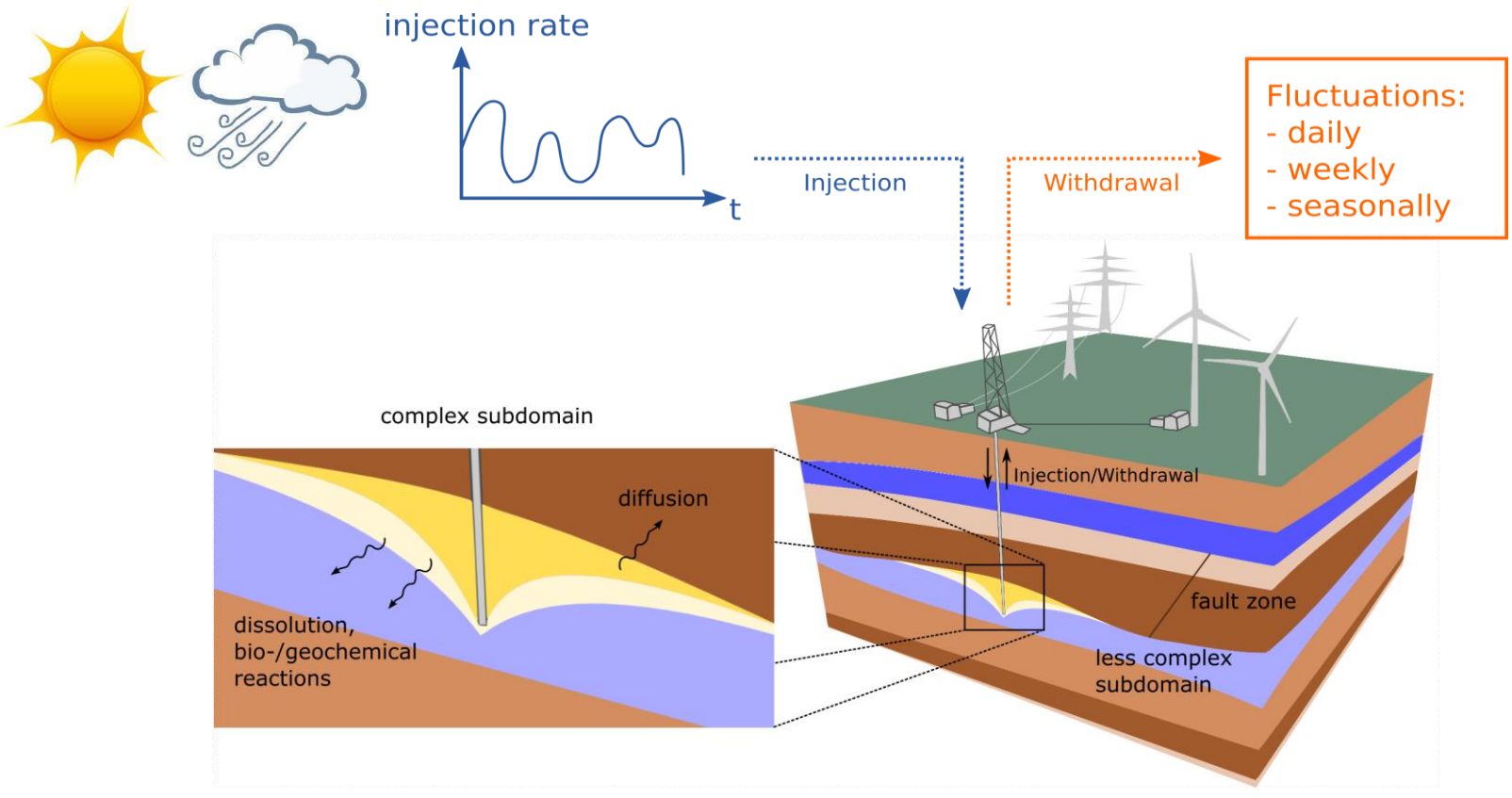
Thermal

Compressed air energy storage

Hydrogen/SNG storage

Hot/cold water storage

# Gas storage: Modeling challenges

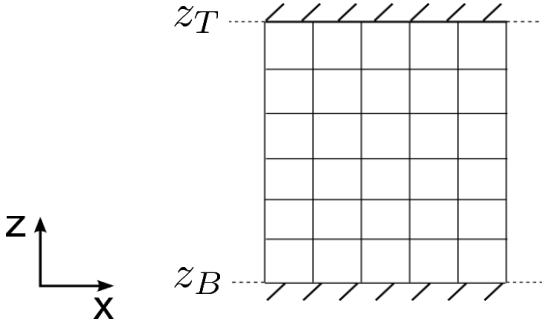



- Large domains and limited data

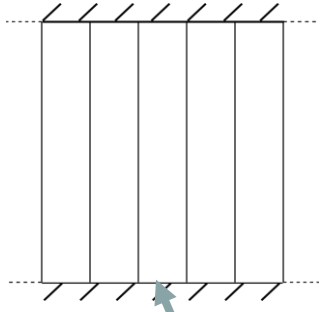
# Vertical equilibrium model

## Governing equations

2D




VE



$$\frac{\partial}{\partial t}(\varrho_\alpha \phi s_\alpha) + \nabla \cdot (\varrho_\alpha \mathbf{u}_\alpha) = \varrho_\alpha \mathbf{q}_\alpha$$

$$\mathbf{u}_\alpha = -\mathbf{k}\frac{\mathbf{k_{r,\alpha}}}{\mu_\alpha}(\nabla \mathbf{p}_\alpha - \varrho_\alpha \mathbf{g})$$

$$\int_{z_B}^{z_T} \dots \, \mathrm{dz}$$

$$\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla_{||} \cdot (\varrho_\alpha \mathbf{U}_\alpha) = \varrho_\alpha \mathbf{Q}_\alpha$$

$$\mathbf{U}_\alpha = -\mathbf{K}\frac{\mathbf{K_{r,\alpha}}}{\mu_\alpha}(\nabla_{||} \mathbf{P}_\alpha - \varrho_\alpha \mathbf{G})$$

$$P_c(S_\alpha)$$

$$\sum S_\alpha = 1$$

$$S_\alpha, \; P_\alpha$$



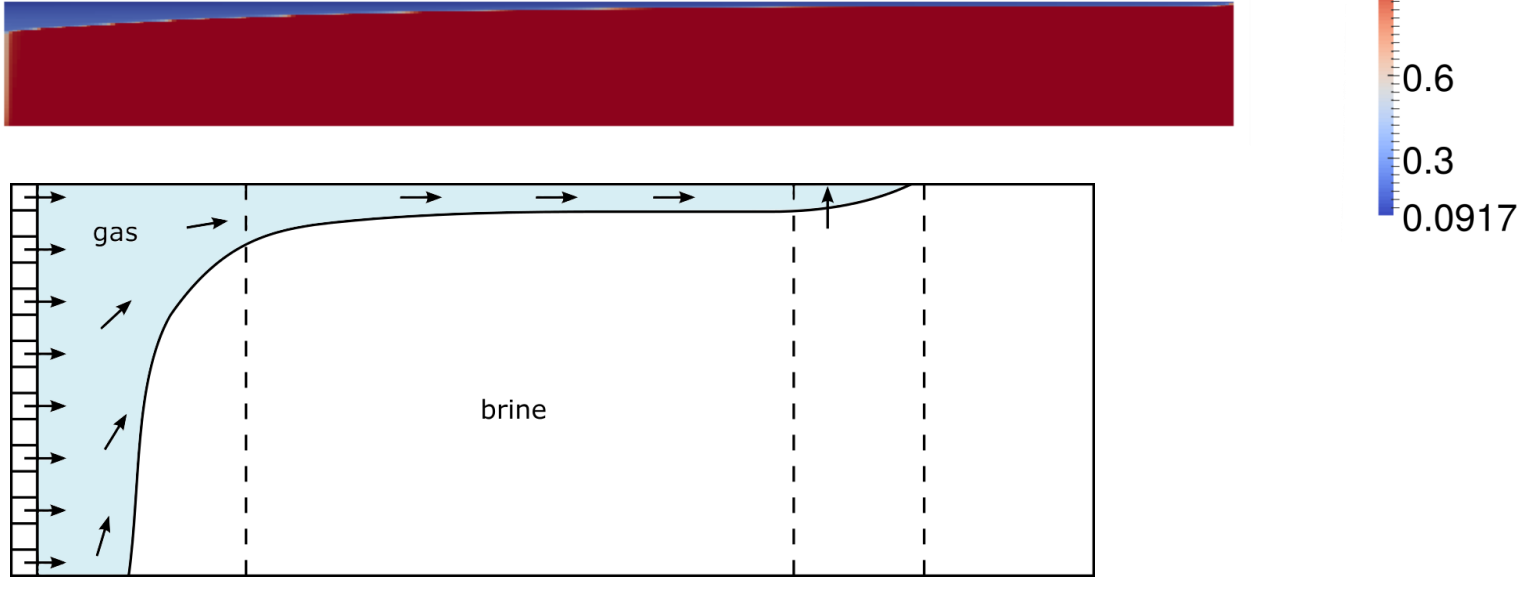
(Nordbotten & Celia, 2012)

# Vertical equilibrium model

## Vertical equilibrium assumption

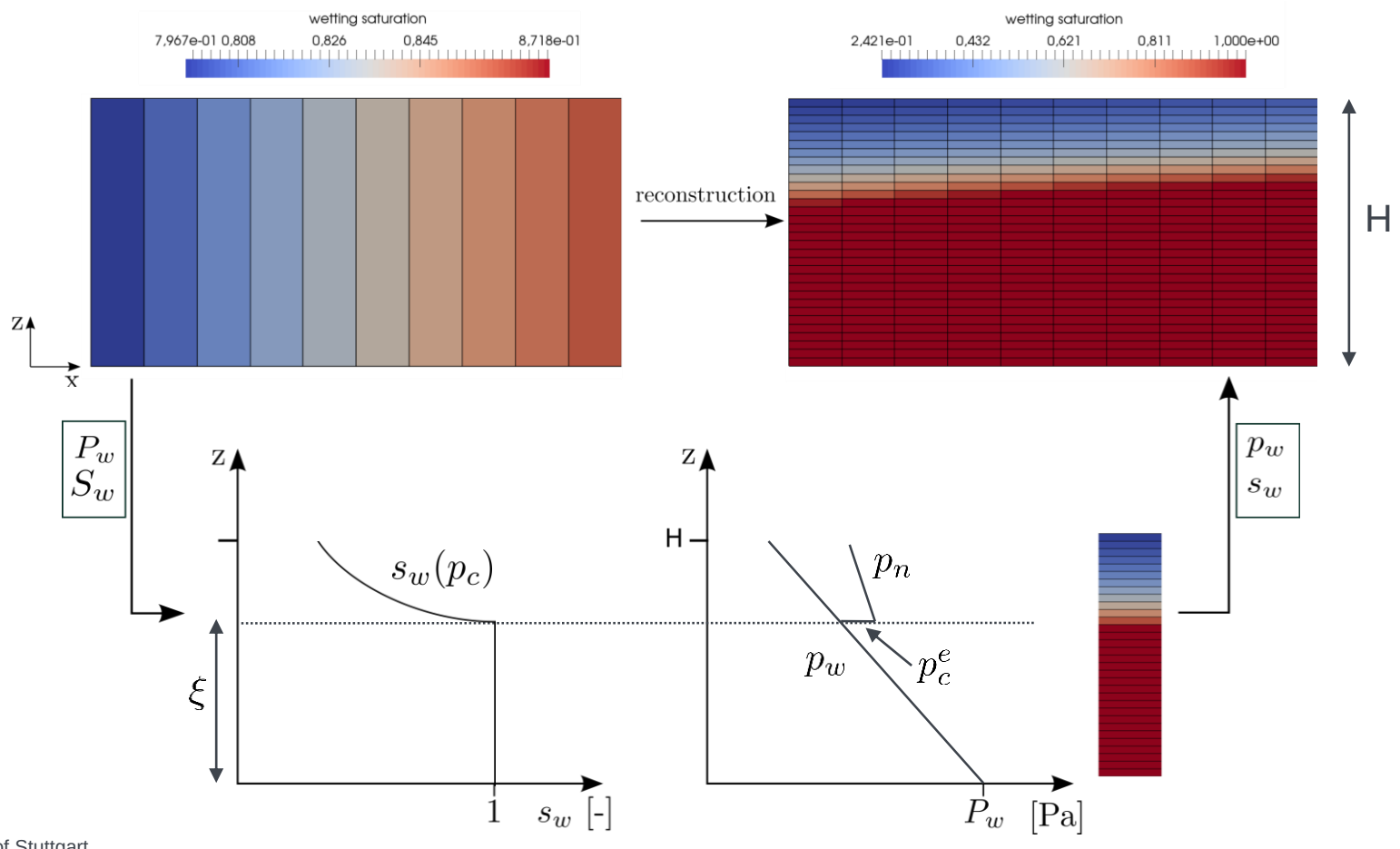
- Hydrostatic pressure profiles in the vertical direction

  ➡ Gas and brine phase are in vertical equilibrium

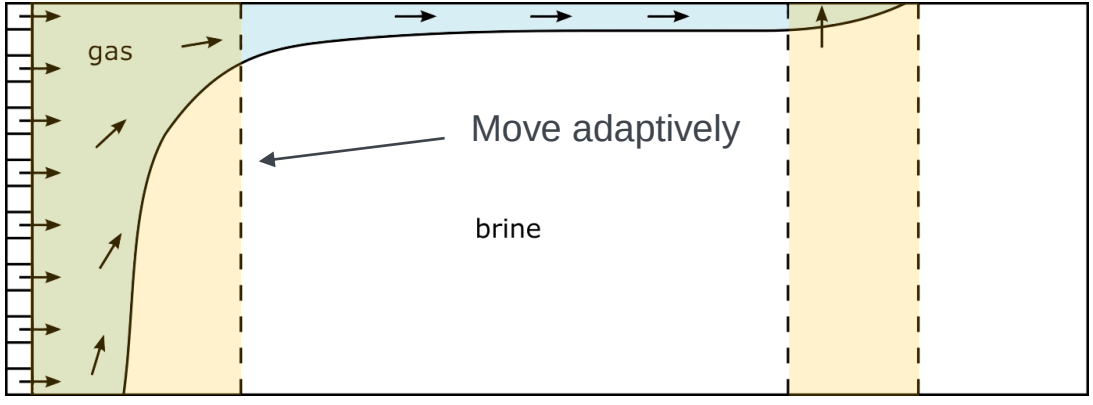


# Vertical equilibrium model

## Reconstruction of fine scale solution



# Multiphysics (hybrid) model




More complex area,
Horizontal and vertical flow

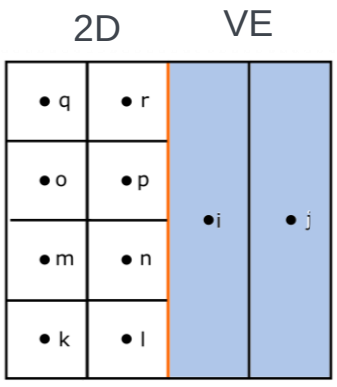
Full multidimensional model

Less complex area,
Horizontal flow,
Segregation of phases

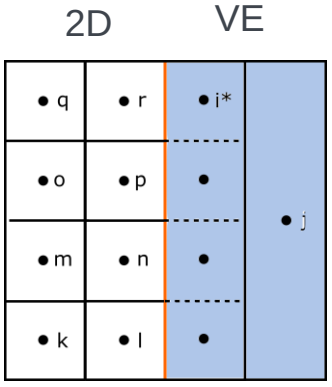
Vertical Equilibrium model

# 2D-VE coupling

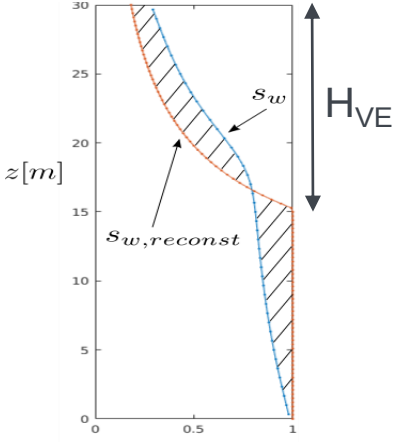
- Fluxes over boundary between subdomains




Introduce ghost cells




- Switch criterion based on column profiles




$$c_{sat} = \frac{\int_0^H |s_w - s_{w,reconst}| \mathrm{dz}}{H_{VE}}$$

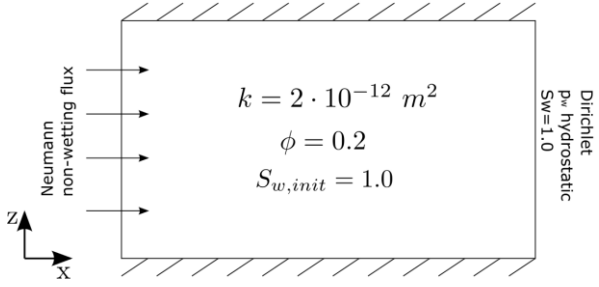
$$c_{relPerm} = \frac{\int_0^H |k_{rw} - k_{rw,reconst}| \mathrm{dz}}{H_{VE}}$$

$$c_{crit} < \epsilon_{crit}$$

Turn column into VE column

# Results 2D-VE coupling

## Adaptive coupling




Brooks-Corey cap. pressure:

$\lambda = 2.0$, $p_e = 1\ bar$

Phase properties ($CH_4$, water):

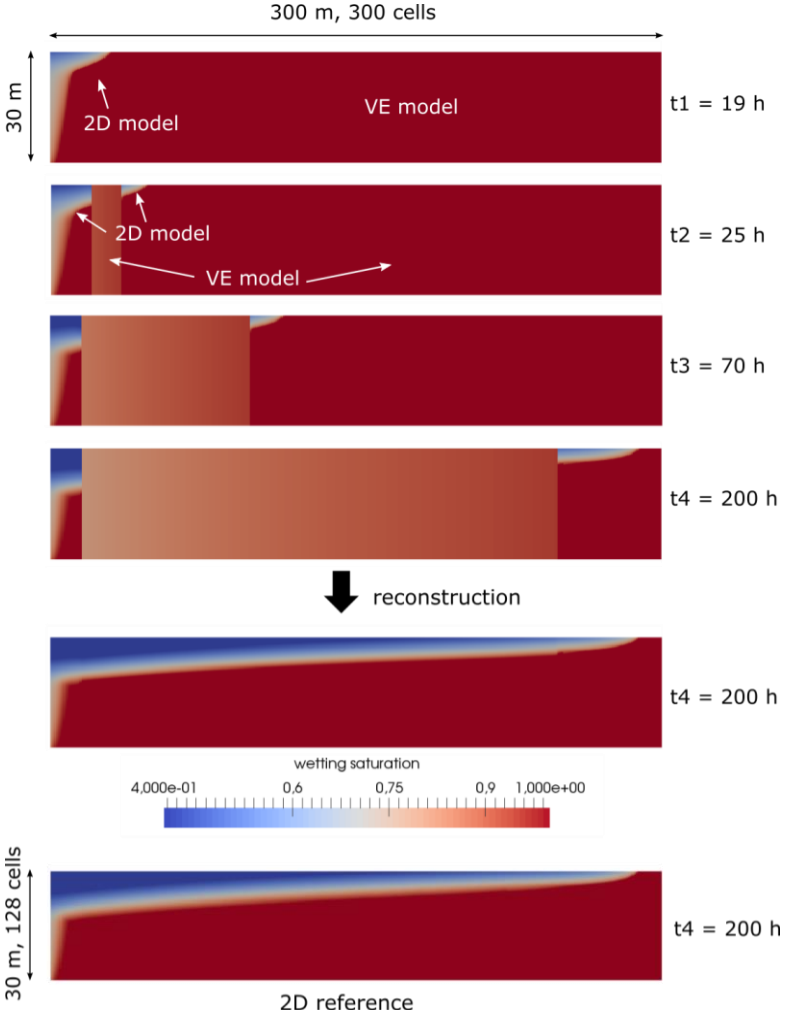
$\varrho_n = 59.2\ kg/m^3$

$\varrho_w = 991\ kg/m^3$

$\mu_n = 1.2 \cdot 10^{-5}\ Pa\,s$

$\mu_w = 5.2 \cdot 10^{-4}\ Pa\,s$

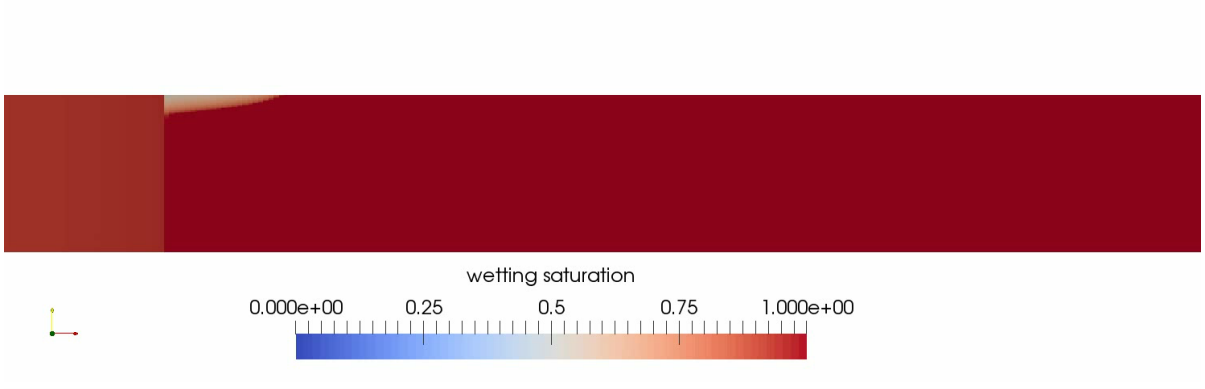
Injection rate: $Q_{nw} = 552\ t/m/a$



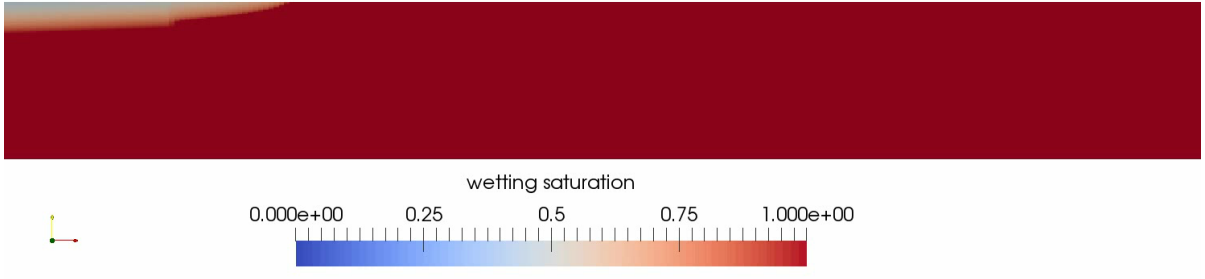
# Results 2D-VE coupling

## Adaptive coupling, example with low-permeability lens

Simulation result




Reconstruction



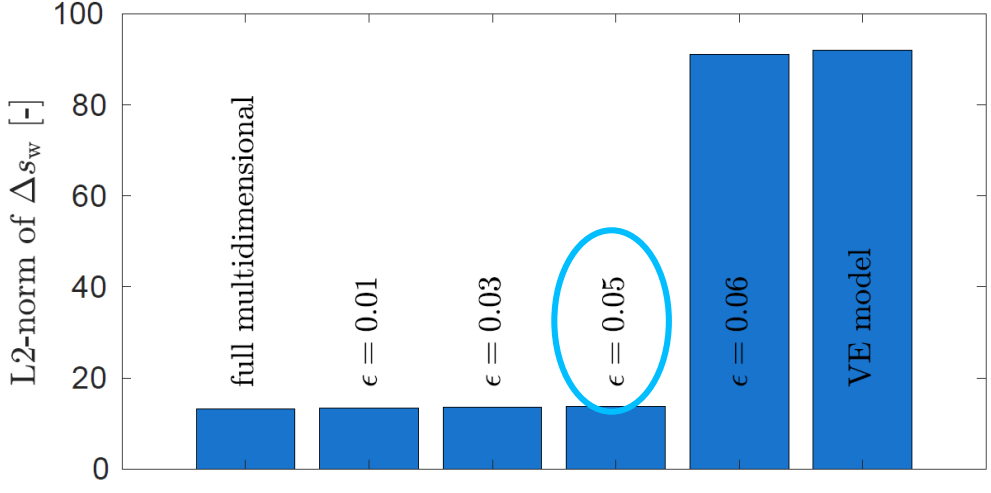



(Becker et al., 2018, submitted to WRR)

# Efficiency of the multiphysics model

Efficiency:
Speed ✖ Accuracy

| Model | relative average number of cells [-] | relative CPU time [-] |
|---|---|---|
| Full VE | 0.008 | 0.003 |
| Multiphysics $\epsilon_{\text{relPerm}} = 0.06$ | 0.04 | 0.03 |
| Multiphysics $\epsilon_{\text{relPerm}} = 0.05$ | 0.11 | 0.05 |
| Multiphysics $\epsilon_{\text{relPerm}} = 0.04$ | 0.12 | 0.06 |
| Multiphysics $\epsilon_{\text{relPerm}} = 0.03$ | 0.19 | 0.12 |
| Multiphysics $\epsilon_{\text{relPerm}} = 0.02$ | 0.3 | 0.18 |
| Multiphysics $\epsilon_{\text{relPerm}} = 0.01$ | 0.41 | 0.22 |
| Full multidimensional | 1 | 1 |




(Becker et al., 2018, submitted to WRR)

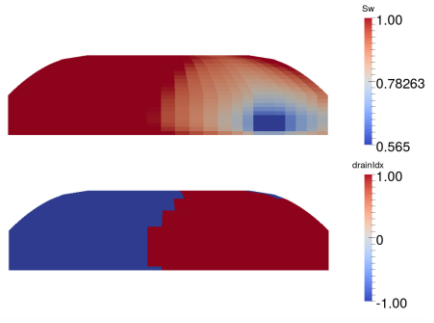
# Outlook

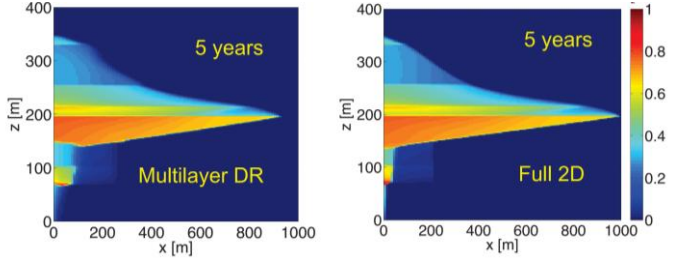
- Adaptive coupling I
  - Further tests, application of energy storage

- Adaptive coupling II
  - Combine with multi-layer coupling
  - VE model with non-isothermal effects
  - VE model with compositional effects

  ➡ include in adaptive coupled model

DuMu$^x$




(Guo, 2016)

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# Thank you!

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# Thank you!

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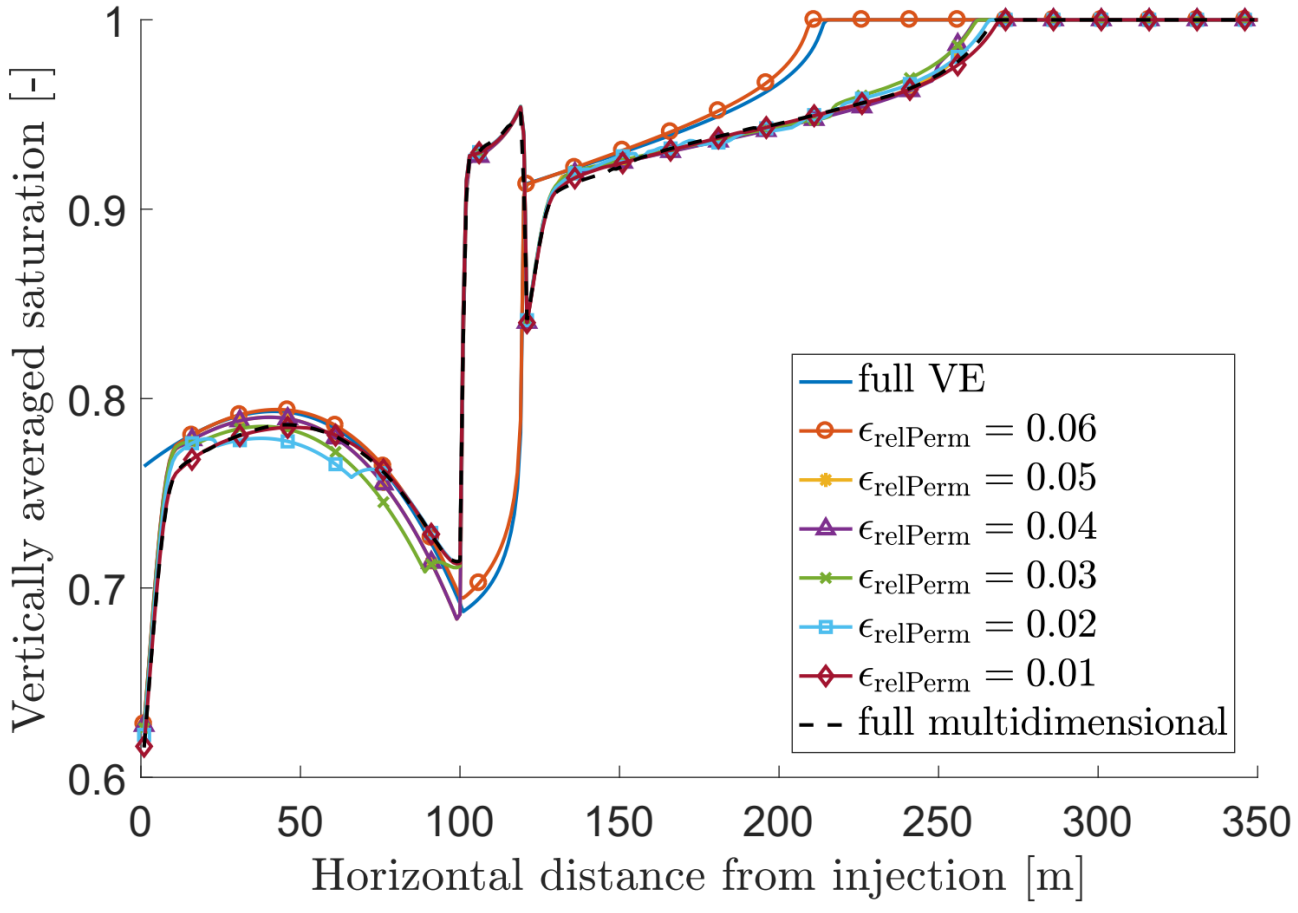
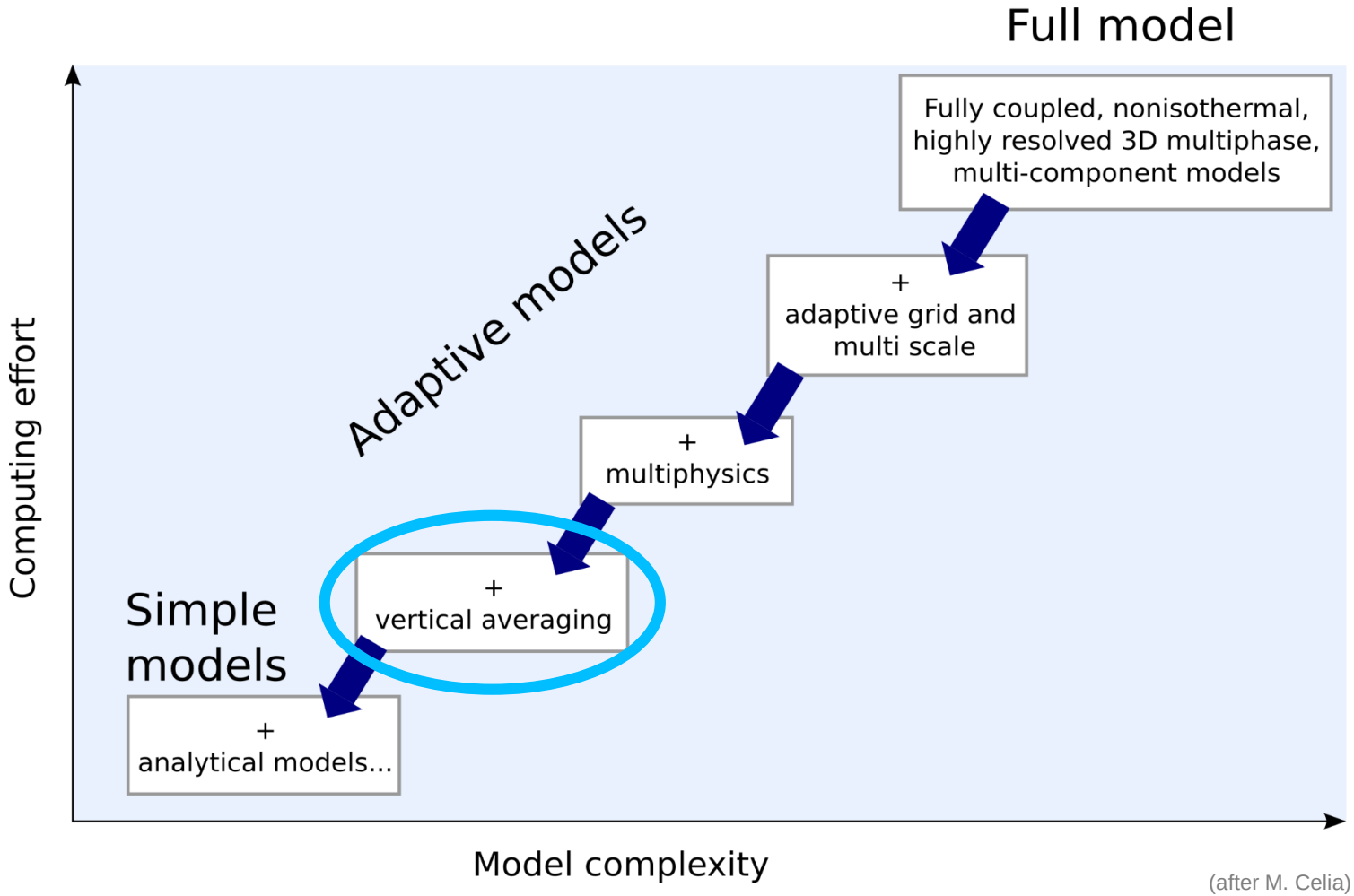
# Choice of threshold value for VE-criterion






(Becker et al., 2018, submitted to WRR)

# Model complexity




(after M. Celia)