Dual-domain modeling of discharge dynamics in a laboratory-scale fractured porous matrix system

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DFG

→ *Fractured porous media contribute to ∼ 75% of global aquifers* (Dietrich et al., 2005)

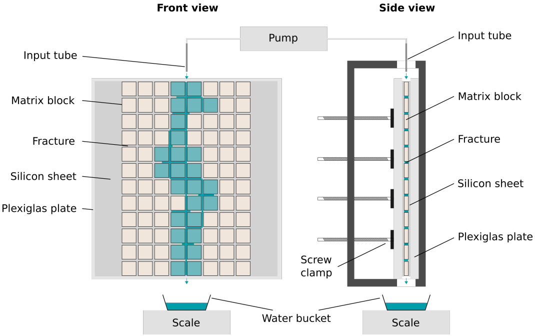
- Vadose zone, above groundwater table (variably saturated)
  - Fractures and fracture networks
  - Matrix
  - → High contrasts in hydraulic conductivities

→ *Water migrates on a wide range of time and spatial scales due to their homogeneous natures* (Pruess, 1998)

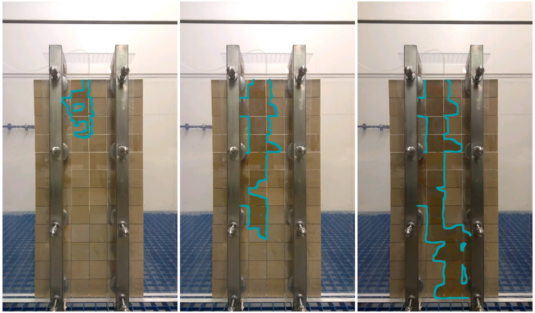
- This study
  - Simplified analog infiltration experiments at lab-scale
  - Modeling recharge dynamics with a dual-domain approach
  - Rüdiger et al. (2022)
- Our aims
  - Process understanding (Appendix A)
    - Fracture flow- and intersection dynamics
    - Fracture-matrix interactions
  - Model validation

Approach: Laboratory experiments in well-controlled fracture-matrix systems

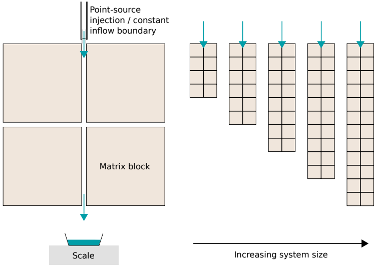
General setup



Wetting front propagation

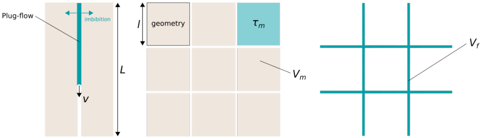


Approach: Simplified laboratory setup and dual-domain modeling



- m x 2 porous blocks network systems
  - Varying total vertical length ($m = 2, 4, 6, 8, 10, 12$)
  - Constant aperture of 1 mm
  - Constant inflow rate of 1.5 ml · min^{-1}
  - Seeberger sandstone
    - Homogenous matrix (18.6 % effective porosity)
- Infiltration experiments → measuring discharge
- Qualitative observations → Appendix B

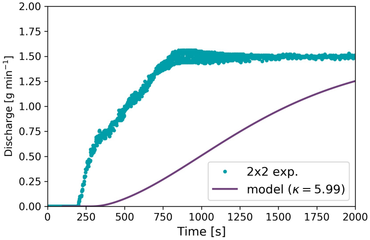
Dual-porosity model after Neuweiler et al. (2012)



- Memory function ϕ (Equation 3)
  - describes fracture-matrix mass exchange
- Parameters
  - Matrix-fracture volume ratio $\kappa = V_m / V_f$
  - Characteristic imbibition time τ_m
  - Fracture flow velocity $v = Q_0 / aW$
- Model assumptions
  - Plug-flow in fractures
  - Perfectly coupled domains
- Appendix C and D

Original parameterization

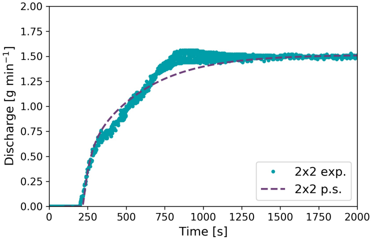
- $\tau_m = 600$ s
- $v \rightarrow$ experimentally determined L/t_1
- κ derived from setup geometry $(= 5.99)$



- Strong deviations of first arrival and dispersion of outflow signal

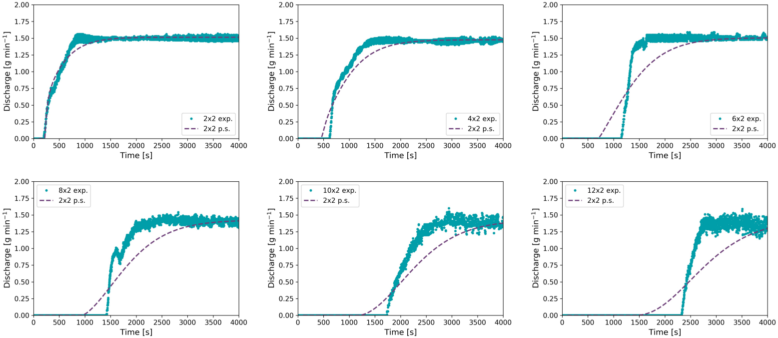
Calibration

- $\tau_m = 600$ s
- $v \rightarrow$ calibrated (v^*)
- $\kappa \rightarrow$ calibrated (κ^*)



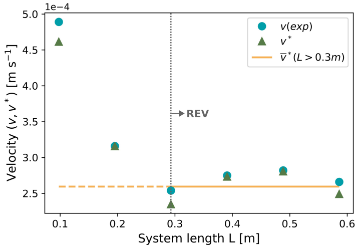
- Calibrated model recovers discharge dynamics very well

Quantitative results: Up-scaling with unit-cell parameter set



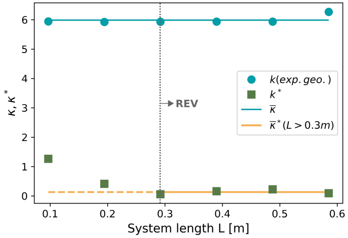
- Deviations increase with increasing system length (L)

Velocity



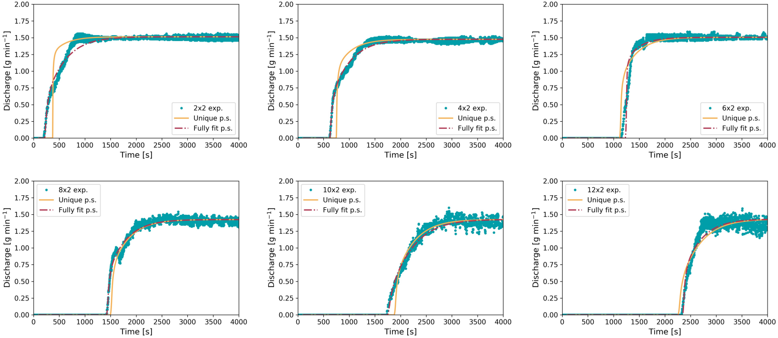
- Observed v and calibrated v^* almost the same
- Both converge toward limit for $L \geq 0.3$ m
- Averaged velocity $\overline{v^*} = 2.6e^{-4}$ m s^{-1}

Domain-coupling parameter



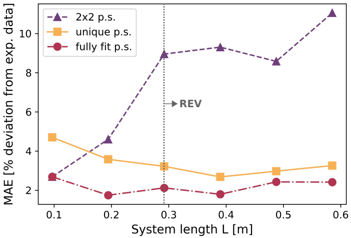
- Calibrated κ^* < geometrical determined κ
- Calibrated converges toward limit for $L \geq 0.3$ m
- Averaged transfer coefficient $\overline{\kappa^*} = 0.1356$
- Scaling factor $\alpha = \overline{\kappa^*}/\kappa = 0.0226$

Quantitative results: Unique parameter set and fully calibrated fits



- Fully calibrated fits recover observed discharge dynamics
- Unique parameter set performs better for larger systems

Parameter sets



Unique

- Performs less well for very small systems below REV
- Describes discharge dynamics in sufficiently large systems with high accuracy (MAE $<$ 4%)
- Performs almost as good as the model fully calibrated for each L individually

2x2

- Deviation increases with increasing system length L
- Strong impact of partitioning dynamics at fracture intersection on discharge dynamics

Thank you for your attention!

If you have any questions feel free to contact me (fruediger@gwdg.de)

References

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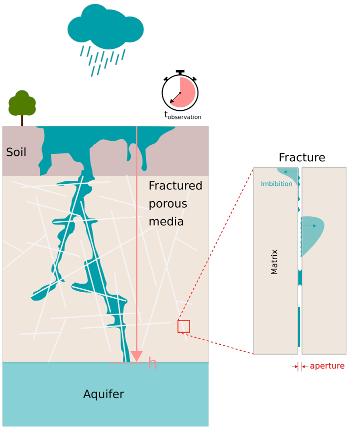
- Preferential flow and recharge dynamics as function of
  - Input conditions (infiltration)
    - Magnitude
    - Concentrated vs. diffuse
    - Temporal vs. steady
  - Fracture network properties
    - Density
    - Aperture
    - Topology (intersections, connectivity)
  - Fracture-matrix interactions
    - Imbibition
  - Fracture flow regimes
    - Discrete slugs
    - Films
- Flow path formation (volume or interface area)

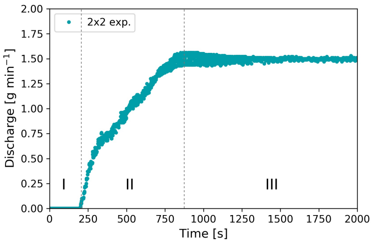
→ *Observed arrival times contradict common notion that flow in fractures only occur under equilibrium conditions* (Dahan et al., 2000)

→ *No ubiquitous classification for the onset of preferential flow exists* (Nimmo, 2012)

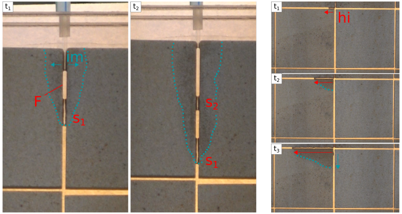


Example: 2 x 2 blocks network

- Three main phases (I, II, III)
  - I Redistribution water through fracture network and matrix imbibition
  - II Onset of discharge, ongoing matrix imbibition
  - III Quasi-steady state, matrix reached maximum saturation



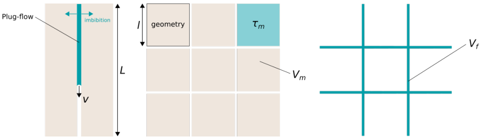
Flow modes and partitioning dynamics



- Two dominant flow modes
  - Slugs (S_1,S_2)
  - Films (F)
- Matrix imbibition (im) slows down fracture flow progression
- Slugs (S_2) and films (F) above the wetting front move extremely fast
- Intersections (partitioning dynamics)
  - Horizontal infiltration (hi)
  - By-passing

Appendix C: Dual-domain modeling

Dual-porosity model after Neuweiler et al. (2012)



- Equation 1 analytically solved
  - Initial boundary condition
  - Solution in Equation 5
- Memory function ϕ (Equation 3)
  - describes fracture-matrix mass exchange
- Parameters
  - Matrix-fracture volume ratio $\kappa = V_m / V_f$
  - Characteristic imbibition time τ_m (Equation 4)
  - Fracture flow velocity $v = Q_0 / aW$
- Model assumptions
  - Plug-flow in fractures
  - Perfectly coupled domains

Main equations

$$\frac{\delta S_f(z,t)}{\delta t} + \kappa \frac{\delta S_m(z,t)}{\delta t} - v \frac{\delta S_f(z,t)}{\delta z} = 0 \quad (1)$$

$$S_m = \int_0^t dt' \, \phi(t-t') S_f(t') \quad (2)$$

$$\phi^*(\lambda) = \frac{1}{\sqrt{\lambda \tau_m}} tanh\left(\sqrt{\lambda \tau_m}\right) \quad (3)$$

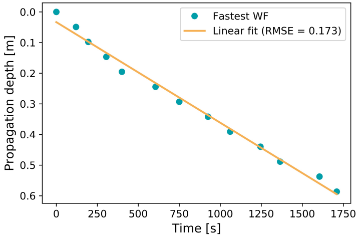
$$\tau_m = \frac{l^2}{D} \quad (4)$$

$$j^*(\lambda) = Q_0 \cdot \lambda^{-1} \cdot exp[-La\lambda(1+\kappa\phi^*)/v] \quad (5)$$

S_f, S_m	Saturation fracture, -matrix
V_f, V_m	Volume fracture, -matrix
D	Diffusion coefficient
l	Length scale characteristic geometry
a	Fracture aperture
W	Fracture width
$j^*(\lambda)$	Volumetric outflow rate (Laplace space)
Q_0	Volumetric inflow rate
L	Vertical system length

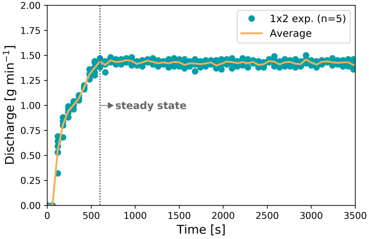
Appendix D: Preliminary investigations - Flow progression and time-scale of fracture-matrix interaction

12 x 6 blocks network



- Infiltration front into initially air-dry system progresses with constant velocity
- Supports plug-flow assumption
- v $\approx 3.28e^{-4}$ m s^{-1}

1 x 2 blocks network



- Characteristic imbibition time $\tau_m(exp.) \approx$ 600 s
- $\tau_m(ana.) = l^2/D \approx 147$ s

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l Block length = 0.04785 m

D Diffusion coefficient = $1.56e^{-5}$ m s^{-1}

- Based on parameter estimation (Shigorina et al., 2021)
- Calculated with equation 20 (Neuweiler et al., 2012)
- Taken for water content = 0.9

- Difficult to set up experiments
  - Stability criteria
  - Study suitability of fracture network
- New potential sites: Ossenfeld and Vogelbeck
- Study analog to lab experiments

Ossenfeld

Vogelbeck