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Modelling rapid subsurface flow at the hillslope scale with explicit representation of preferential flow paths

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Rapid lateral flow processes via preferential flow paths are widely accepted to play a key role for rainfall-runoff response in temperate humid headwater catchments. A quantitative description of these processes, however, is still a major challenge in hydrological research, not least because detailed information about the architecture of subsurface flow paths are often impossible to obtain at a natural site without disturbing the system.

Our study combines physically based modelling and field observations with the objective to better understand how flow network configurations influence the hydrological response of hillslopes. The system under investigation is a forested hillslope with a small perennial spring at the study area Heumöser, a headwater catchment of the Dornbirnerach in Vorarlberg, Austria. In-situ points measurements of field-saturated hydraulic conductivity and dye staining experiments at the plot scale revealed that shrinkage cracks and biogenic macropores function as preferential flow paths in the fine-textured soils of the study area, and these preferential flow structures were active in fast subsurface transport of artificial tracers at the hillslope scale.

For modelling of water and solute transport, we followed the approach of implementing preferential flow paths as spatially explicit structures of high hydraulic conductivity and low retention within the 2D process-based model CATFLOW. Many potential configurations of the flow path network were generated as realisations of a stochastic process informed by macropore characteristics derived from the plot scale observations. Together with different realisations of soil hydraulic parameters, this approach results in a Monte Carlo study. The model setups were used for short-term simulation of a sprinkling and tracer experiment, and the results were evaluated against measured discharges and tracer breakthrough curves. Although both criteria were taken for model evaluation, still several model setups produced acceptable matches to the observed behaviour. These setups were selected for long-term simulation, the results of which were compared against water level measurements at two piezometers along the hillslope and the integral discharge response of the spring to reject some non-behavioural model setups and further reduce equifinality.

The results of this study indicate that process-based modelling can provide a means to distinguish preferential flow networks on the hillslope scale when complementary measurements to constrain the range of behavioural model setups are available. These models can further be employed as a virtual reality to investigate the characteristics of flow path architectures and explore effective parameterisations for larger scale applications.