The Critical Role of Groundwater in Mountain Streamflow Response to Drought

Rosemary WH Carroll | IDEAS | June 10, 2025

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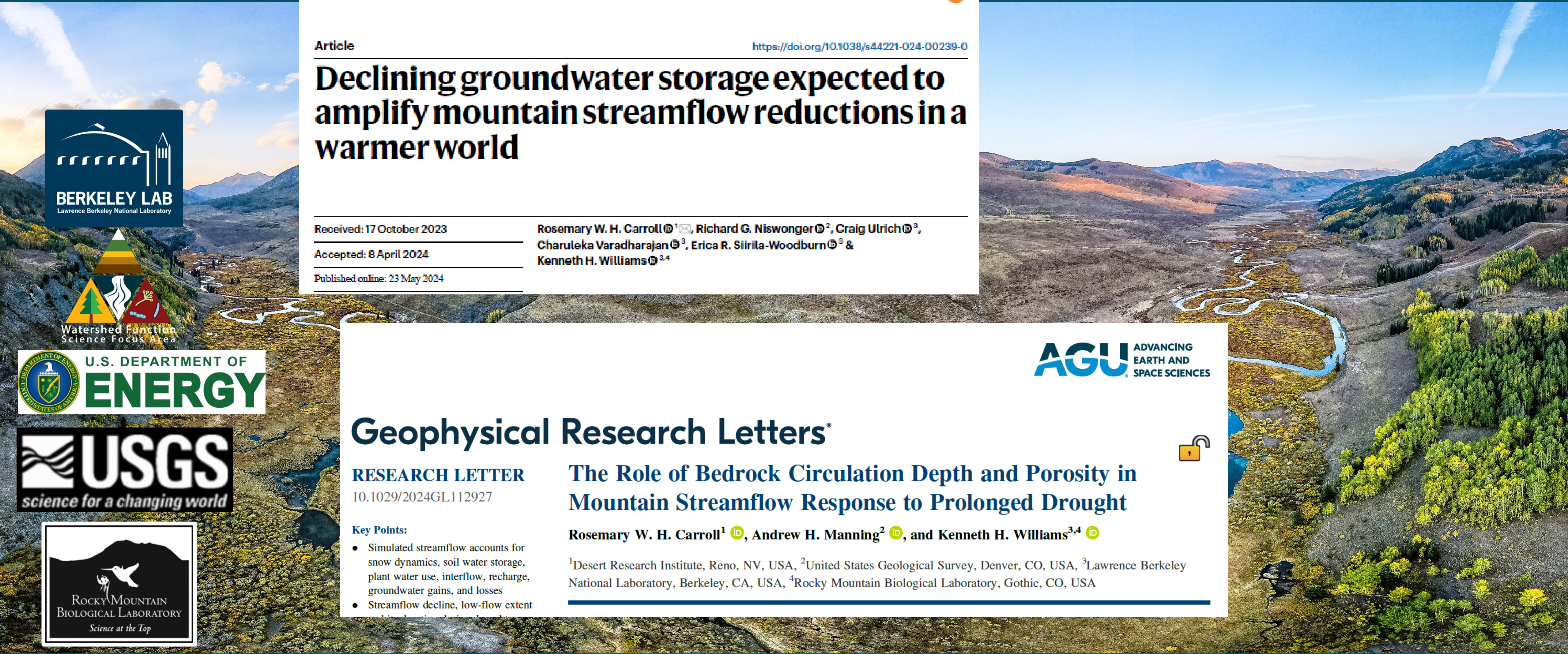

nature water

Article

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Declining groundwater storage expected to amplify mountain streamflow reductions in a warmer world

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Rosemary W. H. Carroll[1], Richard G. Niswonger[2], Craig Ulrich[3], Charuleka Varadharajan[3], Erica R. Siirila-Woodburn[3] & Kenneth H. Williams[3,4]

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL112927

The Role of Bedrock Circulation Depth and Porosity in Mountain Streamflow Response to Prolonged Drought

Rosemary W. H. Carroll[1], Andrew H. Manning[2], and Kenneth H. Williams[3,4]

[1]Desert Research Institute, Reno, NV, USA, [2]United States Geological Survey, Denver, CO, USA, [3]Lawrence Berkeley National Laboratory, Berkeley, CA, USA, [4]Rocky Mountain Biological Laboratory, Gothic, CO, USA

Key Points:

- Simulated streamflow accounts for snow dynamics, soil water storage, plant water use, interflow, recharge, groundwater gains, and losses
- Streamflow decline, low-flow extent

BERKELEY LAB
Lawrence Berkeley National Laboratory

Watershed Function
Science Focus Area

U.S. DEPARTMENT OF ENERGY

USGS
science for a changing world

Rocky Mountain Biological Laboratory
Science at the Top

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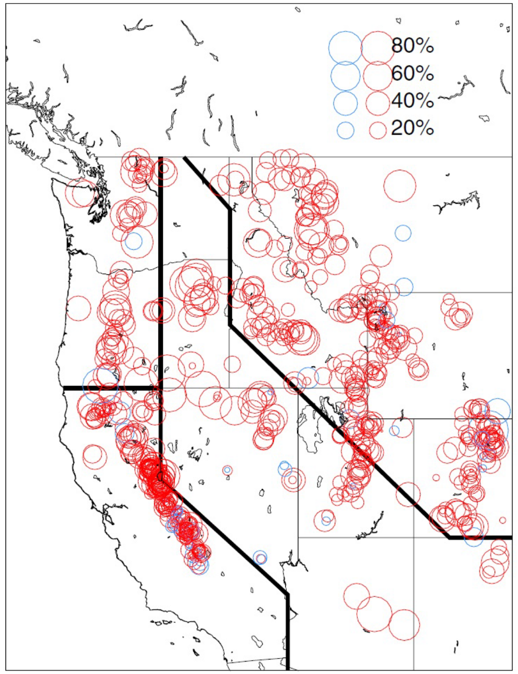
The Colorado River –
emblematic of western US systems under stress

Warming

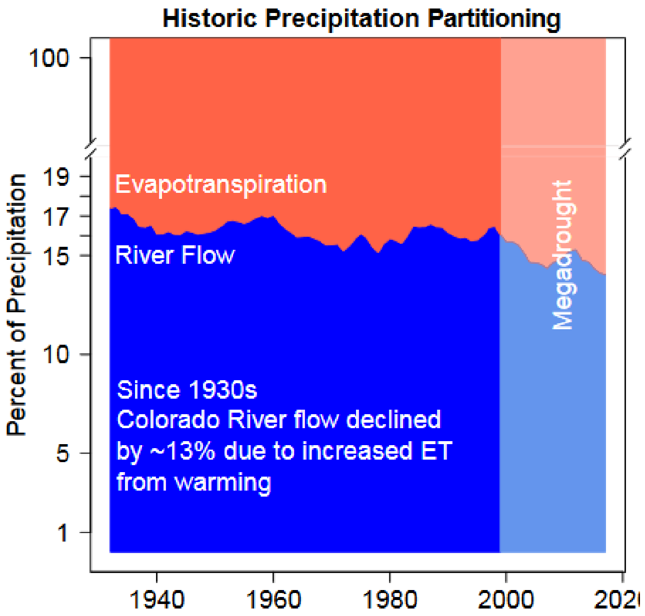
Snow Loss

a) April 1 Observed SWE Trends 1955-2016



Mote et al., 2018

Reduced Streamflow



Overpeck and Udall, 2020

The Colorado River – *emblematic of western US systems under stress*

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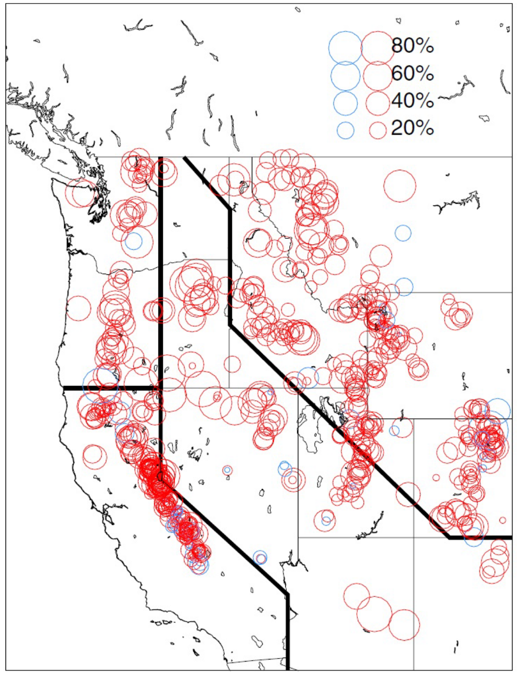

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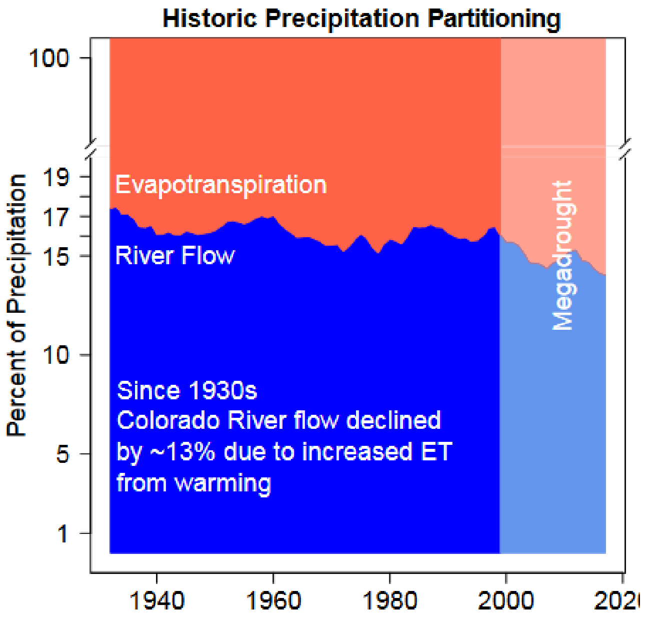
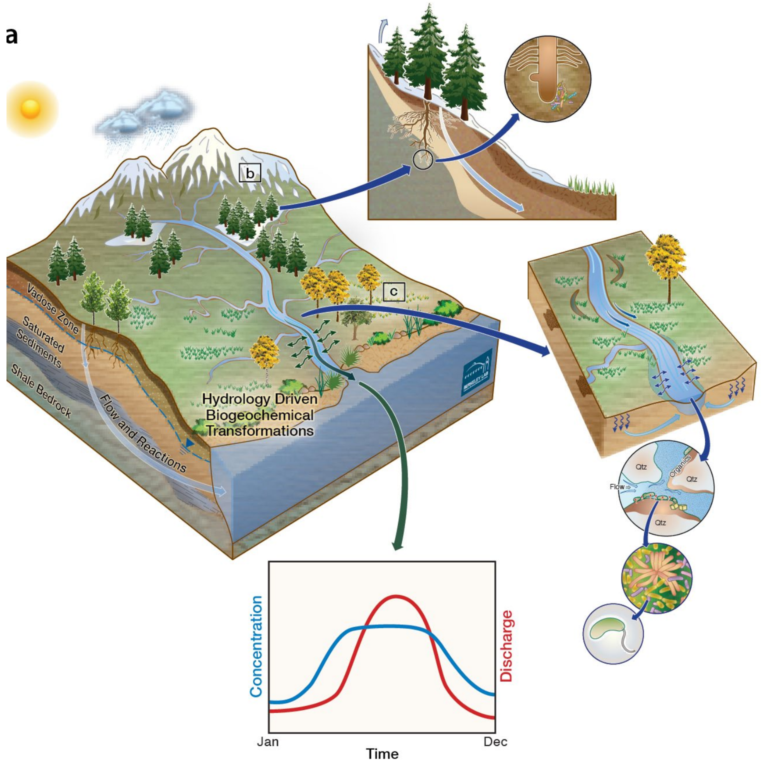


Overpeck and Udall, 2020

What is the role of groundwater in mountain streamflow generation?

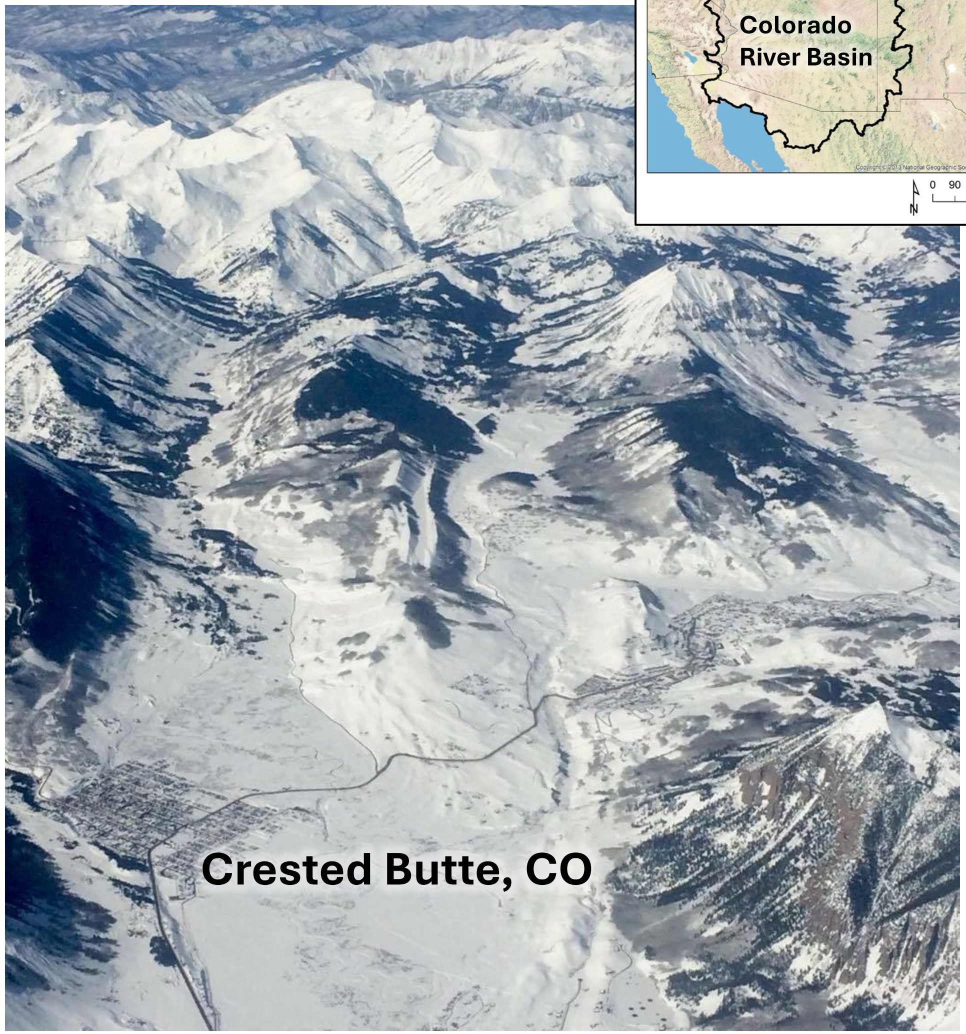
East River, CO (750 km^2)

DOE/LBNL Watershed Function Scientific Focus Area



Hubbard et al., 2018 (VZJ)

Objective: Assess impacts of warming and drought on hydro-biogeochemical functioning of mountainous watersheds from seasonal to decadal timescales



East River, CO (750 km^2)

Integrated Hydrologic Modeling Approach

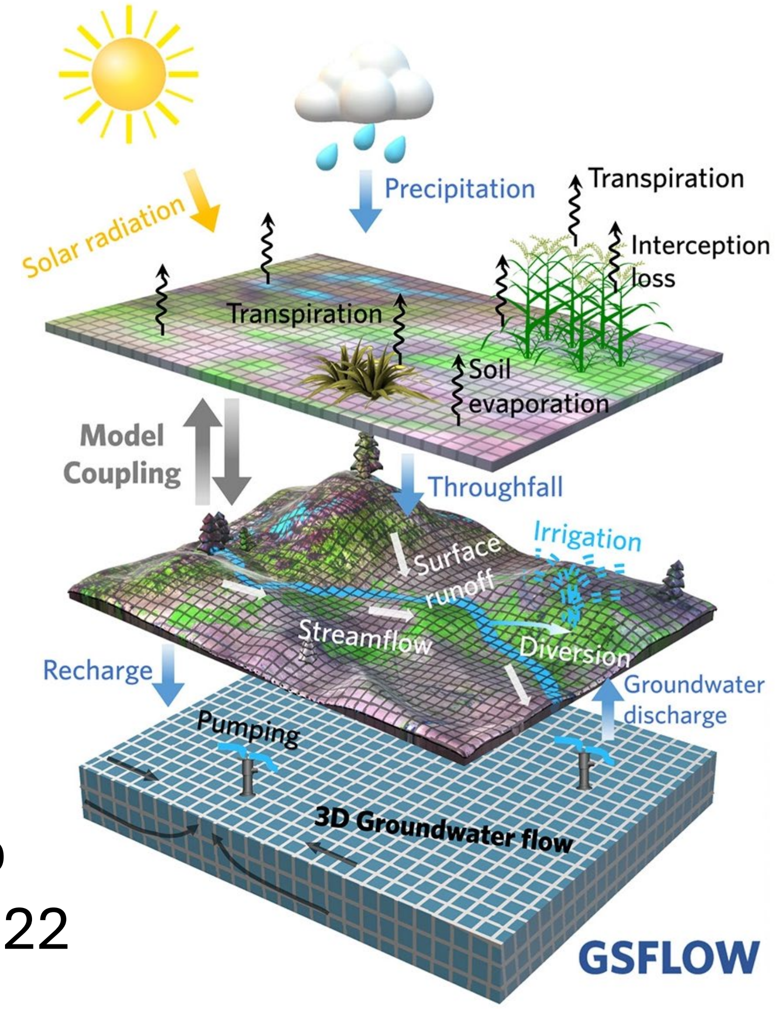
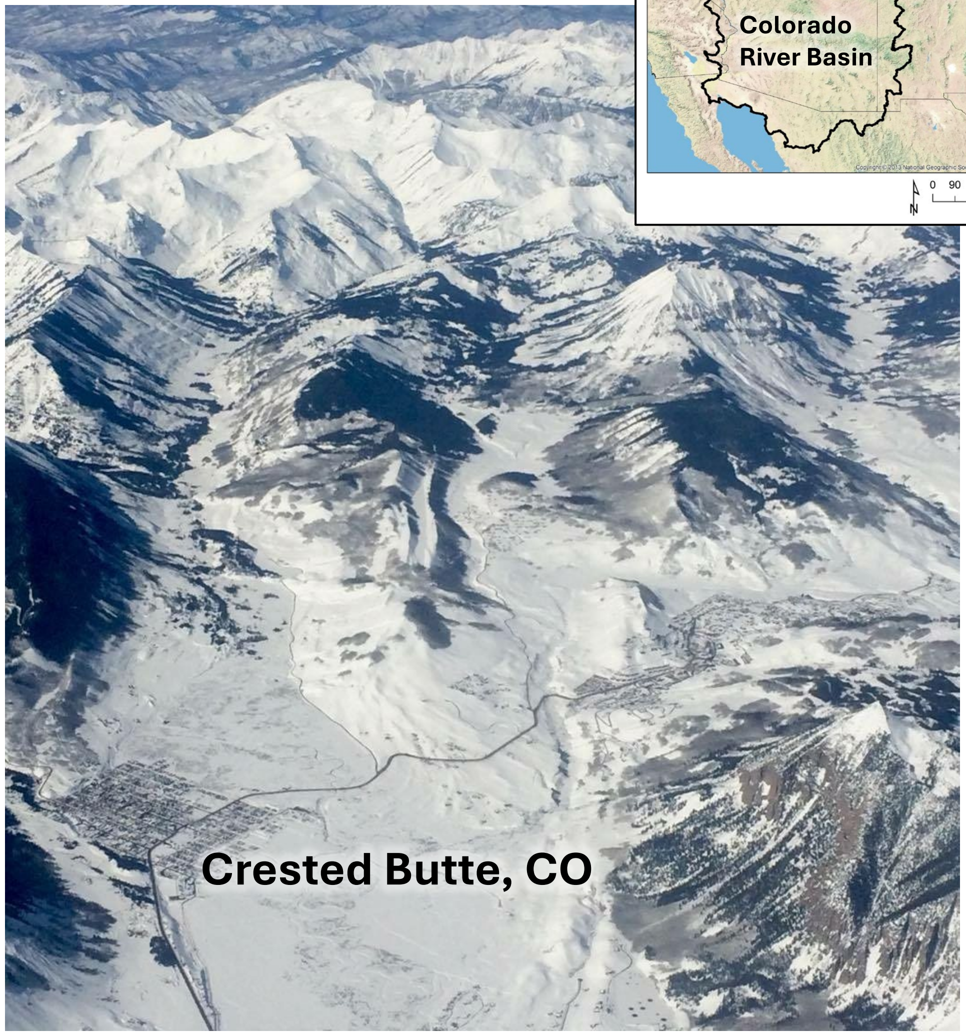


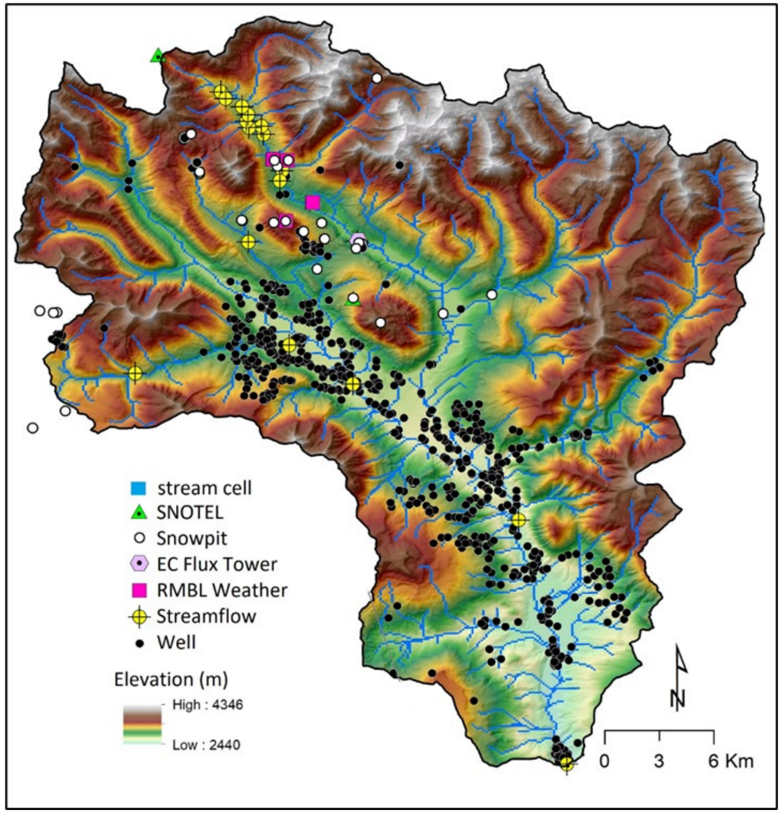
Figure by Zheng et al., 2018

100-m grid
Daily timestep
WY 1987 to 2022

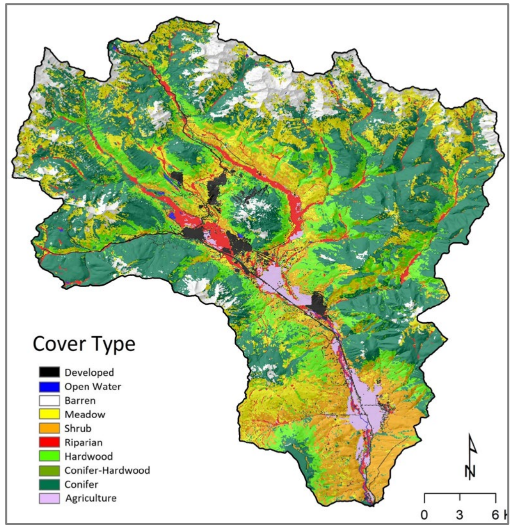


East River Model Built on Extensive Data

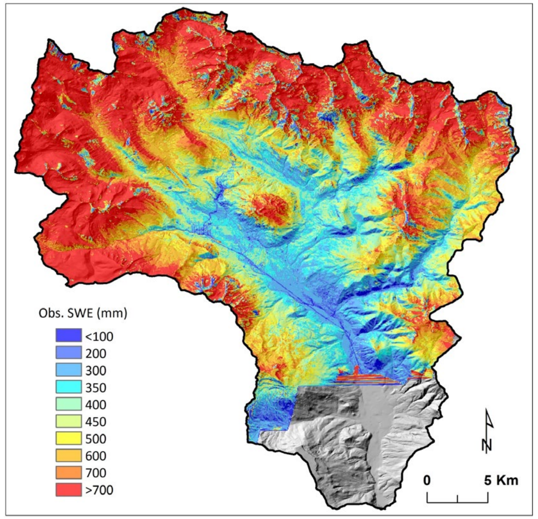
Topography



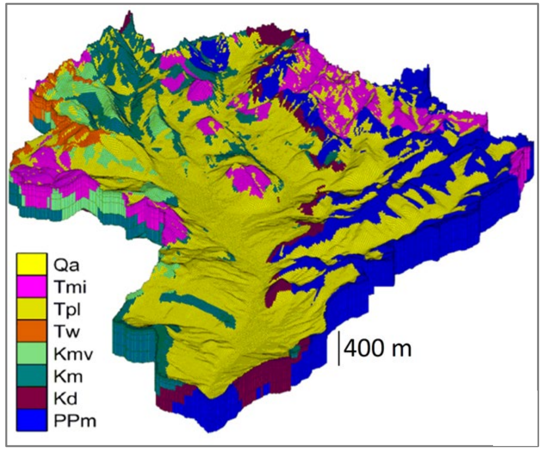
Vegetation



Snowpack Distribution



Geology



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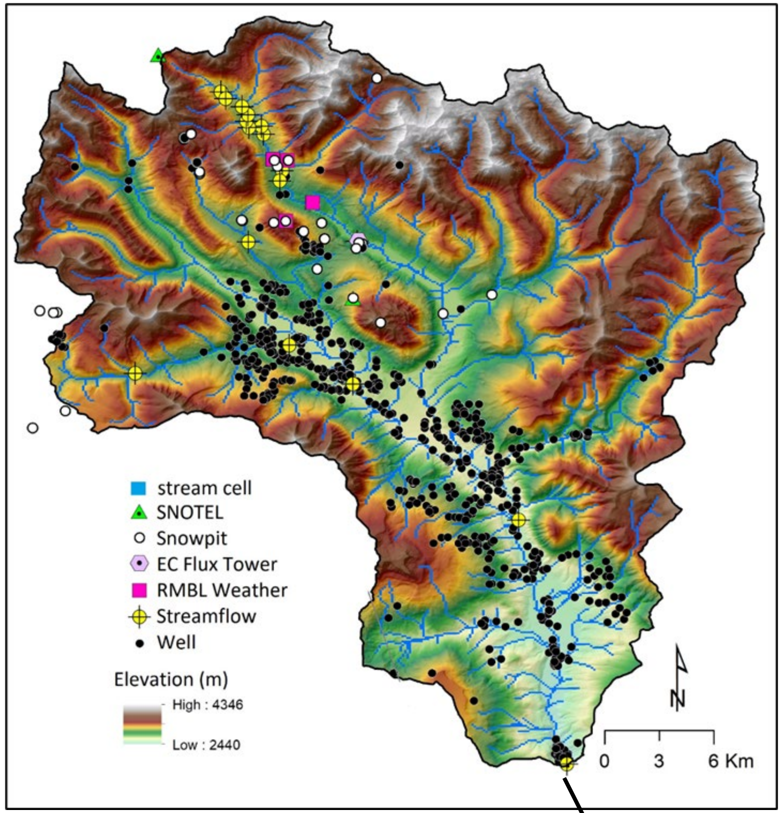

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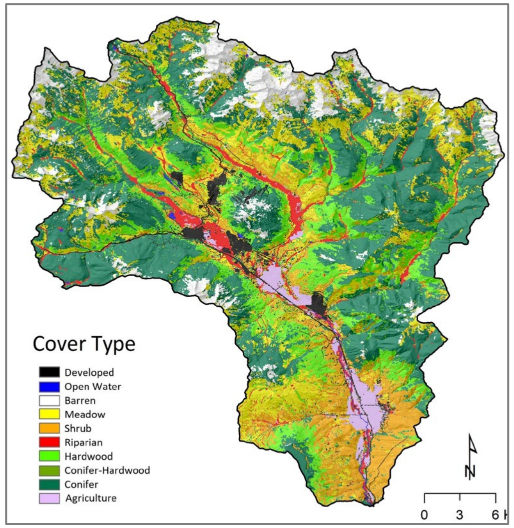

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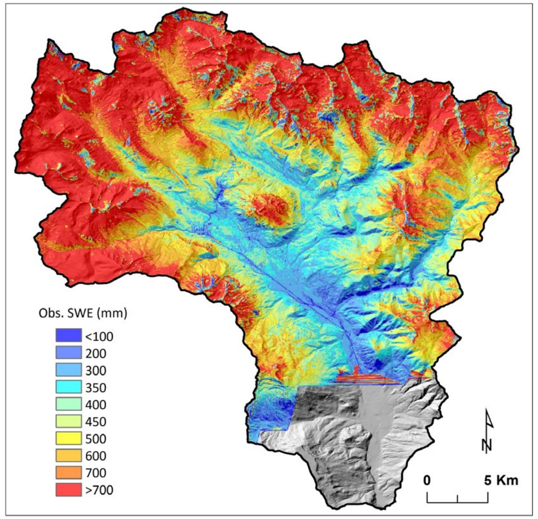

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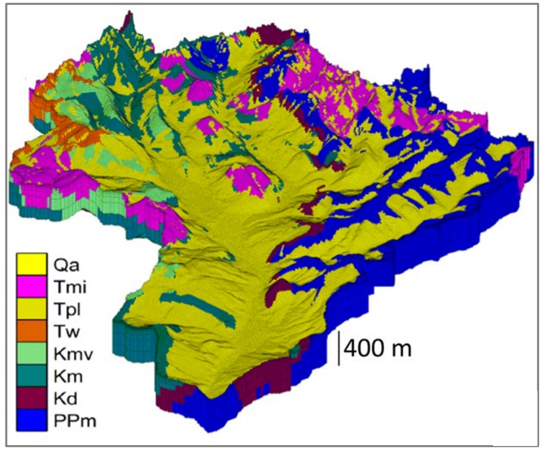
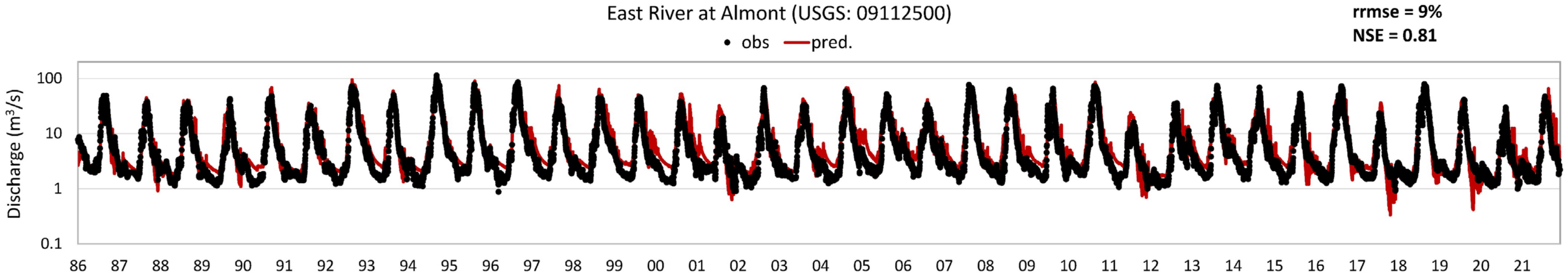


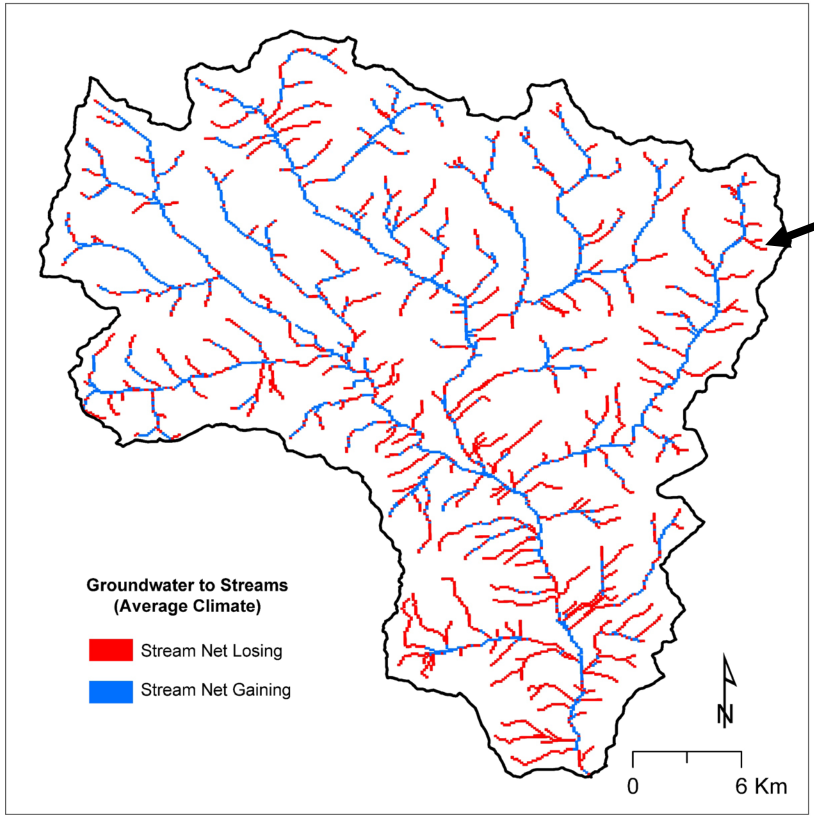


USGS Almont Stream Gage

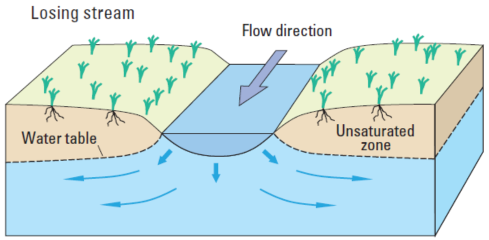
Groundwater = 26±3% streamflow

Groundwater to streams varies in space
function of water table elevation

Net Groundwater Gaining/Losing



Barlow and Leake, 2012



losing to GW
(disconnected=non-perennial)

Groundwater to streams varies in space
function of water table elevation

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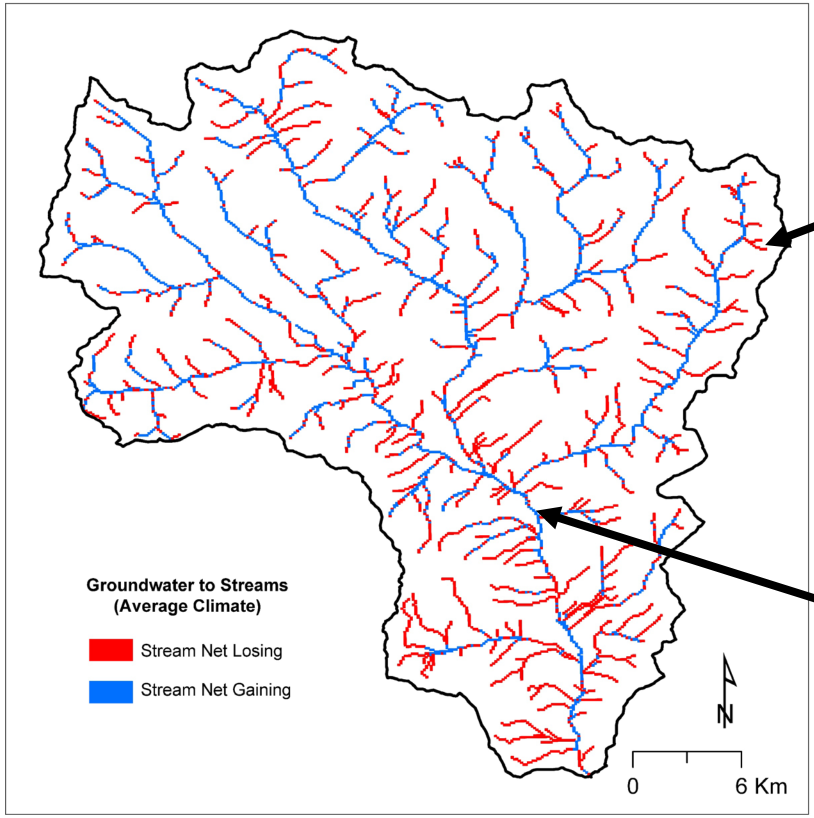

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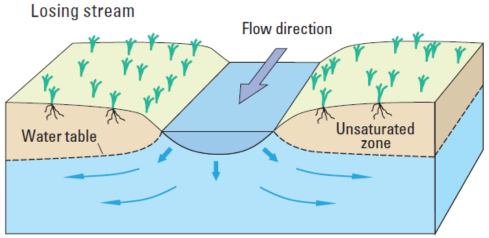

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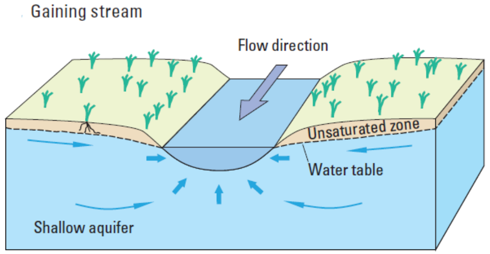
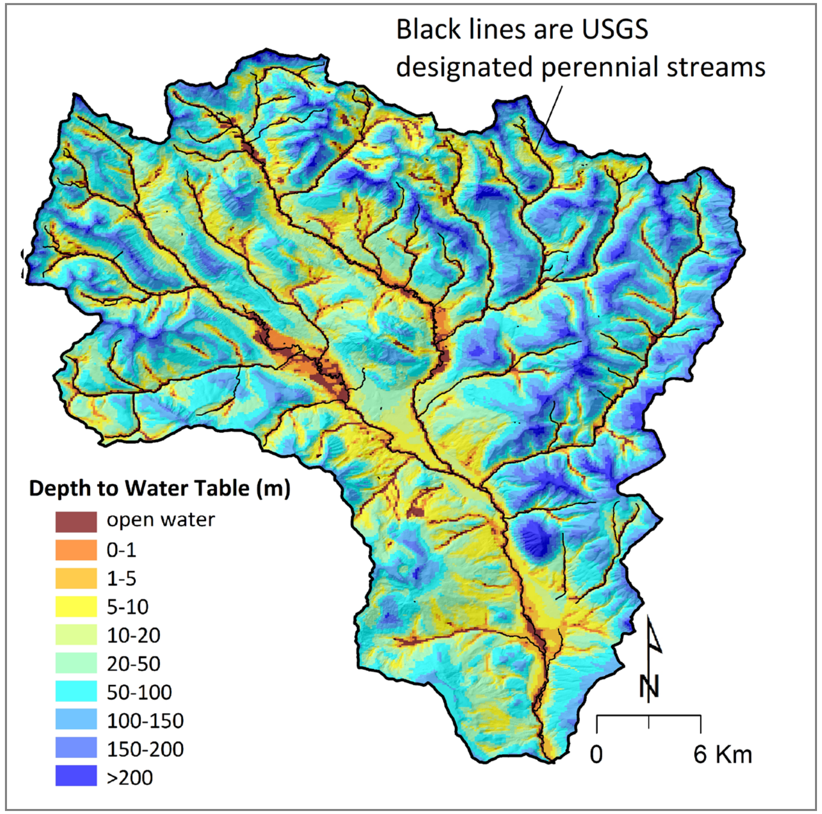
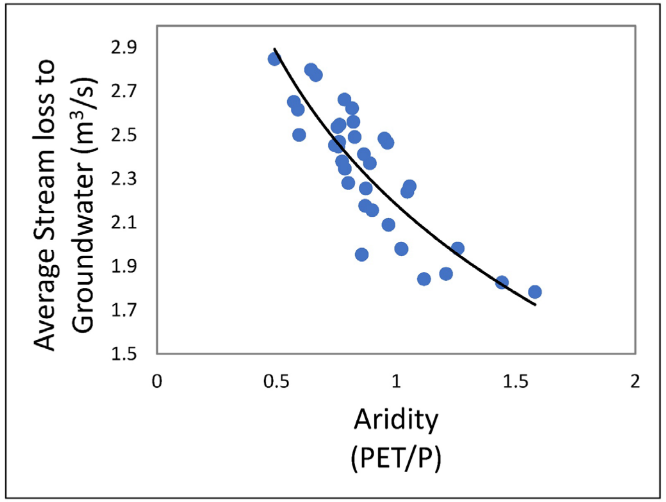


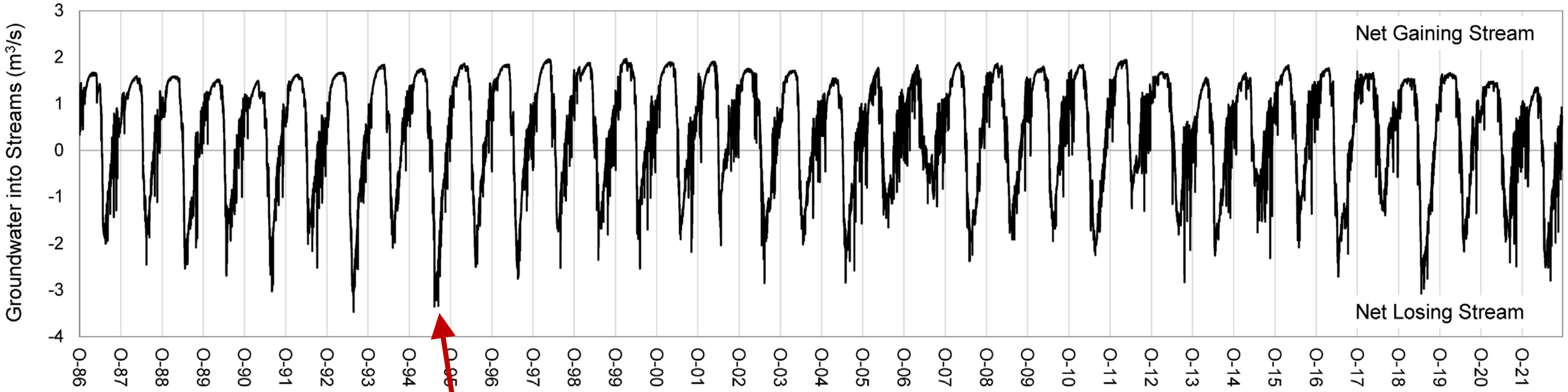
gaining from GW
perennial

Depth to Water Table



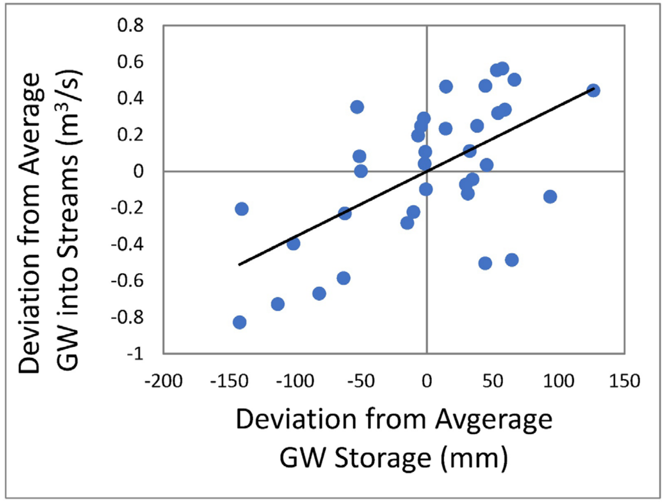
Groundwater to streams varies in time
function of climate (losing)

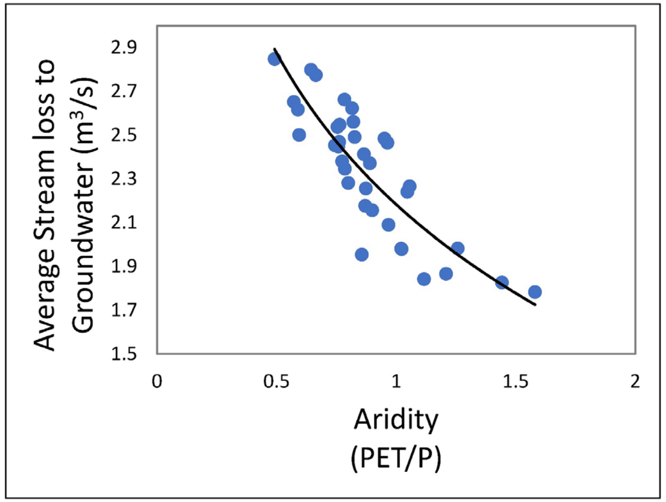




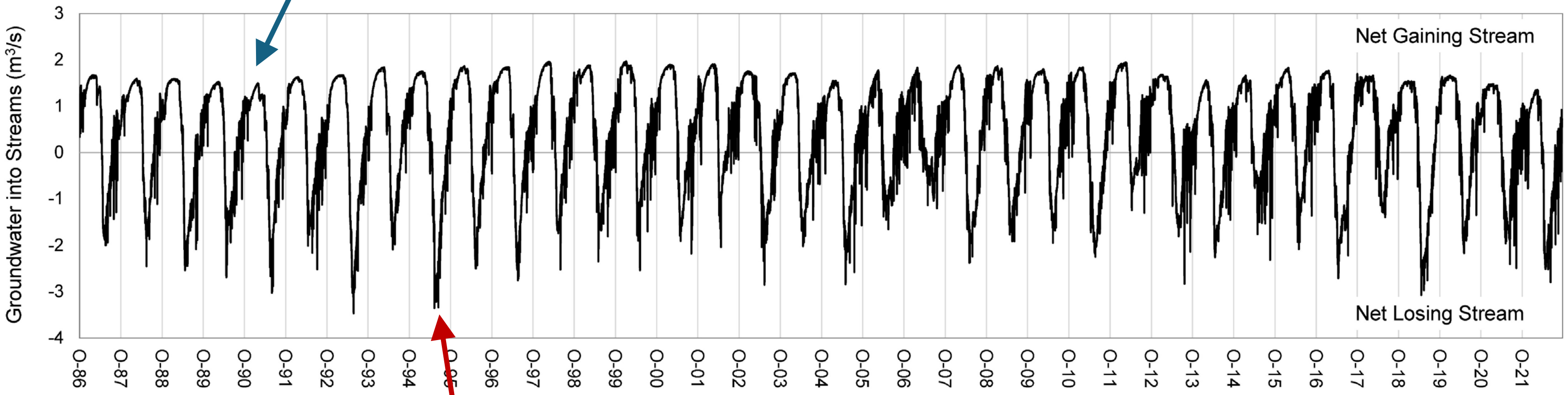
Net losing in the **springtime**: snowmelt in non-perennial streams moves into subsurface.

Groundwater to streams varies in time
function of climate (losing) & GW storage (gaining)



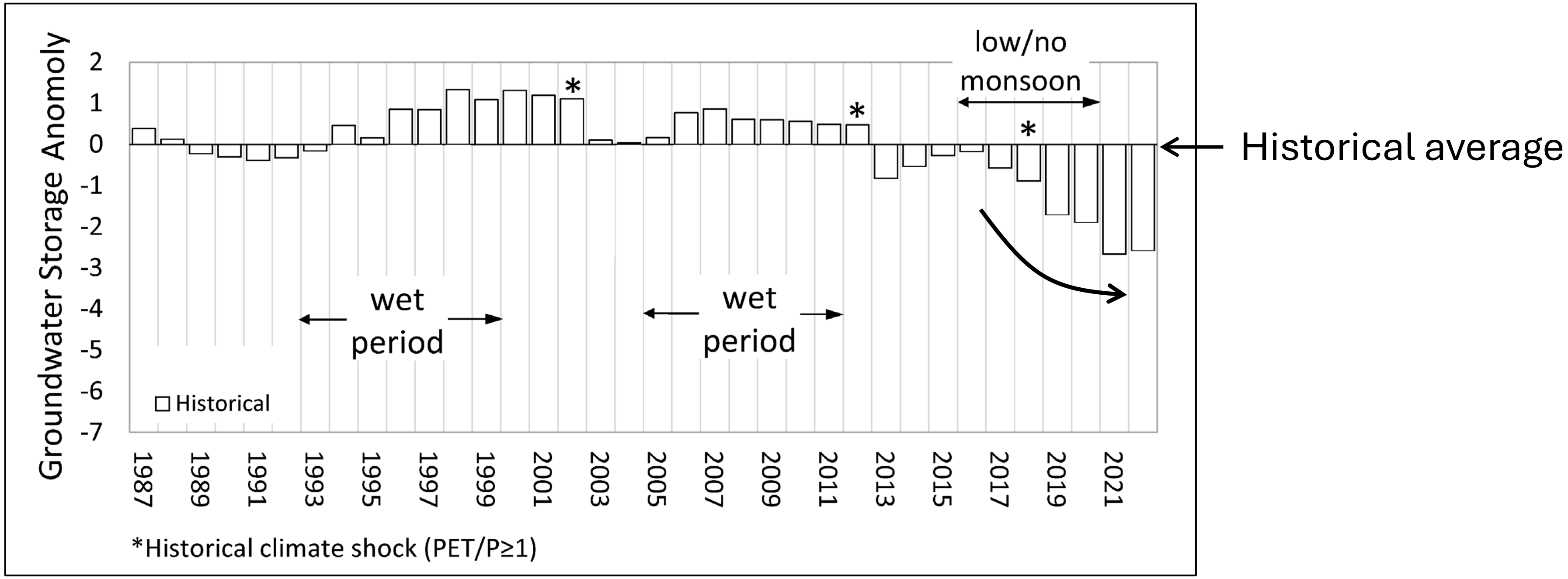


Net gaining in the **wintertime**: Groundwater supports perennial streams is directly related to GW storage



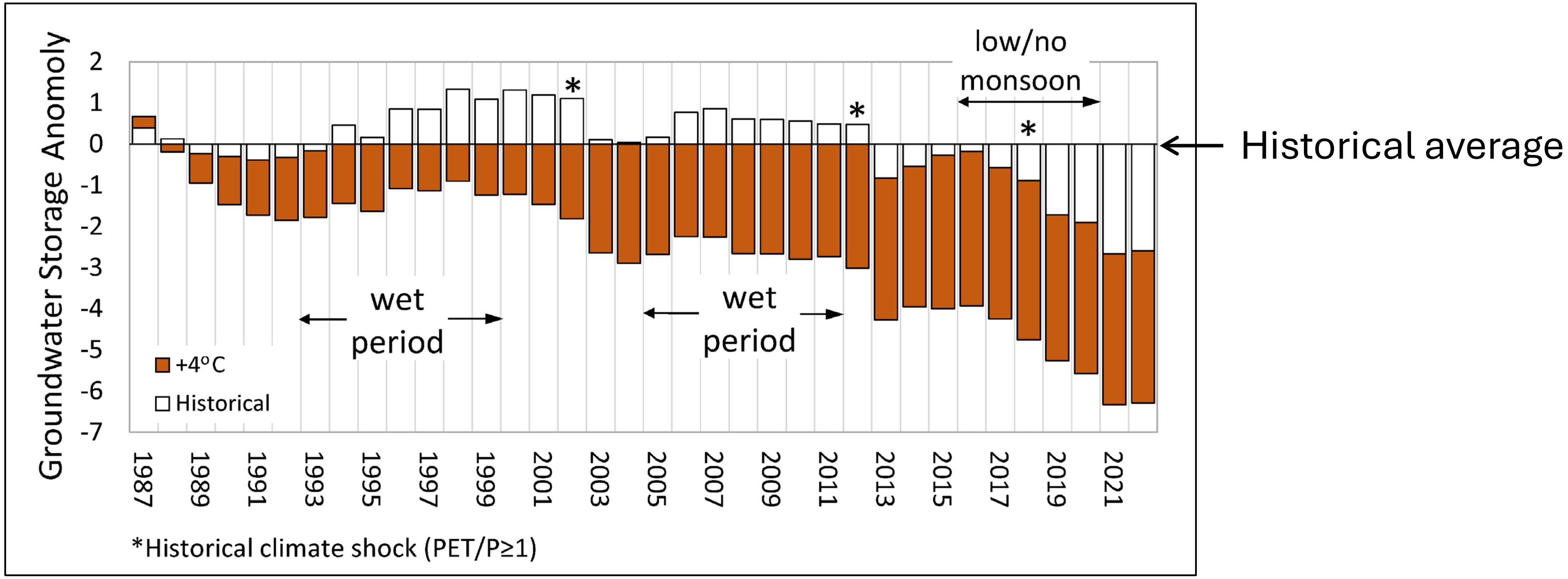
Net losing in the **springtime**: snowmelt in non-perennial streams moves into subsurface as a function of interannual climate variability.

Groundwater Storage: Historical



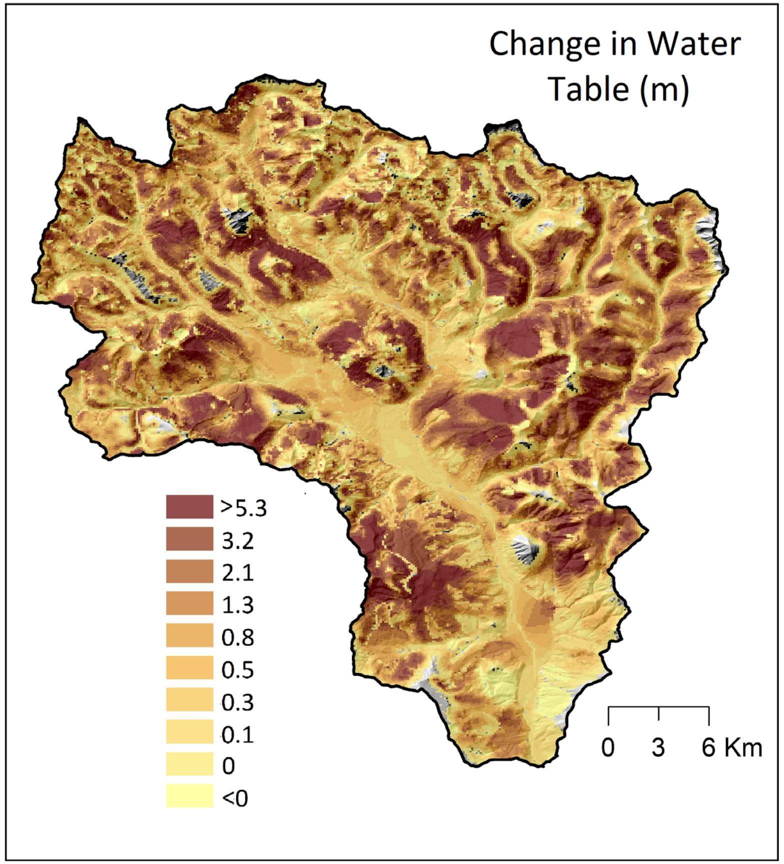
Groundwater Storage: +4°C warming

(Simple) Everything Everywhere All at Once ⦾⦾



Groundwater storage never achieves historical average conditions even with simulated wet periods.

Groundwater storage loss with warming is not uniformly distributed



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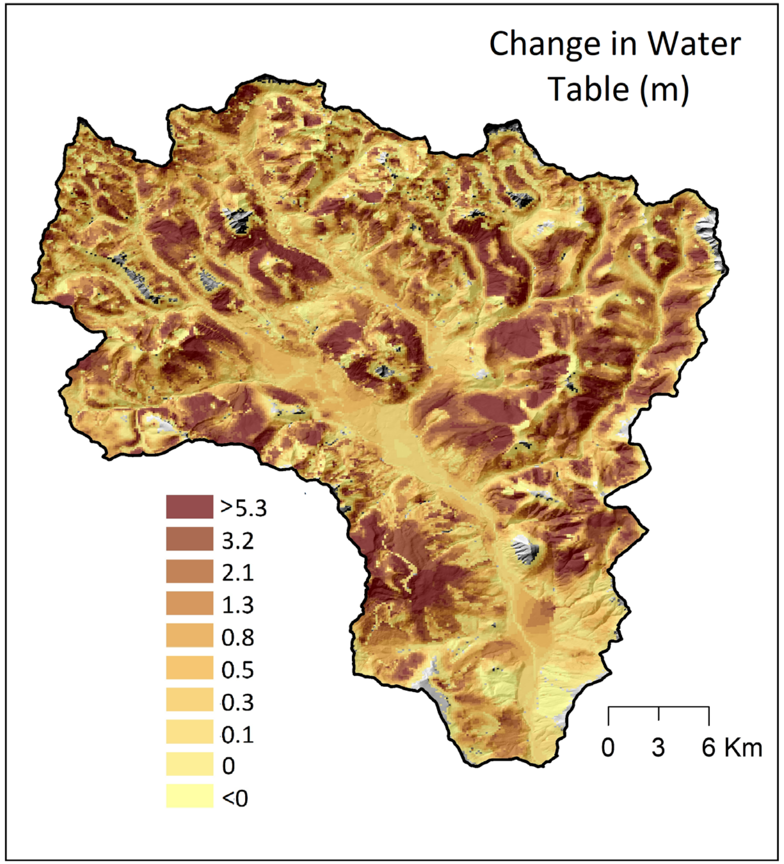
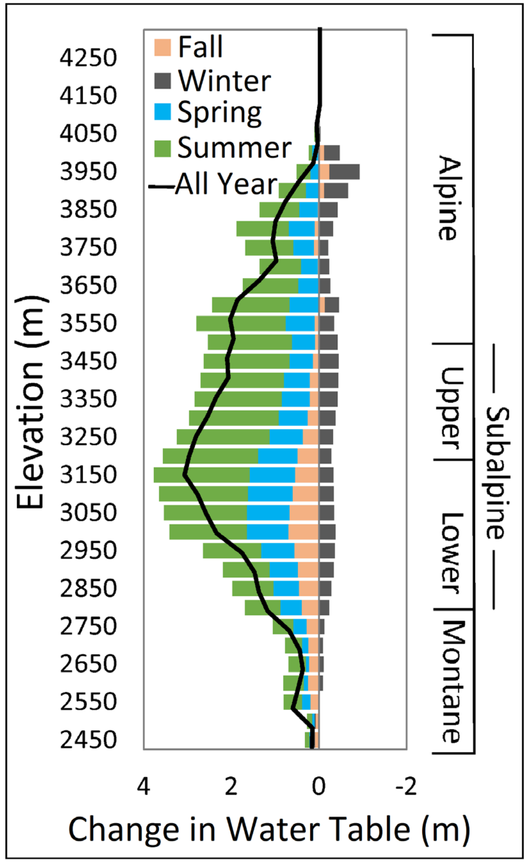


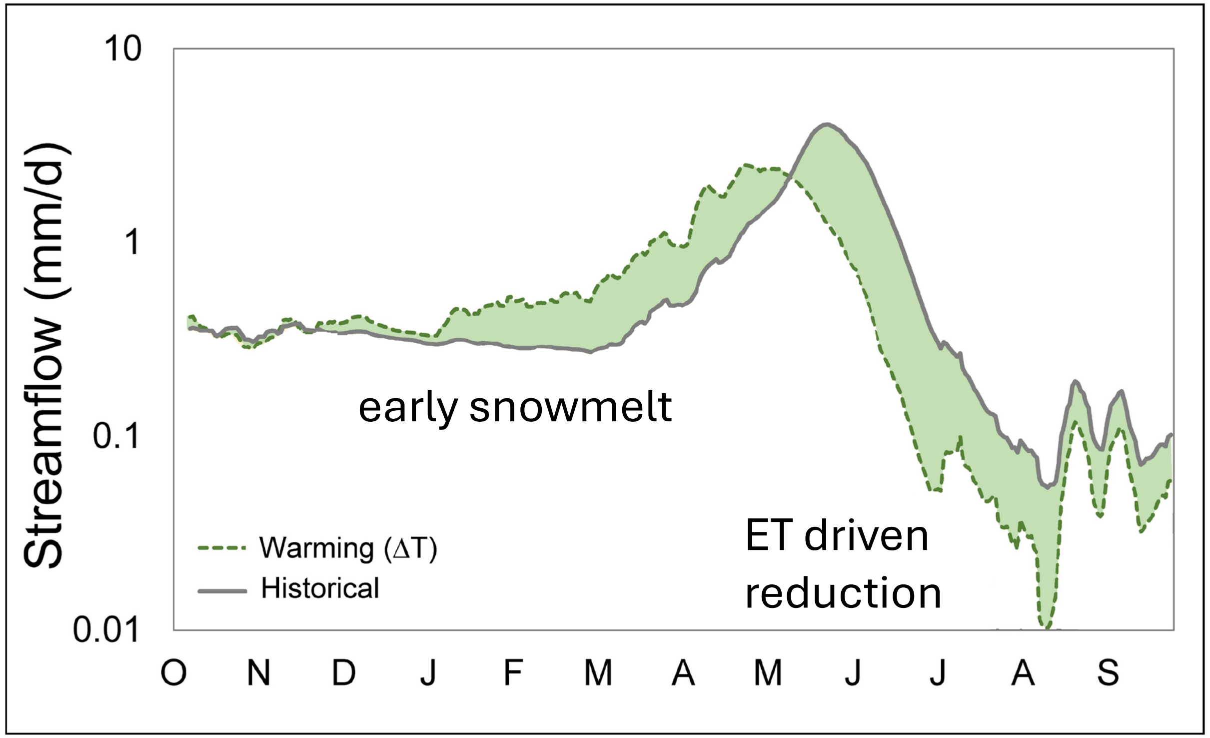


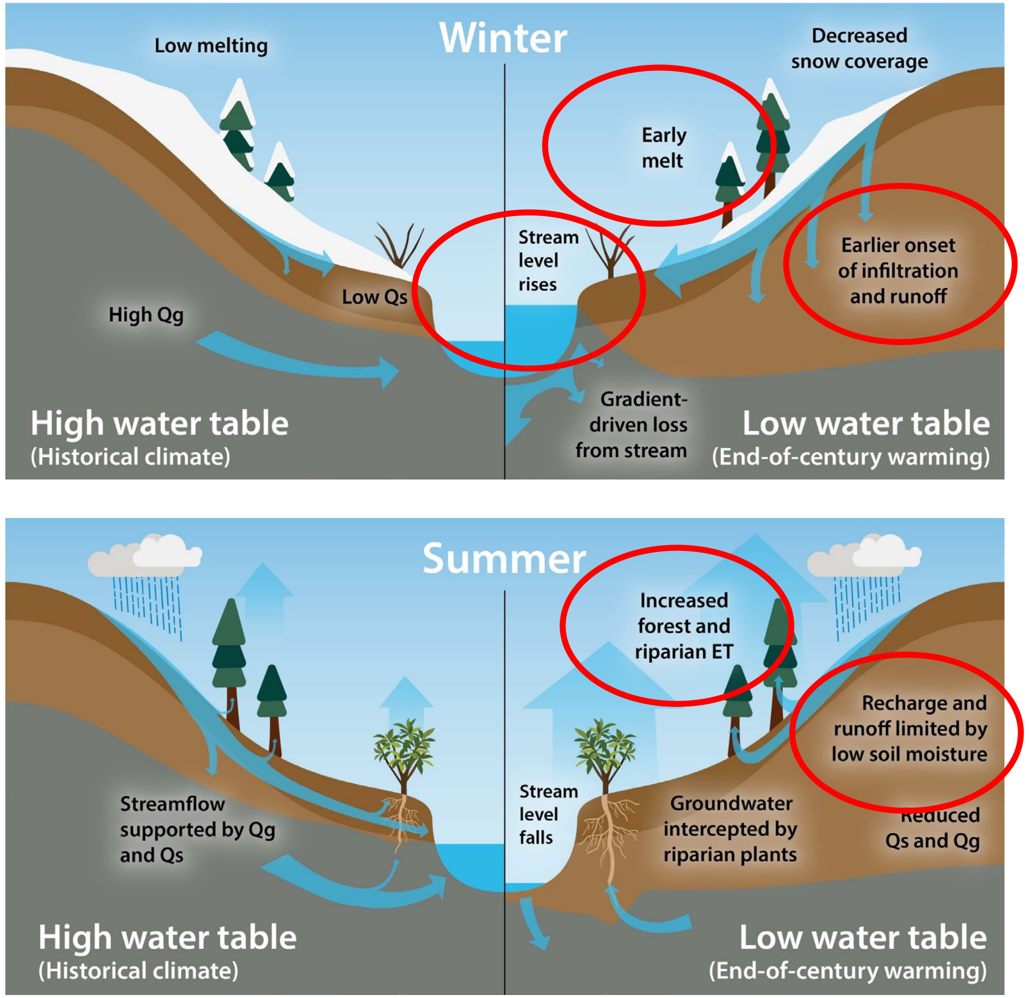
Max. conifer density

- Greatest declines in catchments where conifer forest is most dense
- Summer warming largest contributor to loss.
- Increased PET in energy-limited portions of the basin drive water table declines.

Streamflow reduction related to change in temperature (ΔT)

(Ignore groundwater storage)





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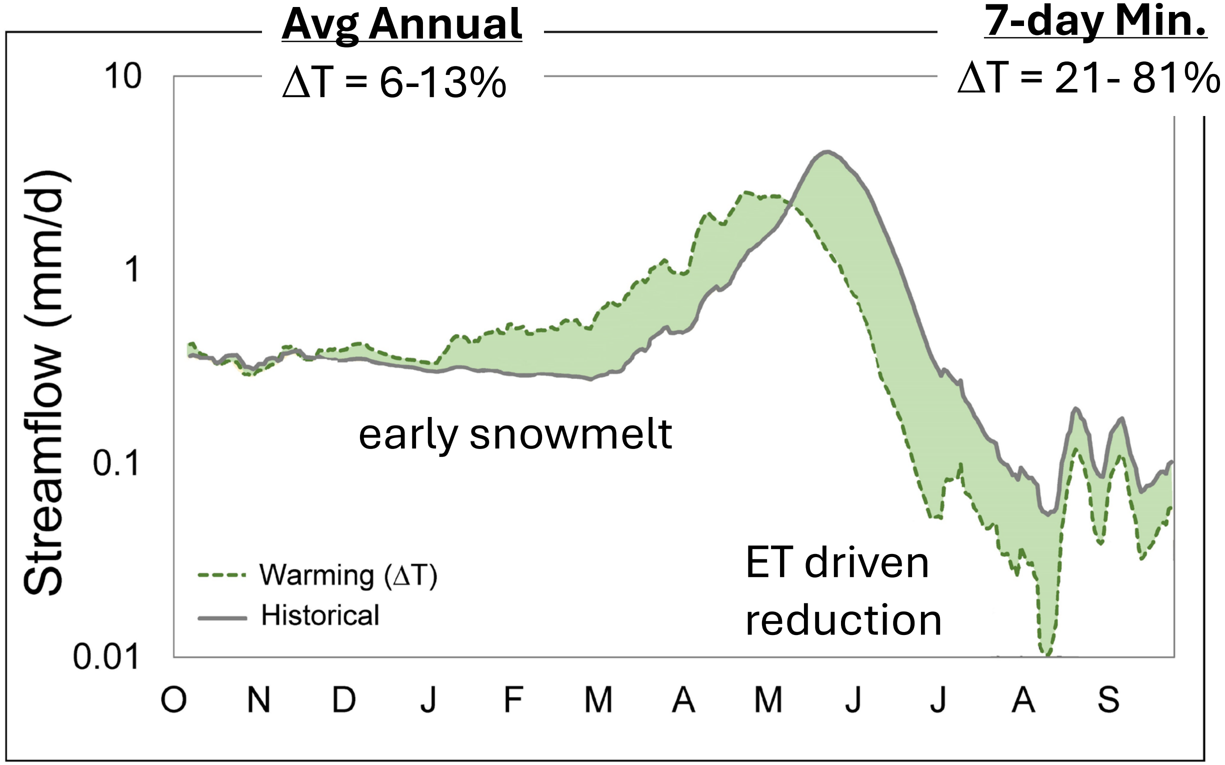
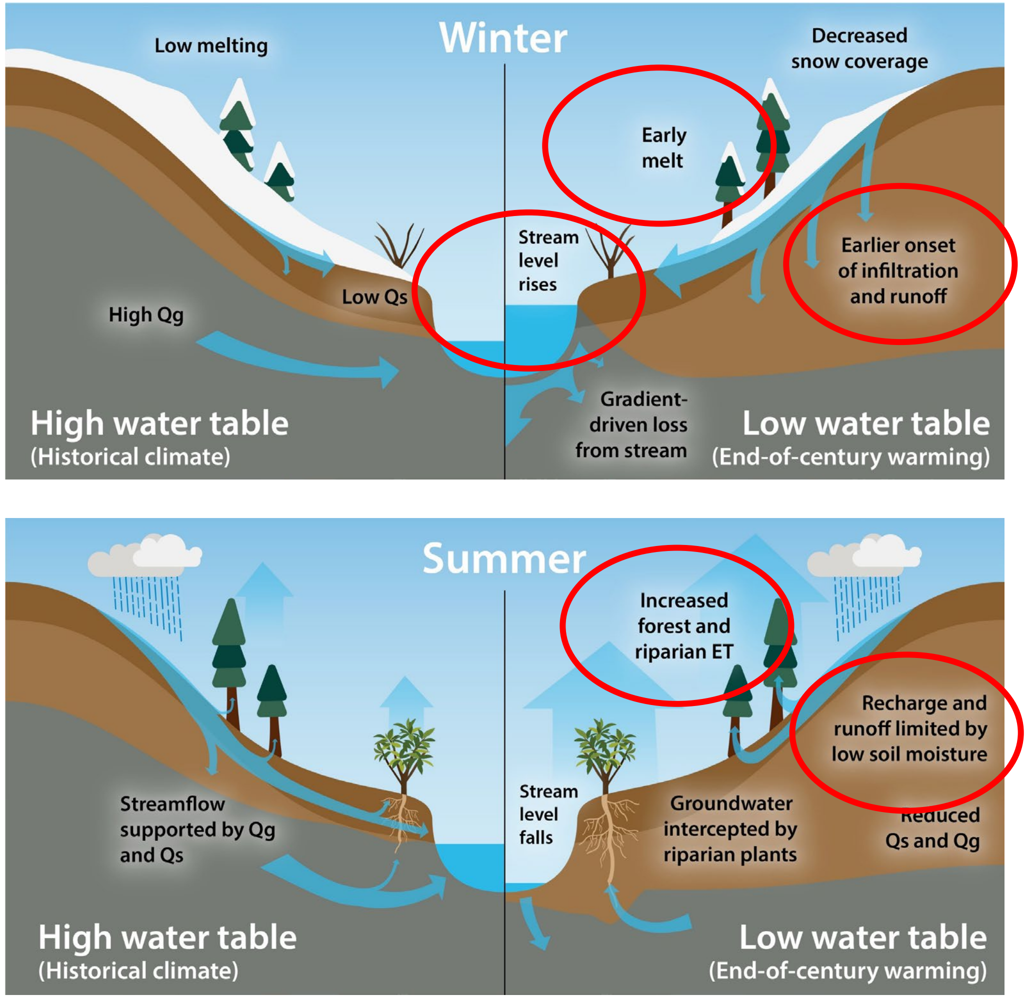
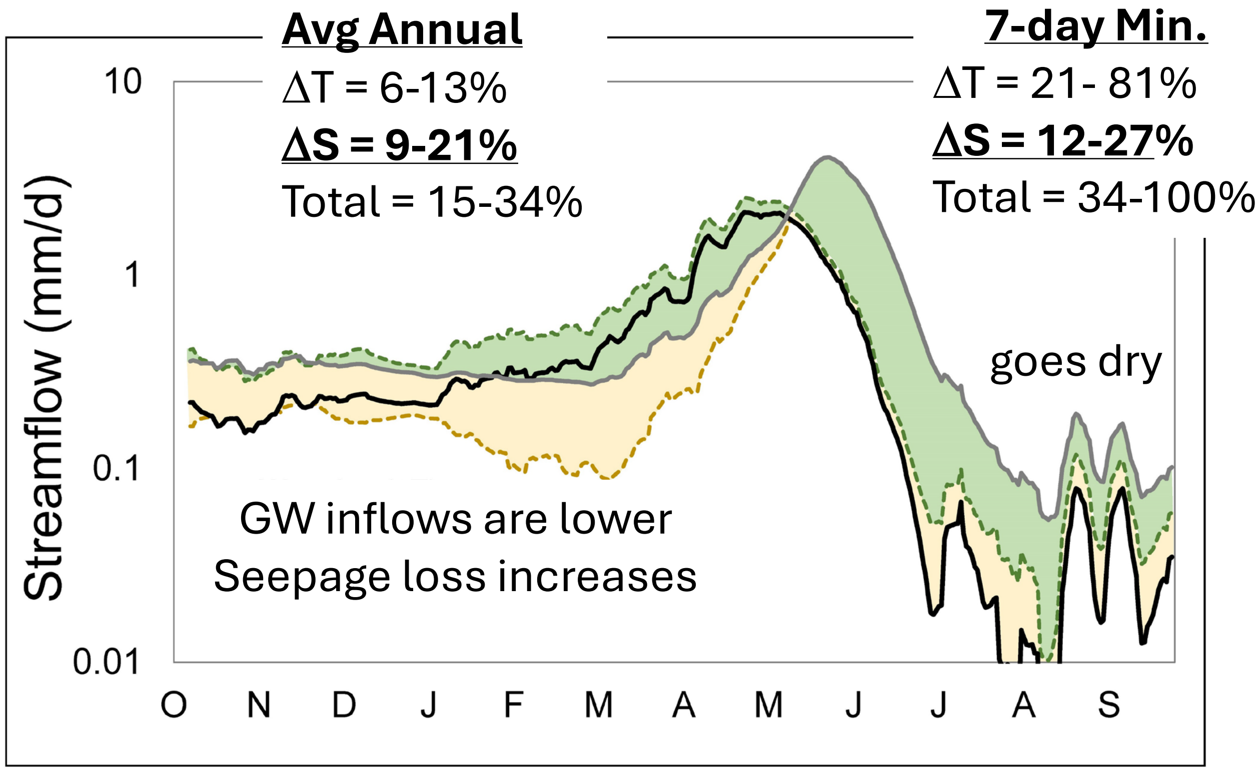
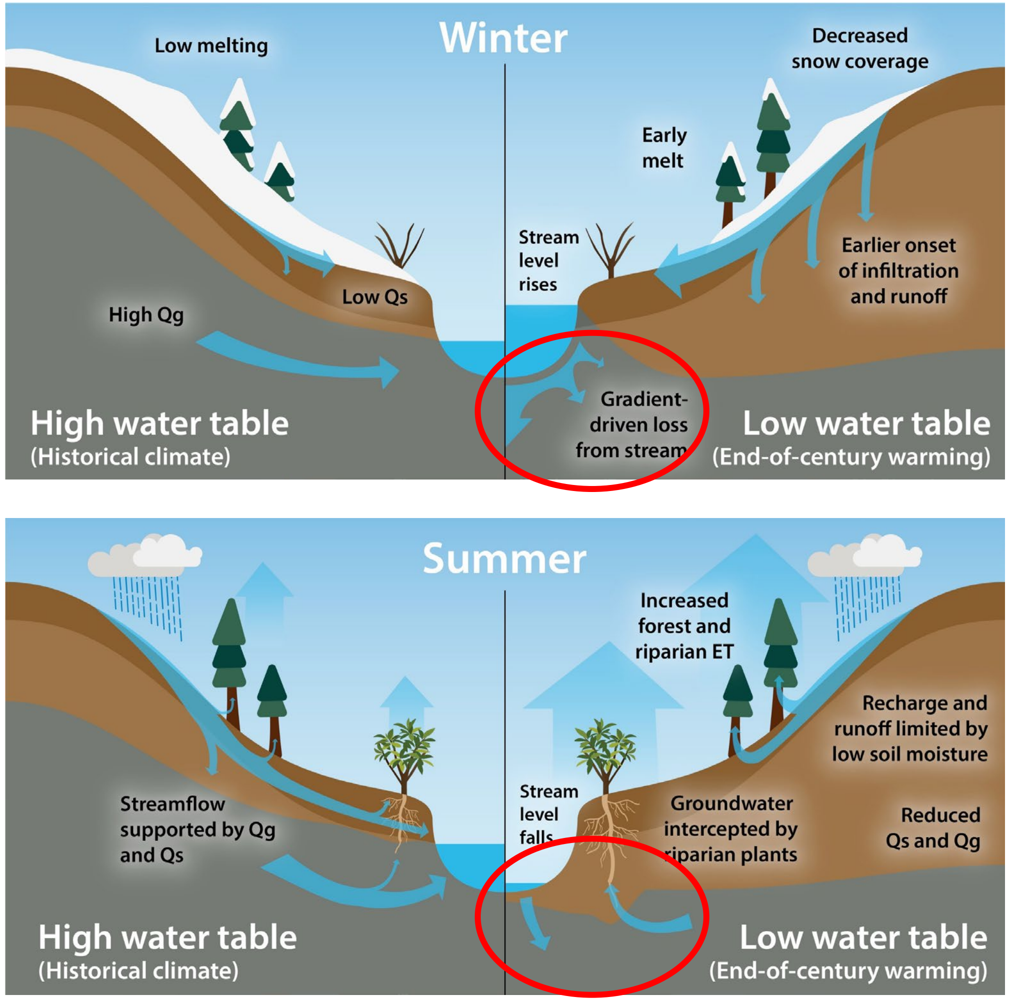




Streamflow reductions increase if GW storage declines included (ΔS)

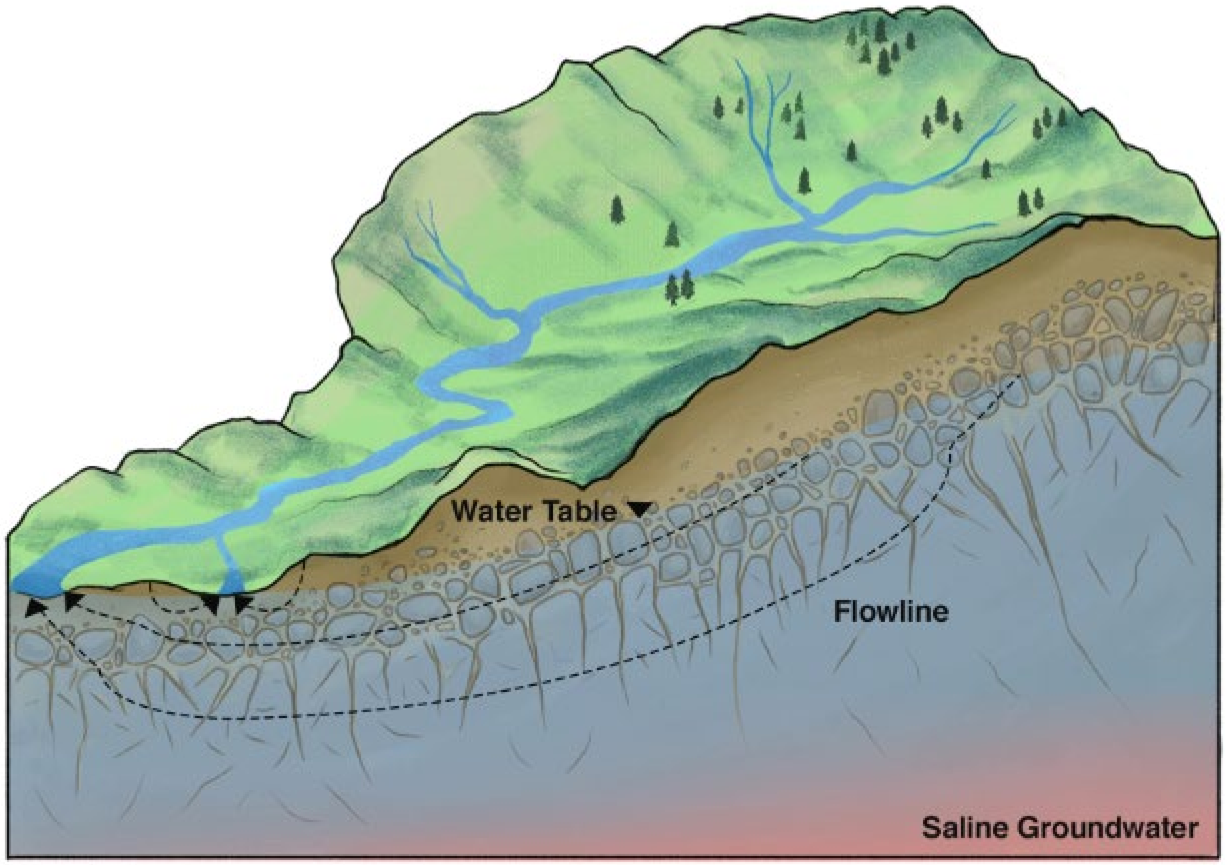




Reduced GW inflows can no longer compensate for increased vegetation water use in the summer

Where is the bottom of the watershed?

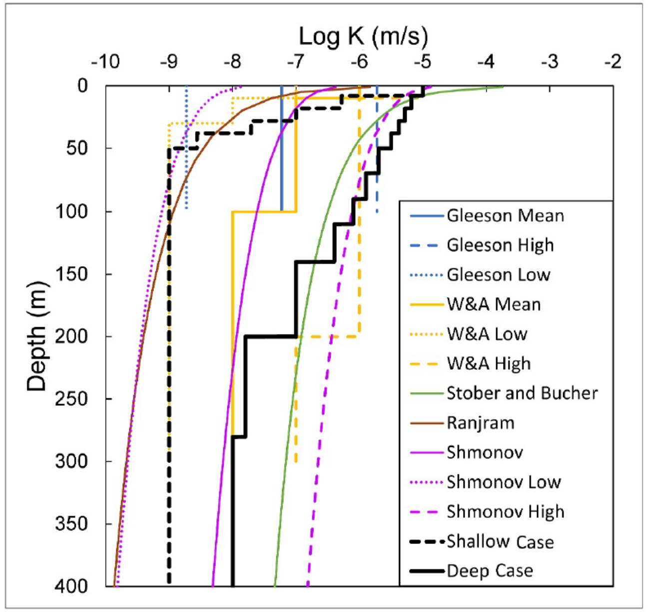
- Depth below which groundwater is negligible.
- Range from 10s to 100s of meters and highly uncertain.
- Does the active circulation depth affect drought response?

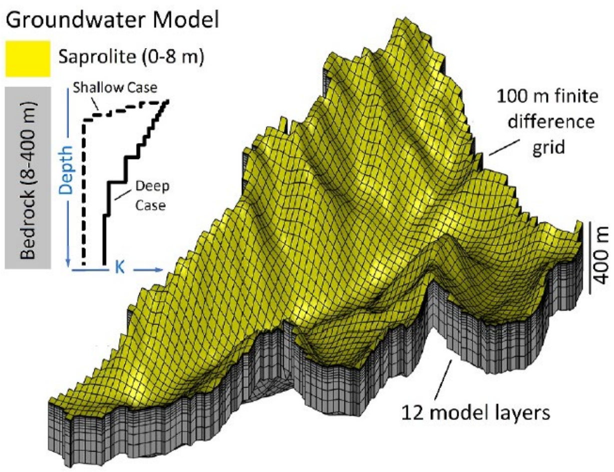


Condon et al., 2019 (WRR)

What is the effect of groundwater circulation depth on streamflow generation?

Observed hydraulic conductivity for crystalline bedrock





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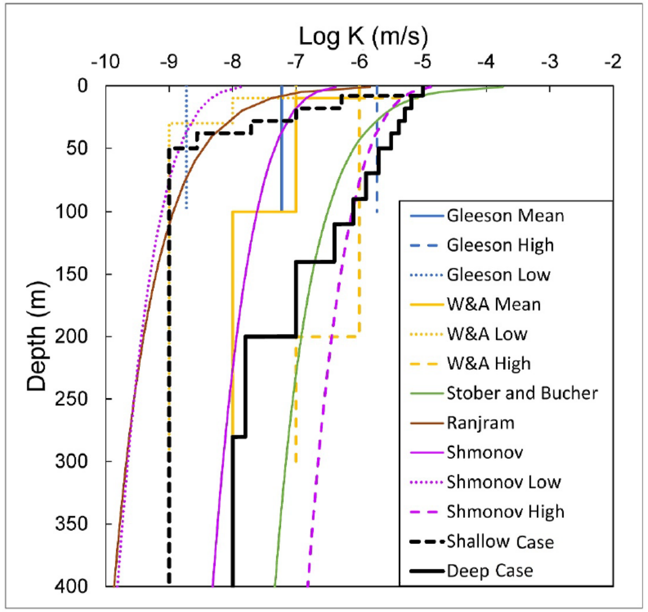

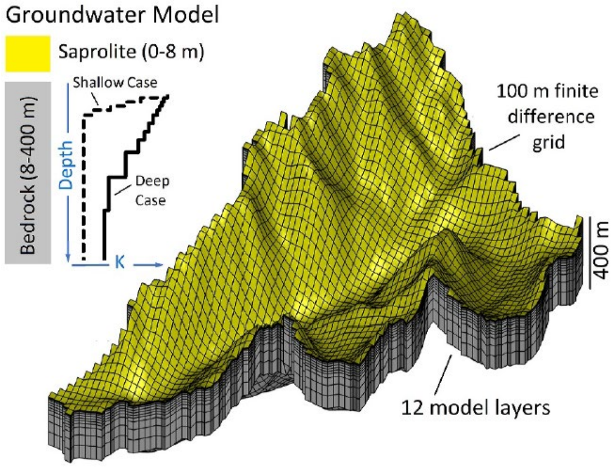

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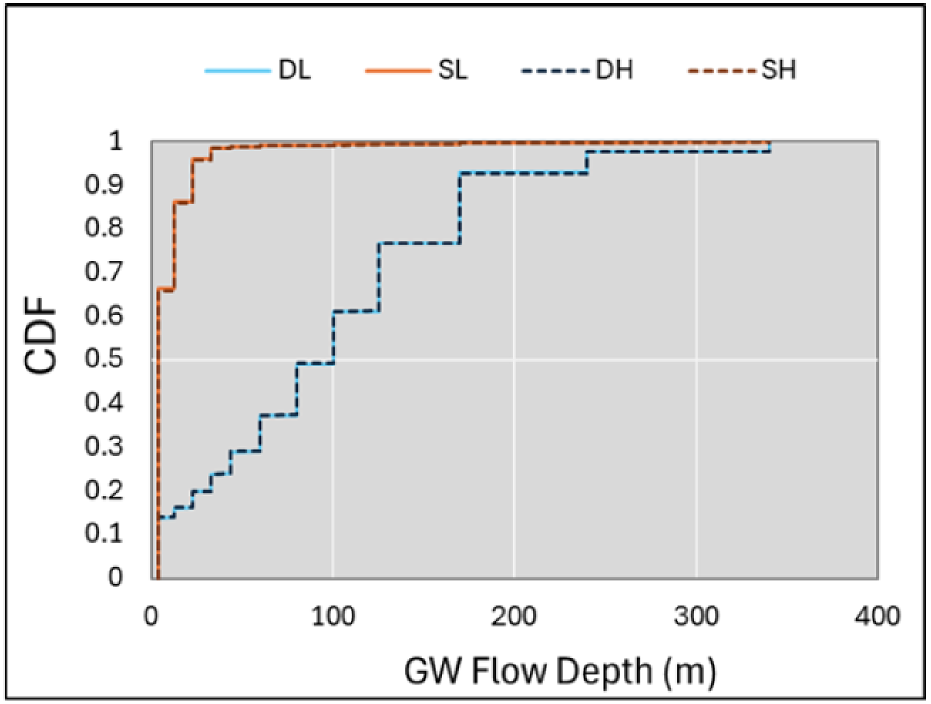


DL = deep circulation, 1% porosity
SL = shallow circulation, 1% porosity
DH = deep circulation, 3% porosity
SH = shallow circulation, 3% porosity

<u>Shallow</u>

<8 m (~70% of flow)

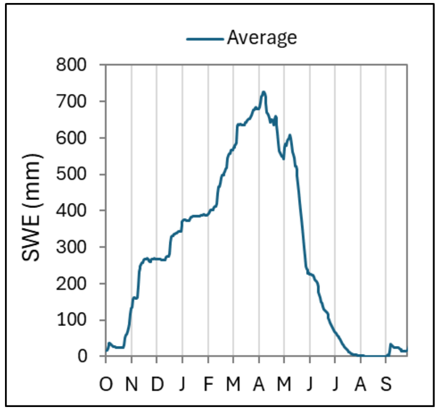
>30 m (8% of flow)

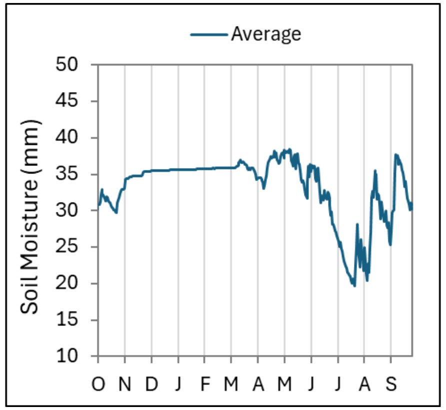
<u>Deep</u>

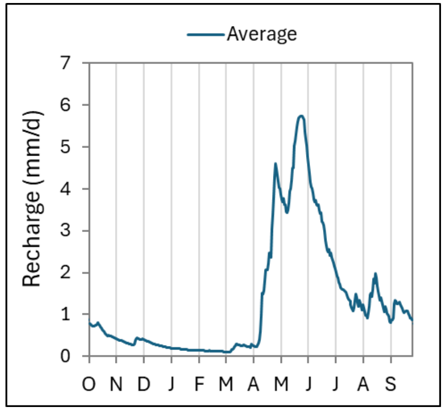
<8 m (13% of flow)

100 m (50% of flow)

Land Surface



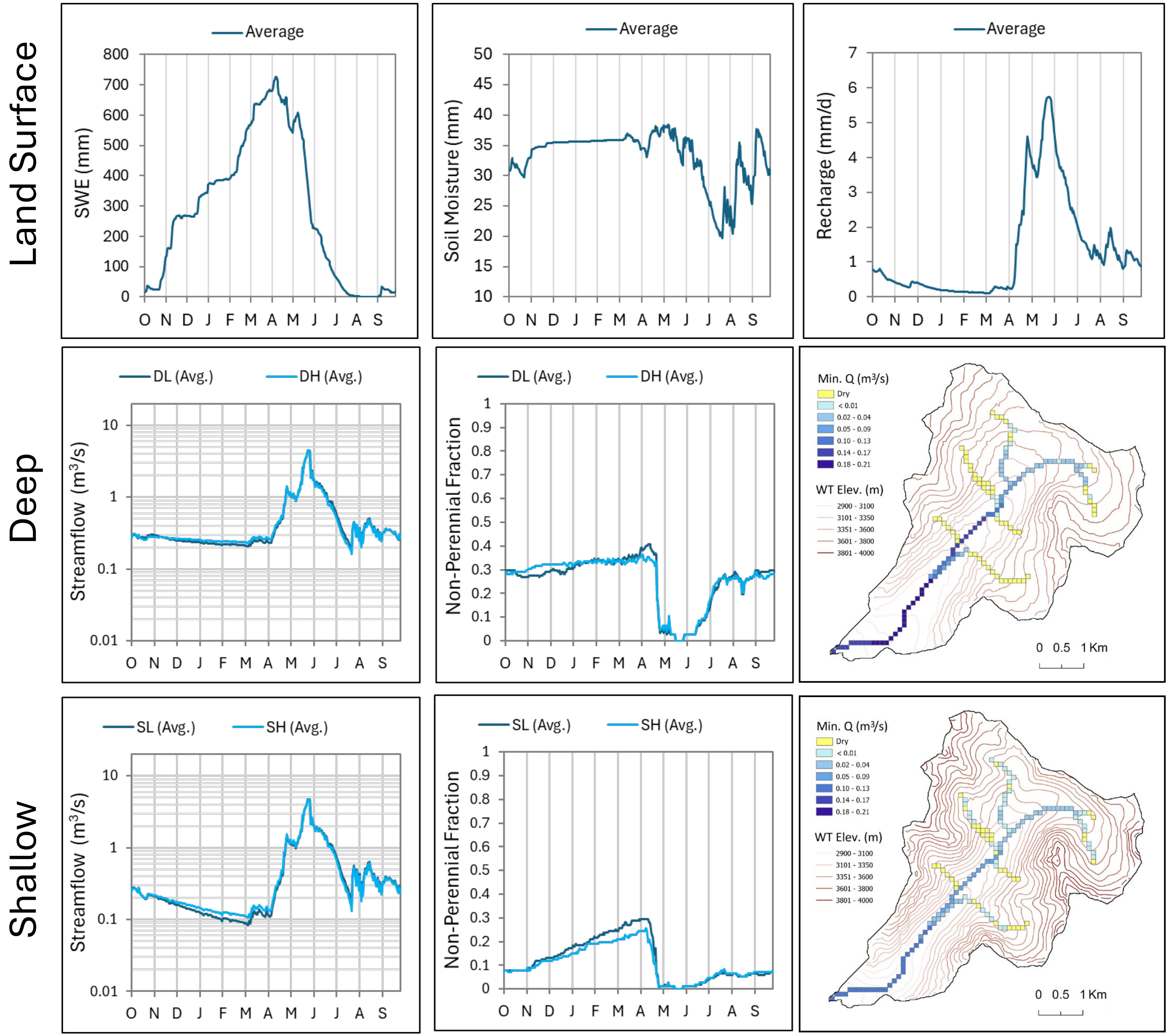




What is the effect of groundwater circulation depth on streamflow generation **avg. climate**

- Average climate conditions based on snotel, PRISM and ASO information

What is the effect of groundwater circulation depth on streamflow generation **avg. climate**



- Average climate conditions based on snotel, PRISM and ASO information
- Peak flows and timing are similar between deep and shallow cases.
- Streamflow response not overtly different based on circulation depth given average climate inputs.
- Porosity (1-3%) is not a first-order control on hydrograph.

DL = deep circulation, 1% porosity
SL = shallow circulation, 1% porosity
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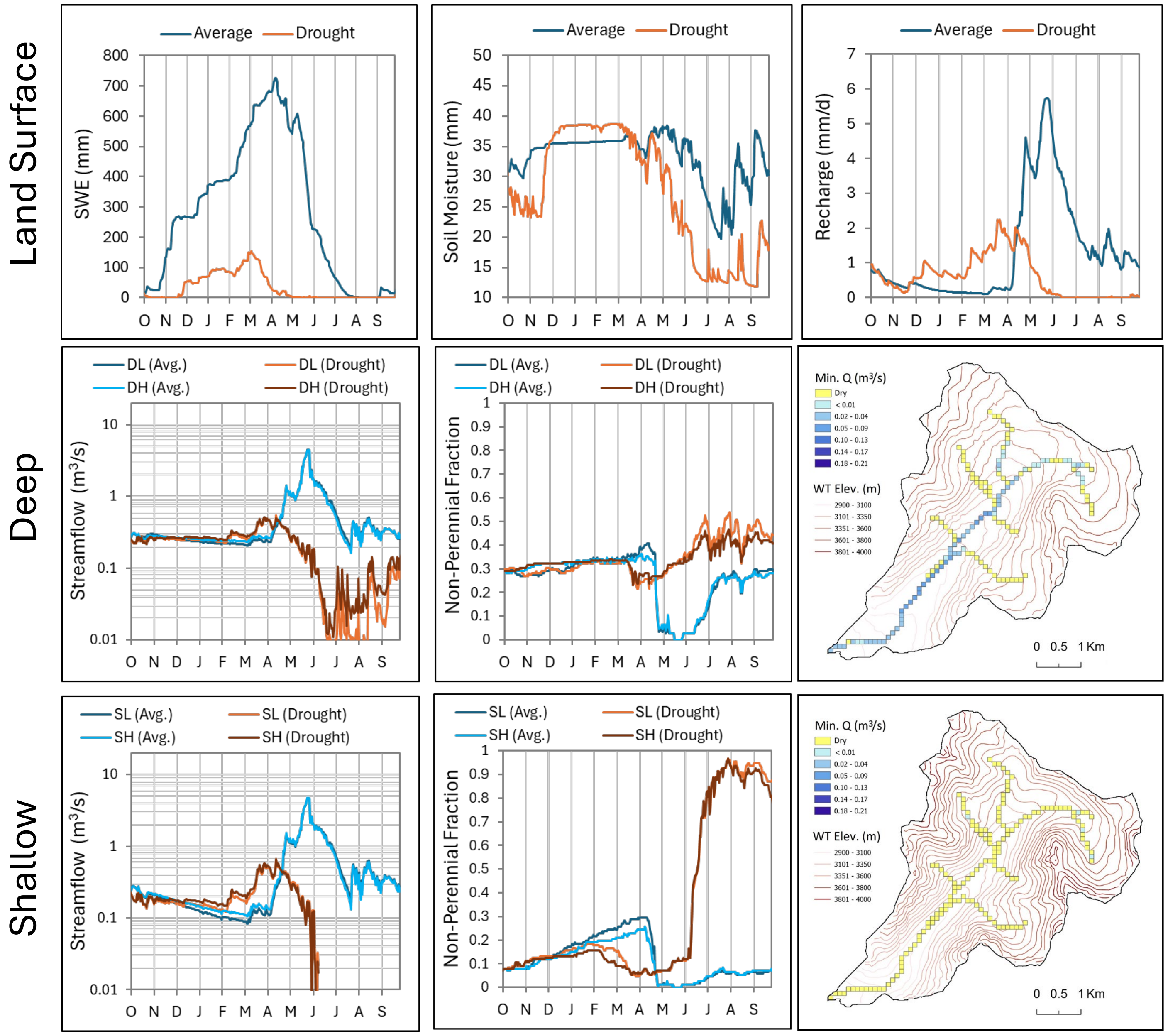
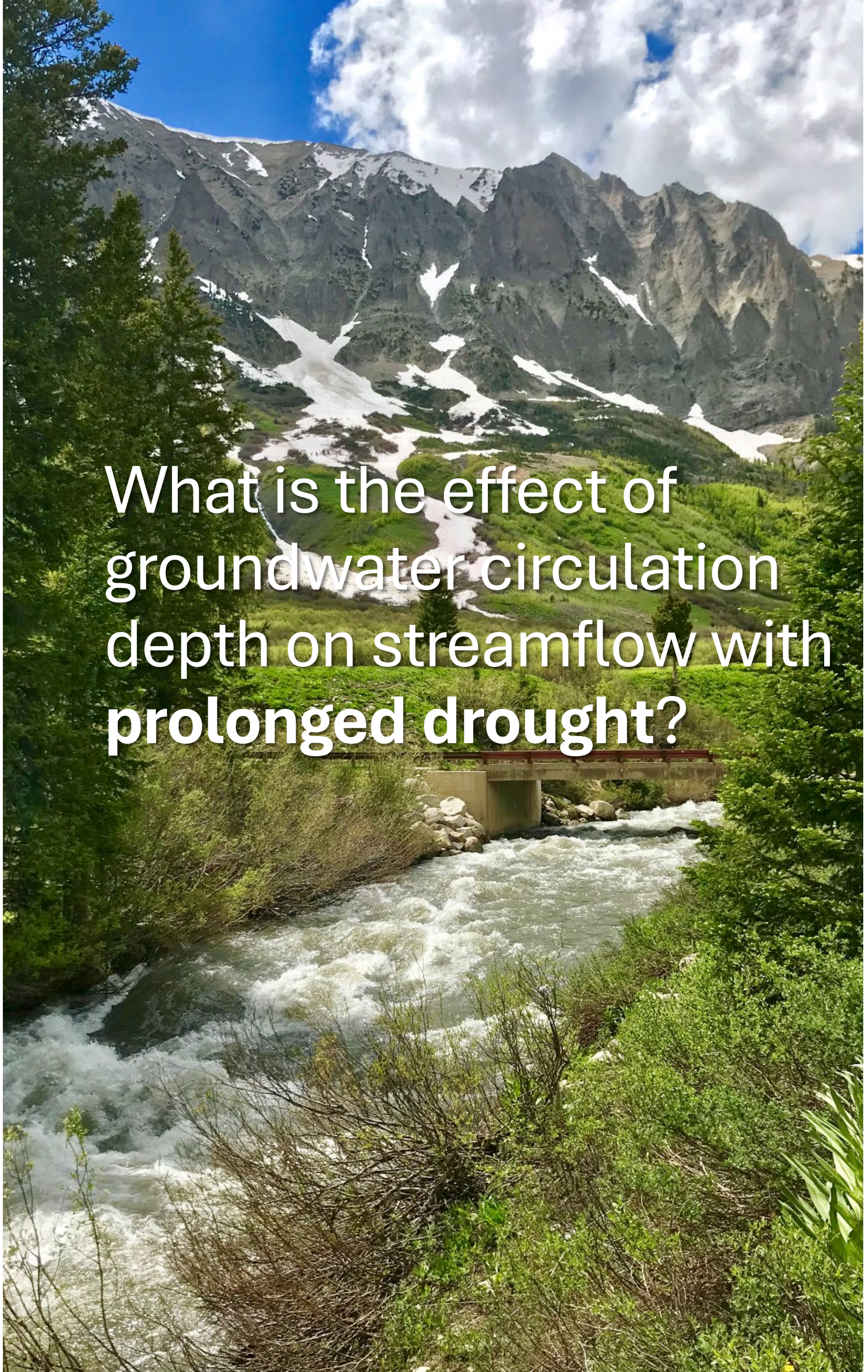
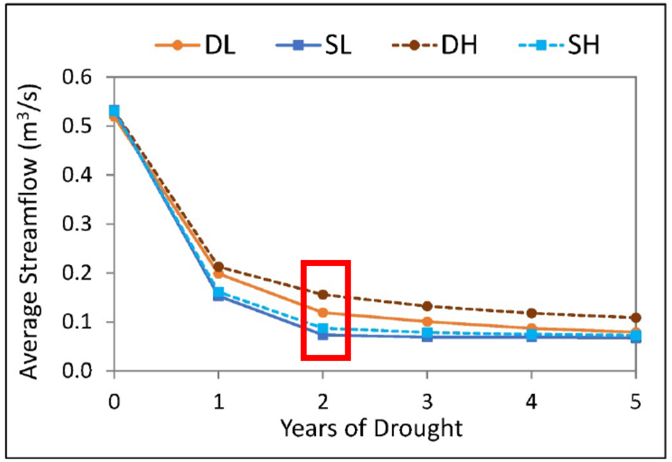


What is the effect of groundwater circulation depth on streamflow generation **with drought**

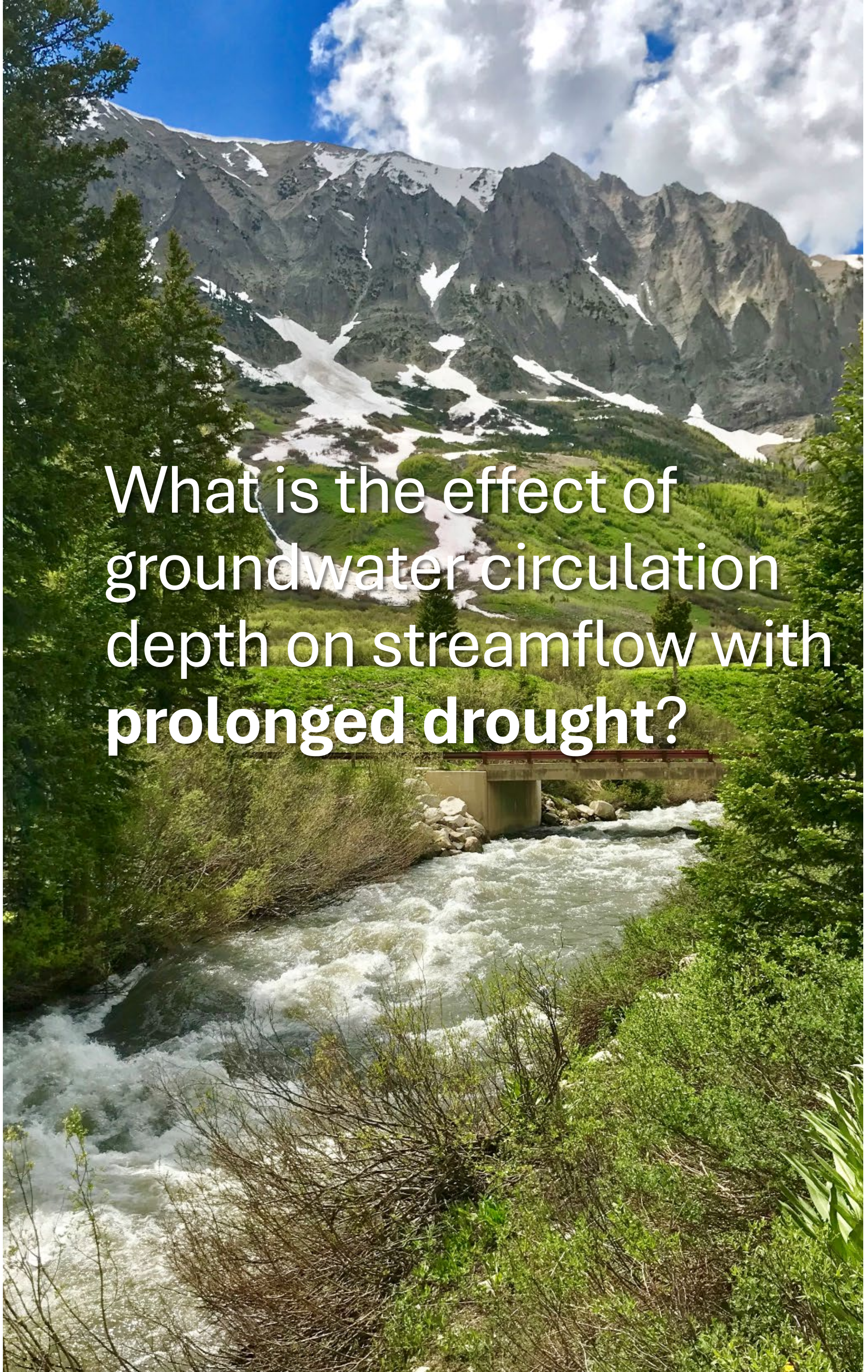
- "Frankenstein" extreme drought (stitch together observed warmest, driest seasonal climate).
- Deep case maintains streamflow along its main stem during drought.
- Shallow case goes dry July.
- Higher porosity buffers drought response more in the deeper case.

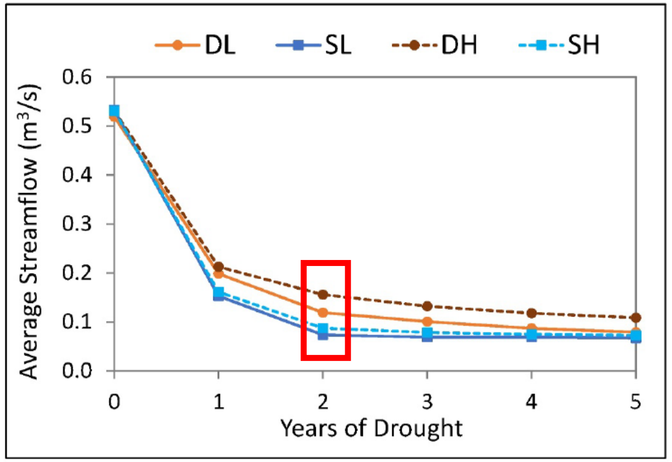
DL = deep circulation, 1% porosity
SL = shallow circulation, 1% porosity
DH = deep circulation, 3% porosity
SH = shallow circulation, 3% porosity





Deep case 60-80% greater than shallow case





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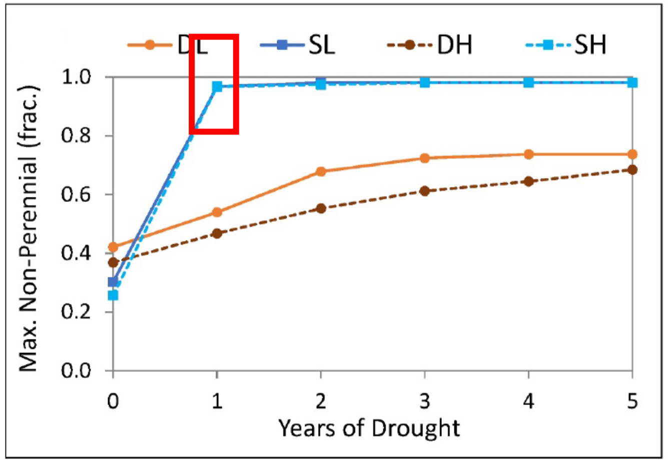
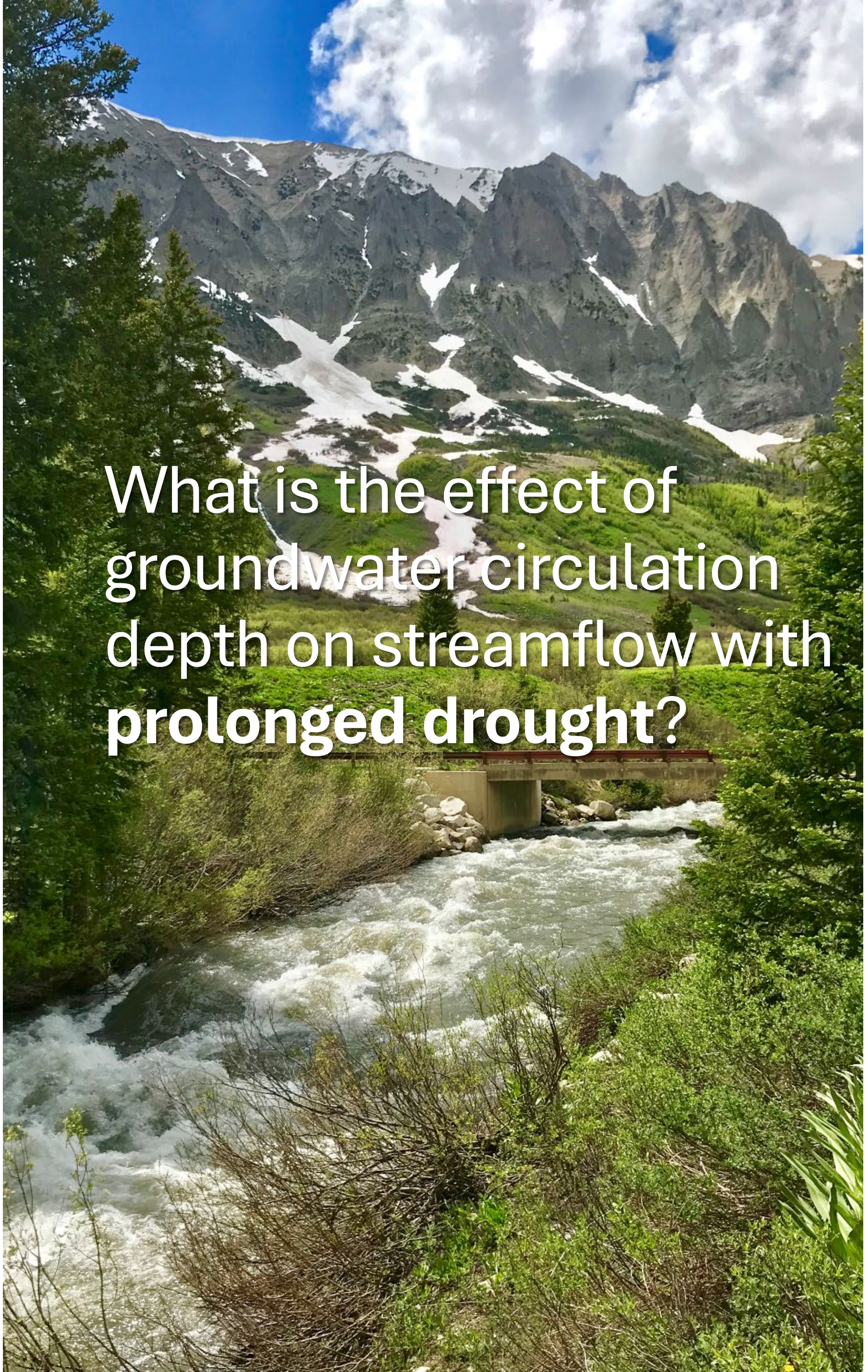
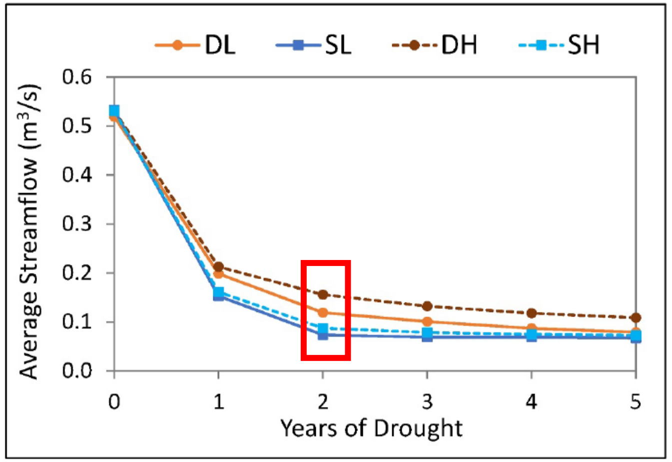


Shallow case is nearly dry after only 1 year of drought. Deep case maintains 40% of reaches with flow.





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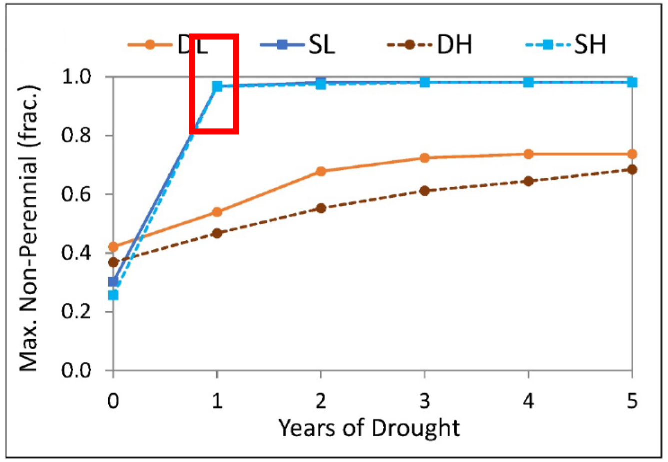

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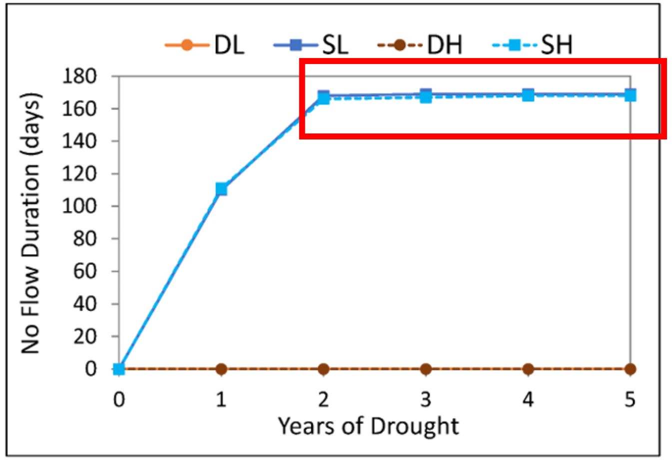


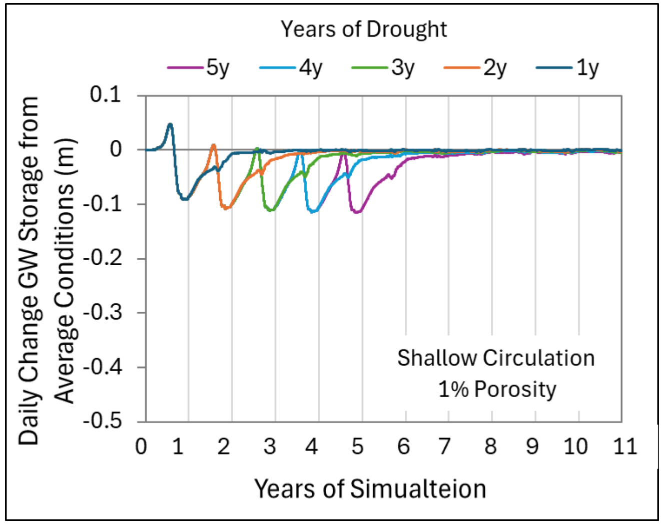
Shallow case is dry for 5.5 months of the year after 2 years of drought.

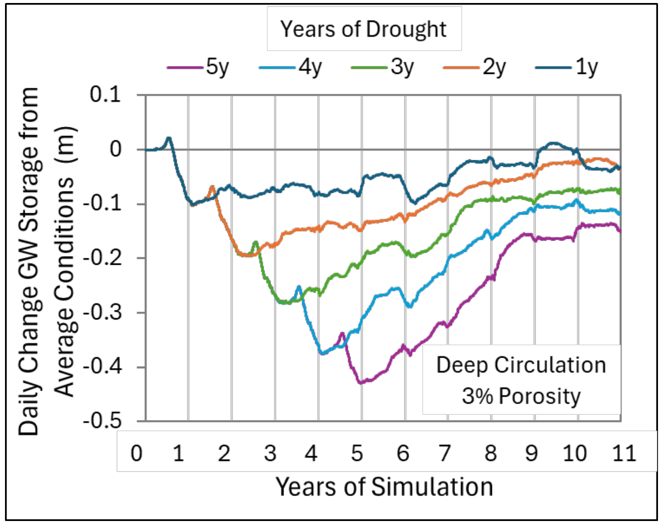
How about groundwater recovery?

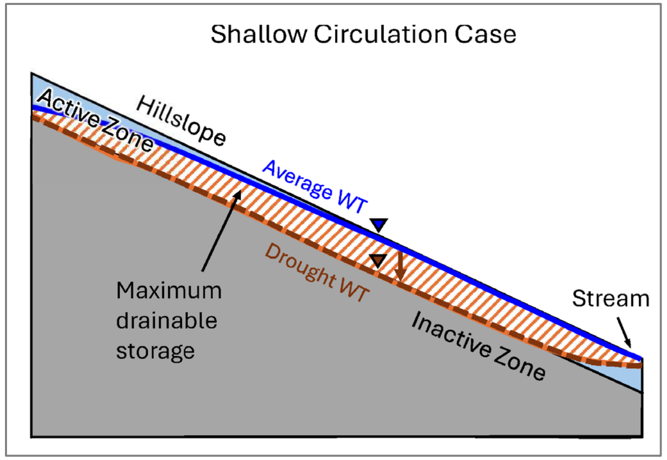
Shallow Circulation

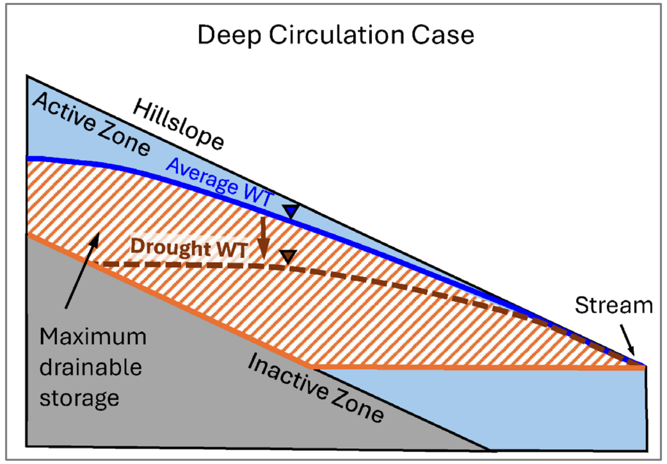
Recovery in <2 years.

High resilience









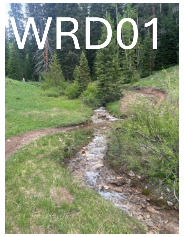
Deep Circulation

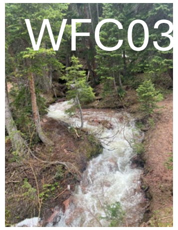
Extensive recovery lasting up to 10 years.

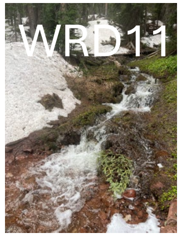
Low resilience

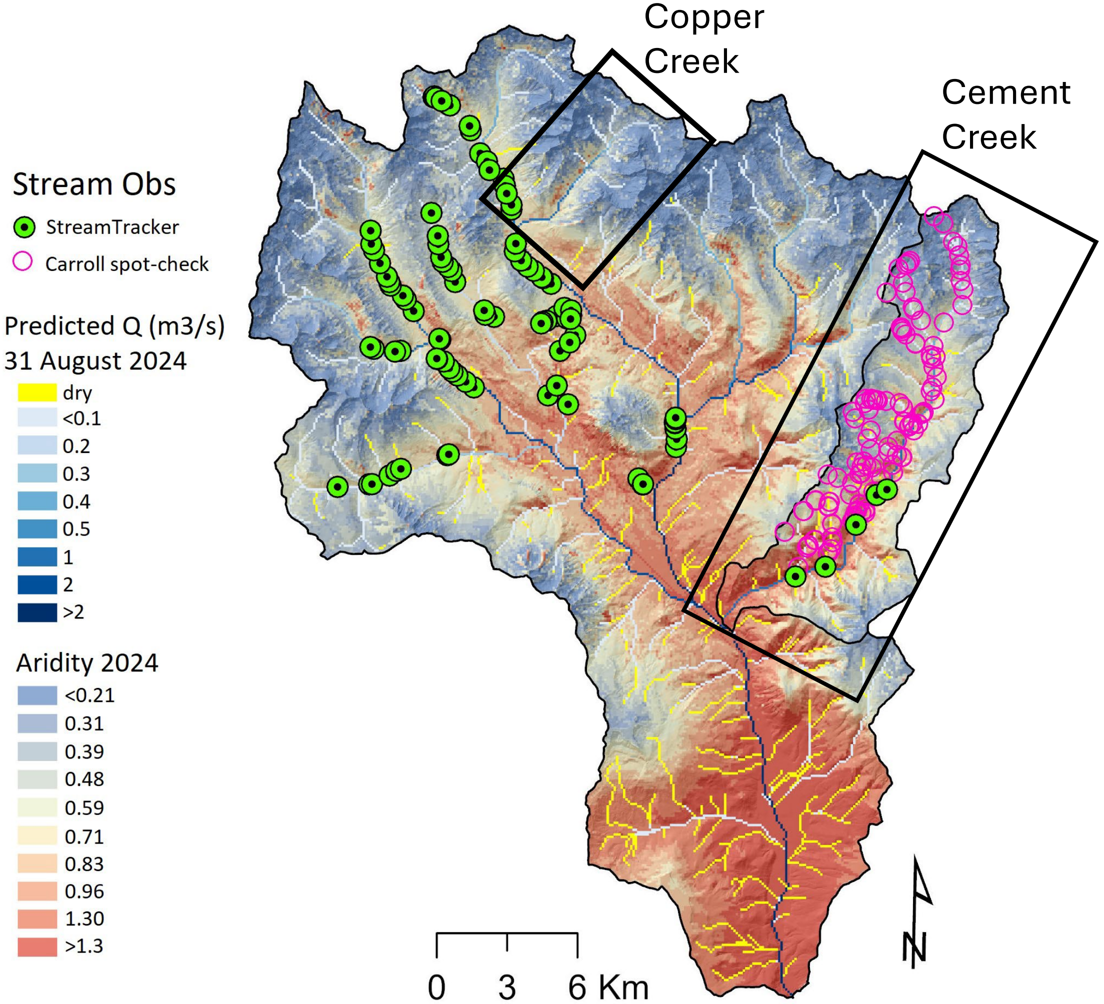
Overlapping disturbance more likely.

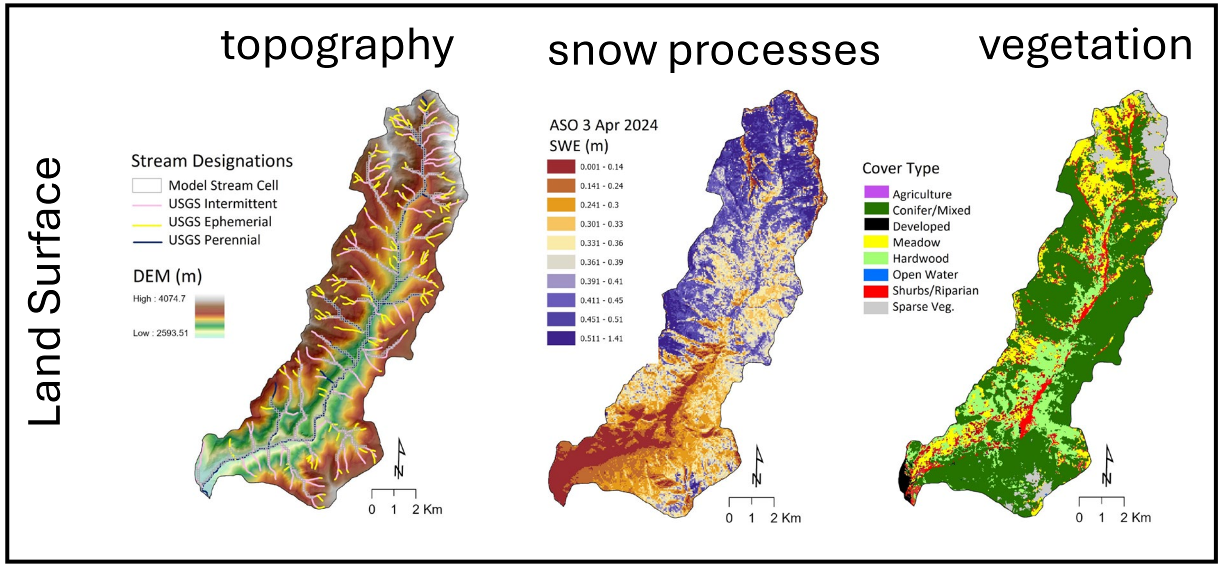
Brief aside: Current work on sensitivity of non-perennial streams to climate and watershed traits

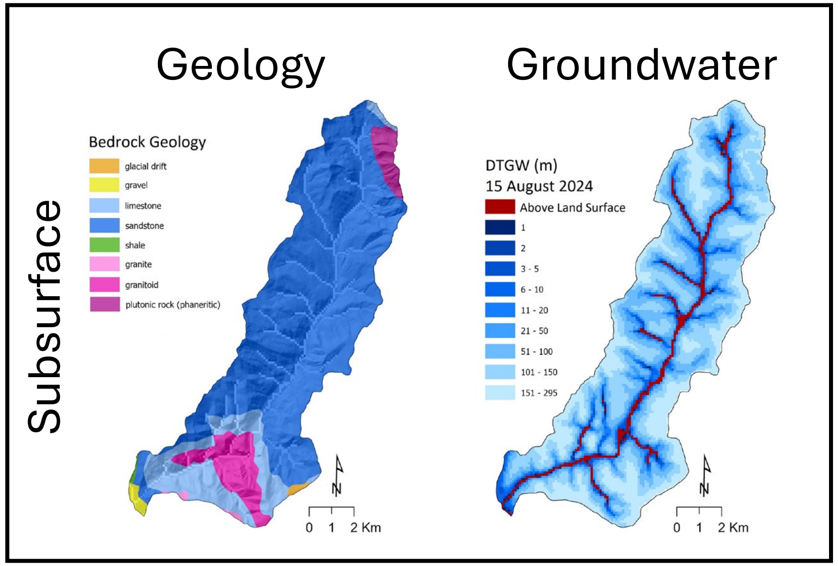












- Cement Creek is an endmember geologically and climatically with exceptional access. Establishing C-Q stations.
- Work with citizen science out of CSU.
- Link in with NEON campaign and ML/remote sensing

Key Points

Groundwater contributions to streamflow are significant and stable water source but do vary in time as a function of groundwater storage.

Key Points

Forest water use in upland catchments drives groundwater storage reductions in a warmer world.

Key Points

Inclusion of groundwater storage deficits are estimated to double streamflow reductions and push the East River toward dry conditions during low precipitation years.

Key Points

Groundwater circulation depth is a fundamental control on streamflow response to drought and groundwater recovery time.

Thank you!

BERKELEY LAB
Lawrence Berkeley National Laboratory
Watershed Function Science Focus Area
U.S. DEPARTMENT OF ENERGY
USGS
science for a changing world
Rocky Mountain Biological Laboratory
Science at the Top

Rosemary WH Carroll | IDEAS | June 10, 2025

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