Coupling of a full-dimensional multiphase model to a vertical equilibrium model for the simulation of underground gas storage

Beatrix Becker, Bernd Flemisch, Rainer Helmig
University of Stuttgart
In cooperation with Bo Guo and Mike Celia
Princeton University

University of Stuttgart
Germany

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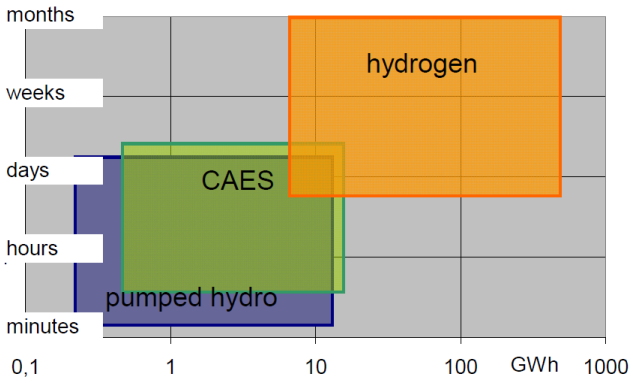


Crotogino et al., 2010

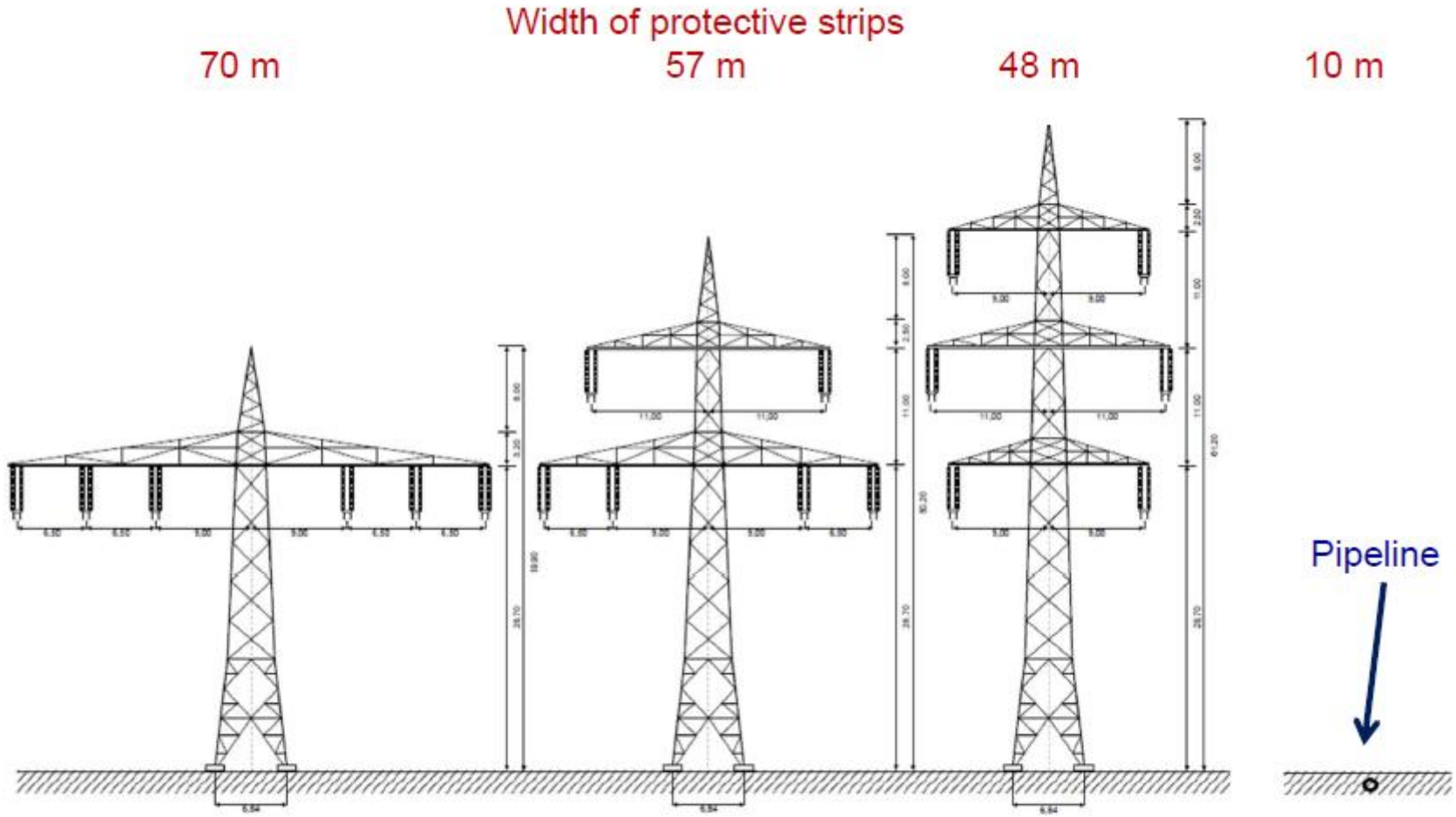
Storage option	Capacity	Volume
Hydrogen	167 TWh	4.1 km³
Pumped hydro	74 TWh	106 km³
Adiabatic CAES	80 TWh	29 km³

(400-600 caverns, 85 in Germany)

Germany: 0.04 TWh

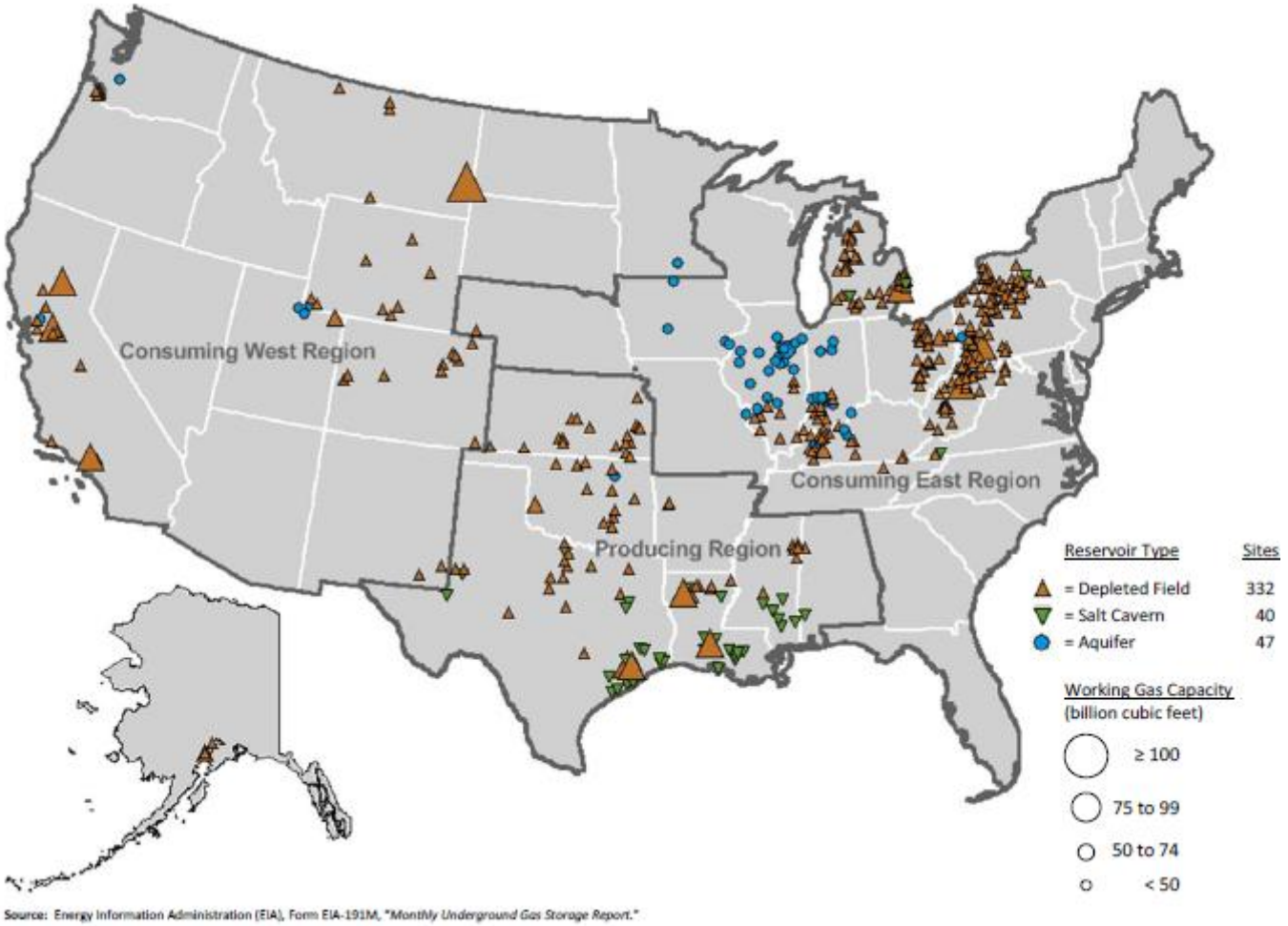
Hoffmann, et al., 2009

Transmission



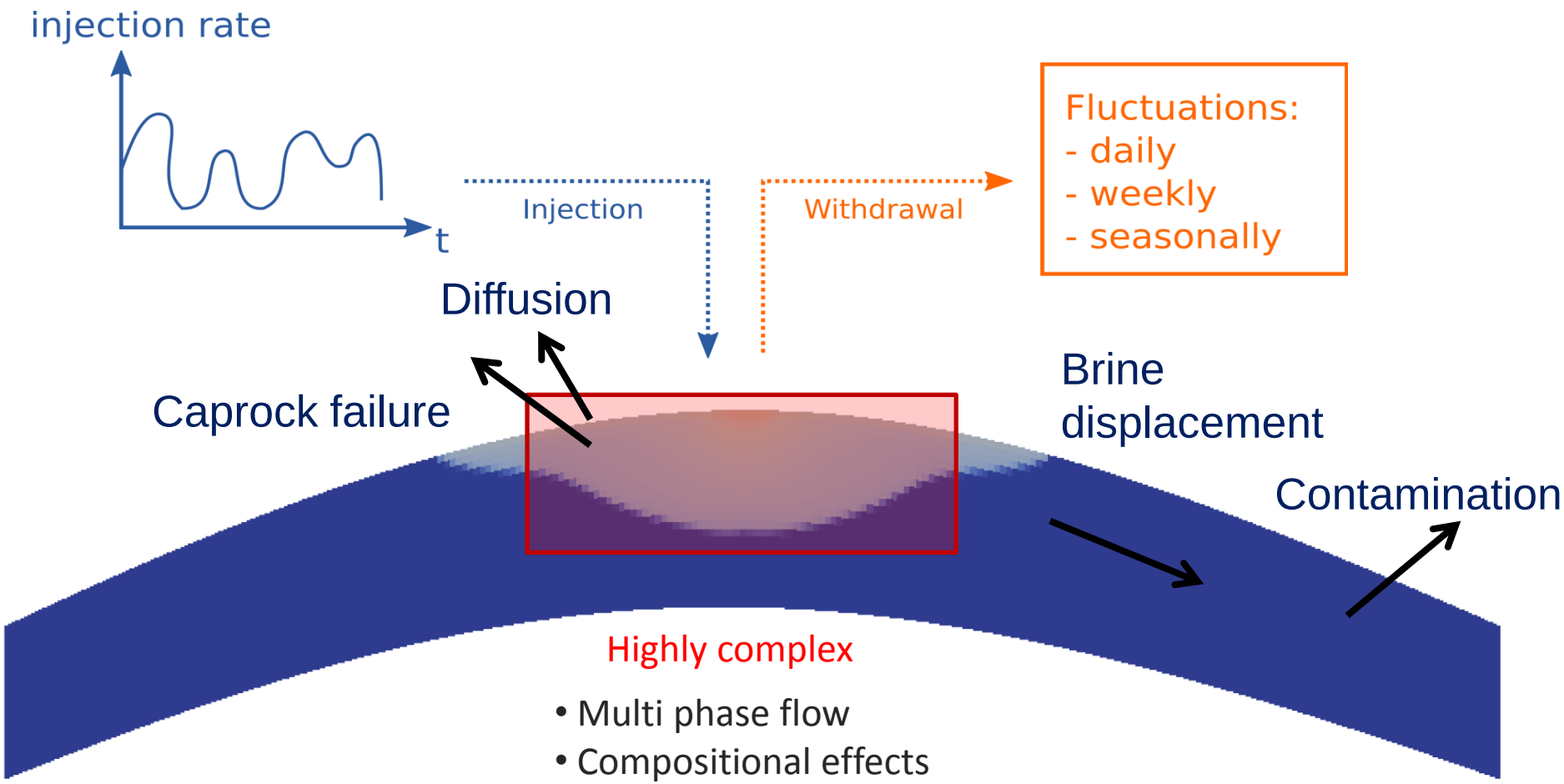
Picture of power poles from Hofman: Technologien zur Stromübertragung, IEH, http://nvonb.bundesnetzagentur.de/netzausbau/Vortrag_Hofmann.pdf

Underground natural gas storage facilities in the US (2013)



Source: Energy Information Administration (EIA), Form EIA-191M, "*Monthly Underground Gas Storage Report.*"

Modeling Challenges

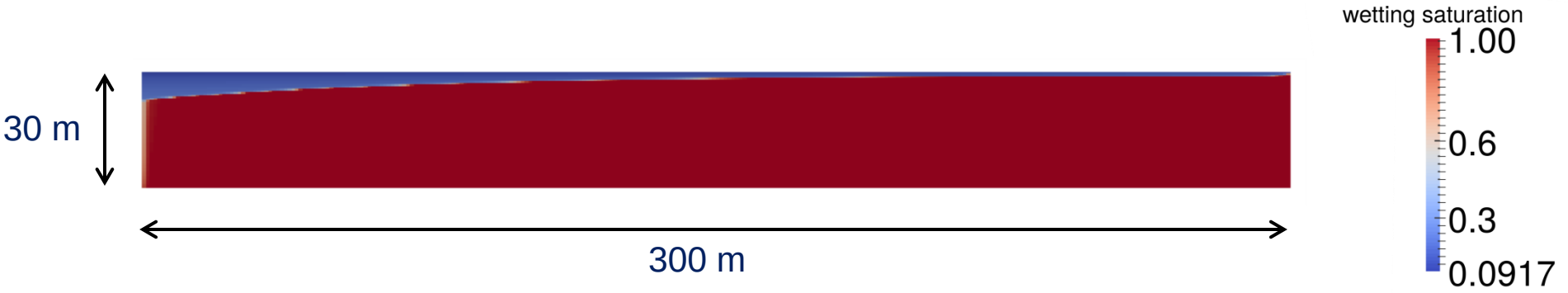


Highly complex

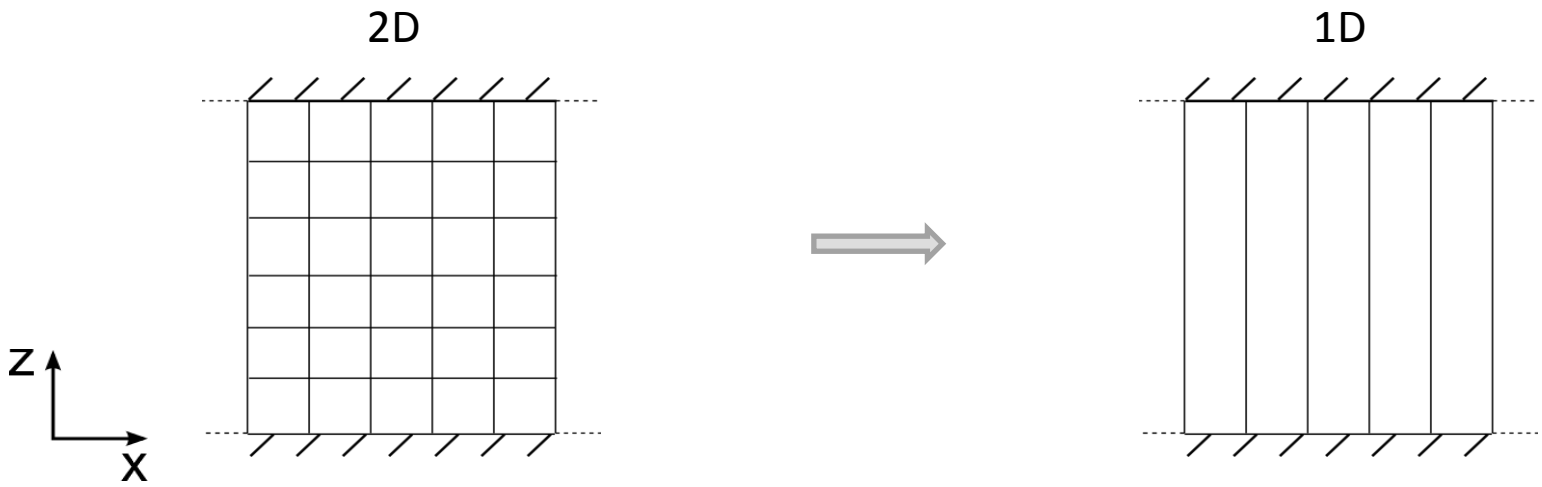
- Multi phase flow
- Compositional effects
- Non-isothermal
- Fingering
- Strongly hysteretic

Less complex

Gas injection 2D



VE model



$$\frac{\partial}{\partial t}(\varrho_\alpha \phi s_\alpha) + \nabla \cdot (\varrho_\alpha \boldsymbol{u}_\alpha) = \varrho_\alpha \psi^\alpha \qquad \frac{\partial}{\partial t}(\varrho_\alpha \Phi S_\alpha) + \nabla \cdot (\varrho_\alpha \boldsymbol{U}_\alpha) = \varrho_\alpha \Psi^\alpha$$

$$\boldsymbol{u}_\alpha = -\frac{k_{r,\alpha}\boldsymbol{k}}{\mu_\alpha}(\nabla p_\alpha - \varrho_\alpha \mathbf{g}) \qquad \boldsymbol{U}_\alpha = -\mathbf{K}\Lambda_\alpha(\nabla P_\alpha - \varrho_\alpha \mathbf{G})$$

$$P^{\mathrm{cap}}(S_\alpha)$$

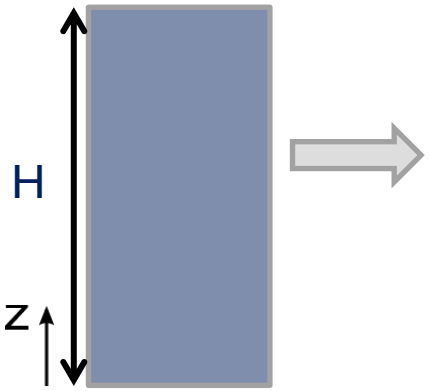
$$\sum S_\alpha = 1$$

(Nordbotten & Celia, 2012) $S_\alpha,\ P_\alpha$

Reconstruction – sharp interface model

Static (Dupuit) reconstruction $p_\alpha(z) = P_\alpha + \varrho_\alpha(\boldsymbol{g}\cdot\boldsymbol{e}_z)z$

Injection

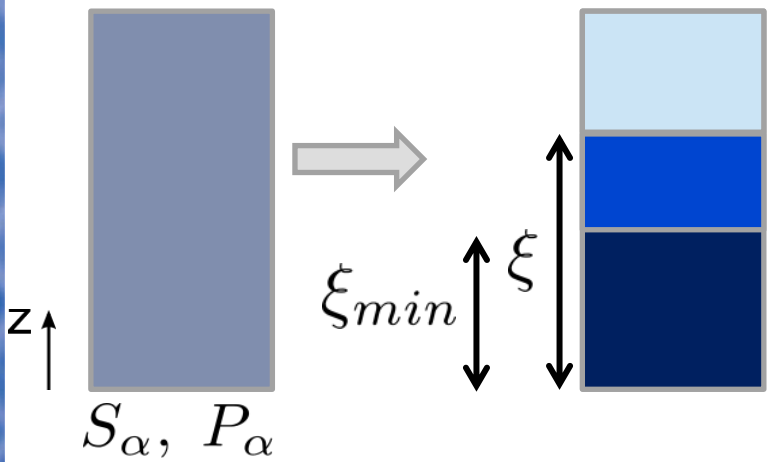


$$S_w = S_{wr} \Longrightarrow \lambda_w = 0$$

$$S_w = 1 \Longrightarrow \lambda_w = 1$$

$$\Lambda_w = \frac{\xi}{H\mu}$$

Injection and withdrawal



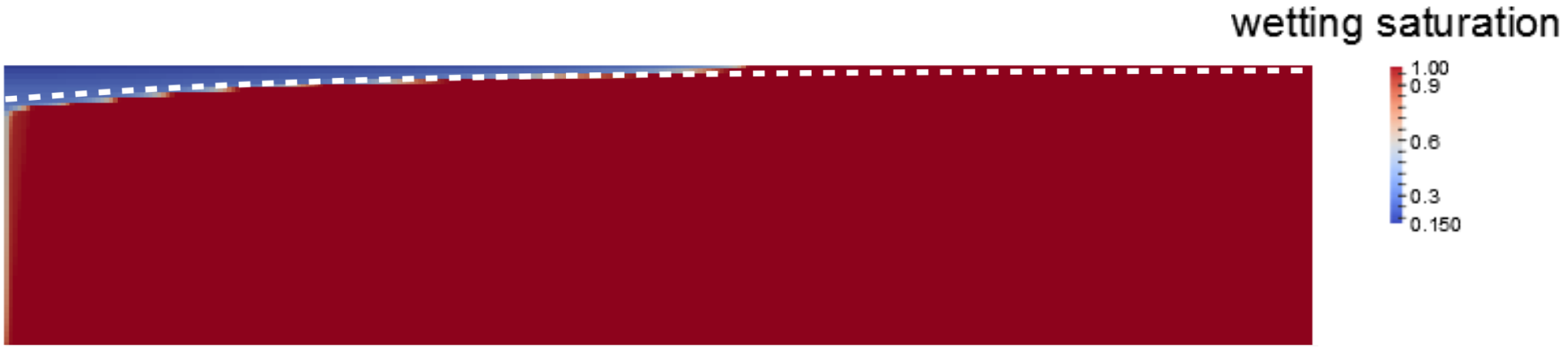
$$S_w = S_{wr} \Longrightarrow \lambda_w = 0$$

$$S_w = 1 - S_{nr} \Longrightarrow \lambda_w = 1$$

$$S_w = 1 \Longrightarrow \lambda_w = 1$$

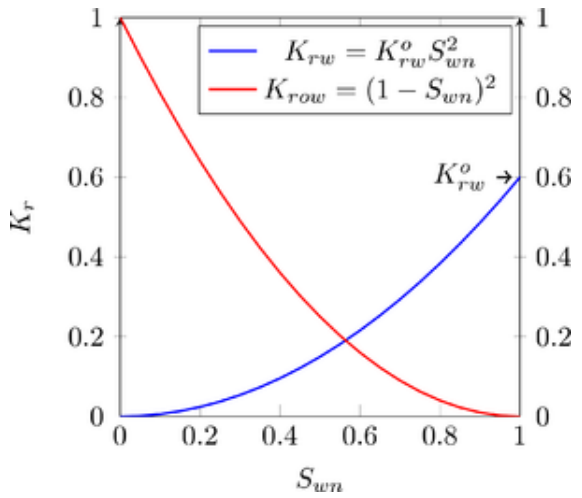
$$\Lambda_w = \frac{\xi}{H\mu}$$

VE model vs. 2D model



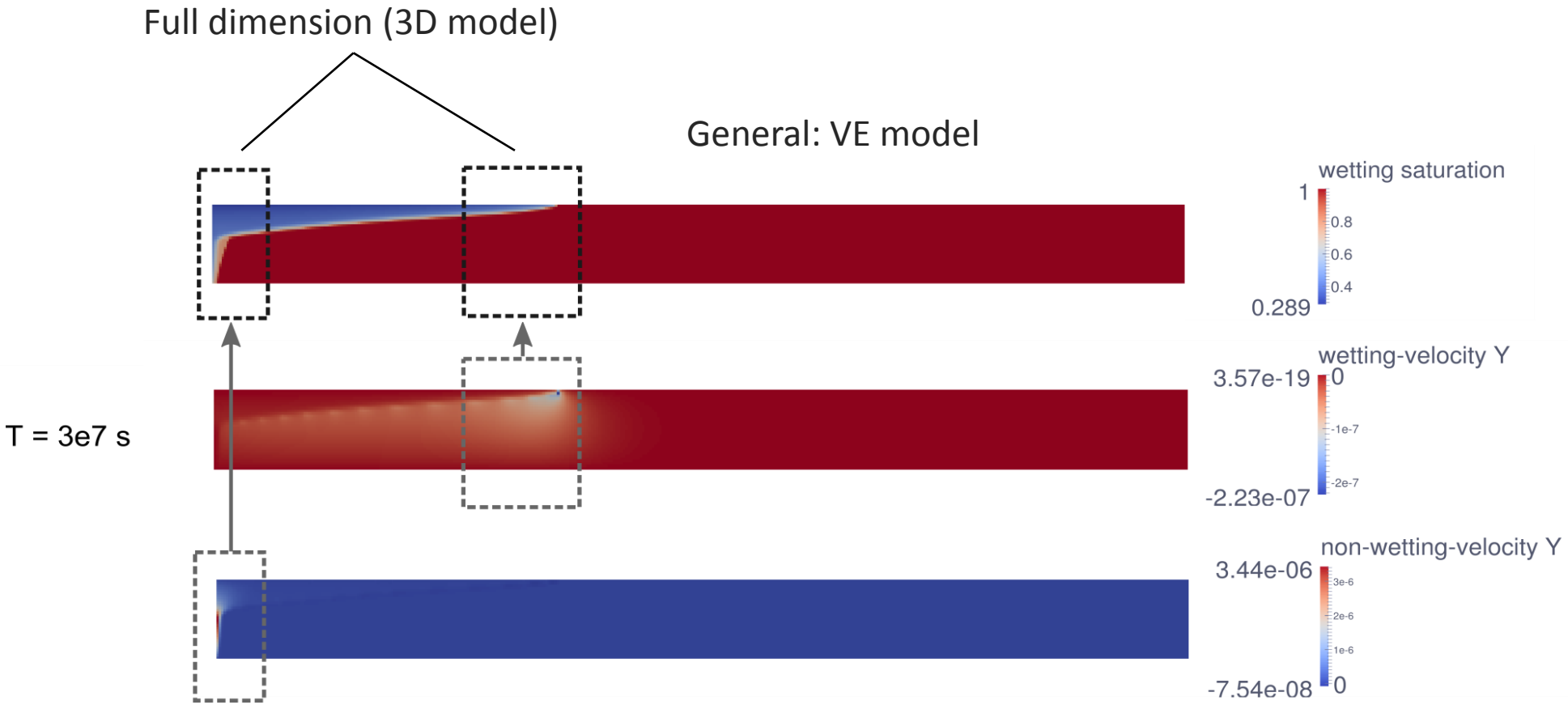
$$t_s \sim \frac{H\phi\mu_b}{k_{r,b,\mathrm{local}} k_z \Delta\varrho g}$$

$$t_s \ll T \Longrightarrow$$ Vertical Equilibrium

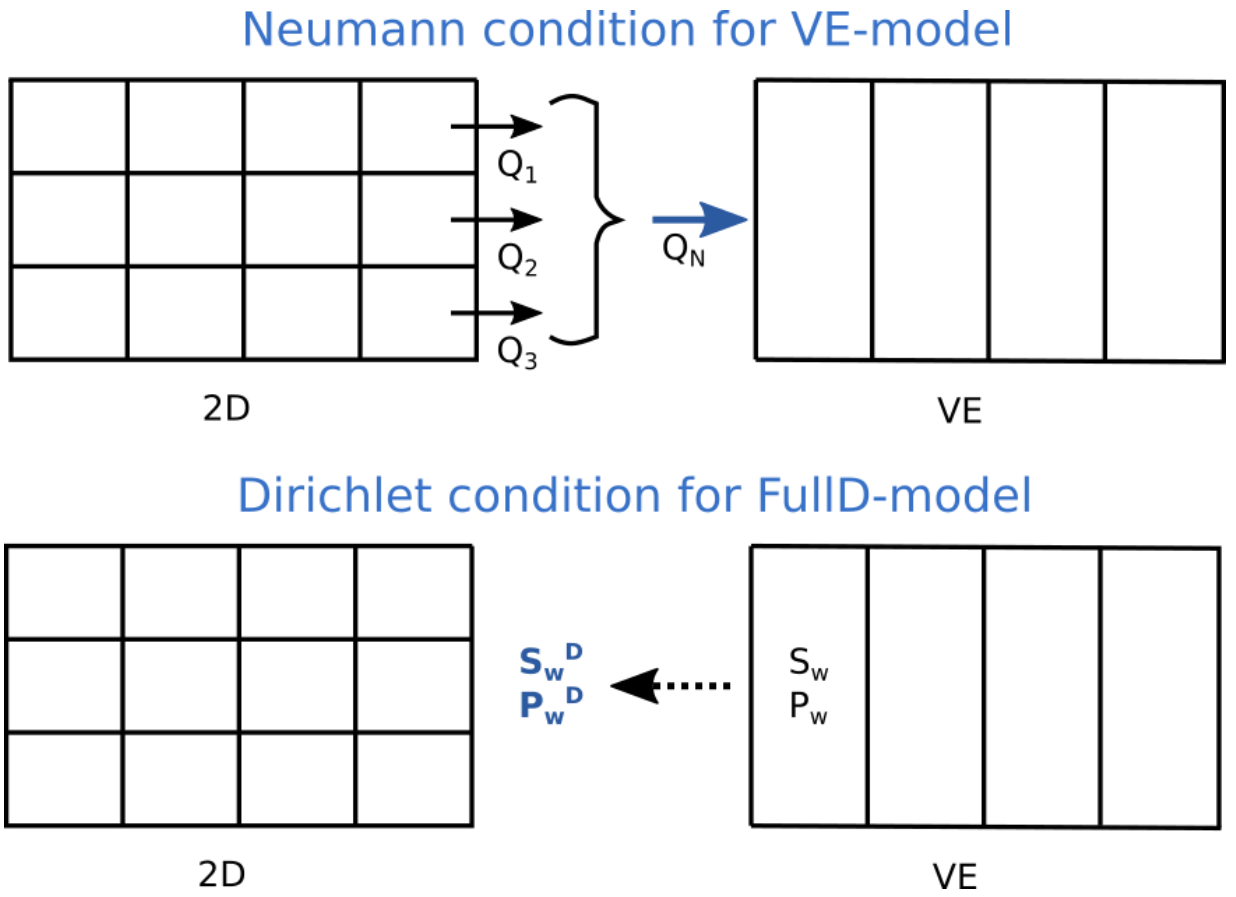


(Court, et al., 2012)

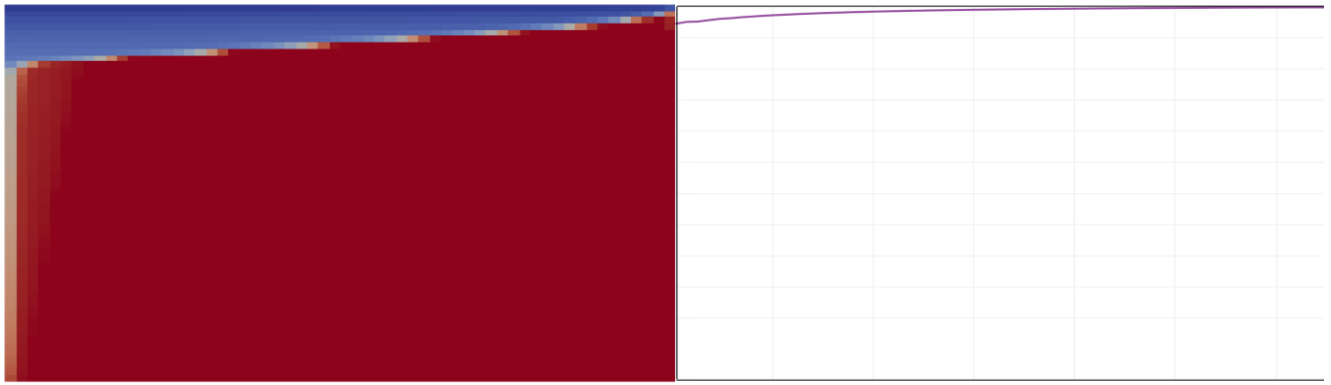
Coupling of a VE to a 2D model



Coupling boundary

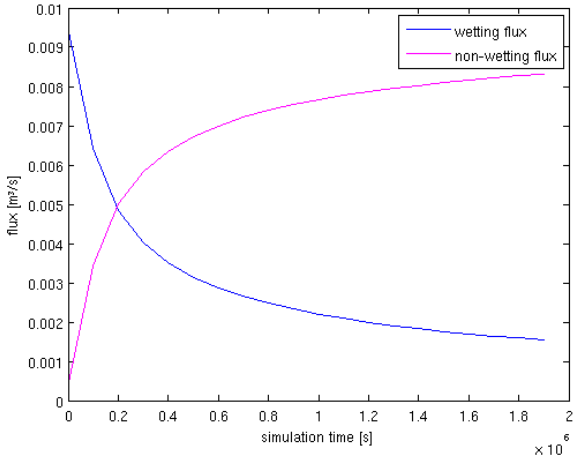


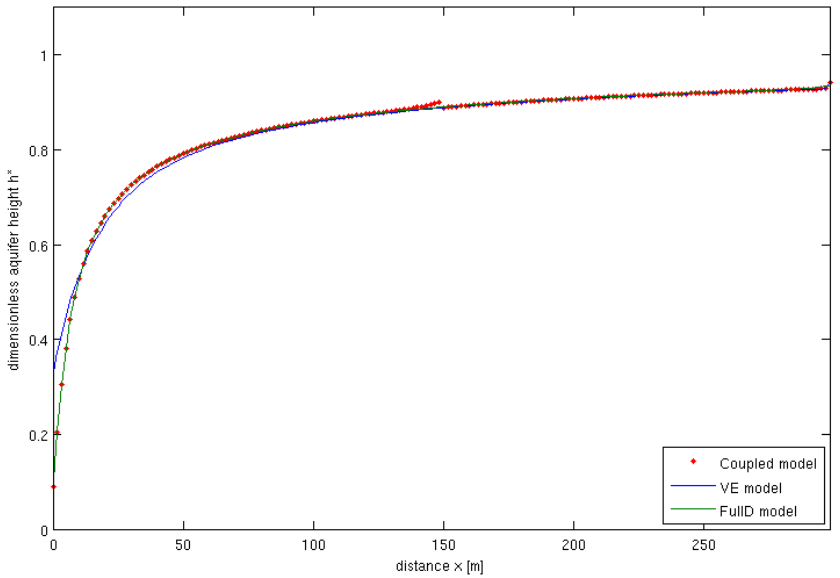
Results coupled model



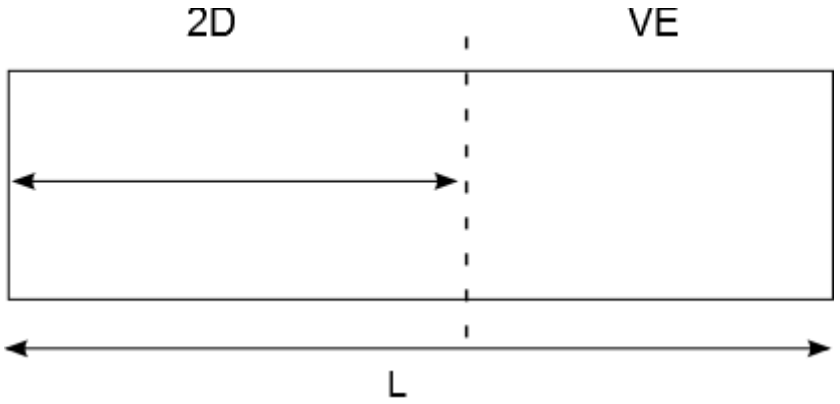
CPU time:

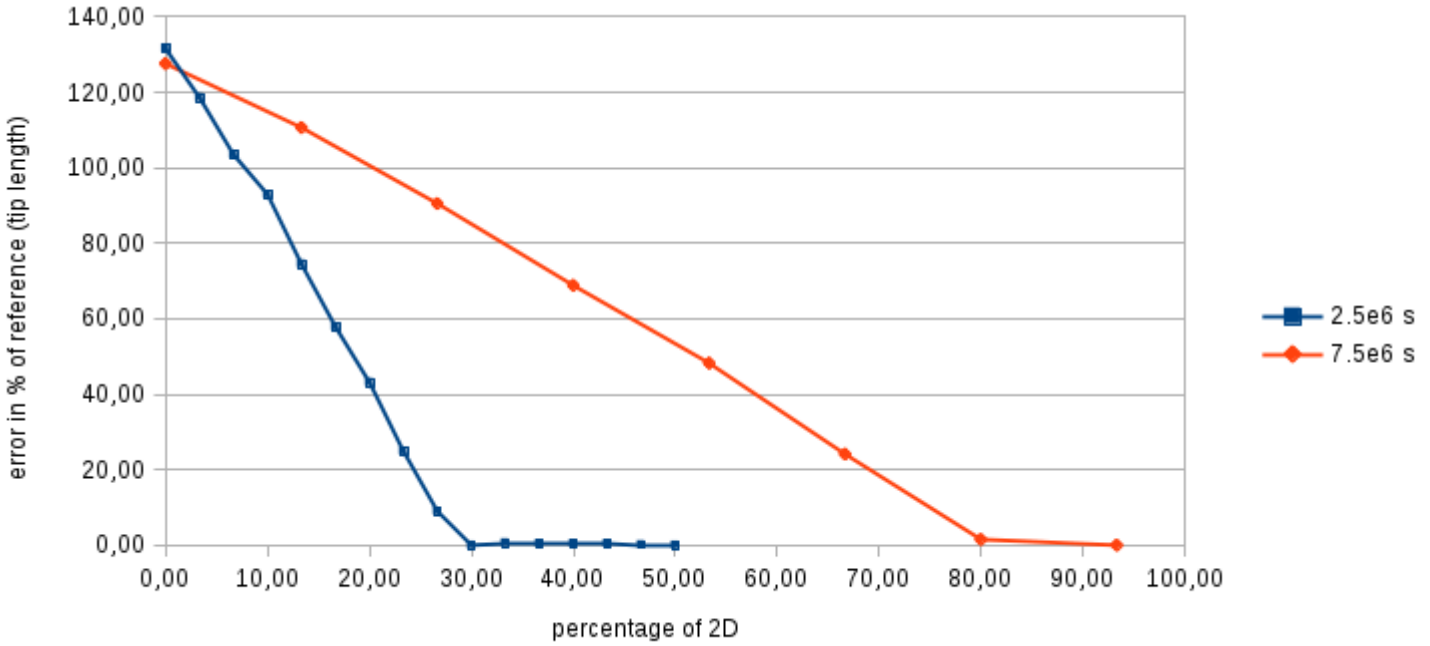
- 2D model: 100%
- VE model: 3%
- Coupled model: 30%





Varying the coupling boundary: distance of gas plume tip – preliminary results





Summary and outlook

- First steps:
  - Sequential coupling of VE model to Full-D model
  - Model switching criteria ⇨ adaptive coupling (monolithic model)
  - VE-DR model (Guo, et al., 2014)
  - In cooperation with Bo Guo and Mike Celia, Princeton University
- Including heterogeneity
- Including hysteresis (Papafotiou, et al., 2010)

- Including multi-physics (Faigle, et al., 2014)

Thank you for your attention!

References

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