Free-Surface flow dynamics and its effect on travel time distribution in unsaturated fractured zones - findings from analogue percolation experiments

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To assess the vulnerability of an aquifer system it is of utmost importance to recognize the high potential for a rapid mass transport offered by flow through unsaturated fracture networks. Numerical models have to reproduce complex effects of gravity-driven flow dynamics to generate accurate predictions of flow and transport. However, the non-linear characteristics of free surface flow dynamics and partitioning behaviour at unsaturated fracture intersections often exceed the capacity of classical volume-effective modelling approaches. Laboratory experiments that manage to isolate single aspects of the mass partitioning process can enhance the understanding of underlying dynamics, which ultimately influence travel time distributions on multiple scales.

Our analogue fracture network consists of PMMA (poly(methyl methacrylate)) cubes with dimensions of 20 x 20 x 20 cm creating simple geometries of a single or a cascade of consecutive horizontal fractures. Gravity-driven free surface flow (droplets; rivulets) is established via a high precision multichannel dispenser at flow rates ranging from 1.5 to 4.5 ml/min. Finally, a digital balance provides real-time data of the cumulative mass bypassing the network. Single-inlet experiments show the influence of variable flow rate, atmospheric pressure and temperature on the stability of flow modes and allow to delineate a droplet and rivulet regime. The transition between these regimes exhibits mixed flow characteristics. Additionally, multi-inlet setups with constant total inflow rates decrease the variance induced by erratic free-surface flow dynamics. We investigate the impacts of variable aperture widths, horizontal offsets of vertical fracture surfaces, and alternating injection methods for both flow regimes. Hereby, growing fracture cascades delay arrival times but also enhance variance. Normalized fracture inflow rates allow to demonstrate and compare the effects of variable geometric features. Firstly, the fracture filling can be described by plug flow. At later stages it transitions into a Washburn-type flow, which we compare to an analytical solution for the case of rivulet flow. Observations show a considerably higher bypass efficiency, where droplet flow is the prevailing regime. This behaviour may not be recovered by plug flow but also transitions into a Washburn stage.