Analogue laboratory of preferential flow dynamics in porous fractured media: Importance of fracture intersections and porous matrix imbibition processes

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Objectives

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- Develop a better understanding of rapid preferential flow dynamics in the vadose zone of fractured aquifers.
- Reproduce free-surface flow (i.e. droplet vs. rivulet flow) in controlled lab experiments to investigate (i) mass partitioning at unsaturated fracture intersections and (ii) the effect of imbibition with a porous matrix on the discharge signal.
- Test analytical approach for upscaling repetitive capillary driven fracture-filling in idealized fracture cascades without imbibition.

Methods

Analogue percolation experiments I (no imbibition)

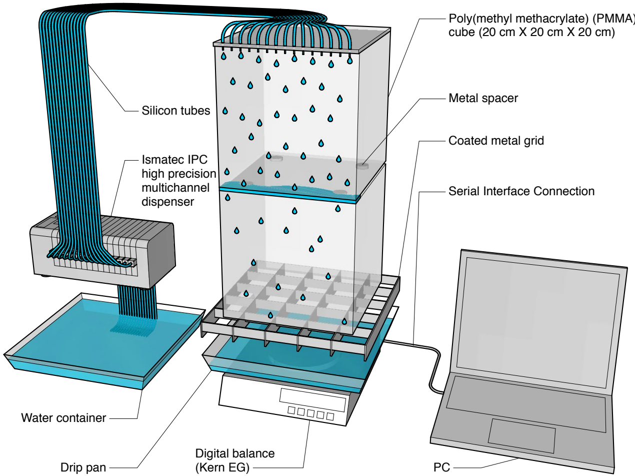

Figure 1: Laboratory setup (Kordilla et al. 2017, Noffz et al. 2019)

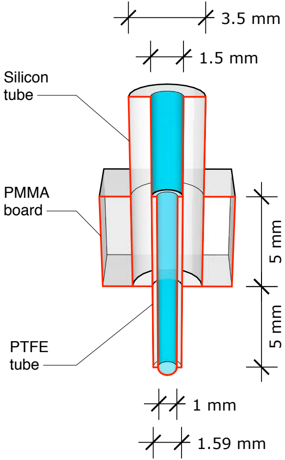

Figure 2: Inlet geometry (Noffz et al. 2019)

Analogue percolation experiments I (no imbibition)

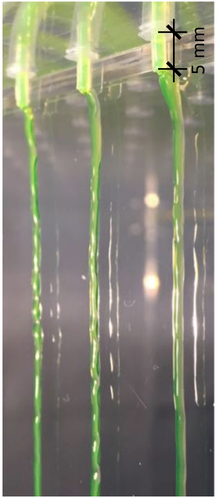

Figure 3: Inlets and rivulets

- Total flow rate $Q_0 = 15\,\mathrm{ml/min}$
- Flow regimes: Droplet ($15 \times 1\,\mathrm{ml/min}$) and rivulet flow ($3 \times 5\,\mathrm{ml/min}$)
- Aperture width d_f between $0.7\,\mathrm{mm}$ and $2.5\,\mathrm{mm}$
- Horizontal offset d_o between $-4\,\mathrm{mm}$ and $4\,\mathrm{mm}$
- Static contact angle $\theta_0 \approx 65°$
- For rivulet flow the cascade was extended up to three horizontal fractures

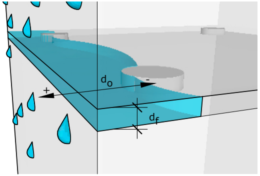

Figure 4: Inlet array

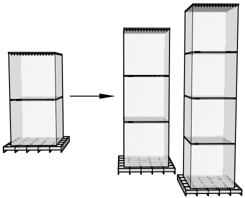

Figure 5: Fracture cascades

Analogue percolation experiments II (with imbibition)

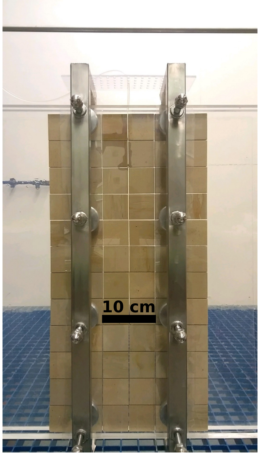

Figure 6: Sandstone network (Rüdiger et al. 2020, under review)

- Applied flow rate Q_0 is 0.75 ml/min to 3.5 ml/min
- Size of a single sandstone slice $\approx 5\,\text{cm} \times 5\,\text{cm} \times 1\,\text{cm}$
- Aperture used throughout all experiments is 1 mm
- Network is arranged with and without horizontal offset at each intersection
- Experiments of the same geometry but using non-porous acrylic glass slices were conducted for comparison

Results & Discussion

Partitioning dynamics I (no imbibition)

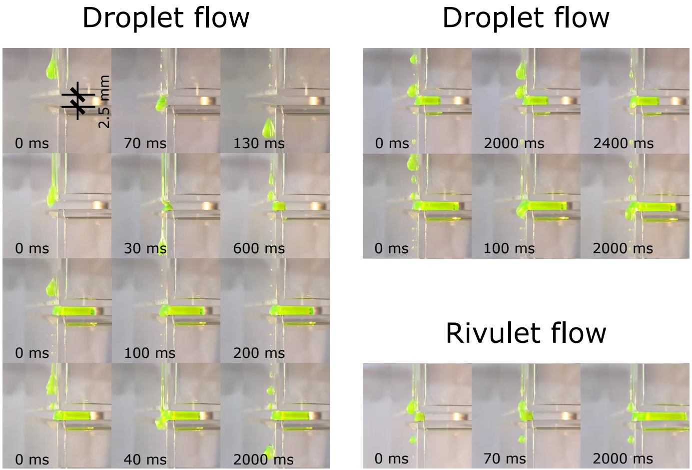

Figure 7: Partitioning dynamics captured at 240 fps (Noffz et al. 2019)

- Droplet flow: Exhibits complex partitioning dynamics and may bypass the aperture or contribute to its filling
- Rivulet flow: Hydraulically connects inlet and the encountered fracture

Partitioning dynamics I (no imbibition)

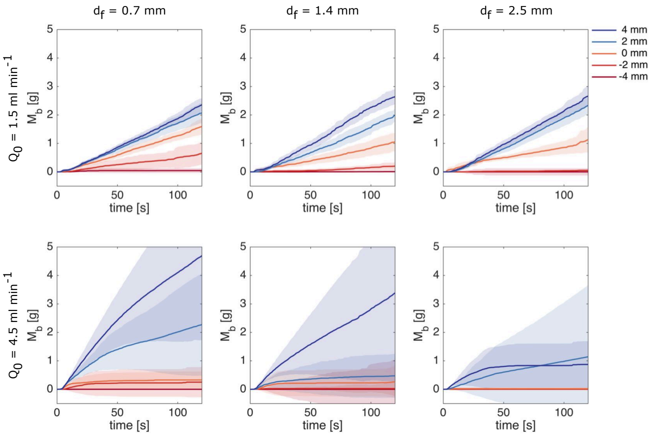

Figure 8: Bypassing mass M_b vs. time for variable fracture geometry

- Negative horizontal offsets d_o reduce the bypass efficiency of droplet and rivulet flow
- Small opening widths d_f benefit the mass transport across the aperture

Partitioning dynamics II (with imbibition)

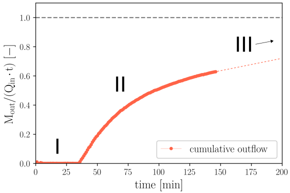

Figure 9: Stages of the discharge signal (Rüdiger et al. 2020, under review)

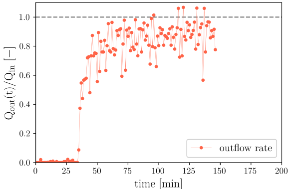

Figure 10: Normalized discharge rate (Rüdiger et al. 2020, under review)

- I: Pre-arrival; no mass accumulation (i.e. introduced water distributes in the fracture network and pore space)
- II: First-arrival; first discharge pulse accumulates on the drip pan and the discharge rate successively approximates the inflow
- III: Steady-state; inflow rate equals the discharge (not fully established in this experiment)

Partitioning dynamics II (with imbibition)

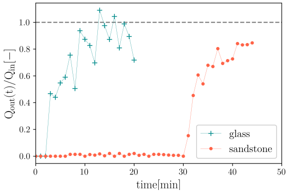

Figure 11: Normalized discharge (Rüdiger et al. 2020, under review)

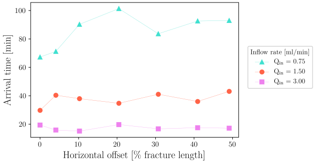

Figure 12: Arrival times for variable offsets (Rüdiger et al. 2020, under review)

- At an equal flow rate arrival times and the amplitude of pulsating flow signals during infiltration in porous vs. non-porous network differ strongly (i.e. the arrival is delayed, where imbibition occurs)
- Higher flow rates result in earlier arrival times
- For a low flow rate a successive increase of the horizontal offset tends to increase arrival times, which is not apparent at higher rates

Analytical approach

Transfer-function

A transfer function accounts for characteristic flow partitioning into a horizontal fracture

$$\varphi(t) = \frac{dQ_1(t)}{dt} = -\frac{dQ_f(t)}{dt}\,, \tag{1}$$

which can be approximated by a Gaussian

$$\varphi(t) \propto \frac{\exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right]}{\sqrt{2\pi\sigma^2}}\,, \tag{2}$$

$$\int_0^\infty dt\varphi(t) = 1\,. \tag{3}$$

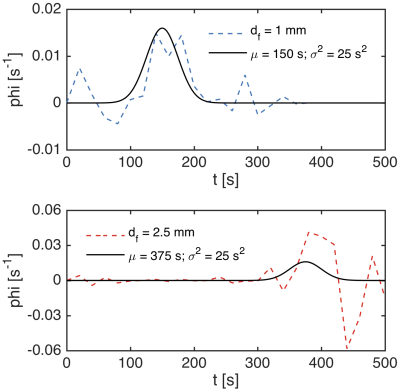

Figure 13: Normalized fracture inflow rate vs. time; $d_f = 1\,\mathrm{mm}$ (Noffz et al. 2019)

Transfer-function

The total fracture outflow Q_{f,n_f} after n_f fractures is

$$Q_{f,n_f}(t) = Q_0 \left[1 - \int_0^t dt_{n_f-1} \varphi(t - t_{n_f-1}) \cdots \int_0^{t_3} dt_2 \varphi(t_3 - t_2) \int_0^{t_2} dt_1 \varphi(t_1) \right] . \qquad (4)$$

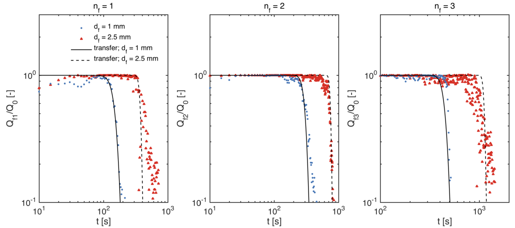

Figure 14: Normalized fracture inflow rate vs. time; $d_f = 1\,\text{mm}$ (Noffz et al. 2019)

- Predictive modeling by Gaussian transfer-function approximates the fracture filling with limitations
- "Tailing" not accurately recovered yet

Conclusion

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- Gravity-driven free surface flow modes can be accurately delineated in analogue percolation experiments. Here, rivulet flow is shown the most effective wetting of an unsaturated horizontal fracture.
- Geometric alterations of the fracture intersection influence the bypass behaviour of droplets and rivulets (i.e. postive offsets further benefited a bypass).
- Application of Gaussian transfer-function recovers repetitive fracture filling and enables predictive modeling for rivulet flow, where imbibition with a porous matrix does not occur.
- Imbibition of a porous matrix tends to dampen the amplitude of discharge pulses and delays steady state conditions (i.e. inflow equals outflow rate).
- Hence, process-orientated analytical approaches demand further refinement to account for such effects across scales.

Outlook:

- To investigate the mass redistribution in natural settings it is planned to conduct further field percolation experiments in well characterized lime- and sandstone formations.

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