University of Stuttgart
Institute for Modelling Hydraulic and Environmental Systems
Department of Hydromechanics and Modelling of Hydrosystems
Collaboration with
Princeton University
Subsurface Hydrology Research Group
Department of Civil and Environmental Engineering

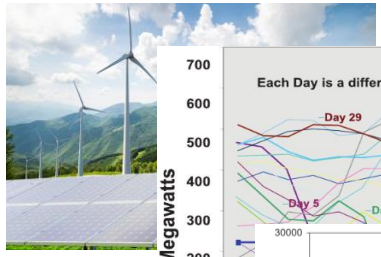
Development of multi-physics models accounting for hysteresis and reversible flow at various subsurface energy storage sites

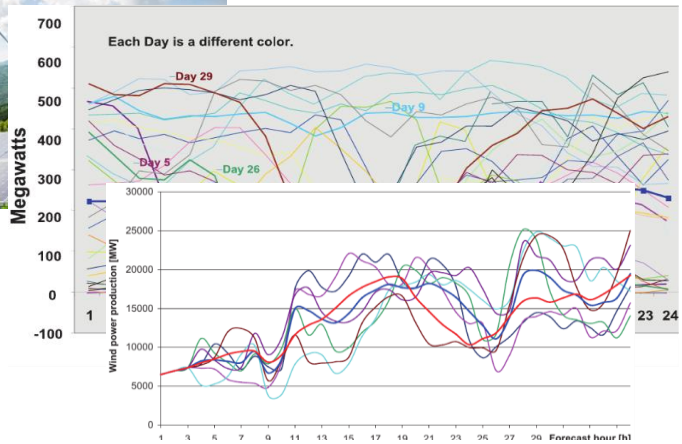
Milestone Presentation by Beatrix Becker, M.Sc.

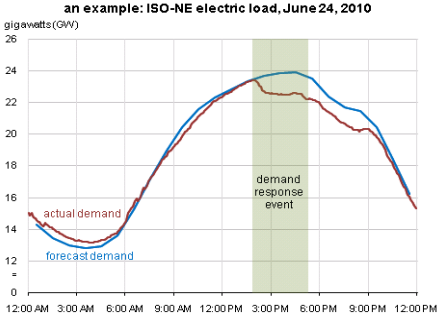
Examiner: Prof. Dr. Michael Celia, Prof. Dr. Christian Rohde
Supervisor: Prof. Dr. Rainer Helmig

LH²
Subsurface Hydrology RESEARCH GROUP

Why store energy?

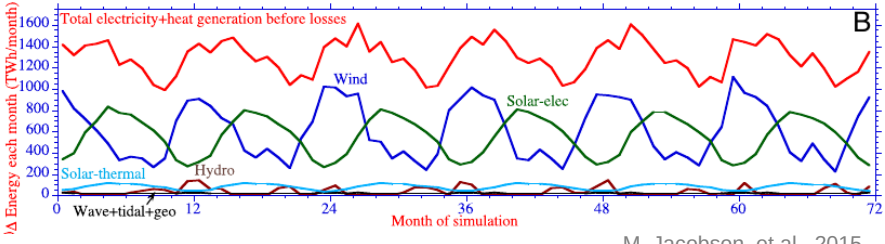






?

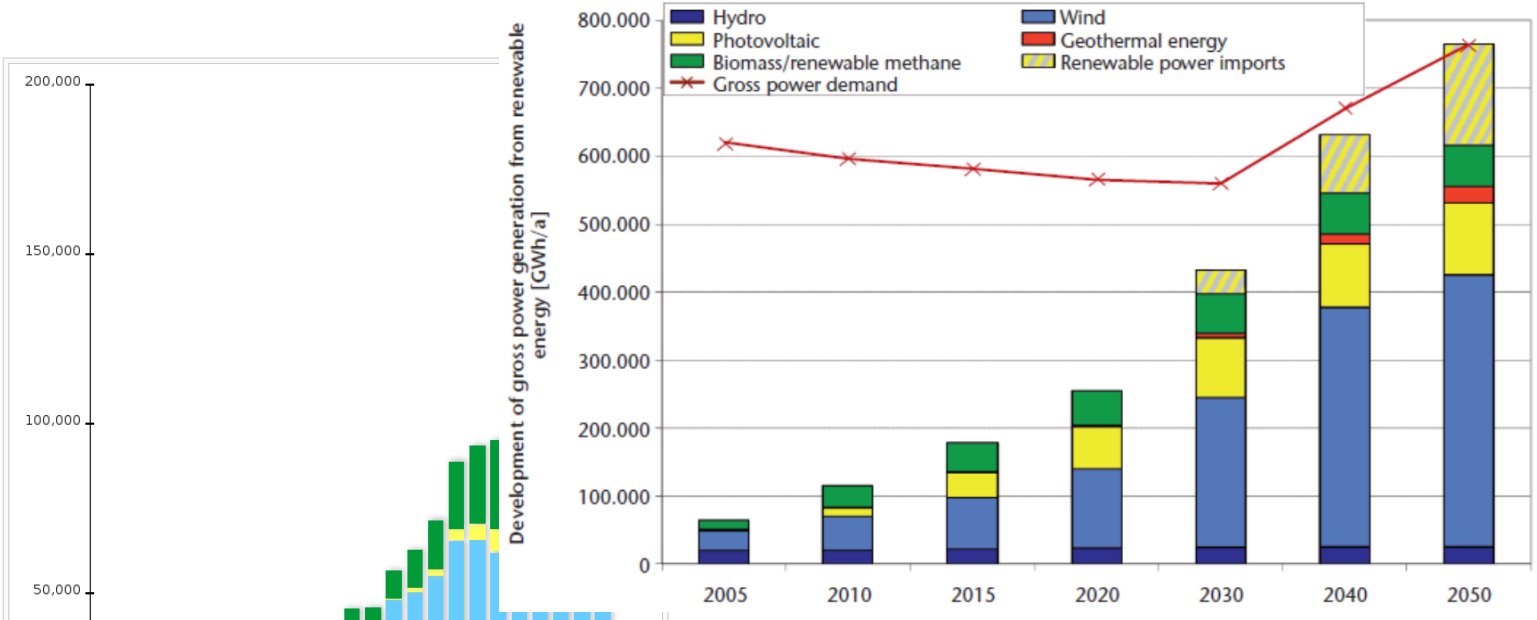
http://www.eia.gov/todayinenergy/images/ele_load_curve.PNG



M. Jacobson, et al., 2015

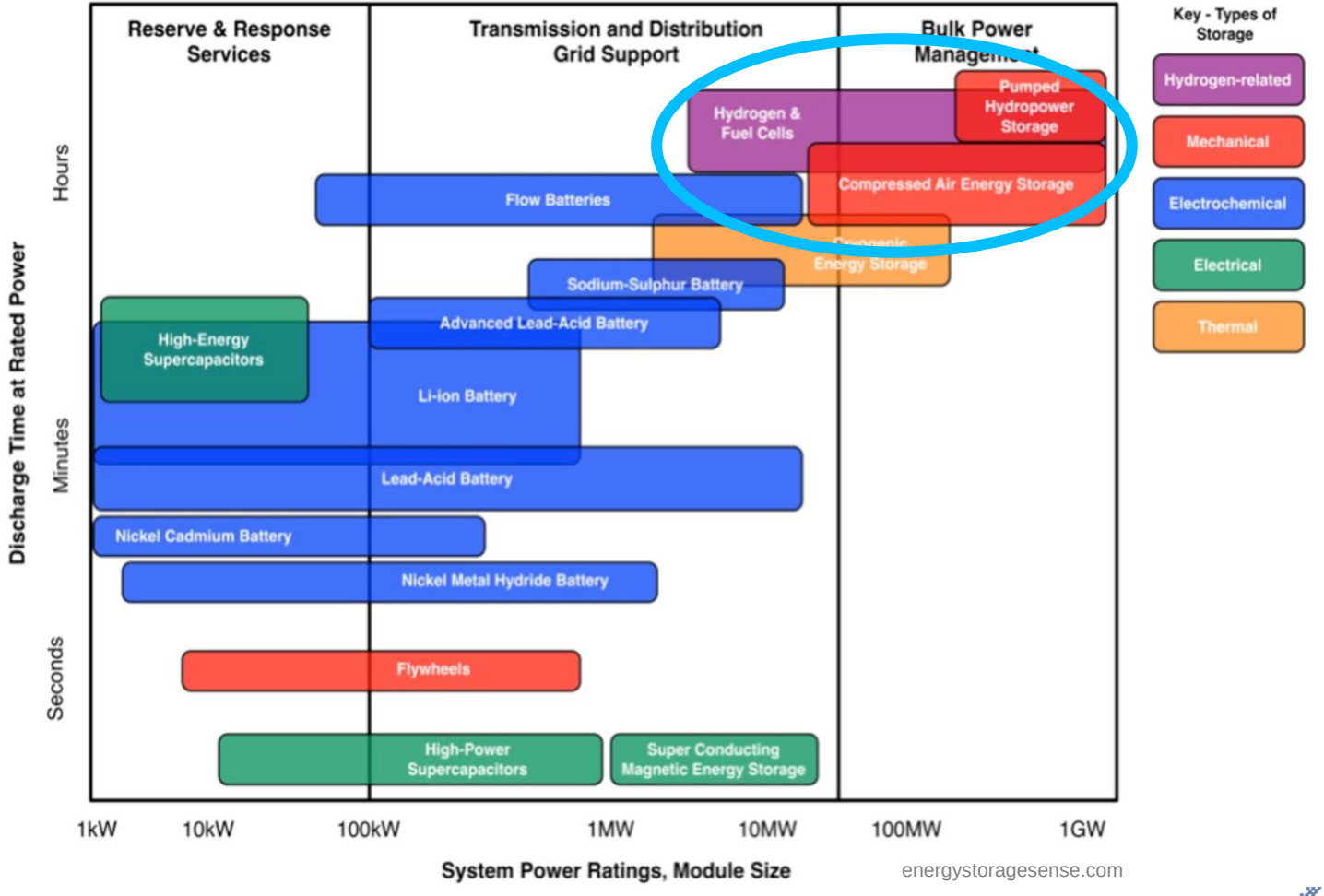
Energy storage

Why store energy in Germany?

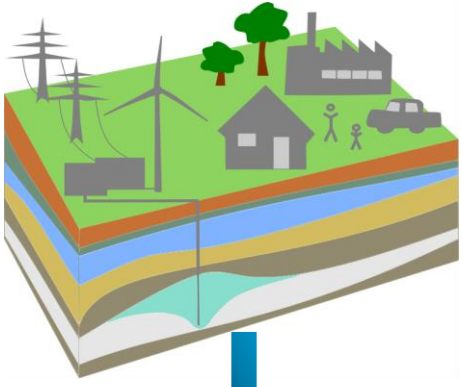


(BMWi, 2014)

Energy storage



Underground energy storage



Mechanical

Chemical

Thermal

Compressed air energy storage

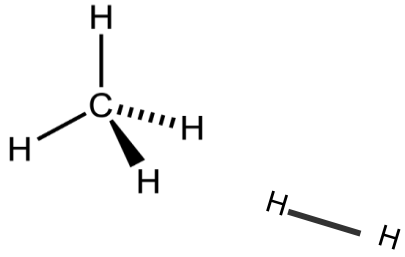
Hydrogen/SNG storage

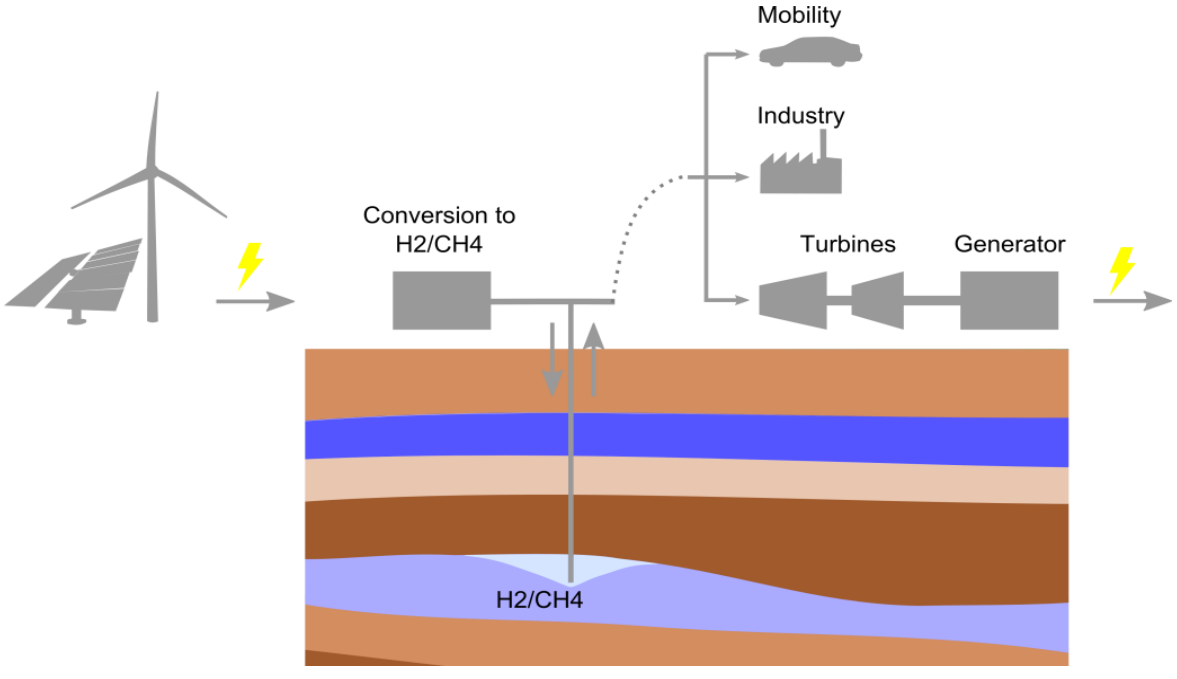
Hot/cold water storage

Hydrogen storage

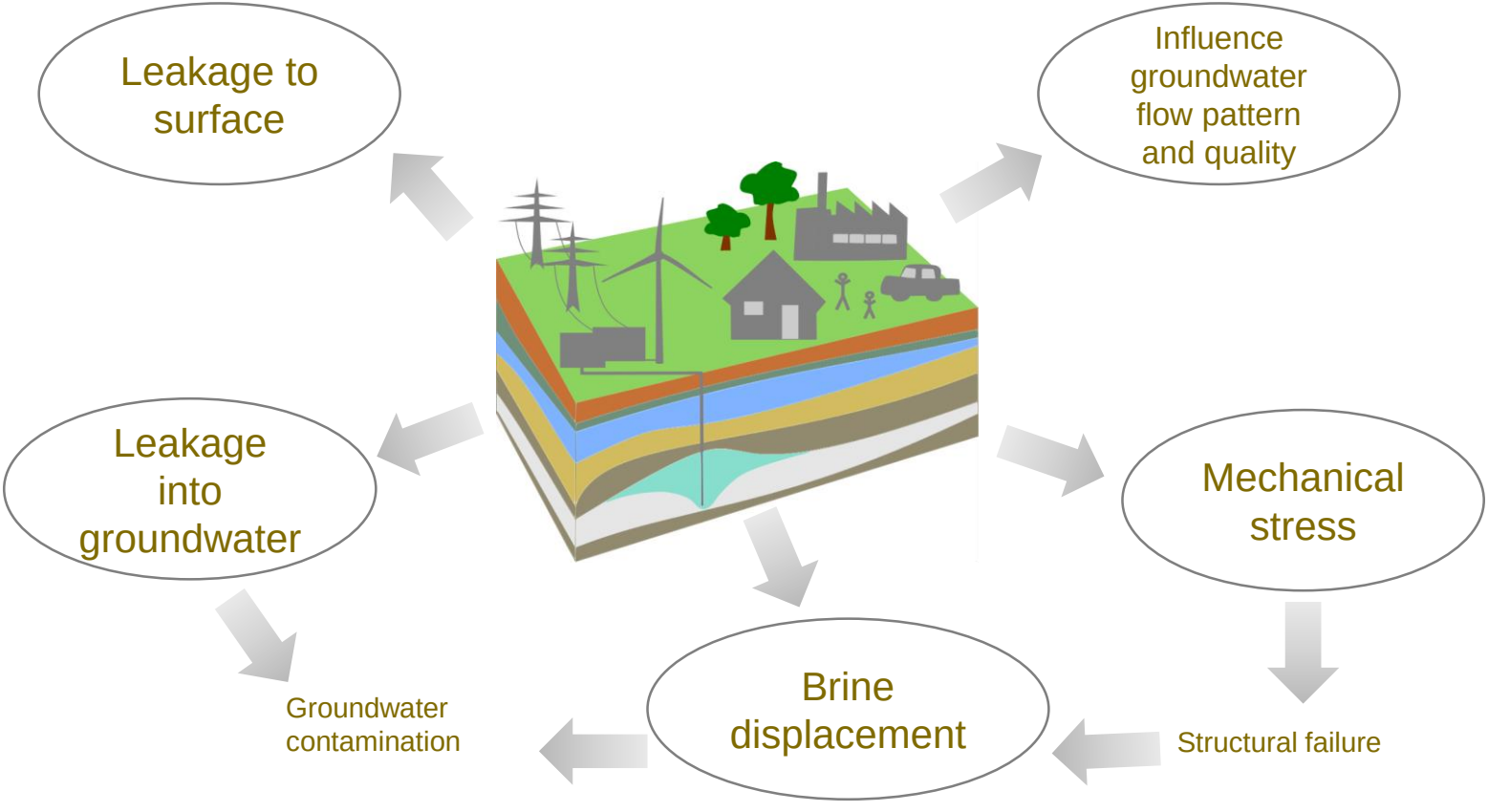
Chemical

- Highly mobile gas (H_2/SNG)
- Chemical/Biochemical processes

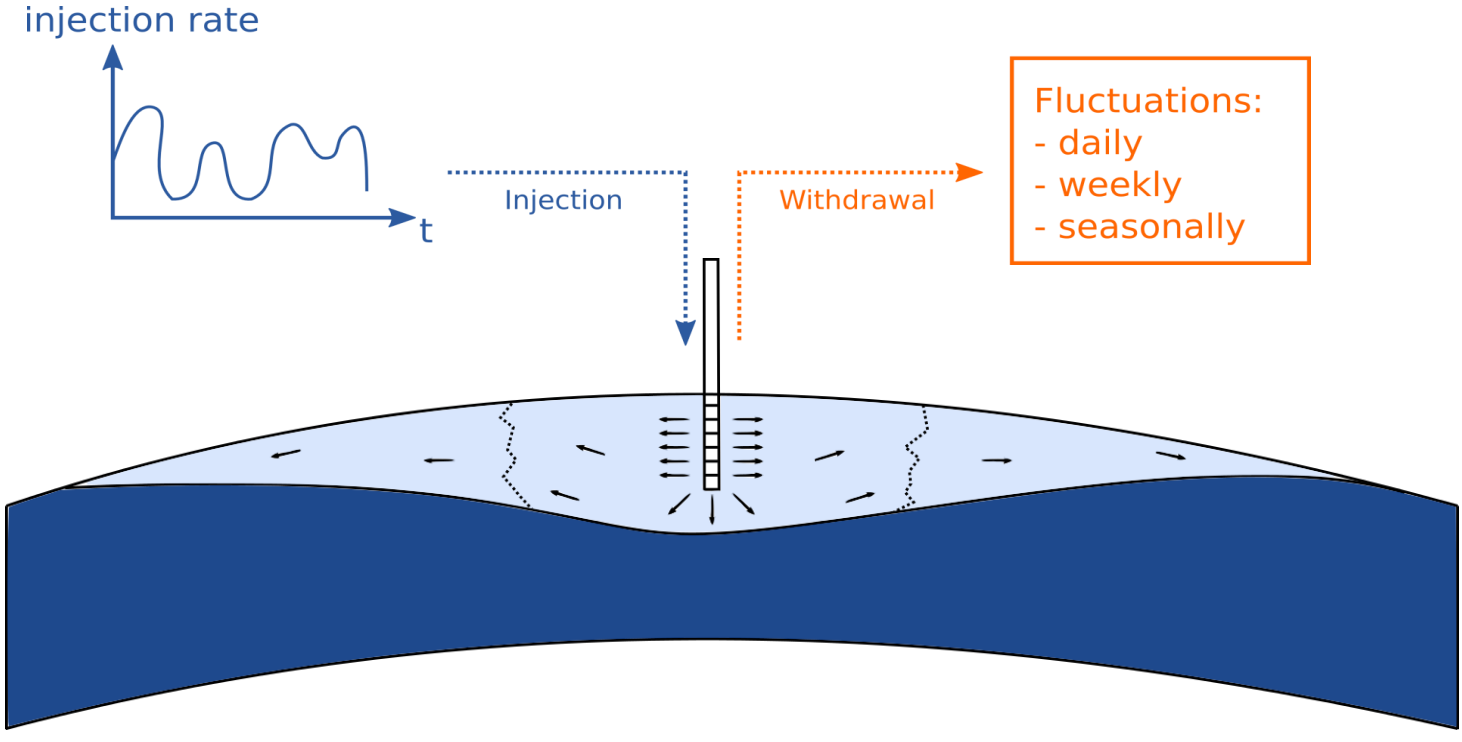




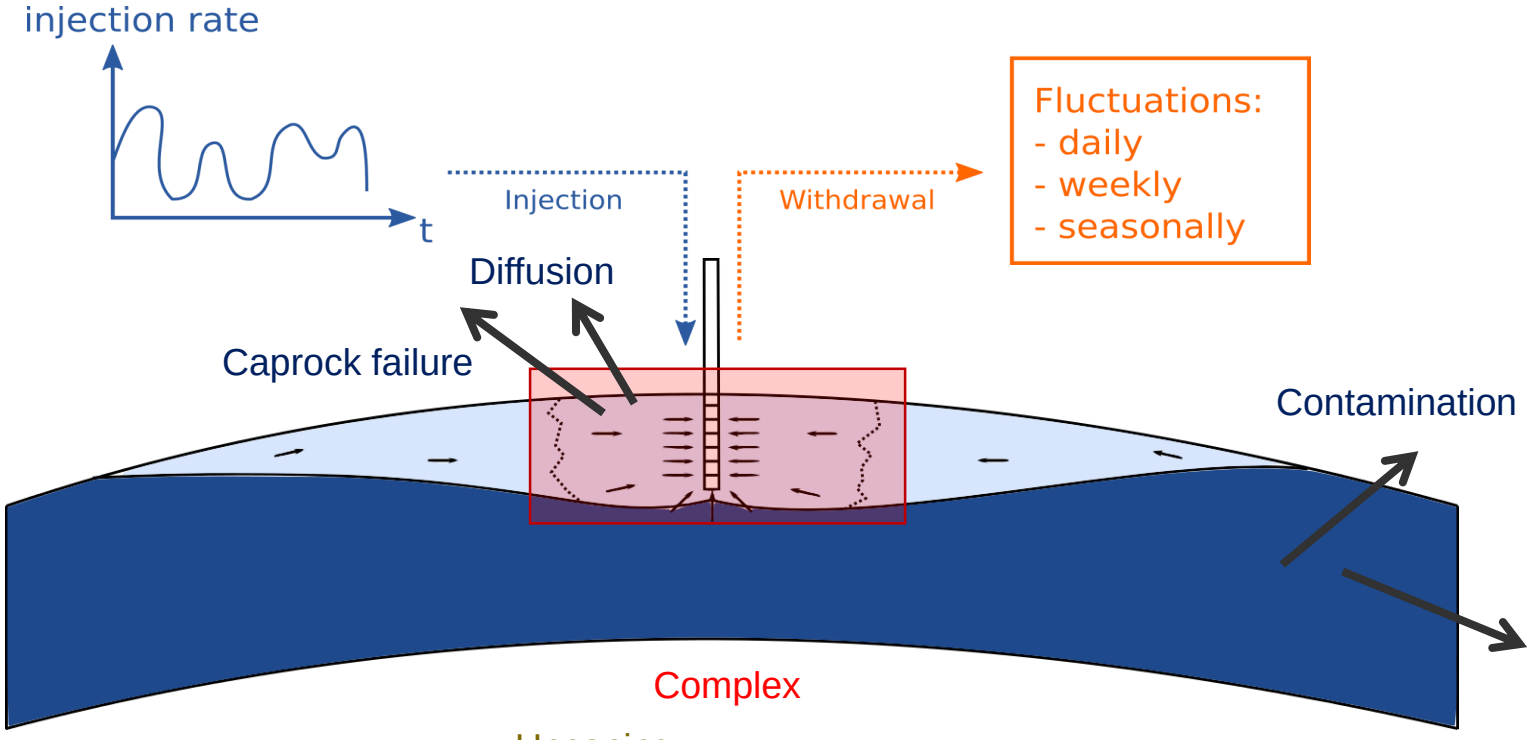
Why simulate underground energy storage?



Challenges in modeling underground energy storage



Challenges in modeling underground energy storage



The multi-x adaptive model: a vision

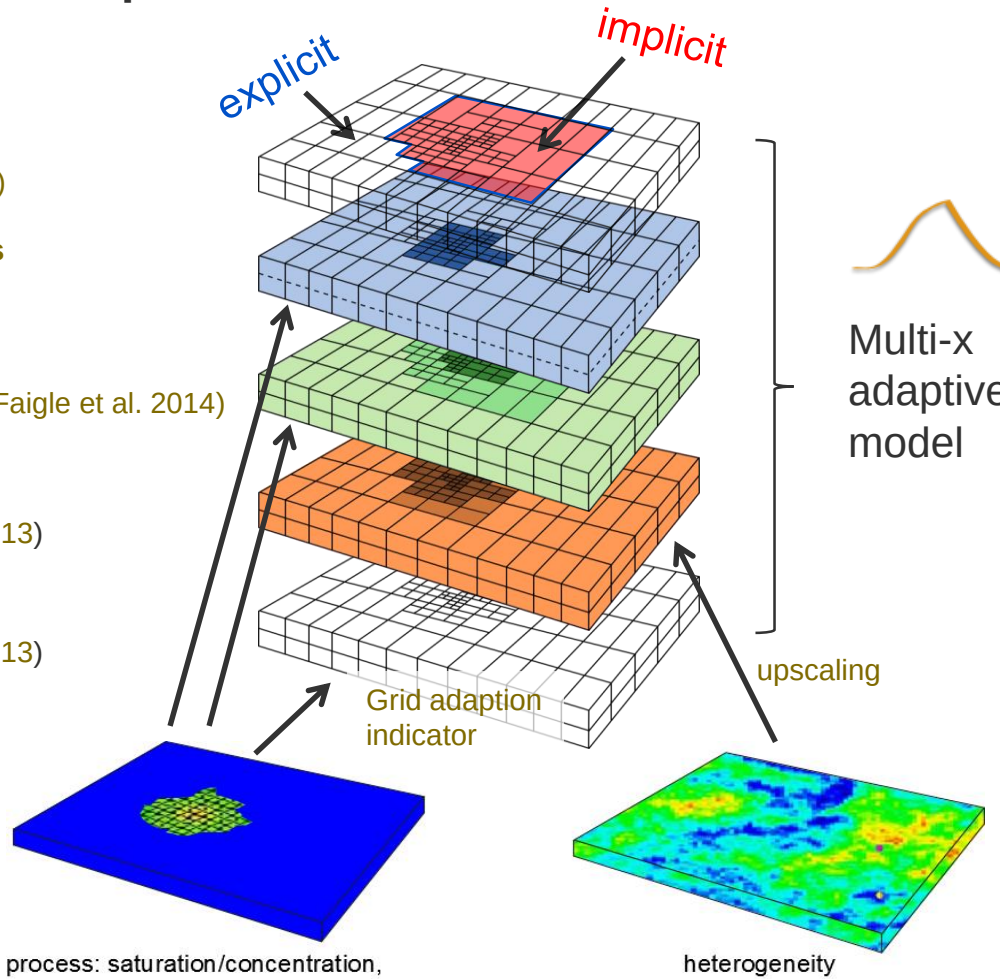
Multi time discr.
(Martin Schneider)

Multi dimensions

Multi physics
(Fritz et al. 2011, Faigle et al. 2014)

Multi scale
(M. Wolff, et al. 2013)

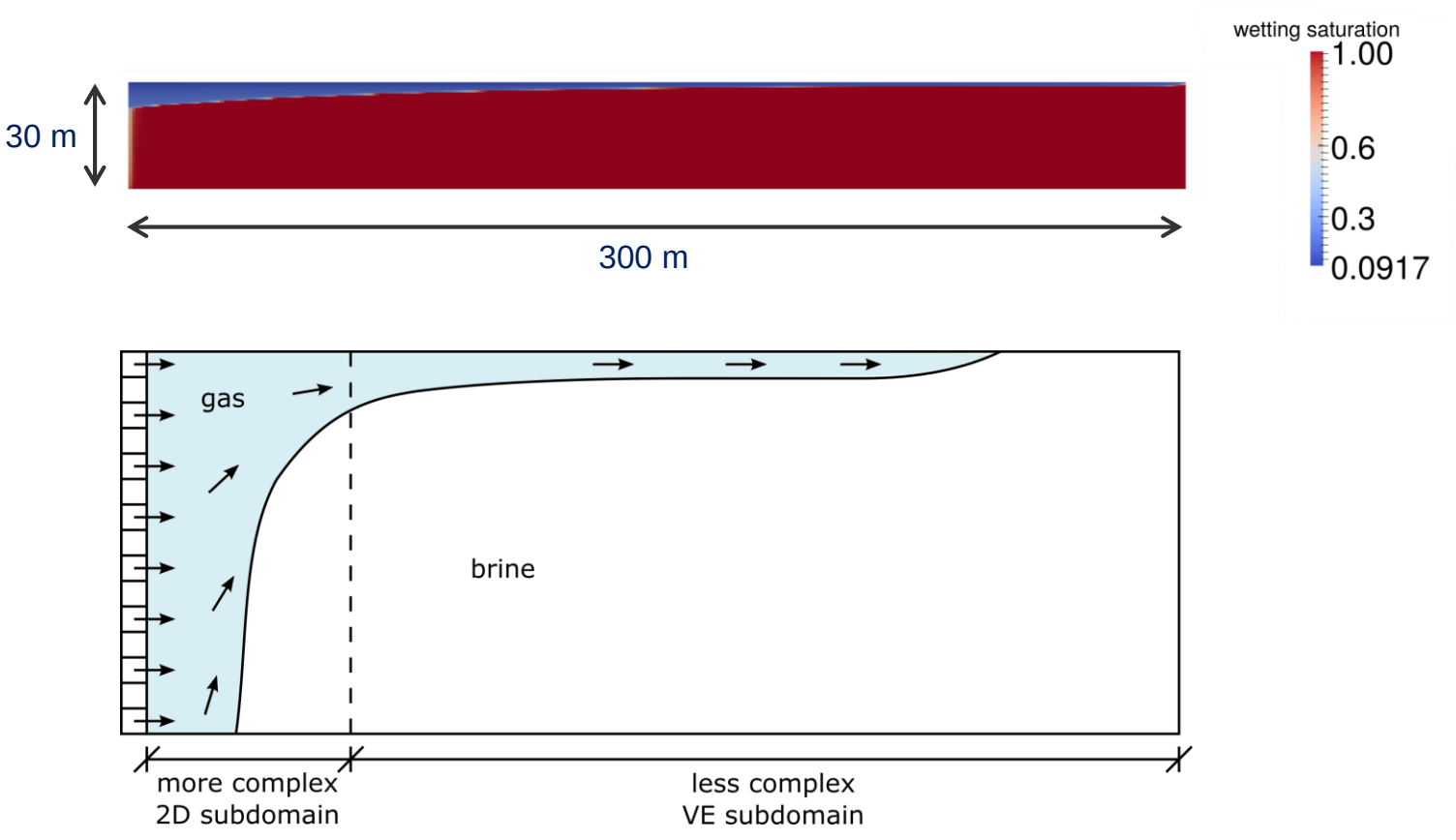
Adaptive grid
(M. Wolff, et al. 2013)



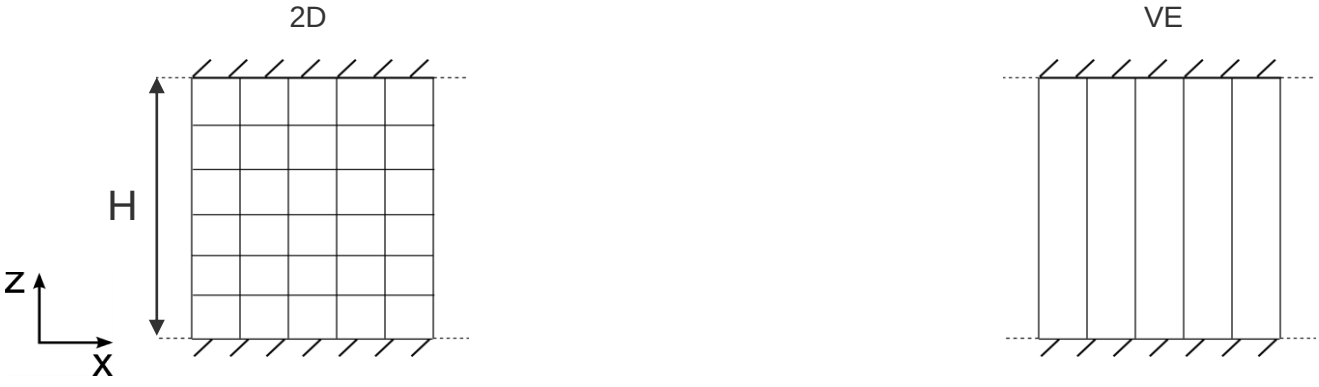
DuMu^x

Multi-x adaptive model

Multi-dimensions in gas storage



Vertical equilibrium model – governing equations



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

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

$$\frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla \cdot (\varrho_\alpha \mathbf{U}_\alpha) = \varrho_\alpha \mathbf{\Psi}_\alpha$$

$$\mathbf{U}_\alpha = -\mathbf{K}\frac{\mathbf{K_r}_{,\alpha}}{\mu_\alpha}(\nabla \mathbf{P}_\alpha - \varrho_\alpha \mathbf{G})$$

$$\frac{1}{H}\int_{z_B}^{z_T} \ldots \, \mathrm{dz}$$

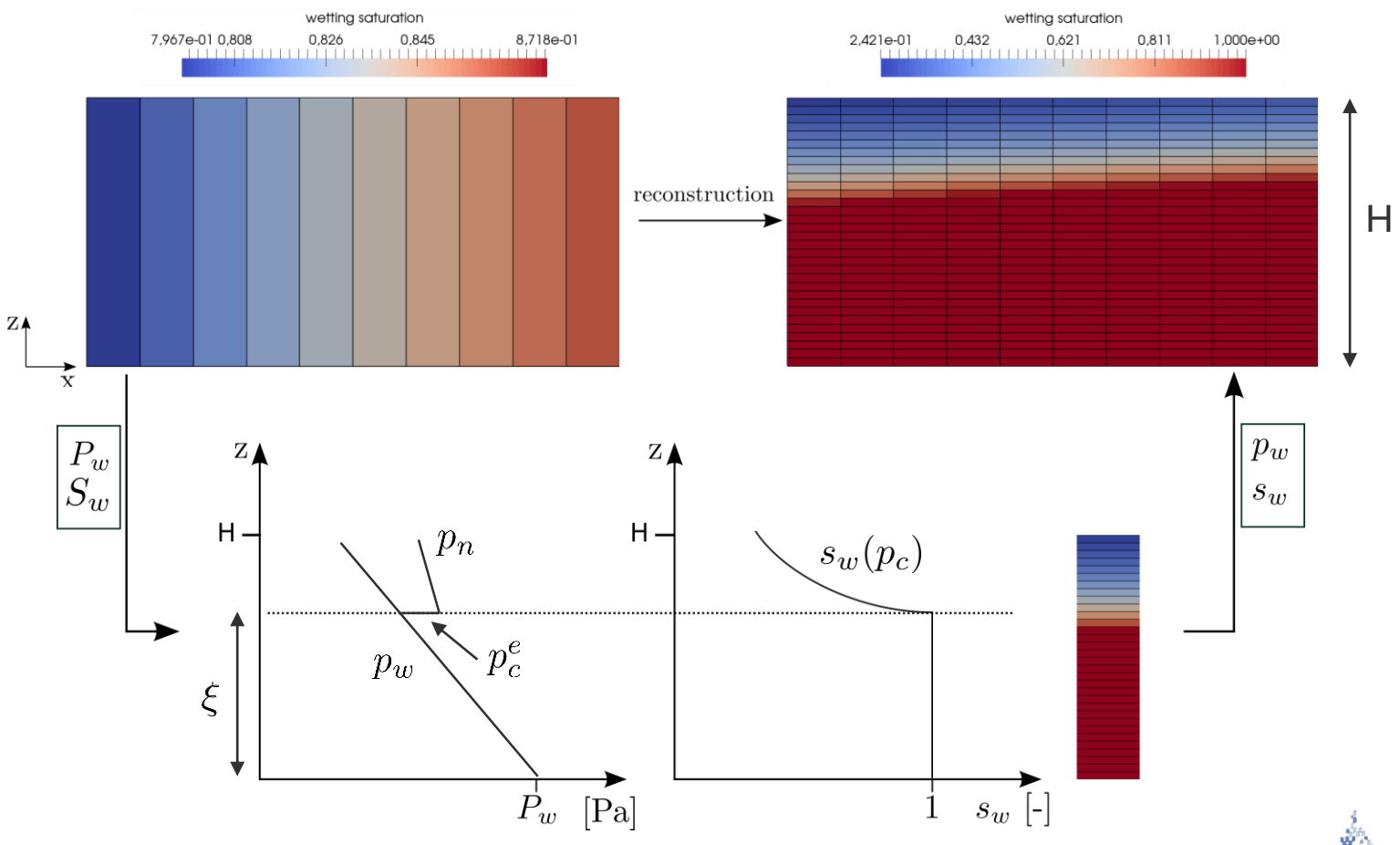
$$P_c(S_\alpha)$$

$$\sum S_\alpha = 1$$

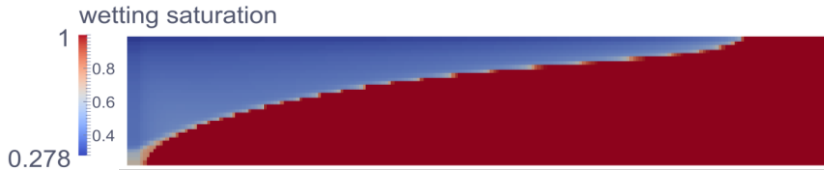
$$S_\alpha, \; P_\alpha$$

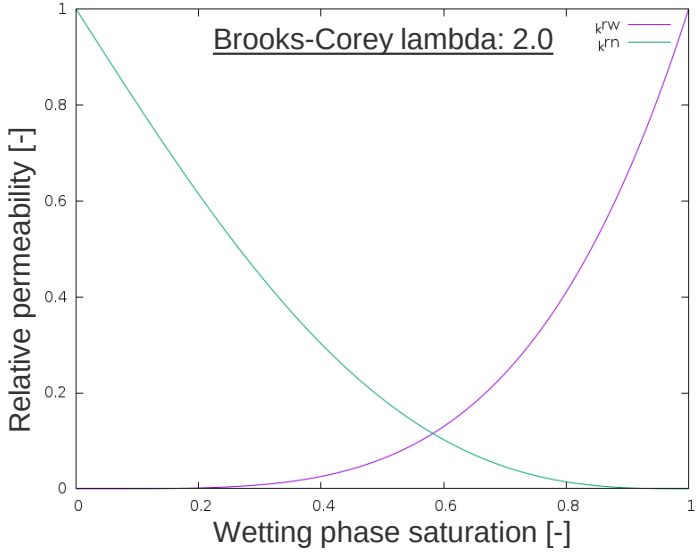
(Nordbotten & Celia, 2012)

Vertical equilibrium model – reconstruction of fine scale solution



Segregation time





- Segregation time:

$$t_{seg} = \frac{H\phi\mu_w}{k^{\dagger}_{r,w} K(g(\varrho_w - \varrho_n))}$$

$$k_r(s_w) = \left(\frac{s_w - s_{w,r}}{1 - s_{w,r} - s_{n,r}}\right)^{\left(\frac{2}{\lambda}+3\right)}$$

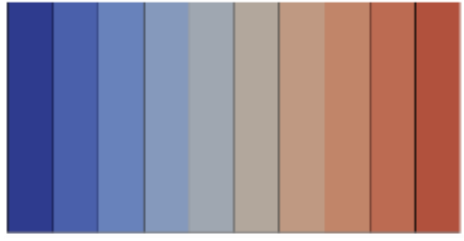
- Inverse of segregation time (Brooks-Corey relationship inserted):

$$s_w = s^*_{wr} = \left(\frac{H\phi\mu_w}{tK(\rho_w - \rho_n)g}\right)^{\frac{1}{\left(\frac{2}{\lambda}+3\right)}} (1 - s_{wr} - s_{nr}) + s_{wr}$$

Use as pseudo-residual saturation
in reconstruction step for modified VE-model

Modified VE model

Calculation results
(coarse scale)



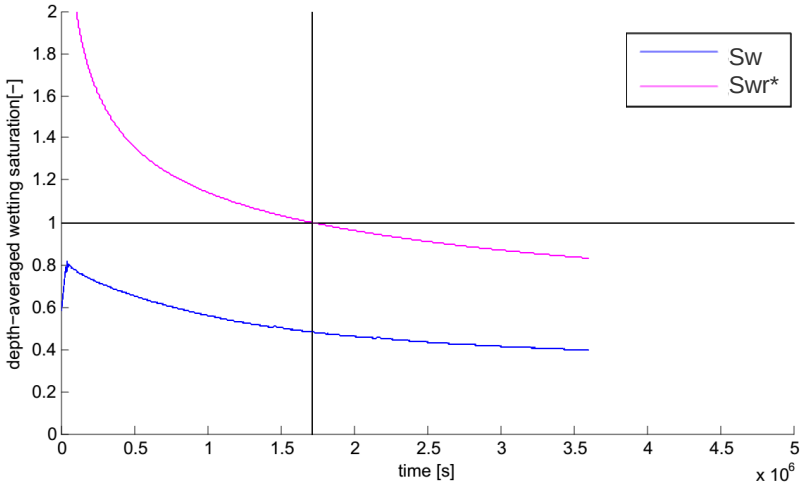
Reconstruction
VE

Reconstruction
Modified VE

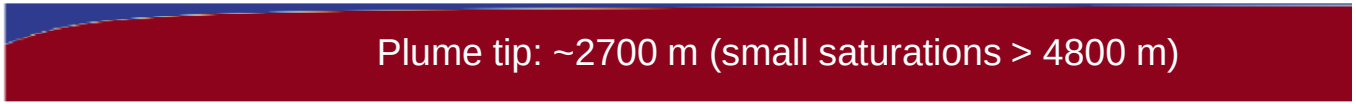
$s_w = s_{wr}$ (e.g. $s_w = s_{wr} = 0.0$)

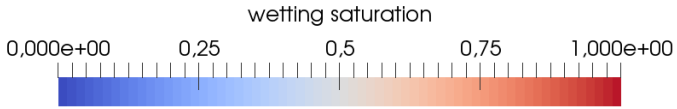
$s_w = s^*_{wr}(t)$

Modified VE model – preliminary results

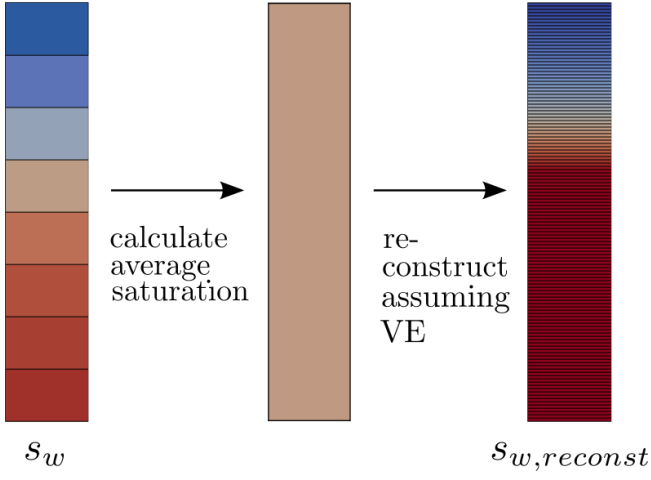


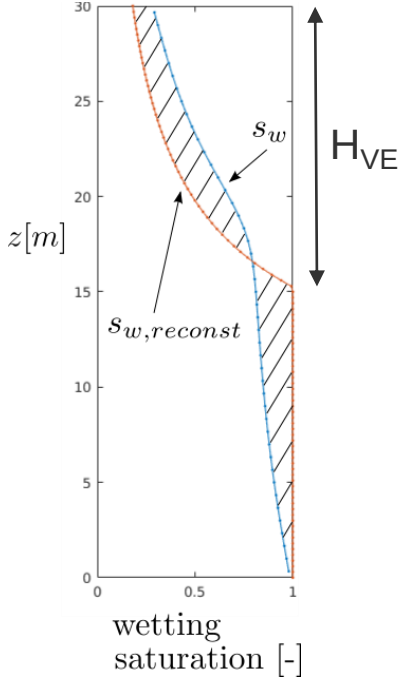
Simulation parameters:
- Gas injection: 552 t/(m a)
- Porosity: 0.2
- Brooks-Corey lambda: 2.0
- No capillary pressure
- Permeability: 2e-13 m²
- Simulation time: 3.5e6 s (twice t_{seg})





Applicability of VE models – criterion based on column profiles

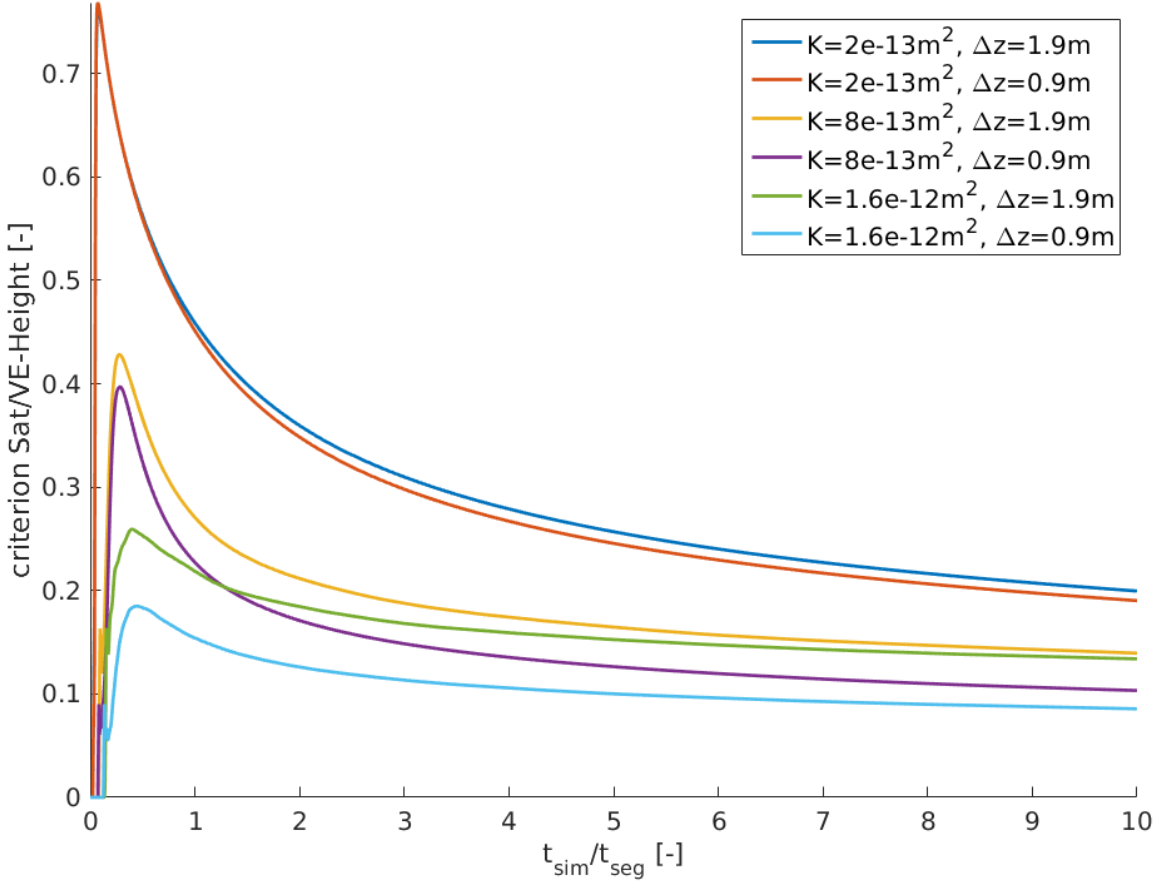




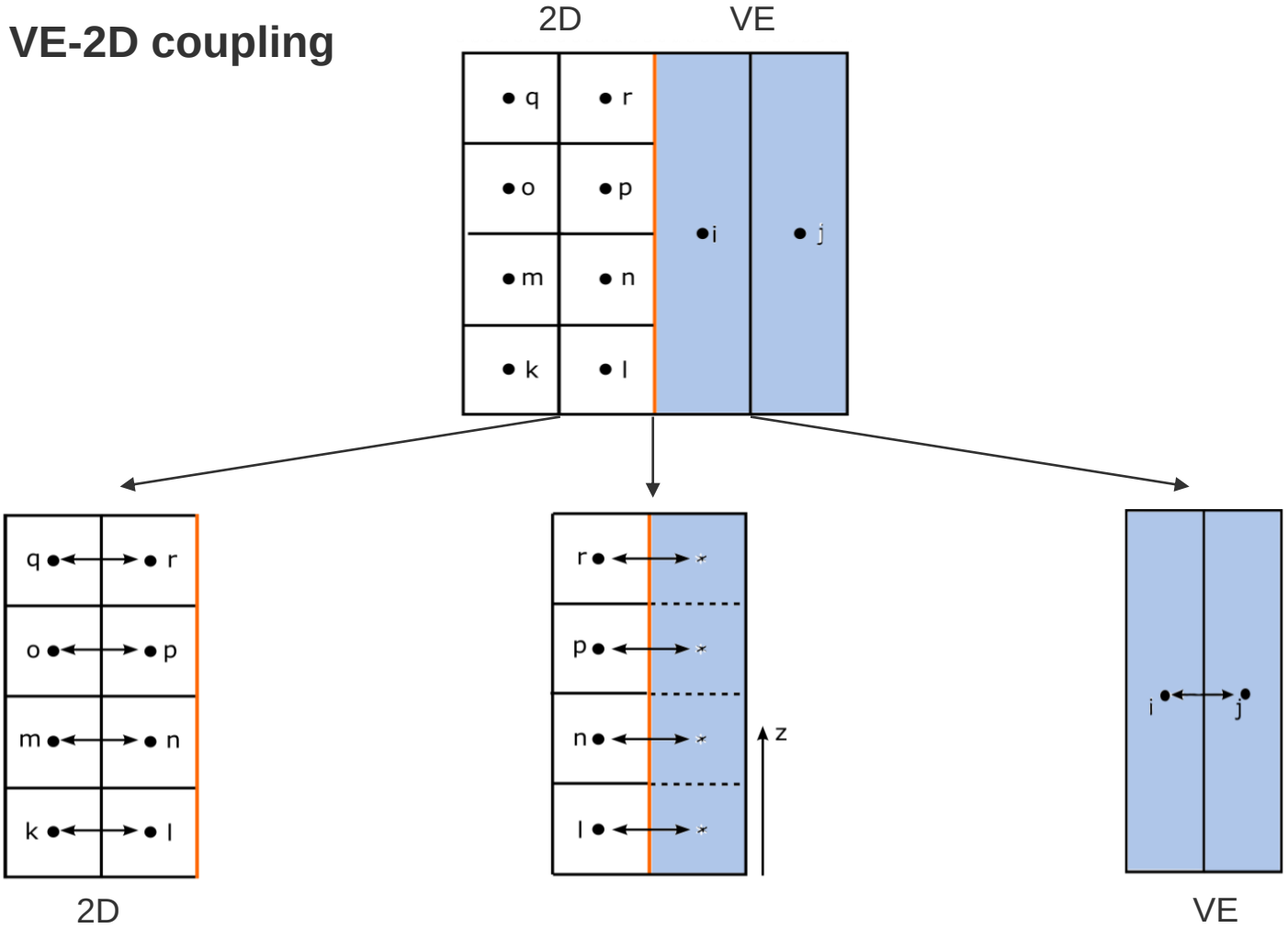
$$c_{sat} = \frac{\int_0^H |s_w - s_{w,reconst}| \mathrm{dz}}{H_{VE}}$$

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

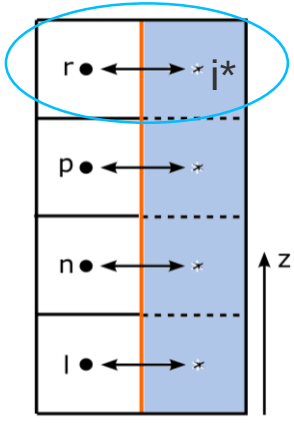
Applicability of VE models – criterion values for one column



VE-2D coupling



VE-2D coupling (IMPES)



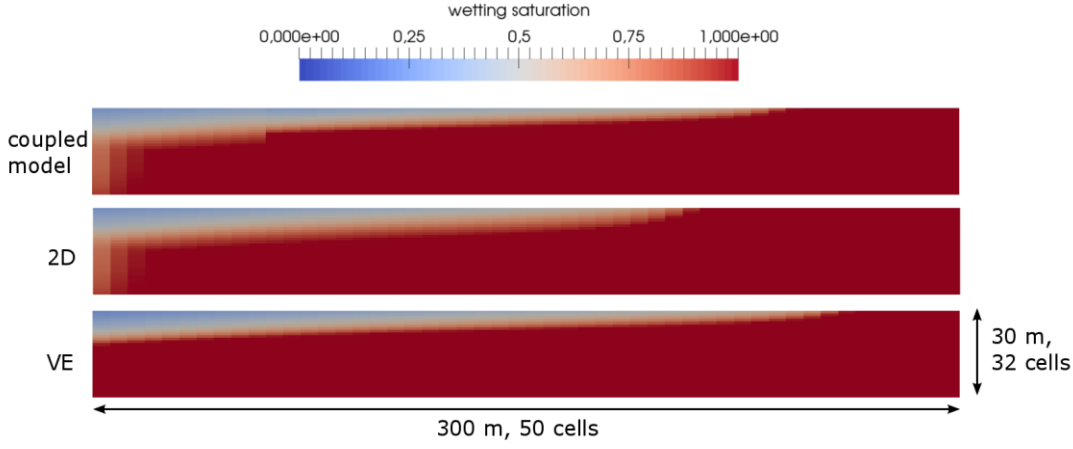
$$v_{tot,i^*r} = -k\lambda_{tot}\left(\frac{p_{wr}-p^*_{wi}}{\Delta x} + f_n\frac{p_{cr}-p^*_{ci}}{\Delta x}\right)$$

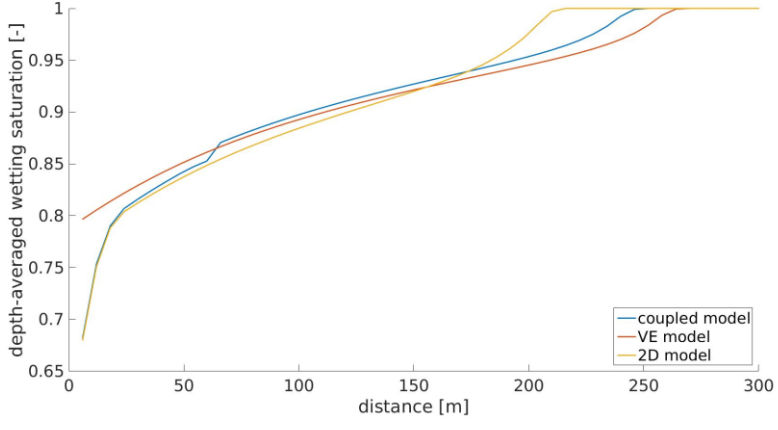
$$p^*_{wi} = P_{wi} - \varrho_w g z$$

$$p^*_{ci} = \begin{cases} 0 & \text{for sharp interface model} \\ p_c(s^*_w) & \text{for sharp capillary fringe model} \end{cases}$$

$$\lambda_{tot}, f_n \quad \text{all depending on } \bar{s}^*_w$$

Results for VE-2D coupling





Brooks-Corey cap. pressure:

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

Phase properties (CH_4, water):

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

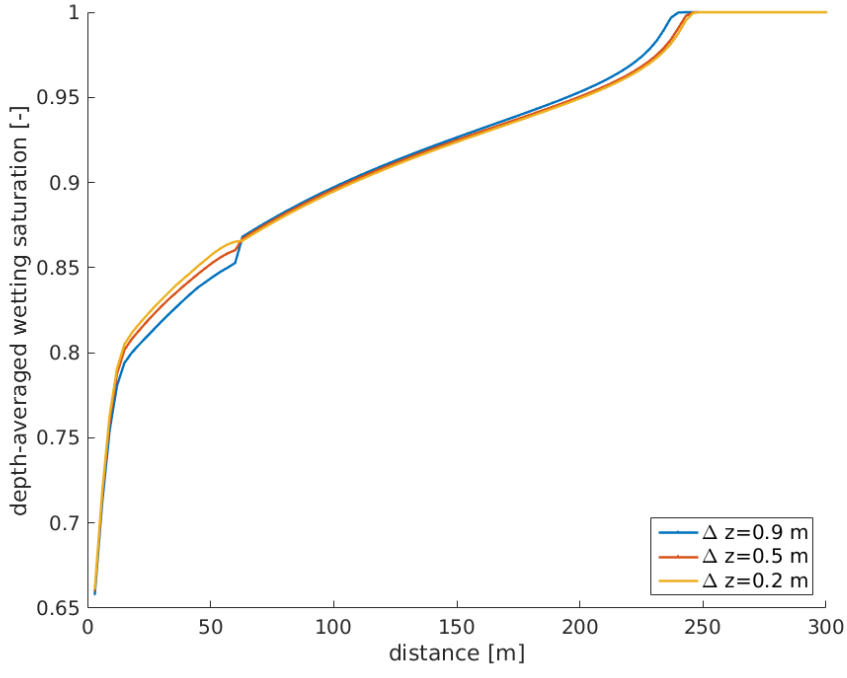
$\varrho_w = 991\ kg/m^3$

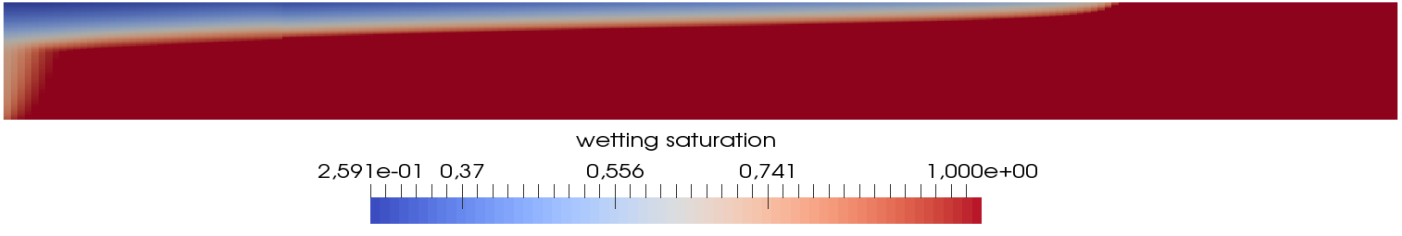
$\mu_n = 1.2 \cdot 10^{-5}\ Pa\,s$

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

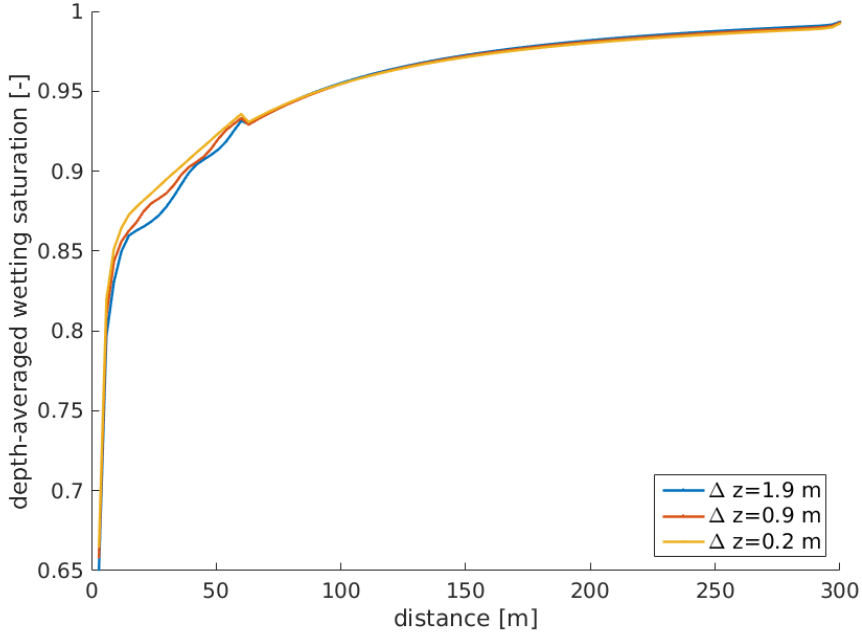
Injection rate: $Q_{nw} = 552\ t/m/a$

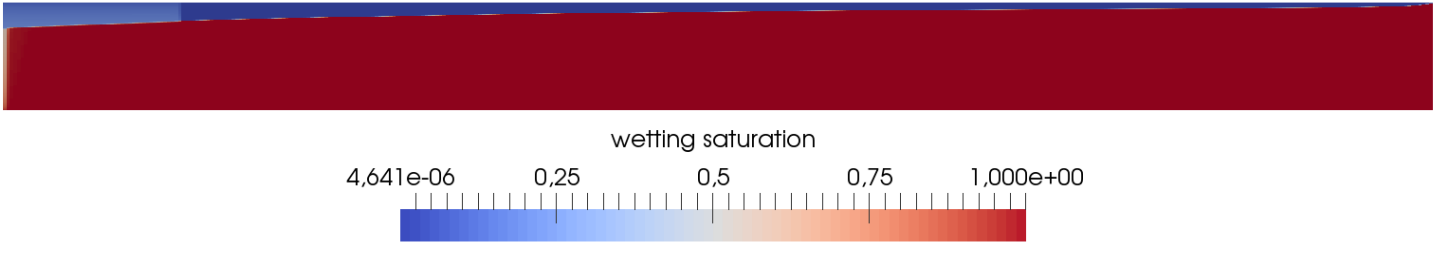
Large capillary fringe



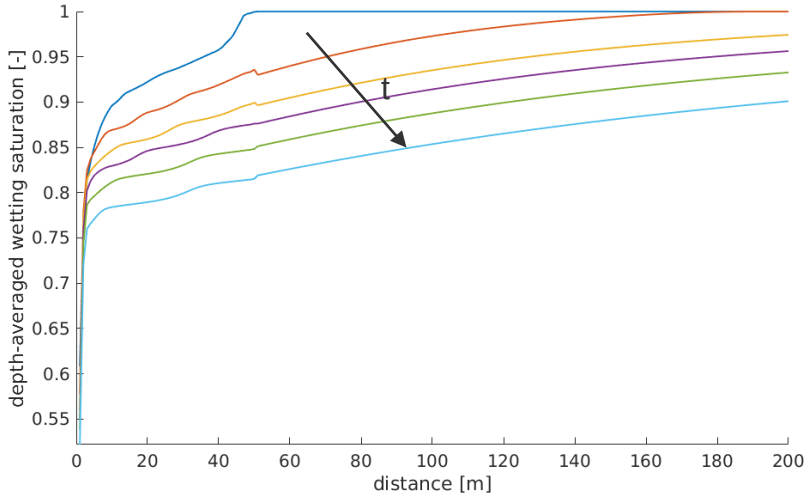


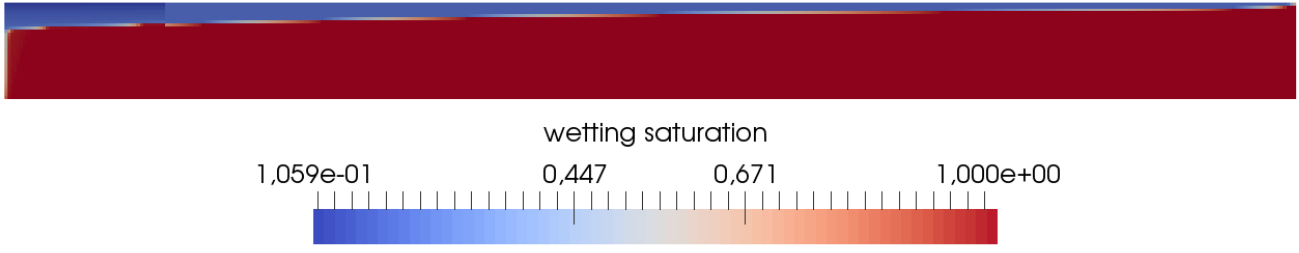
Small capillary fringe



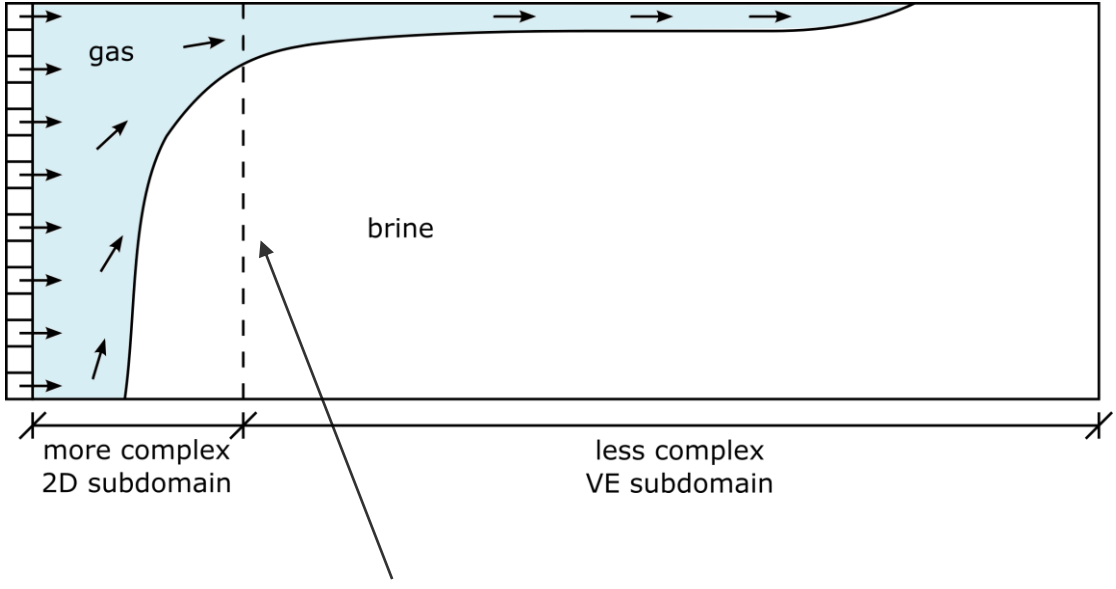


Preliminary results with modified* VE model





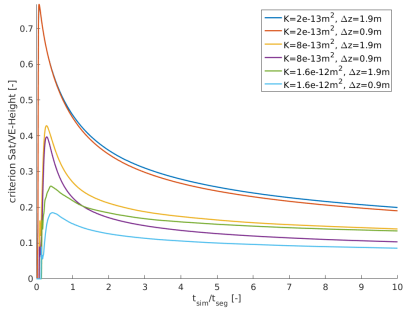
Outlook: adaptive model



Move adaptively based on criterion for applicability

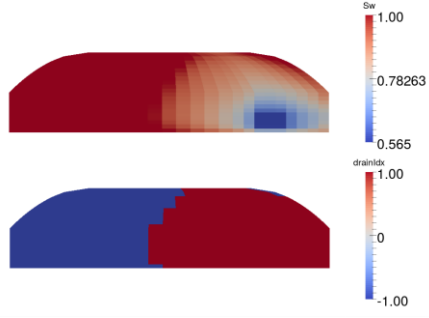
Summary

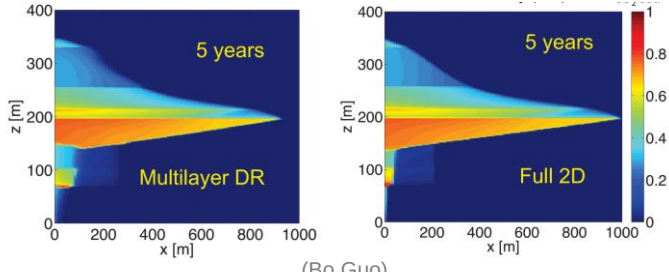
- Modified VE model with broader applicability
- Criterion for applicability of VE model
- Coupled 2D-VE model



Future work

- Adaptive coupling
  - Test criteria for applicability
  - Test modified VE model
- Hysteresis
  - Relevance for gas storage?
  - Stability
- Combine with multi-layer coupling





(Bo Guo)

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Thank you!

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