From Rain to Runoff: Unraveling Hidden Subsurface Flowpaths in Hillslopes

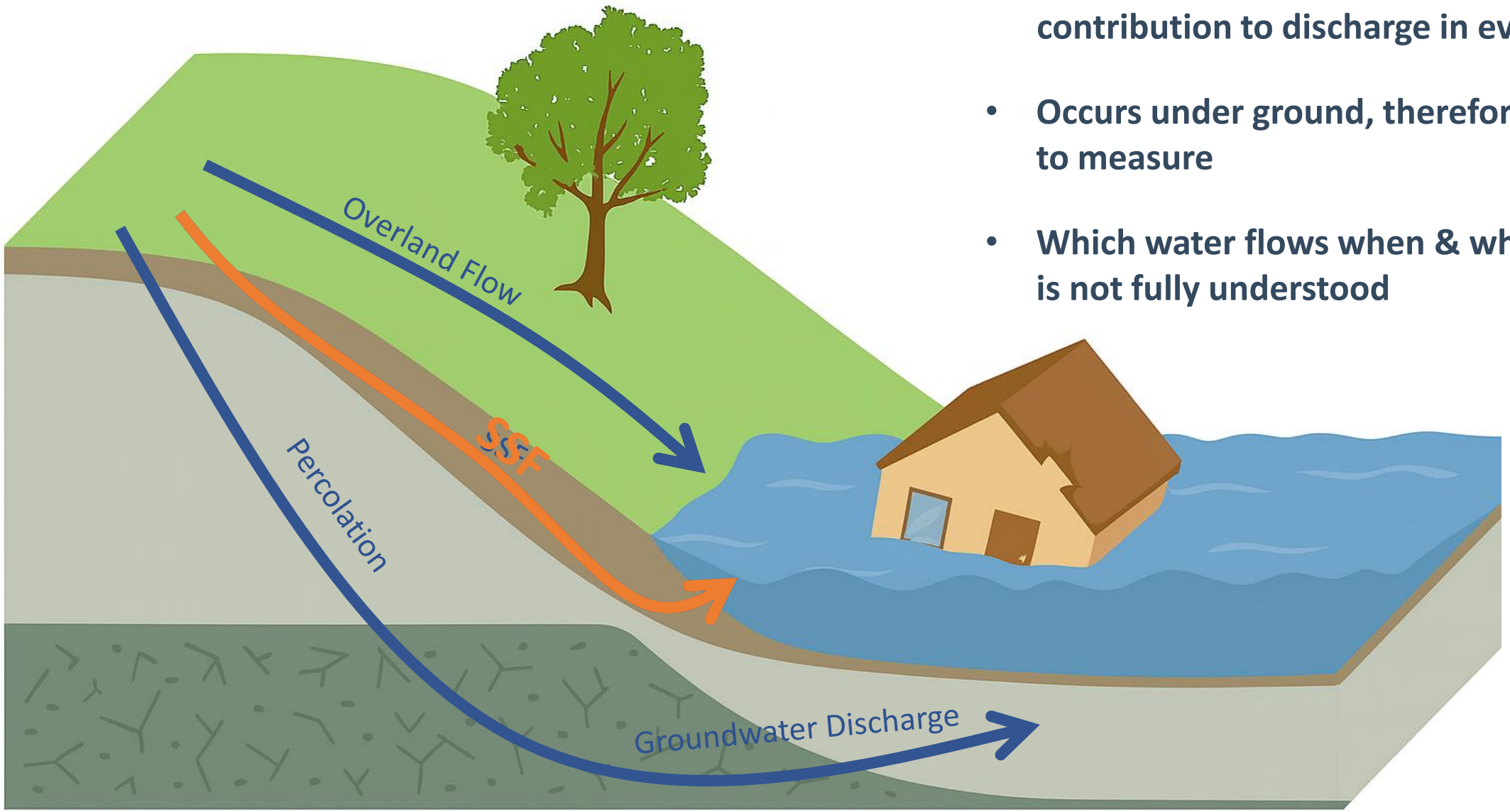
Jonas Pyschik

Alexey Kuleshov, Emanuel Thoenes, Christina Fasching, Stefan Achleitner, Theresa Blume, Peter Chifflard, Luisa Hopp, Bernhard Kohl, Markus Weiler

- **Subsurface Stormflow (SSF): Substantial contribution to discharge in events**

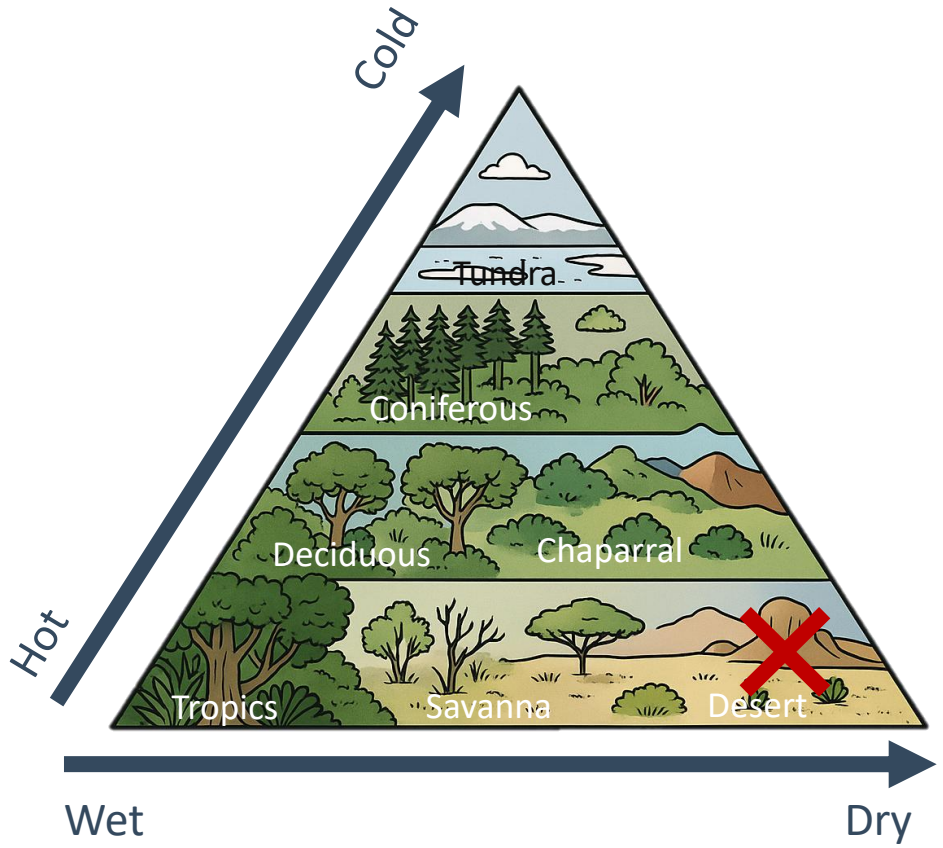
Beasley, 1976

- **Occurs under ground, therefore it is hard to measure**
- **Which water flows when & where is not fully understood**



What we do know about SSF

SSF can occur (nearly) everywhere

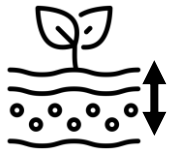


McMillan et al., 2025

Reported controls

Concave & Convergent Hillslopes

Anderson and Burt, 1978



Soil Depth & Storage Capacity

van Verseveld et al., 2017

Impeding / highly conductive layers

Whipkey, 1965

Bedrock Topography (sinks)

Freer et al., 2002

Connectivity of contributing areas

Hopp and McDonnell, 2009

Preferential Flow

Angermann et al., 2017

Intensity & Threshold based

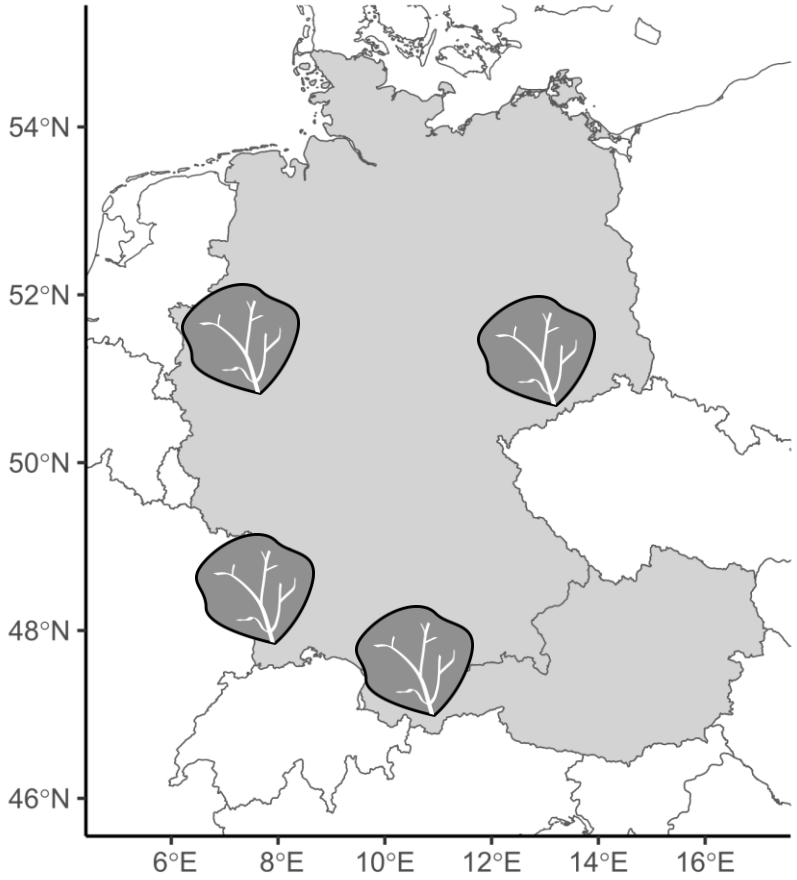
Tromp-van Meerveld and McDonnell, 2006

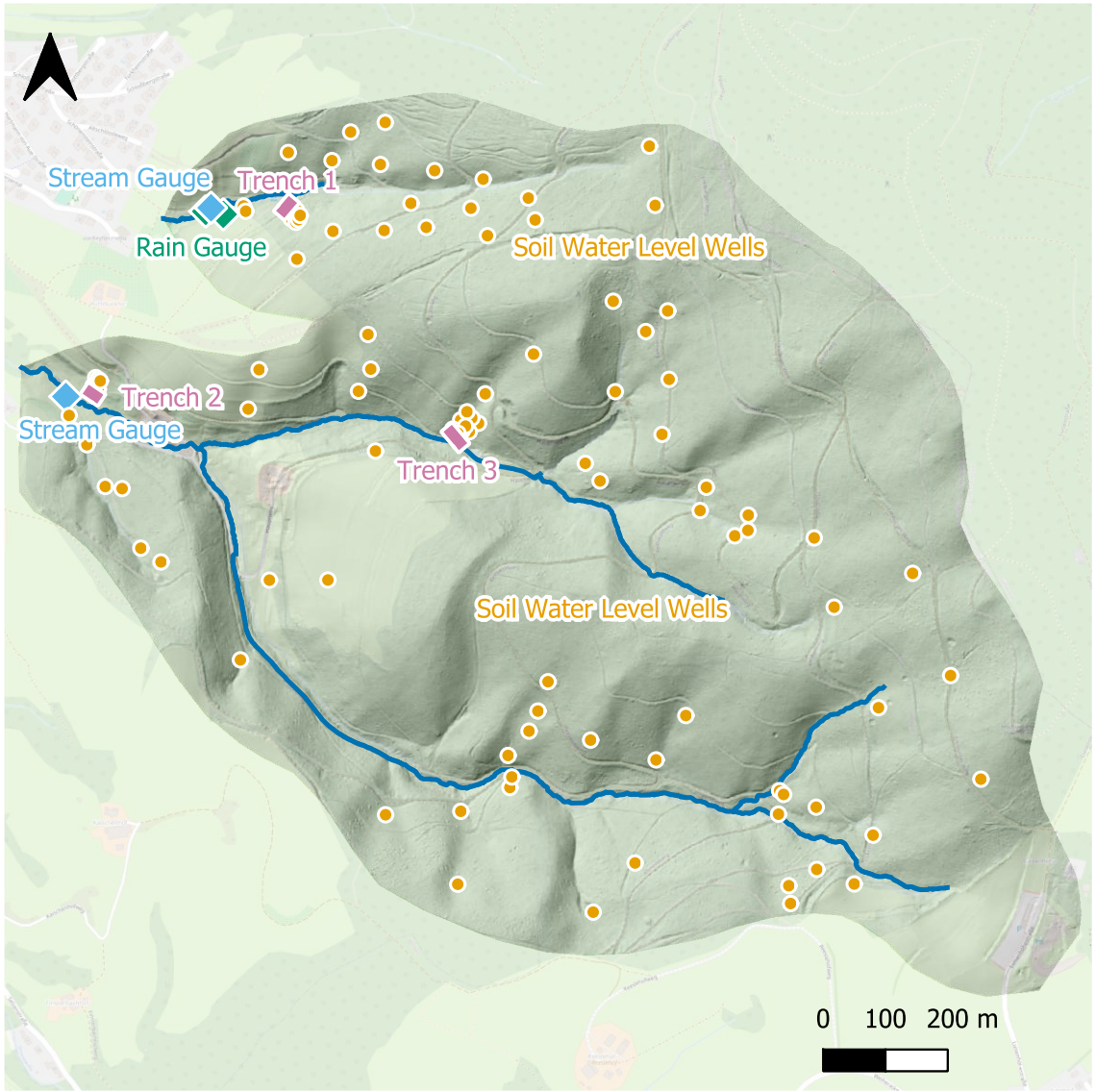
Old Water

Fritz et al., 1976

universität freiburg

The Research Catchments

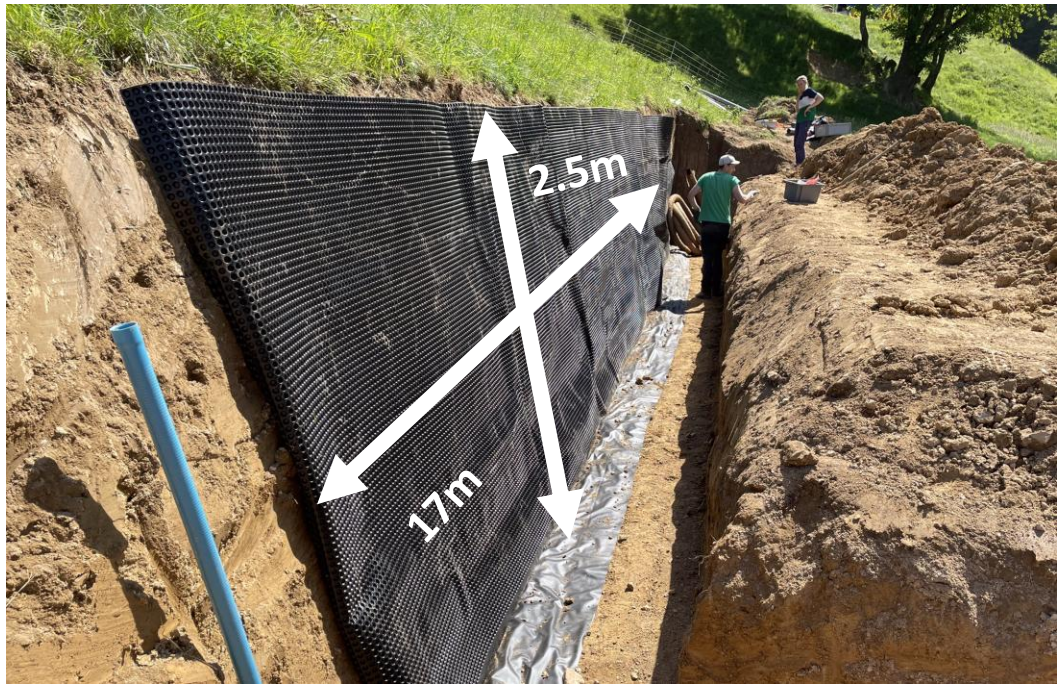




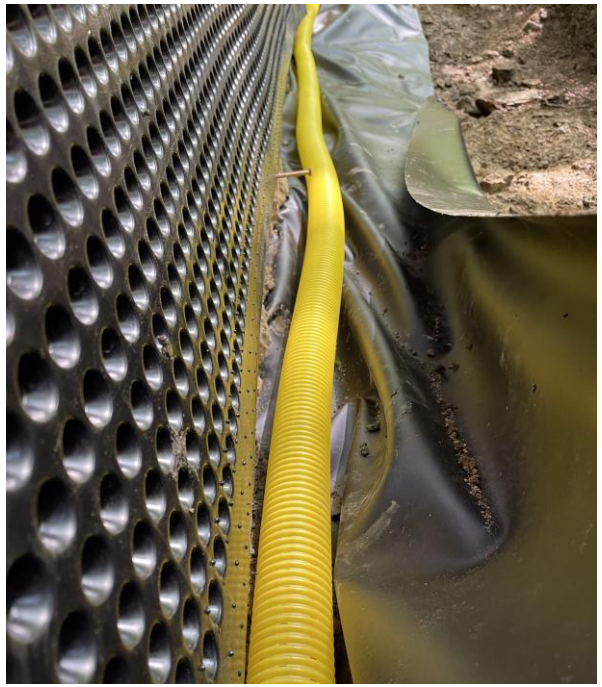
1. How does precipitation become SSF?

2. Is there a constant event water contribution to SSF or does it change from event to event?

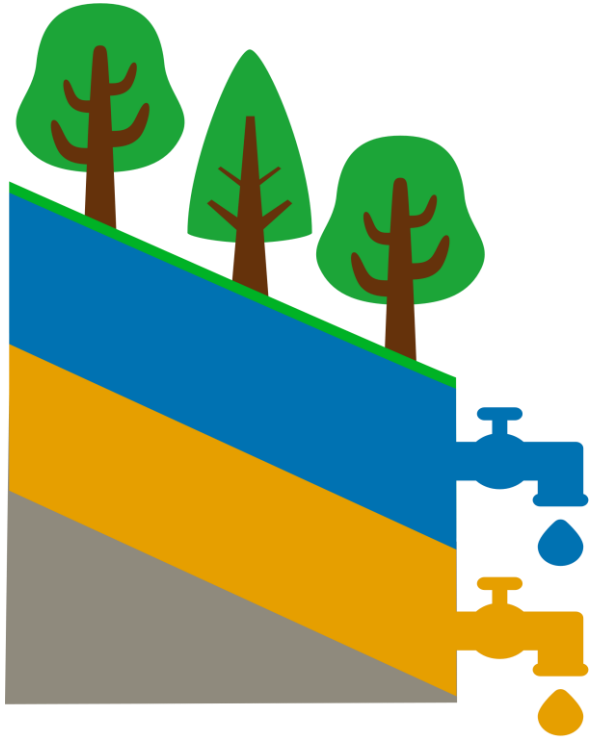
Constructing SSF Trenches



Trench excavated

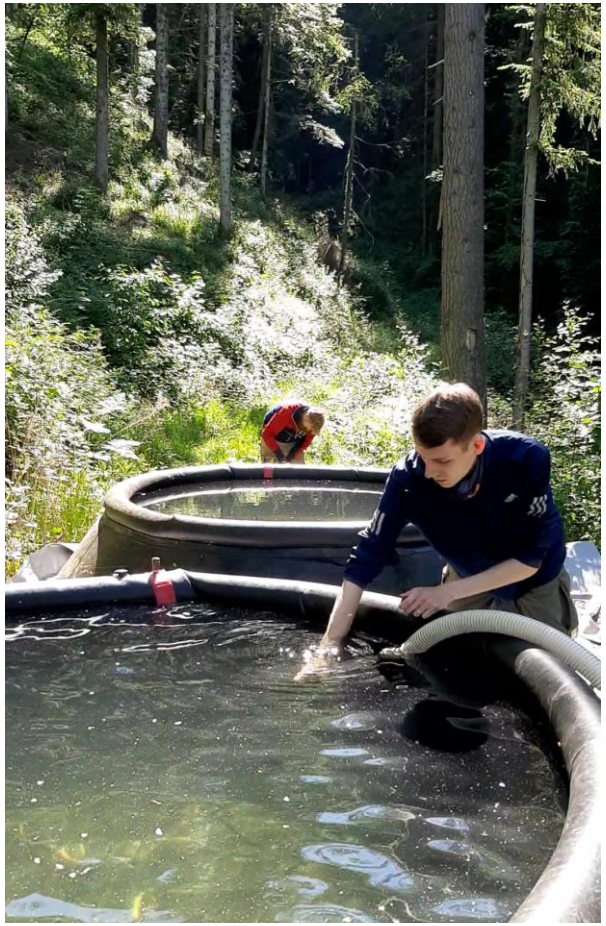


Pond foil & pipe funnel water out



Capturing Flow in
Top: 0-80 cm
Bottom: 80-250 cm

Conducting Sprinkling Experiments



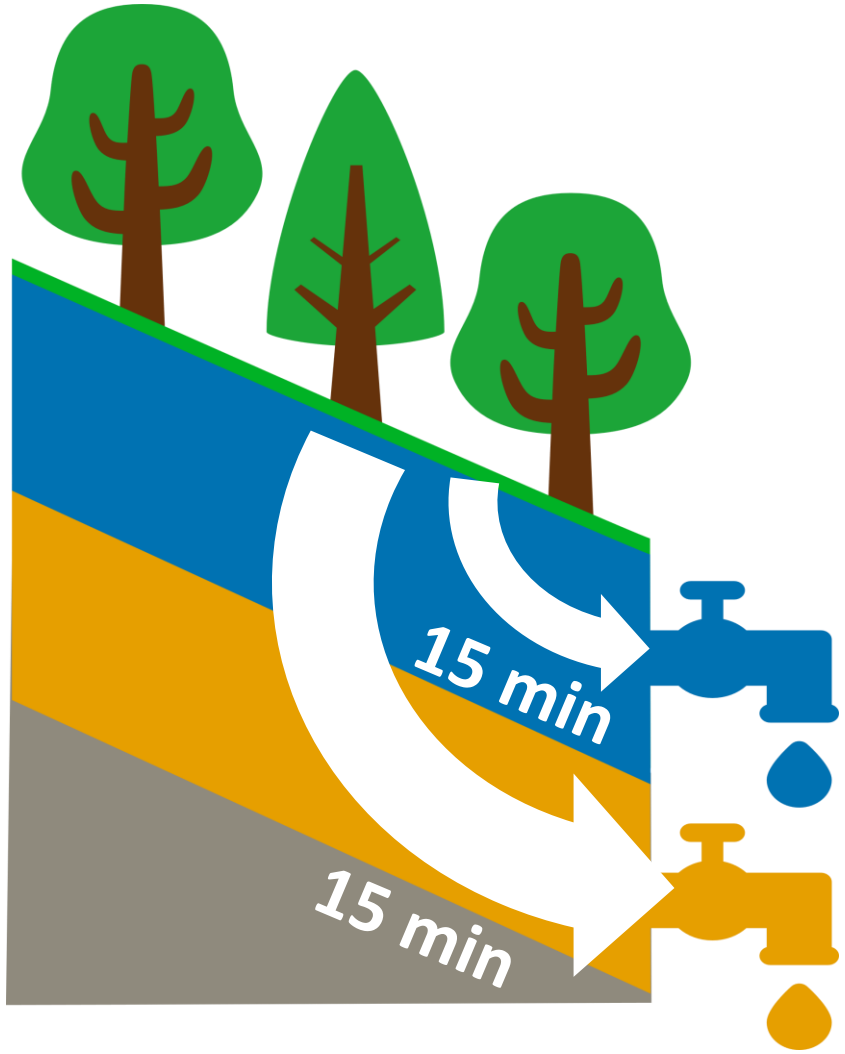
2x 4.5 m³ Reservoirs
1x labeled δ^2H to +220 ‰

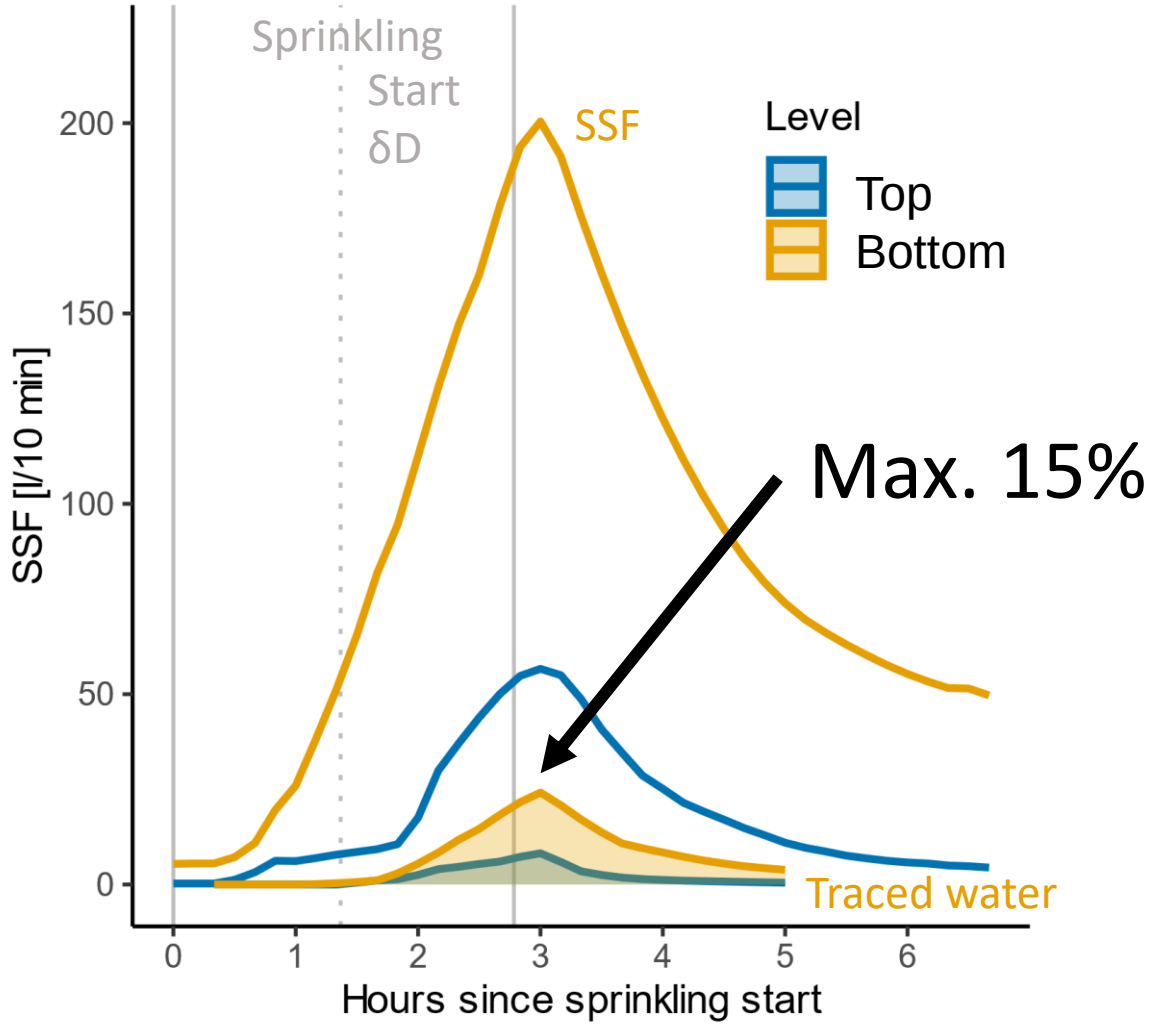
Sprinkled with 16 mm/h for 3h
Deuterated water start 1.5 h

Continuous outflow monitoring

Manual samples every 20 min

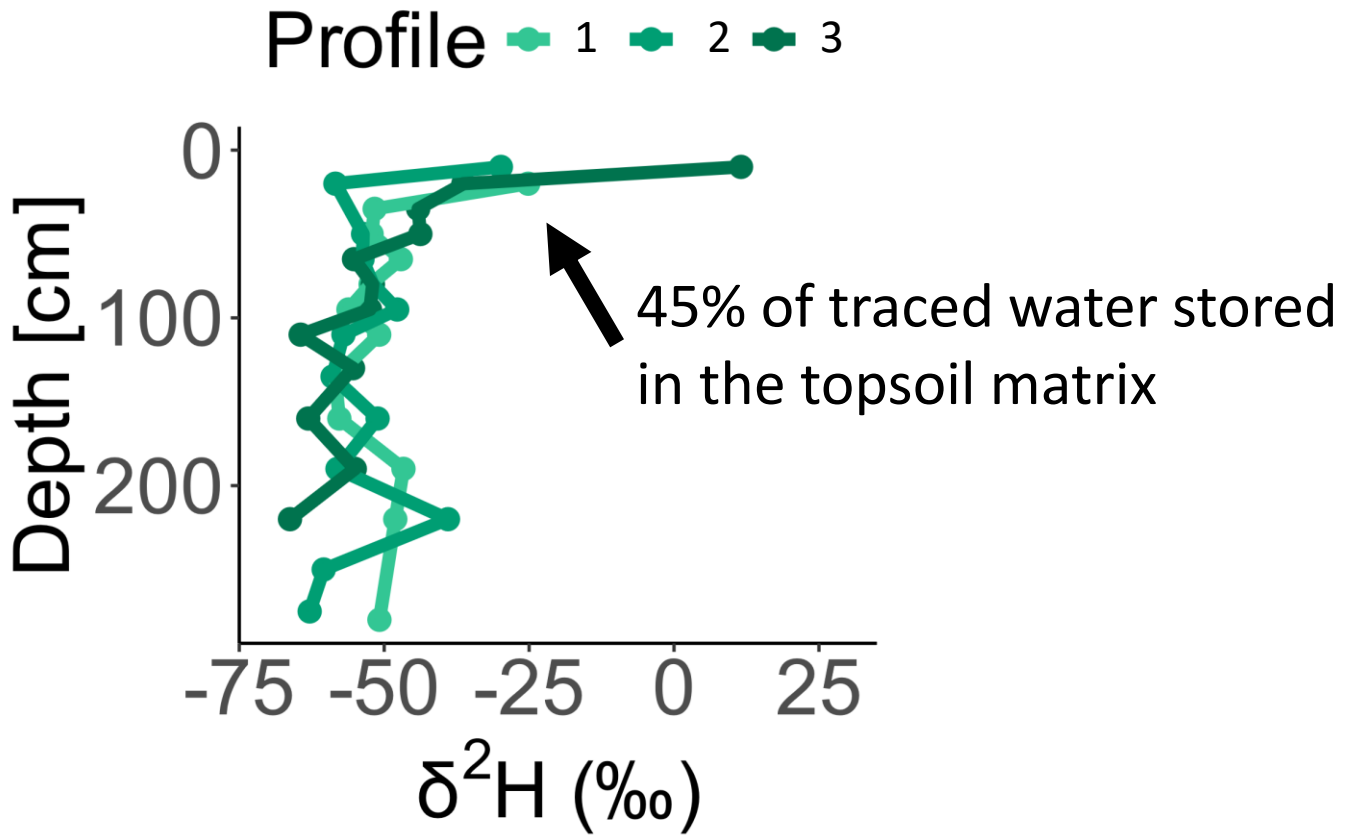
Result: Quick but minor traced water reaction





Only 7.5% discharged the first day
but runoff coefficient = 0.6

Storage and Remobilisation



1 day after irrigation

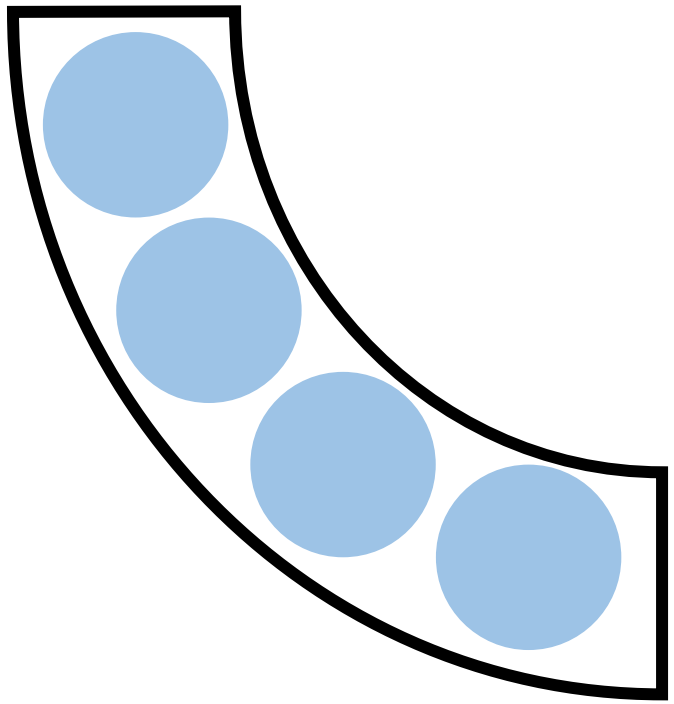
The mechanism: Two end members in a two domain system

Soil Matrix

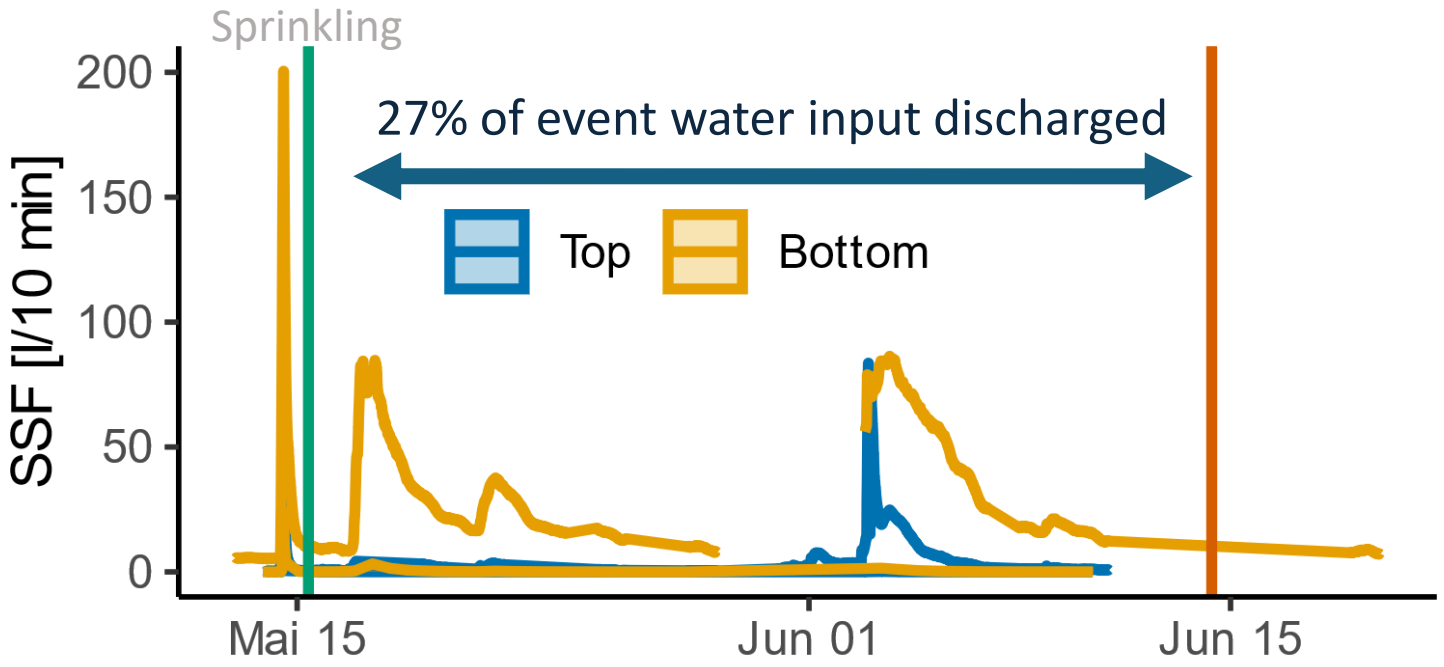
Translatory (Piston) Flow

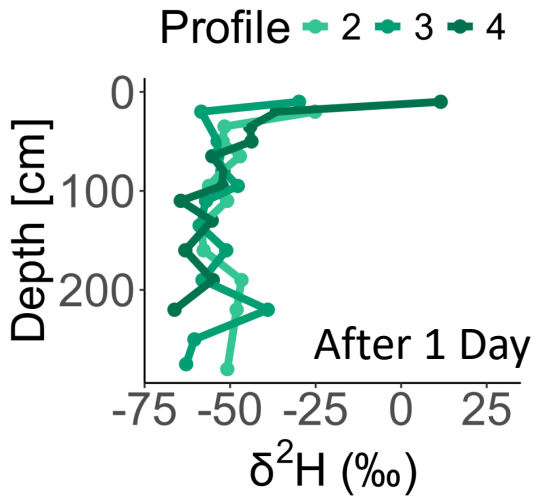
Most SSF pre-event water stems from the soil matrix

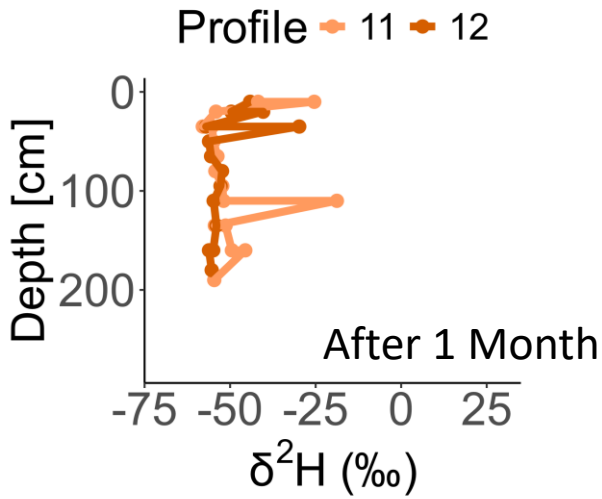
All observed event water traveled through preferential flowpaths



Storage and Remobilisation





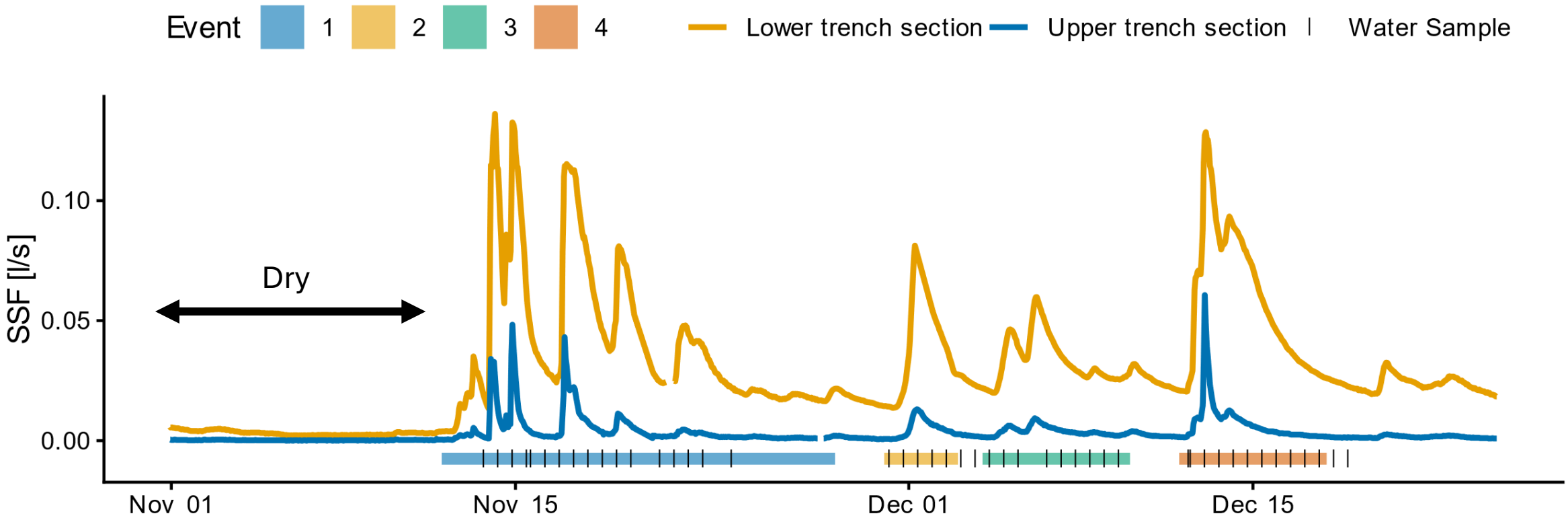


- Traced water is percolating & released from soil storage

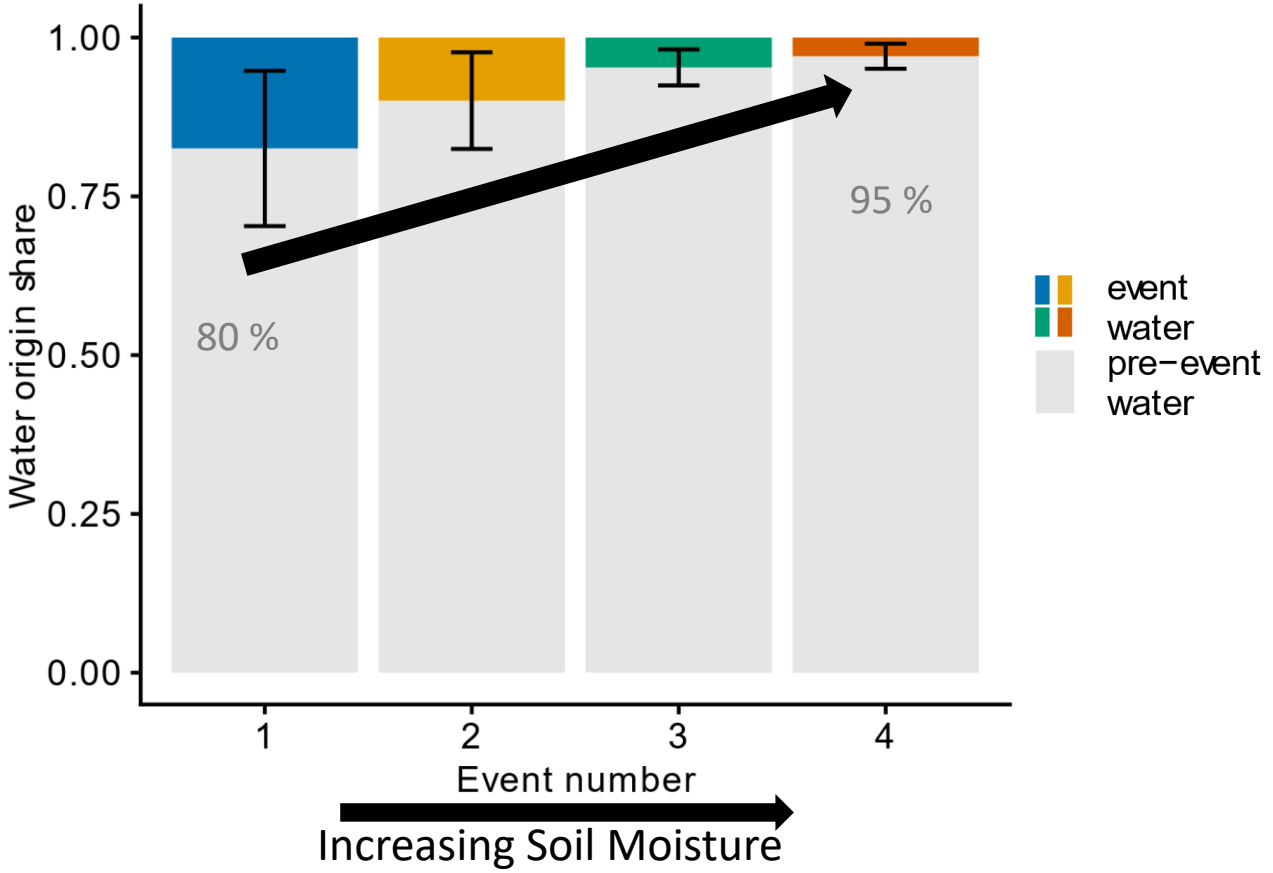
1. How does precipitation become SSF?

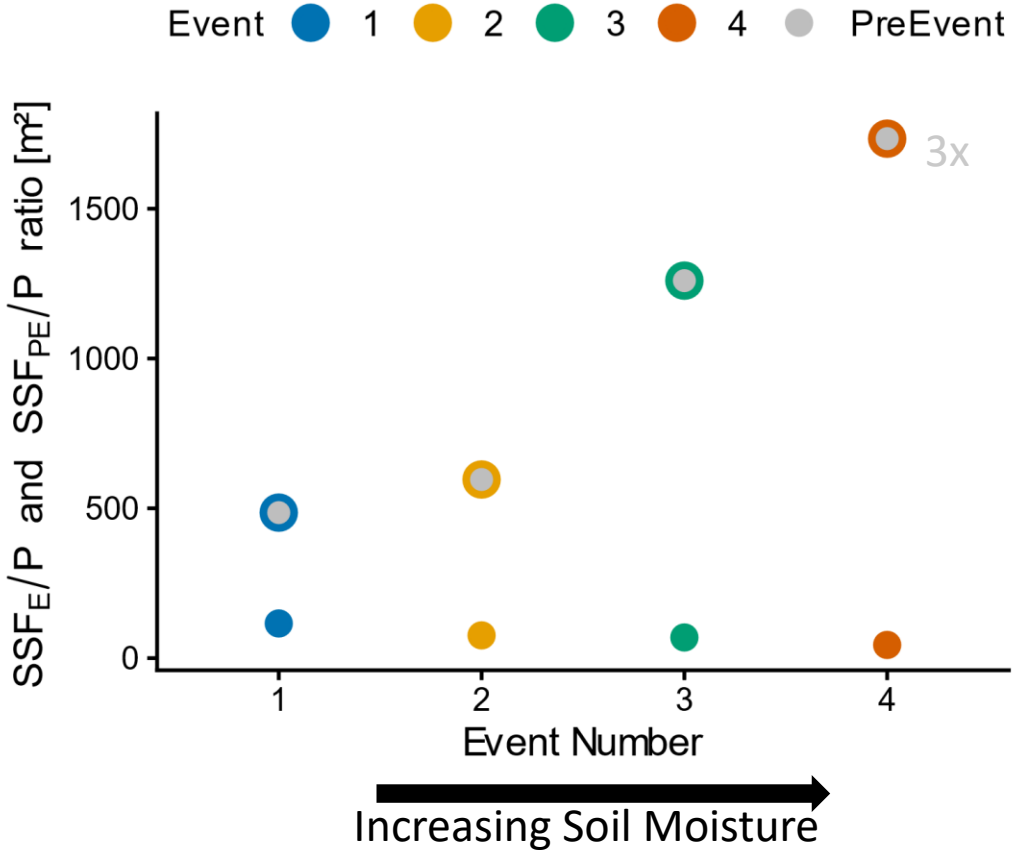
- *max. 15% of SSF during sprinkling experiment is event water*
- *Event water discharged in SSF travels through preferential flowpaths*
- *Remaining Event water infiltrates into soil matrix where it:*
  - *remobilizes PreEvent water via piston flow*
  - *is stored in the soil matrix, remobilized in next events*

Natural SSF Event Samples



Hillslope wetup SSF event water dynamics





Event water = preferential flow

➢ more active flowpaths or increased velocity

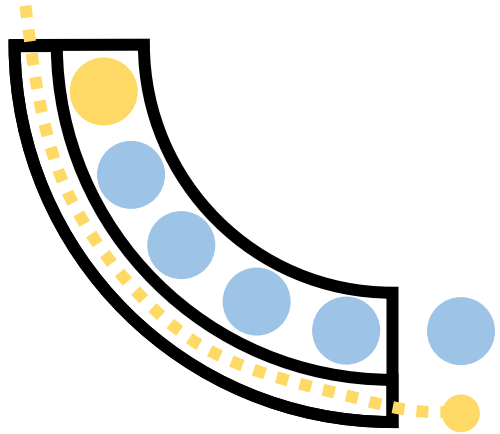
2. Is there a constant event water contribution to SSF

or does it change from event to event?

- *Event volume contribution depends on precipitation volume*
- *Wetter hillslopes mobilize PreEvent water more efficiently*

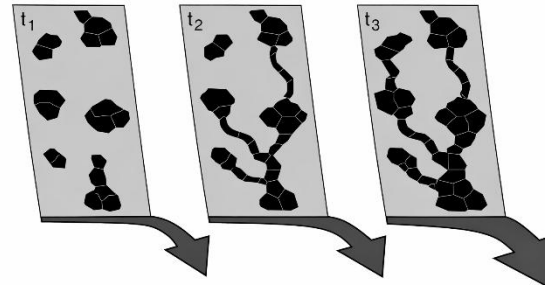
Conclusion

1. Different water-ages travel via different SSF flow domains



pre-event water = matrix piston flow	event water = preferential flow

2. Wetter hillslopes mobilize substantially more pre-event SSF



Connect-and-react mechanism

Bachmair & Weiler 2011

Gefördert durch
DFG Deutsche Forschungsgemeinschaft

Thank you!

Sources

Anderson, M. G., & Burt, T. P. (1978). The role of topography in controlling throughflow generation. *Earth Surface Processes*, *3*(4), 331–344. https://doi.org/10.1002/esp.3290030402

Angermann, L., Jackisch, C., Allroggen, N., Sprenger, M., Zehe, E., Tronicke, J., Weiler, M., & Blume, T. (2017). Form and function in hillslope hydrology: Characterization of subsurface flow based on response observations. *Hydrology and Earth System Sciences*, *21*(7), 3727–3748. https://doi.org/10.5194/hess-21-3727-2017

Beasley, R. S. (1976). Contribution of subsurface flow from the upper slopes of forested watersheds to channel flow. *Soil Science Society of America Journal*, *40*(6), 955–957. https://doi.org/10.2136/sssaj1976.03615995004000060039x

Freer, J., McDonnell, J. J., Beven, K. J., Peters, N. E., Burns, D. A., Hooper, R. P., Aulenbach, B., & Kendall, C. (2002). The role of bedrock topography on subsurface storm flow. *Water Resources Research*, *38*(12), 5-1–5-16. https://doi.org/10.1029/2001WR000872

Fritz, P., Cherry, J. A., Sklash, M., & Weyer, K. U. (1976). Storm runoff analysis using environmental isotopes and major ions. In *Interpretation of environmental isotope and hydrochemical data in groundwater hydrology* (pp. 111–130). https://inis.iaea.org/records/bzat4-nh314

Hopp, L., & McDonnell, J. J. (2009). Connectivity at the hillslope scale: Identifying interactions between storm size, bedrock permeability, slope angle and soil depth. *Journal of Hydrology*, *376*(3–4), 378–391. https://doi.org/10.1016/j.jhydrol.2009.07.047

McMillan, H., Araki, R., Bolotin, L., Kim, D.-H., Coxon, G., Clark, M., & Seibert, J. (2025). Global patterns in observed hydrologic processes. *Nature Water*, 1–10. https://doi.org/10.1038/s44221-025-00407-w

Tromp-van Meerveld, H. J., & McDonnell, J. J. (2006). Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope: Subsurface flow relations, 1. *Water Resources Research*, *42*(2). https://doi.org/10.1029/2004WR003778

van Verseveld, W. J., Barnard, H. R., Graham, C. B., McDonnell, J. J., Brooks, J. R., & Weiler, M. (2017). A sprinkling experiment to quantify celerity–velocity differences at the hillslope scale. *Hydrology and Earth System Sciences*, *21*(11), 5891–5910. https://doi.org/10.5194/hess-21-5891-2017

Whipkey, R. Z. (1965). Subsurface stormflow from forested slopes. *International Association of Scientific Hydrology. Bulletin*, *10*(2), 74–85. https://doi.org/10.1080/02626666509493392