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From Rain to Runoff: Unraveling Hidden Subsurface Flowpaths in Hillslopes

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Subsurface stormflow (SSF) can be a significant runoff mechanism in many headwater catchments, accounting for up to 90% of streamflow during rainfall-runoff events. Despite its hydrological significance, the processes controlling SSF are not yet fully understood. In order to investigate SSF dynamics and flowpath behavior in more detail, we conducted several field experiments including artificial rainfall simulations with deuterium-labelled water, monitored SSF response of artificial and natural rainfall events and performed soil core isotope profiling on a forested hillslope in a Black Forest catchment.

A dual-layer trench system captured SSF in two soil depth layers during experimental and natural events. Labelled rainfall water infiltrated to depths of over 1 m within minutes; however, isotope profiles revealed that the labelled water was largely confined to the top 20 cm of the soil matrix, indicating rapid bypass flow via deep preferential pathways. While only ~10% of the applied labelled water was recovered as SSF outflow, ~45% remained in the topsoil. SSF outflow was dominated by pre-event water, suggesting displacement via piston flow due to infiltrating labelled water, supporting a dual-domain conceptual model. During natural rainfall, the ratio of pre-event to event water varied with antecedent soil moisture, indicating that the storage–remobilization behavior was modulated by initial wetness conditions — wetter soils remobilized stored pre-event water more effectively. Additionally, event water volumes scaled linearly with precipitation inputs, indicating that larger storms activate more flowpaths and/or increase transport velocities.

These results highlight the complexity and spatial heterogeneity of subsurface flow paths in hillslopes. They emphasize the importance of high-resolution monitoring and targeted experiments in improving our understanding and representations of SSF dynamics in catchment-scale models, particularly with regard to solute transport and runoff generation.