HYDROLOGY

universität freiburg

Hidden Pathways: Unraveling Subsurface Flow Processes of Water with Stable Isotopes

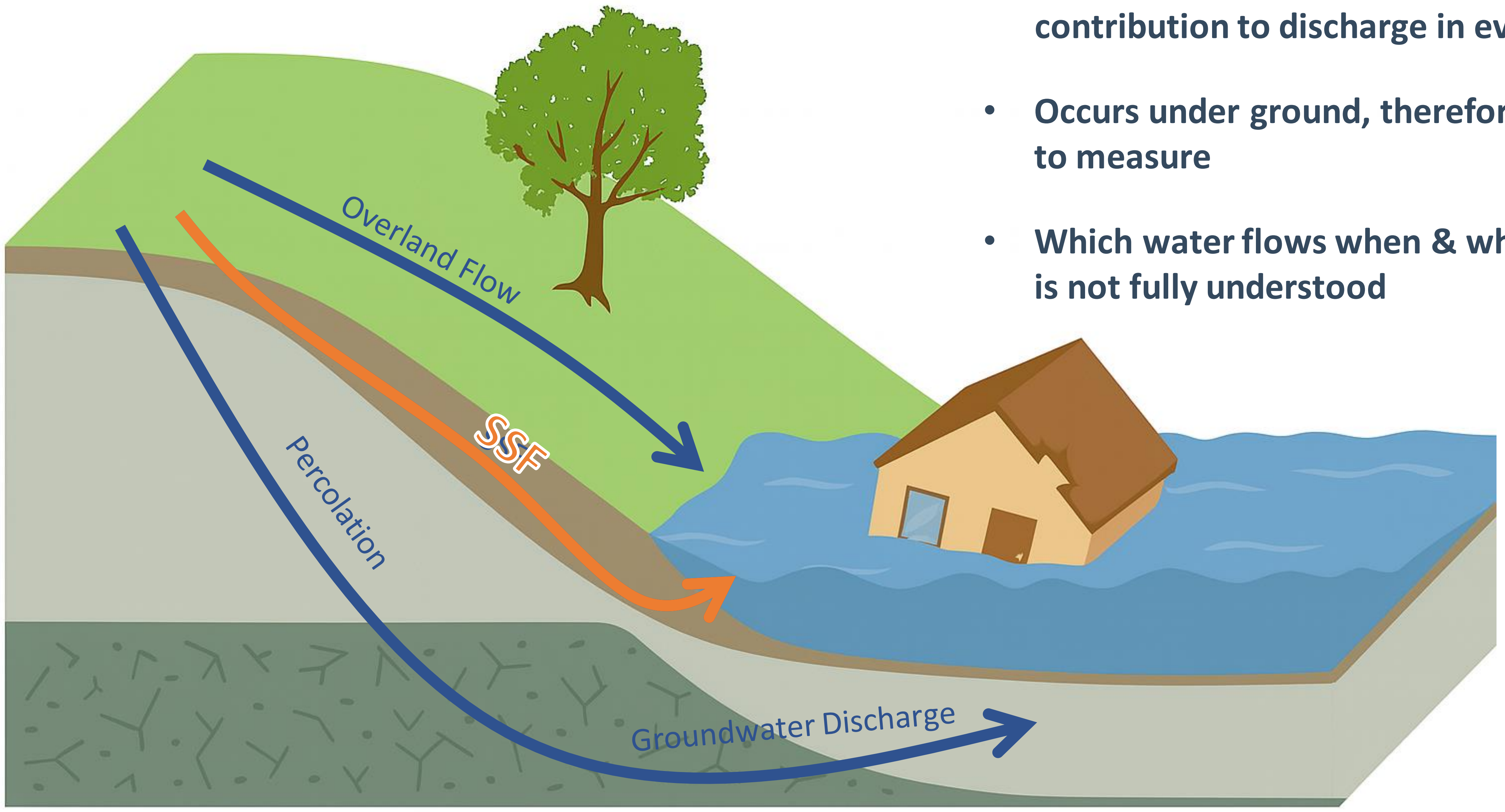
Disputation Jonas Pyschik

14.11.2025

- 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



Introduction

- What we know about subsurface flow
- What research is currently lacking

Preferential Profiles

- “Detecting the occurrence of preferential flow in soils with stable water isotopes” - Pyschik & Weiler (2025, submitted to HESS)

Sprinkling

- „Tracing Subsurface Stormflow: Insights into Preferential Flow and Pre-Event Water Contributions from Controlled Sprinkling Experiments ”- Pyschik et al.; in prep.

Multitracer

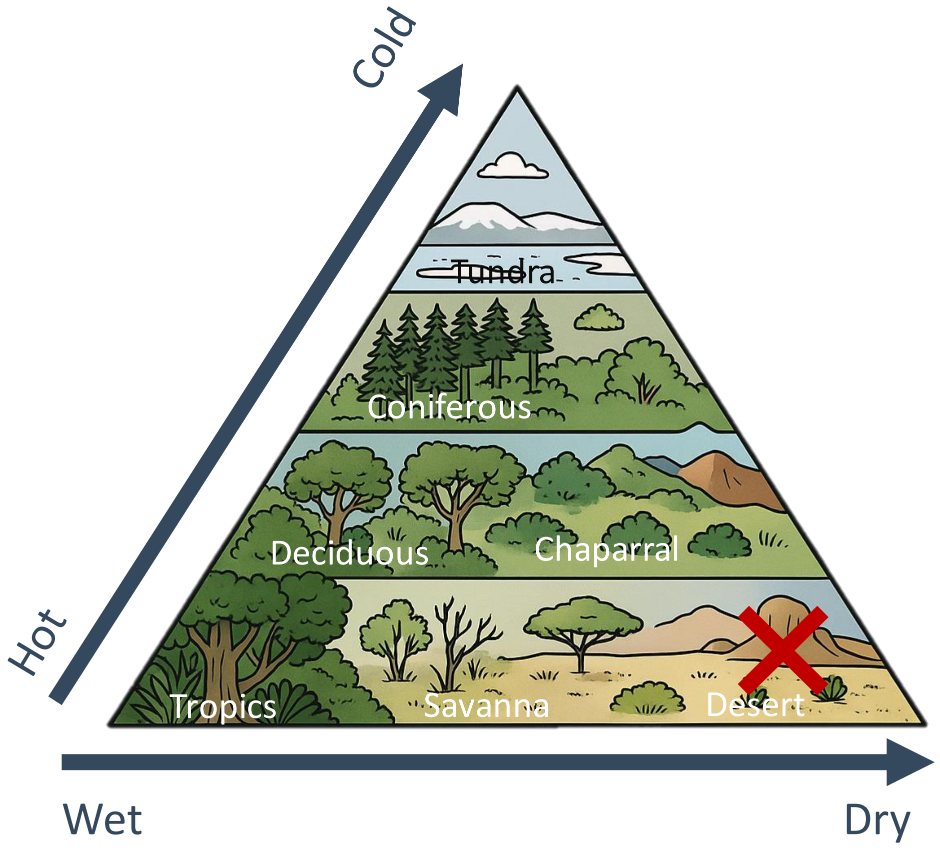
- „Subsurface Stormflow Dynamics and Water Mixing: Insights from Multi-Tracer Analyses Across Hillslope Trenches”- Pyschik et al. (2025, submitted to WRR)

Conclusion

- Insights gained through my research
- Next steps in investigating subsurface flow mechanisms

What we do know about SSF

SSF can occur (nearly) everywhere

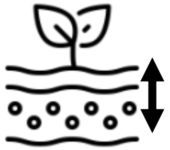


McMillan et al., 2025

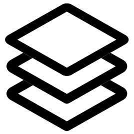
Reported controls


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

What subsurface flow research is often lacking

- Only one catchment and hillslope

or

- Only single events

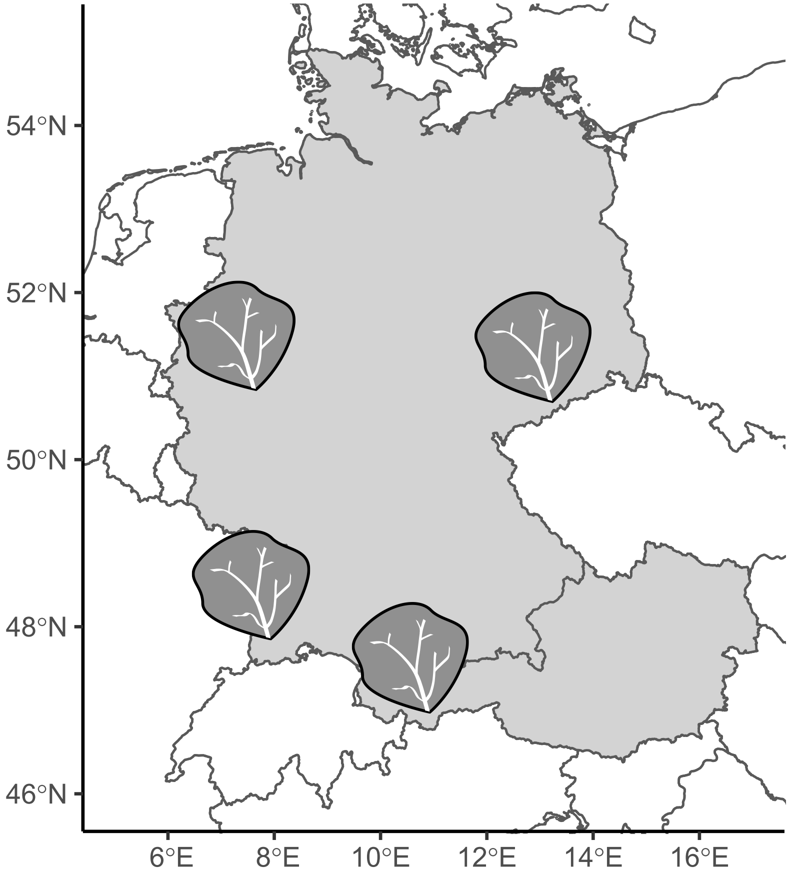
or

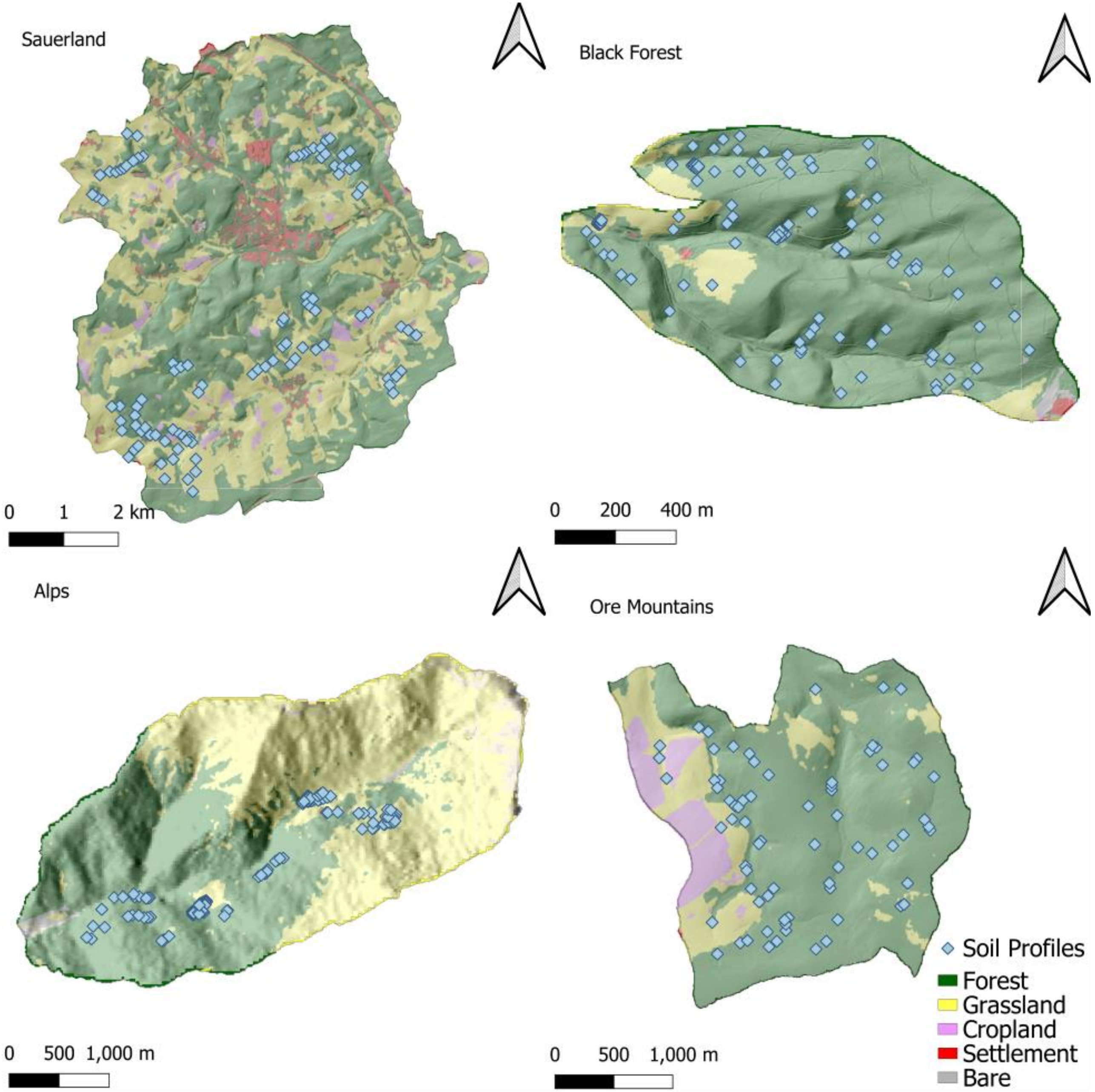
- No measuement of water chemistry,

therefore no information about water origin

➢ *Systematic approach with identical design over multiple catchments & hillslopes is needed*

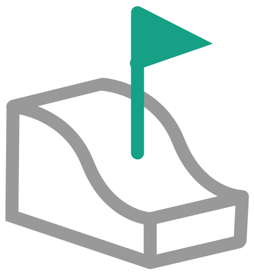
The Research Catchments





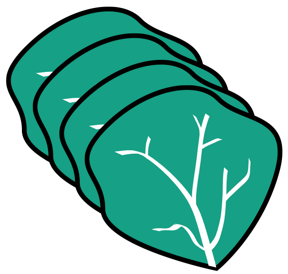
Preferential Profiles

Spatial Scale



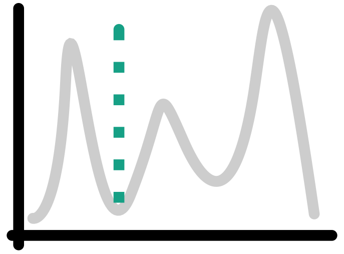
Point

Catchments



All Catchments

Temporal Scale



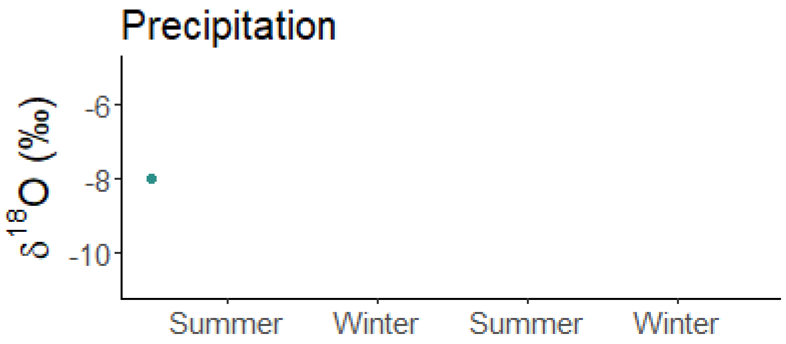
Snapshot

"Detecting the occurrence of preferential flow in soils with stable water isotopes"
Pyschik & Weiler (2025, submitted to HESS)

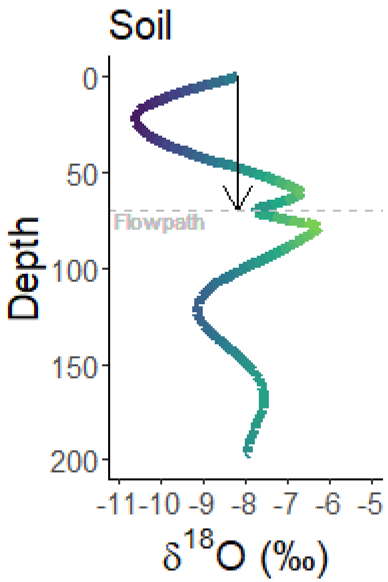
Can we detect preferential flow with stable water isotopes?

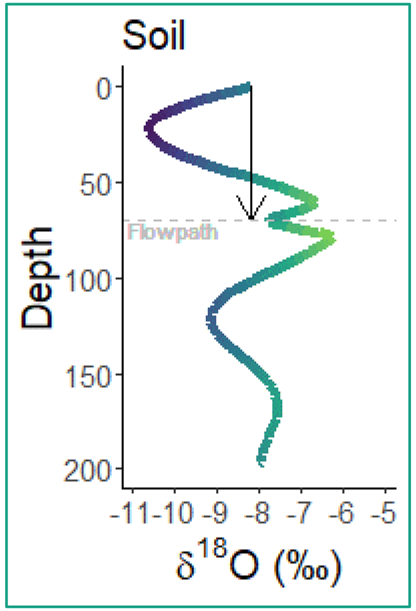
Is preferential flow equally distributed in/between catchments?

Timestamping Water: Isotopic seasonality of precipitation



- $\delta^{18}O$ to $\delta^{2}H$ of precipitation vary seasonally
- Soils preserve seasonality with matrix infiltration
- Preferential flow transport event water, altering the isotope profile
- Snapshot sample should identify these pathways





Taking 400+ soil cores & analyzing them

Drilling

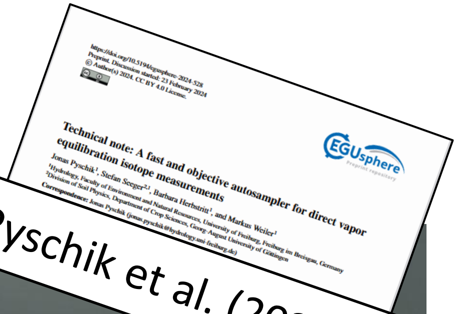
5000+ samples collected

Sampling

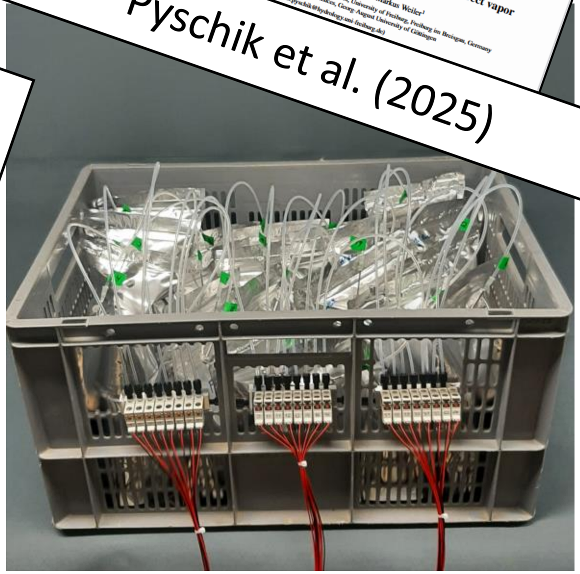
Direct Vapor Equillibration

Wassenaar et al., 2008

Equilibration

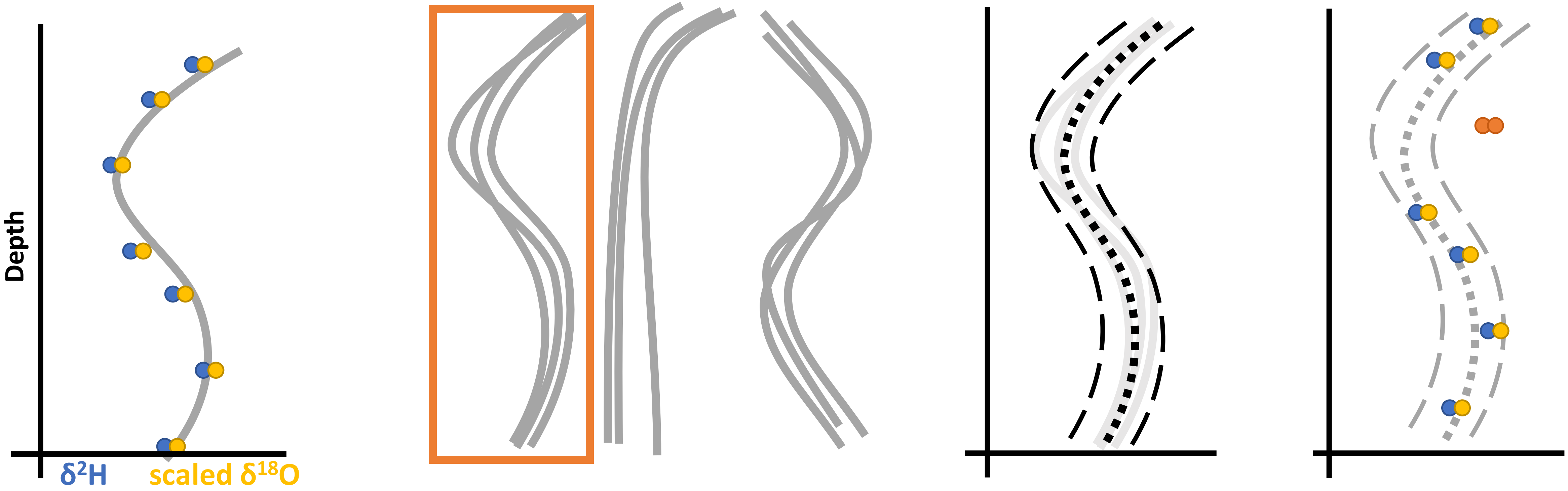


Pyschik et al. (2025)



Analysis

Extracting seasonality profiles



Scale $\delta^{18}O$ to δ^2H value range & fit polynomial

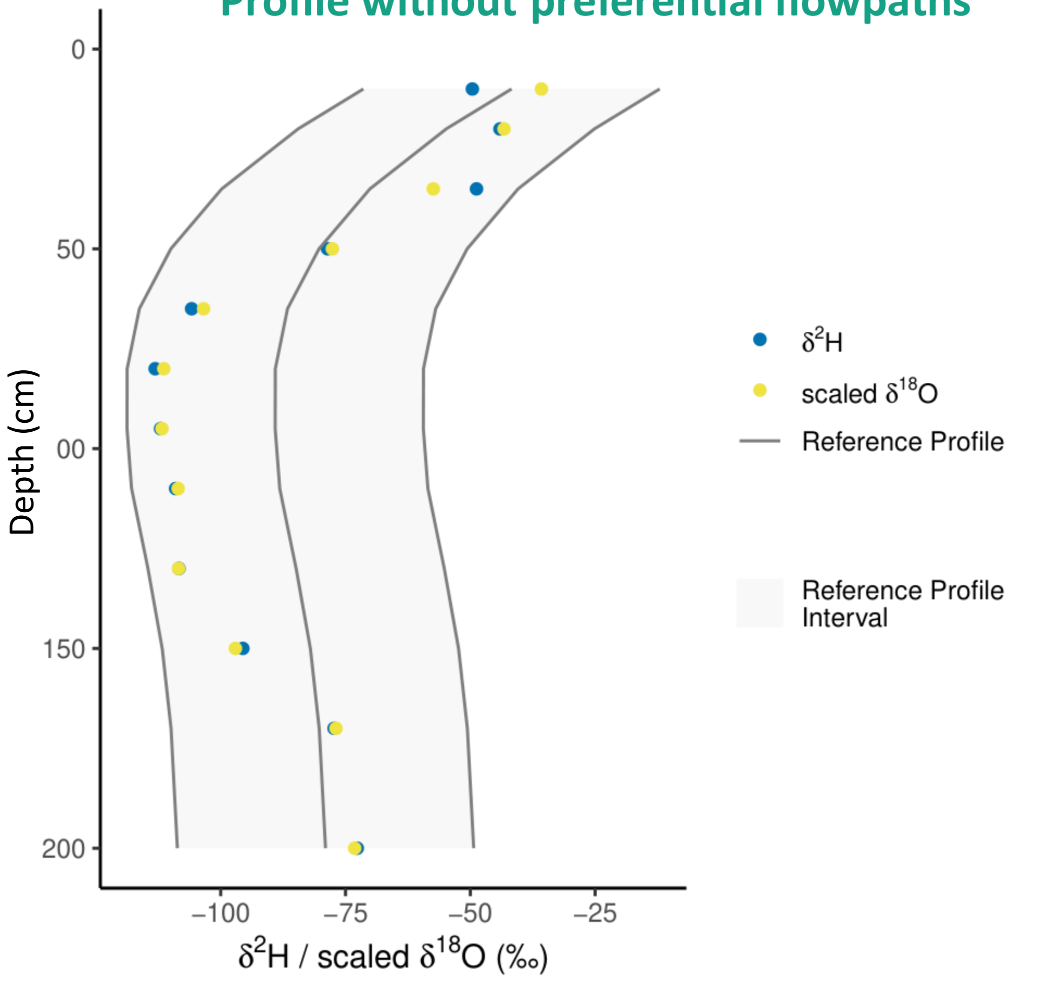
Cluster the polynomials of all profiles & select matching seasonality

Calculate mean & 2 sd threshold

Reference the Profiles & Identify Outliers

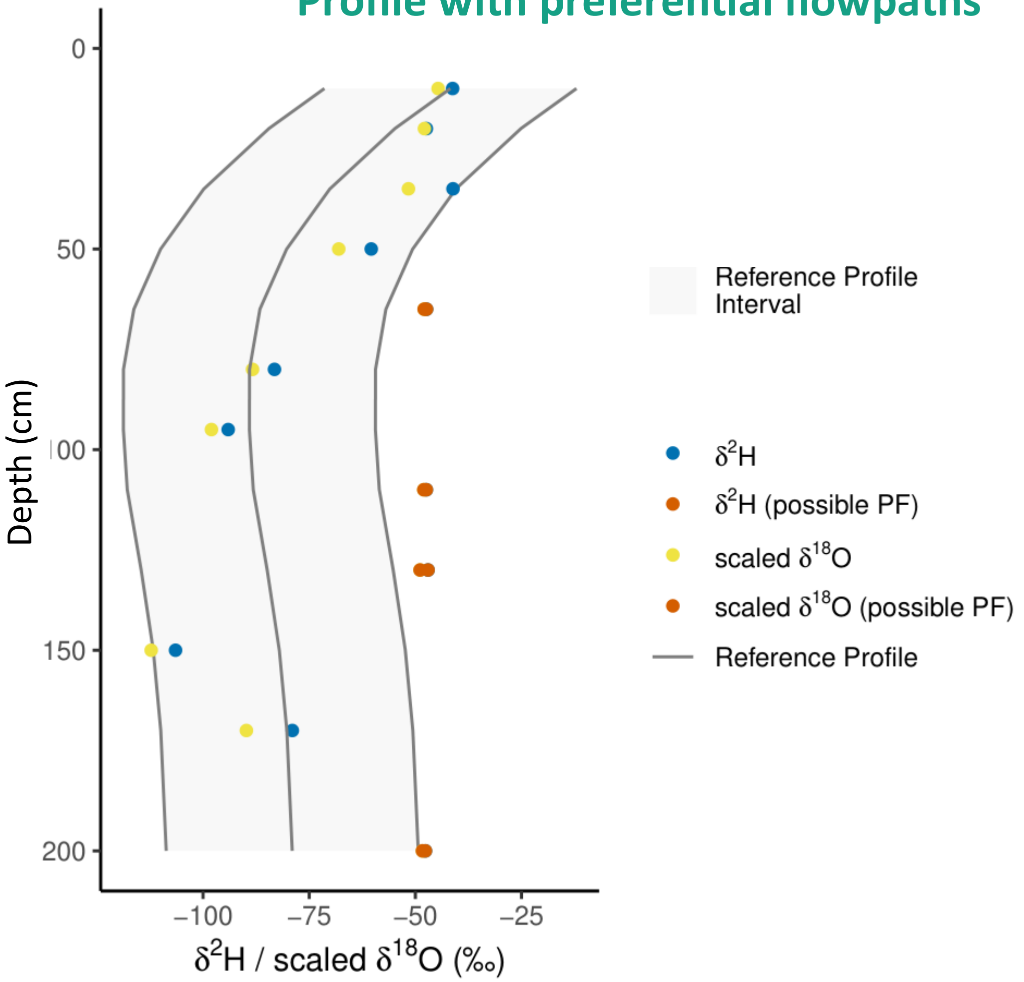
Results: Identified Profiles

Profile without preferential flowpaths



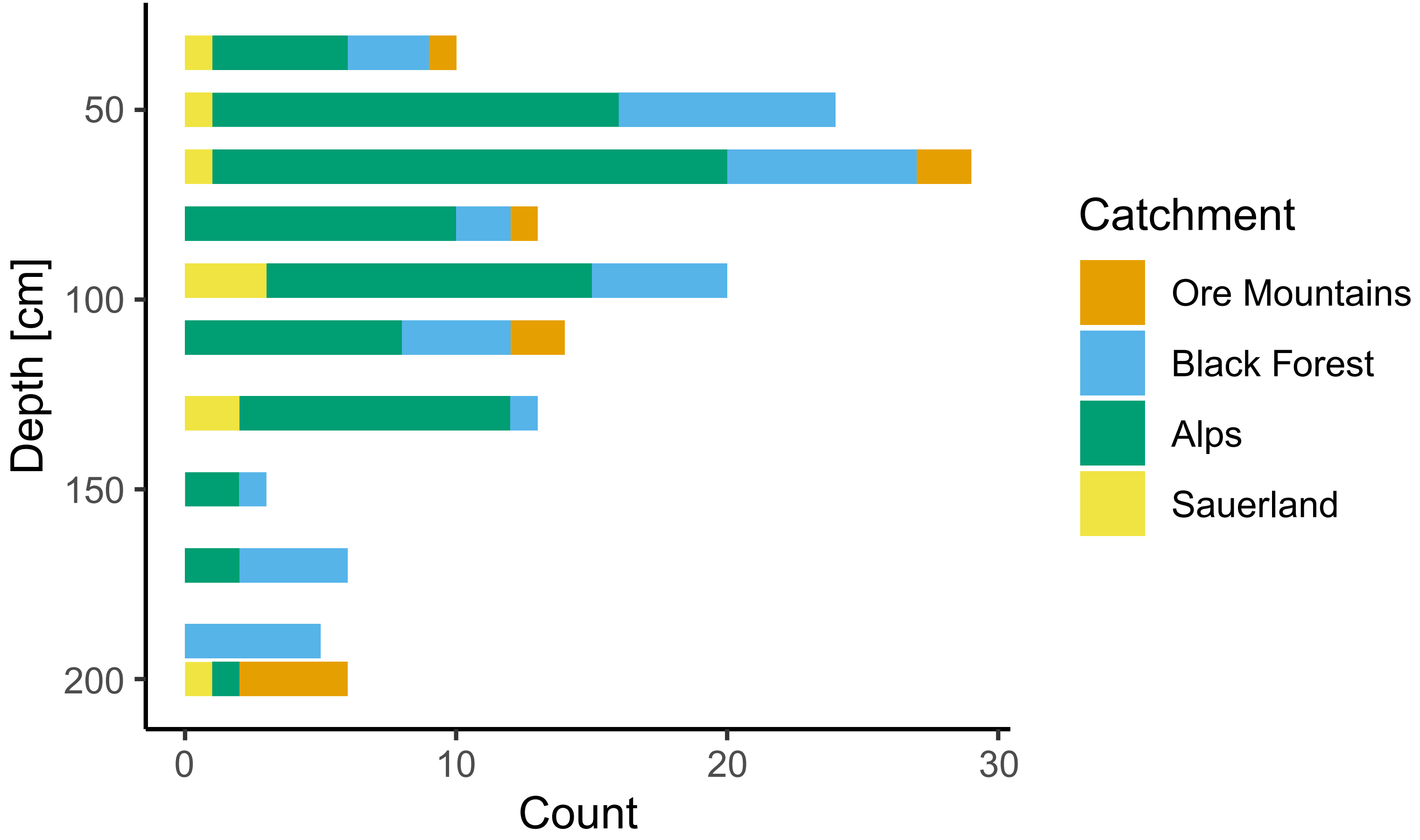
330 Profiles

Profile with preferential flowpaths



63 Profiles

Results: Identified Depths



Results: Correlations

Elevation

Slope

Aspect

Landuse

N **2.7x** more likely to have PF than S

$p = 0.025$

Conclusion

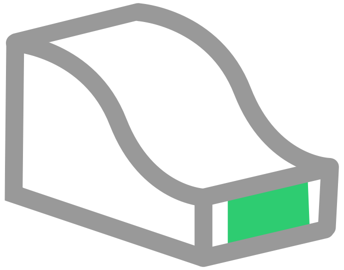
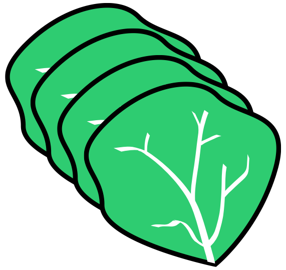
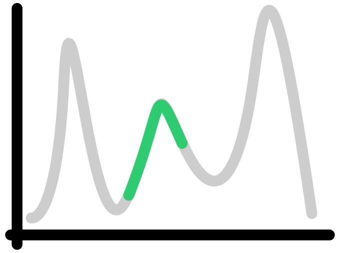
Can we detect preferential flow with stable water isotopes?

- *Yes, but only with large sample campaigns*

Is preferential flow equally distributed in/between catchments?

- *Yes, between catchments*
- *No, within catchments, north facing hillslopes have more PF*

Sprinkling

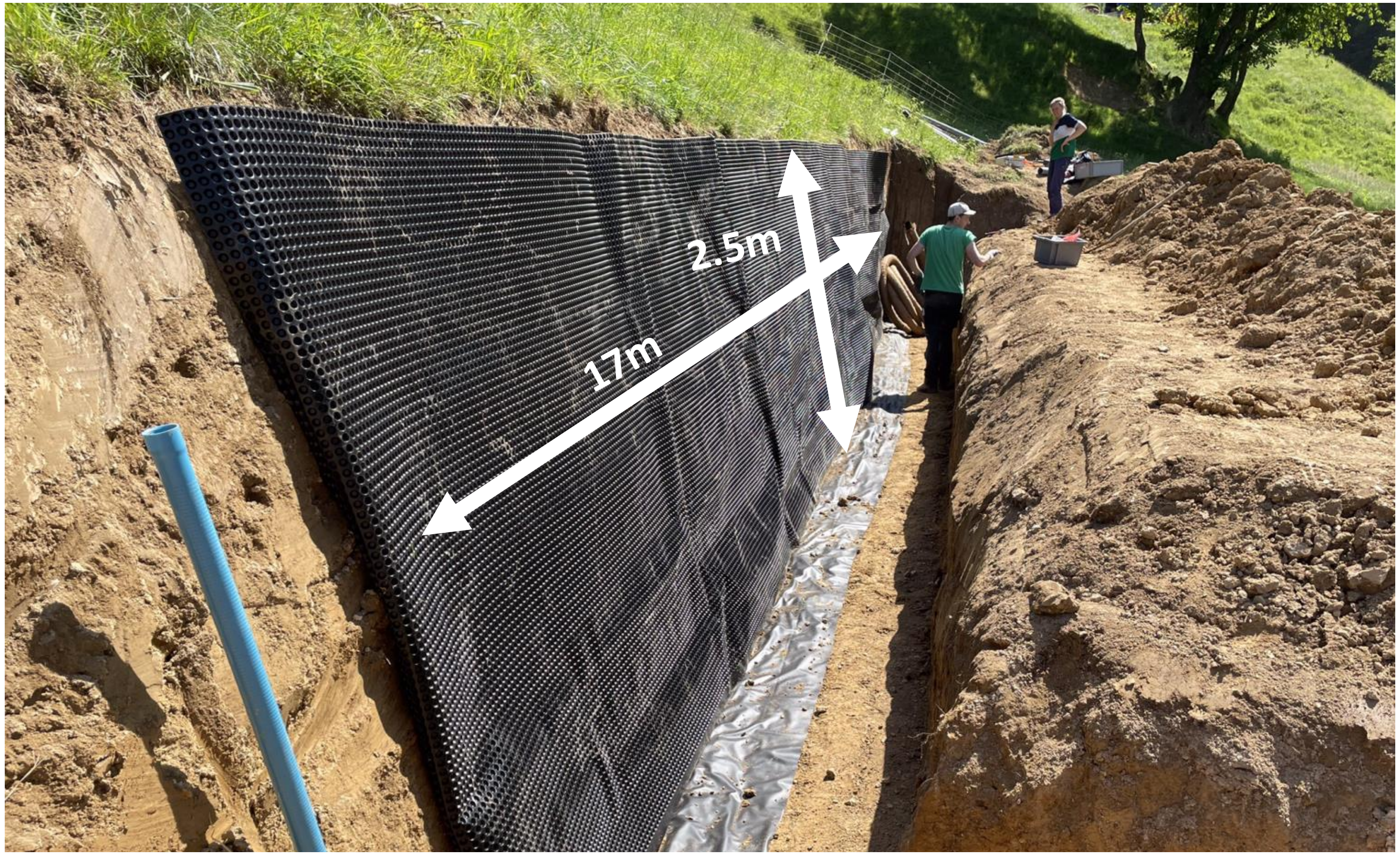
Spatial Scale	Catchments	Temporal Scale
		
7 Hillslopes	All Catchments	1 Sprinkling Event

„Tracing Subsurface Stormflow:
Insights into Preferential Flow and Pre-Event Water Contributions from Controlled Sprinkling Experiments"
Pyschik et al.; in prep.

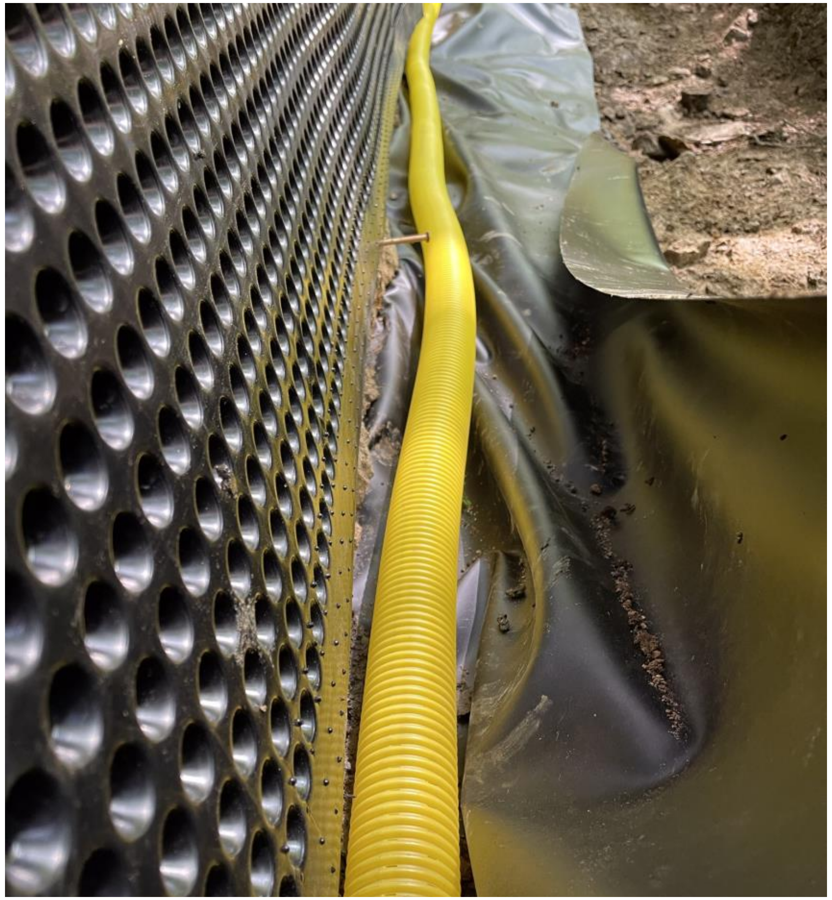
SSF is a fast event response - so how much is event-water?

How does precipitation become SSF?

Constructing SSF Trenches

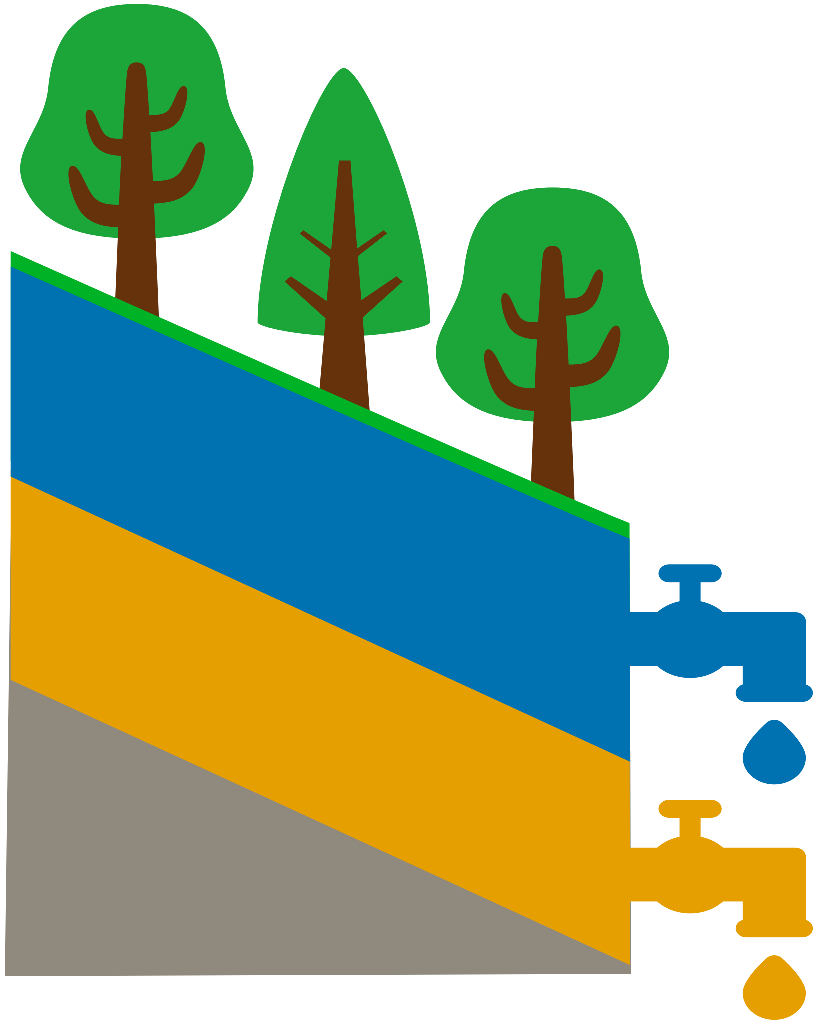


Trench excavated



Pond foil & pipe funnel water out

Constructing SSF Trenches

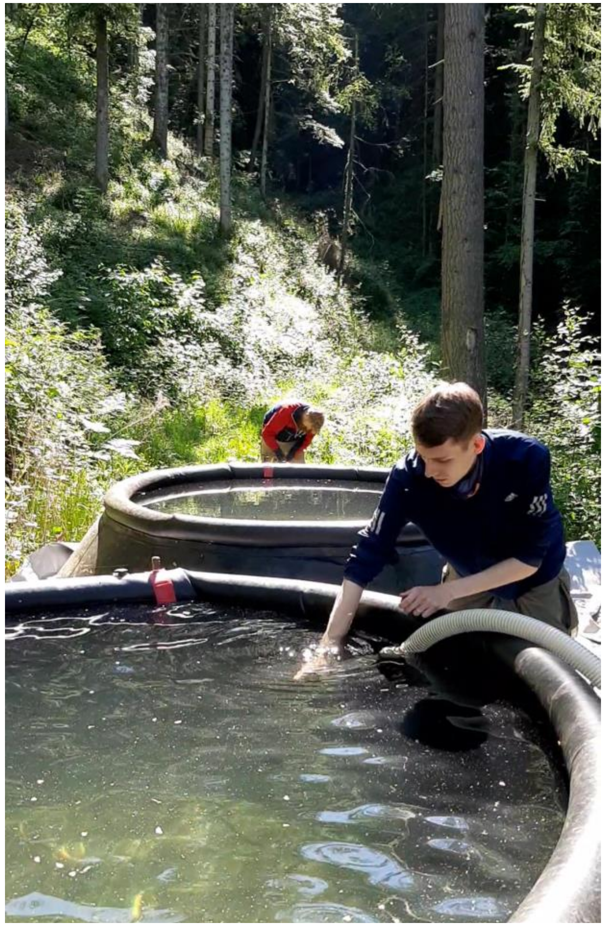


Capturing Flow in

Top: 0-80 cm

Bottom: 80-250 cm

Conducting Sprinkling Experiments



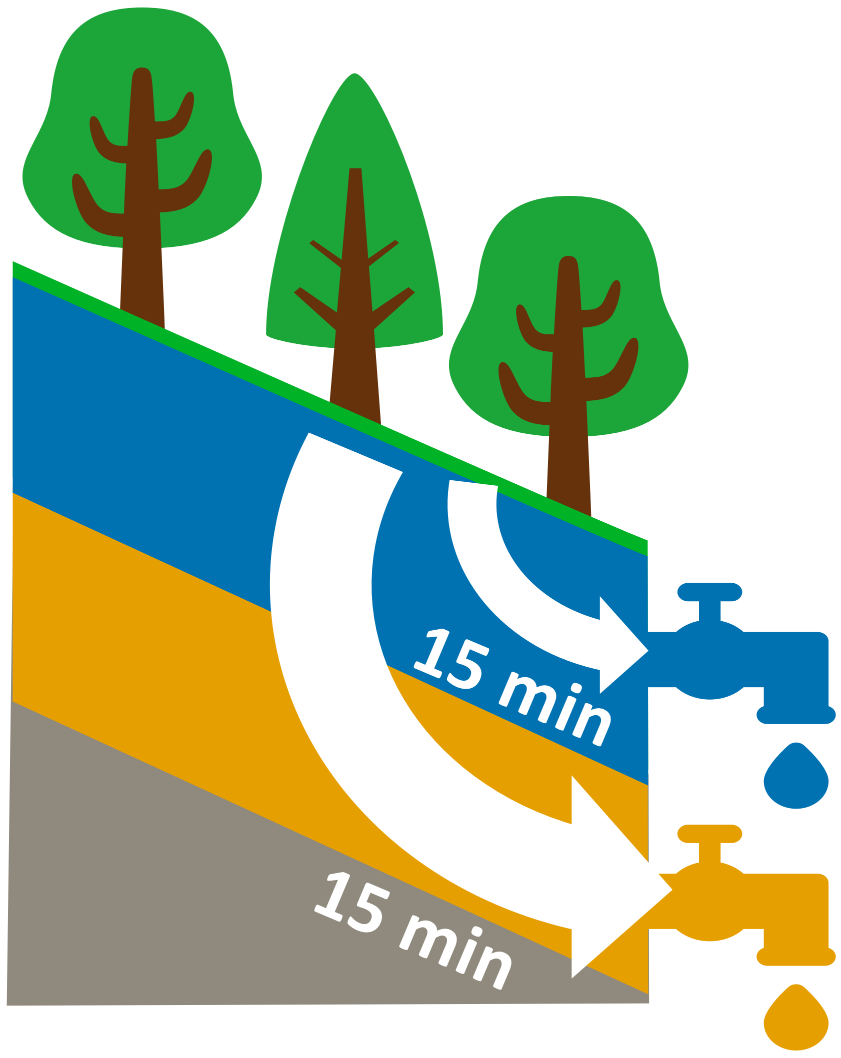
2x 4.5 m³ Reservoirs
1x labeled δ^2H to +220 ‰

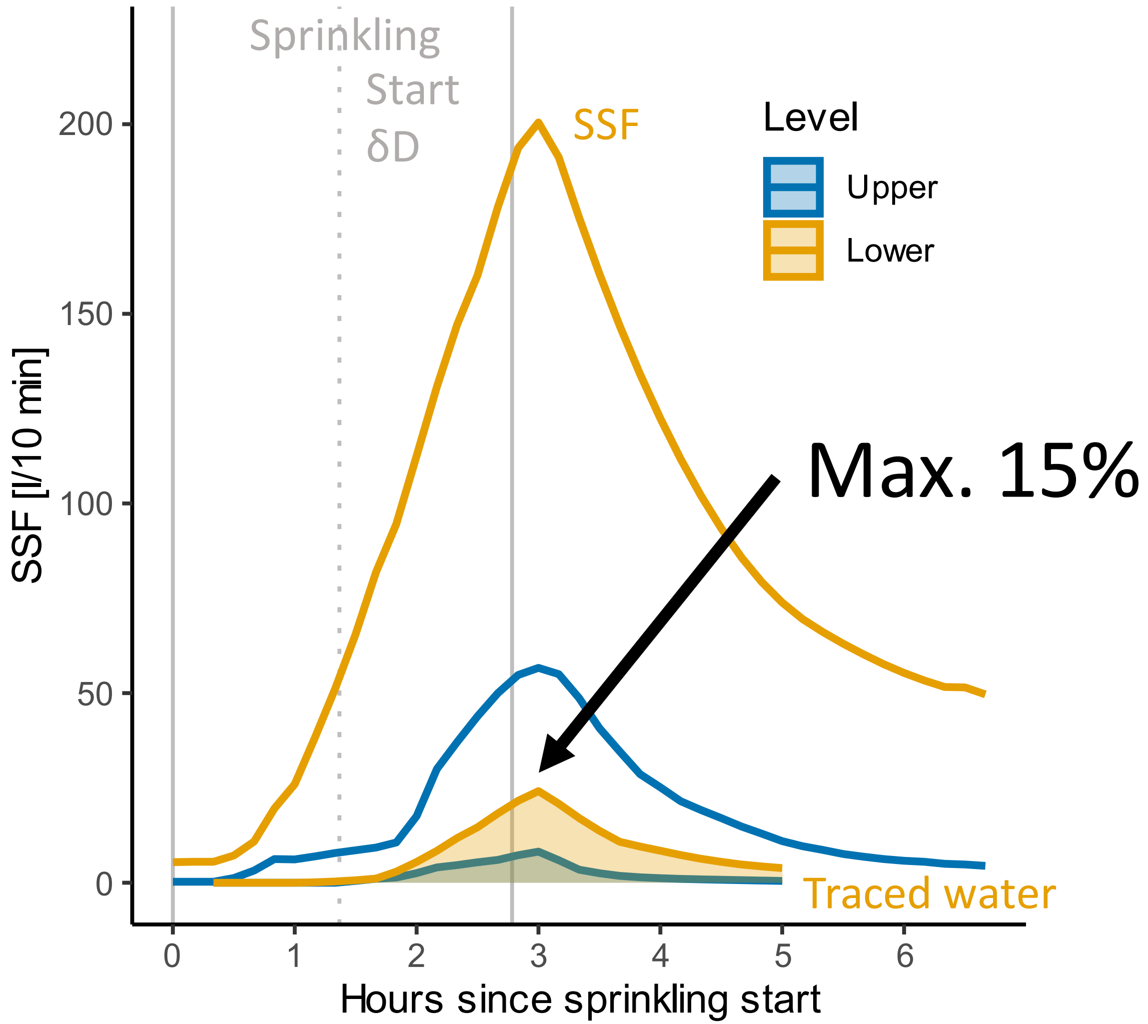
Sprinkled with 16 mm/h for 3h
Deuterated water start 1.5 h

Continuous outflow monitoring

Manual samples every 20 min

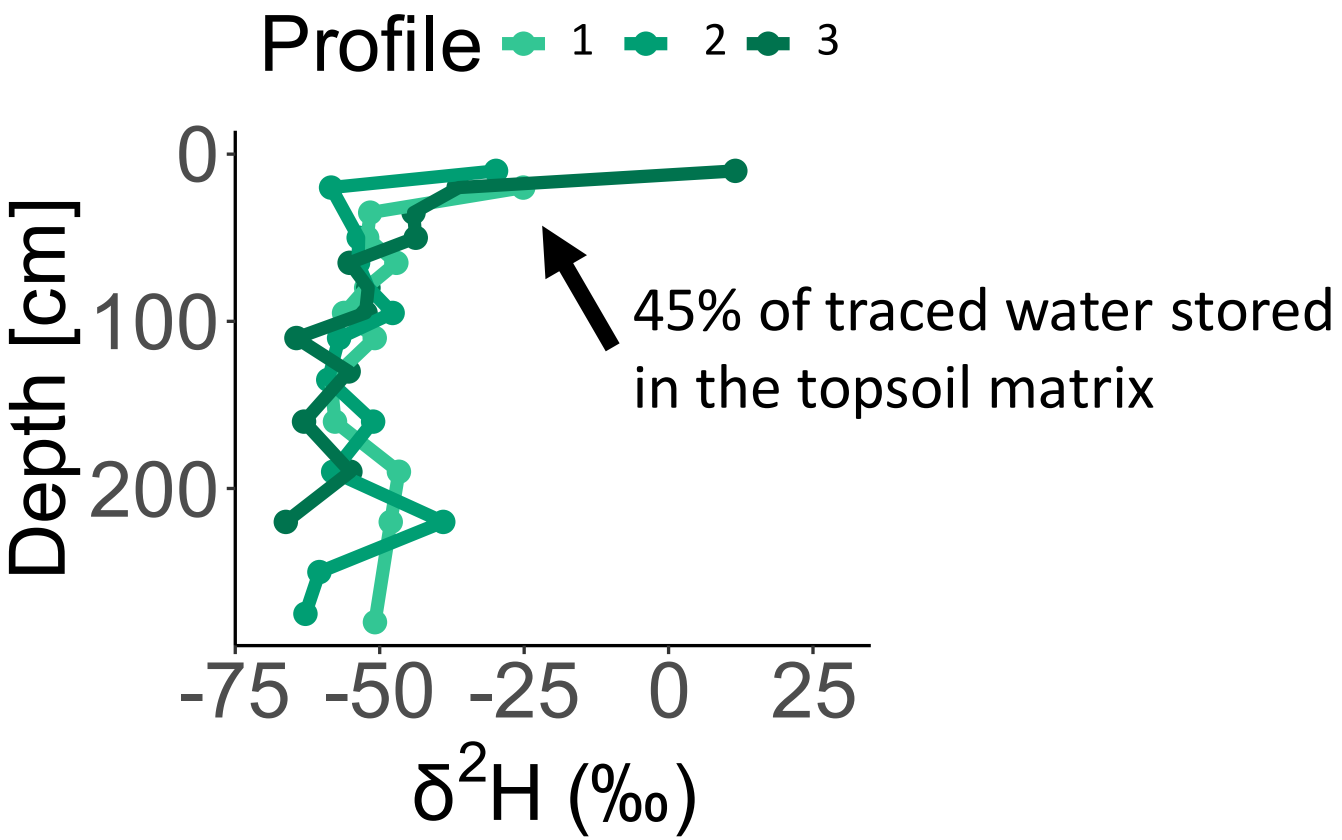
Result: Quick but minor traced water reaction





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

Storage and Remobilisation



1 day after irrigation

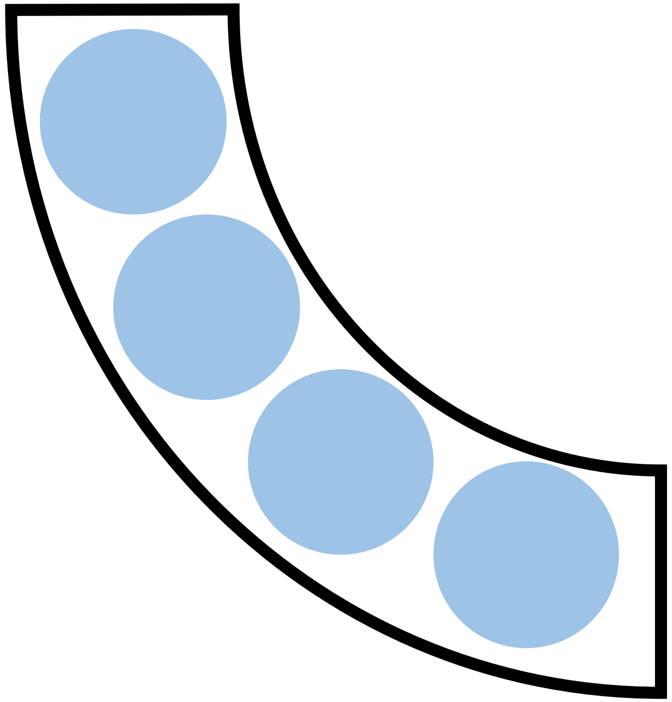
The mechanism: Two end members in a two domain system

Soil Matrix

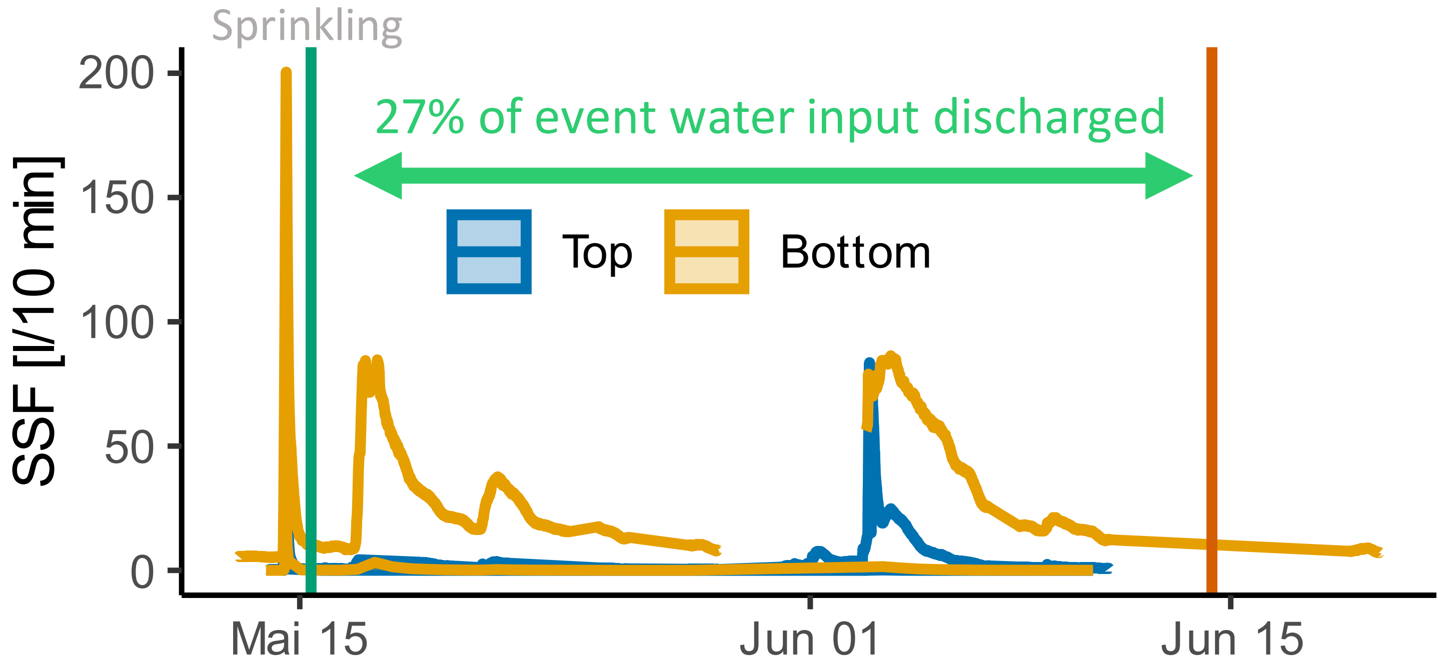
Translatory (Piston) Flow

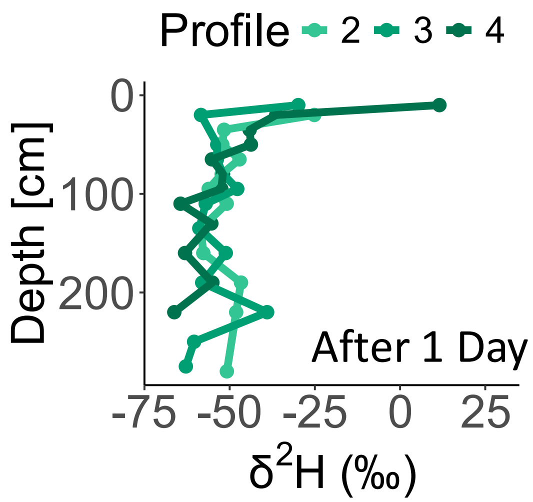
Most SSF pre-event water stems from the soil matrix

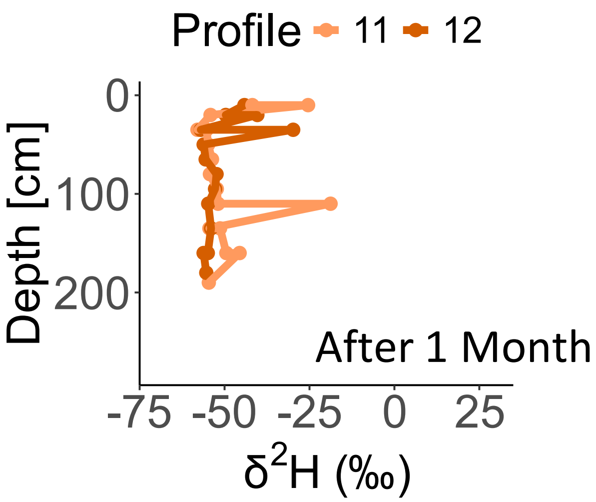
All observed event water traveled through preferential flowpaths



Storage and Remobilisation







- Traced water is percolating & released from soil storage

Conclusion

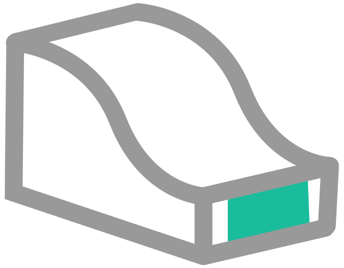
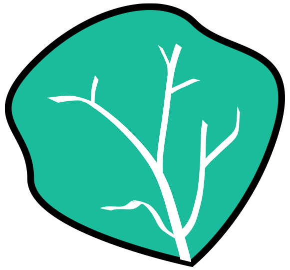
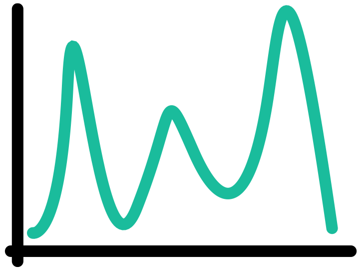
SSF is a fast event response - so how much is event-water?

- *max. 15% of SSF is event water*

How does precipitation become SSF?

- *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*

Multitracer

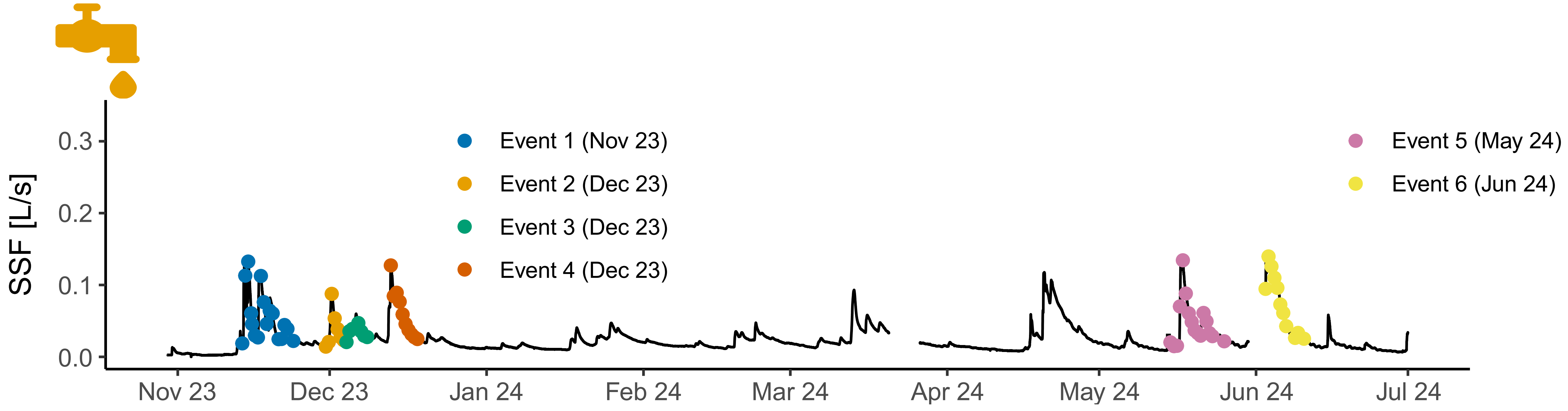
Spatial Scale	**Catchments**	**Temporal Scale**
		
3 Hillslopes	Black Forest	Multiple Events

„Subsurface Stormflow Dynamics and Water Mixing: Insights from Multi-Tracer Analyses Across Hillslope Trenches”
Pyschik et al. (2025, submitted to WRR)

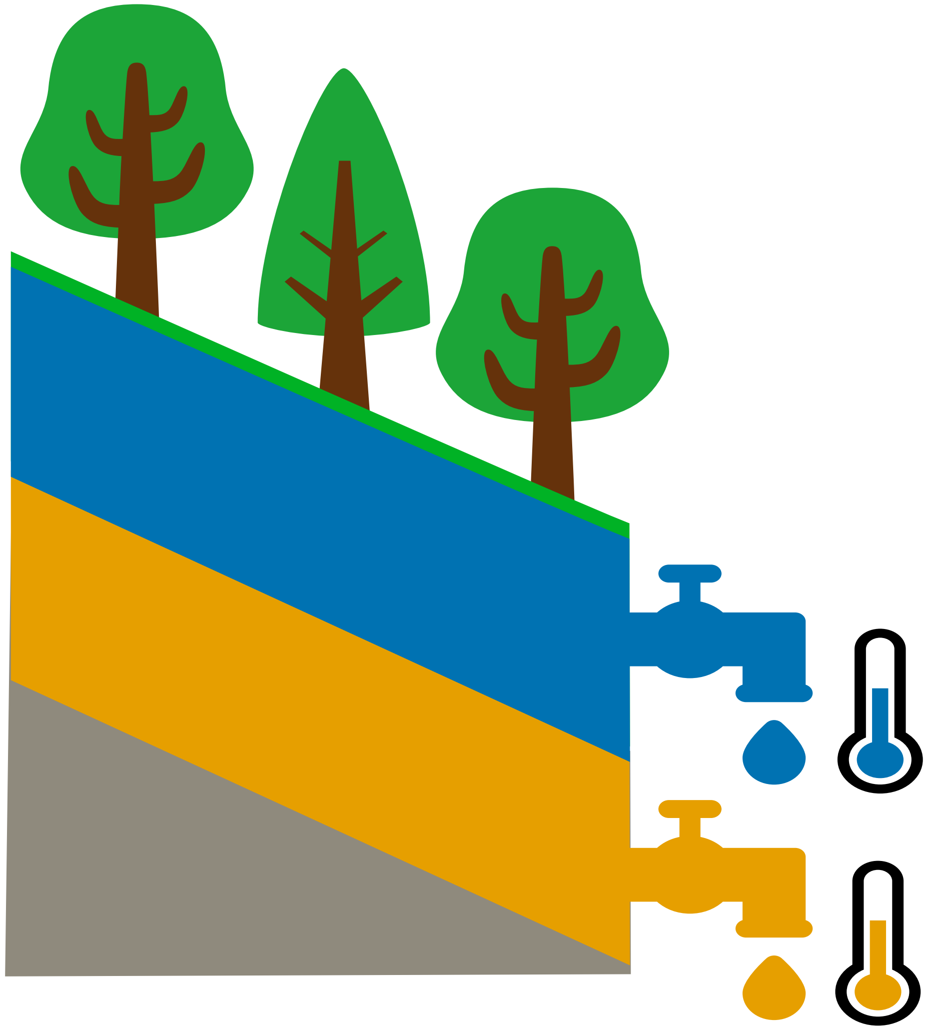
At what depth does SSF occur?

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

SSF Event Samples



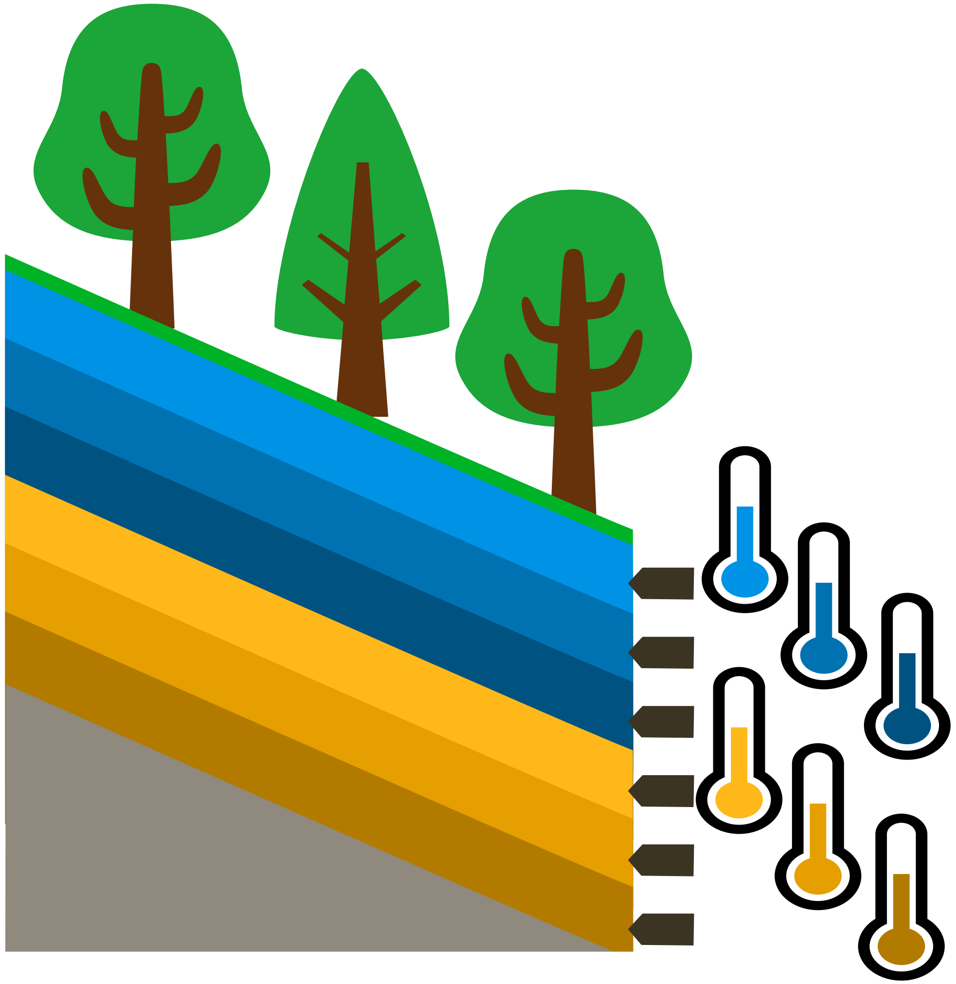
Constructing SSF Trenches



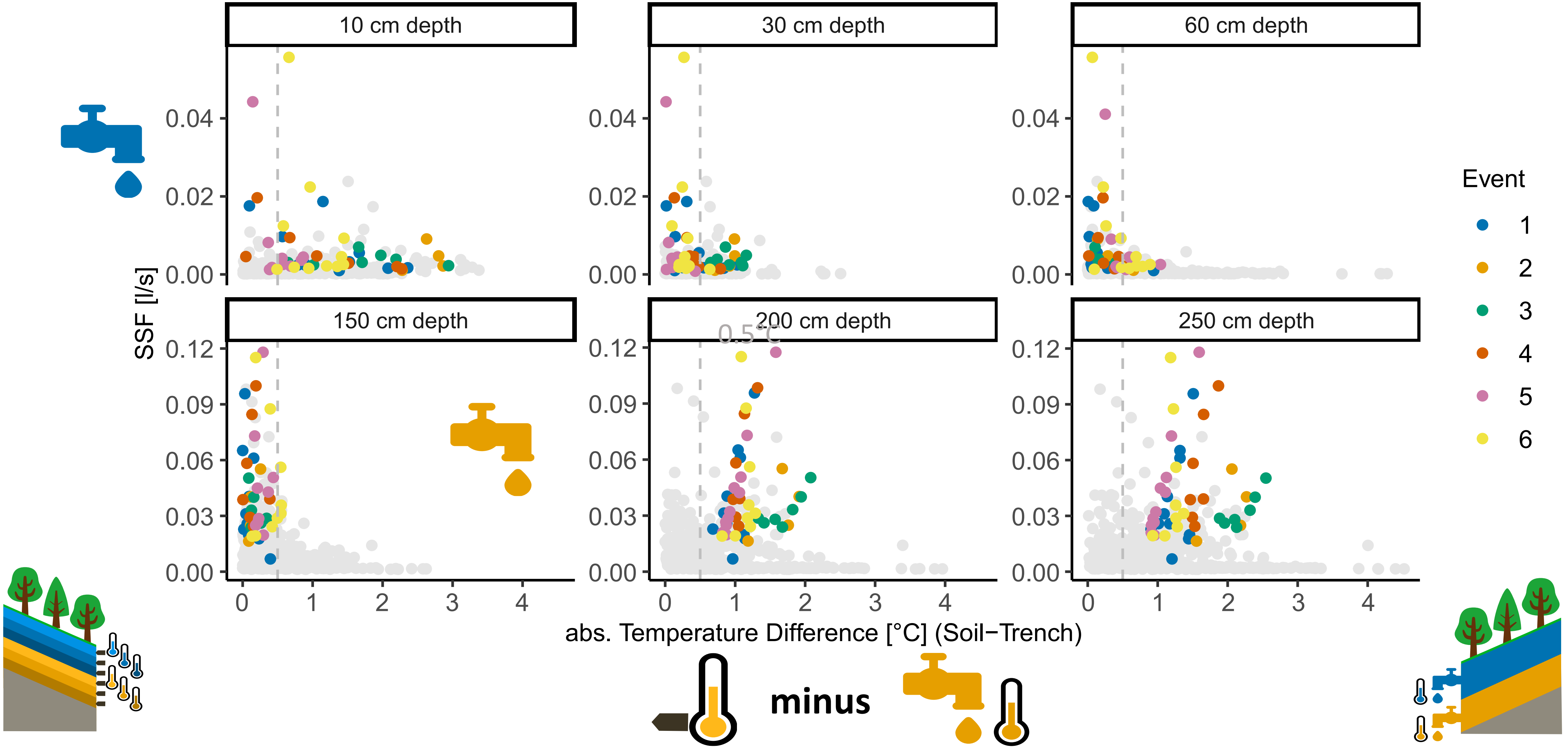
Capturing Flow in
Top: 0-80 cm
Bottom: 80-250 cm
+ measuring its temperature

Constructing SSF Trenches

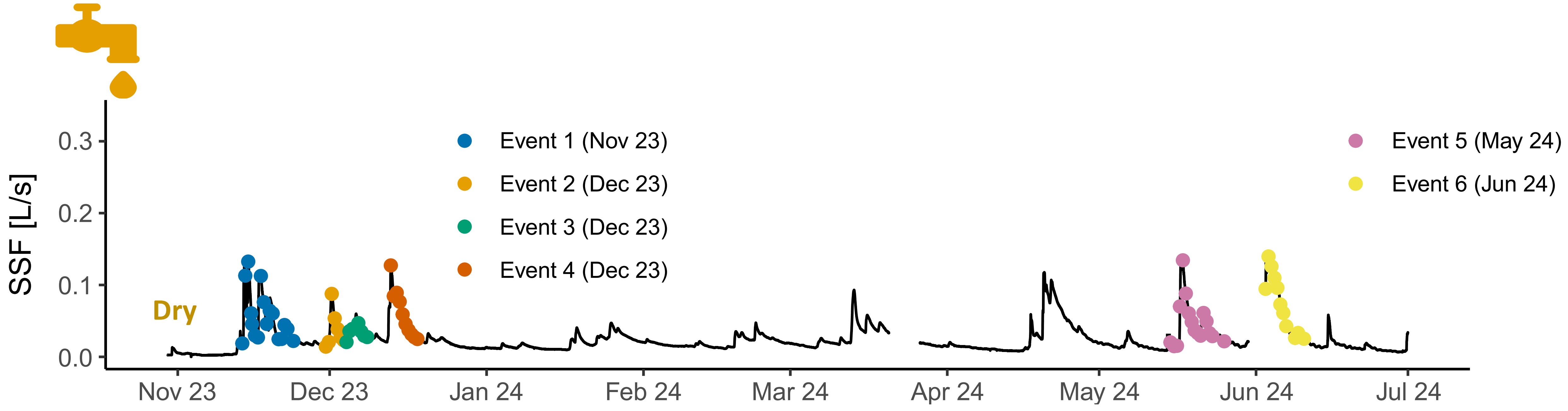
Soilmoisture sensor profile which also measures temperature



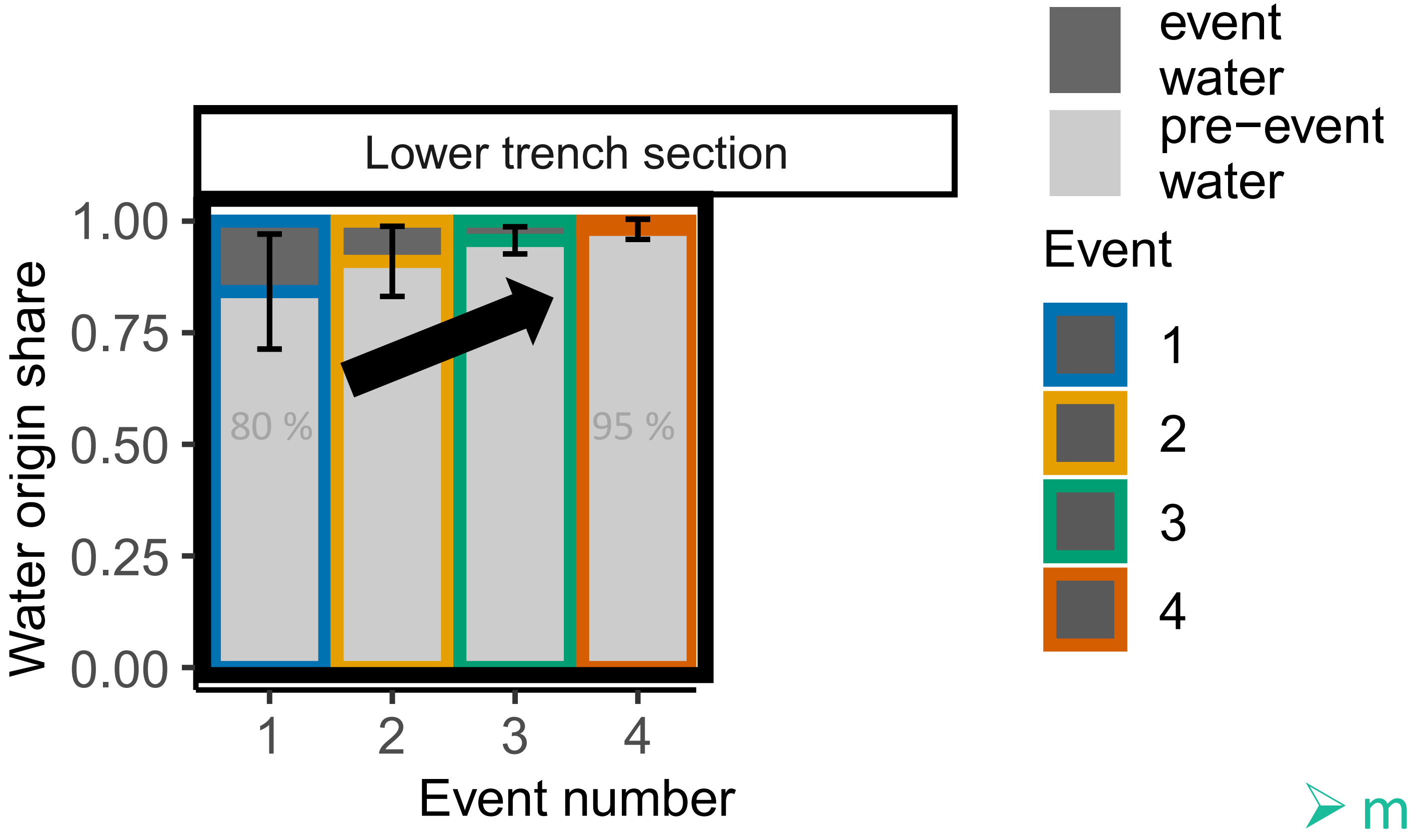
Relating SSF Depth to SSF Discharge

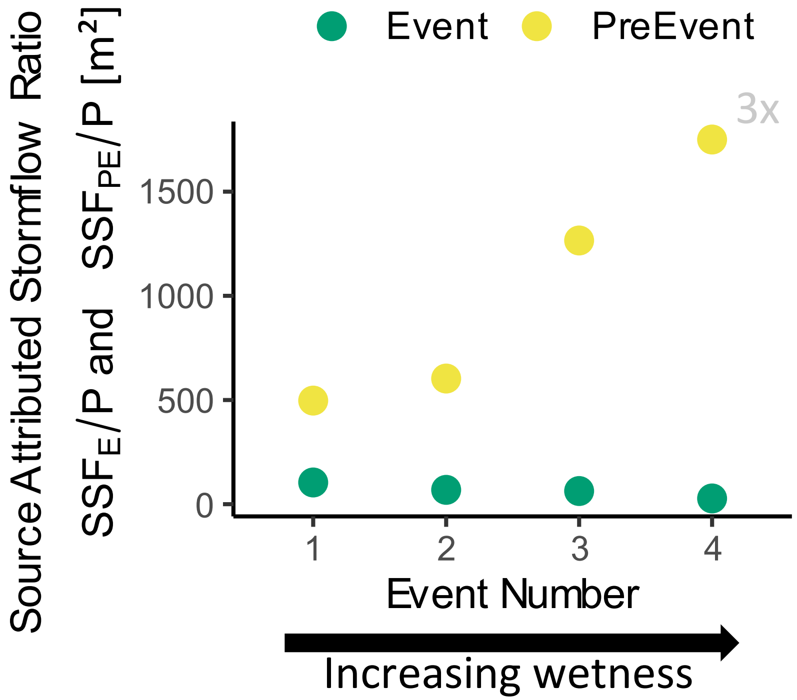


SSF Event Samples



Reasons for decreasing event water proportion





Event water = preferential flow

- more active flowpaths or increased velocity

Conclusion

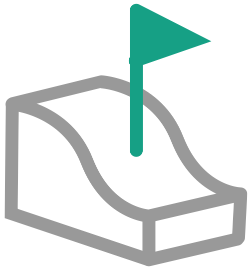
At what depth does SSF occur?

- *SSF occurs in a depth consistent between events*
- *not exclusively at soil-bedrock*

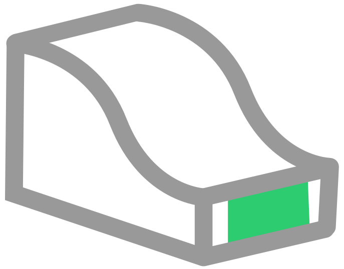
Is there a constant event water contribution to SSF or does it change from event to event?

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

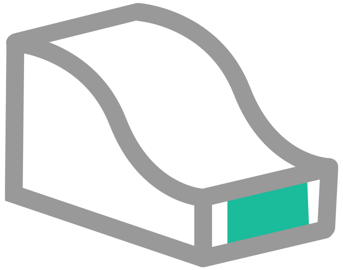
Spatial Scale



Point



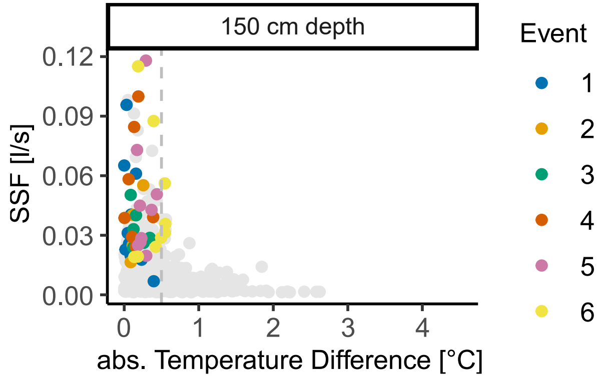
7 Hillslopes



3 Hillslopes

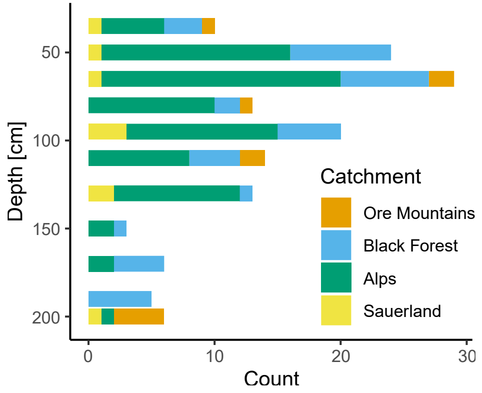
Summary

SSF consistently occurs in a preferred depth



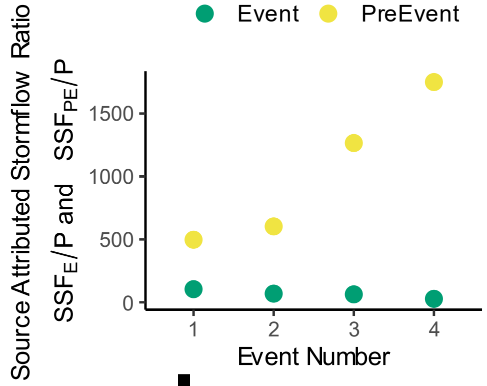
Multitracer

Preferential flowpaths exist in those depths

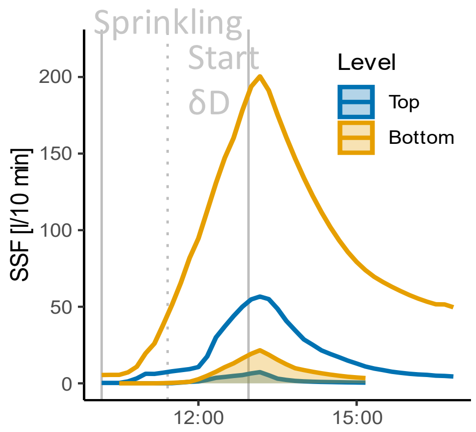


Preferential Profiles

Event water volume is proportional to precipitation volume, indicating more rain activates more flowpaths

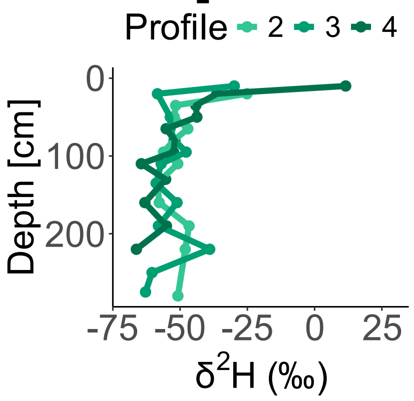


Multitracer



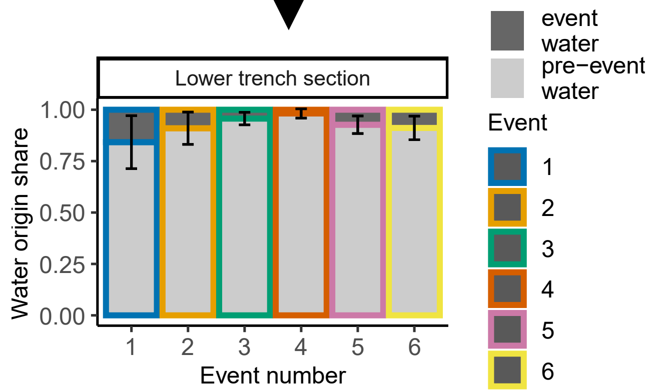
SSF is mostly PreEvent water

Sprinkling



SSF mostly piston flow in matrix, event water travels through preferential flowpaths

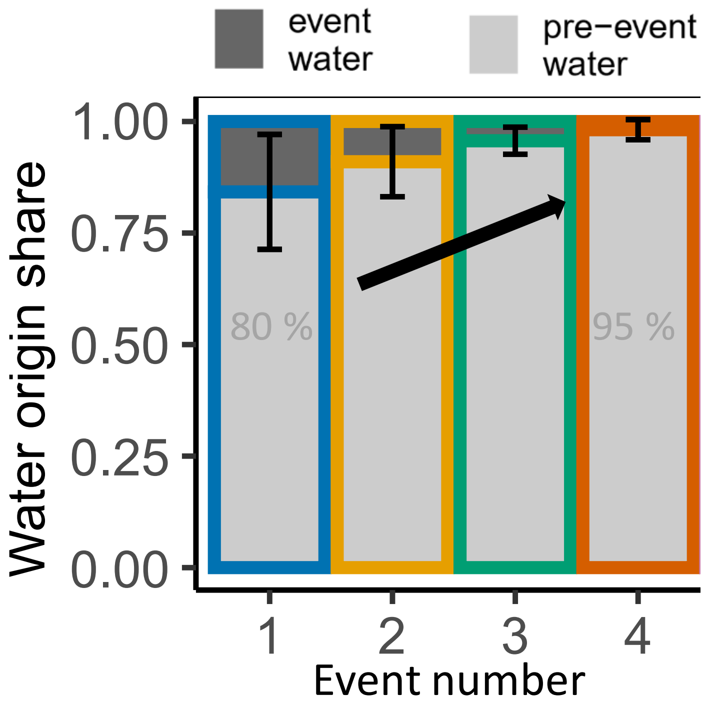
Sprinkling



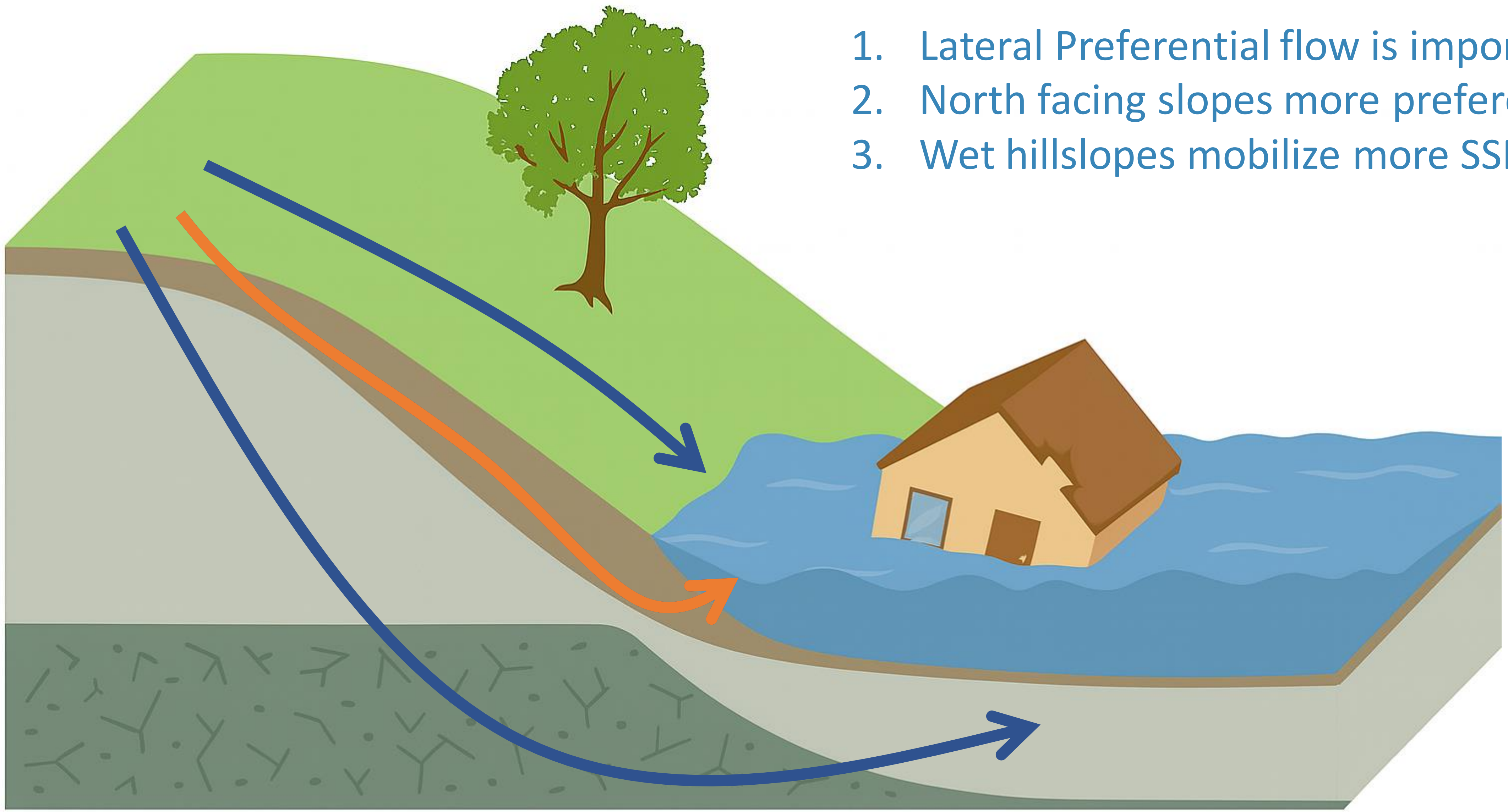
After dry period, soil matrix storage is empty; wetup fills storage mobilizing more pre-event water

Multitracer

Whats next?



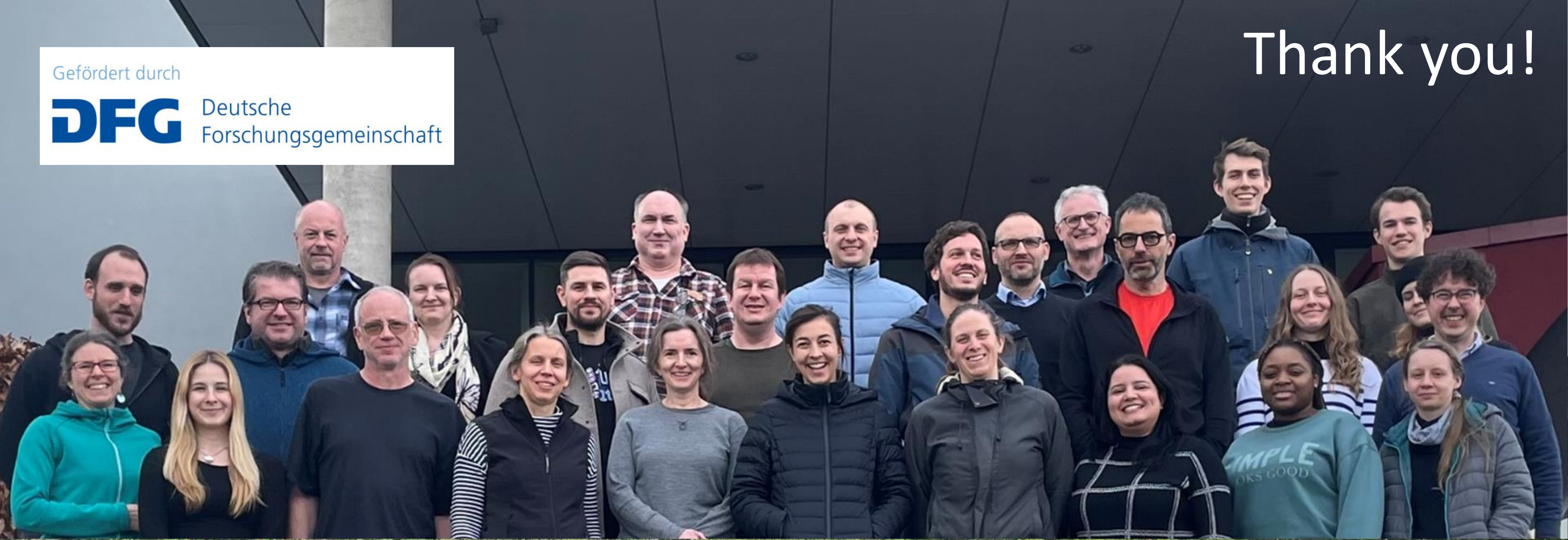
Hillslope to catchment scale:
How does this signal propagate?
Are there landuse differences?



1. Lateral Preferential flow is important
2. North facing slopes more preferential flow
3. Wet hillslopes mobilize more SSF

Thank you!

Gefördert durch
DFG Deutsche Forschungsgemeinschaft



Sources

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