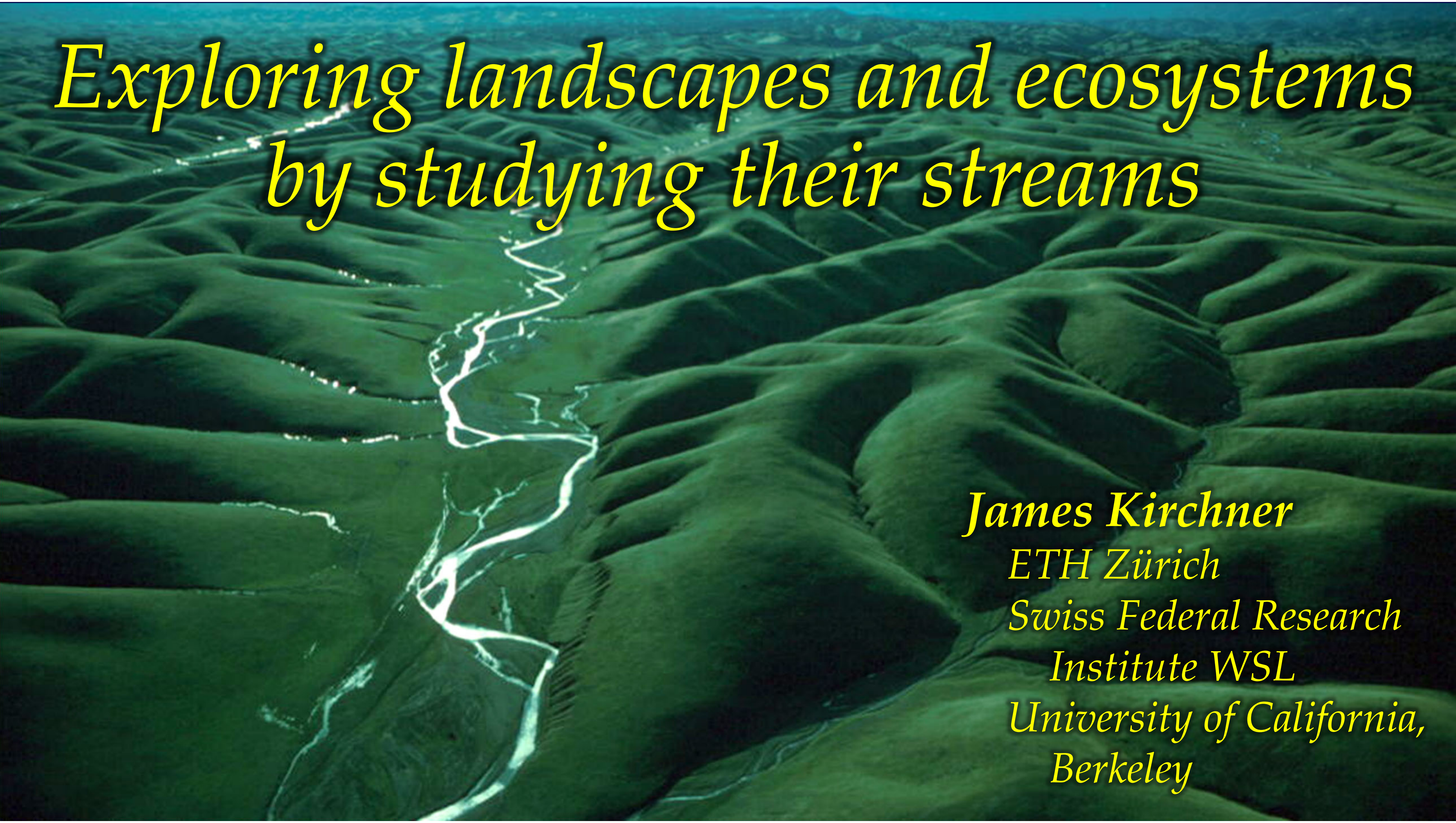


Exploring landscapes and ecosystems by studying their streams

James Kirchner

ETH Zürich

Swiss Federal Research Institute WSL

University of California, Berkeley

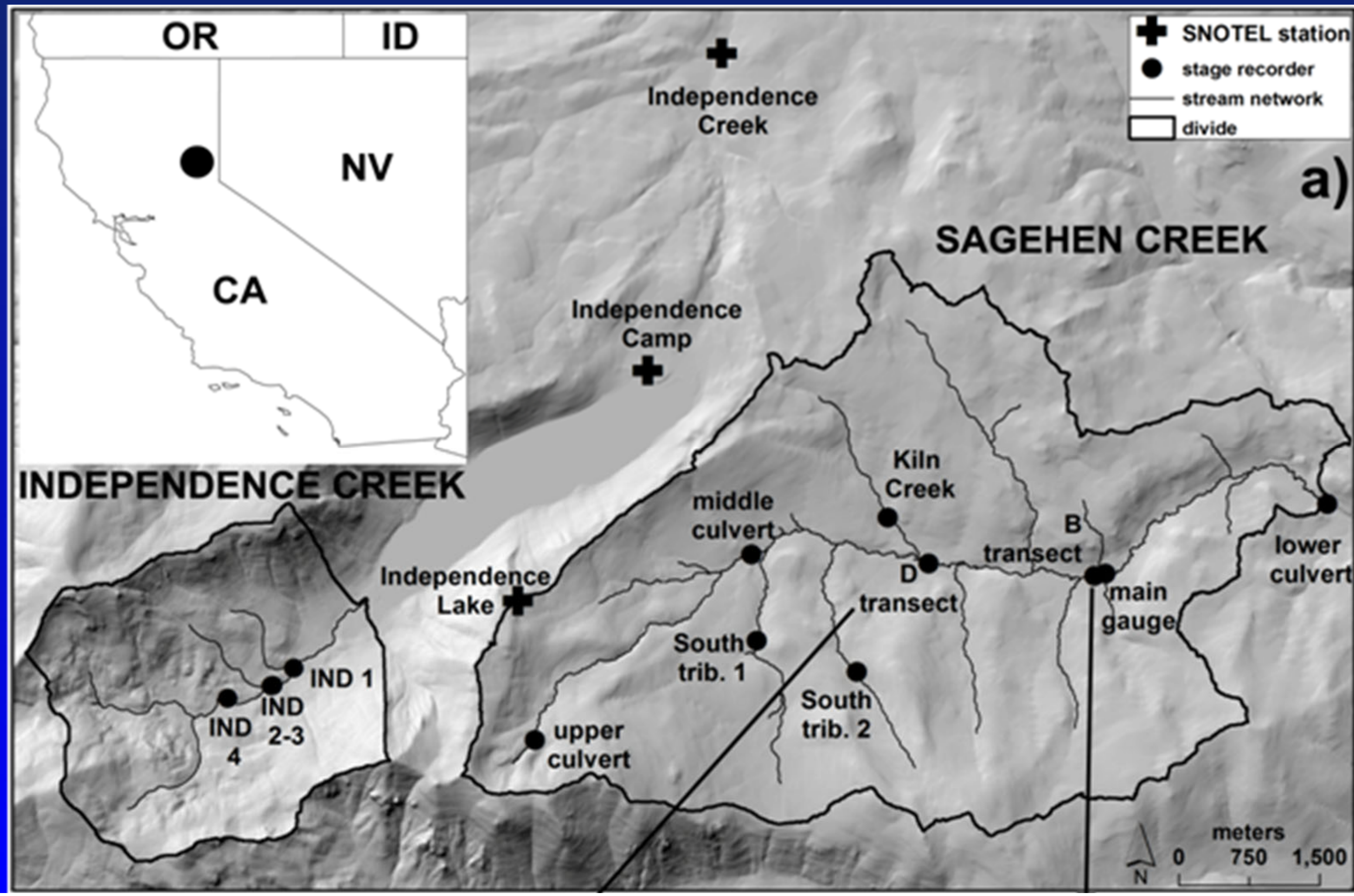
The pulse of a montane ecosystem: coupled diurnal cycles in solar flux, snowmelt, transpiration, groundwater, and streamflow at Sagehen Creek (Sierra Nevada, California)

with:
Daniele Penna (U. of Florence)
Randall Osterhuber (UC Berkeley)
Sarah Godsey (Idaho State U.)
Madeline Solomon (UC Berkeley)
Joe McConnell (Desert Res. Inst.)
Adrian Harpold (Univ. of Nevada)

Sagehen Creek: 27 km^2, 1900-2700 m

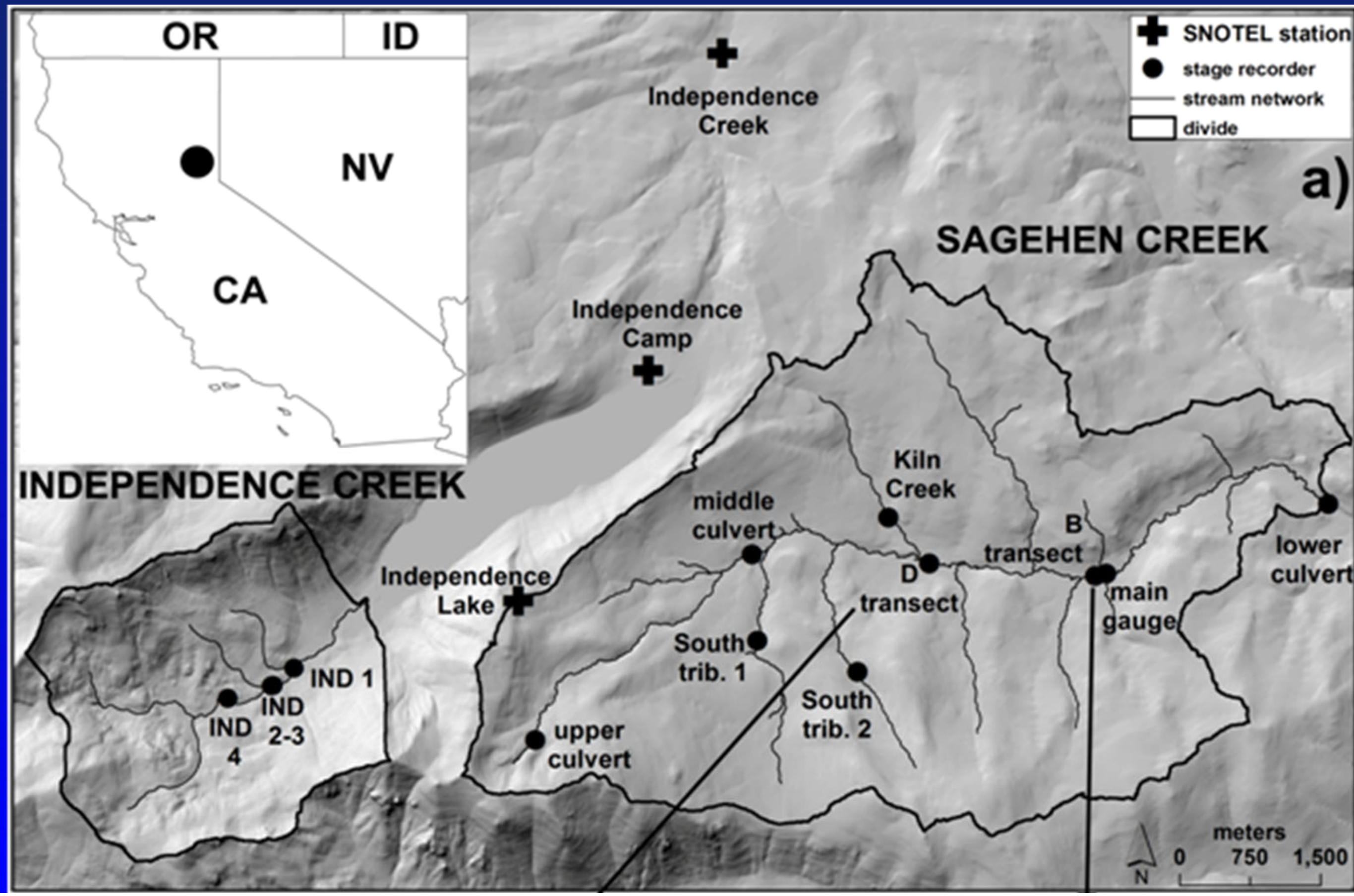
Snow-dominated subalpine forest ecosystem

Mediterranean climate: almost no rainfall April-October (during snowmelt and summer transpiration)

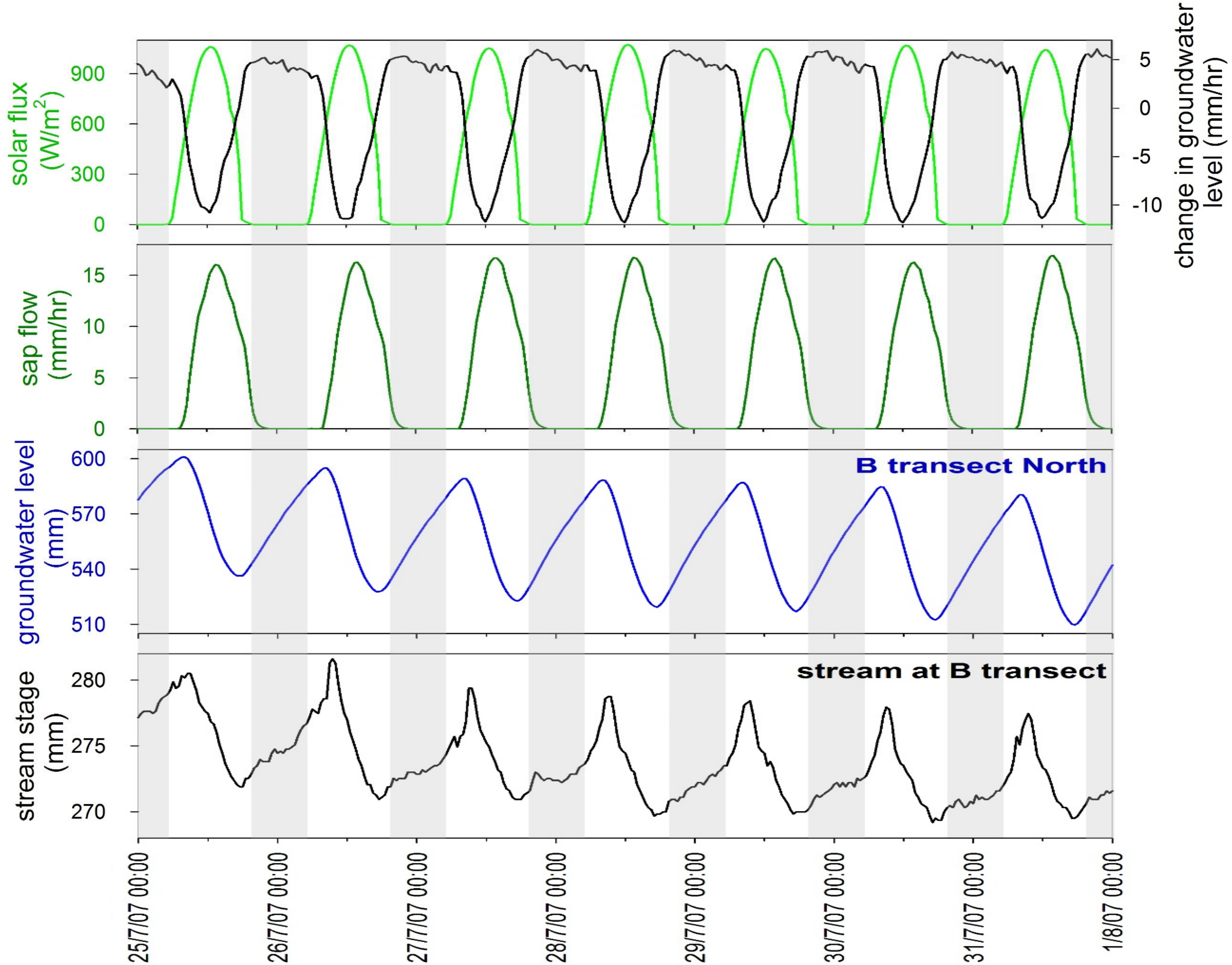


Sagehen Creek: 27 km^2, 1900-2700 m

Stream stage recorded at 6 locations (& 3 tributaries), 2 groundwater well transects, 5 weather stations, 3 SNOTEL sites spanning full altitude range of basin



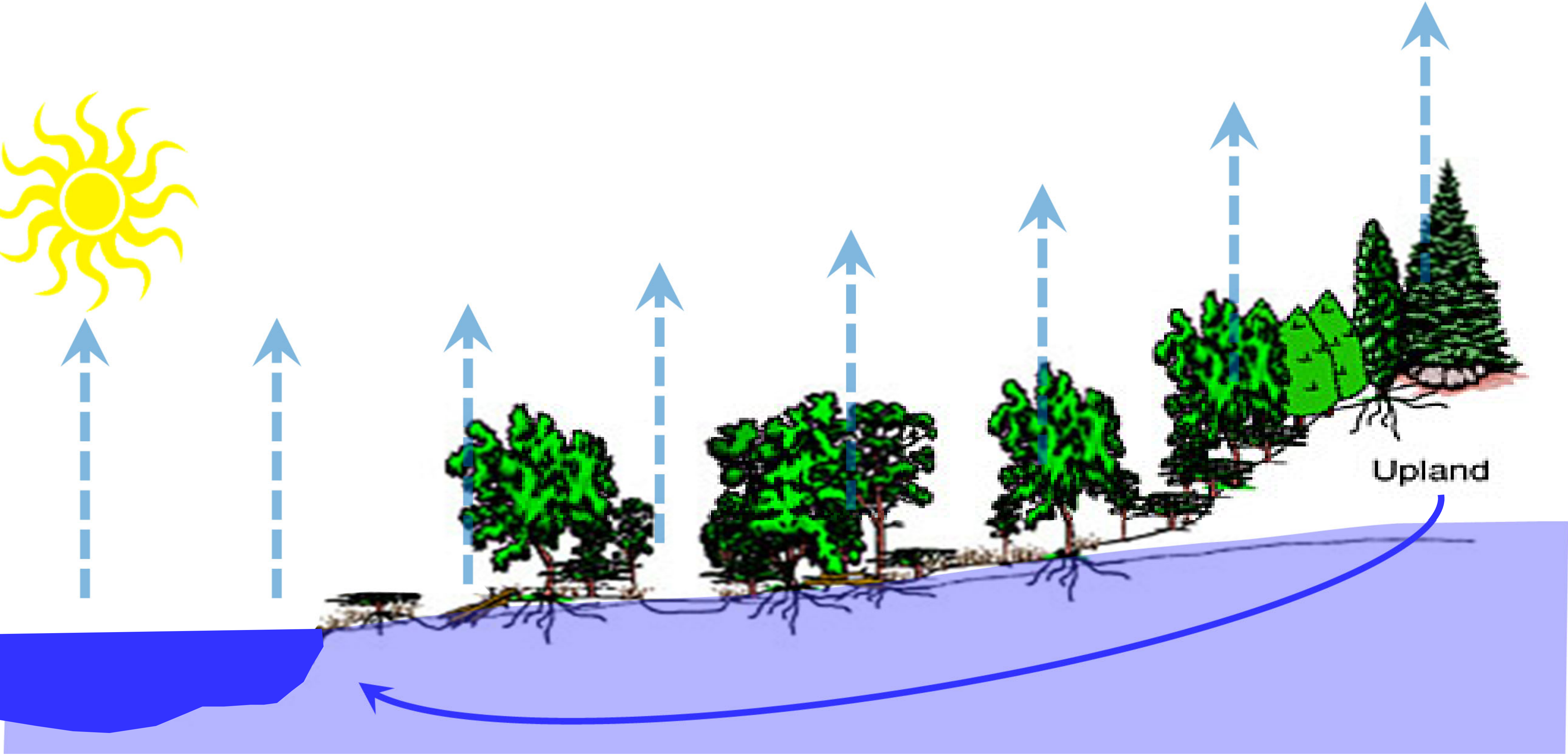

Sapflow tree 4
Sapflow tree 2
Sapflow tree 3
Well
wx tower #1 (30m)
Well
Sapflow tree 1
Well
B transect stage recorders
Well
Well
USGS gauging station
Well
Well
Well
Sagehen Creek, CA: coupled weather, sapflow, and shallow groundwater measurements



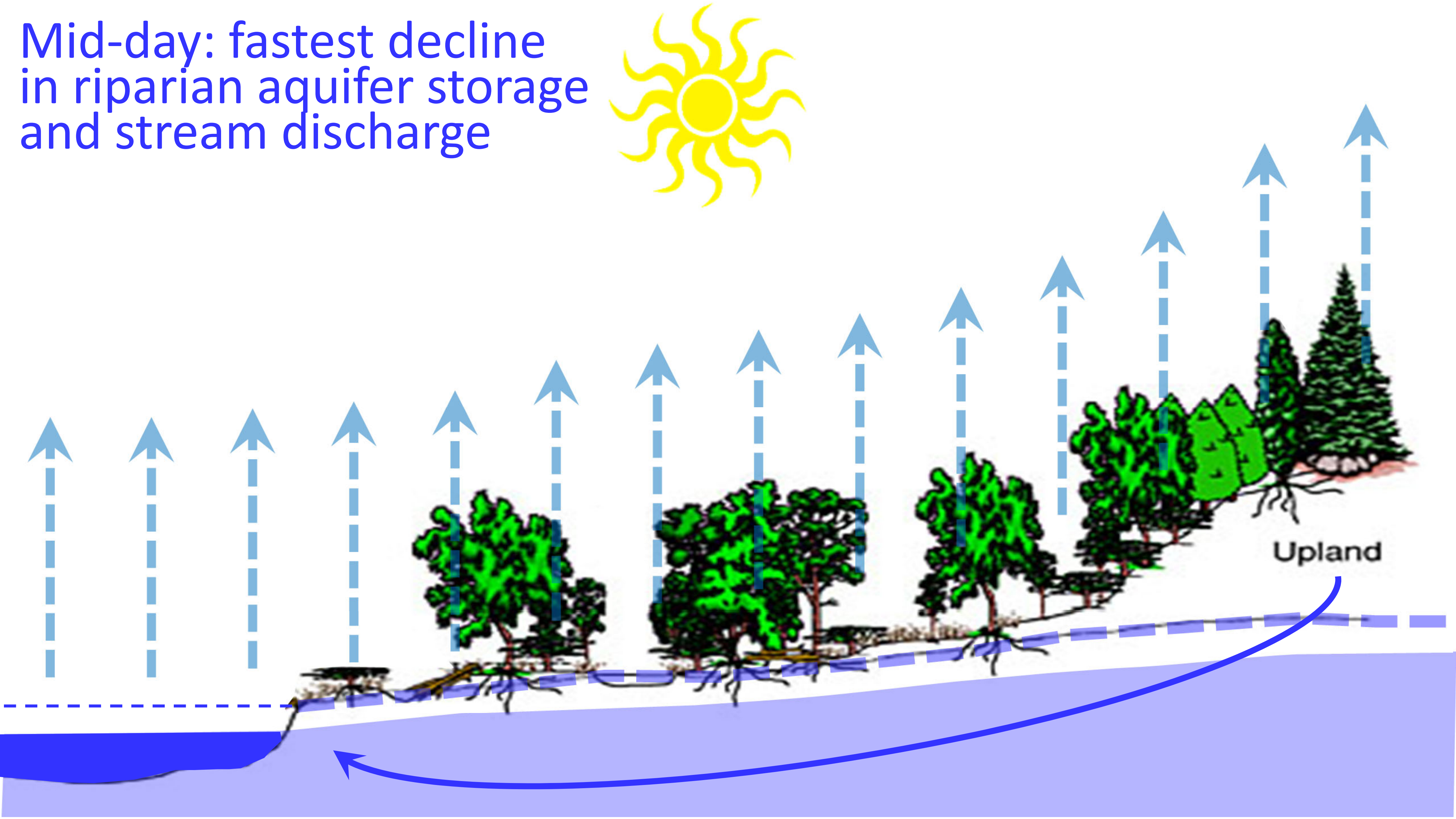
July: ET, driven by solar forcing, pumps down groundwater levels and stream flow during daytime.

*90° **dynamical phase lag** between ET and ground-water levels or stream stage.*

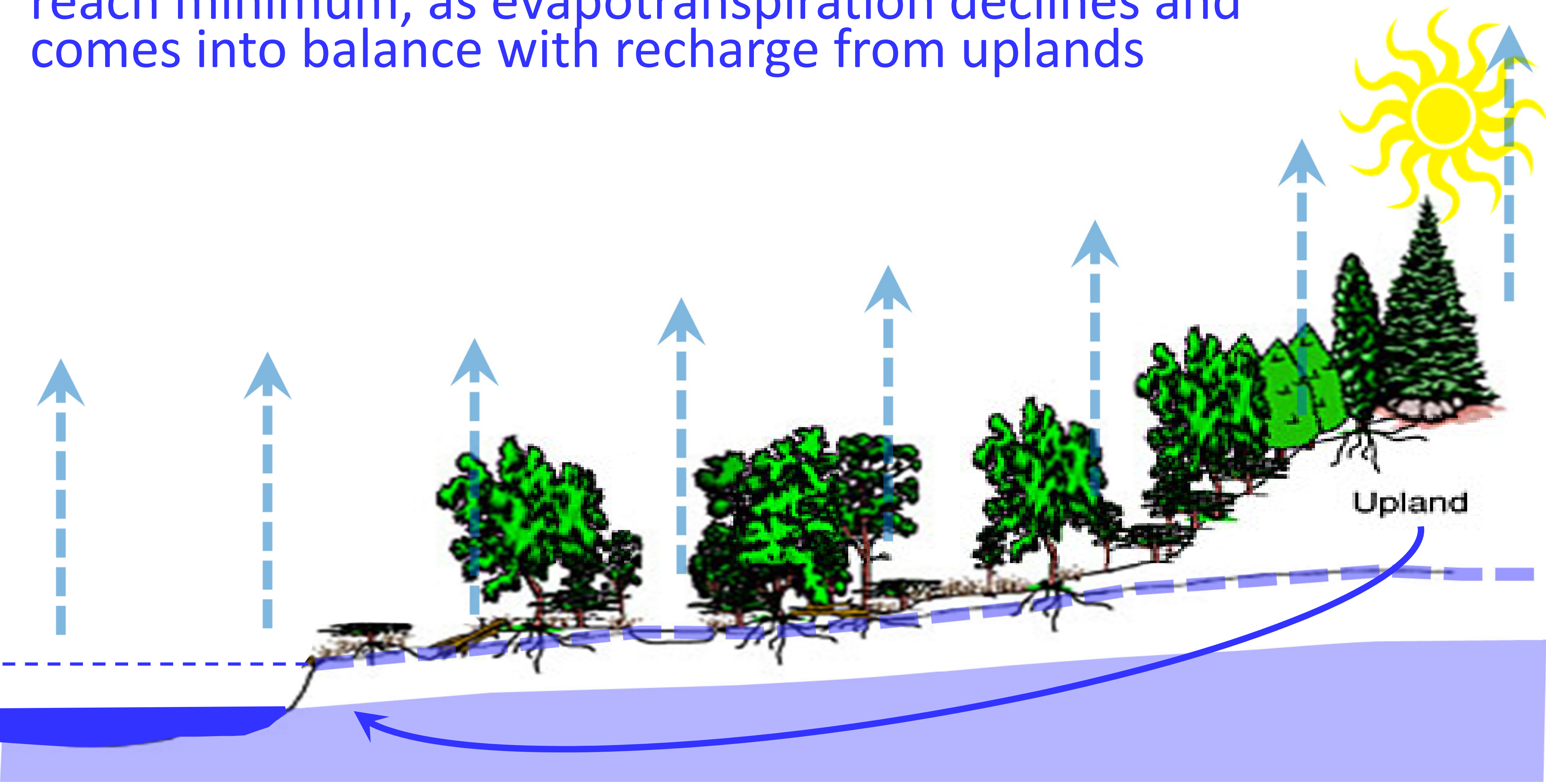
Morning: when ET exceeds recharge from uplands, riparian aquifer storage (and thus stream discharge), begin to decline



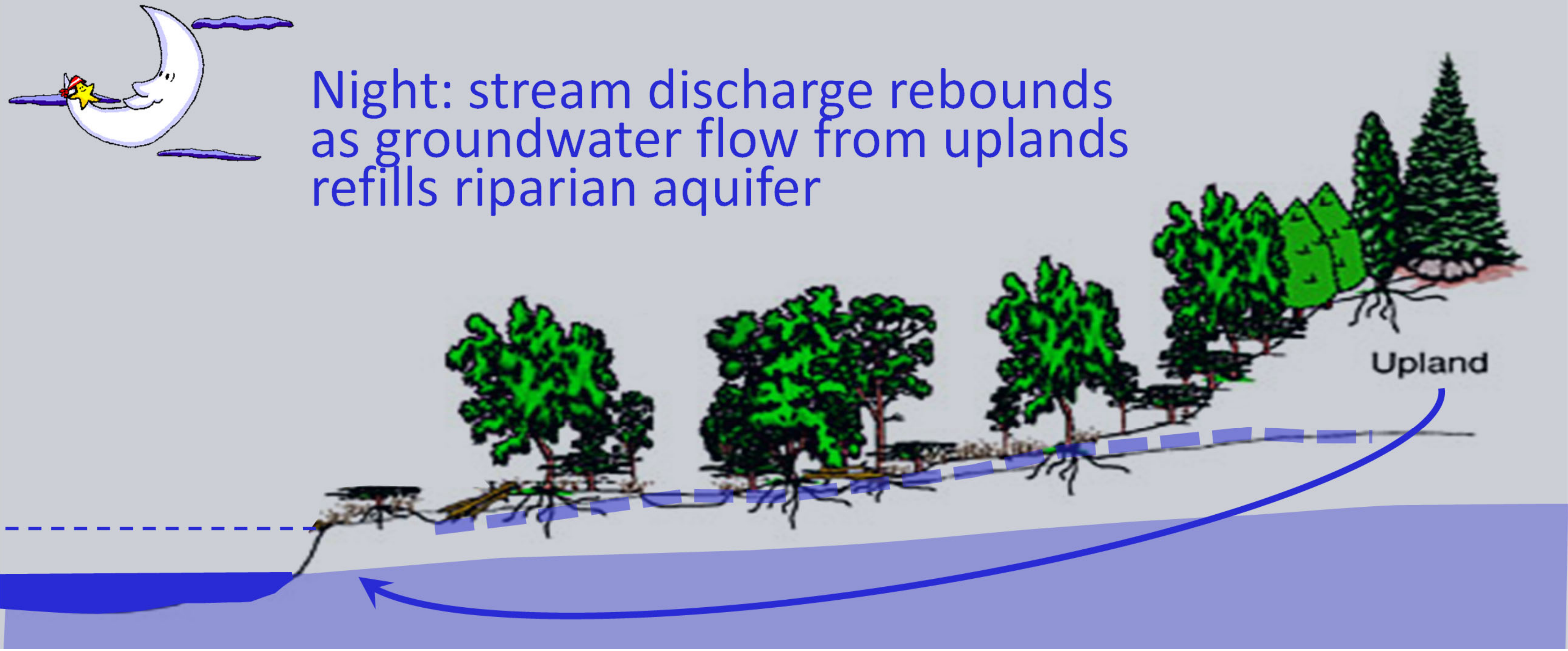
Mid-day: fastest decline in riparian aquifer storage and stream discharge

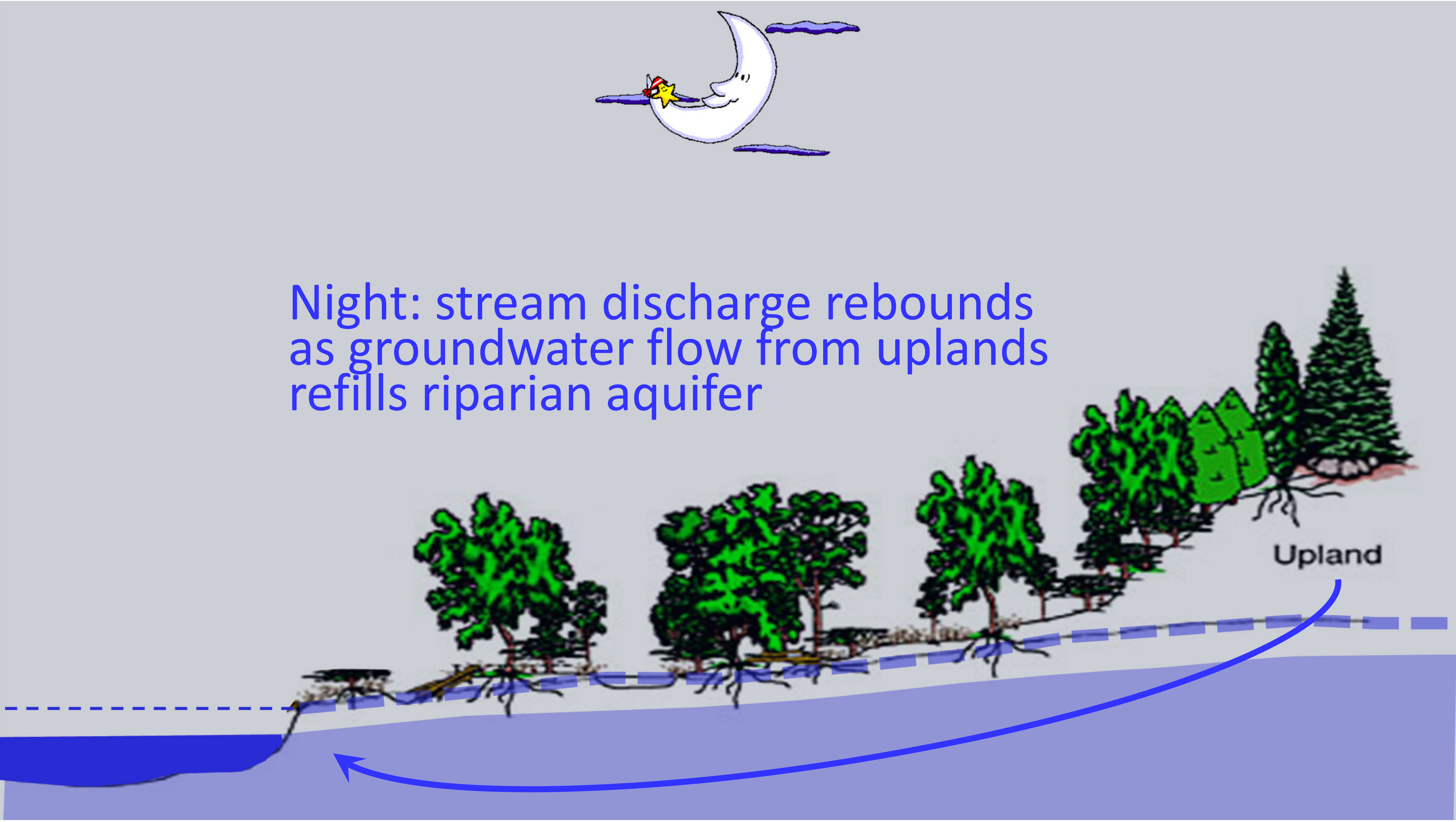


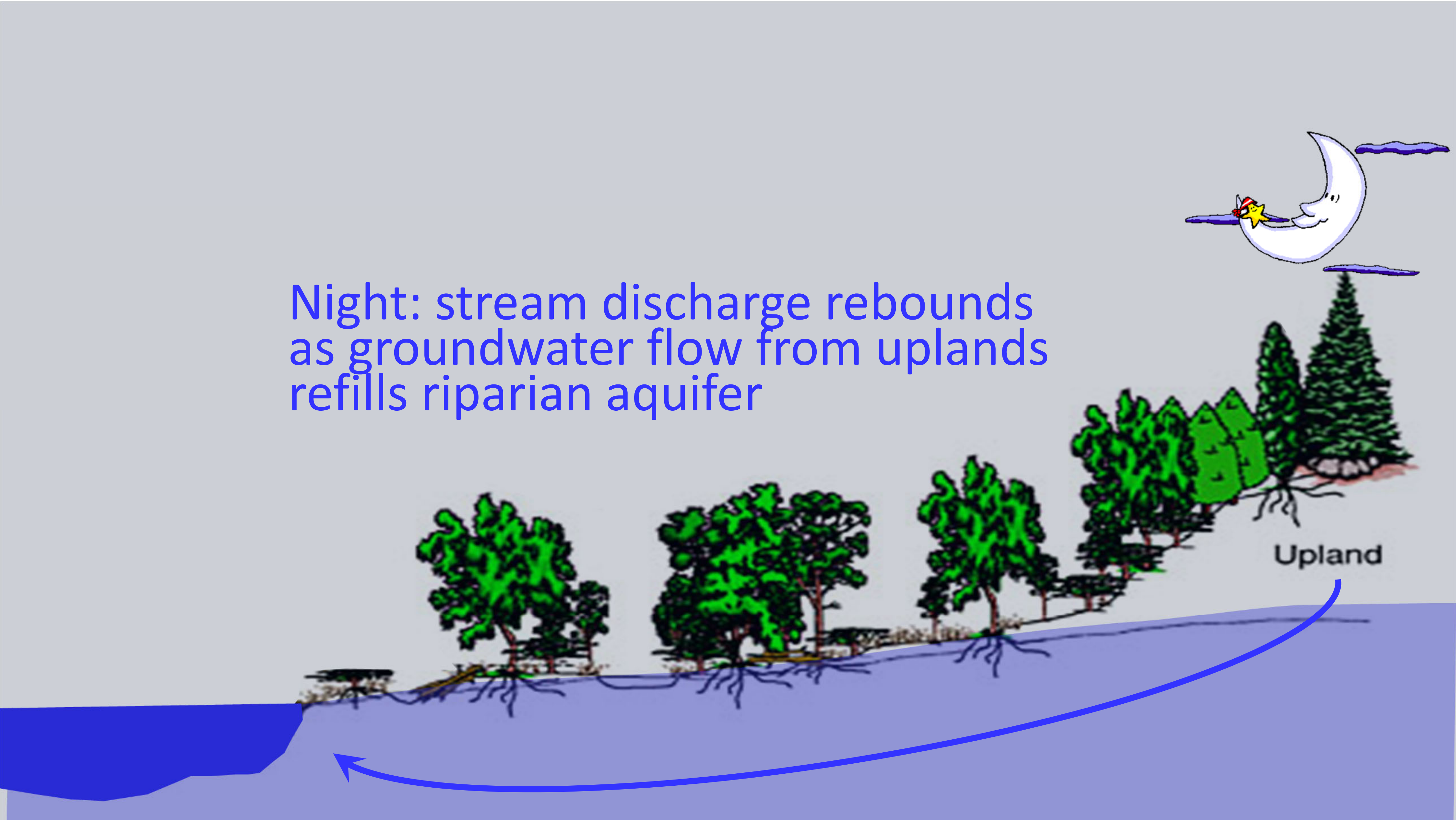
Evening: riparian aquifer storage and stream discharge reach minimum, as evapotranspiration declines and comes into balance with recharge from uplands



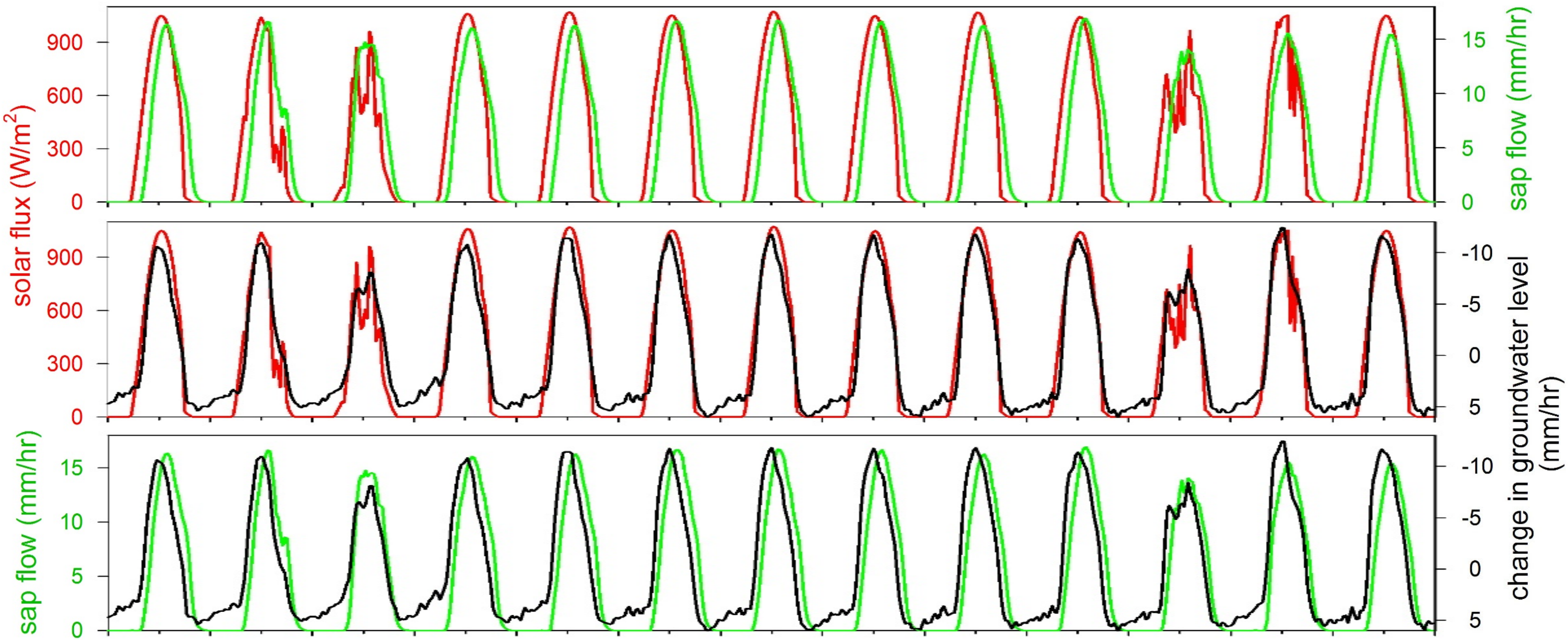
Night: stream discharge rebounds as groundwater flow from uplands refills riparian aquifer

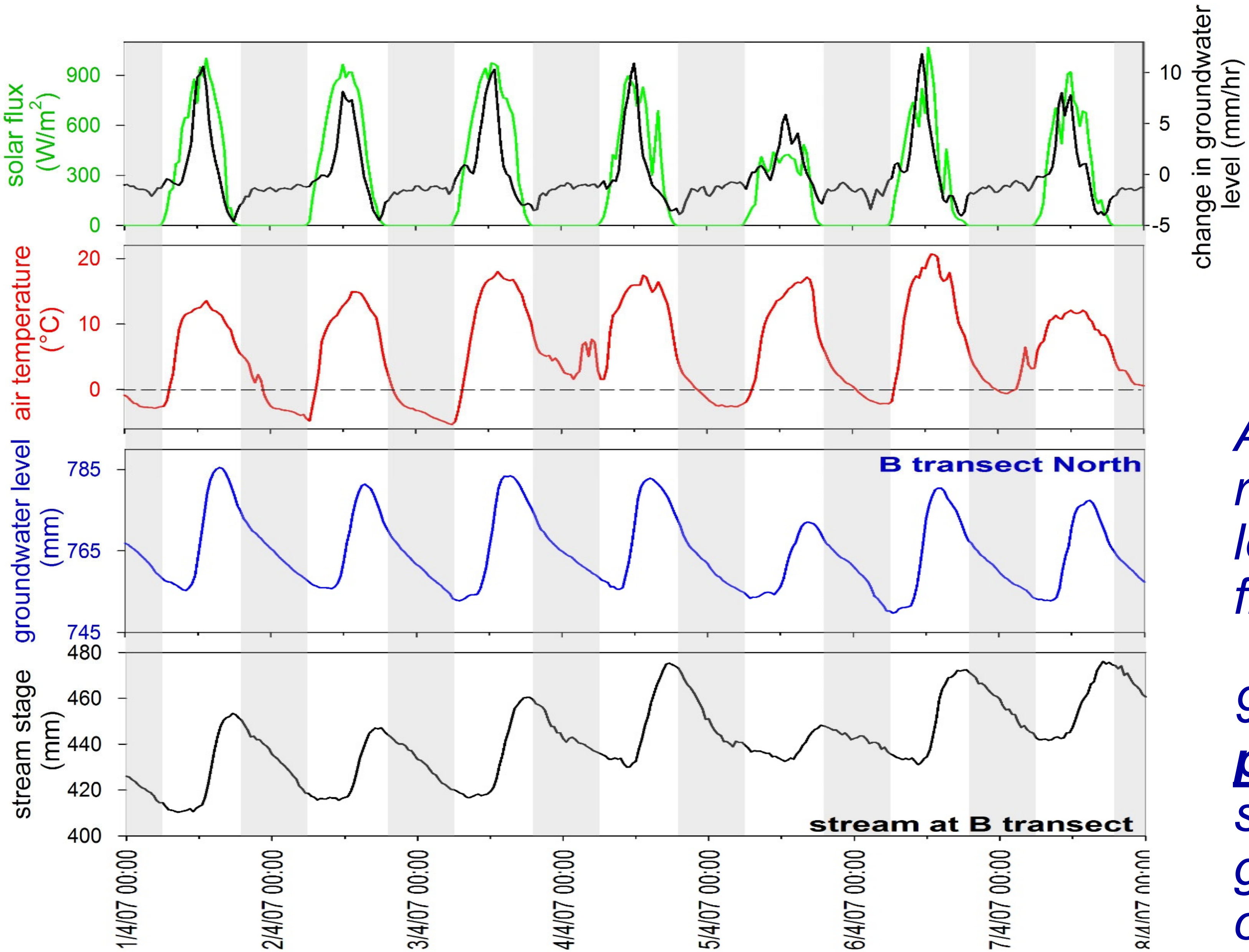



Night: stream discharge rebounds as groundwater flow from uplands refills riparian aquifer
Upland


Night: stream discharge rebounds as groundwater flow from uplands refills riparian aquifer
Upland

Changes in groundwater levels (note reversed scale) are synchronized with solar flux and sap flow

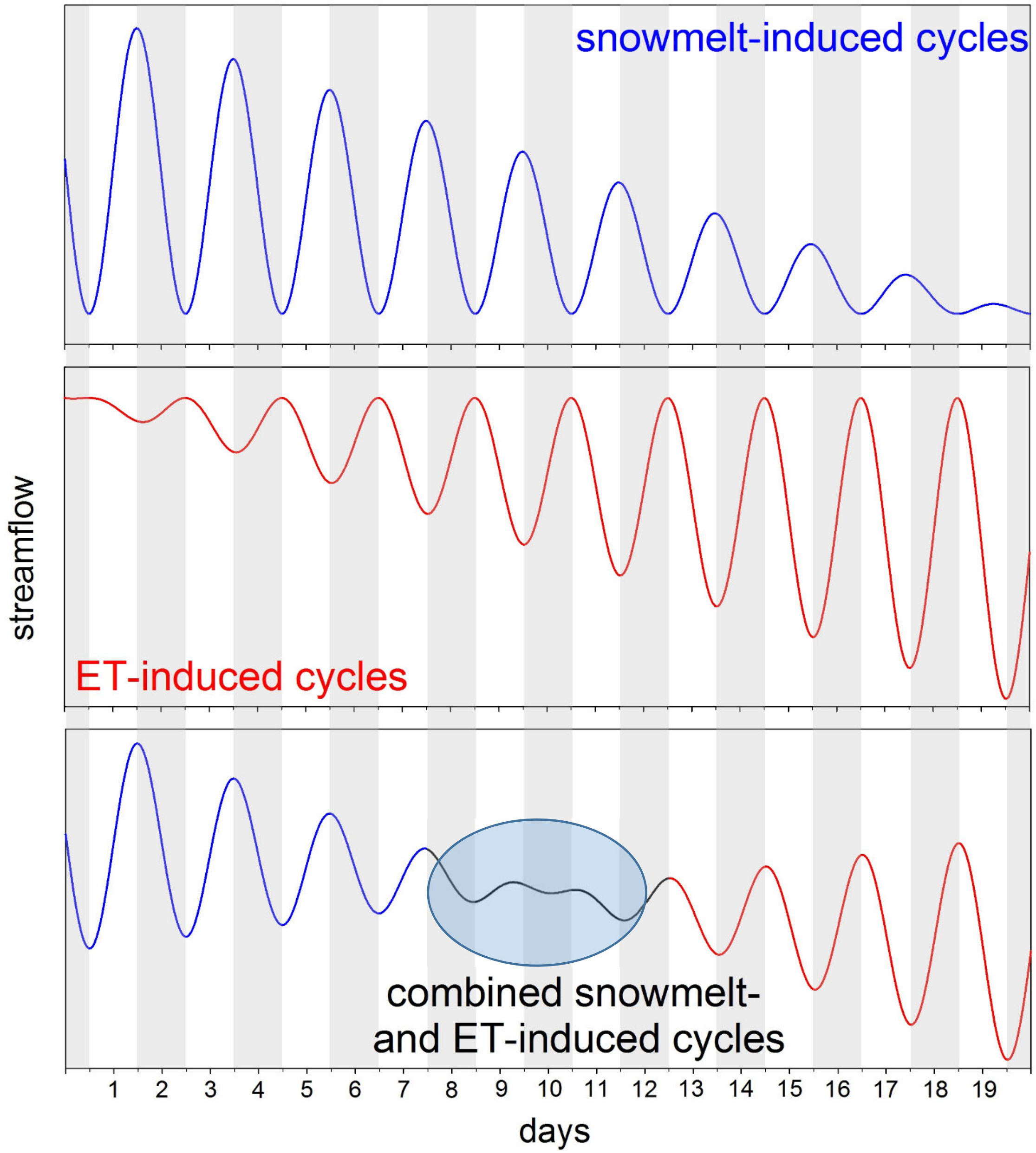




Snowmelt at Sagehen Creek

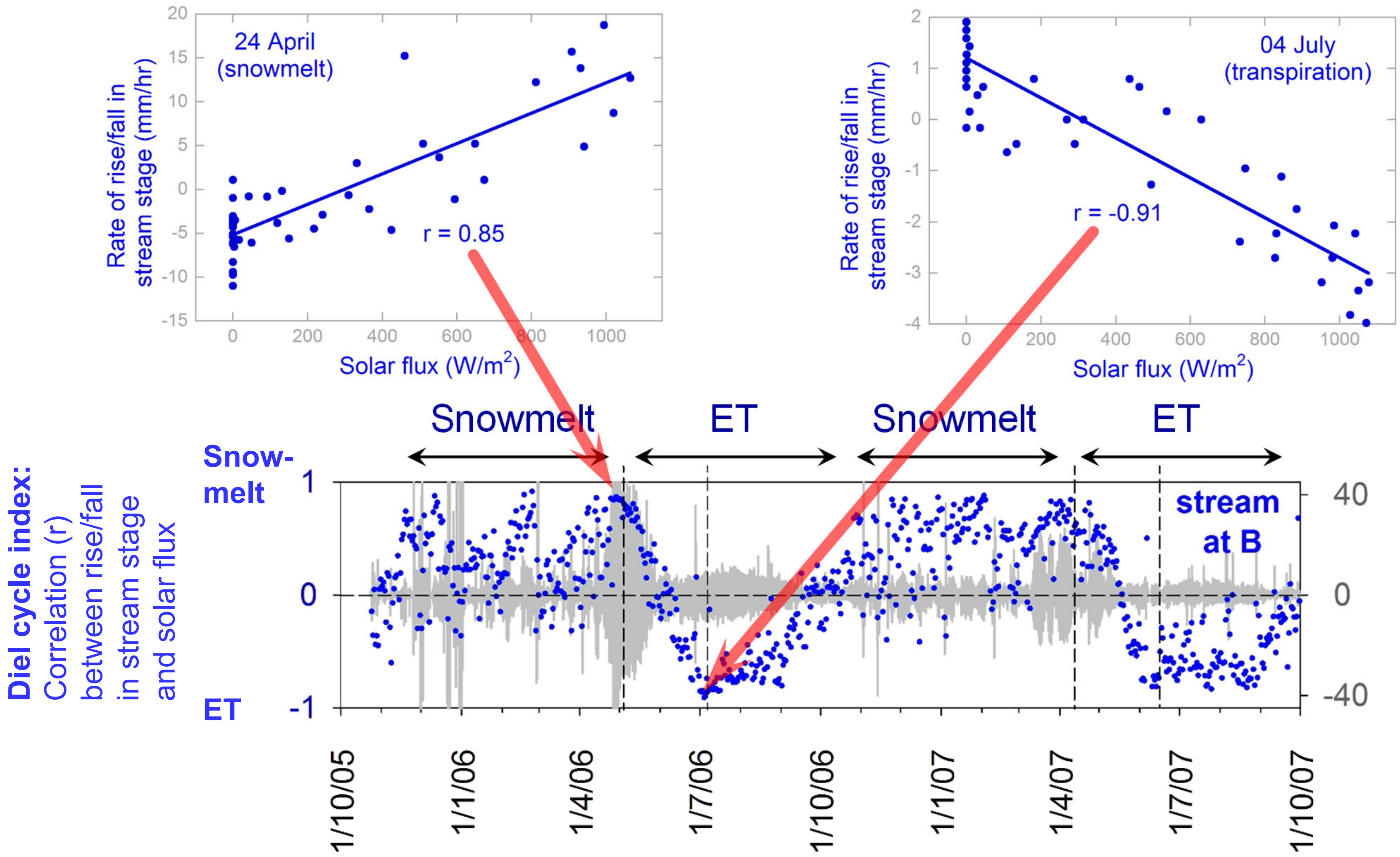
April: snowmelt raises groundwater levels and stream flow each day

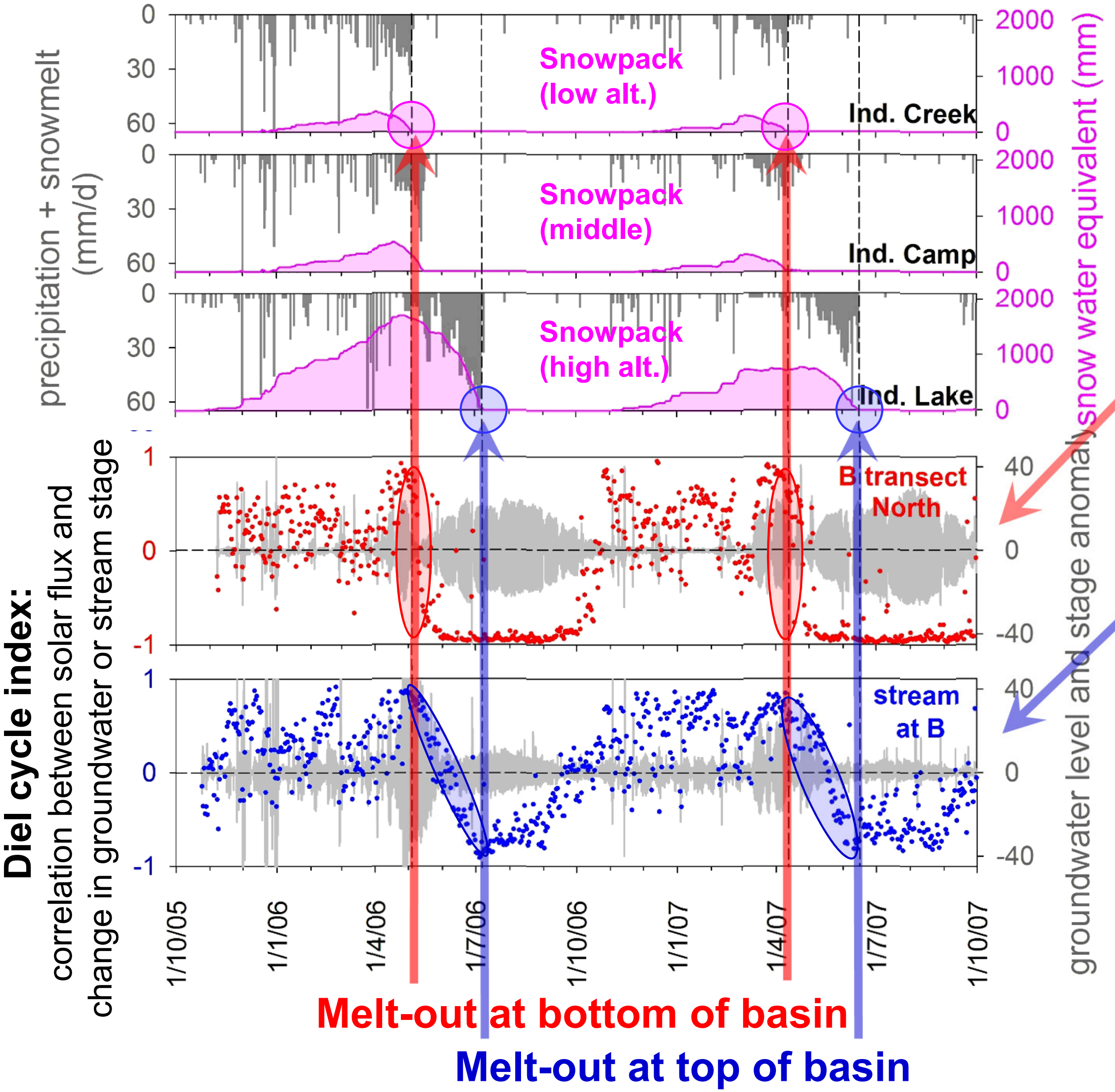
*90º **dynamical phase lag** between snowmelt and groundwater levels or stream stage*



Snowmelt and ET cycles have opposite phase, and cancel one another when their amplitudes match, as dominance shifts from snowmelt to ET.

Daily correlations between solar flux and *rate* of rise/fall indicate relative strength of snowmelt and evapotranspiration signals



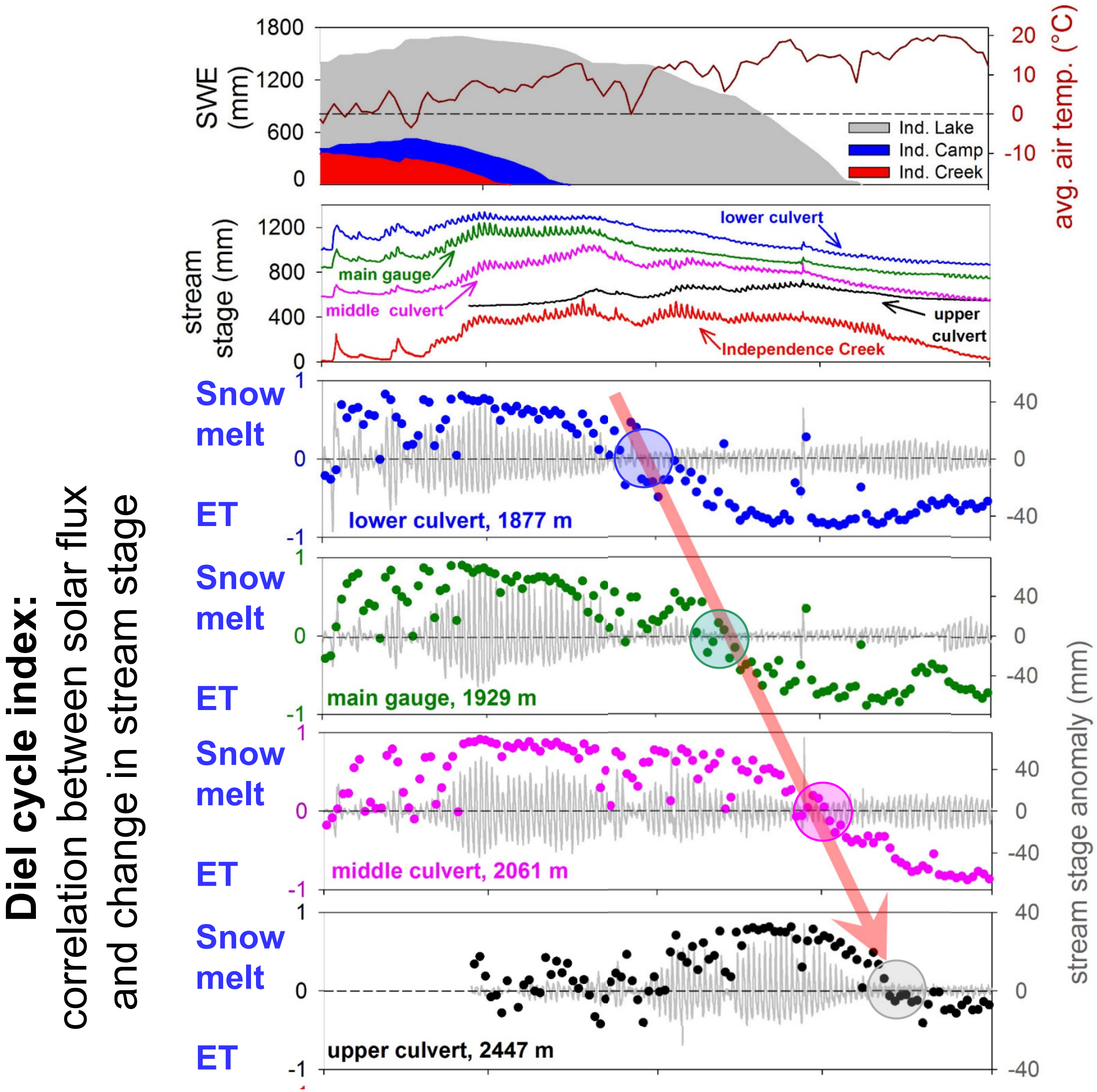


Diel Cycle Index shows transitions from snowmelt to ET cycles.

Groundwater cycle shifts rapidly, coinciding with local loss of snowpack.

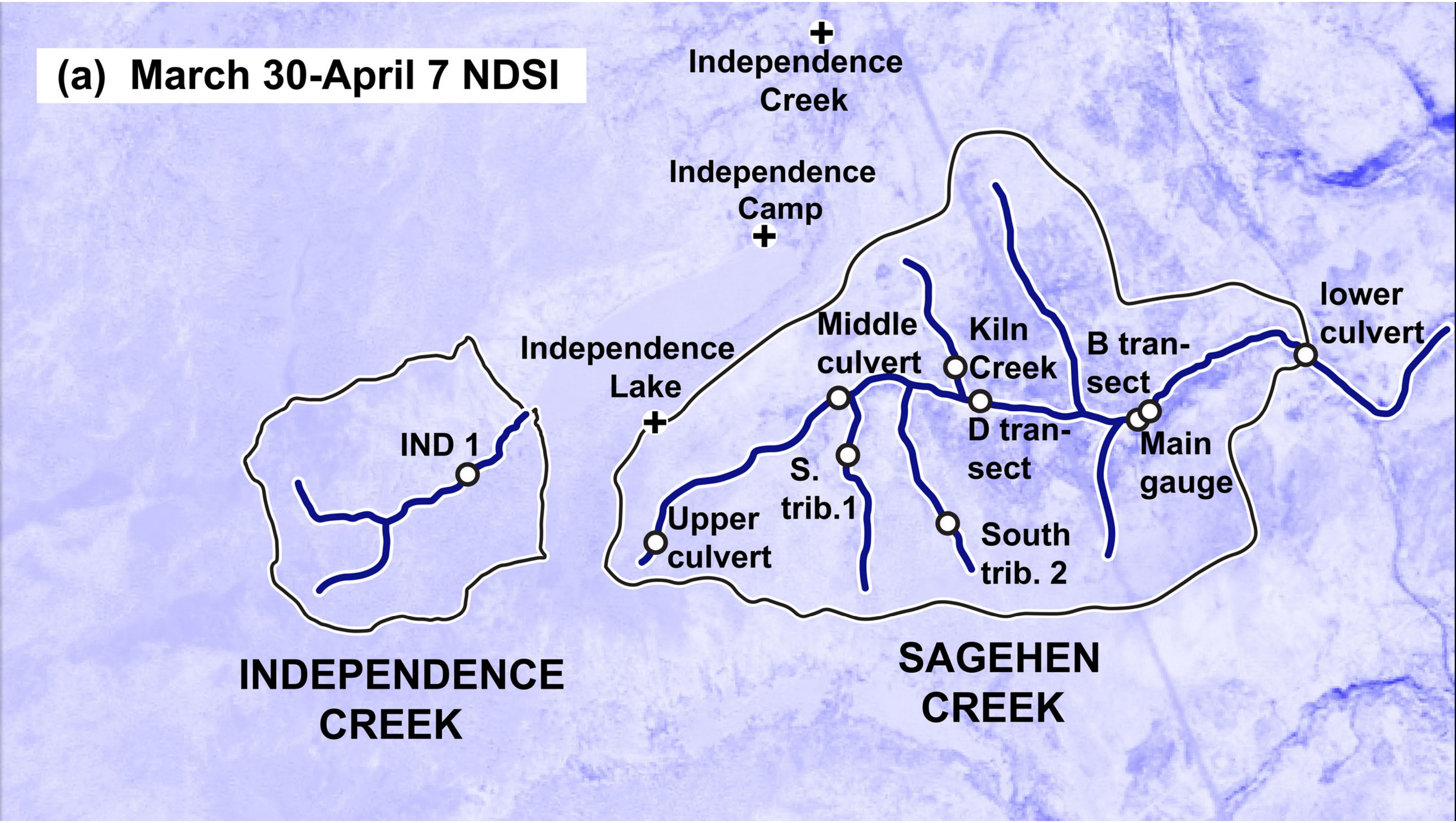
Stream cycle shifts gradually, as snowpack retreats toward top of basin.

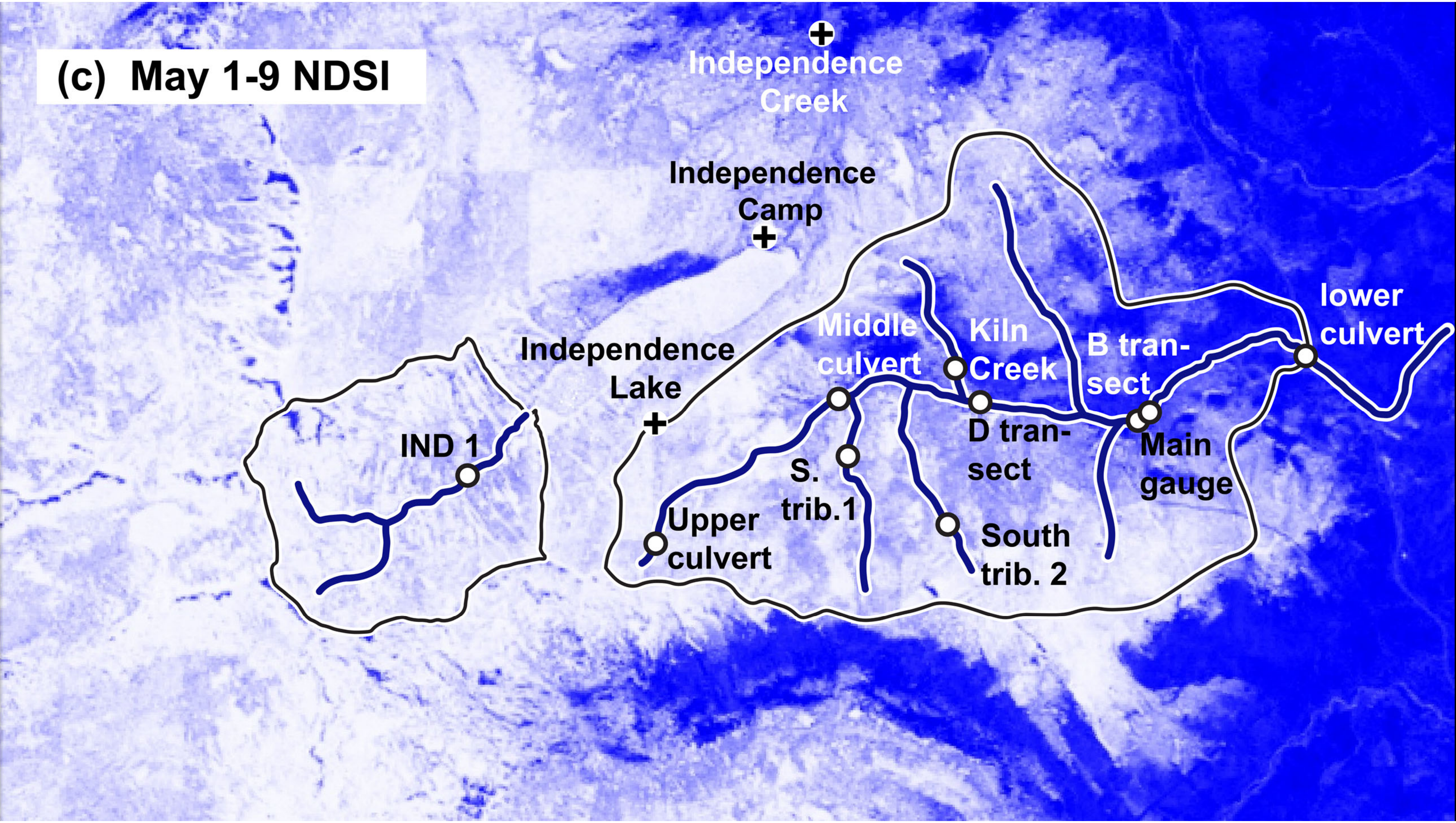
Groundwater cycles reflect the *local* balance between snowmelt and transpiration. *Stream cycles integrate* this balance over the catchment.

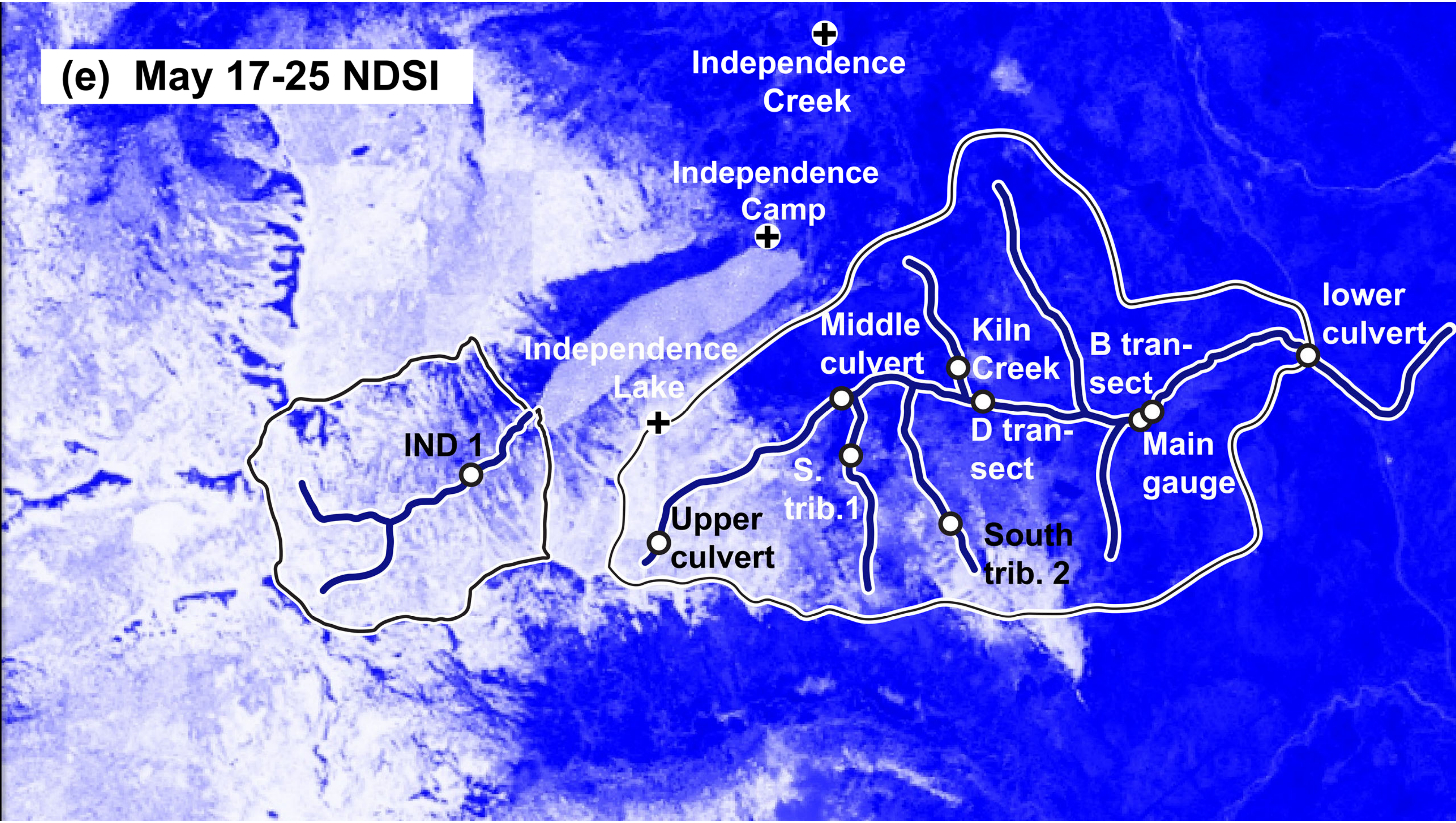


Streamflow correlations with solar flux shift from positive (snowmelt cycles) to negative (ET cycles) later at higher altitudes, reflecting seasonal snowpack retreat.

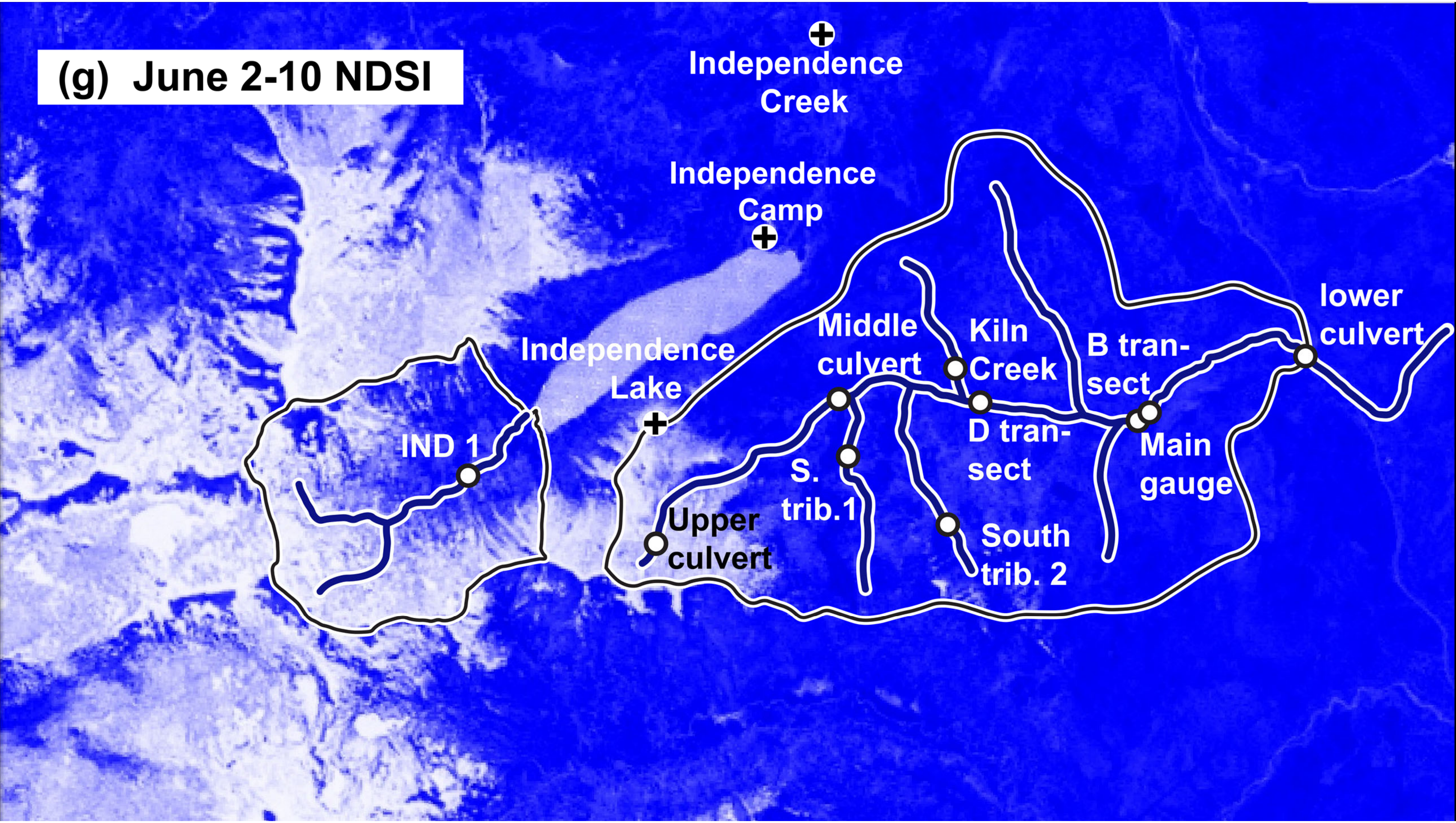
Streams and ground-waters integrate (literally, in both time and space) eco-hydrological fluxes.

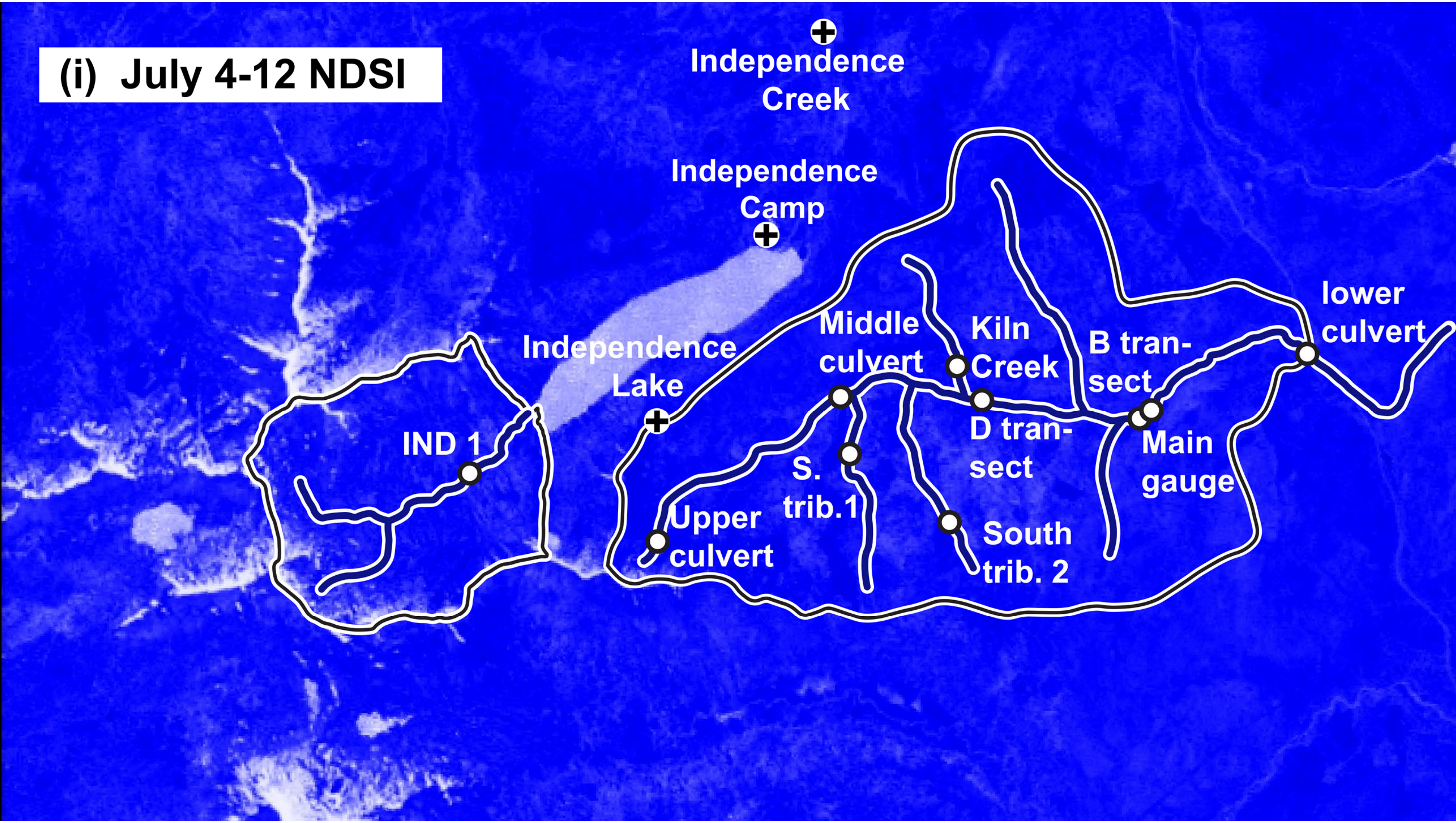

(a) March 30-April 7 NDSI
Independence Creek
Independence Camp
Independence Lake
IND 1
INDEPENDENCE CREEK
Middle culvert
Kiln Creek
B tran-sect
lower culvert
D tran-sect
Main gauge
S. trib.1
Upper culvert
South trib. 2
SAGEHEN CREEK


(c) May 1-9 NDSI
Independence Creek
Independence Camp
Independence Lake
IND 1
Middle culvert
Kiln Creek
B transect
lower culvert
D transect
Main gauge
Upper culvert
S. trib.1
South trib. 2

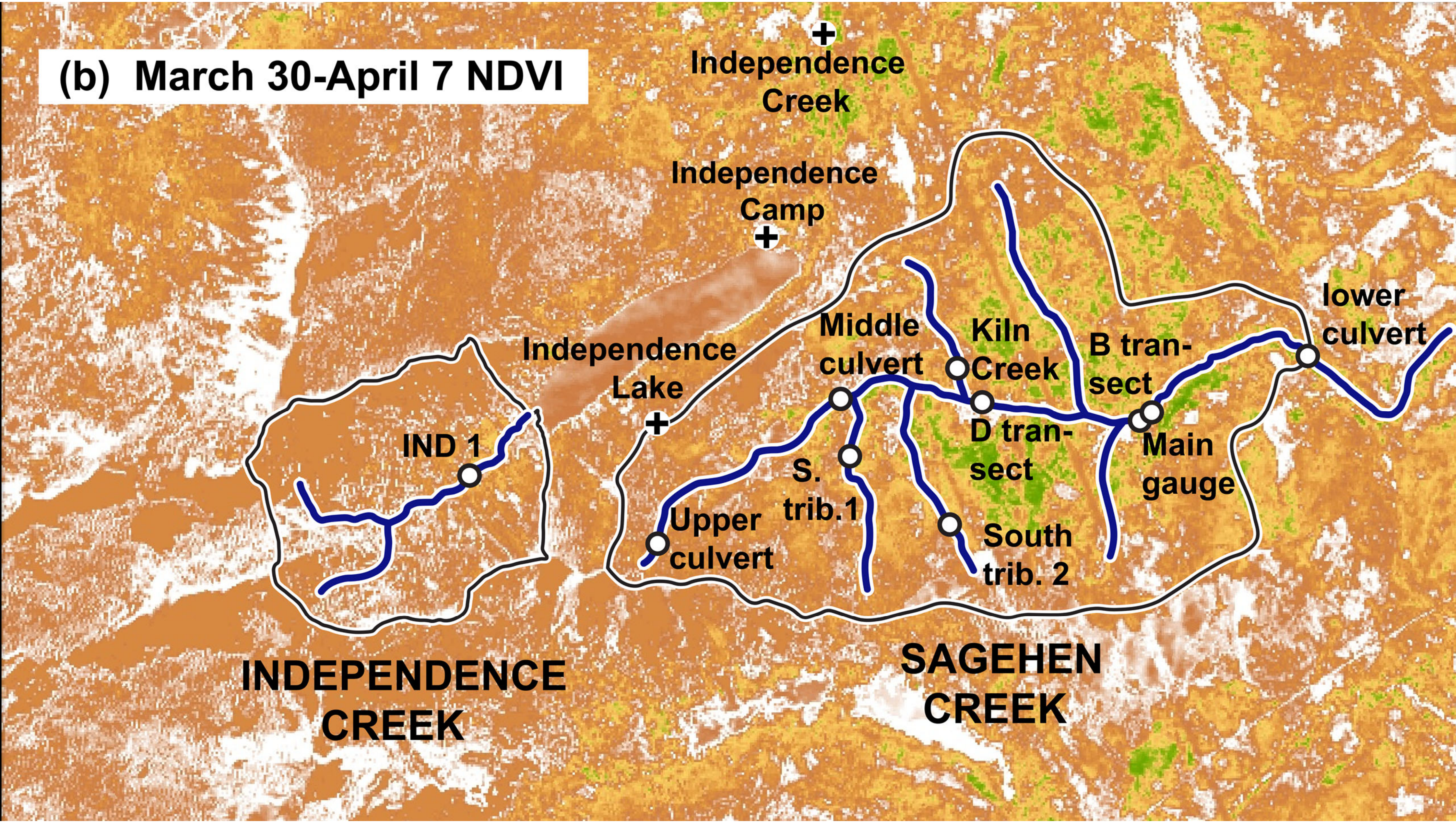


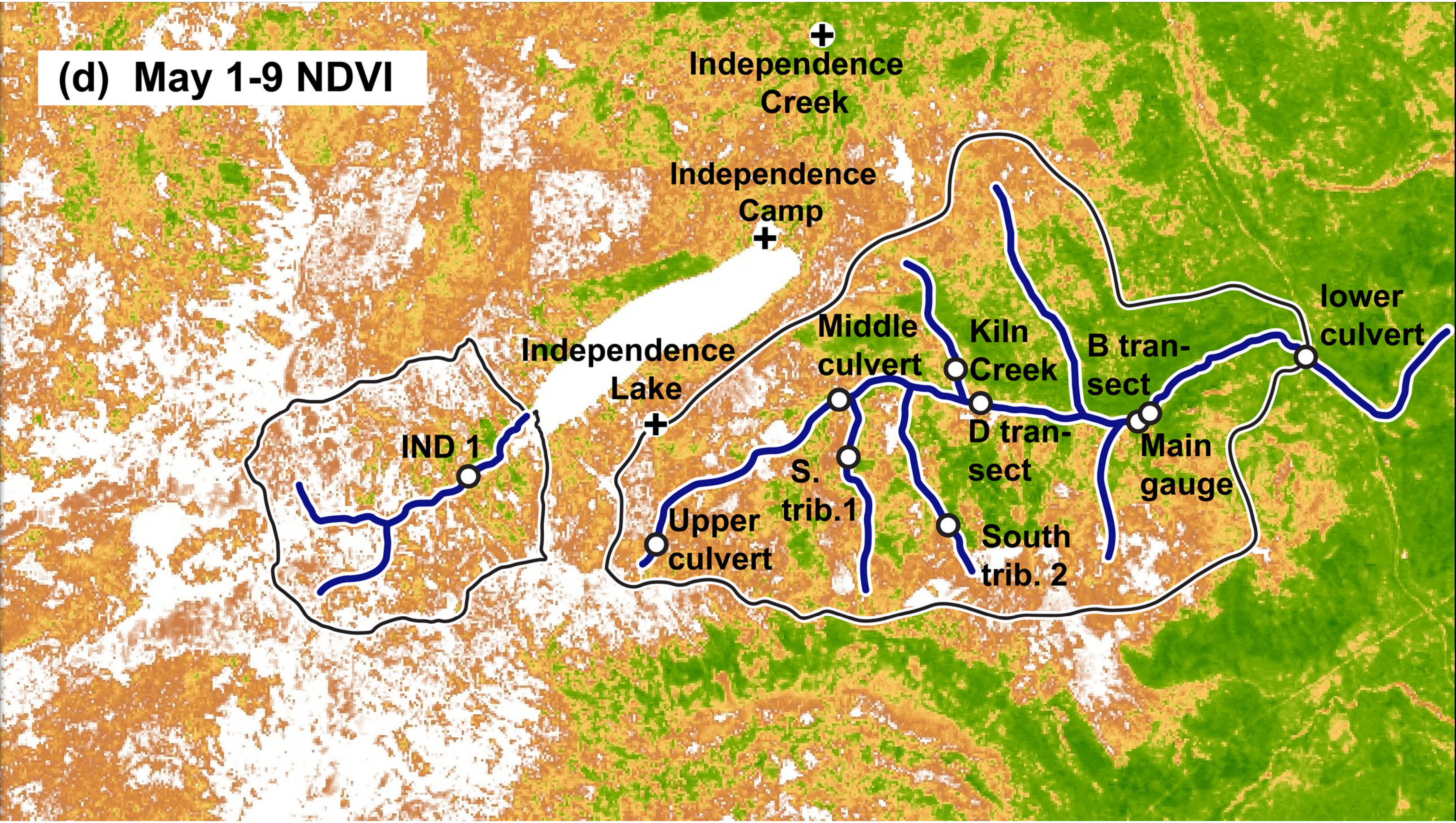
(e) May 17-25 NDSI
Independence Creek
Independence Camp
Independence Lake
IND 1
Middle culvert
Kiln Creek
B tran-sect
lower culvert
D tran-sect
Main gauge
S. trib.1
Upper culvert
South trib. 2

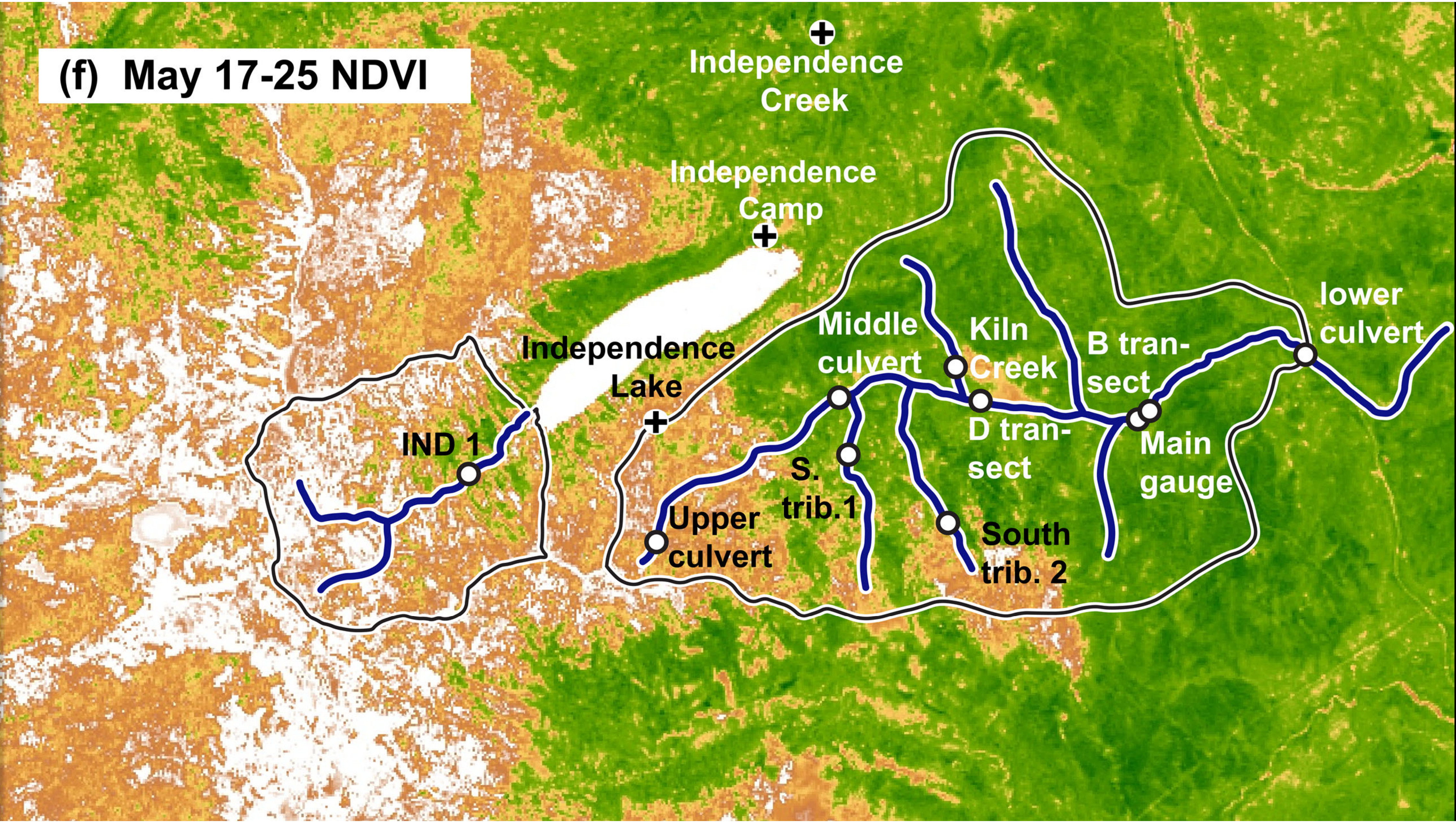

(g) June 2-10 NDSI
Independence Creek
Independence Camp
Independence Lake
IND 1
Upper culvert
Middle culvert
S. trib.1
Kiln Creek
D transect
South trib. 2
B transect
Main gauge
lower culvert

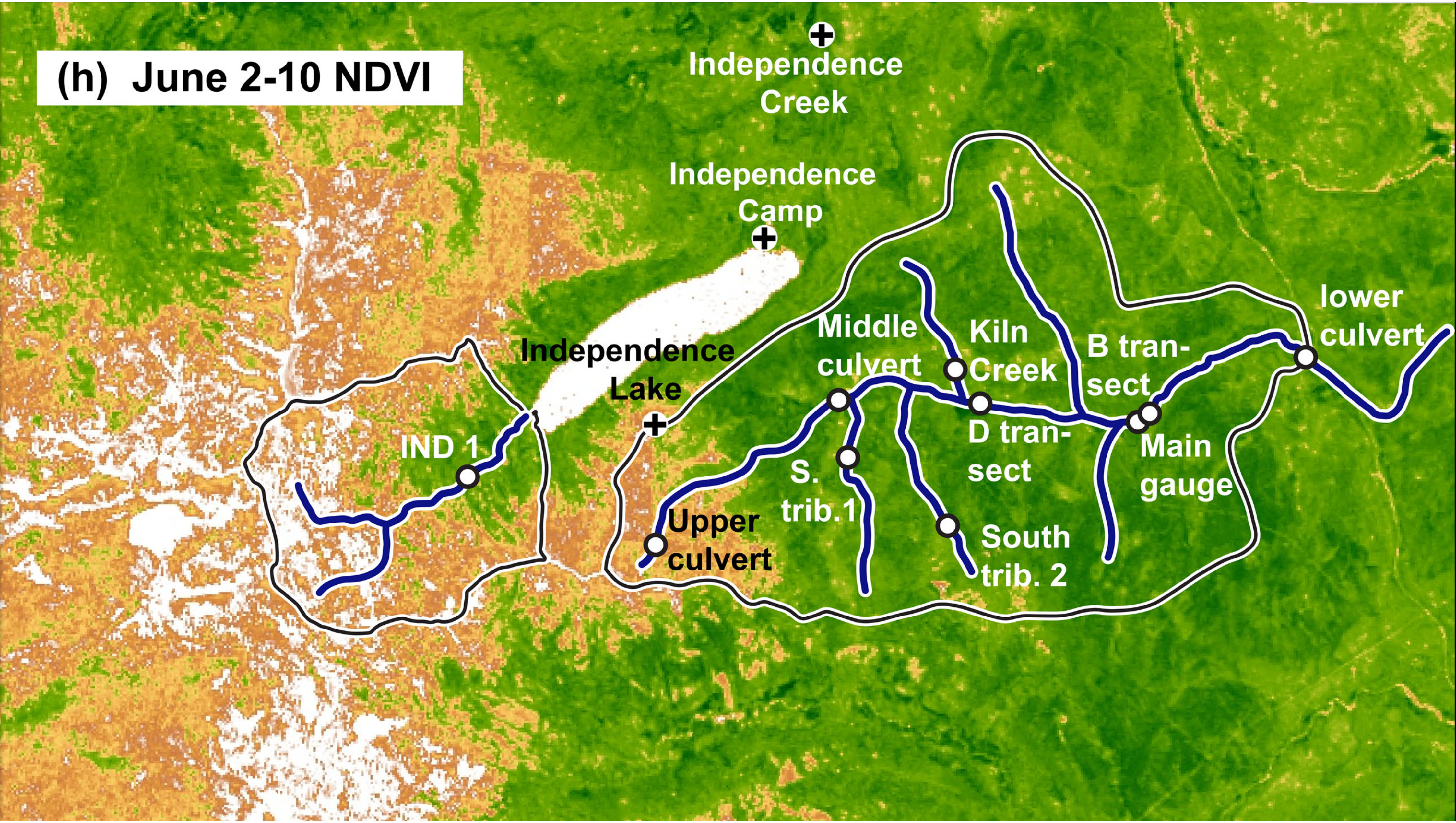


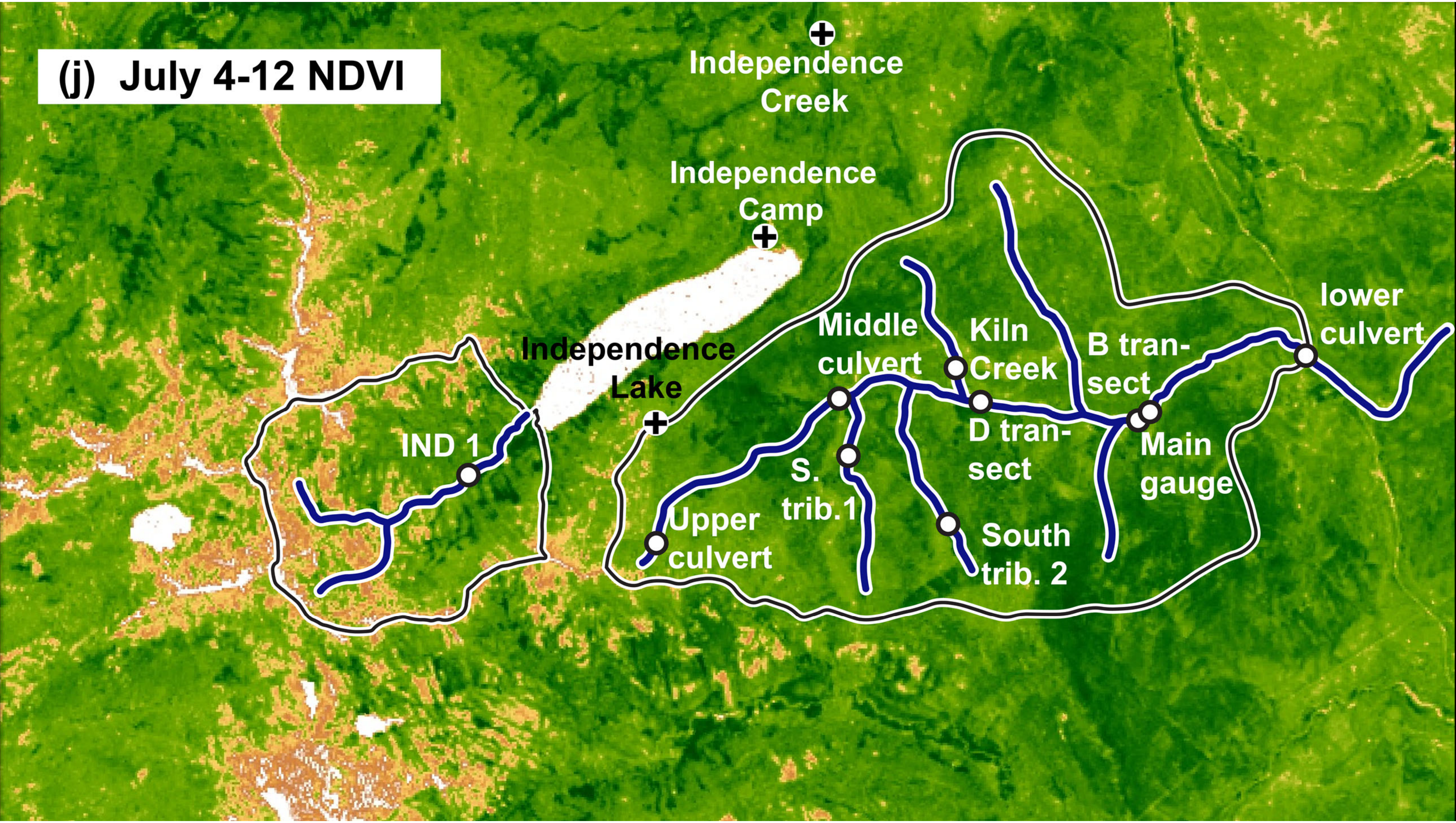
(i) July 4-12 NDSI
Independence Creek
Independence Camp
Independence Lake
IND 1
Middle culvert
Kiln Creek
B tran-sect
lower culvert
D tran-sect
Main gauge
S. trib.1
Upper culvert
South trib. 2


(b) March 30-April 7 NDVI
Independence Creek
Independence Camp
Independence Lake
IND 1
Middle culvert
Kiln Creek
B transect
lower culvert
D transect
Main gauge
S. trib.1
Upper culvert
South trib. 2
INDEPENDENCE CREEK
SAGEHEN CREEK


(d) May 1-9 NDVI
Independence Creek
Independence Camp
Independence Lake
IND 1
Middle culvert
Kiln Creek
B tran-sect
lower culvert
D tran-sect
Main gauge
S. trib.1
Upper culvert
South trib. 2

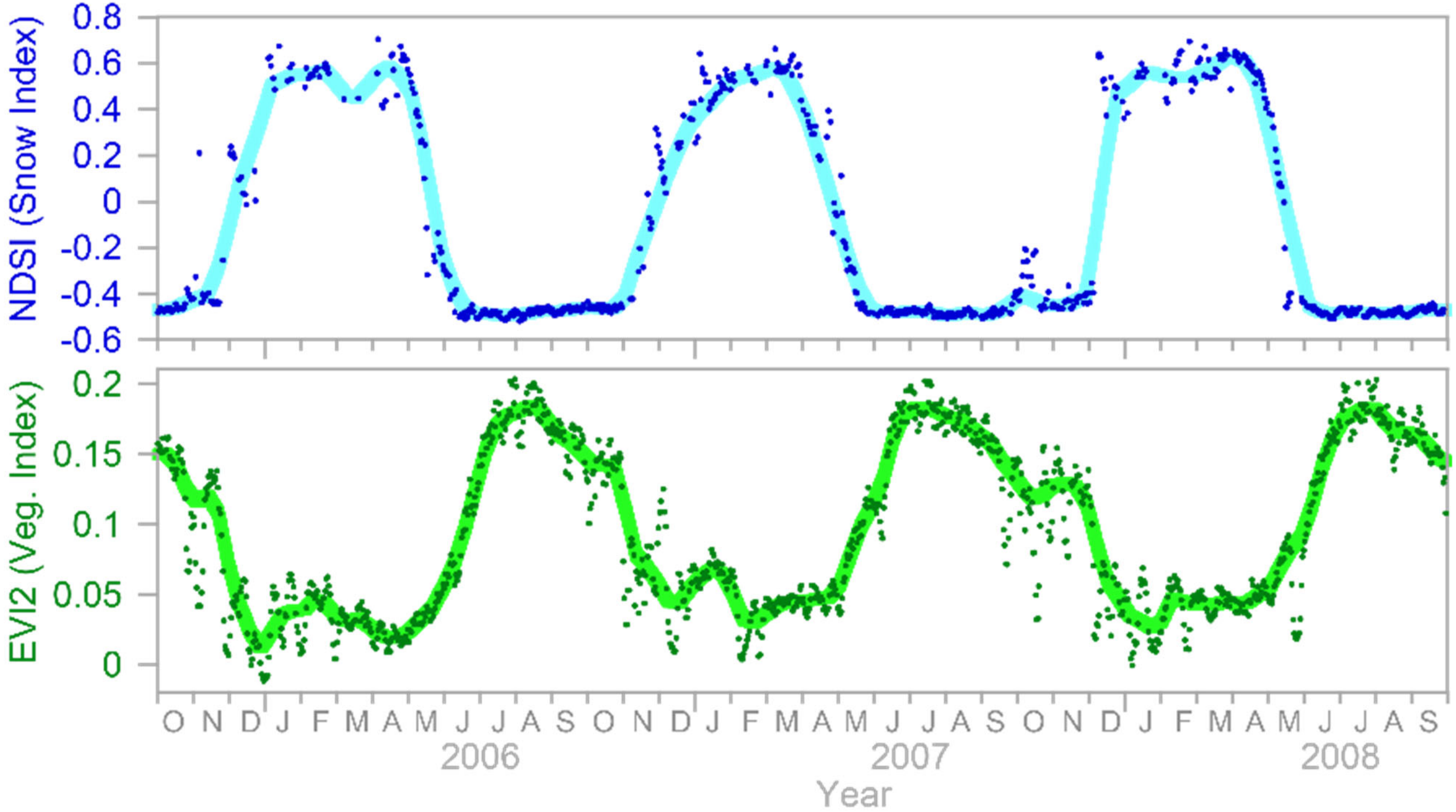

(f) May 17-25 NDVI
Independence Creek
Independence Camp
Independence Lake
IND 1
Middle culvert
Kiln Creek
B transect
lower culvert
D transect
Main gauge
S. trib.1
Upper culvert
South trib. 2

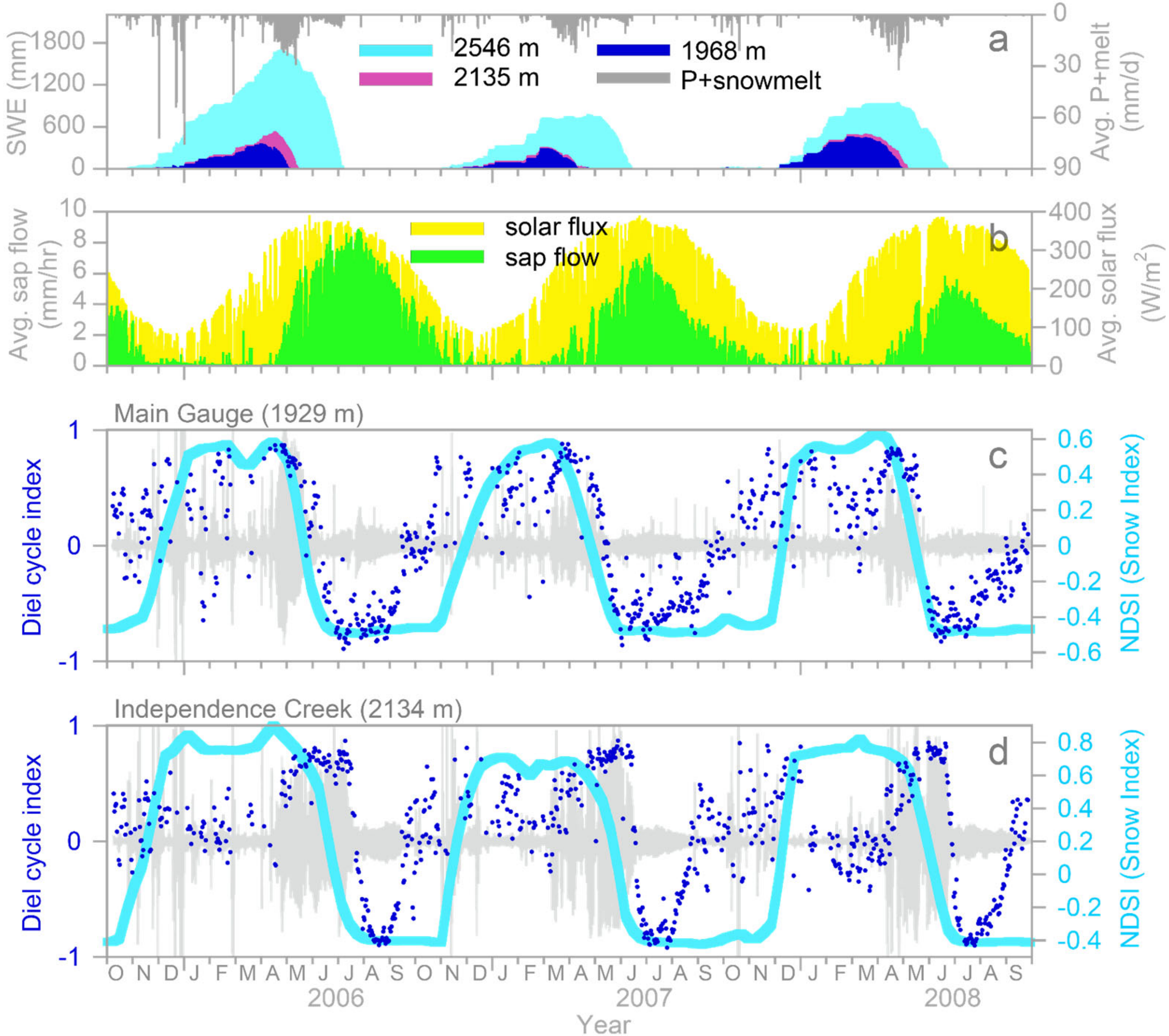

(h) June 2-10 NDVI
Independence Creek
Independence Camp
Independence Lake
IND 1
Upper culvert
Middle culvert
S. trib.1
Kiln Creek
D transect
South trib. 2
B transect
Main gauge
lower culvert


(j) July 4-12 NDVI
Independence Creek
Independence Camp
Independence Lake
IND 1
Middle culvert
Kiln Creek
B transect
lower culvert
D transect
Main gauge
S. trib.1
Upper culvert
South trib. 2

MODIS gives us (almost) daily coverage, but at much lower resolution…

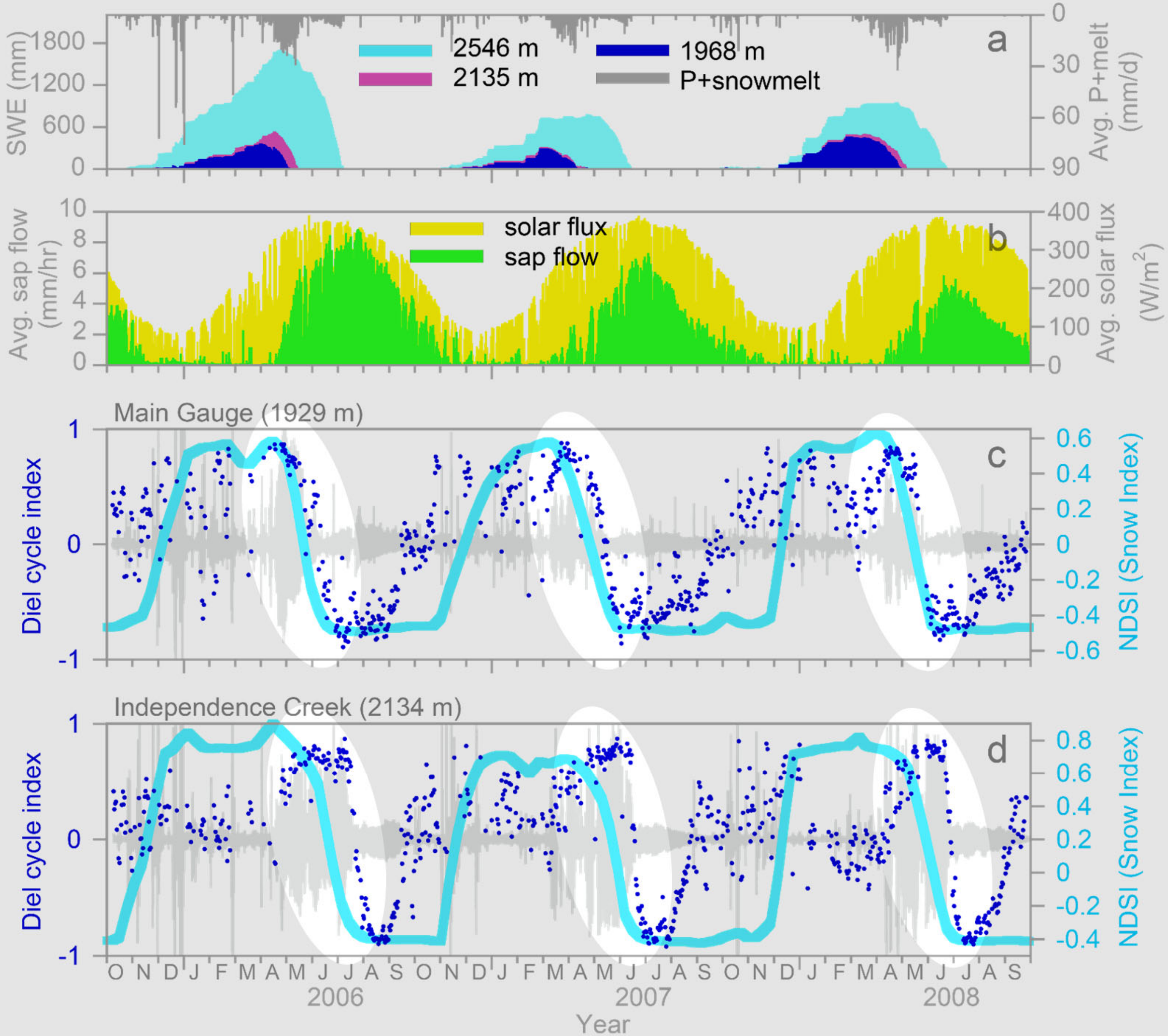
MODIS ~daily catchment averages, with Loess smoothing to show seasonal trends



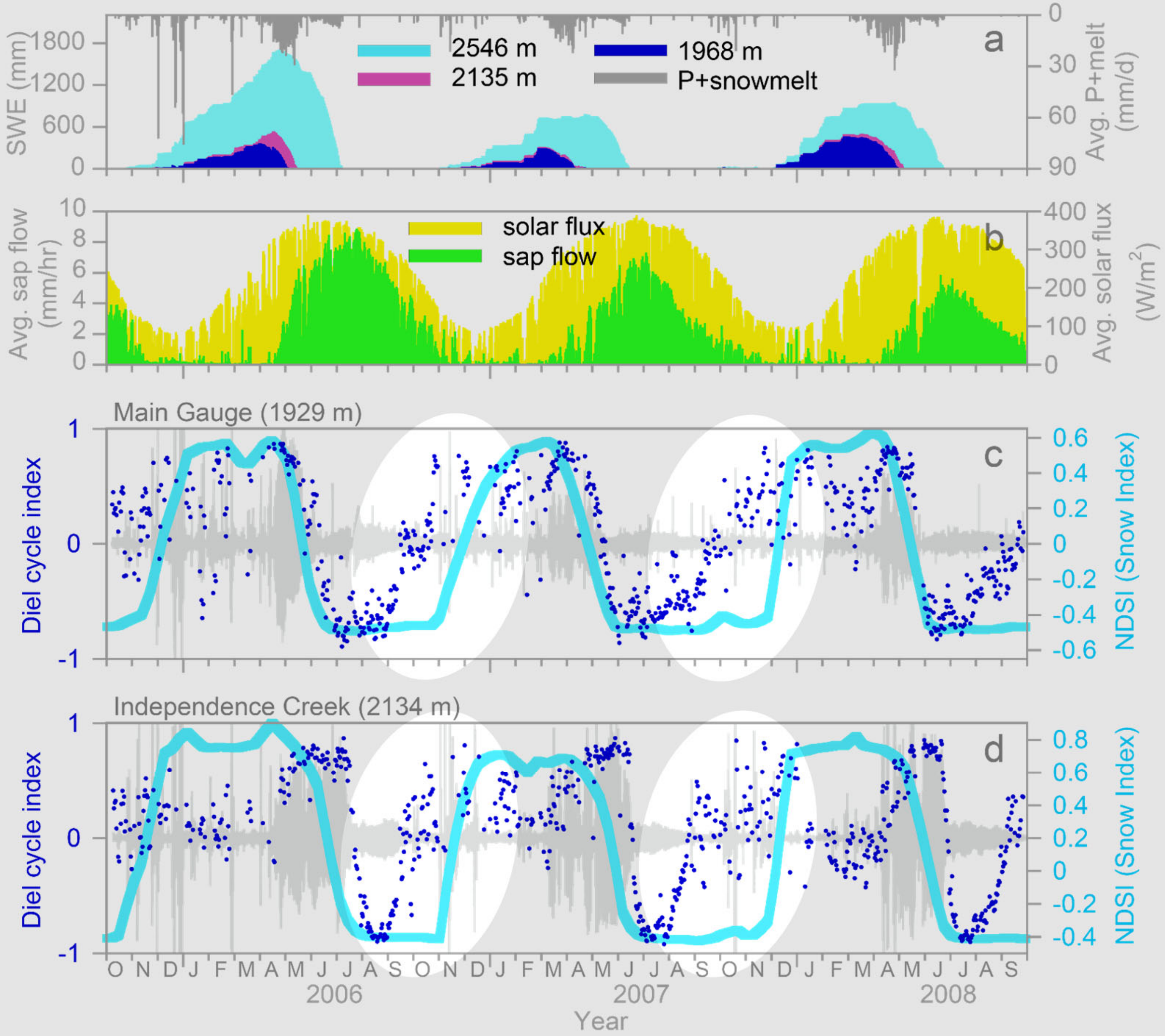


SWE (mm)
1800
1200
600
0
2546 m
2135 m
1968 m
P+snowmelt
a
0
30
60
90
Avg. P+melt (mm/d)
Avg. sap flow (mm/hr)
10
8
6
4
2
0
solar flux
sap flow
b
400
300
200
100
0
Avg. solar flux (W/m²)
Main Gauge (1929 m)
Diel cycle index
1
0
-1
c
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
NDSI (Snow Index)
Independence Creek (2134 m)
Diel cycle index
1
0
-1
d
0.8
0.6
0.4
0.2
0
-0.2
-0.4
NDSI (Snow Index)
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
2006
2007
2008
Year

Diel cycle index values (blue dots) shift from +1 (snowmelt) to -1 (ET) shortly *after* MODIS snow index (blue line) shows melt-out of seasonal snowpack

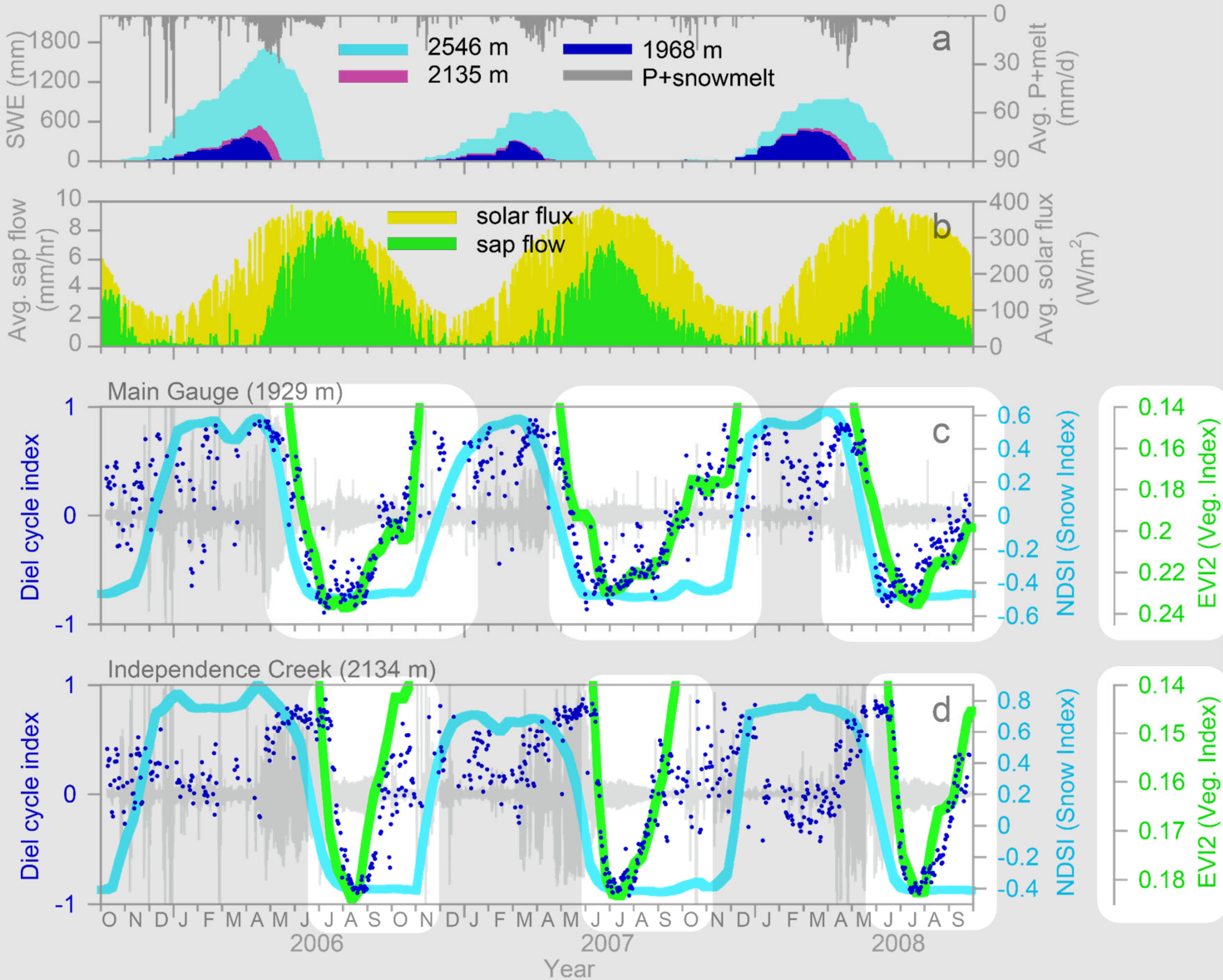


Diel cycle index values (blue dots) shift back from -1 (ET) toward +1 (snowmelt) *several months before* MODIS snow index (blue line) shows re-establishment of seasonal snowpack

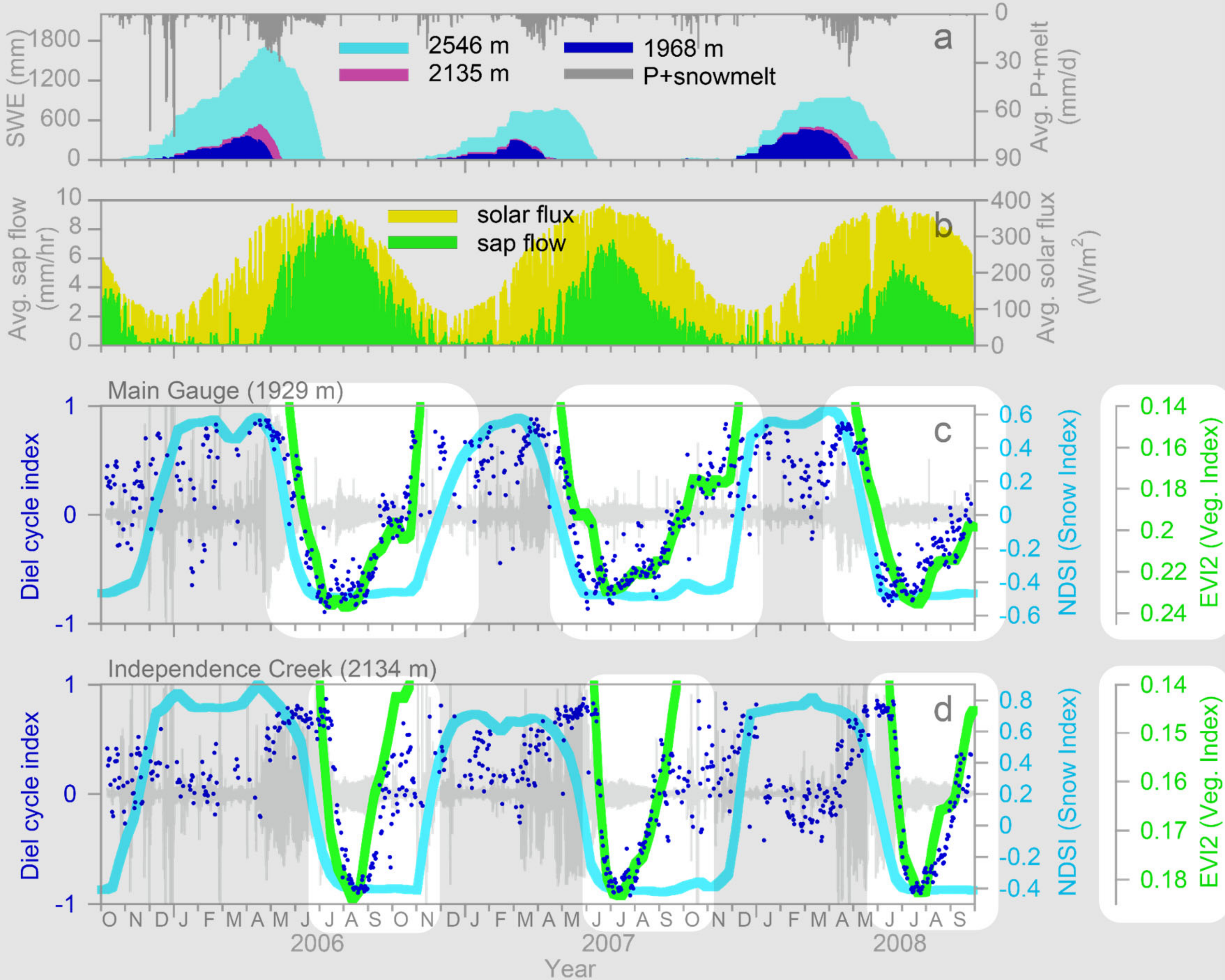


Diel cycle index values (blue dots) shift from +1 (snowmelt) to -1 (ET) and back, mirroring the increase/decrease in the MODIS vegetation index (green lines, note reversed scale).

So… streamflow cycles *mostly reflect the seasonal increase/decrease in vegetation activity*, not (at least directly) snow accumulation and melt.



Different vegetation scales: different rock outcrops



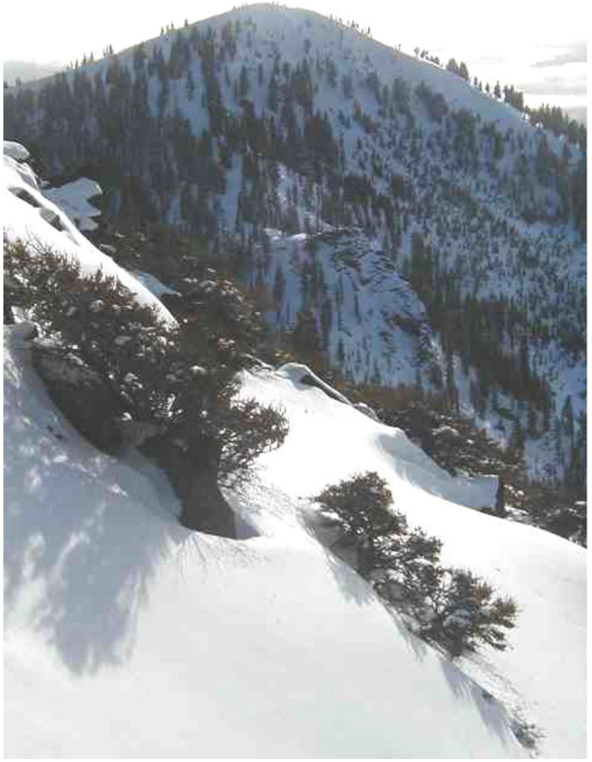

Streams and lakes are mirrors of the landscape

Forecast change in Sierra Nevada snowpack:

By mid-century (2020-2050): -26% to -40%

By end of century (2070-2100): -29% to -89%

Hayhoe, Cayan, et al., Emissions pathways, climate change, and impacts on California, *Proceedings of the National Academy of Sciences*, 101:12422-12427 (2004)



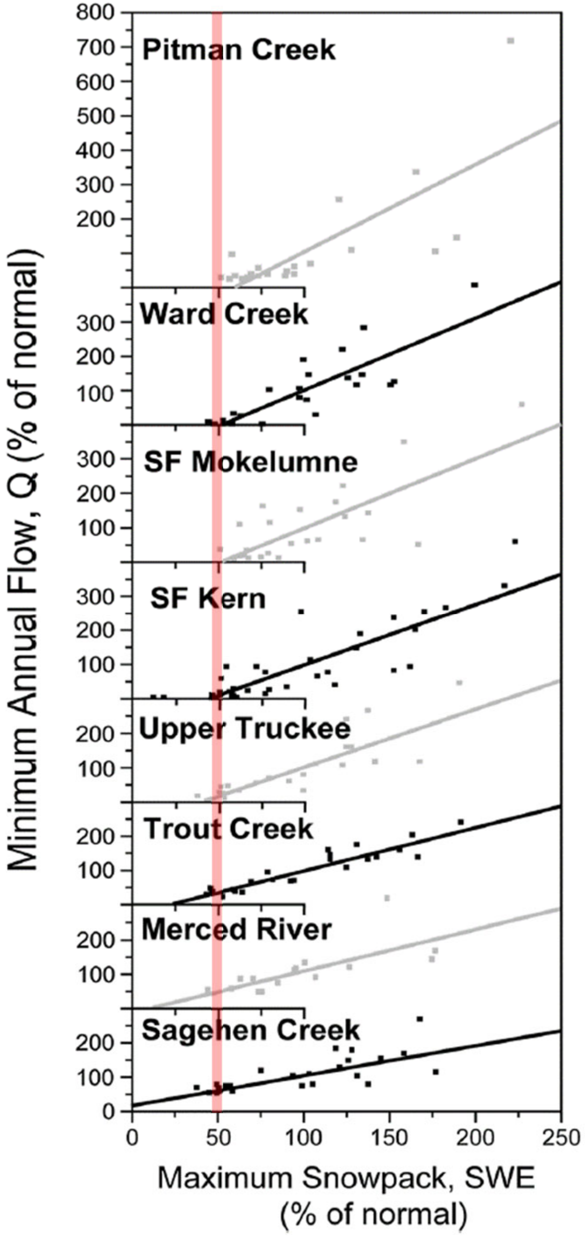
with:

Sarah Godsey
Christina Tague

Compare peak snow accumulation each winter (from snow pillow data) with minimum streamflow the following summer

Snow pillow (weighs overlying snowpack) →

Gauging station (measures streamflow) →



HYDROLOGICAL PROCESSES
Hydrol. Process. **28**, 5048–5064 (2014)
Published online 24 August 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9943

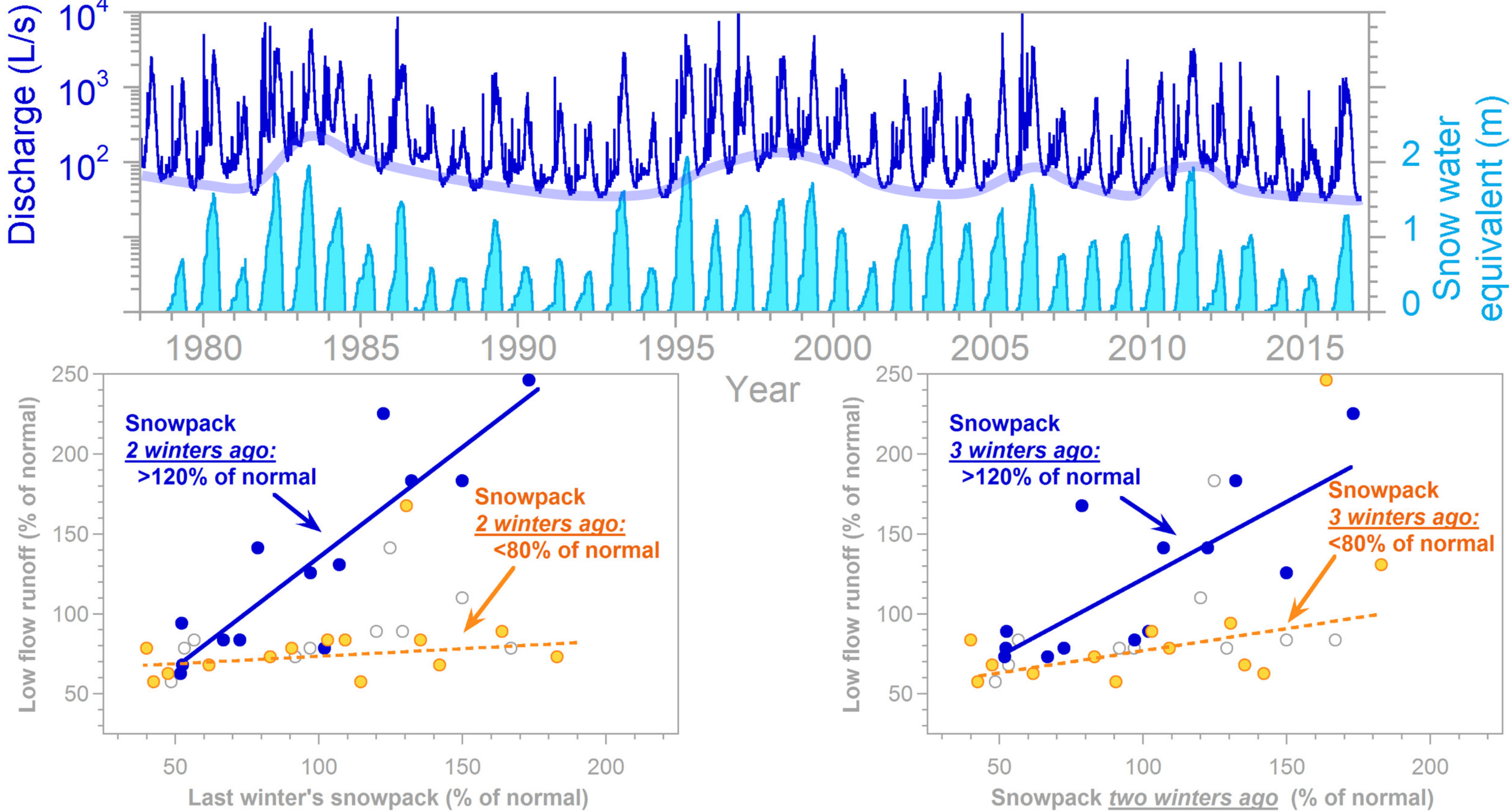
Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA

S. E. Godsey,[1]* J. W. Kirchner[2] and C. L. Tague[3]

Summer low flows are strongly correlated with peak winter snowpacks

Many of these streams are at risk of ***running dry*** in summer (at their current gauging station locations) if snowpacks shrink to ~50% of 'normal'

Sagehen Creek low flows 'remember' snowmelt inputs from *multiple previous winters*




Streams and lakes are mirrors of the landscape
… and remember its history, too

Floods

When rivers flood, surrounding rivers often flood at the same time

2005 Flood Tyrol. Credit: TU Wien/ASI/Land Tirol/BH Landeck

The synchronization of floods amplifies their impacts and financial risks

Q: ***over what scales*** are flood risks synchronized?

The European Flood Database provides unique spatial coverage of floods, but only information on ***timing***, not ***magnitude***

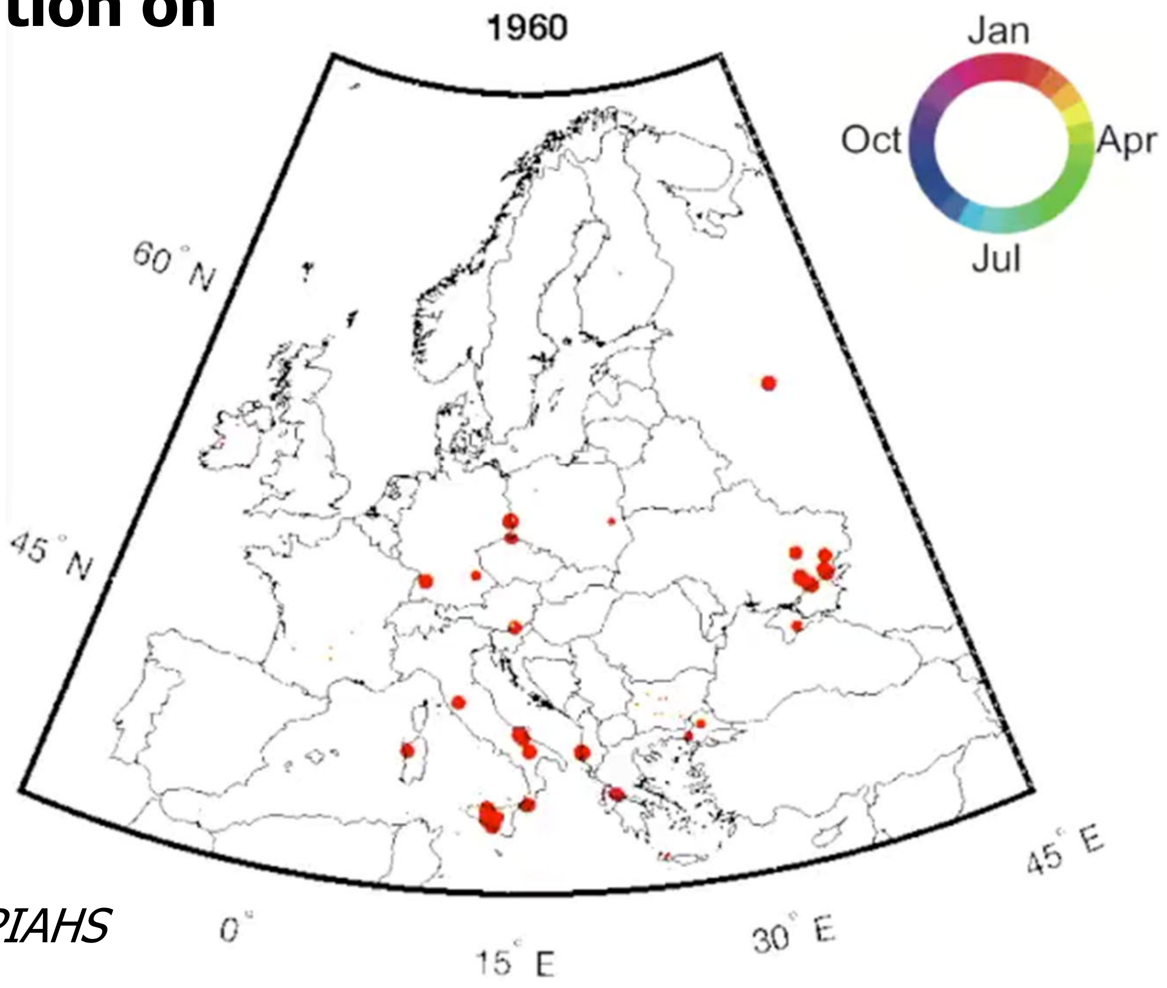
>4000 stations

Period 1960-2010

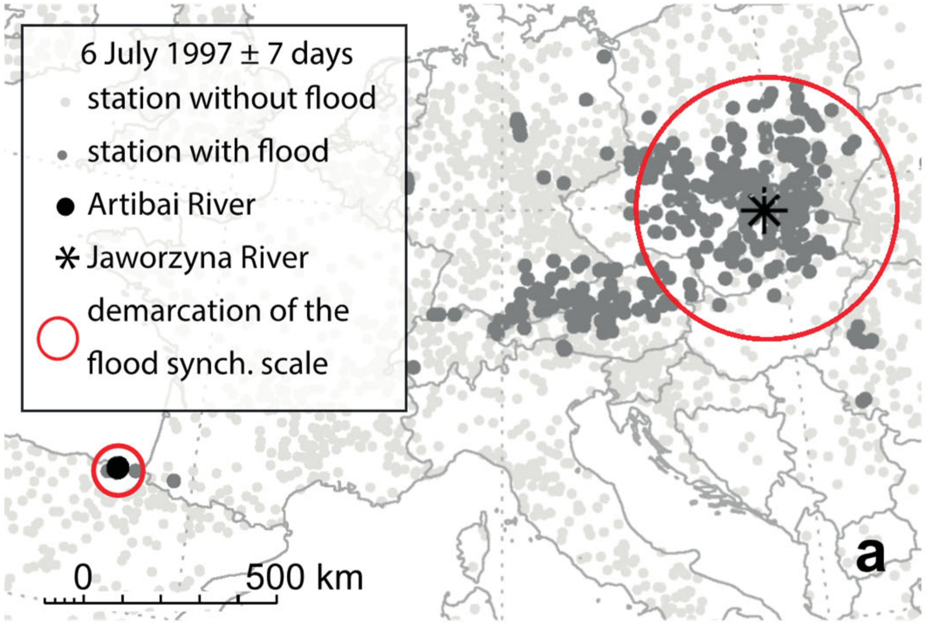
Dates of annual floods

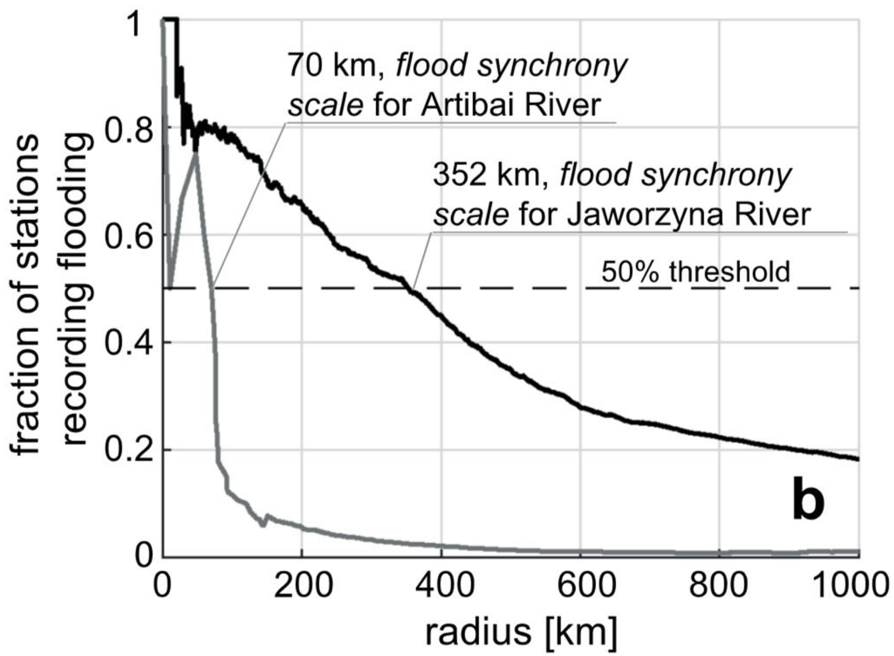
Basins areas ~10-10^4 km

See e.g.
Blöschl et al. (2017) *Science*
Hall et al. (2014, 2018) *HESS* (2015) *PIAHS*
Berghuijs et al. (2019) *GRL*



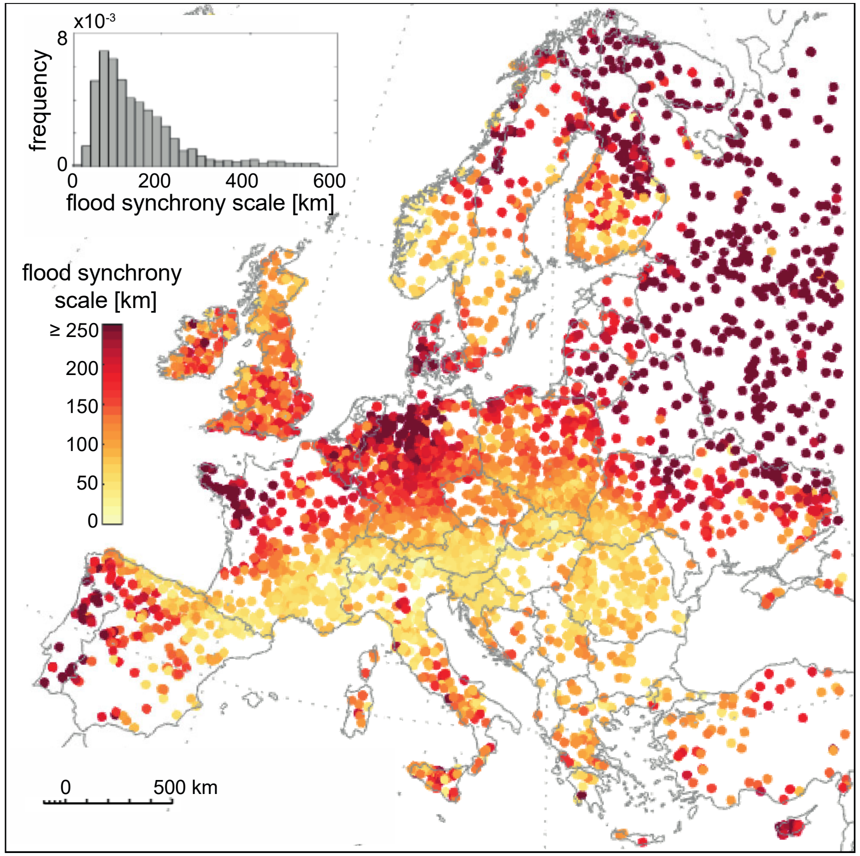
<u>Flood synchrony scale</u> is **maximum radius** around an individual river gauge within which at least **half of the other river gauges also record flooding** almost simultaneously





Berghuijs et al. (2019) *GRL*

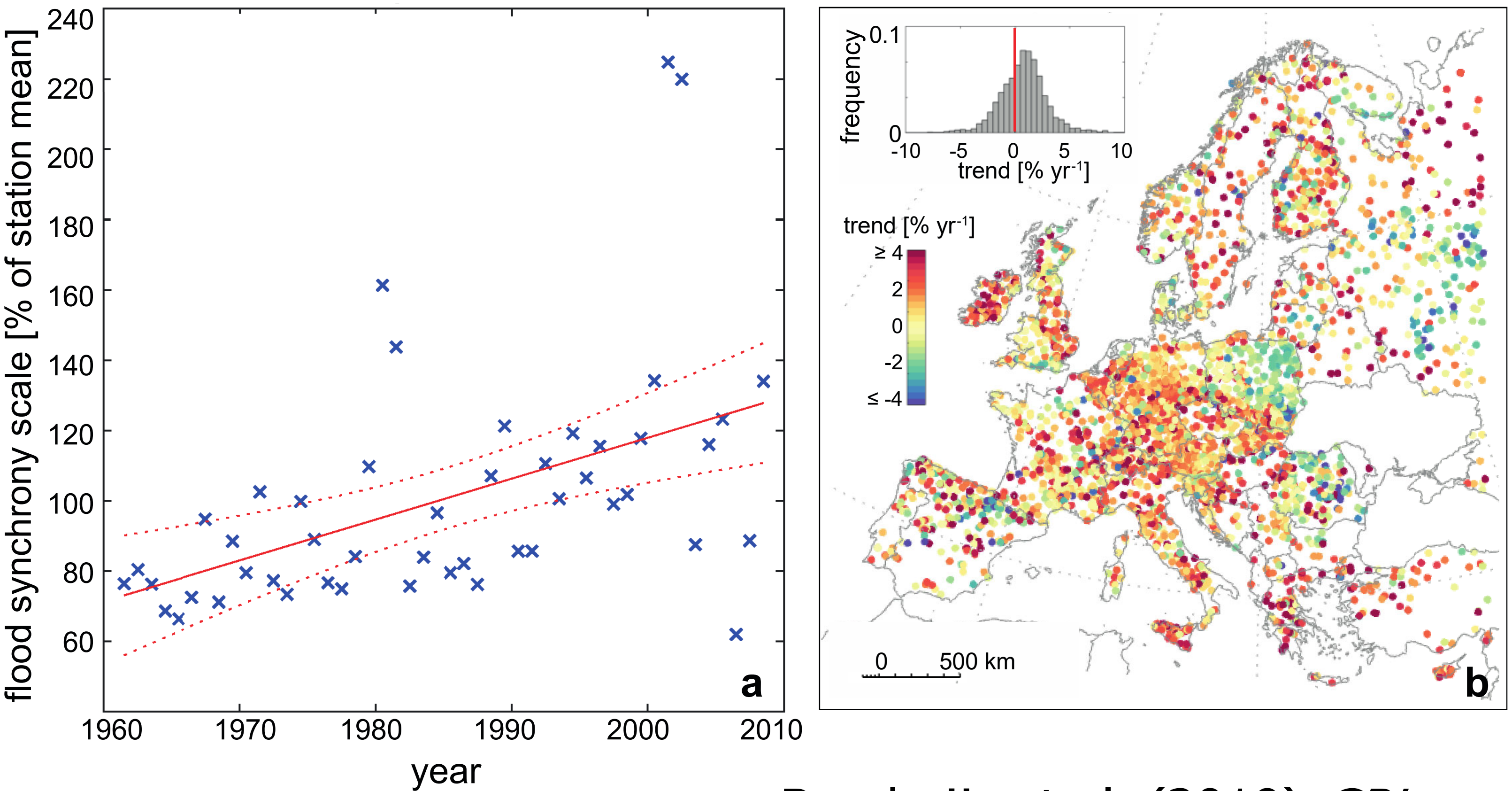
Floods extend far beyond the the scale of individual basins



- **Flood synchrony scales average 148km** (i.e. ~70.000km^2)
- Flooding is often **synchronized across hundreds of kilometers** in western and northeastern Europe
- Flooding is more **localized** in band across the Pyrenees, Alps, and Carpathians

Berghuijs et al. (2019) *GRL*

Flood synchrony scales have grown by ~50% over 1960-2010, but with regional differences



Berghuijs et al. (2019) *GRL*

Conclusions

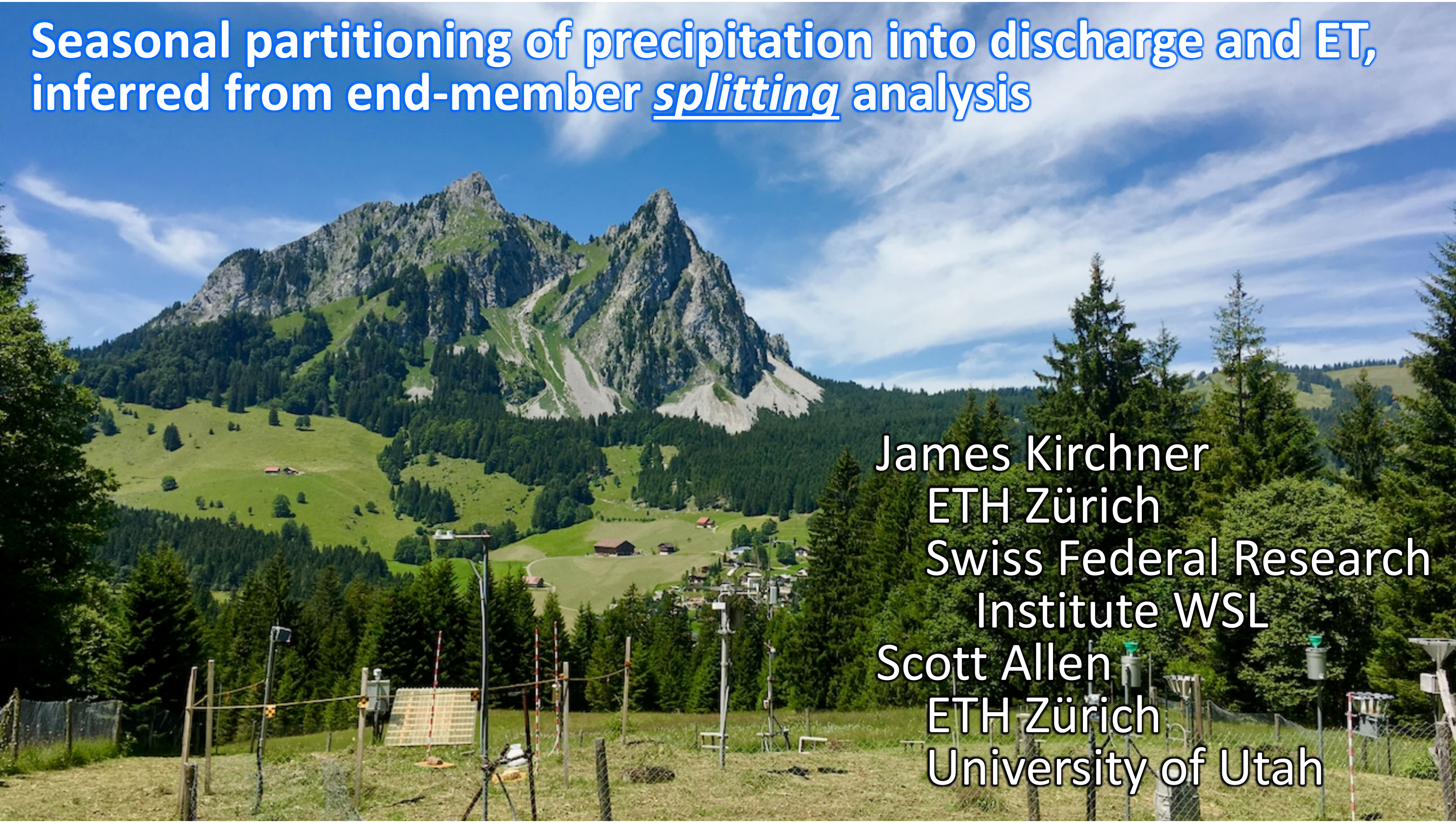
- Annual floods are often synchronized over hundreds of kilometers, but strong regional differences exist in the flood synchrony scale.
- Flood synchrony scale have been growing over the period 1960-2010
- Years with above-average flood synchrony often follow one another
- Flood synchrony patterns are largely disconnected from precipitation synchrony patterns (and the scale of synchronized precipitation is much larger)

References

Berghuijs *et al*. (GRL, 2019) Growing spatial scales of synchronous river flooding in Europe.

Berghuijs *et al*. (WRR, 2019) The relative importance of different flood-generating mechanisms across Europe.

Seasonal partitioning of precipitation into discharge and ET, inferred from end-member ***splitting*** analysis



James Kirchner
ETH Zürich
Swiss Federal Research Institute WSL
Scott Allen
ETH Zürich
University of Utah

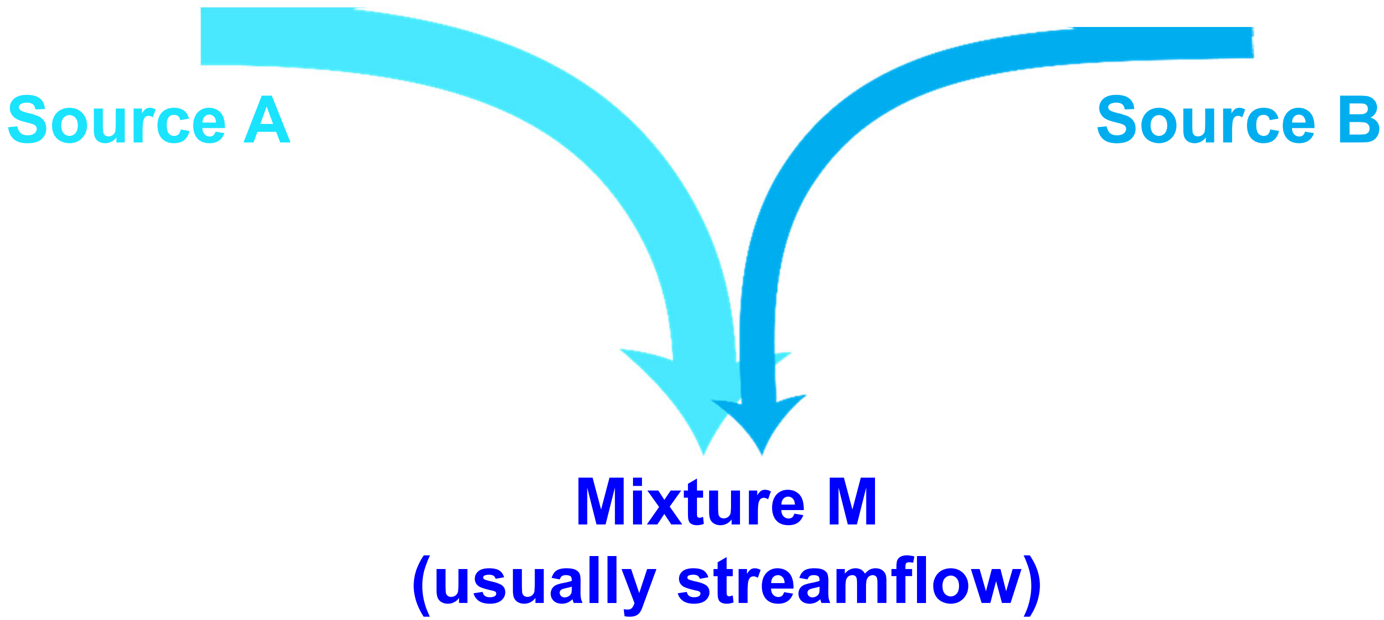
What we tell people that we study:

"where water goes when it rains"

What we actually study instead:

where streamwater comes from!

***End-member mixing analysis*: what fraction of Mixture M comes from Source A vs. Source B?**



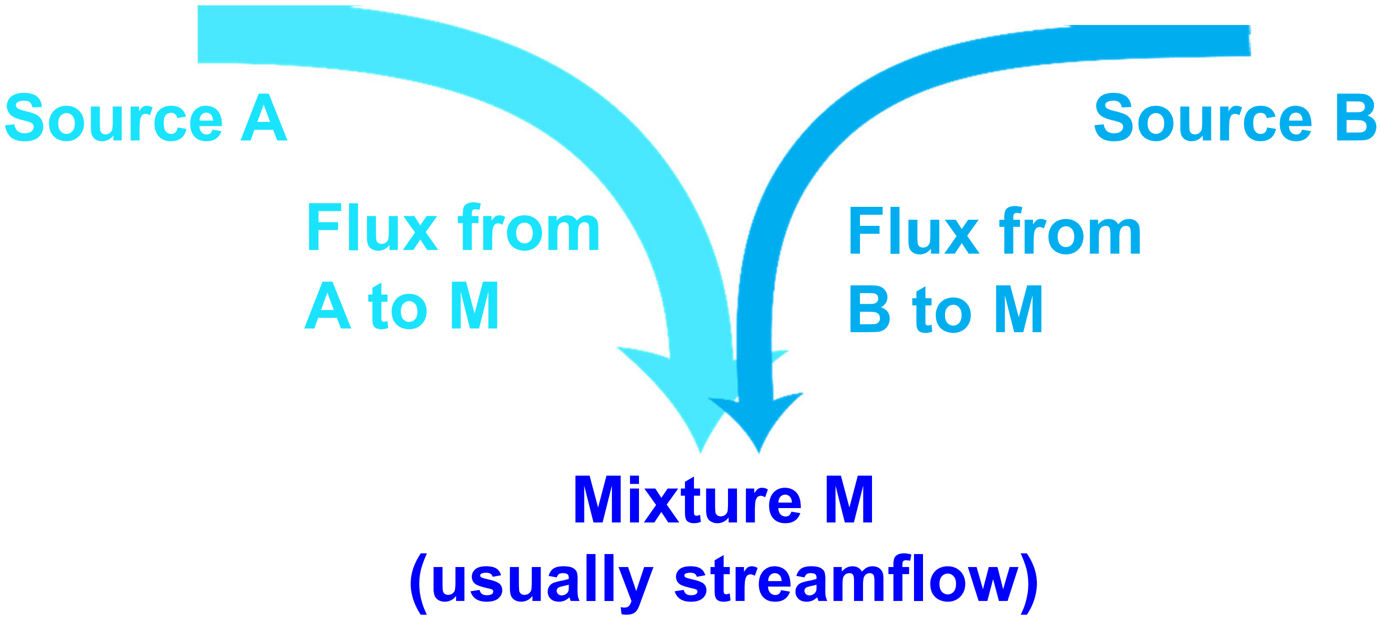
End-member mixing quantifies:

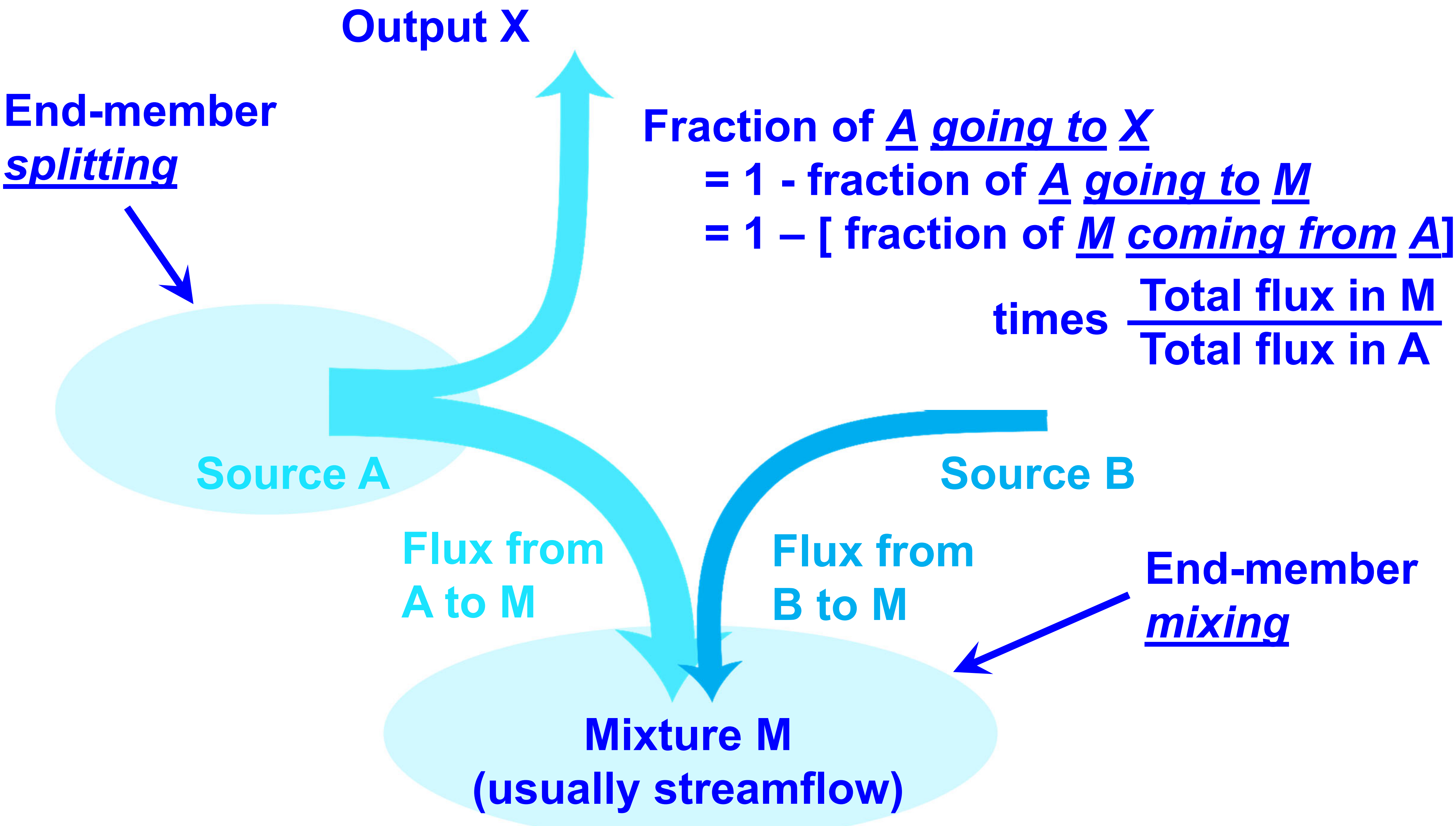
fraction of *M coming from A* = (Flux A→M) / (Total flux in *M*)

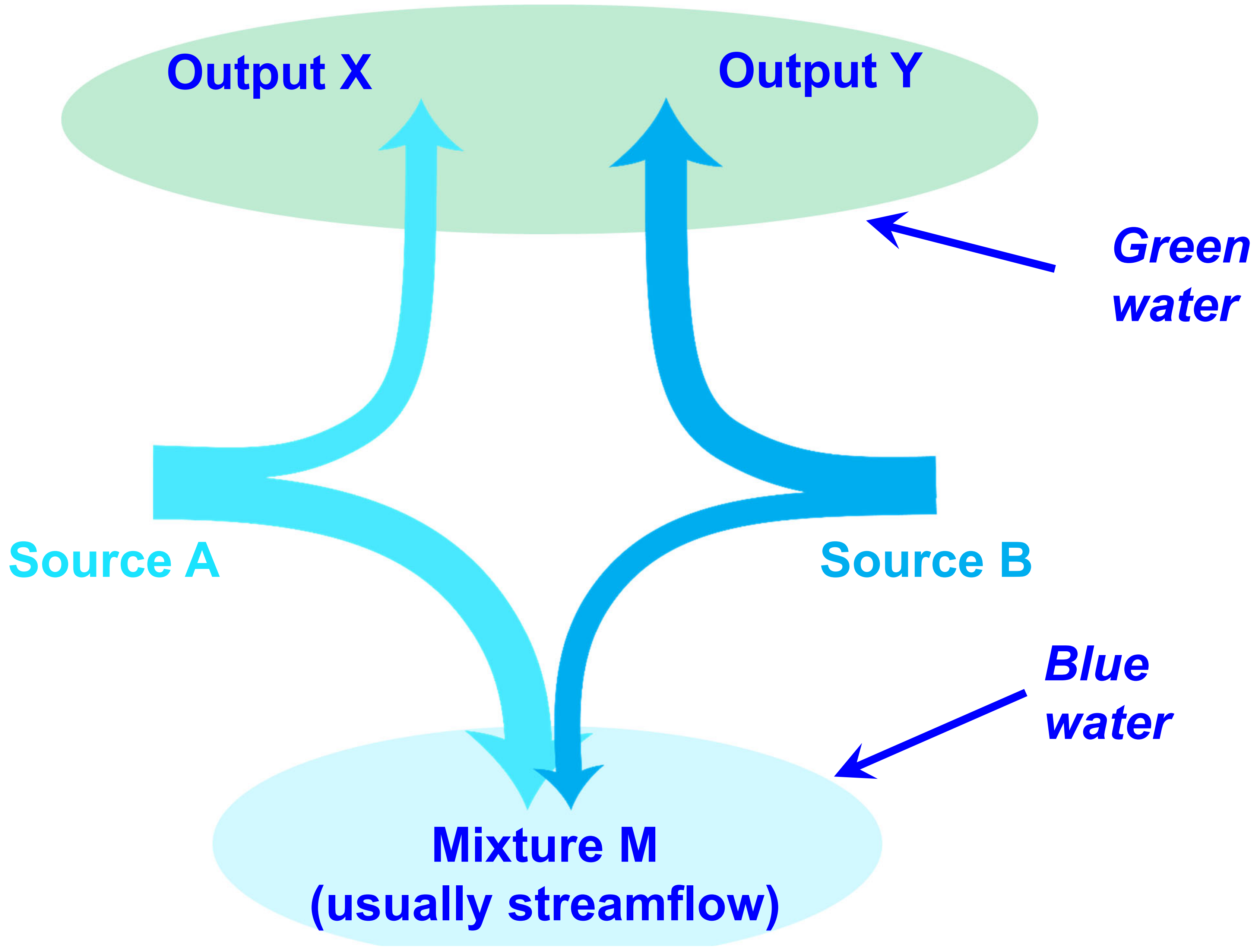
What we want to know:

fraction of *A going to M* = (Flux A→M) / (Total flux in *A*)

$$= \text{fraction of } \underline{\textit{M coming from A}} \; \frac{\text{Total flux in M}}{\text{Total flux in A}}$$




Output X
End-member
splitting
Fraction of A going to X
= 1 - fraction of A going to M
= 1 – [fraction of M coming from A]
times Total flux in M / Total flux in A
Source A
Source B
Flux from
A to M
Flux from
B to M
End-member
mixing
Mixture M
(usually streamflow)


Output X
Output Y
Green water
Source A
Source B
Blue water
Mixture M (usually streamflow)

Proof-of-concept demonstration: watershed 3 at Hubbard Brook (isotope data from Green et al., 2015)

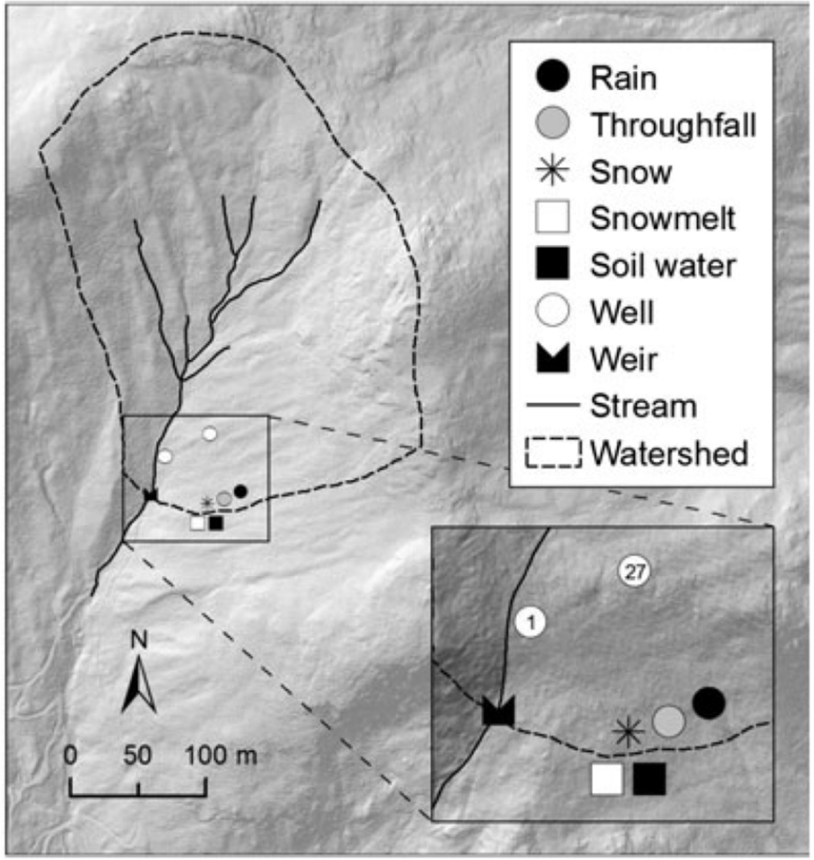
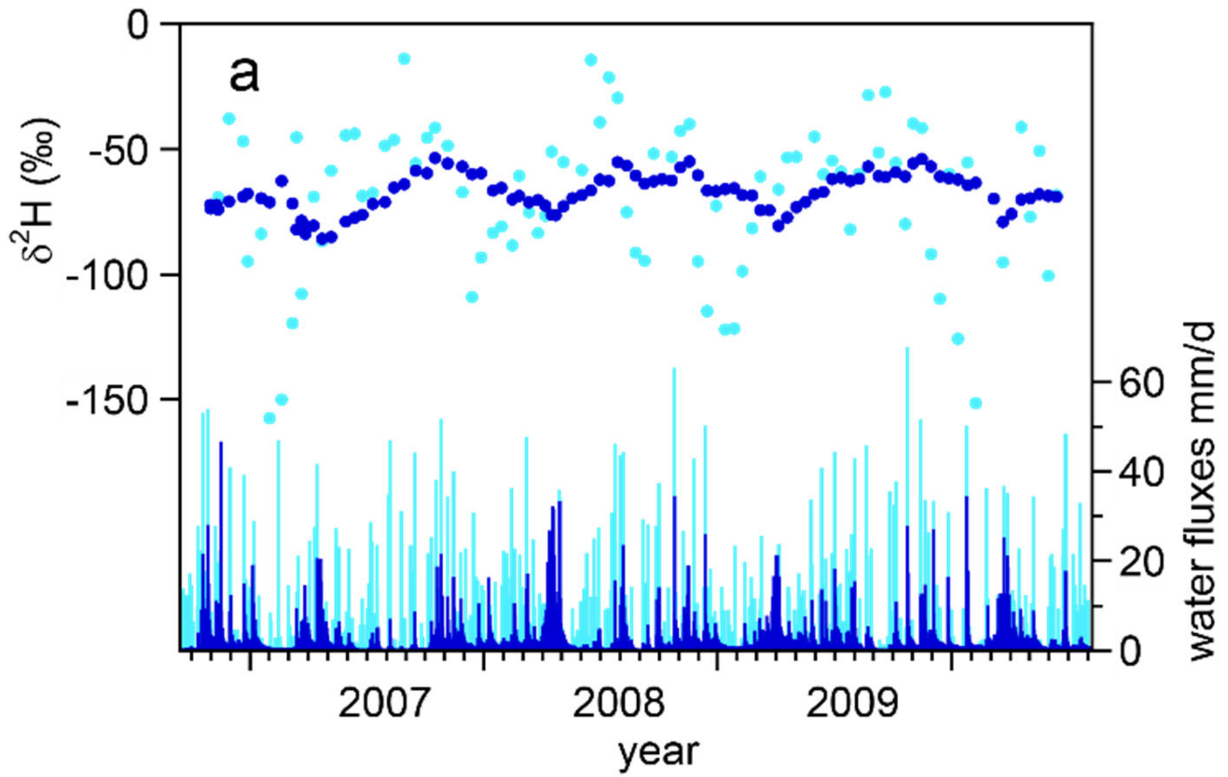
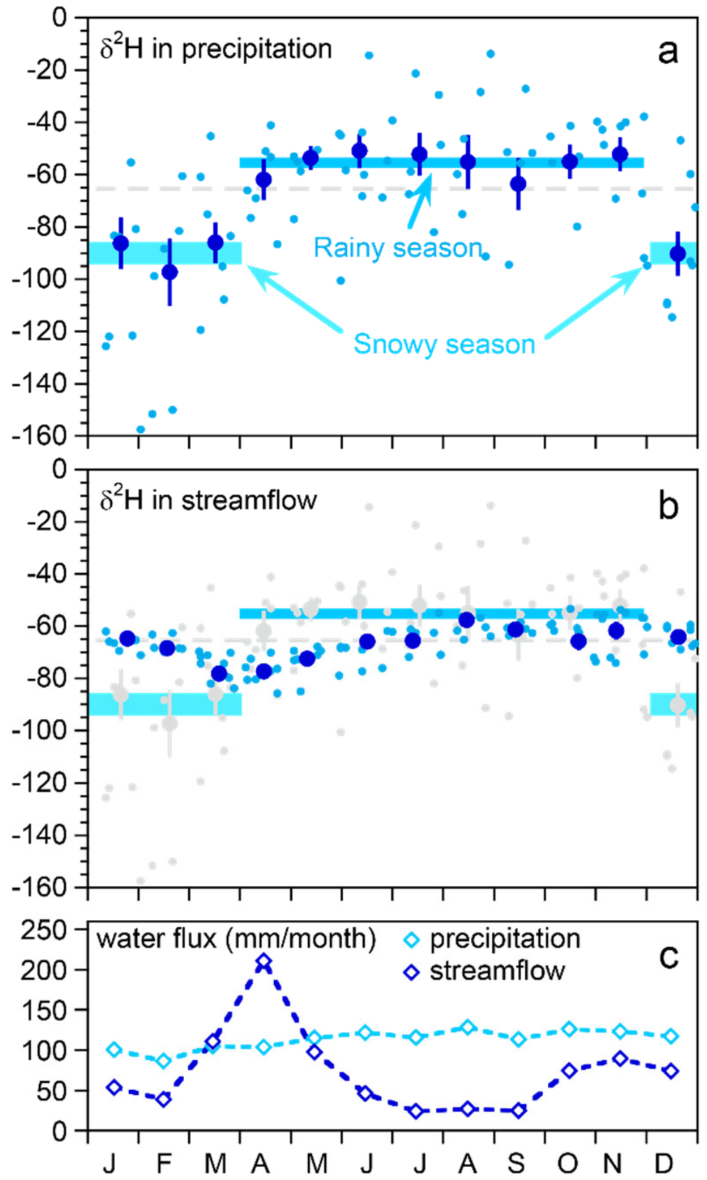


Figure 1. Map of Watershed 3 at the Hubbard Brook Experimental Forest and the location of water sampling sites for this study





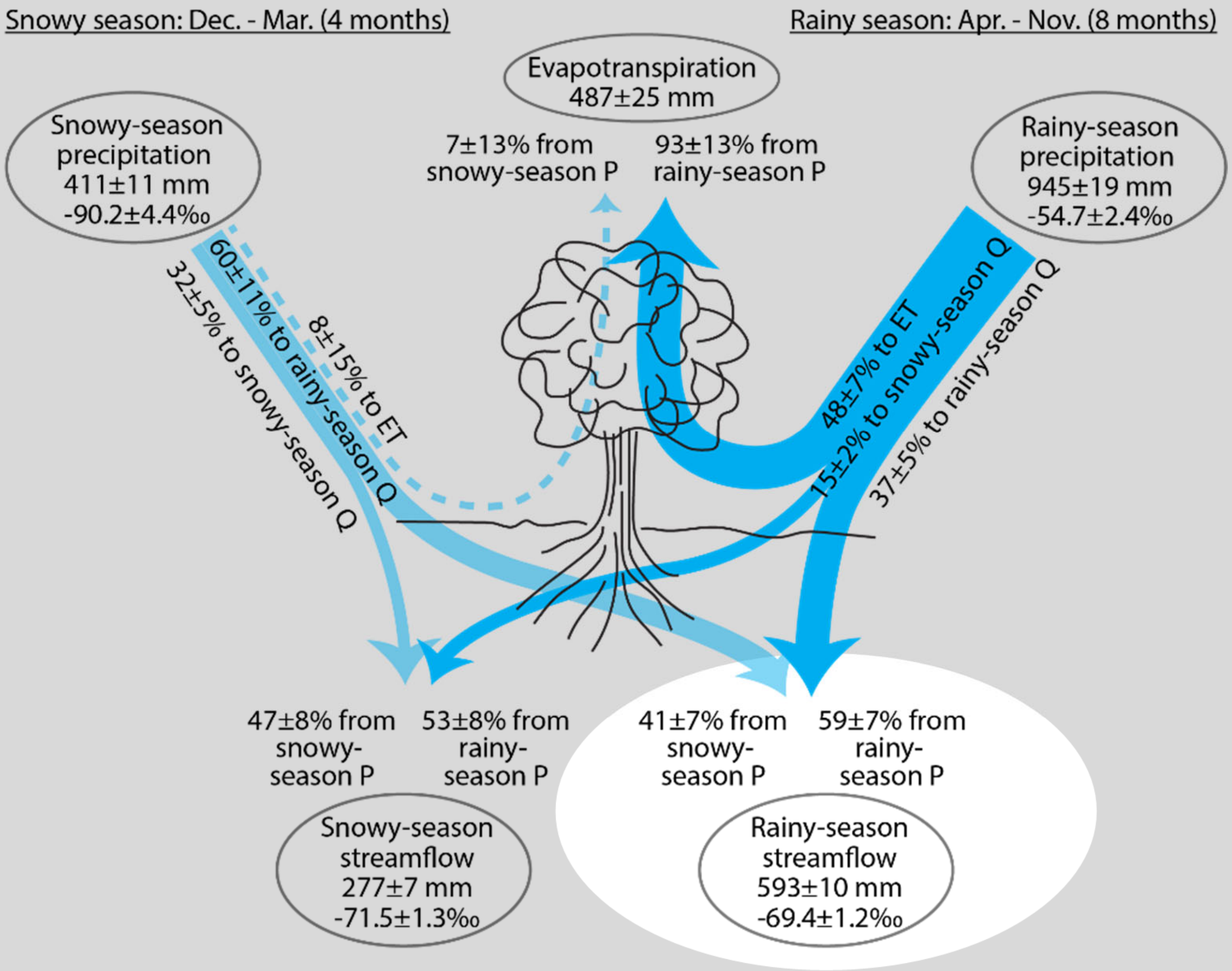
Superimposing all years on top of one another reveals:

Strong isotopic separation between rainy and snowy season precipitation.

Stream gradually shifts toward snowy end member during winter and toward rainy end member during summer.

Stream water fluxes show strong snowmelt peak in March-May and transpiration trough in growing season (June-September).

End-member mixing and splitting at Hubbard Brook Watershed 3

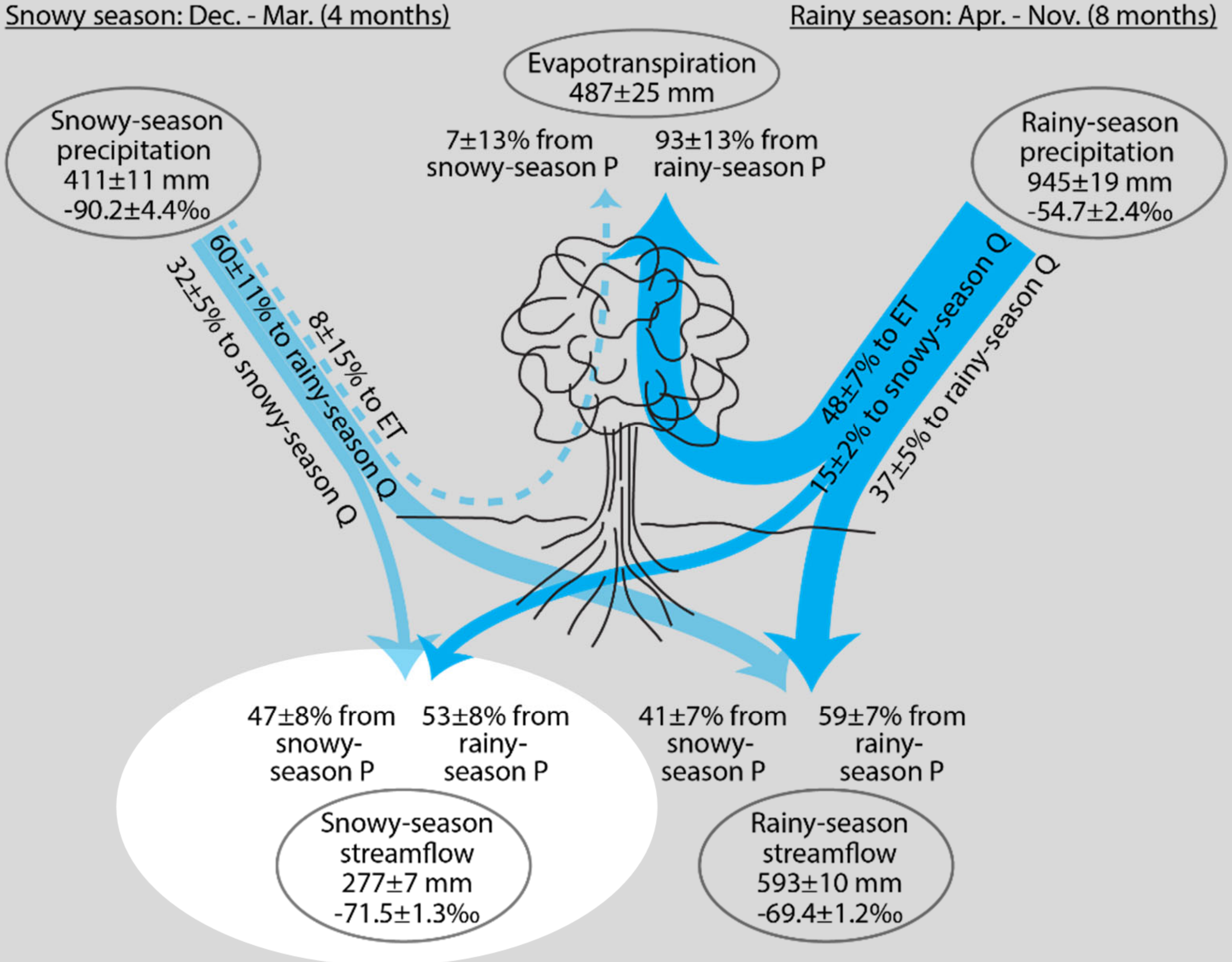


End-member mixing:

~ half of summer (rainy-season) streamflow originates as winter (snowy-season) precipitation.

(Note that snowmelt pulse occurs during ***rainy*** season, not winter snowy season…)

End-member mixing and splitting at Hubbard Brook Watershed 3

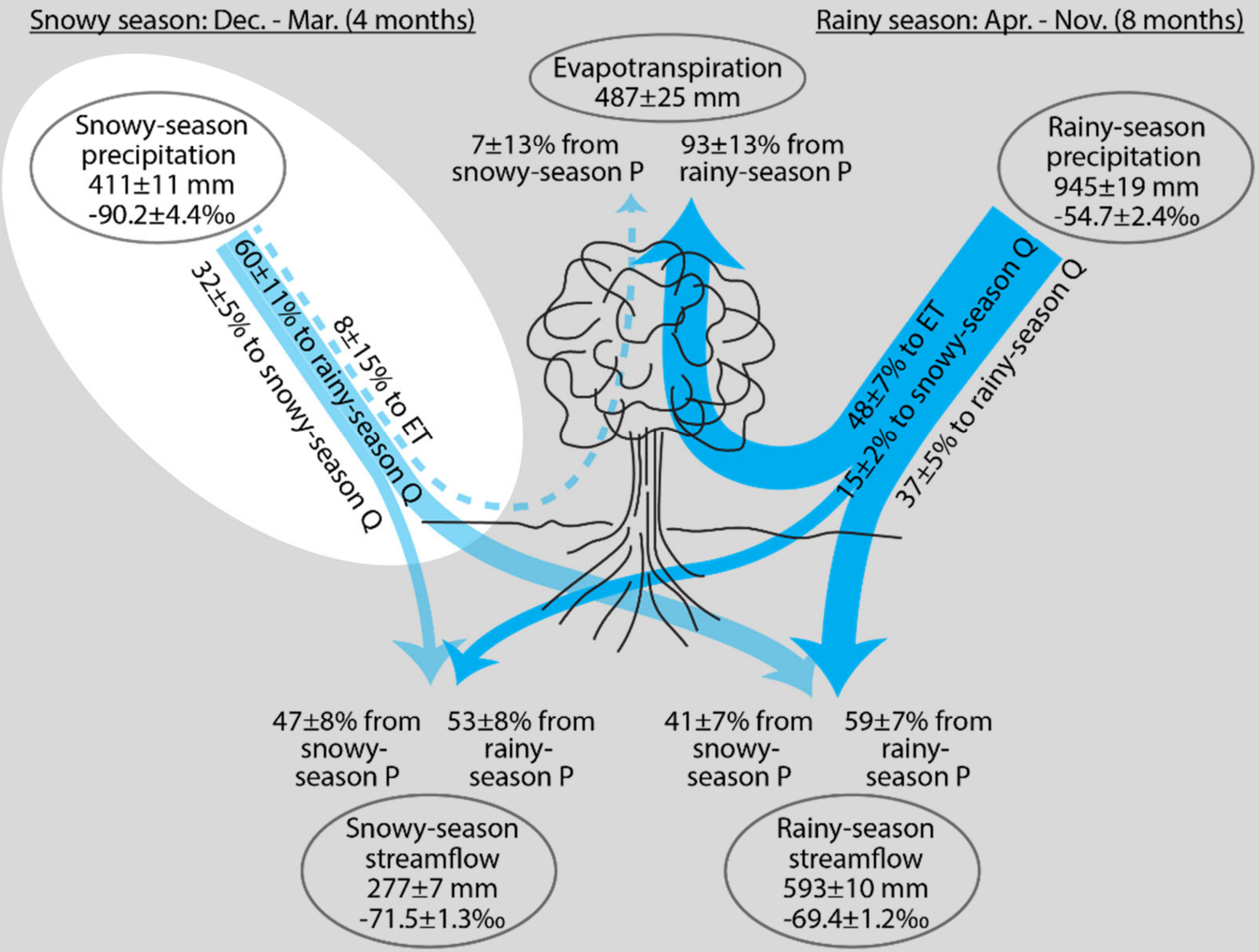


End-member mixing:

~ half of winter (snowy-season) streamflow originates as summer (rainy-season) precipitation.

(Must come from groundwater storage)

End-member mixing and splitting at Hubbard Brook Watershed 3



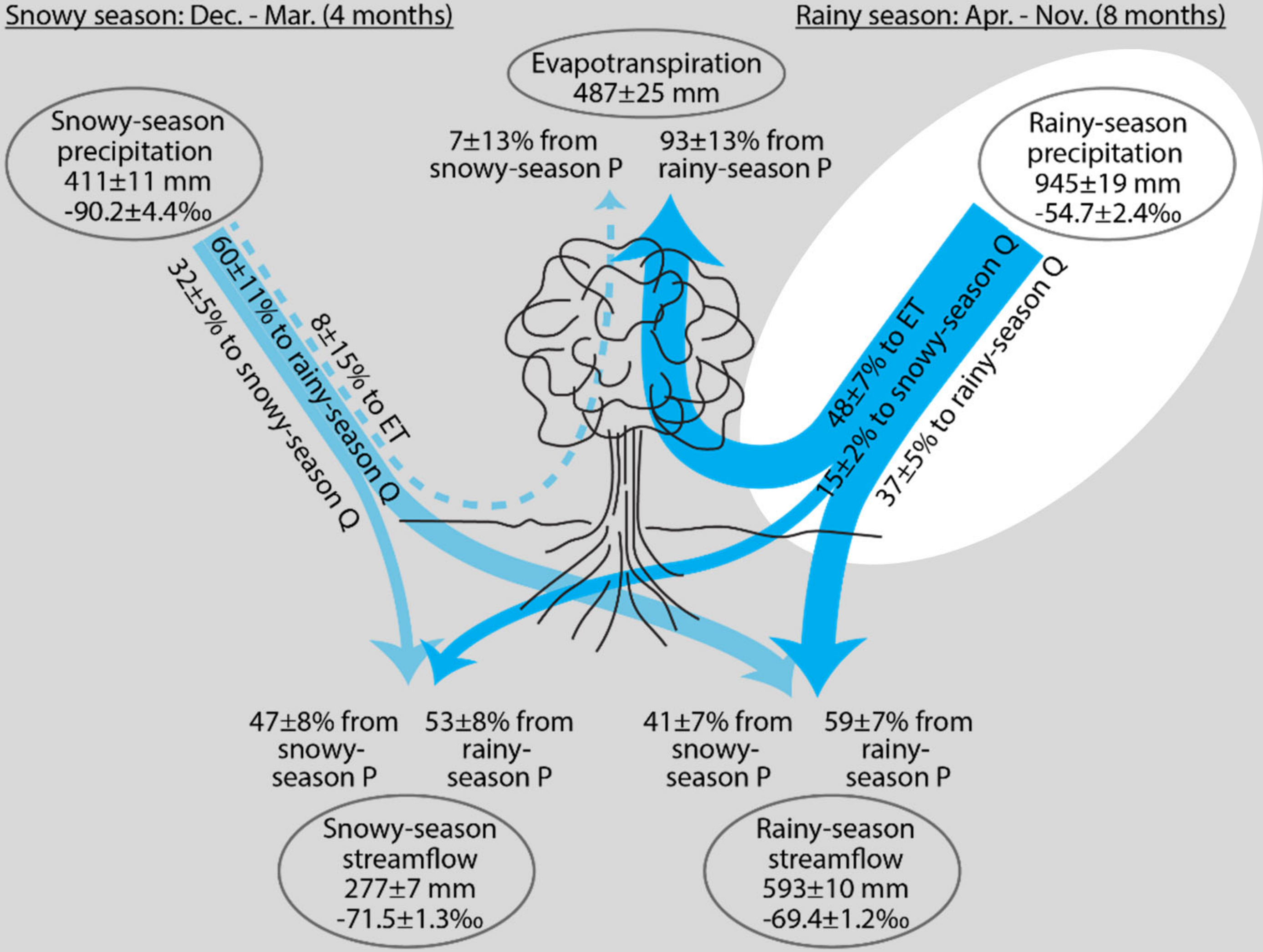
End-member _splitting_:

~ 2/3 of winter (snowy-season) precipitation eventually becomes _summer_ (rainy-season) streamflow.

~ 1/3 becomes snowy-season streamflow.

Very little evapotranspires.

End-member mixing and splitting at Hubbard Brook Watershed 3



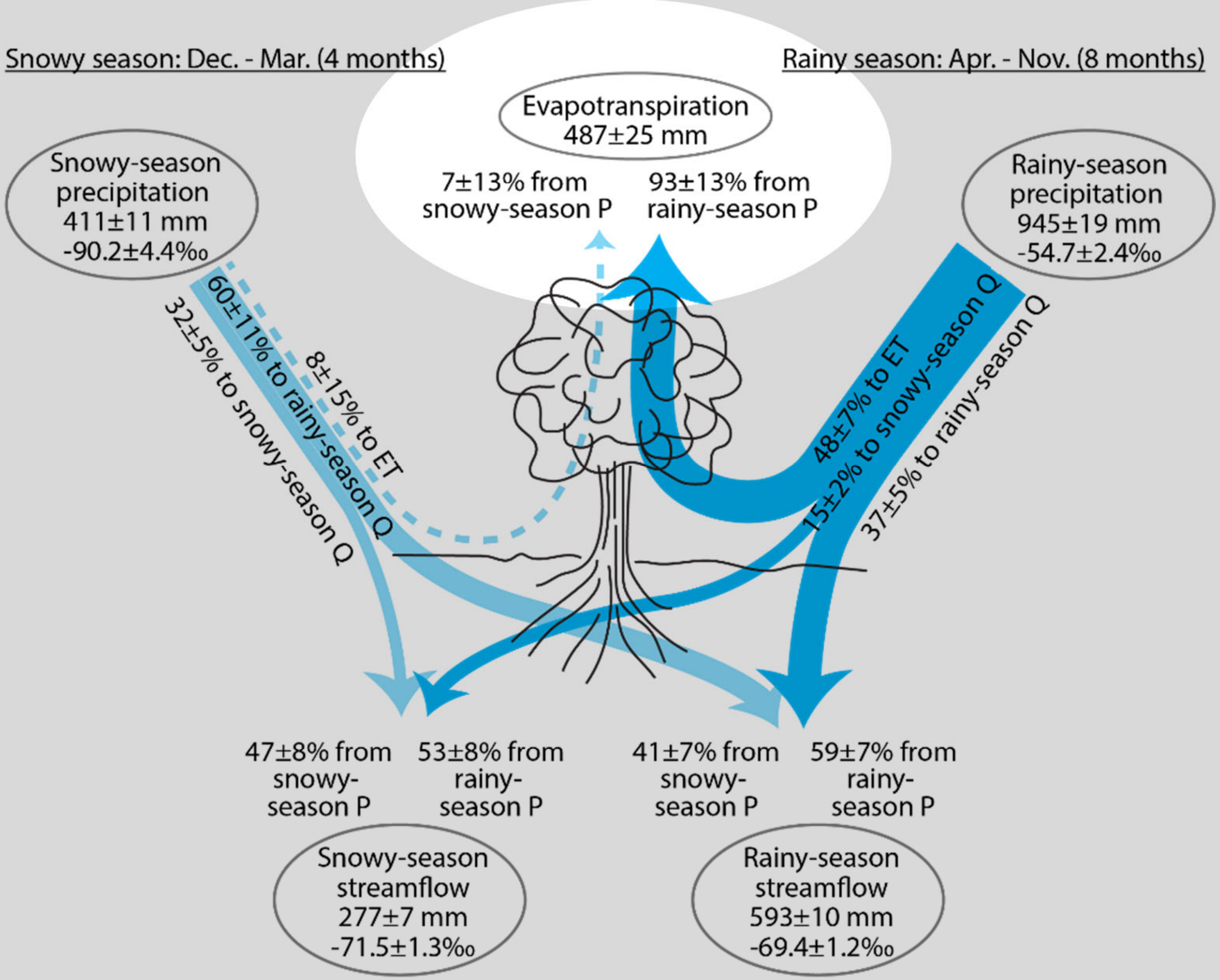
End-member *splitting*:

~ 1/2 of summer (rainy-season) precipitation evapotranspires.

~ 1/3 eventually becomes summer streamflow.

~ 1/6 becomes snowy-season streamflow.

End-member mixing and splitting at Hubbard Brook Watershed 3

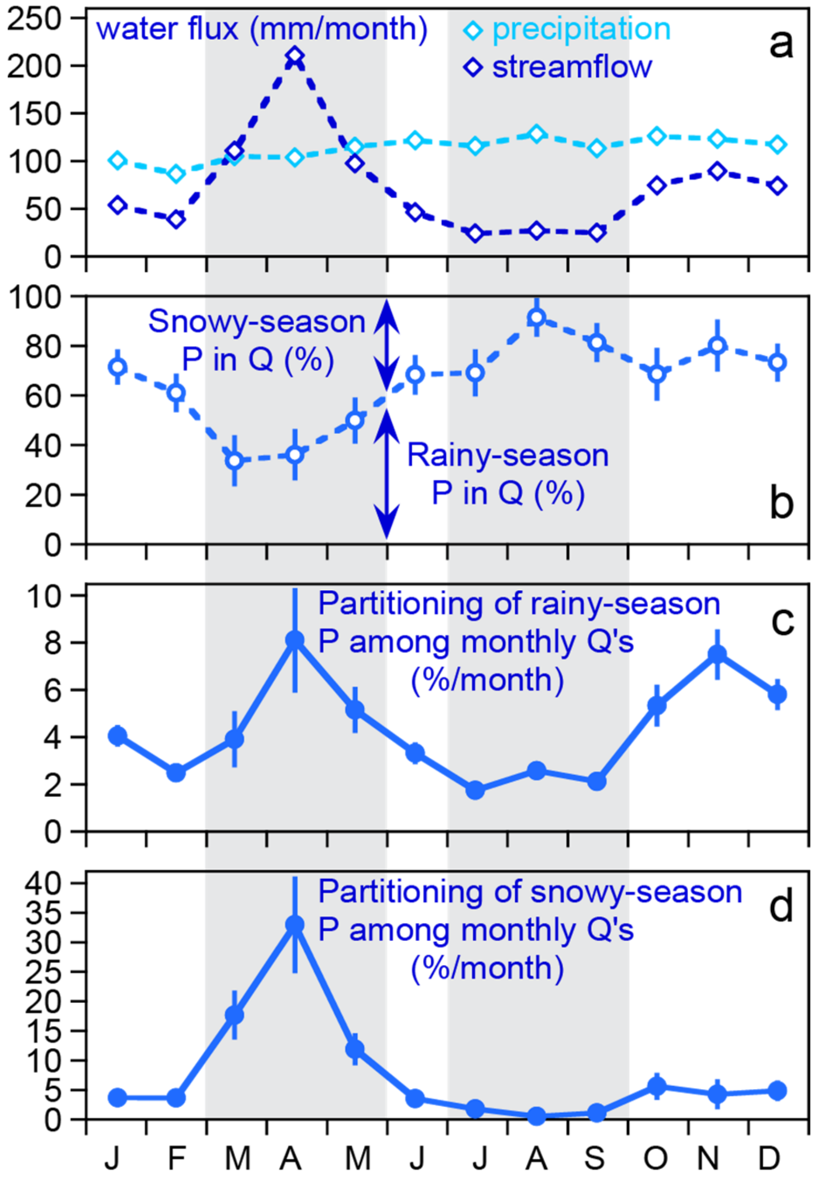


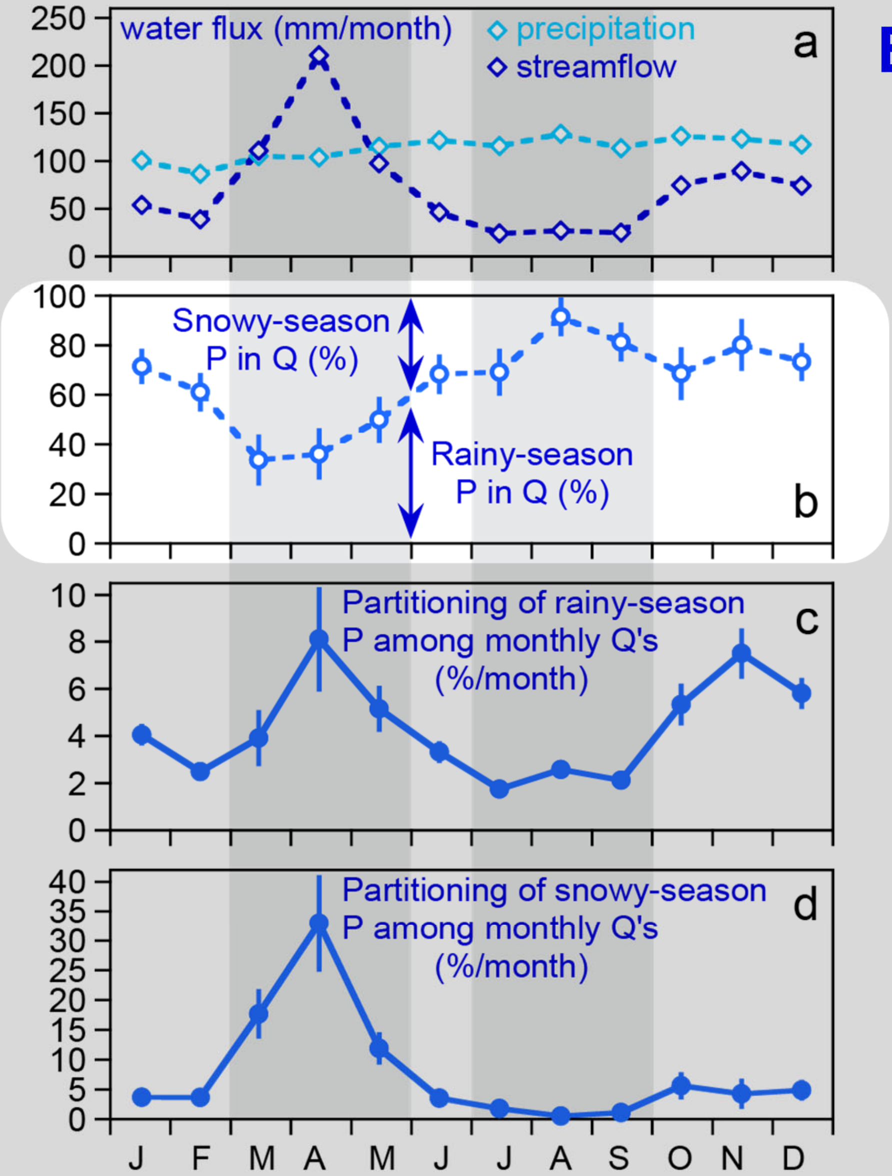
End-member *splitting*:

Almost all evapotranspiration comes from rainy-season precipitation.

Almost none comes from snowy-season precipitation.

End-member mixing and splitting by month

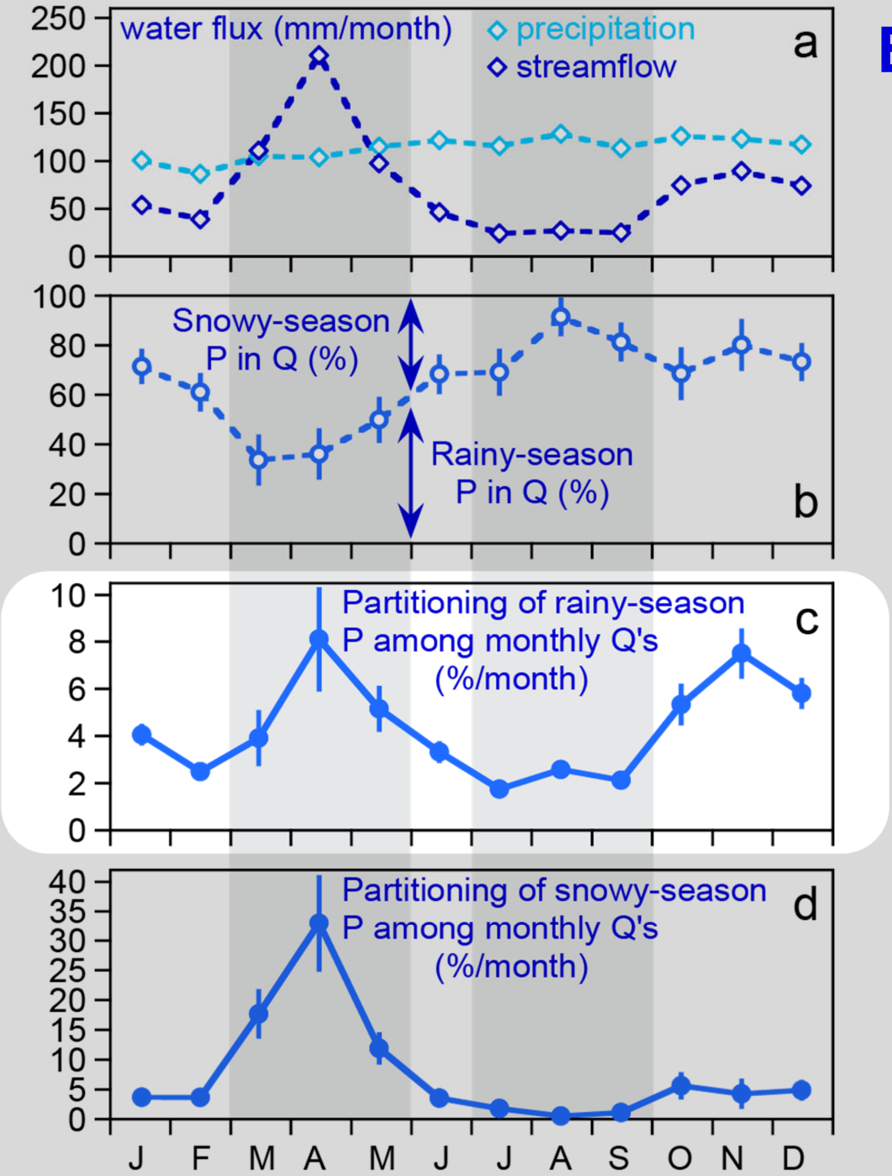




End-member mixing and splitting by month

End-member mixing:

Fraction of streamwater _coming from_ rainy-season precip. is lowest (~1/3) during snowmelt and highest (~90%) during growing season.



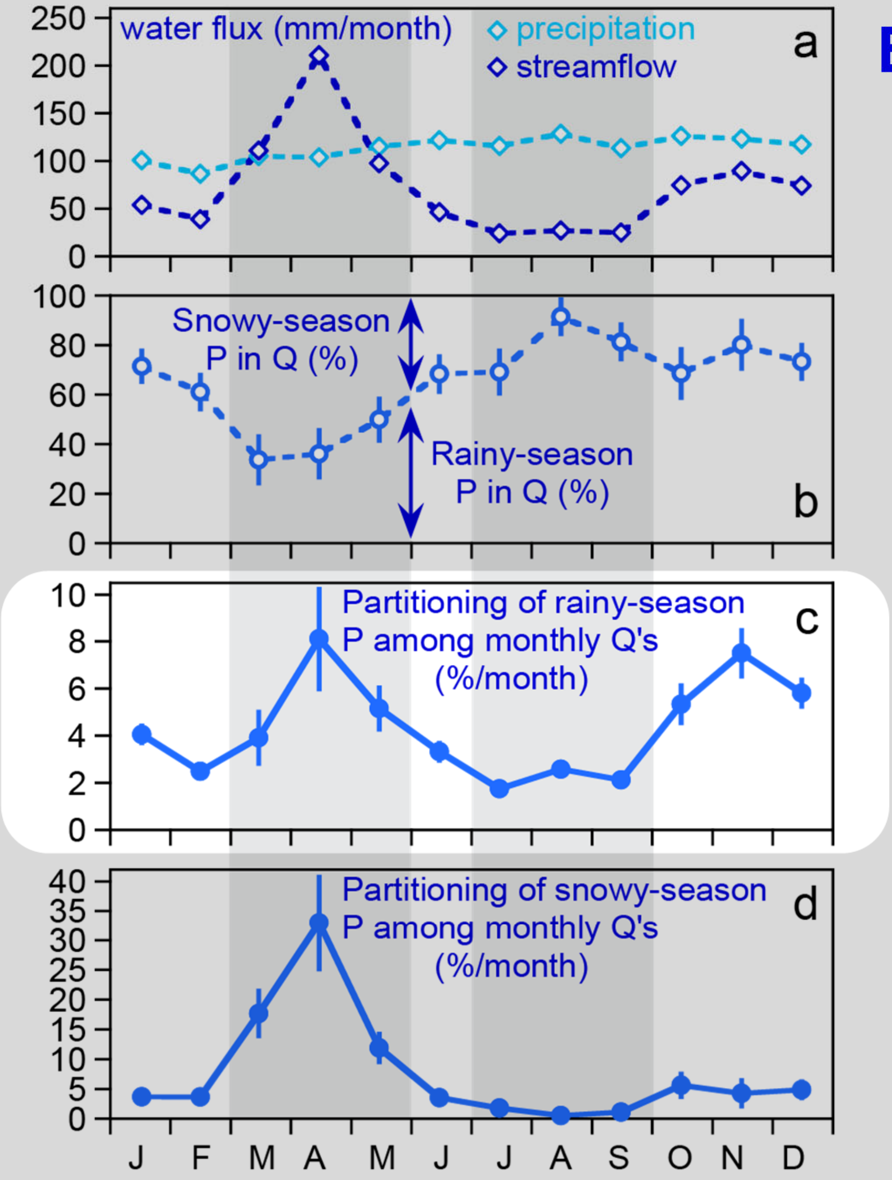
End-member mixing and splitting by month

End-member mixing:

Fraction of streamwater *coming from* rainy-season precip. is lowest (~1/3) during snowmelt and highest (~90%) during growing season.

End-member *splitting*:

Fraction of rainy-season precip. *becoming* streamflow is highest during snowmelt and lowest during growing season! (Increase in flow more than offsets decrease in rainy-season proportion in that flow.)



End-member mixing and splitting by month

End-member mixing:

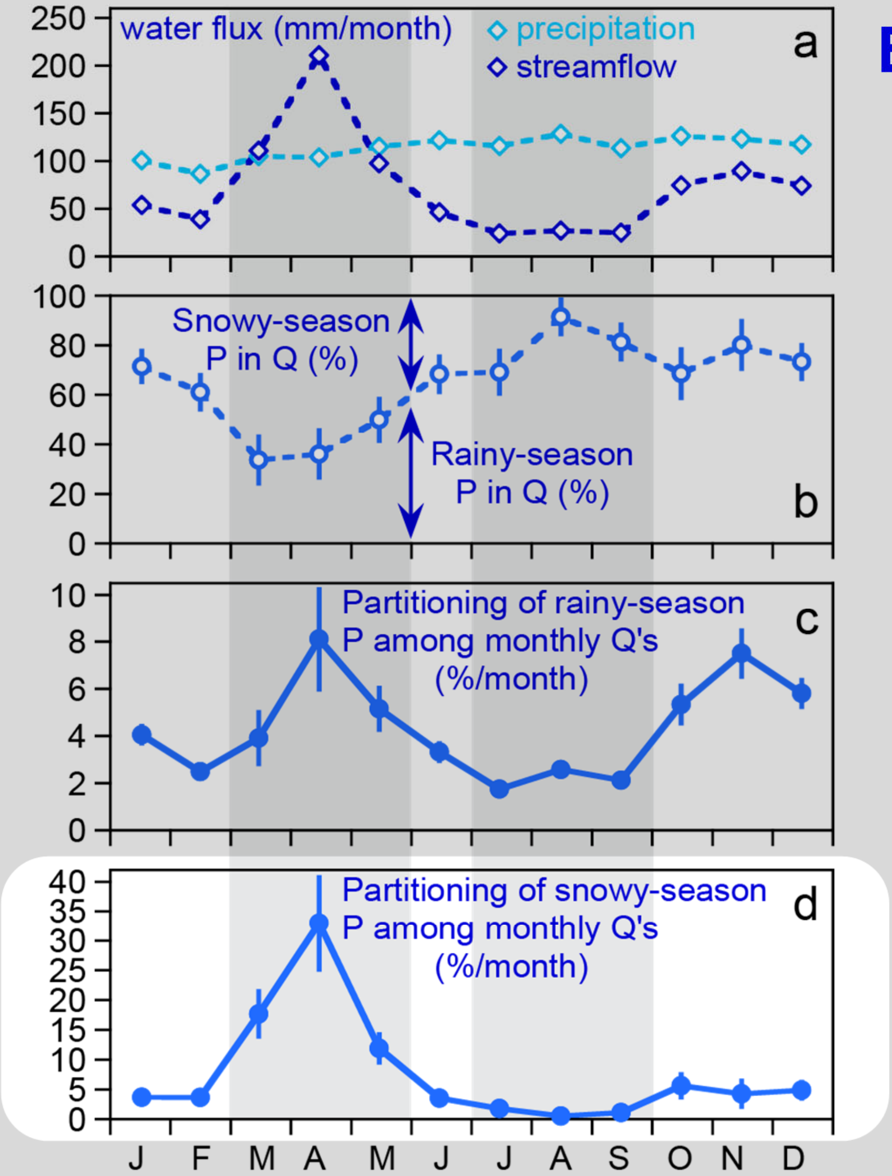
Fraction of streamwater *coming from* rainy-season precip. is lowest (~1/3) during snowmelt and highest (~90%) during growing season.

End-member *splitting*:

Fraction of rainy-season precip. *becoming* streamflow is highest during snowmelt and lowest during growing season!

There's a second peak after the growing season (modest flows but high percentage of rainy season precip.)

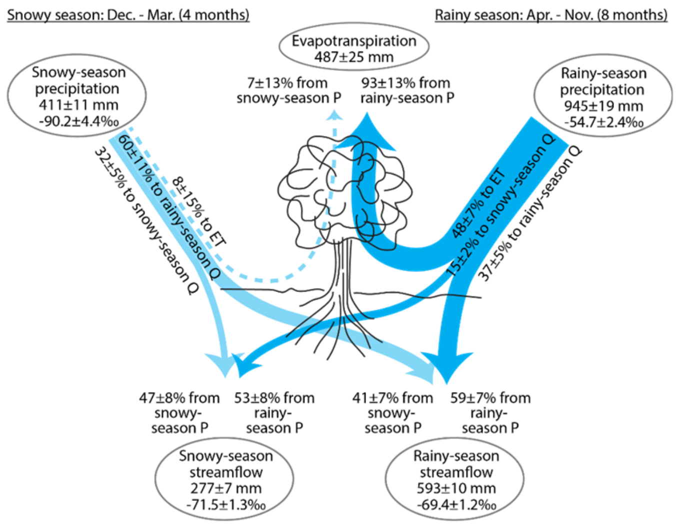
End-member mixing and splitting by month



End-member ***splitting***:

Fraction of snowy-season precip. *becoming* streamflow is highest during snowmelt (no surprise) and lowest during growing season…

… but increases again after the growing season (substantial flows with small percentage of winter precipitation in them).



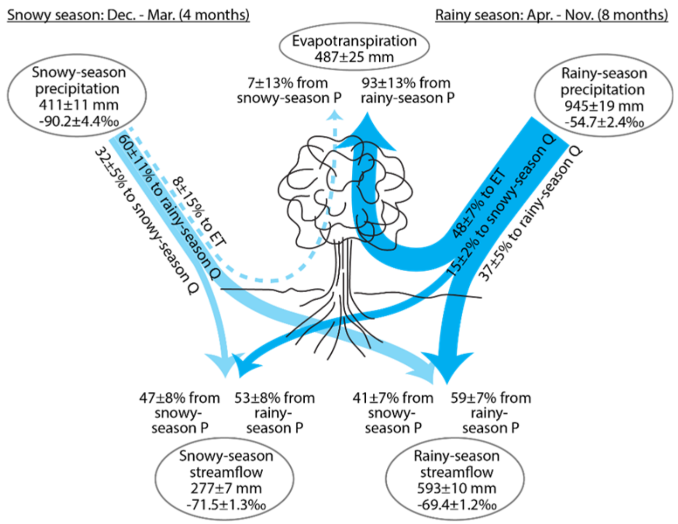
Requirements:

Need two *isotopically distinct* end-members (sources):

- **Winter vs. summer precipitation**
- **Snow vs. rain**
- **High vs. low-altitude precipitation**
- **High-intensity vs. low-intensity rainfall**

Must jointly supply *all* the input.

Need reliable estimates of *water fluxes*.



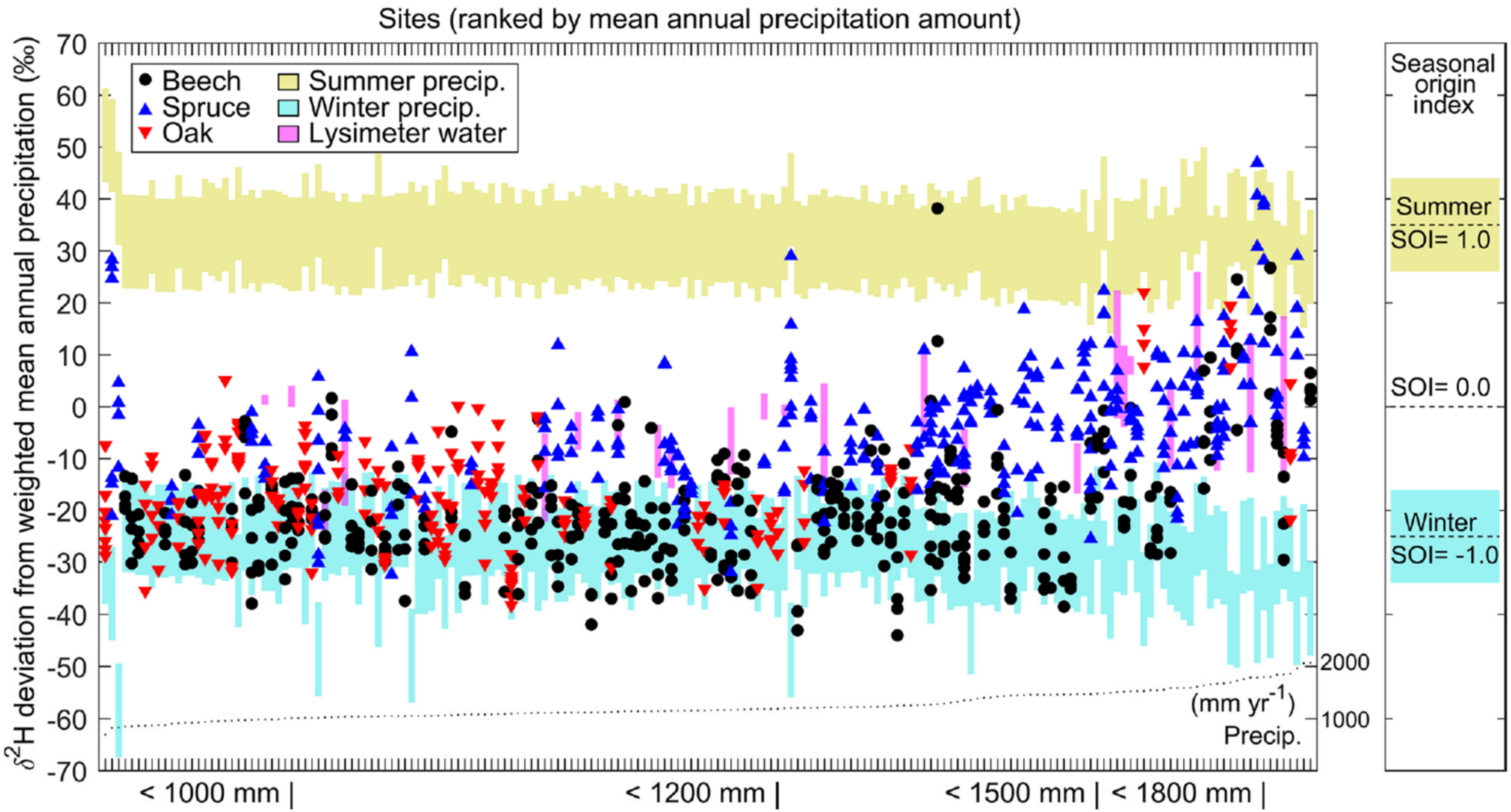
Applications:

Can quantitatively partition (split) inputs among _any number**_ of measured outputs plus one _**unmeasured**_ output (e.g., green water).**

- **Seasonal streamflow**
- **Monthly streamflow**
- **High vs. low flows**
- **Groundwater vs. surface water-dominated streams**

Note: results elsewhere may differ!

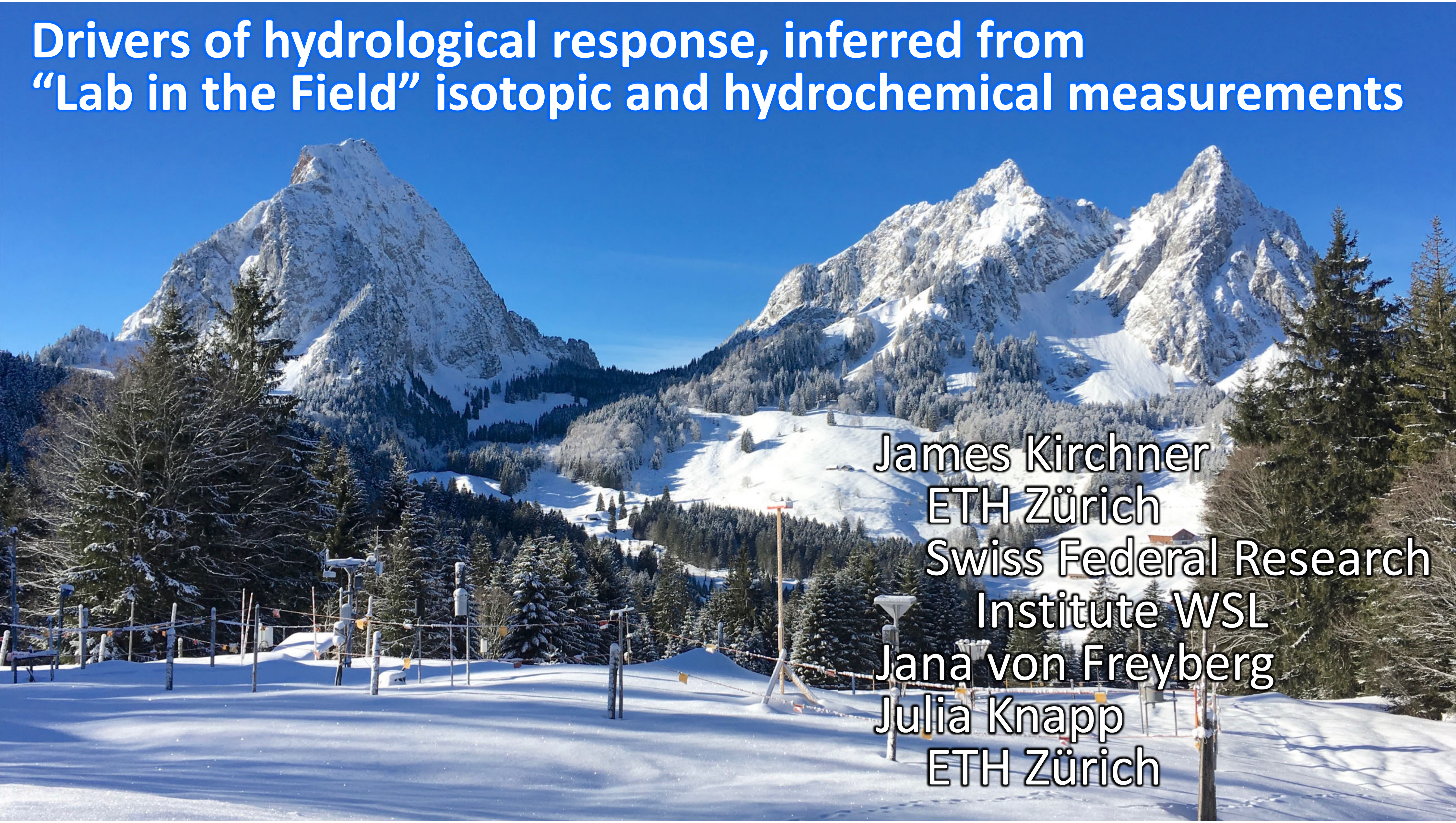
Xylem water isotopes imply that many Swiss forests rely on winter precipitation, even in mid-summer (Allen et al. 2019, HESS)



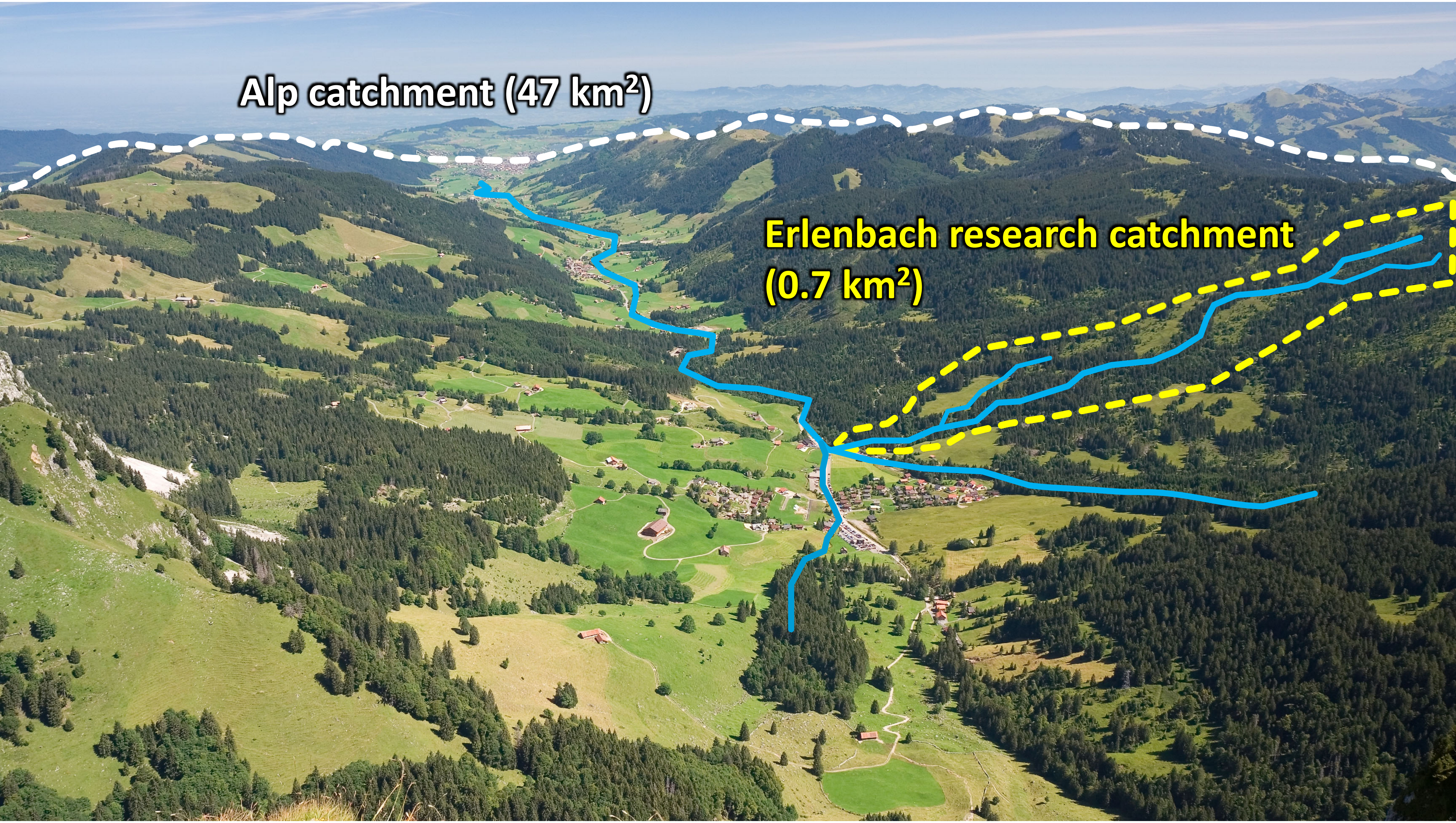
Outlook, Summer 2019: Xylem water sampling in 12 catchments for comparison with end-member splitting calculations.

24 forest plots x 3 species/plot
x 8 individuals/species
= ~600 xylem water isotope samples.

Drivers of hydrological response, inferred from “Lab in the Field” isotopic and hydrochemical measurements



James Kirchner
ETH Zürich
Swiss Federal Research Institute WSL
Jana von Freyberg
Julia Knapp
ETH Zürich



Alp catchment (47 km²)
Erlenbach research catchment
(0.7 km²)

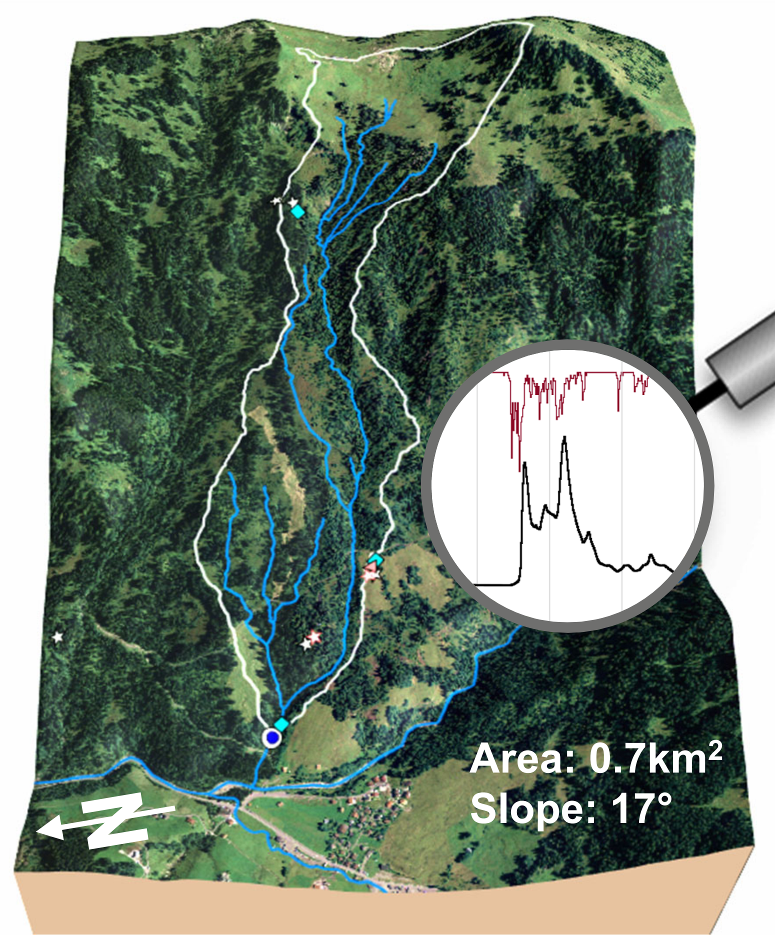
Variable discharge conditions at the *Erlenbach (Alptal)*

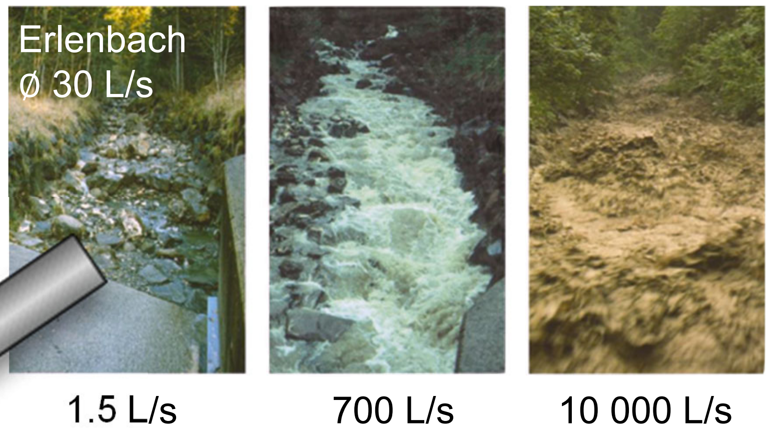
$Q = 0.015\ m^3/s$

$Q = 0.7\ m^3/s$

$Q = 10\ m^3/s$

Streamflow generation in steep catchments

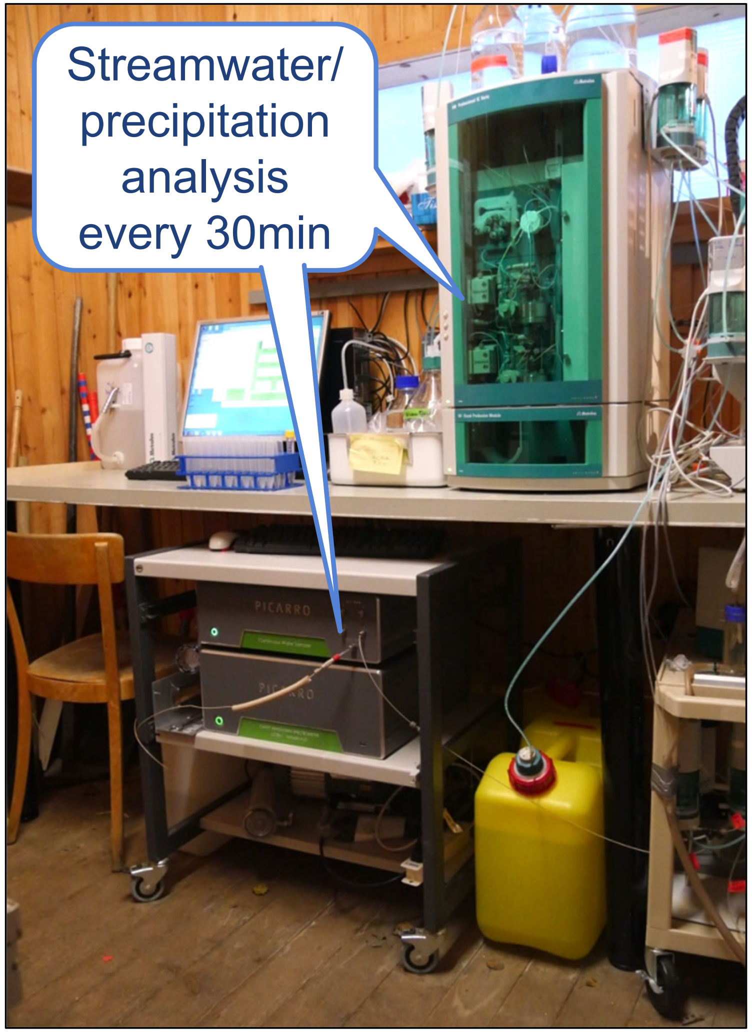




A good process understanding is crucial to develop robust hydrological models for mountainous catchments.

→ Processes happen at short time scales (hours to minutes)!

A lab in the field

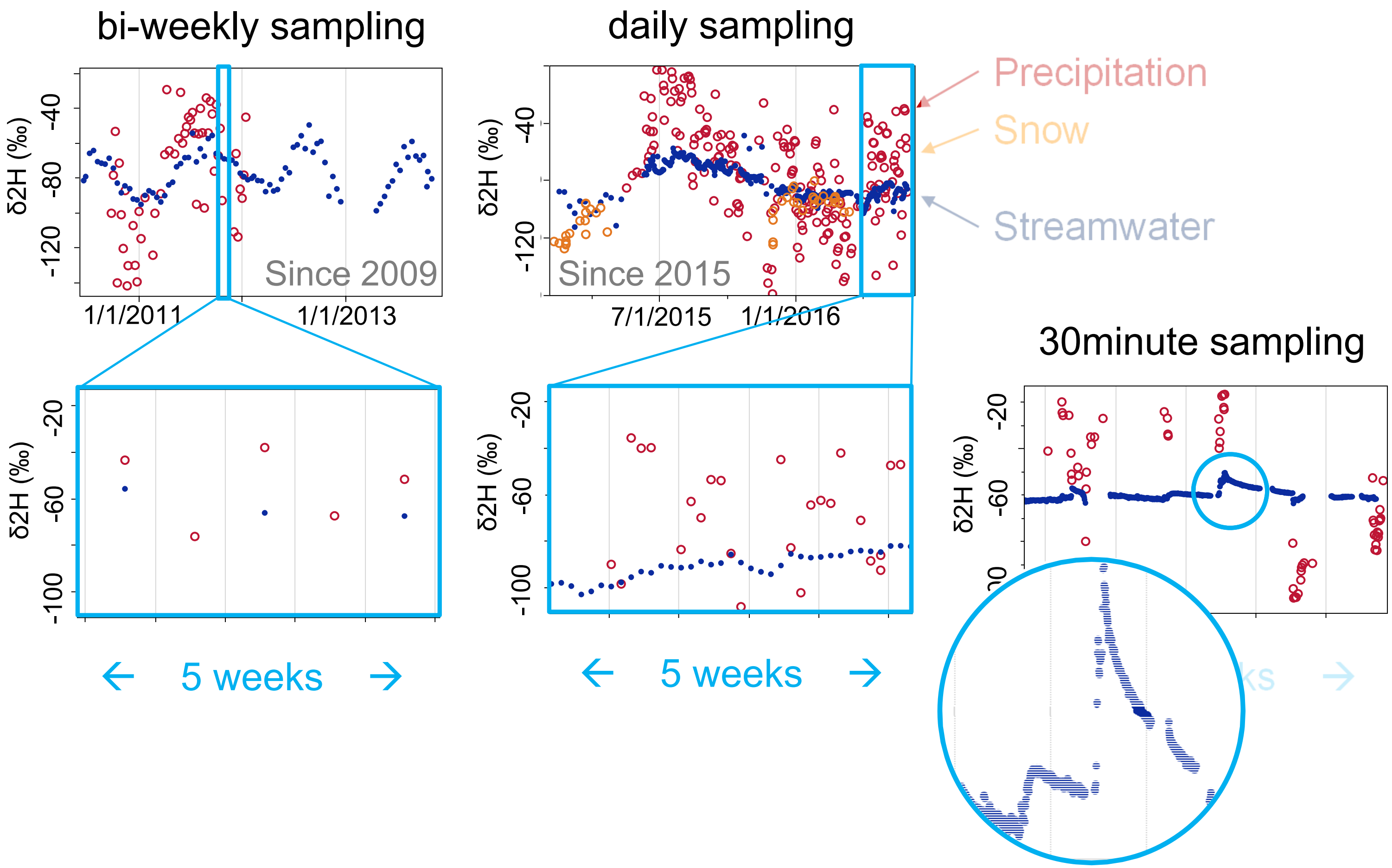


Heated rain gauge and collector outside the hut

Streamwater collection from the nearby channel

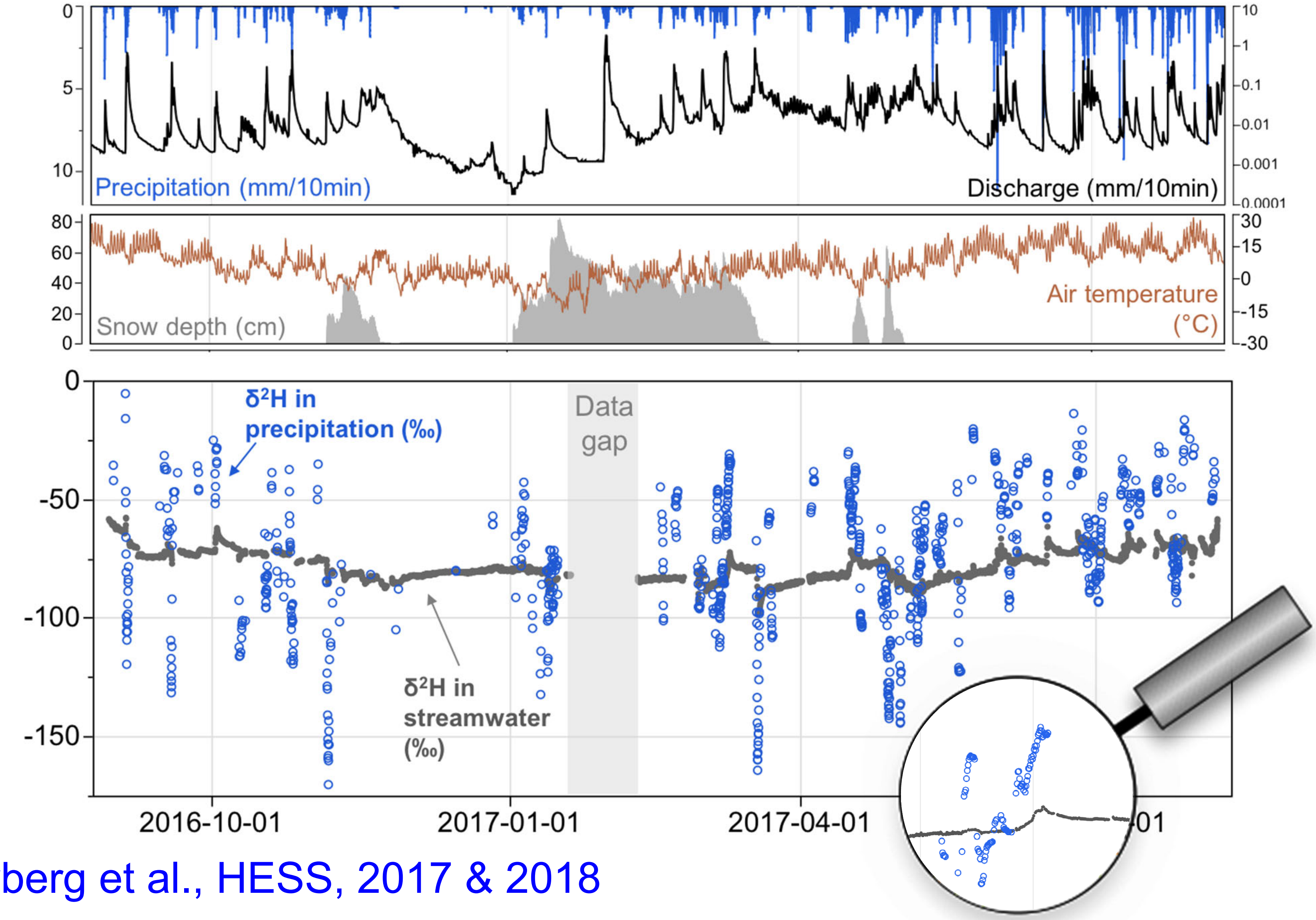
von Freyberg et al., HESS, 2017 & 2018

Long-term isotope measurements at Erlenbach on timescales from 2x per month to ***1440x*** per month (30-minute sampling)



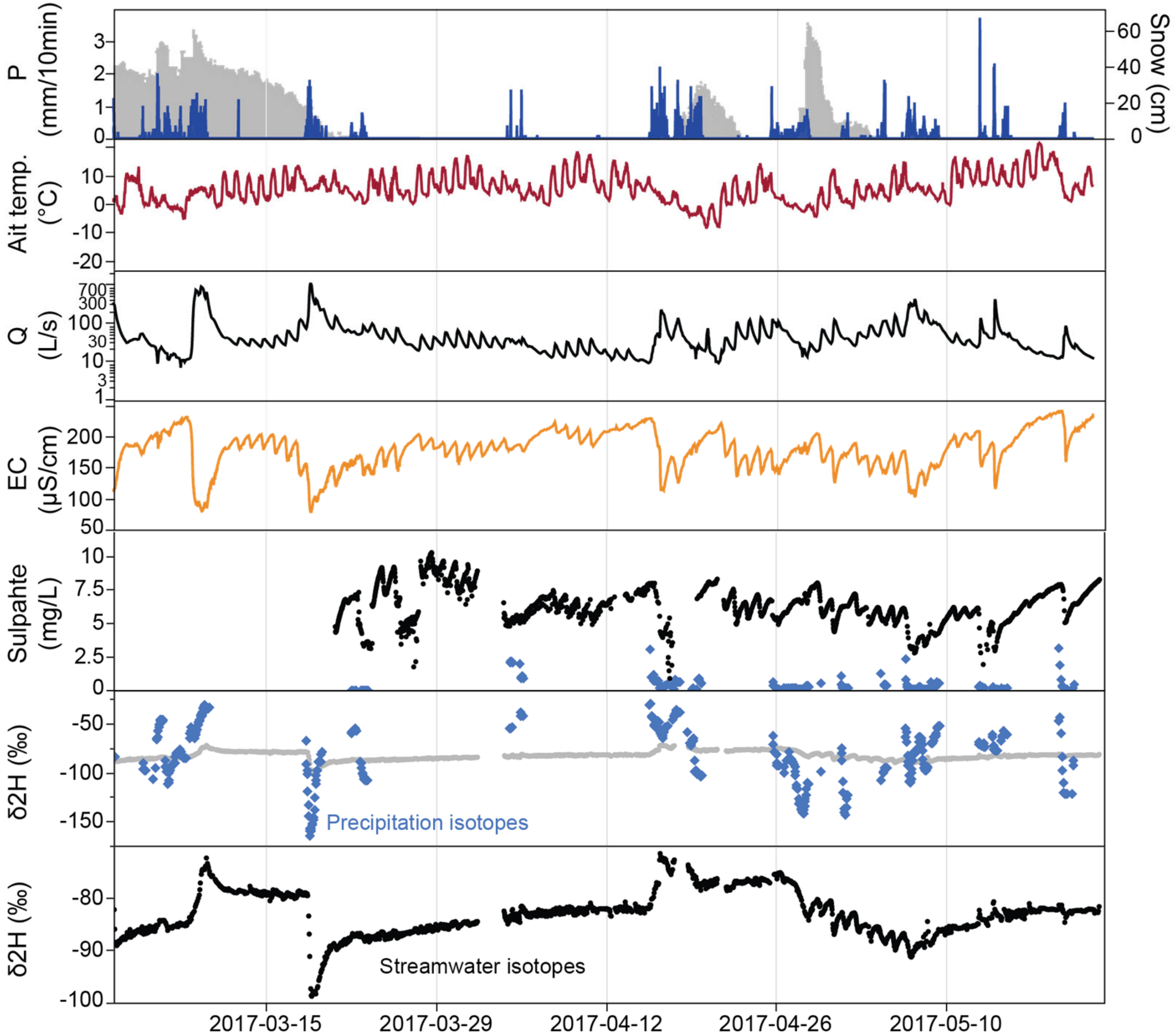
Data: A. Rücker, WSL/ETHZ

Data: B. Fischer and M. Staudinger, UZH



von Freyberg et al., HESS, 2017 & 2018

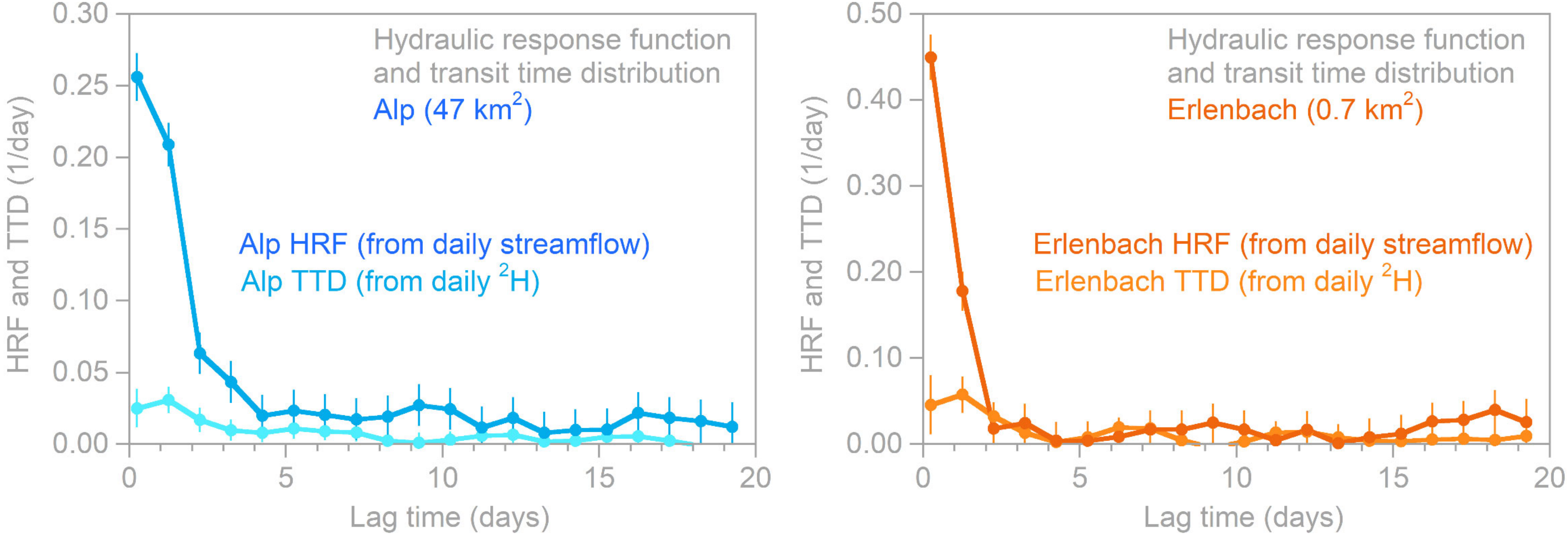
Chemical and isotopic dynamics revealed by "lab in the field" measurements



von Freyberg et al., HESS, 2017 & 2018

Hydraulic response functions vs. transit time distributions

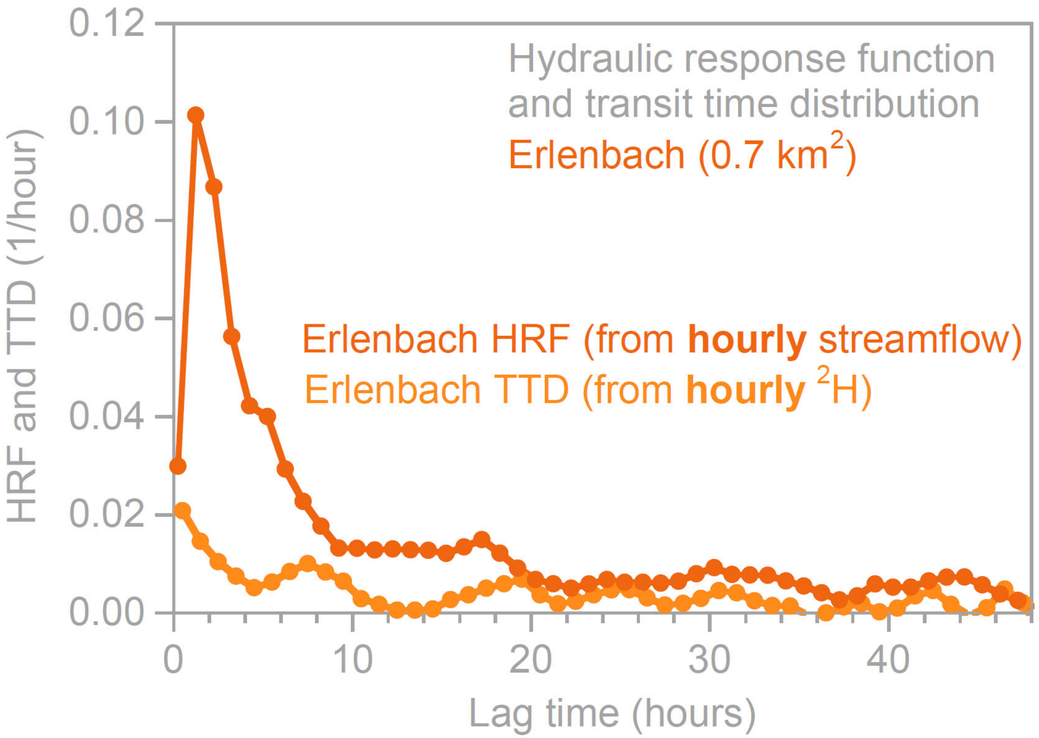
Both catchments **transmit hydraulic potentials much faster**, with **much less dispersion**, than they transport the water itself



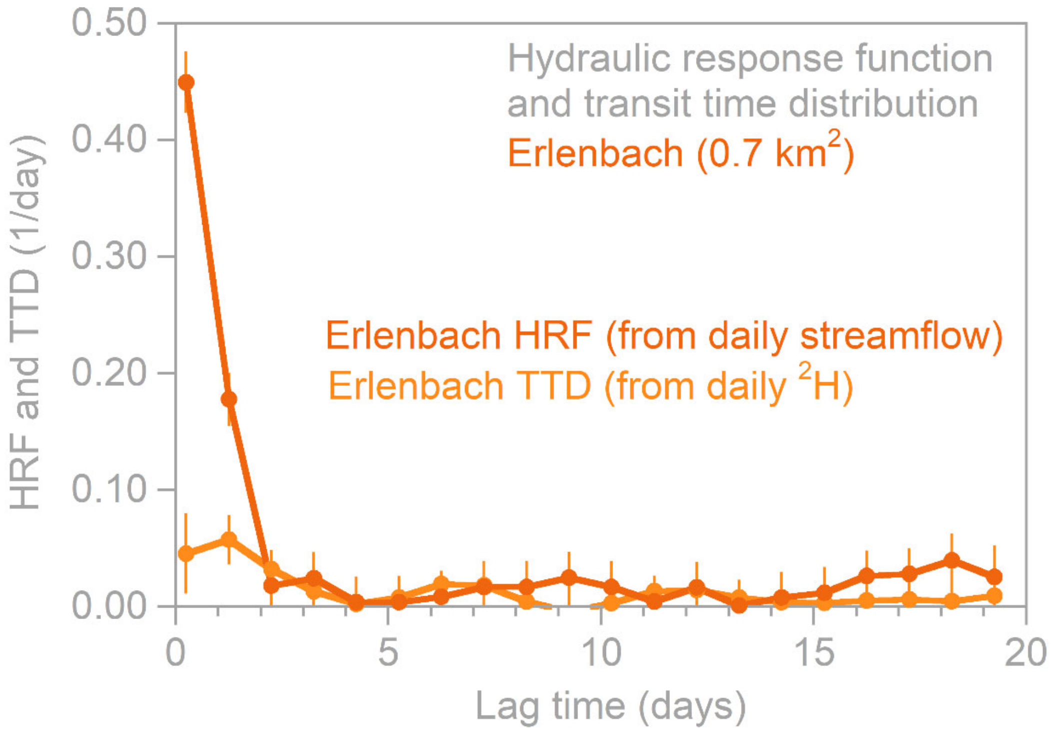
(Note different scales...!)

Hydraulic response functions vs. transit time distributions

On timescales of **hours**



On timescales of **days**



(Note different scales...!)


With thanks to:
Andrea Rücker
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ETH Zürich and Swiss Federal Research Institute WSL