How does subsurface water holding capacity mediate catchment response to rainfall variability?

David Dralle

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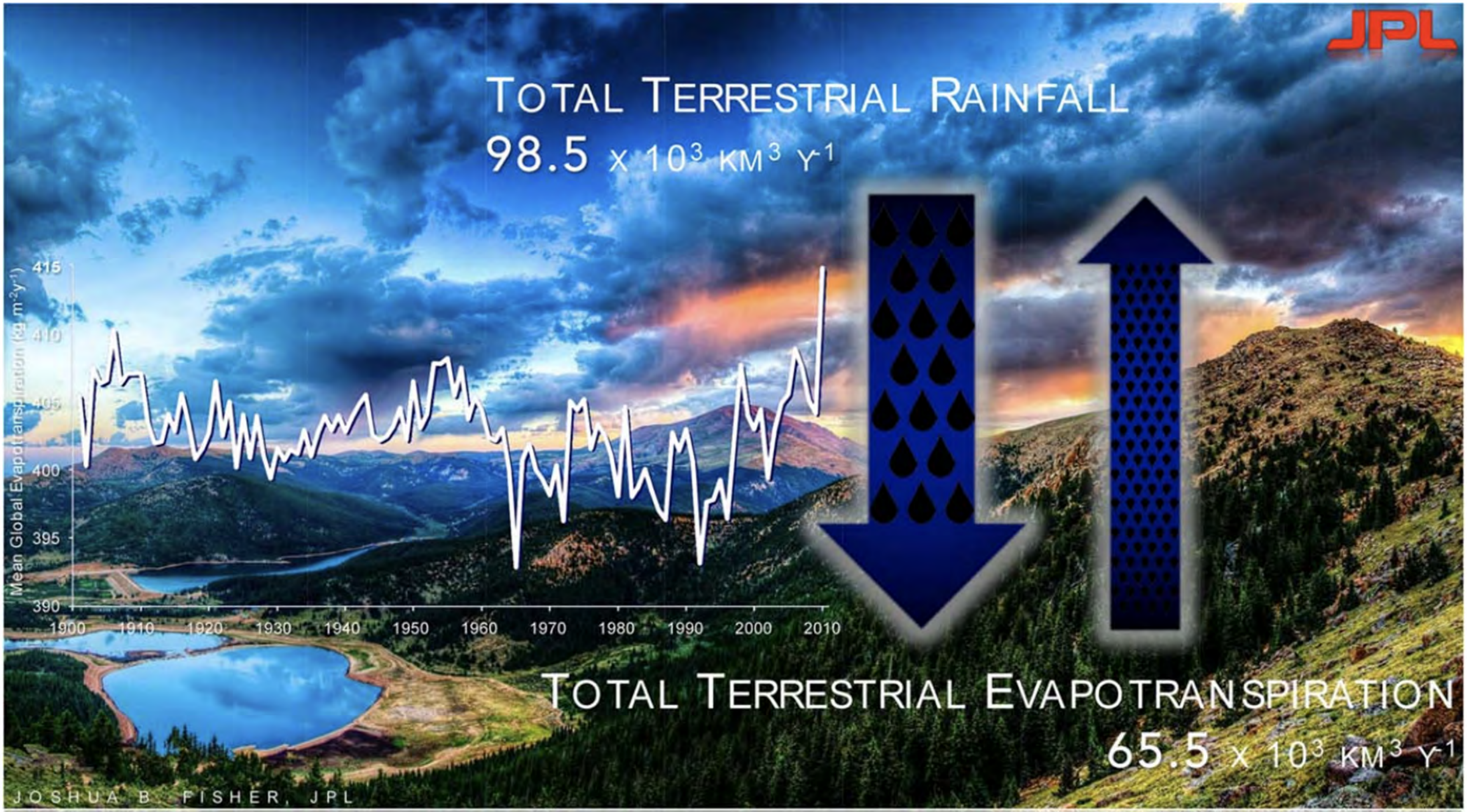
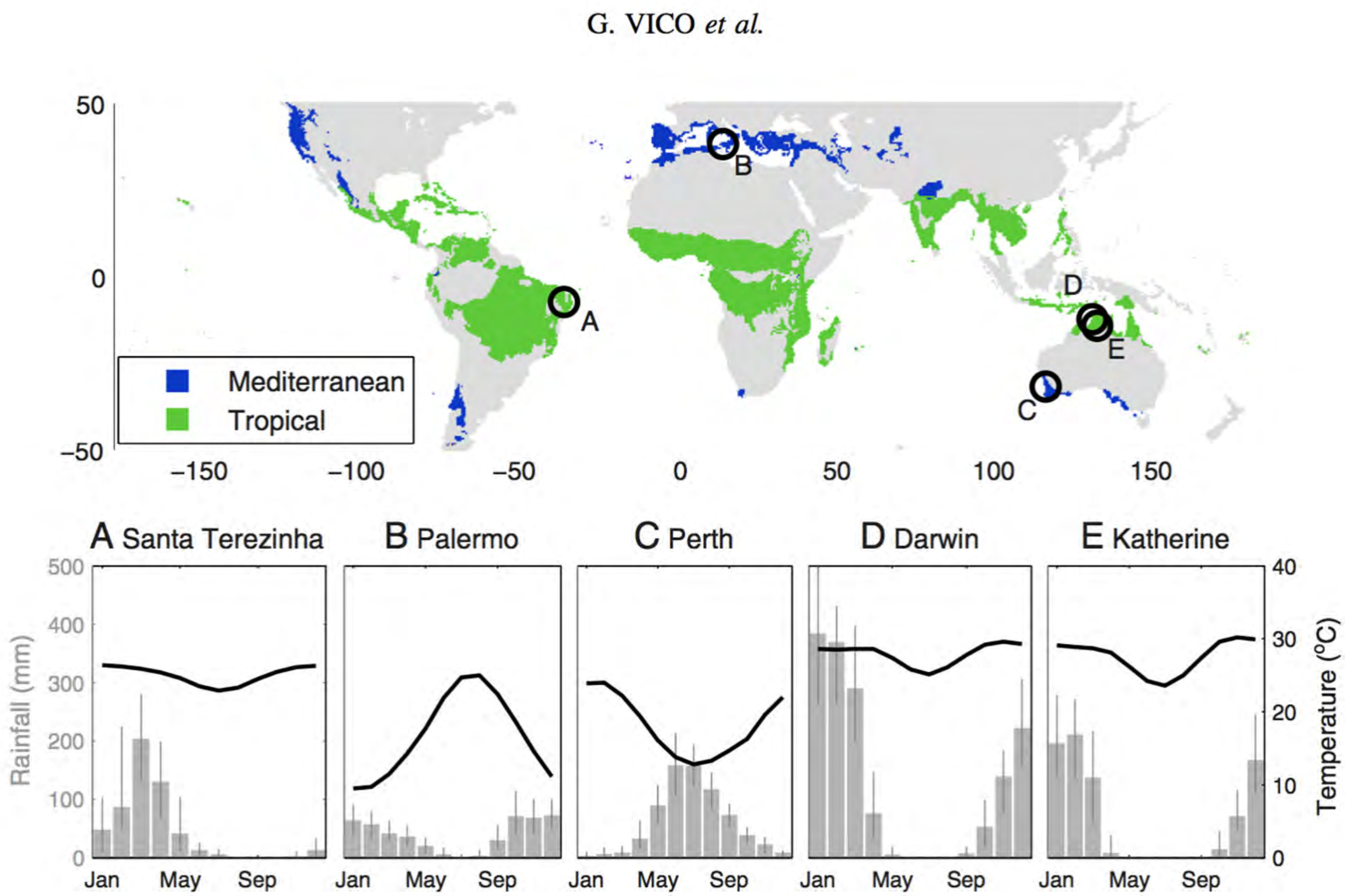
CZO | EEL RIVER
CRITICAL ZONE OBSERVATORY



Fisher, J. B., et al. (2017), The future of evapotranspiration…, WRR

Climate/earth system models struggle in seasonally dry climates

Hickler et al, 2006

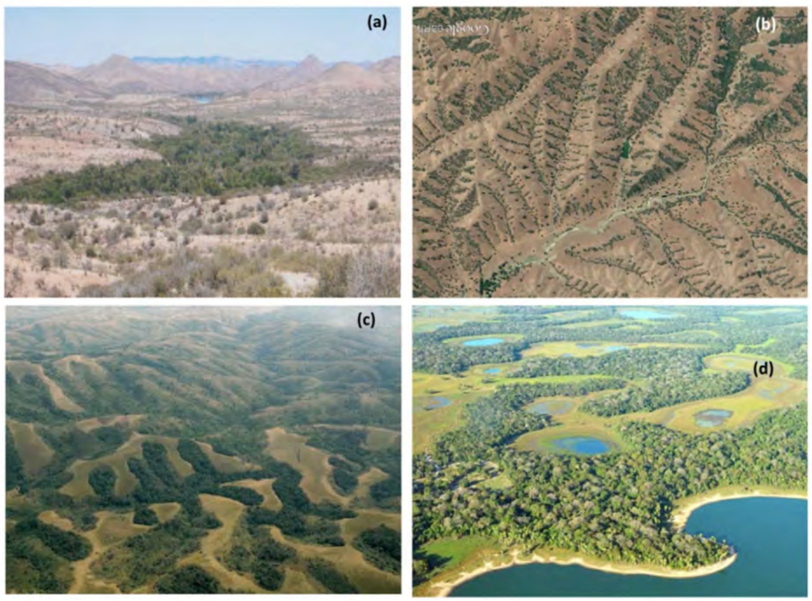


"…tree roots may access water from deeper layers…

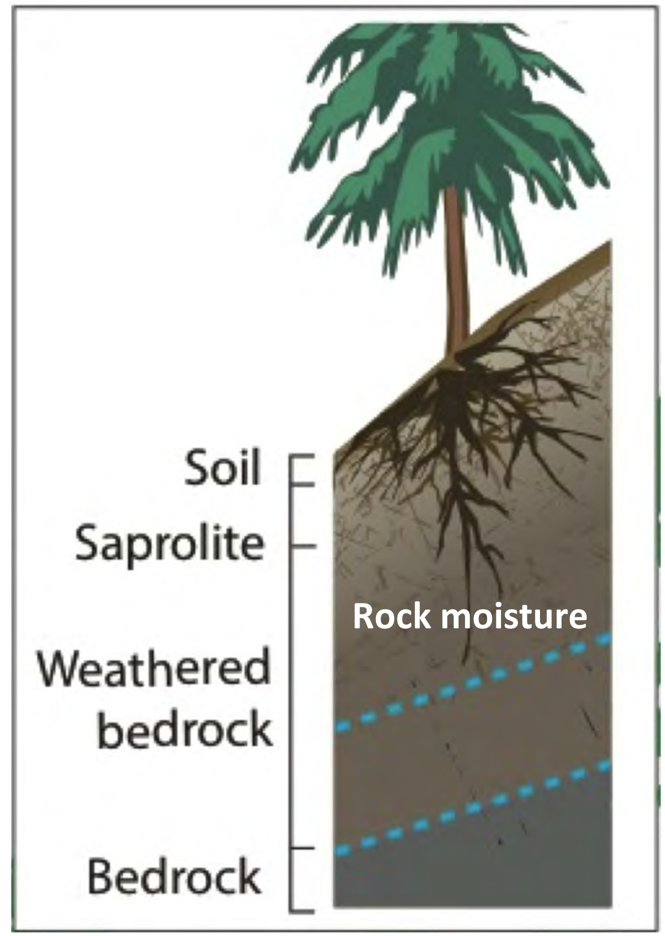
…this property is not captured by the model's simple soil water regime."

Morales et al, 2005

The role of the subsurface

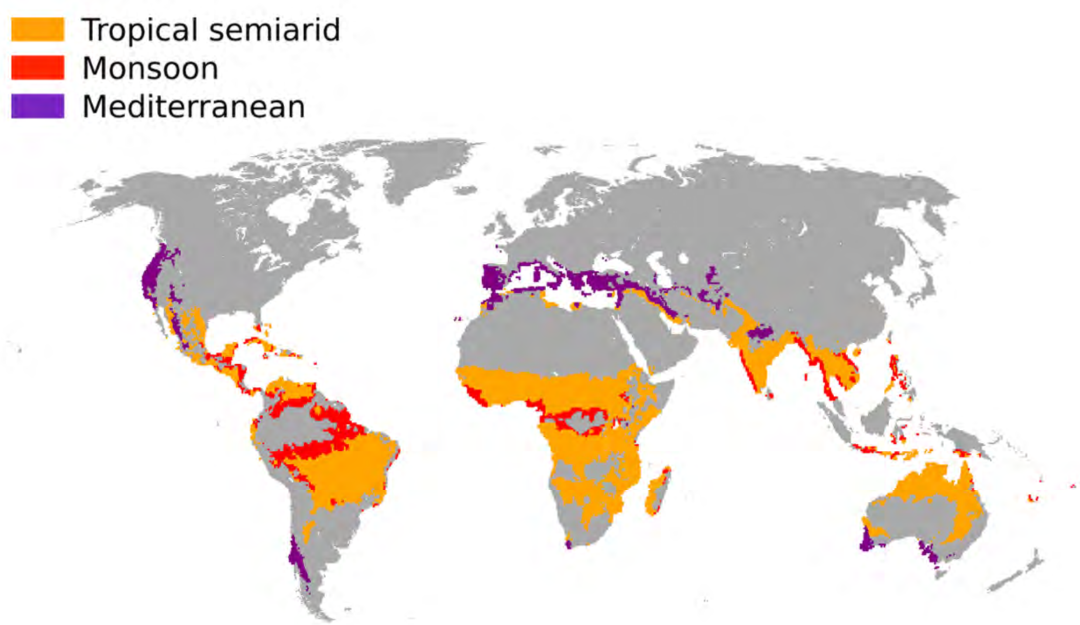


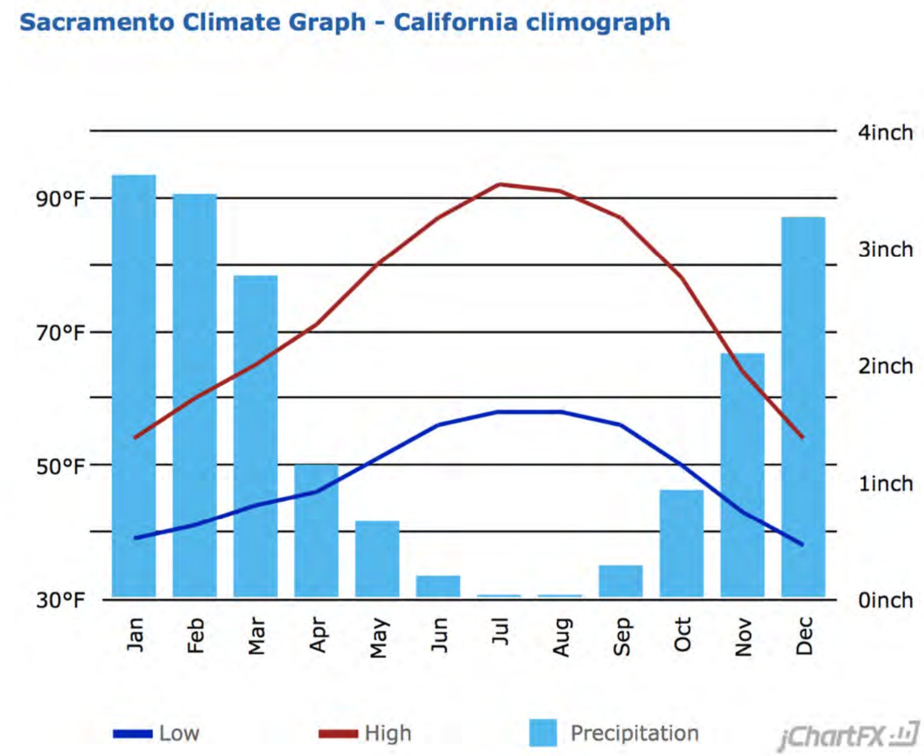
Fan et al (2019) Hillslope Hydrology in Global Change Research and Earth System Modeling, WRR



Rempe and Dietrich, 2018

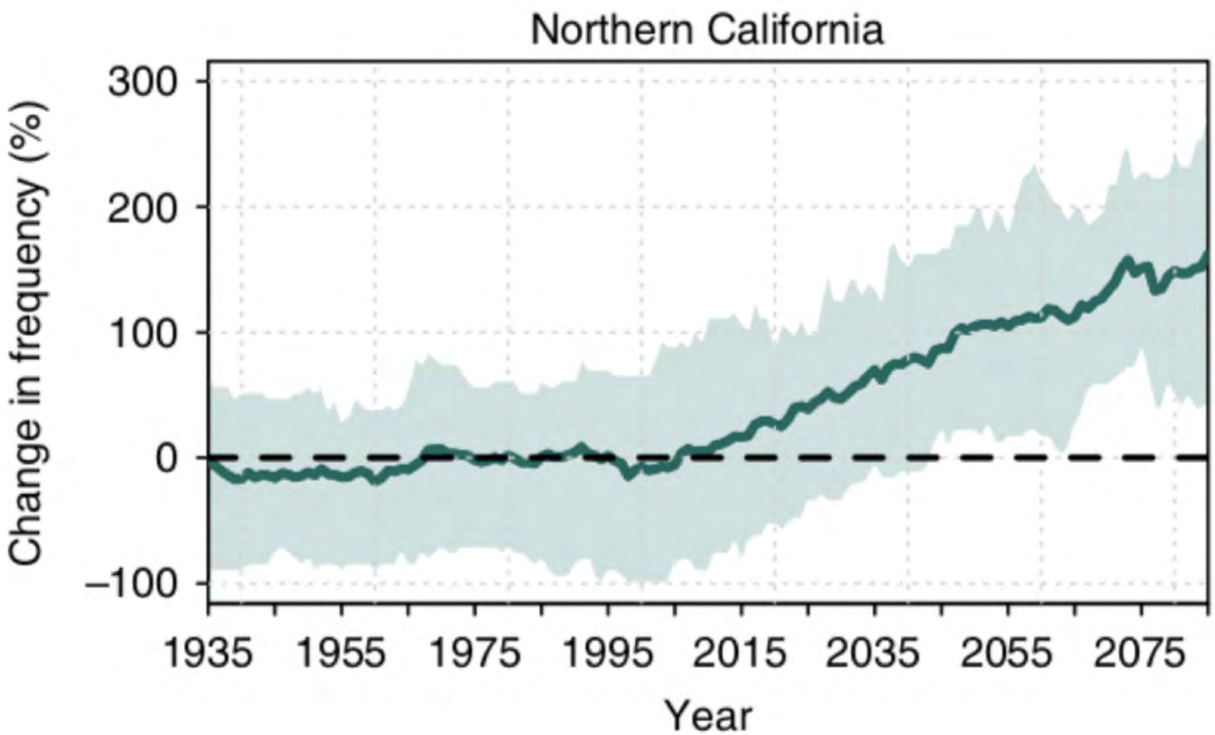
Mediterranean watersheds are storage-dominated systems





Climate models predict a more volatile California

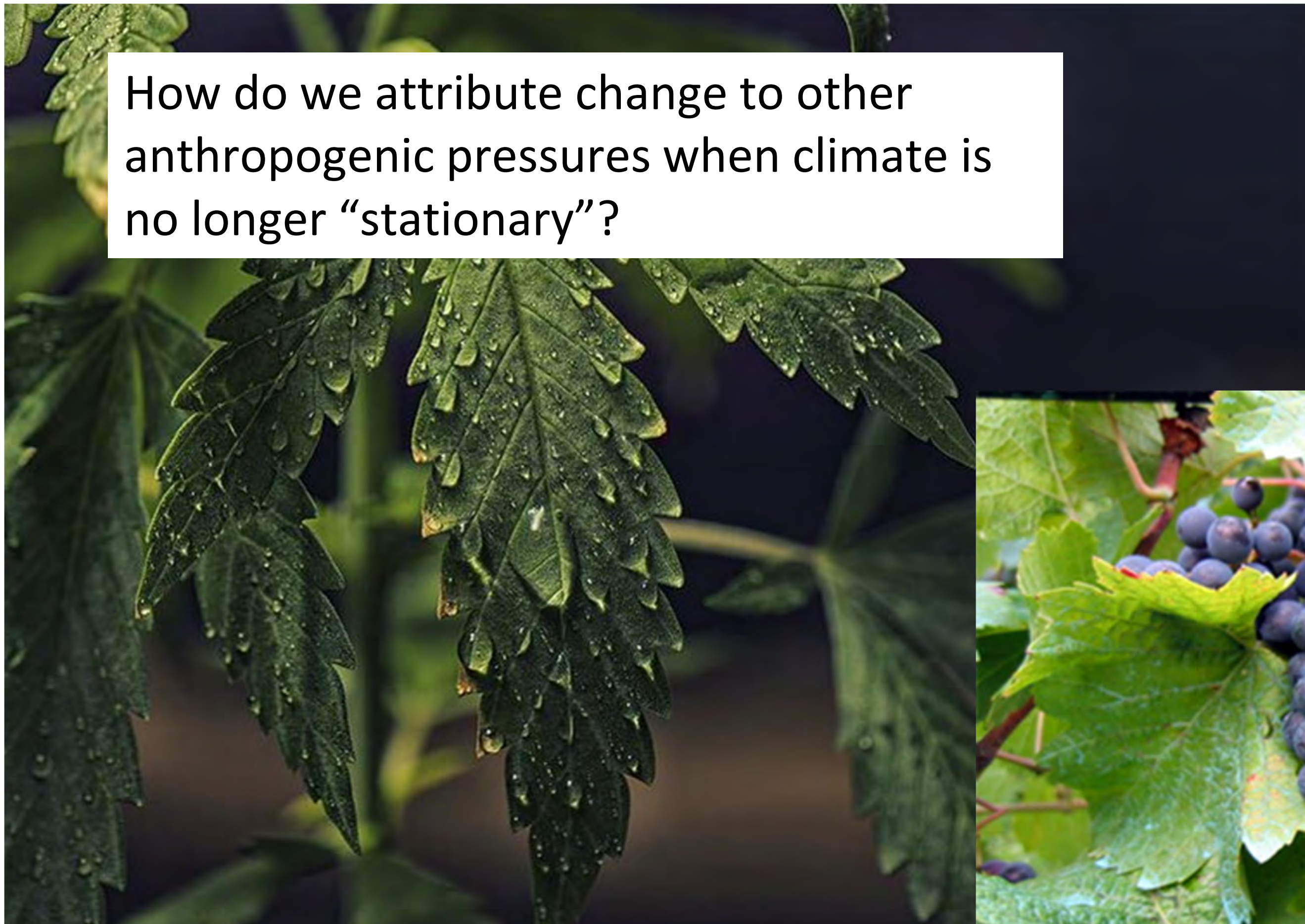
Extremely-wet wet season frequency



Swain et al, 2018, Nature Climate Change

Implications of increased hydroclimatic volatility for baseflows?

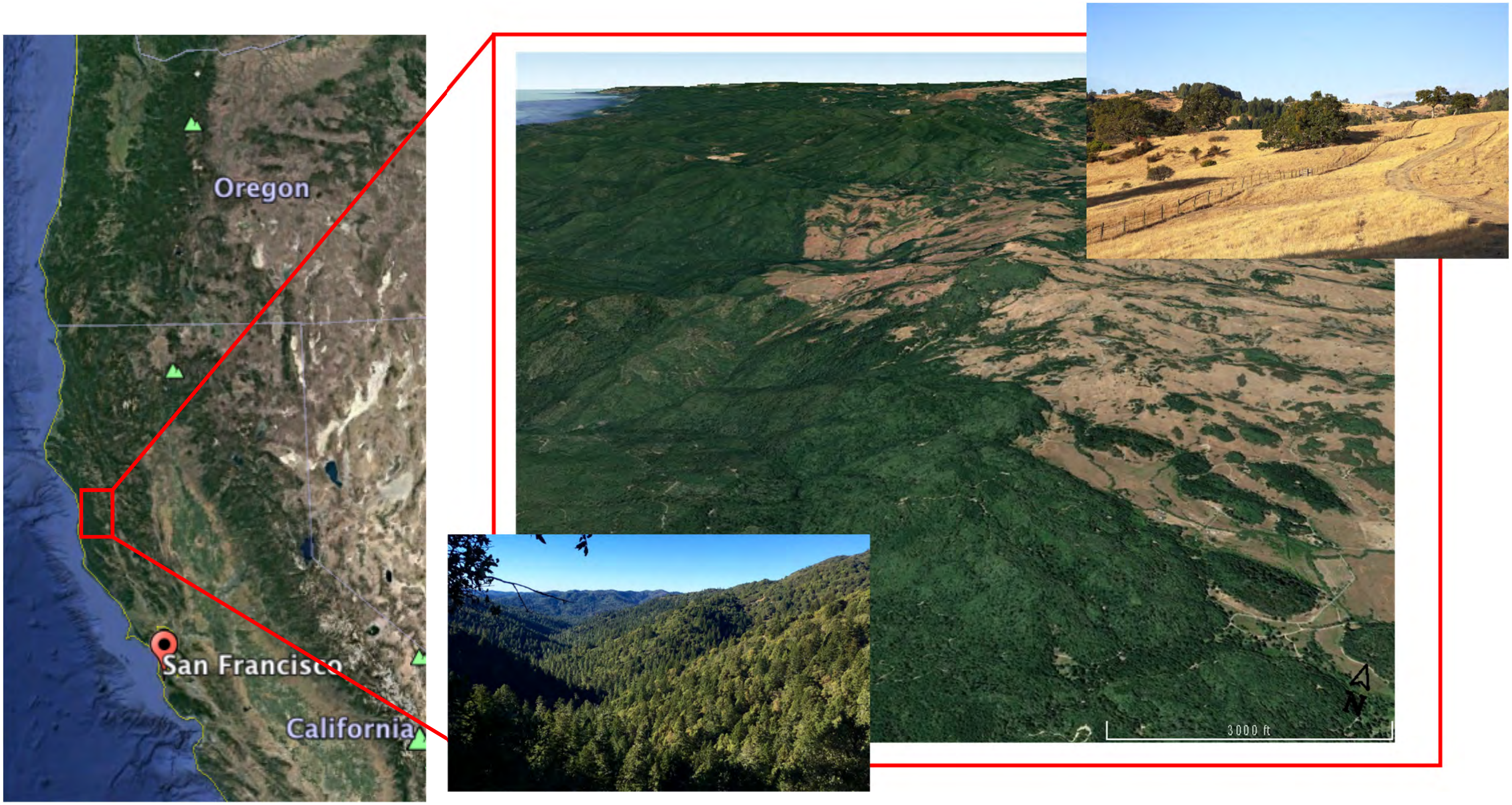
How do we attribute change to other anthropogenic pressures when climate is no longer "stationary"?

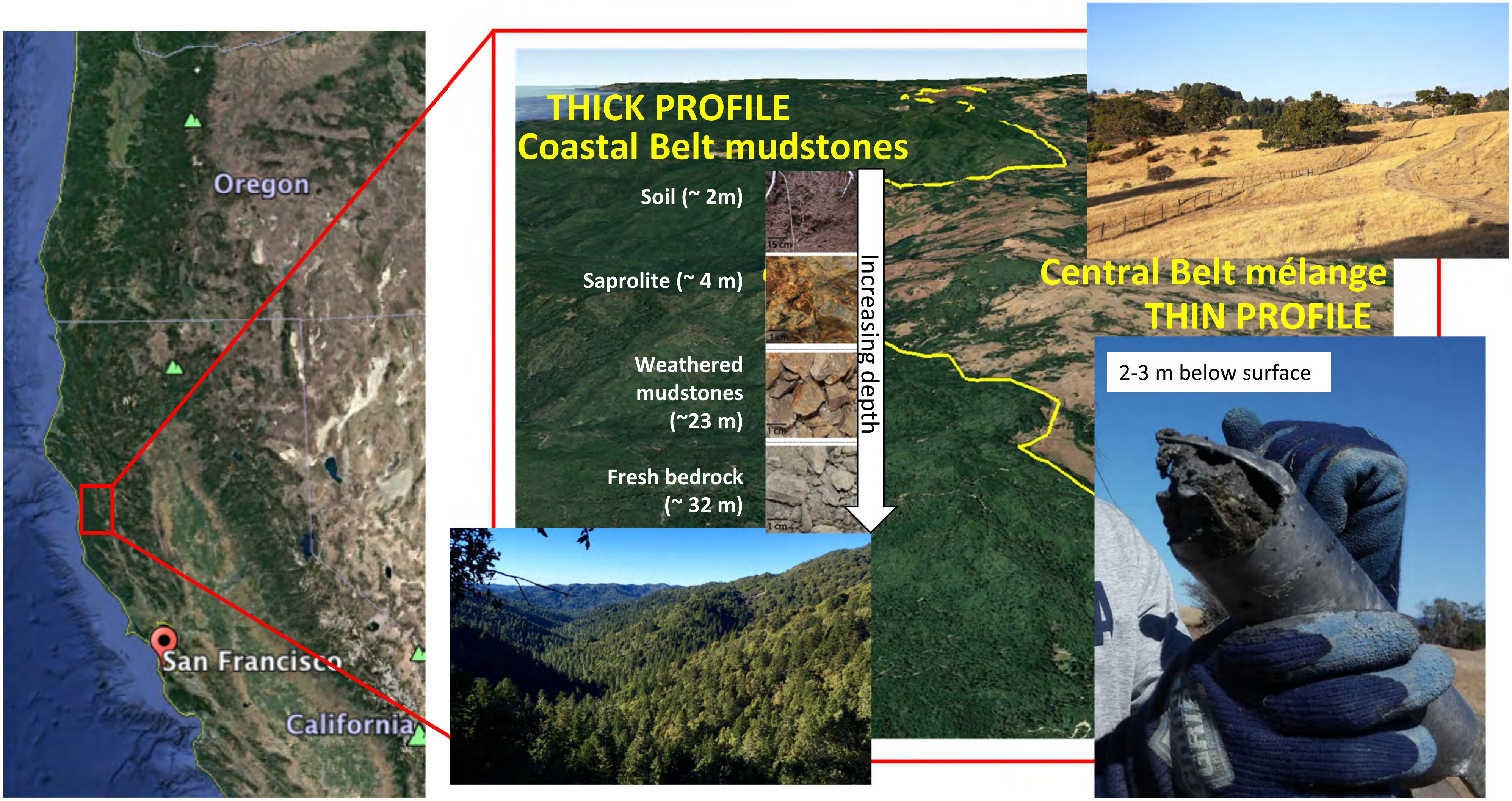


Water storage capacity in the critical zone

Today's outline:

- Rock type, storage capacity, and biogeography
- How does storage capacity mediate plant response to rainfall variability?
- How does storage capacity mediate streamflow response to rainfall variability?

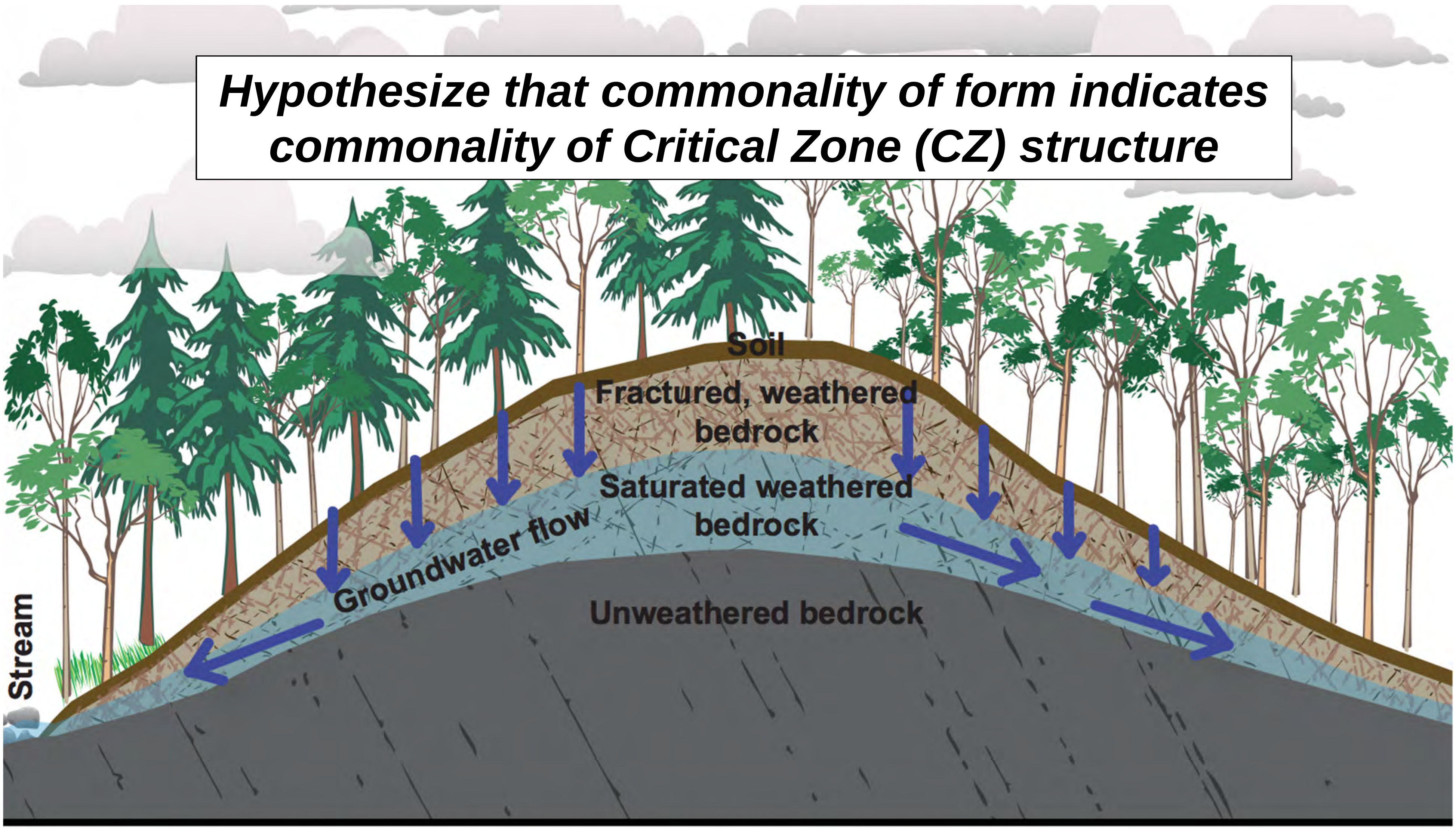

Oregon
San Francisco
California
3000 ft
N



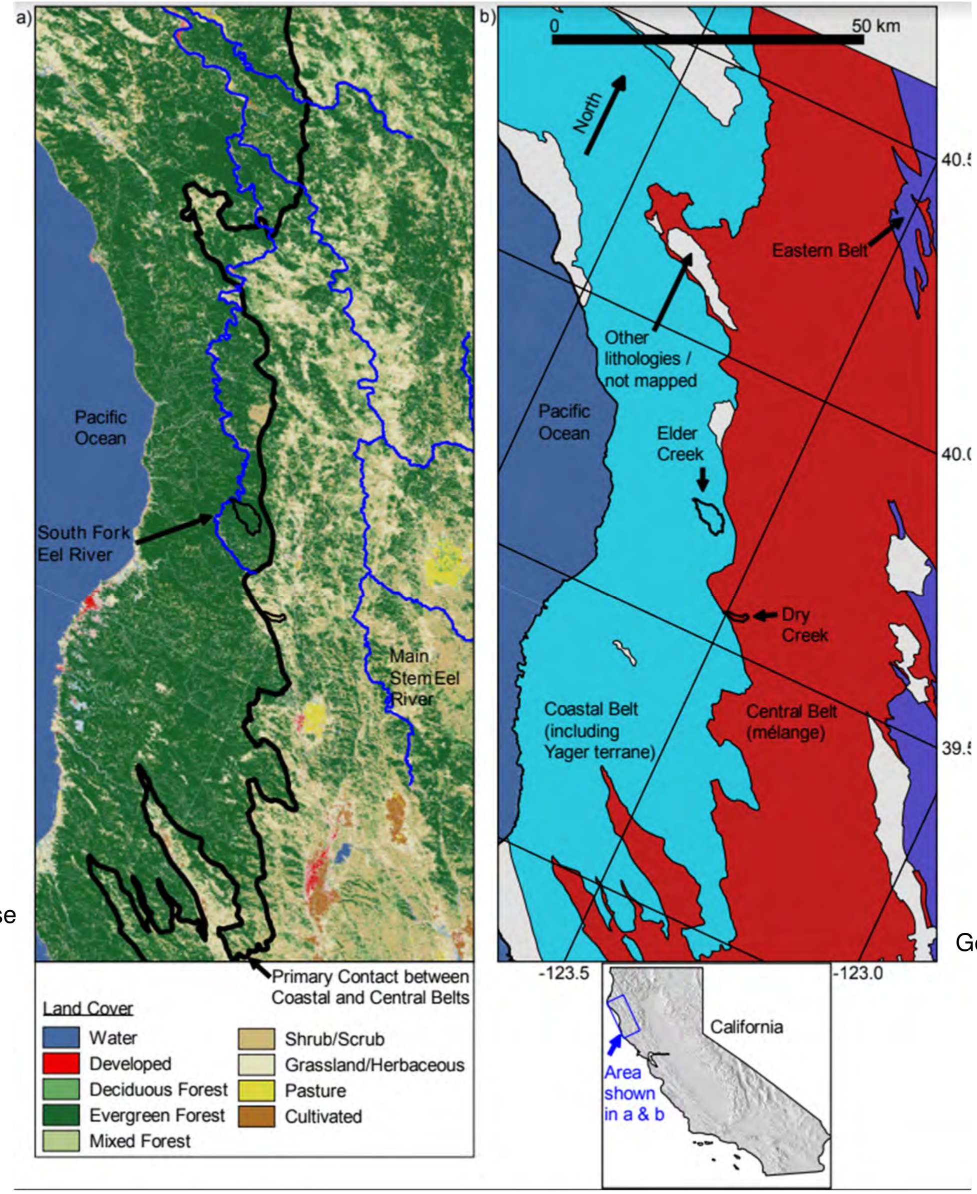
Hahm, Rempe, Dralle, et al, ***Water Resources Research,*** 2019


‘unit hillslope’ approach

Hypothesize that commonality of form indicates commonality of Critical Zone (CZ) structure



Conceptual diagram modified from original by Daniella Rempe

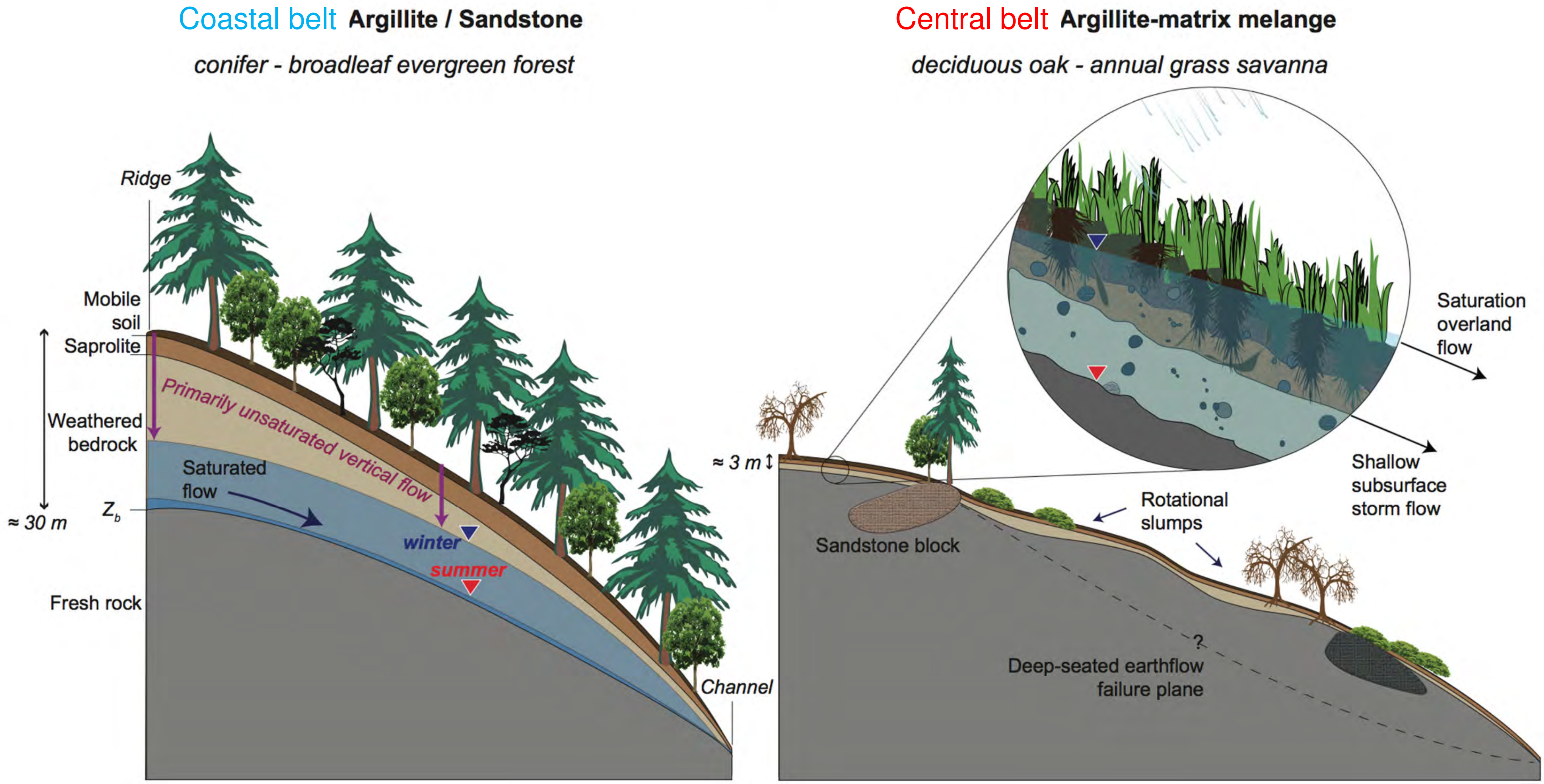


National Land Cover Database data

Geology from Langenheim et al., 2013

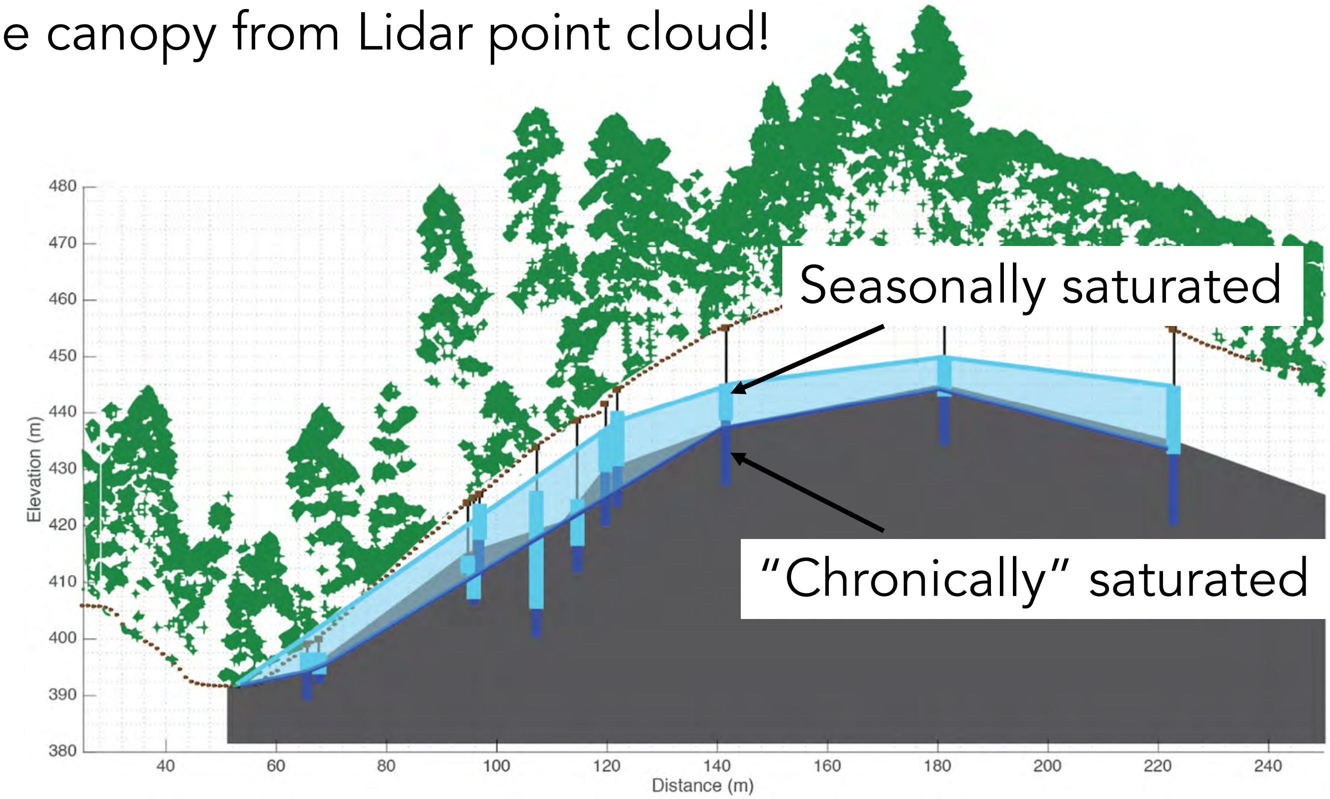
Hahm et al., 2019***, WRR.***

Critical Zone Structure and Runoff Generation in the Franciscan Formation



Hahm, Rempe, Dralle, et al, ***Water Resources Research,*** 2019

Actual tree canopy from Lidar point cloud!



Daniella Rempe figure, NCALM Lidar

Coastal Belt critical zone, showing seasonal hillslope groundwater table at the base of a thick, weathered rock profile

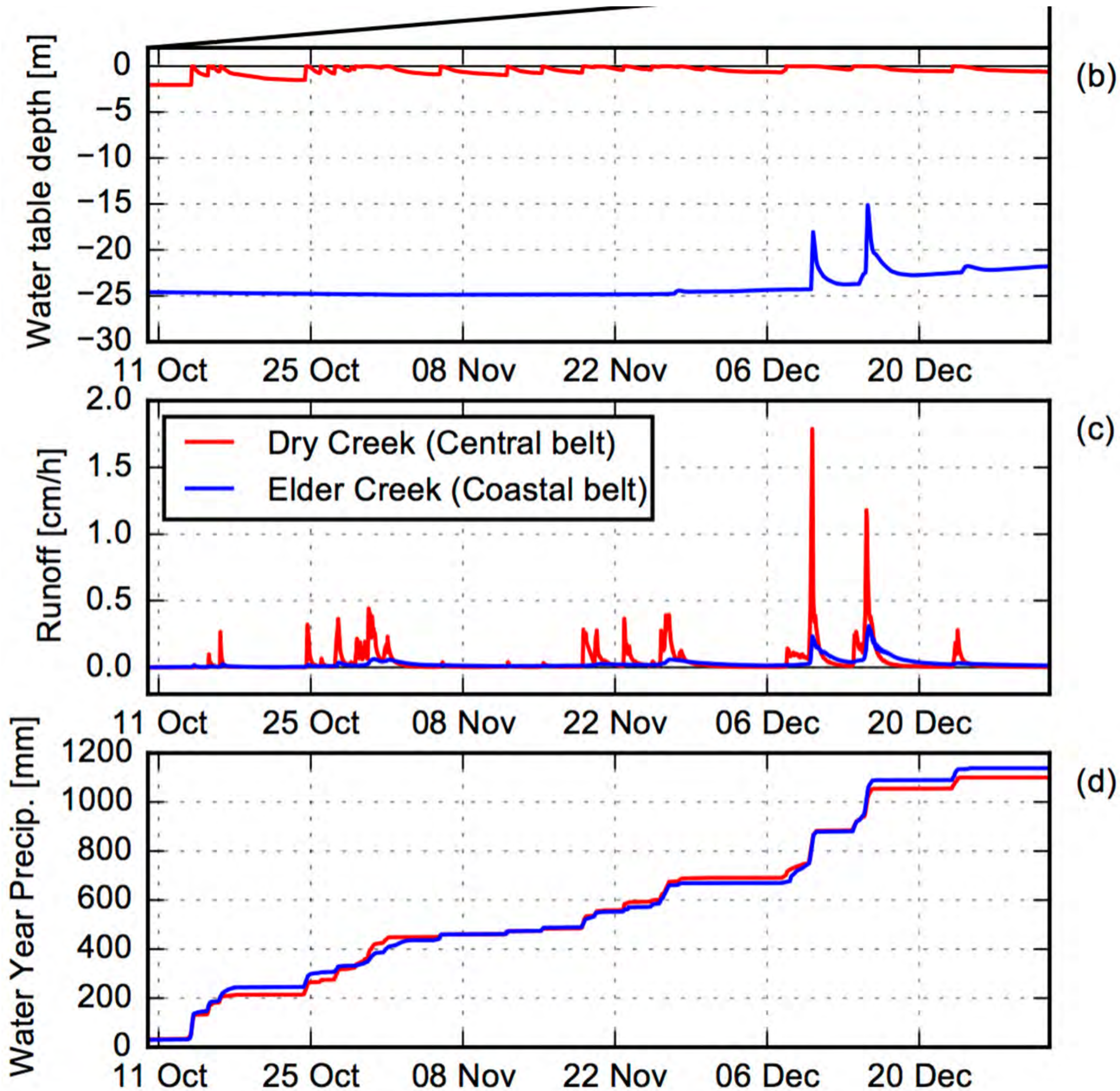
Central Belt critical zone completely saturated in winter, even at topographic ridges

Groundwater

Runoff

Total rainfall

Hahm et al., 2019*, **WRR.***

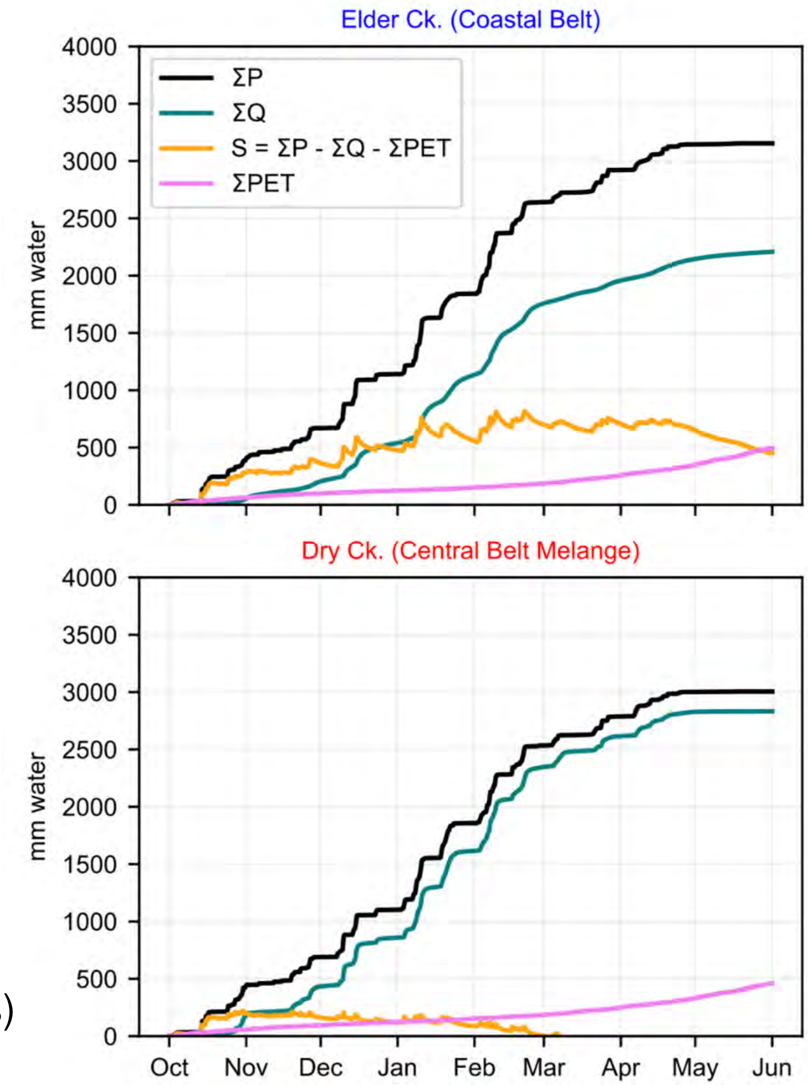


Consistent with catchment-wide storage dynamics

Δ storage (S) = inputs – outputs =
+ precipitation (P)
– runoff (Q)
– evapotranspiration (PET)

Shown: 2017 water year

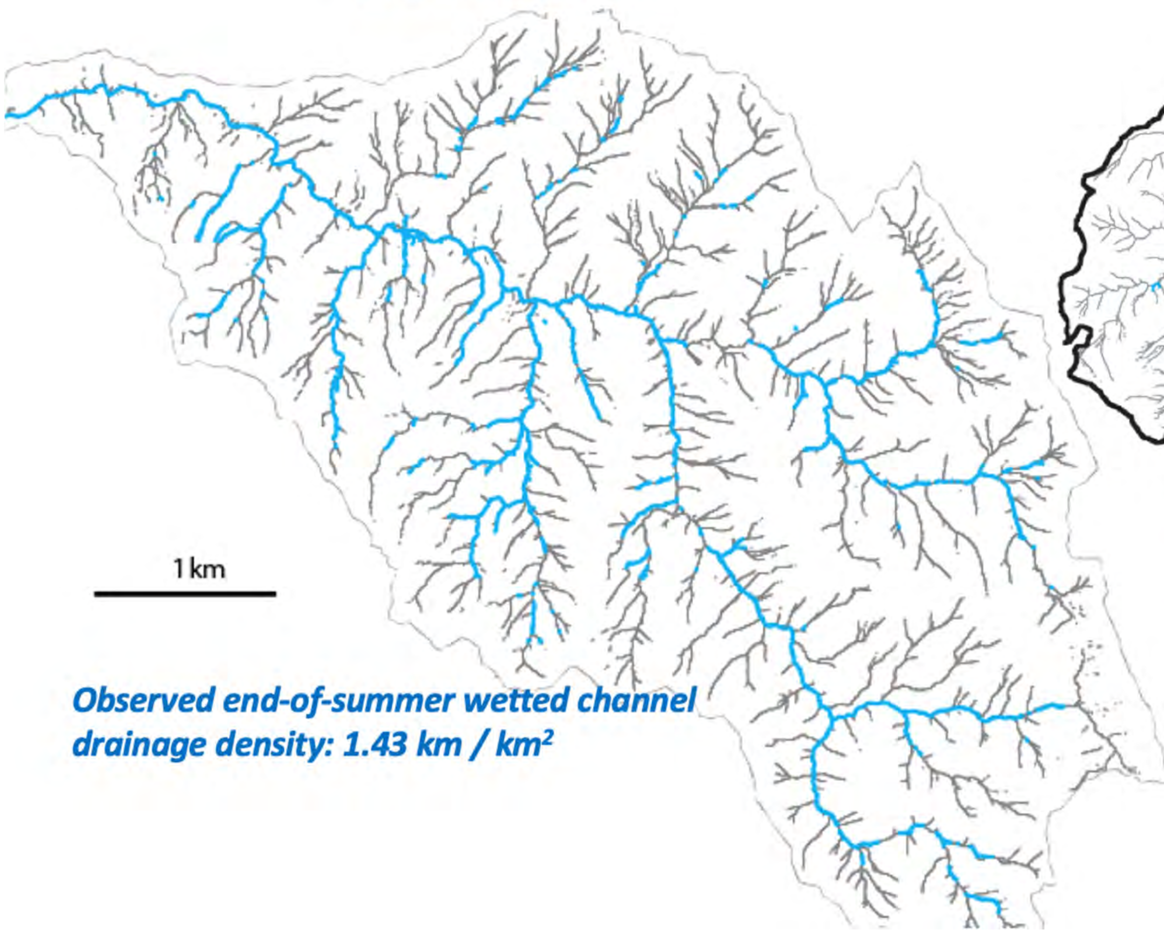
Dralle, Hahm Rempe, et al., 2018 (Hydrol. Processes)



PET inferred from Hargreaves method

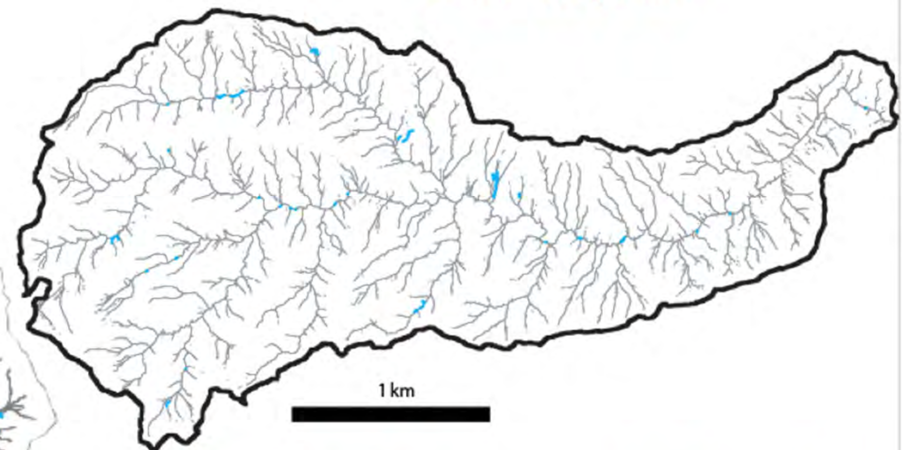
wetted channel dynamics

Coastal belt, 17 km²



Observed end-of-summer wetted channel drainage density: 1.43 km / km²

Central belt, 6 km²



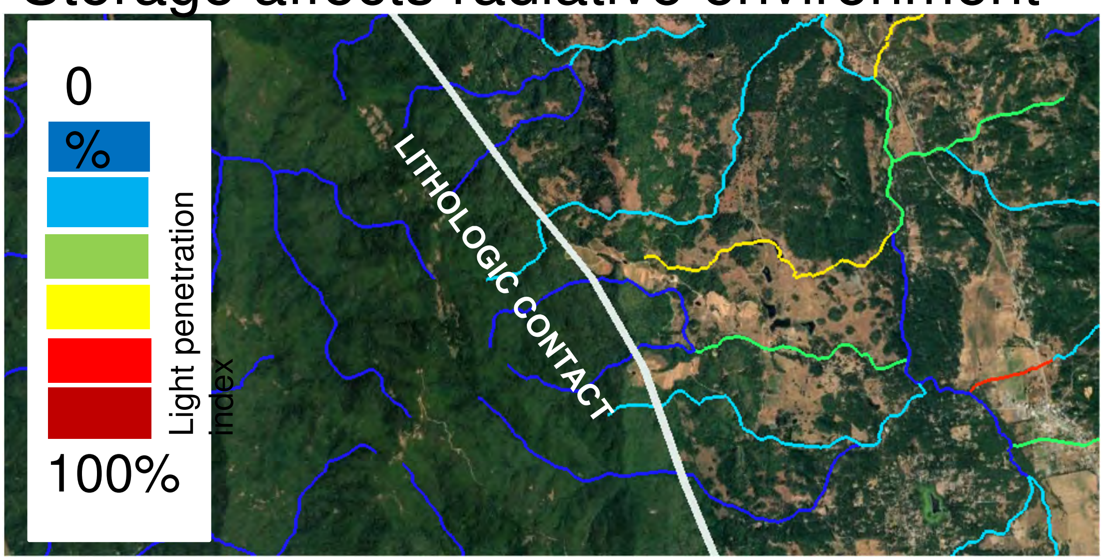
Observed end-of-summer wetted channel drainage density: 0.11 km / km²

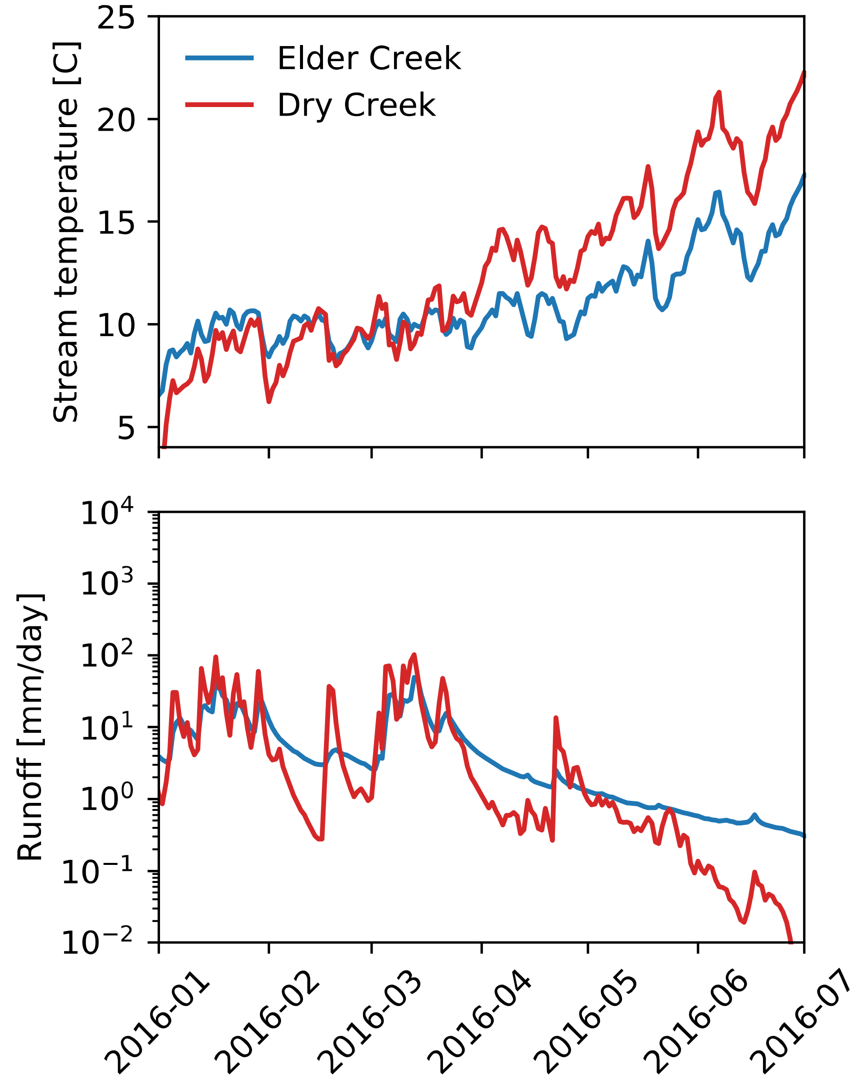
Lovill, Hahm & Dietrich, *2018*,
Water Resources Research

stream temperature

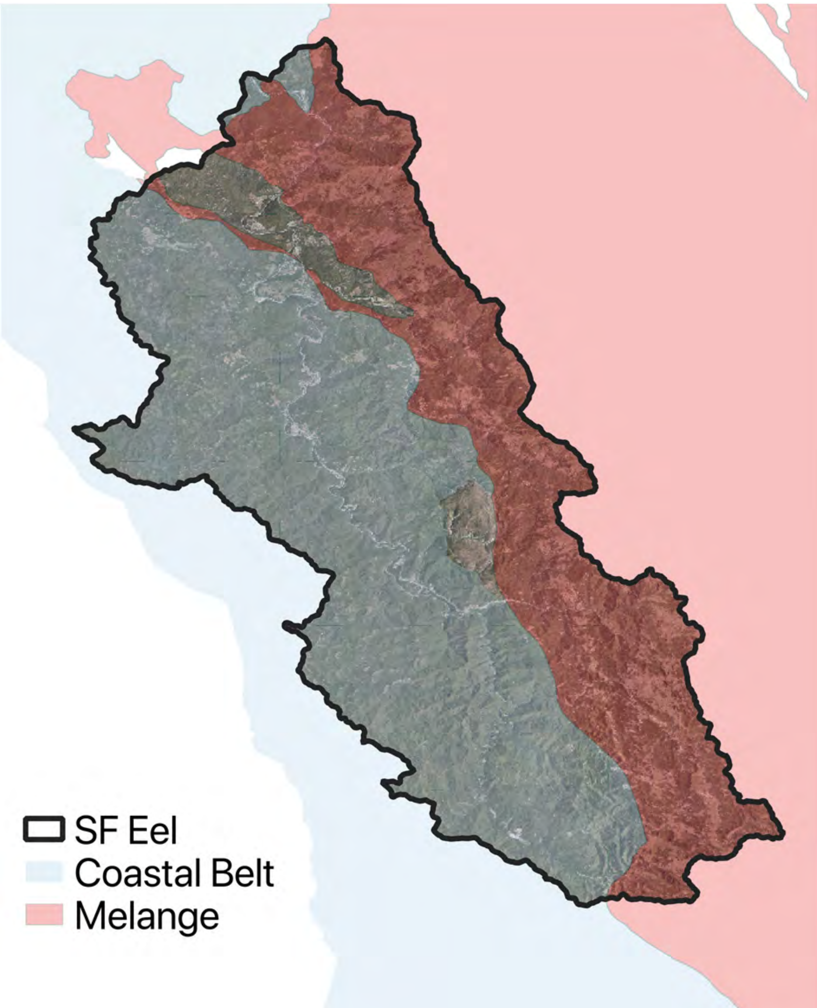
Structure impacts runoff pathways

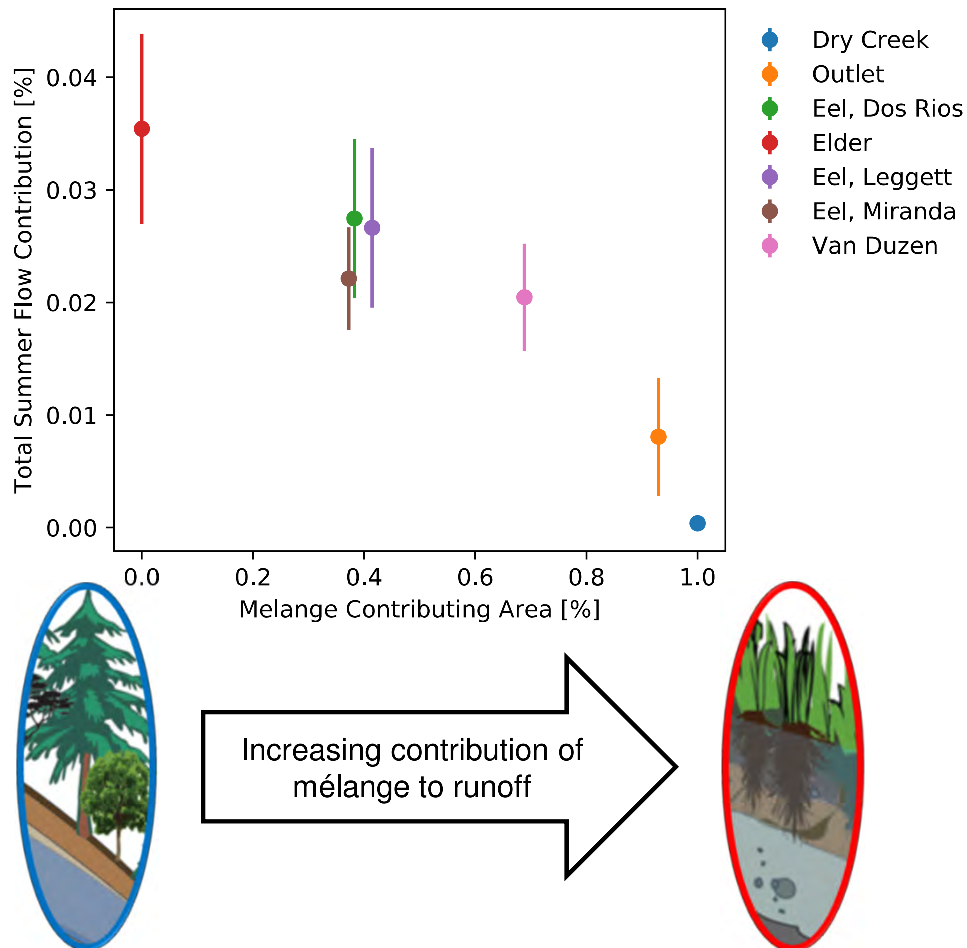
Storage affects radiative environment





from “unit-hillslope” to “watershed”





Dralle, Hahm Rempe, in prep

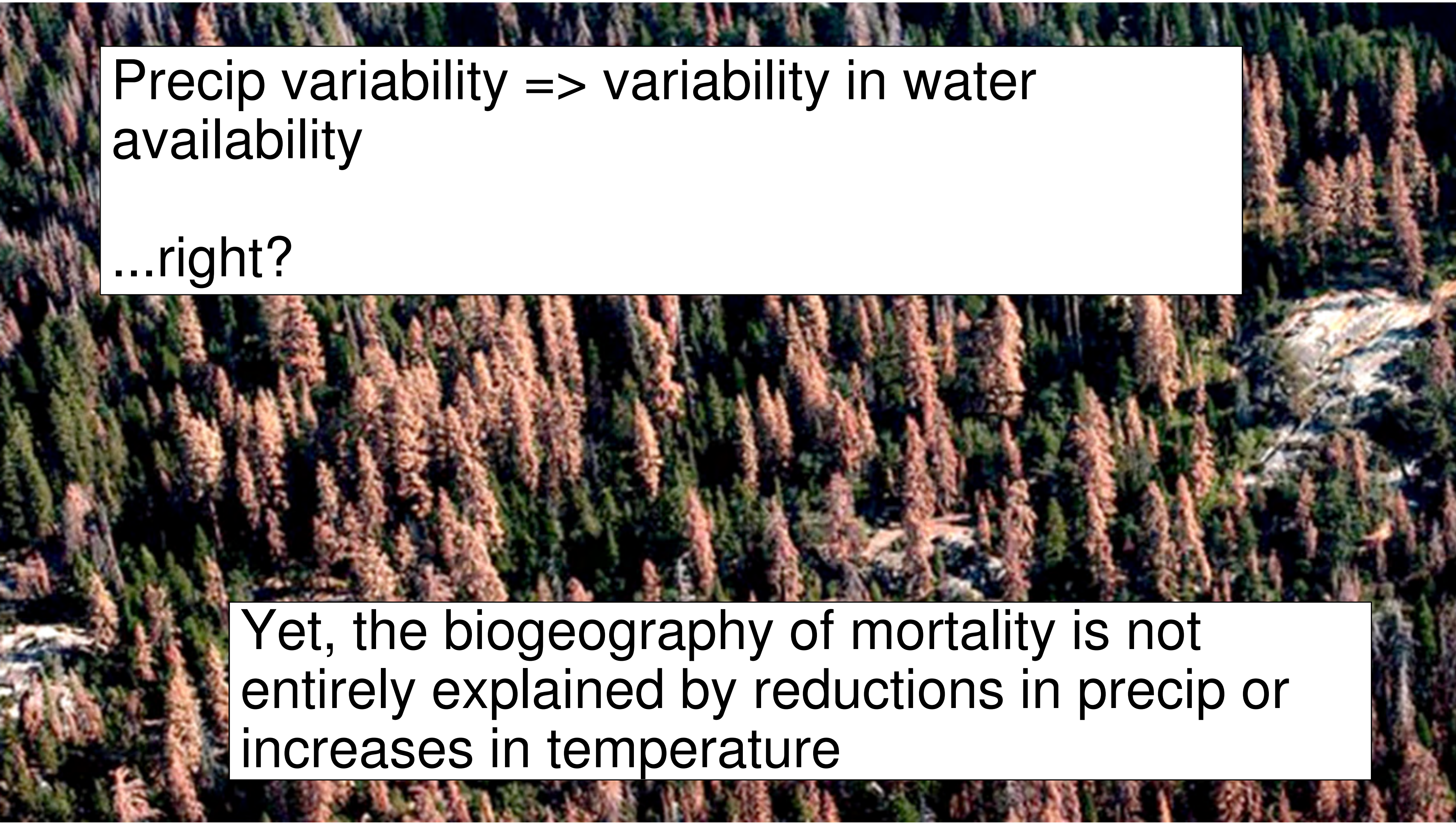
Water storage capacity in the critical zone

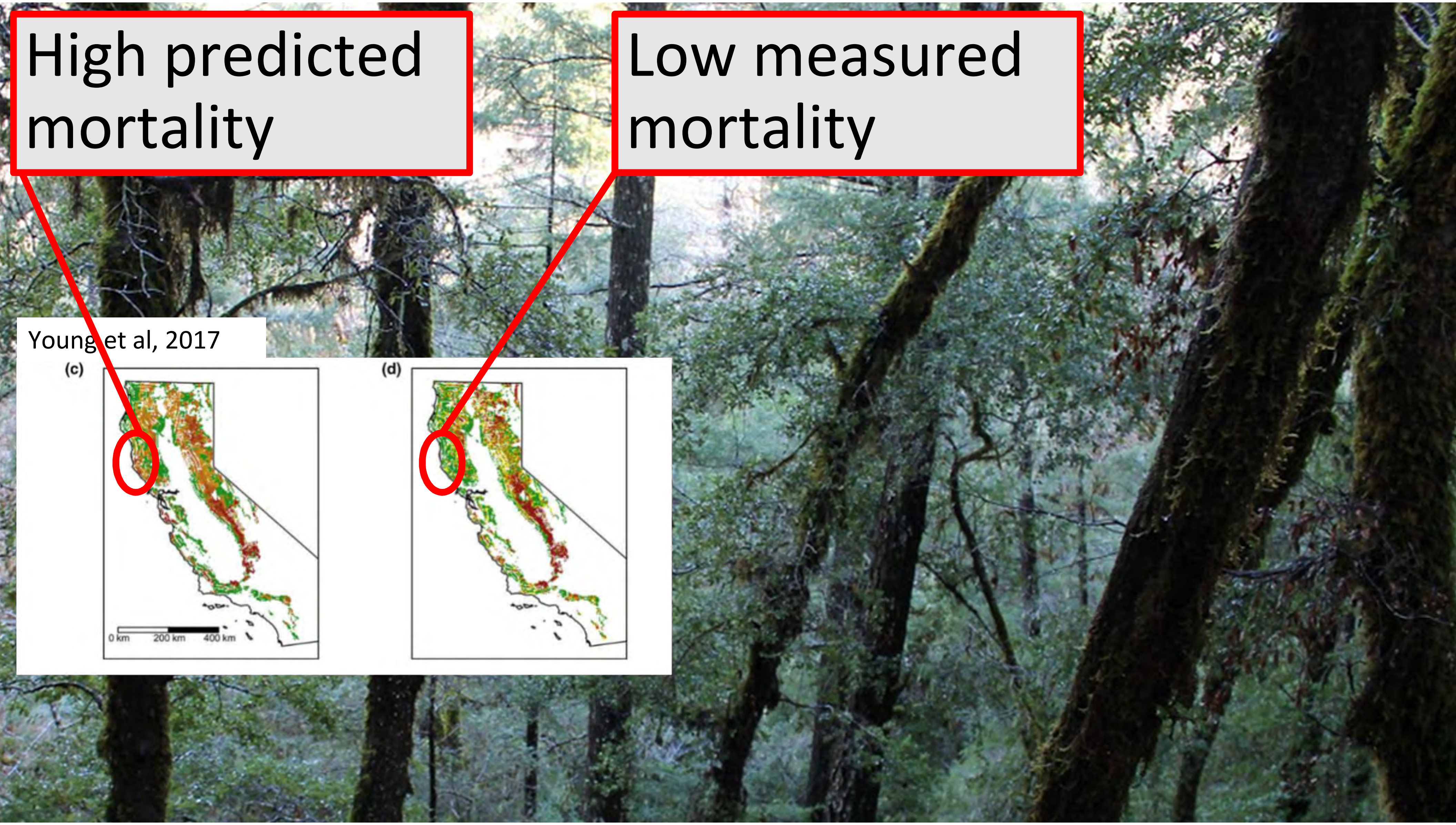
Today's outline:

- Rock type, storage capacity, and biogeography

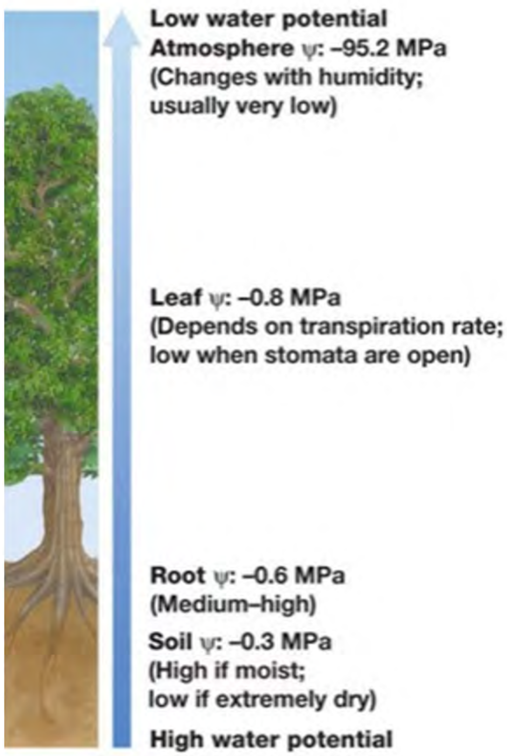
- How does storage capacity mediate plant response to rainfall variability?

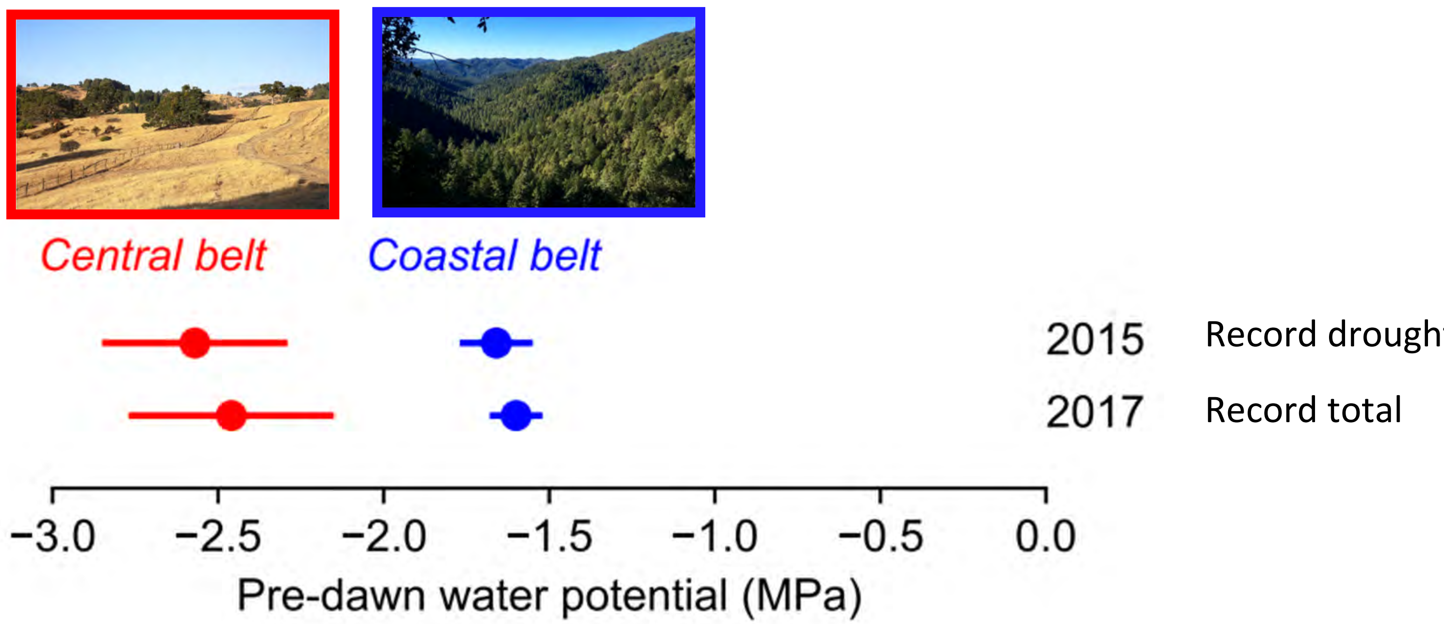
- How does storage capacity mediate streamflow response to rainfall variability?


Precip variability => variability in water availability
...right?
Yet, the biogeography of mortality is not entirely explained by reductions in precip or increases in temperature


High predicted mortality
Low measured mortality
Young et al, 2017
(c)
(d)
0 km
200 km
400 km

Plants had indistinguishable end-of-summer water status between years with radically different rainfall



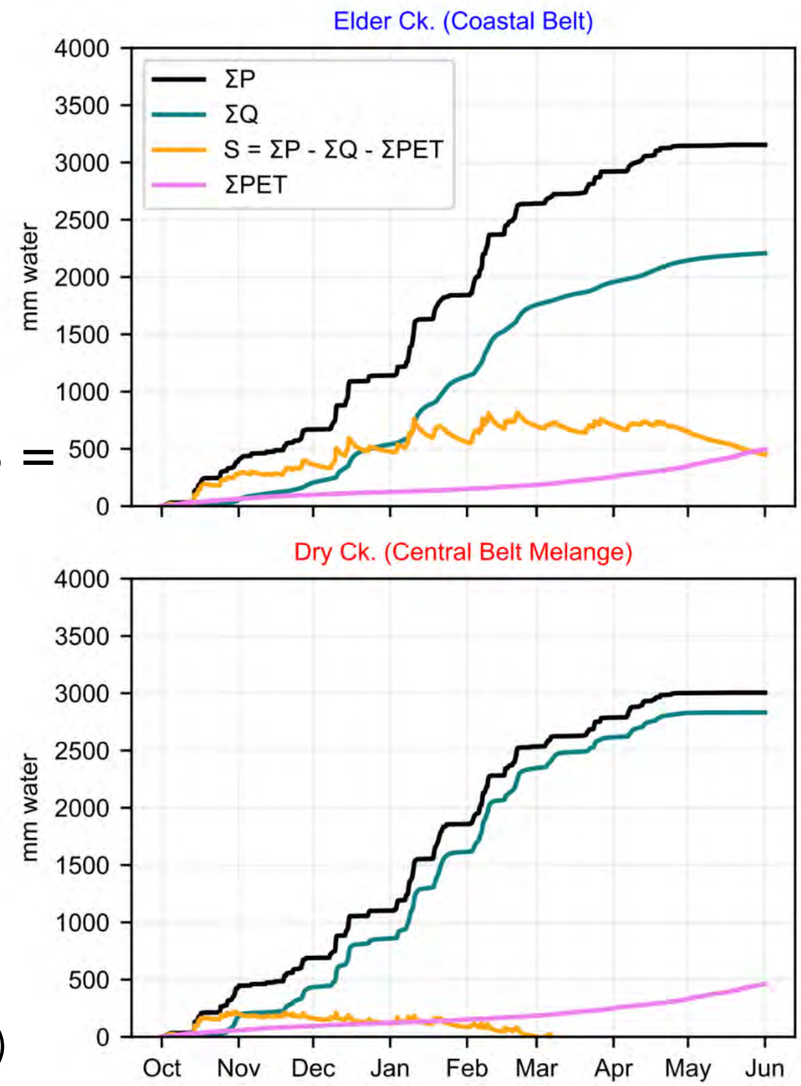


Hint: Storage capacity is finite

Δ storage (S) = inputs – outputs =
+ precipitation (P)
– runoff (Q)
– evapotranspiration (PET)

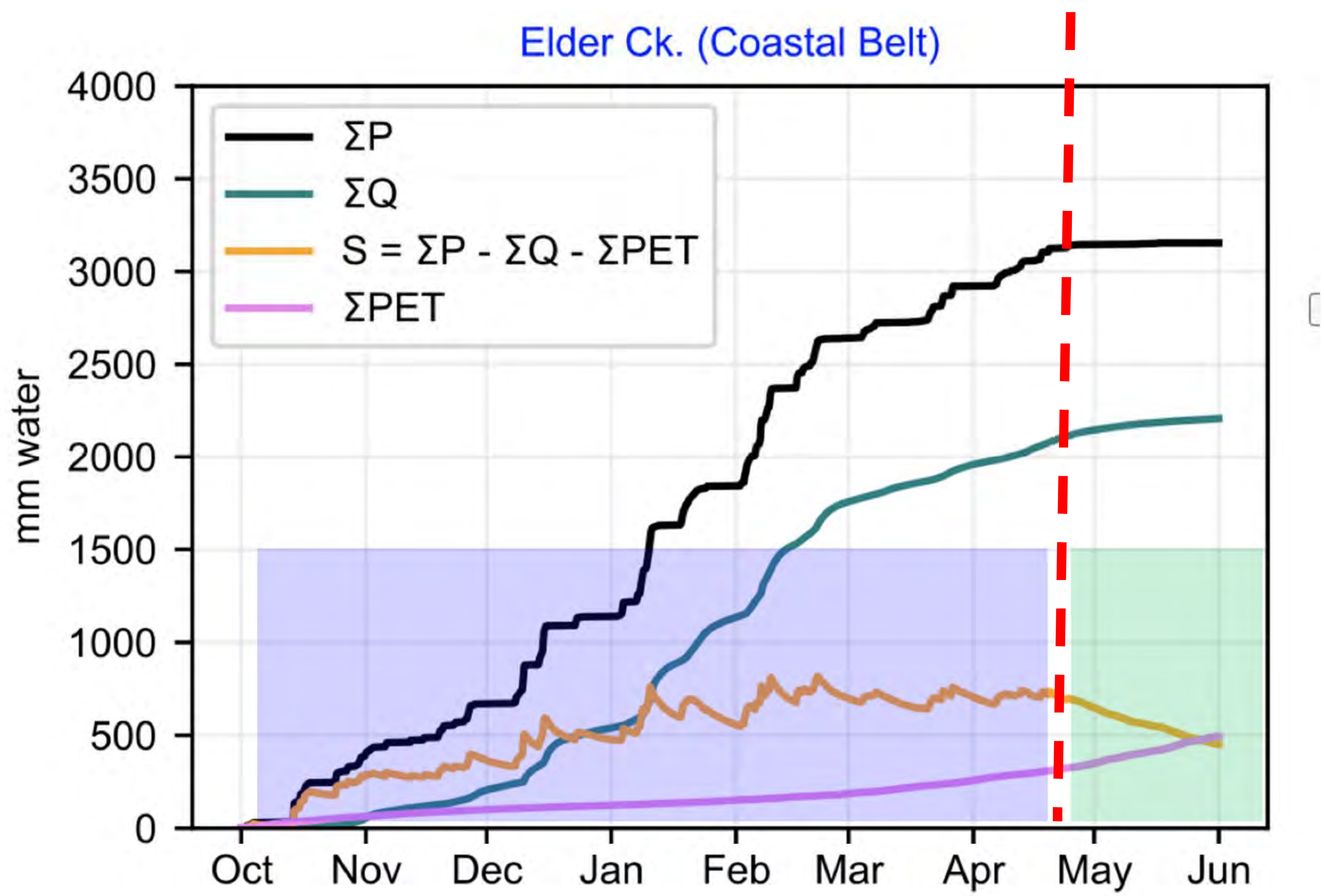
Shown: 2017 water year

See Dralle et al (2018)
or Hahm et al (2019)

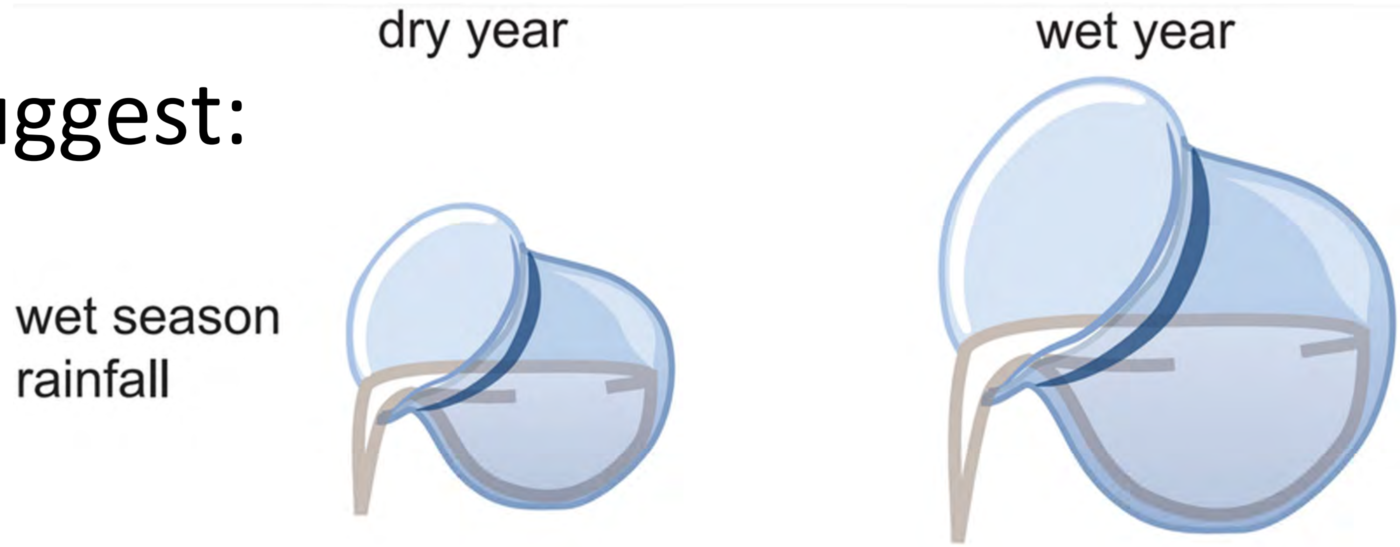


PET inferred from Hargreaves method

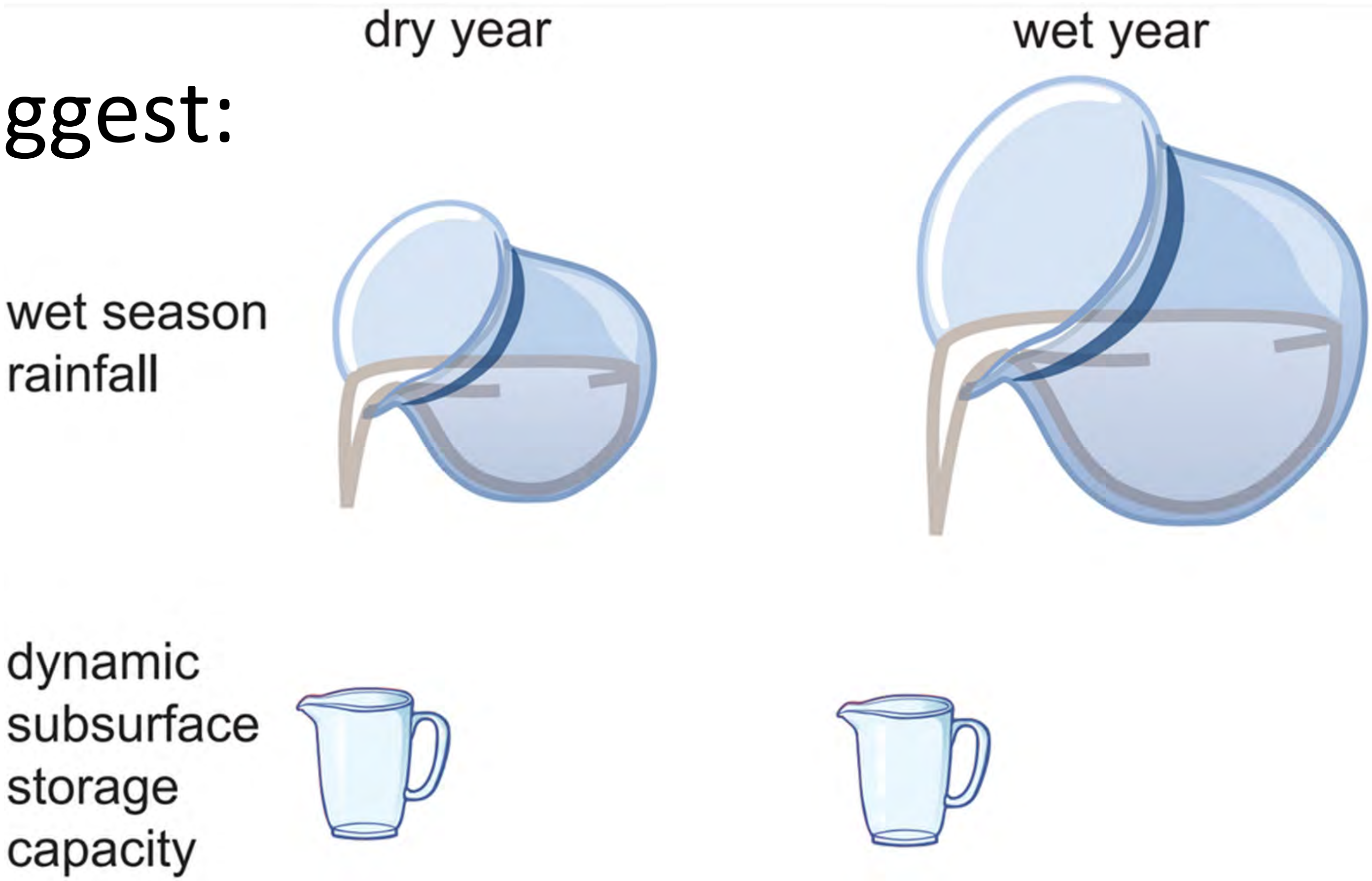
Wet season precip => Dry season storage



Clues suggest:



Clues suggest:



Storage capacity replenished in both wet and dry years => common dry season water availability

Exploring 'storage capacity limitation'

- Track water fluxes in all gauged Mediterranean North American catchments without dams, diversions, disturbance, or snow

- test the hypothesis that:
  - *if* storage is independent of rainfall (diagnostic of storage-capacity limitation)
  - *then* summer plant productivity and water use, as measured by the enhanced vegetation index (EVI), are also uncorrelated with precipitation.

Exploring ‘storage capacity limitation’

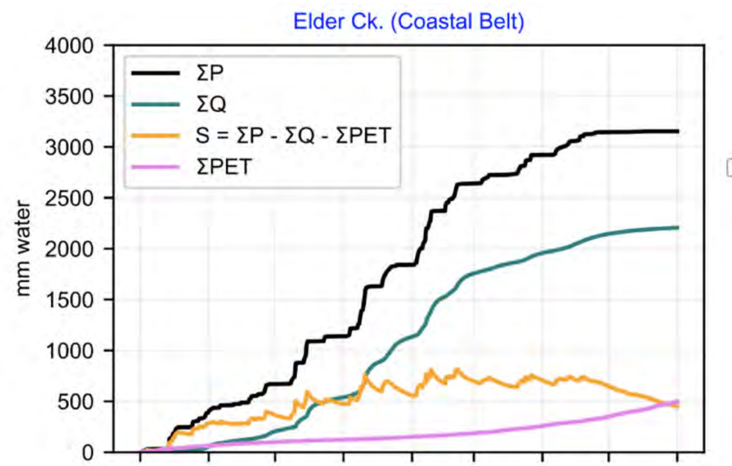
Model rules for a given year

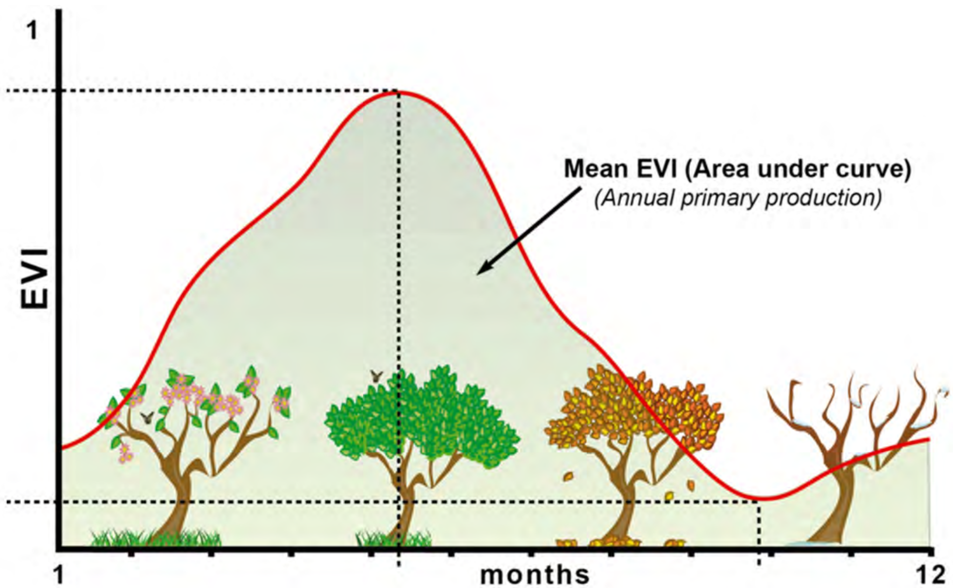
$S = P - ET$ if $P - ET < S_{max}$; $Q = 0$ *Precipitation limited*

$S = S_{max}$ if $P - ET > S_{max}$; $Q = P - ET - S_{max}$ *Storage capacity limited*

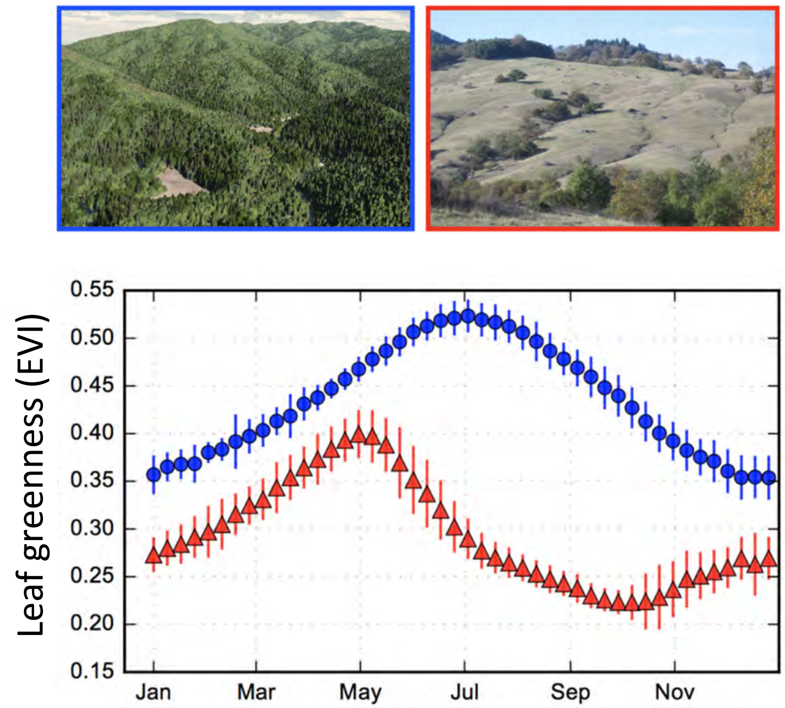
Actual water stored over the wet season

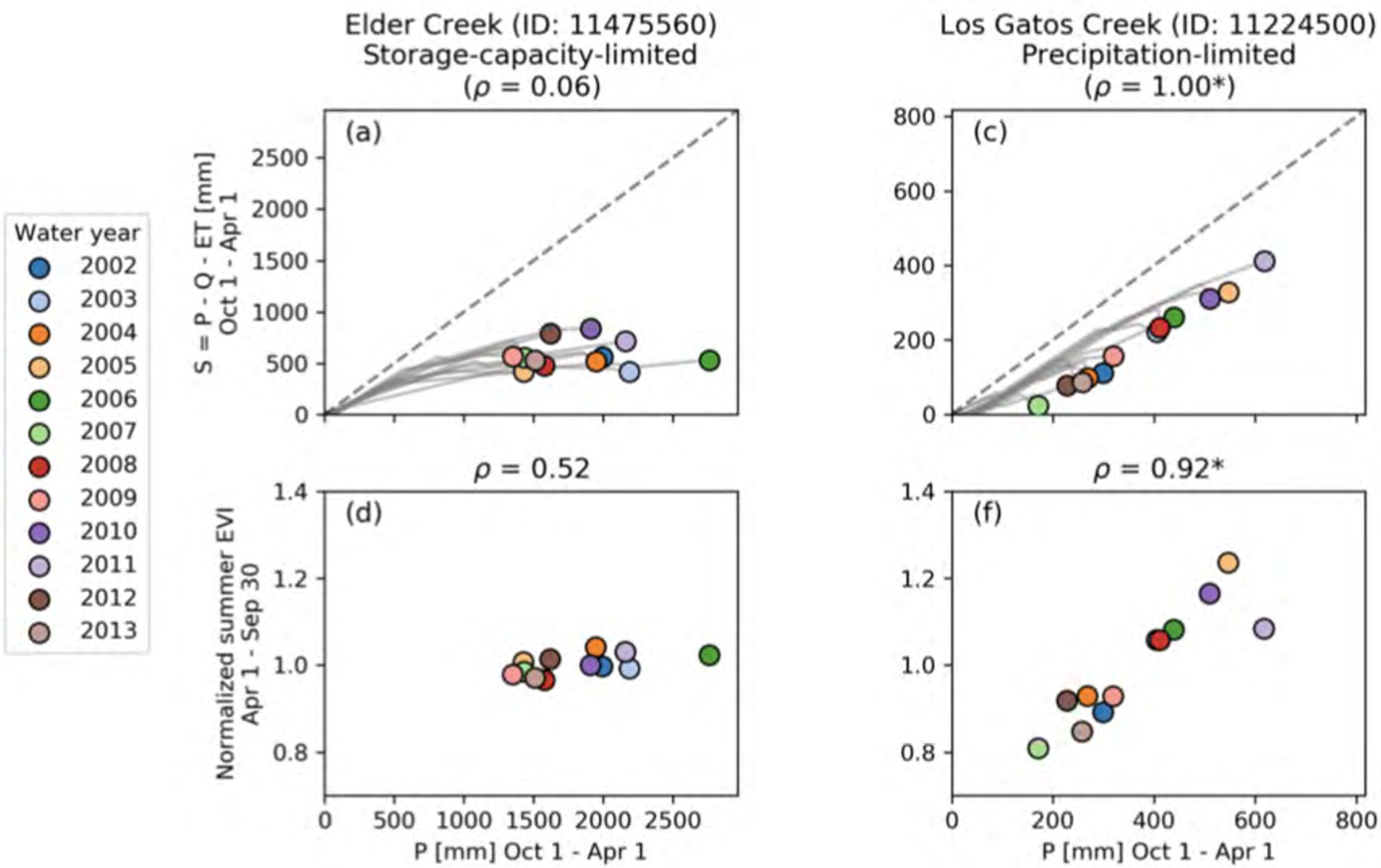
Maximum possible water storage (i.e., subsurface storage capacity)



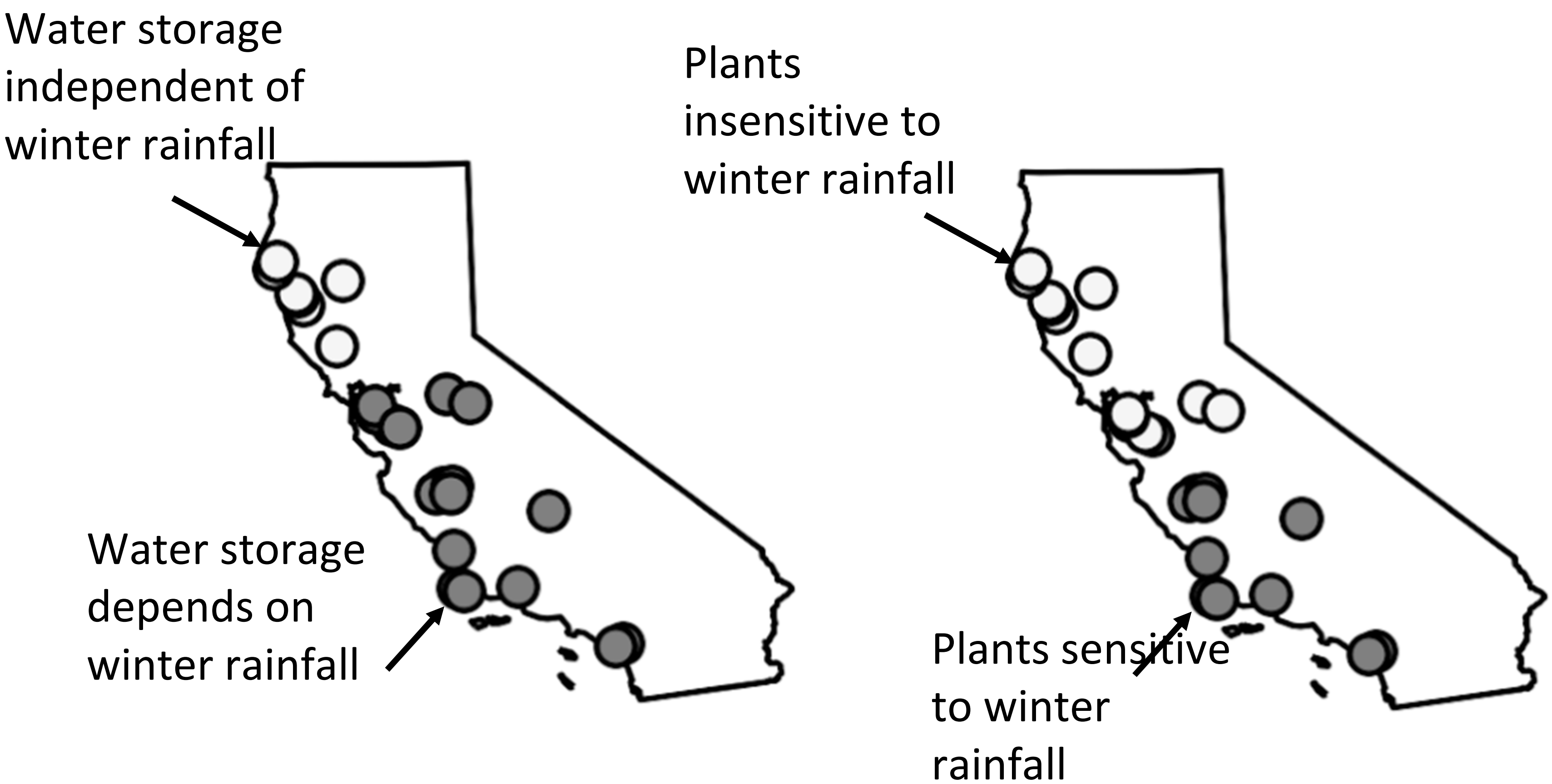


Wikimedia commons
https://en.wikipedia.org/wiki/File:AnualDynamics_EVI_3vars.png#file





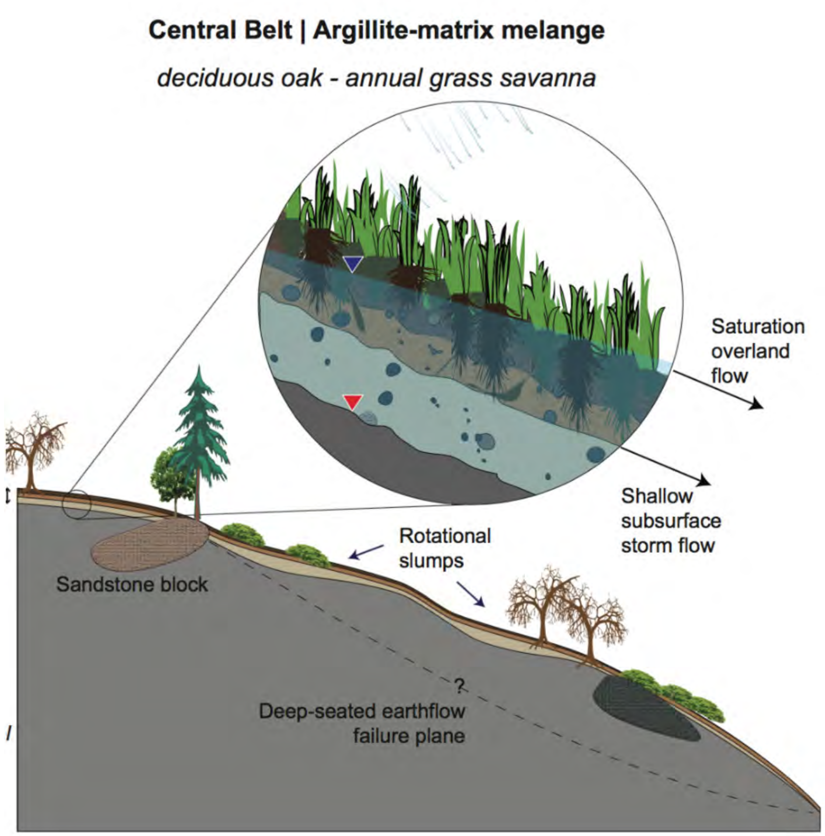
Elder Creek (ID: 11475560)
Storage-capacity-limited
(ρ = 0.06)
Los Gatos Creek (ID: 11224500)
Precipitation-limited
(ρ = 1.00*)
(a)
(c)
S = P - Q - ET [mm]
Oct 1 - Apr 1
Water year
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
ρ = 0.52
ρ = 0.92*
(d)
(f)
Normalized summer EVI
Apr 1 - Sep 30
P [mm] Oct 1 - Apr 1
P [mm] Oct 1 - Apr 1



Hahm, Dralle, Rempe et al. (GRL)

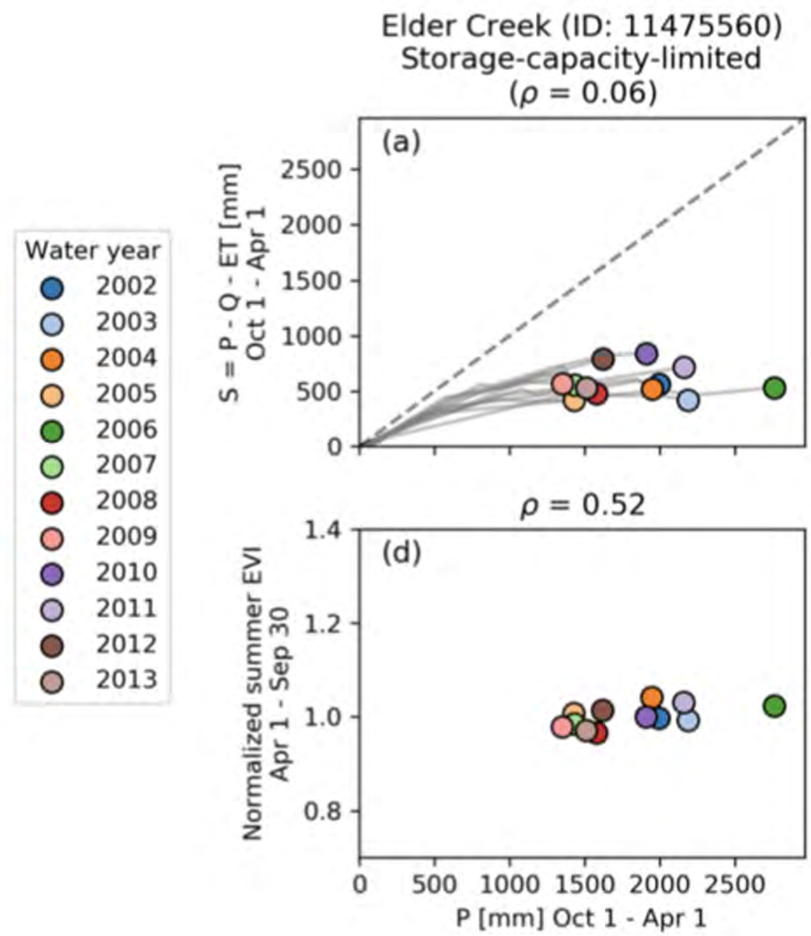
Implications

Where can you get the most bang for your buck with GW recharge projects?



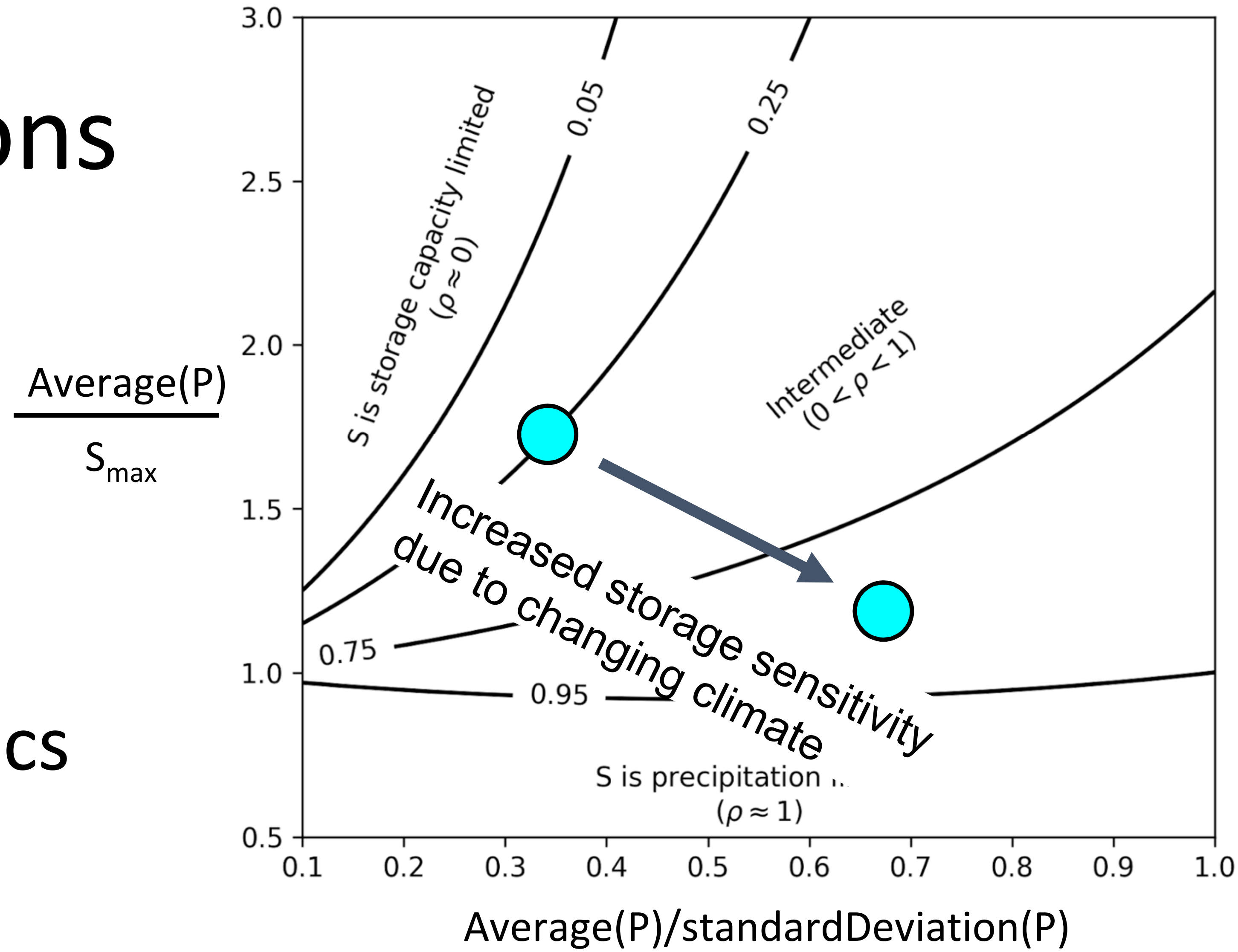
Implications

Big rainfall year does not necessarily mean more water is available in the dry season



Implications

Storage sensitivity response to changes in rainfall statistics



Implications

Are snowy catchments "precipitation limited"?

Switch from snow to rain with warming

A. Harpold

B. Gordon

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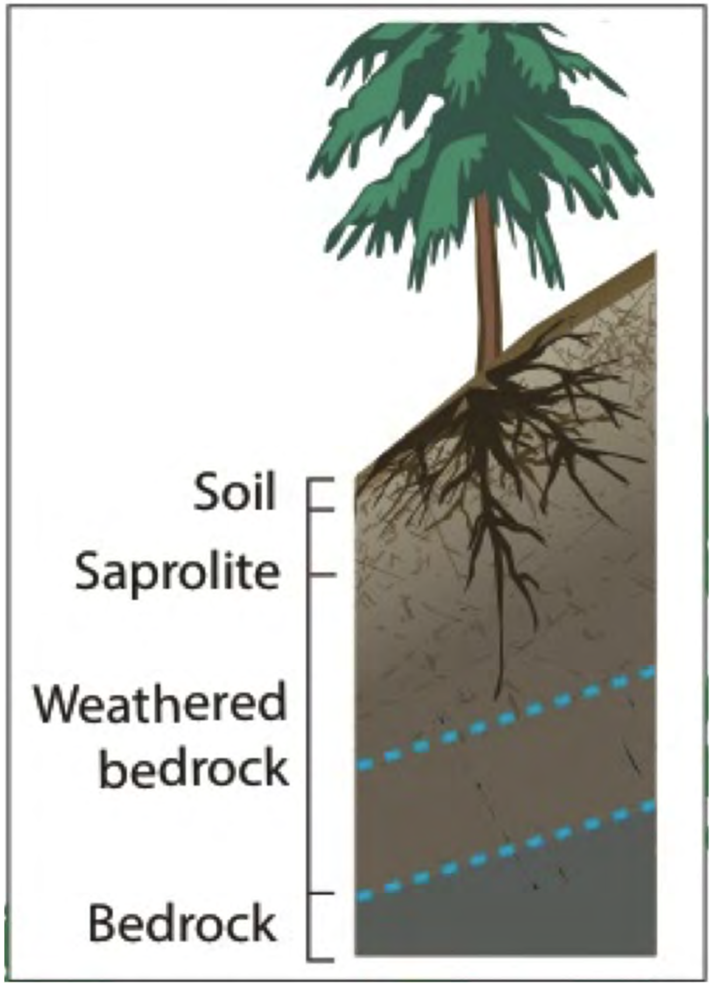
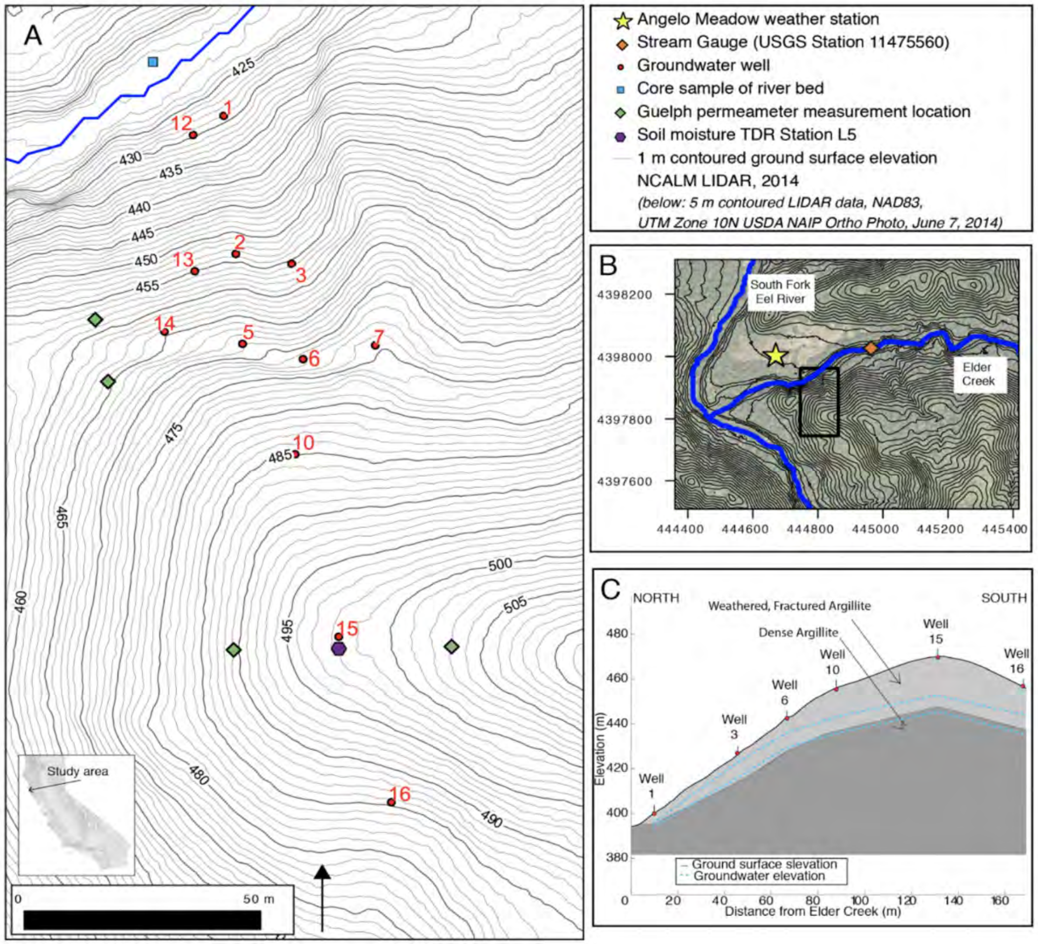
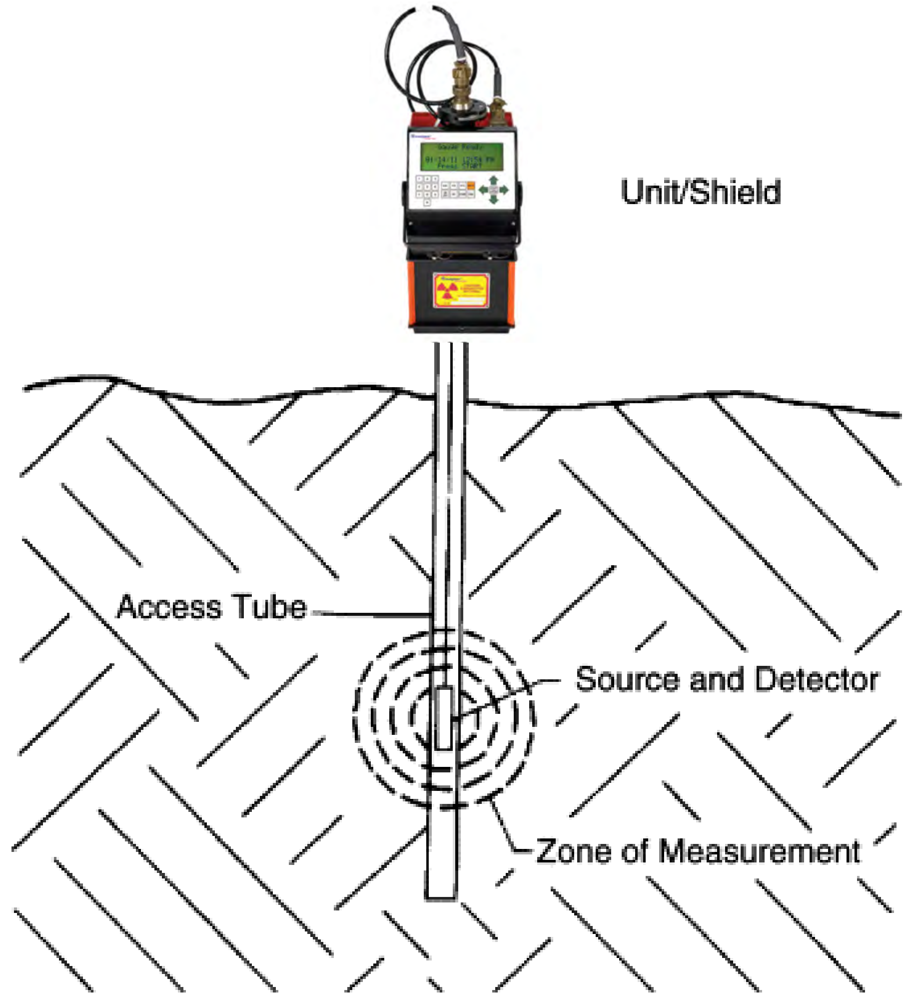
Mechanisms of storage limitation – field capacity



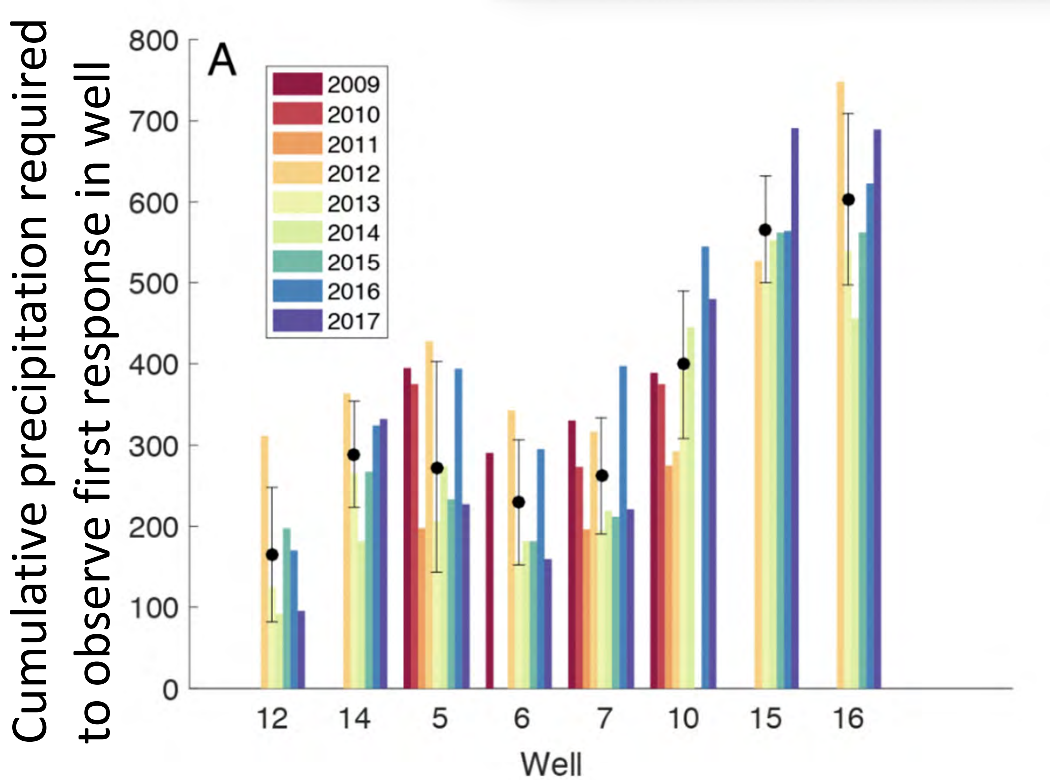
Vertical, unsaturated flow above “field capacity”

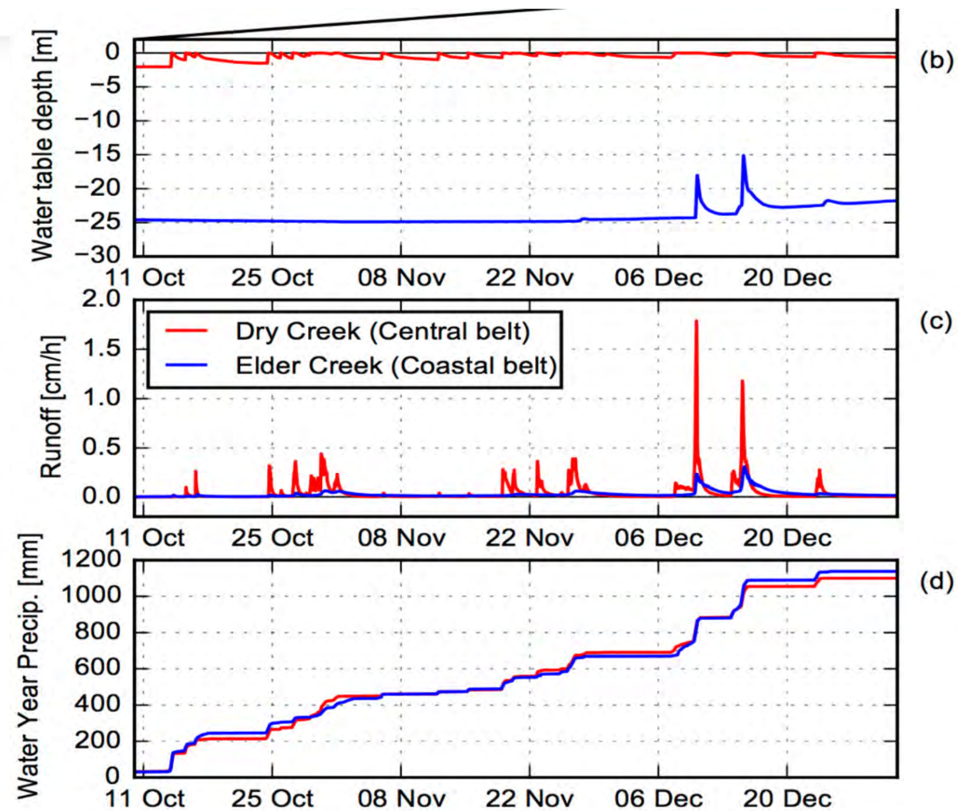
Measuring water content in weathered bedrock vadose zone



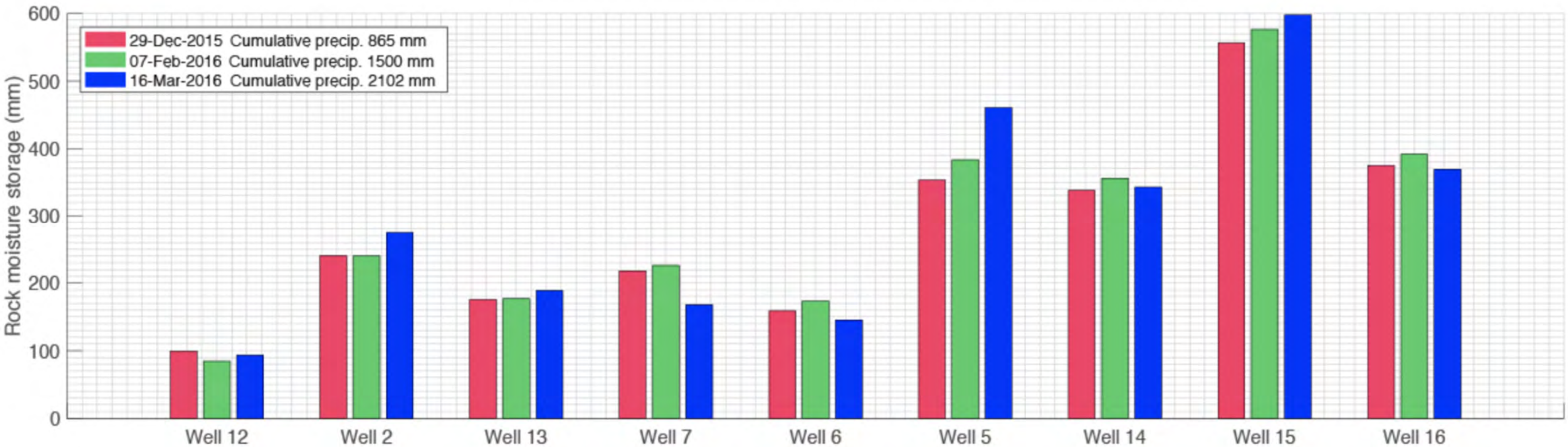


Storage deficit in soil and rock moisture must be fully replenished before significant recharge can occur

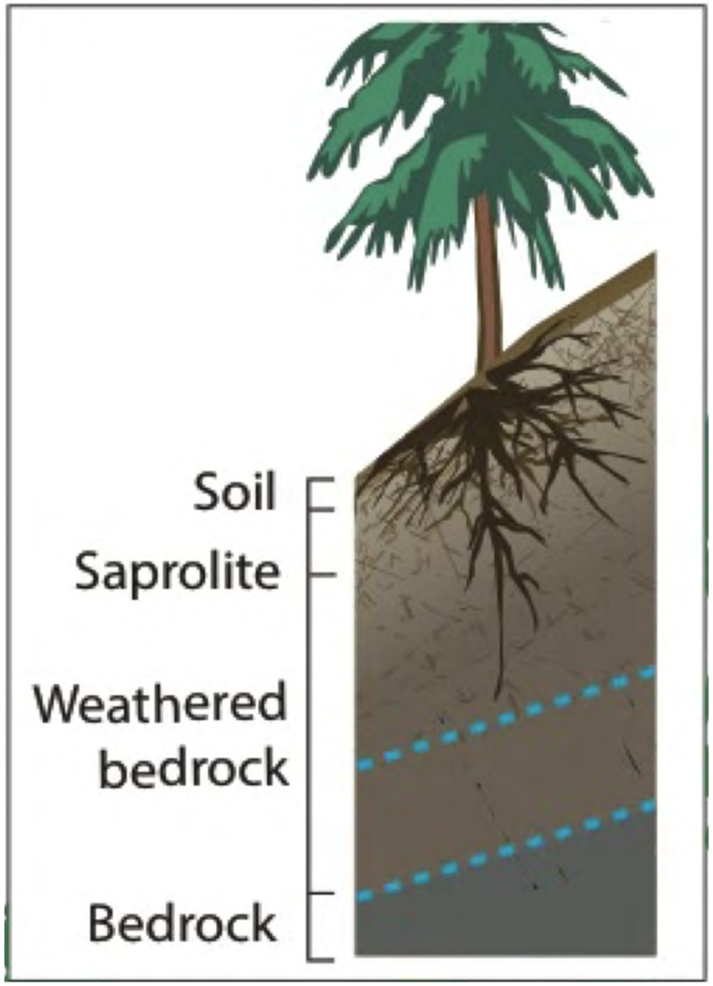


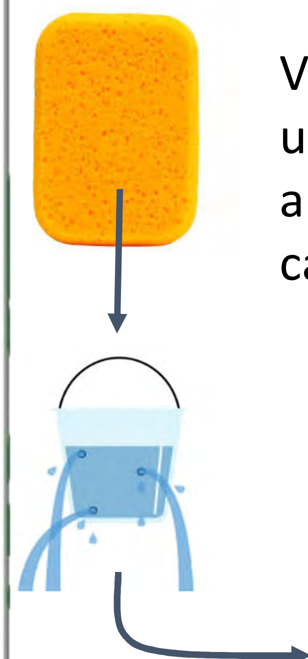


Field capacity storage limitation mechanism in the weathered rock vadose zone



Mechanisms of storage limitation – transmissivity feedback

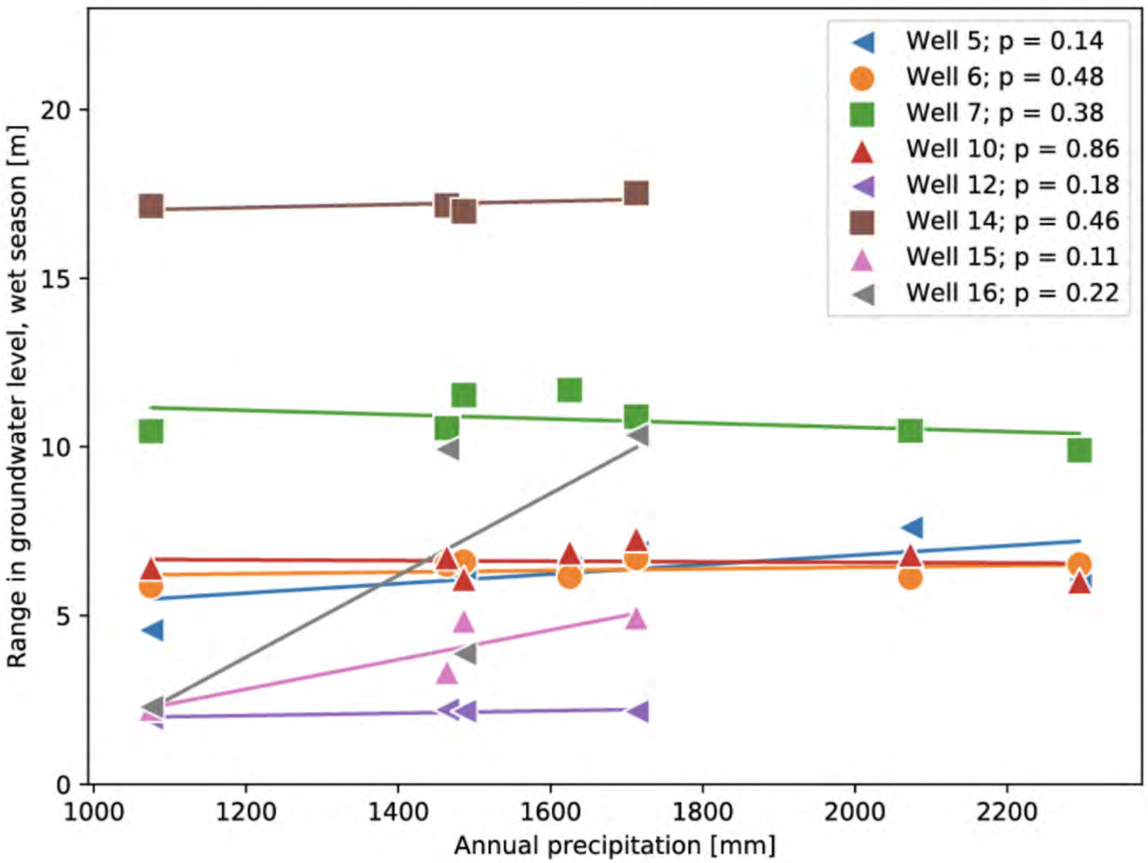




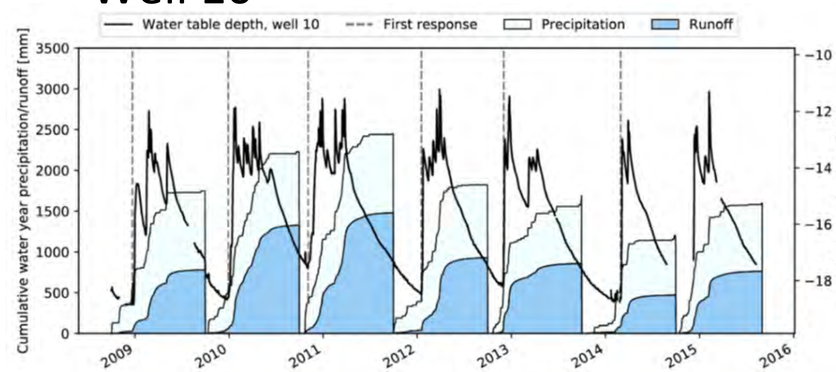
Vertical, unsaturated flow above “field capacity”

Lateral drainage to stream due to sloping water table

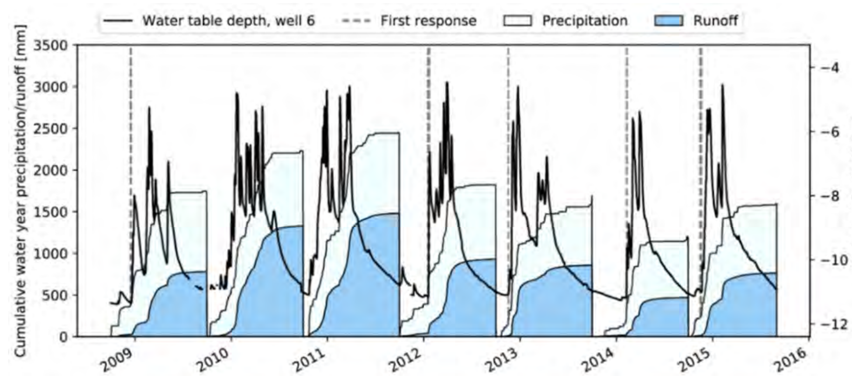
Mechanisms of storage limitation – transmissivity feedback



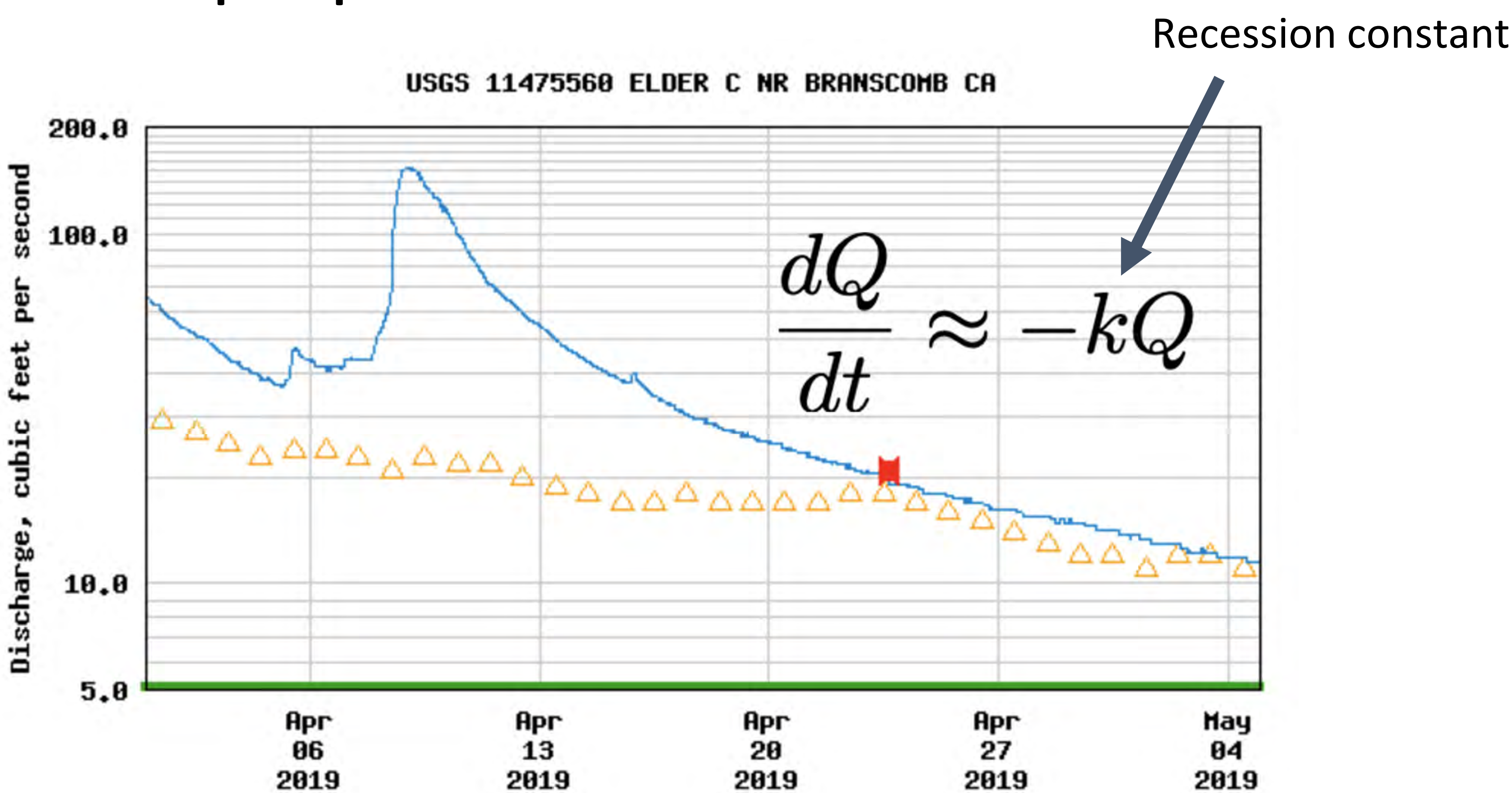
Well 10



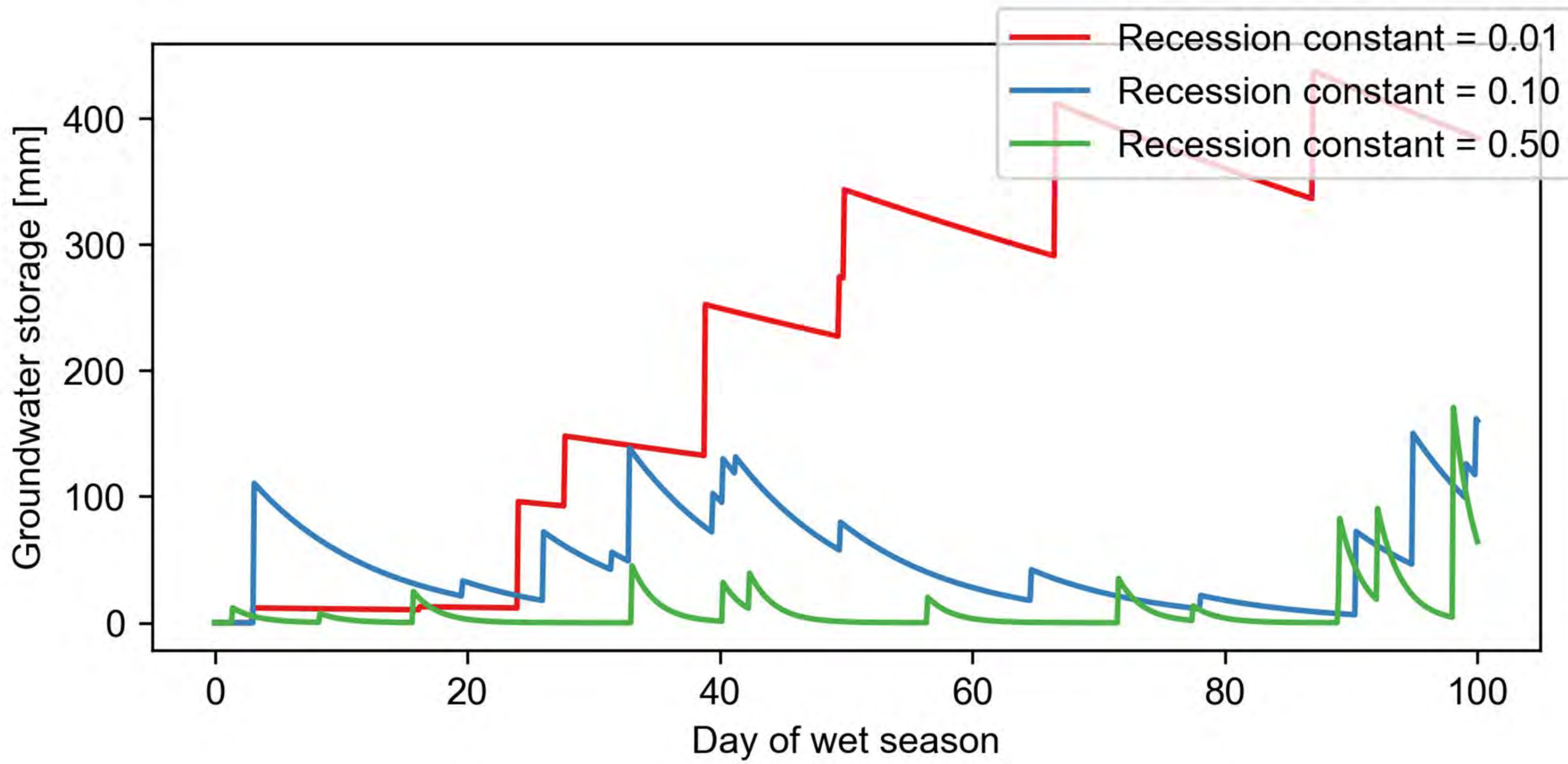
Well 6



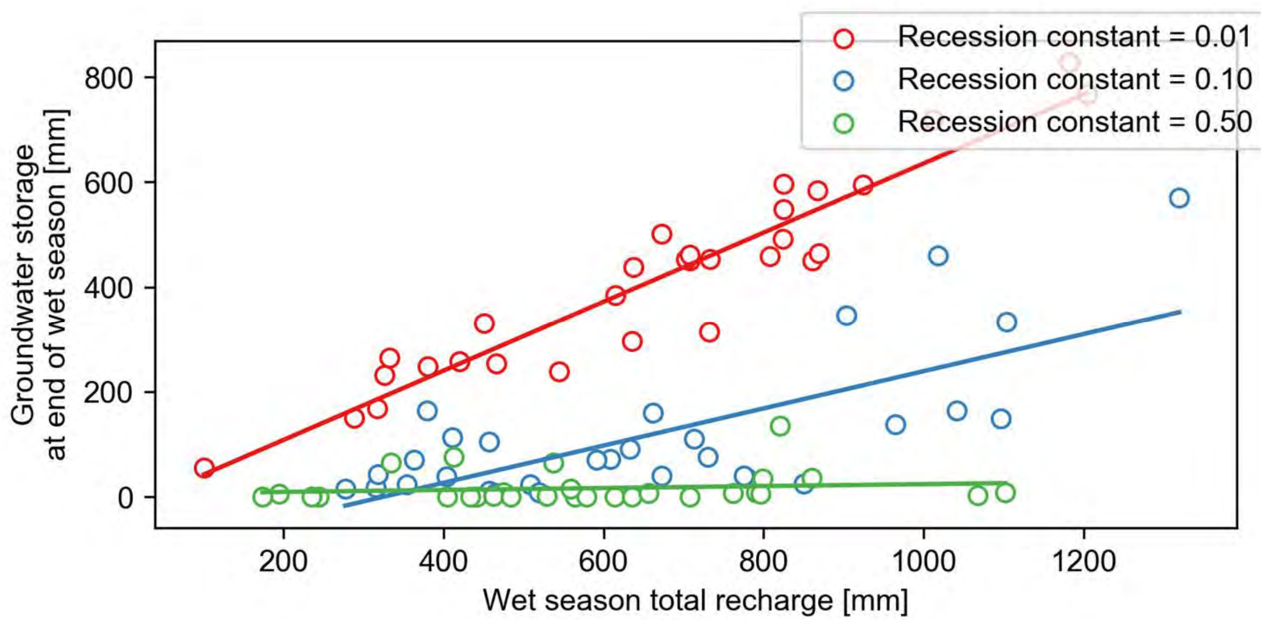
Common recession model - rate of flow decline is proportional to flow



Synthetic hydrographs: Recession constant and accumulation of groundwater storage

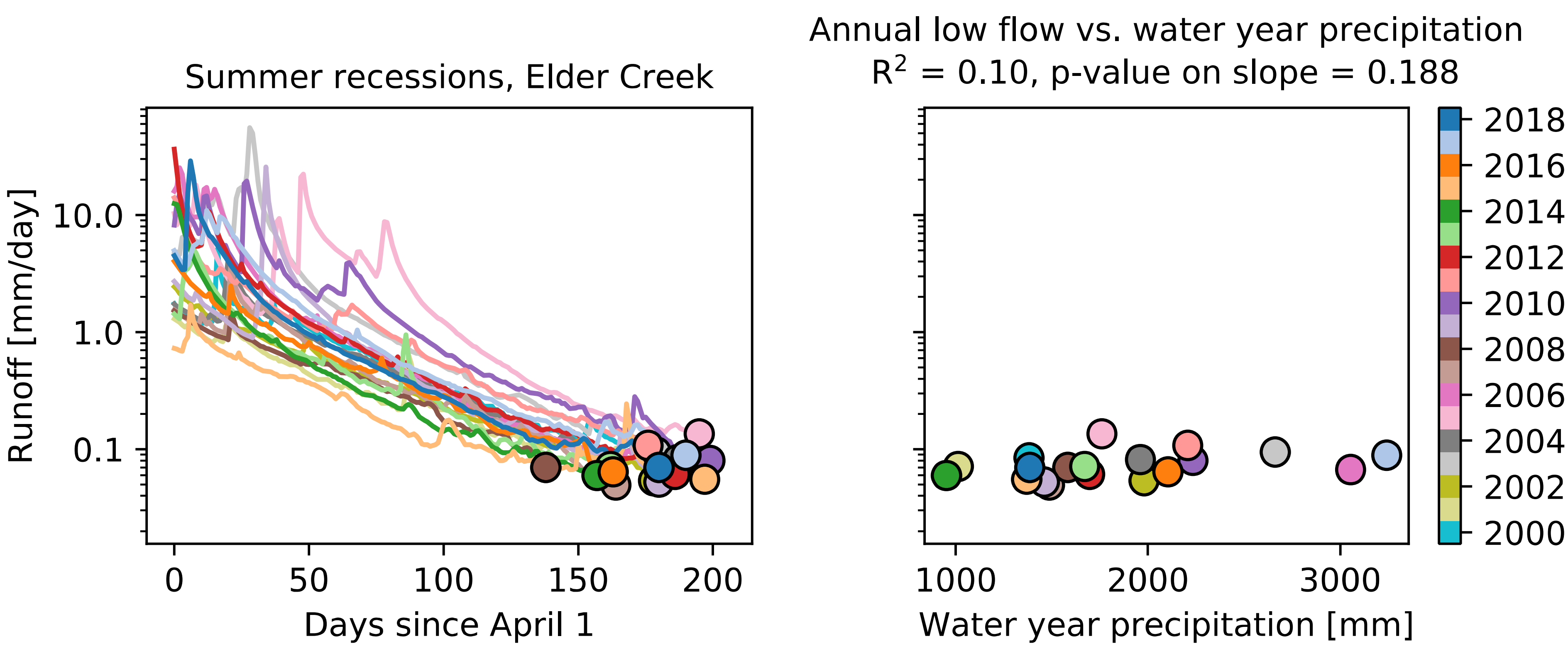


Simulate many wet seasons to explore controls on variability of groundwater carryover

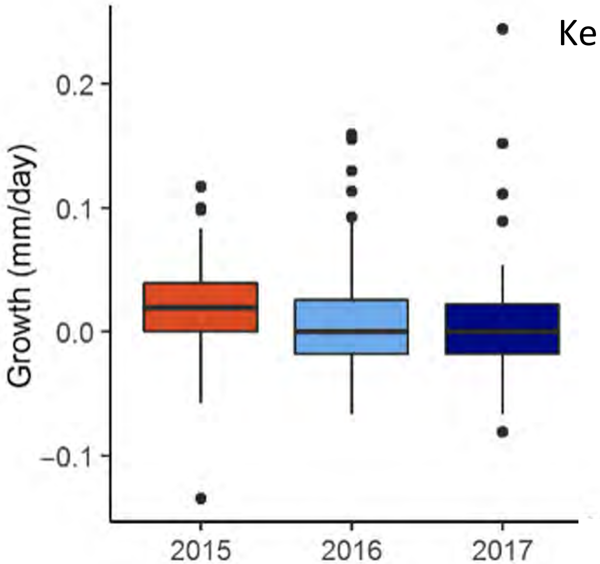


For catchments that drain very slowly (low k), annual recharge may predict summer runoff

More generally, depends on interaction of drainage timescales with rainfall magnitude/frequency and wet season duration

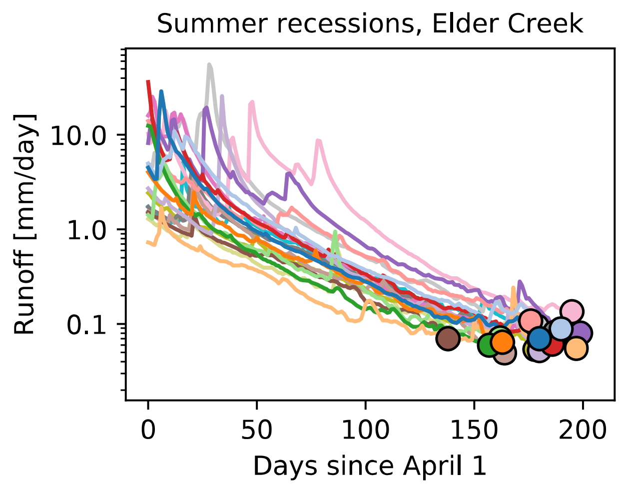


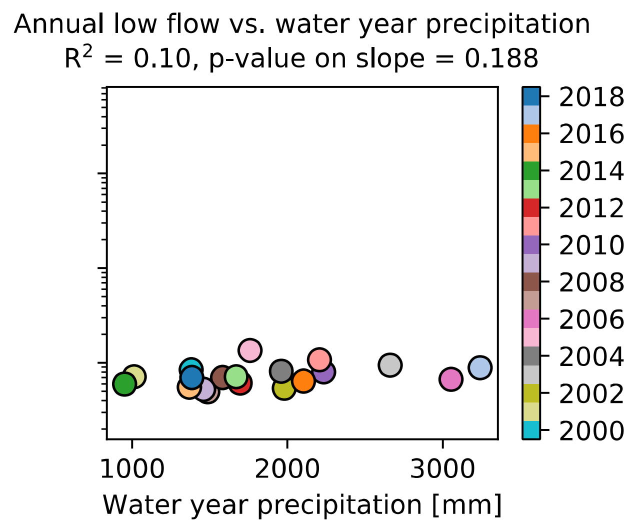
Rempe, Dralle, Hahm, et al, in prep



Kelson and Carlson, Ecosphere, 2019

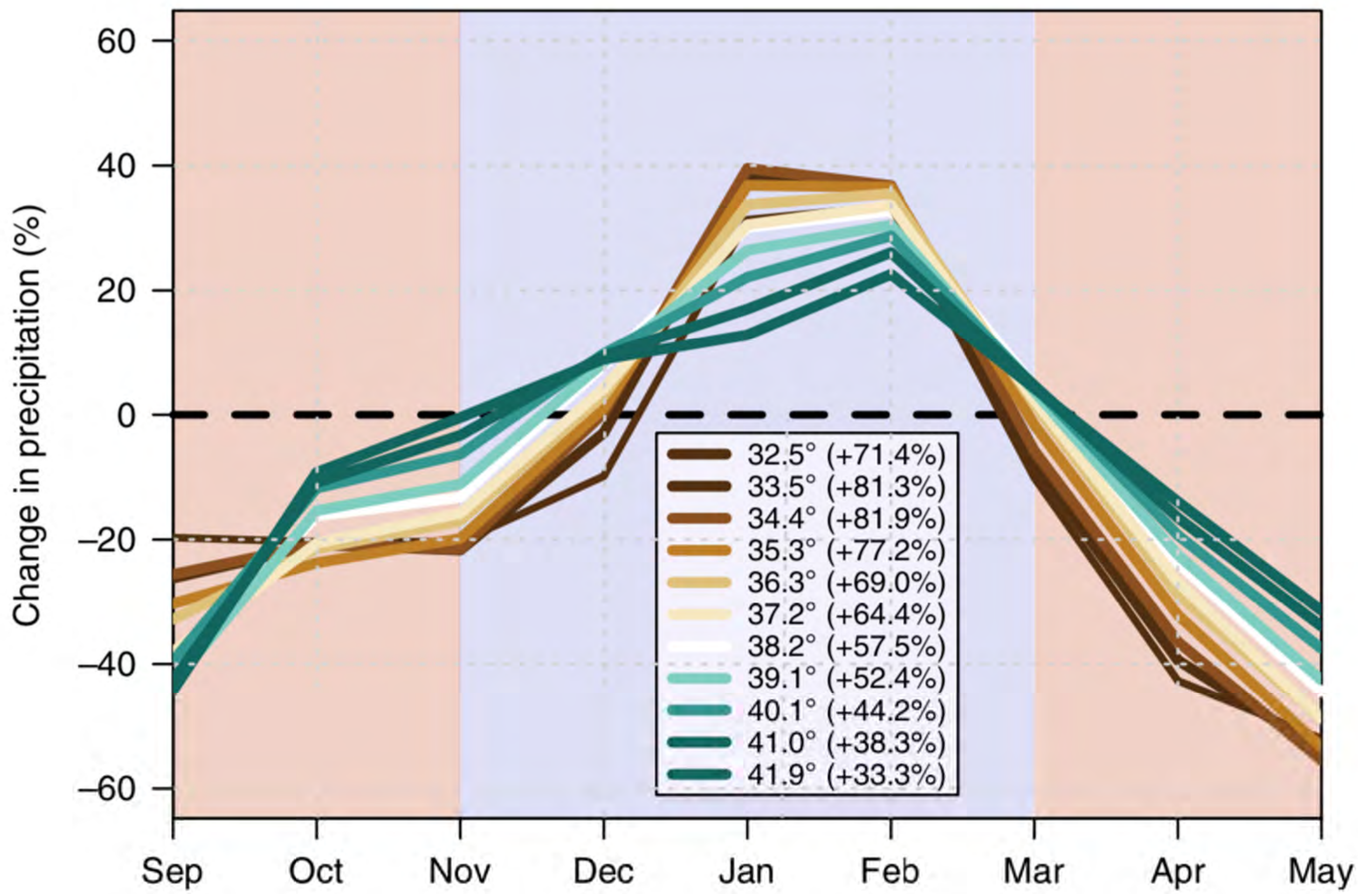
O. mykiss summer growth rates did not vary despite highly variable precipitation





Rempe, Dralle, Hahm, et al, in prep

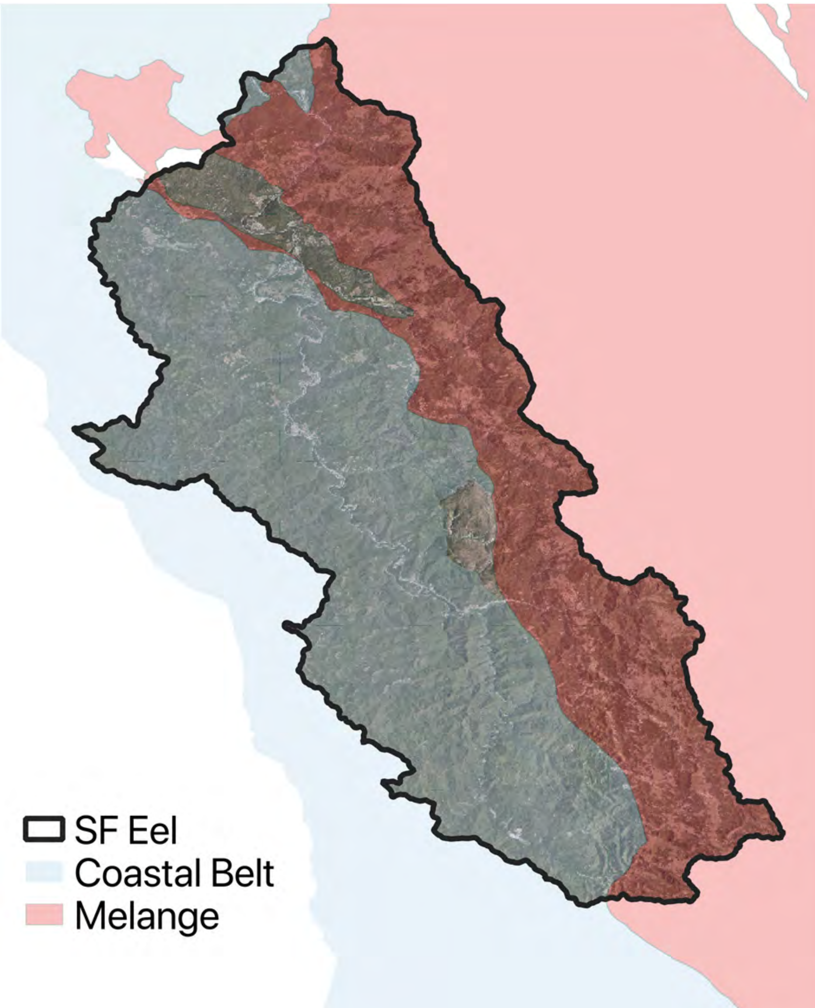
Wet season “sharpening”

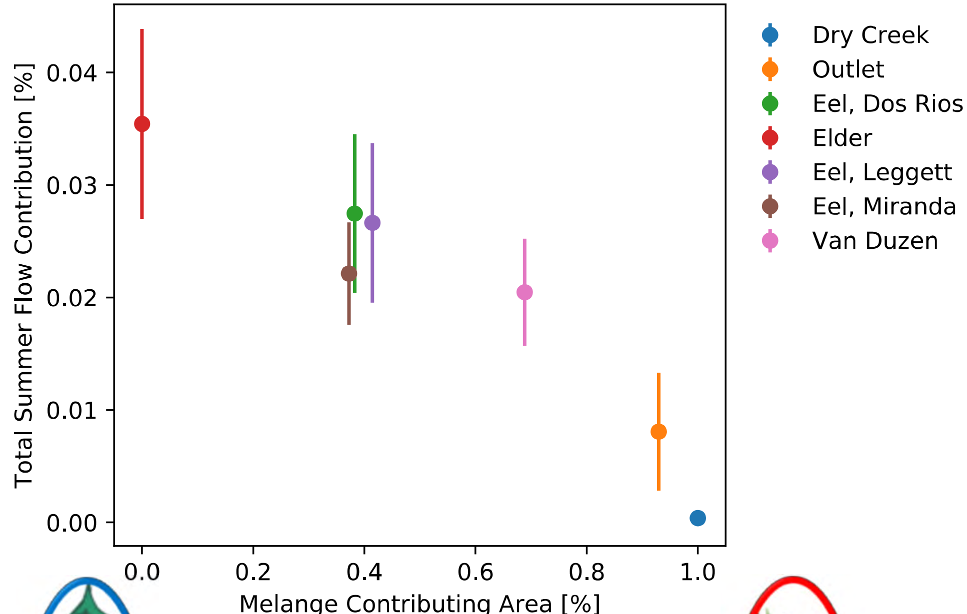


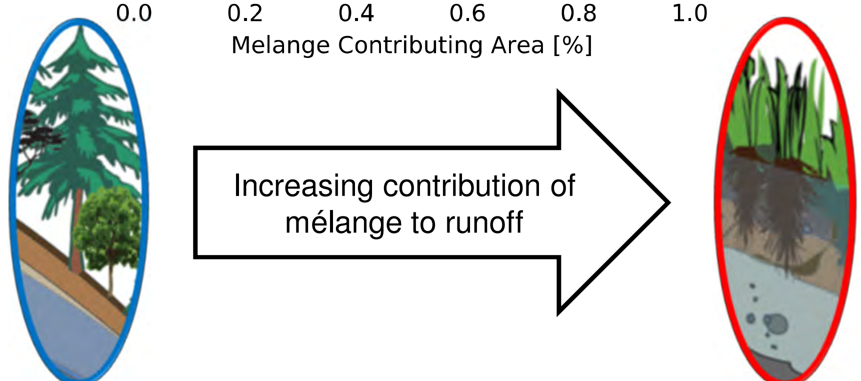
Increasing precipitation volatility in twenty-first-century California

Daniel L. Swain[1,2]*, Baird Langenbrunner[3,4], J. David Neelin[3] and Alex Hall[3]

Implications: Our heterogeneous watershed







Dralle, Hahm Rempe, in prep

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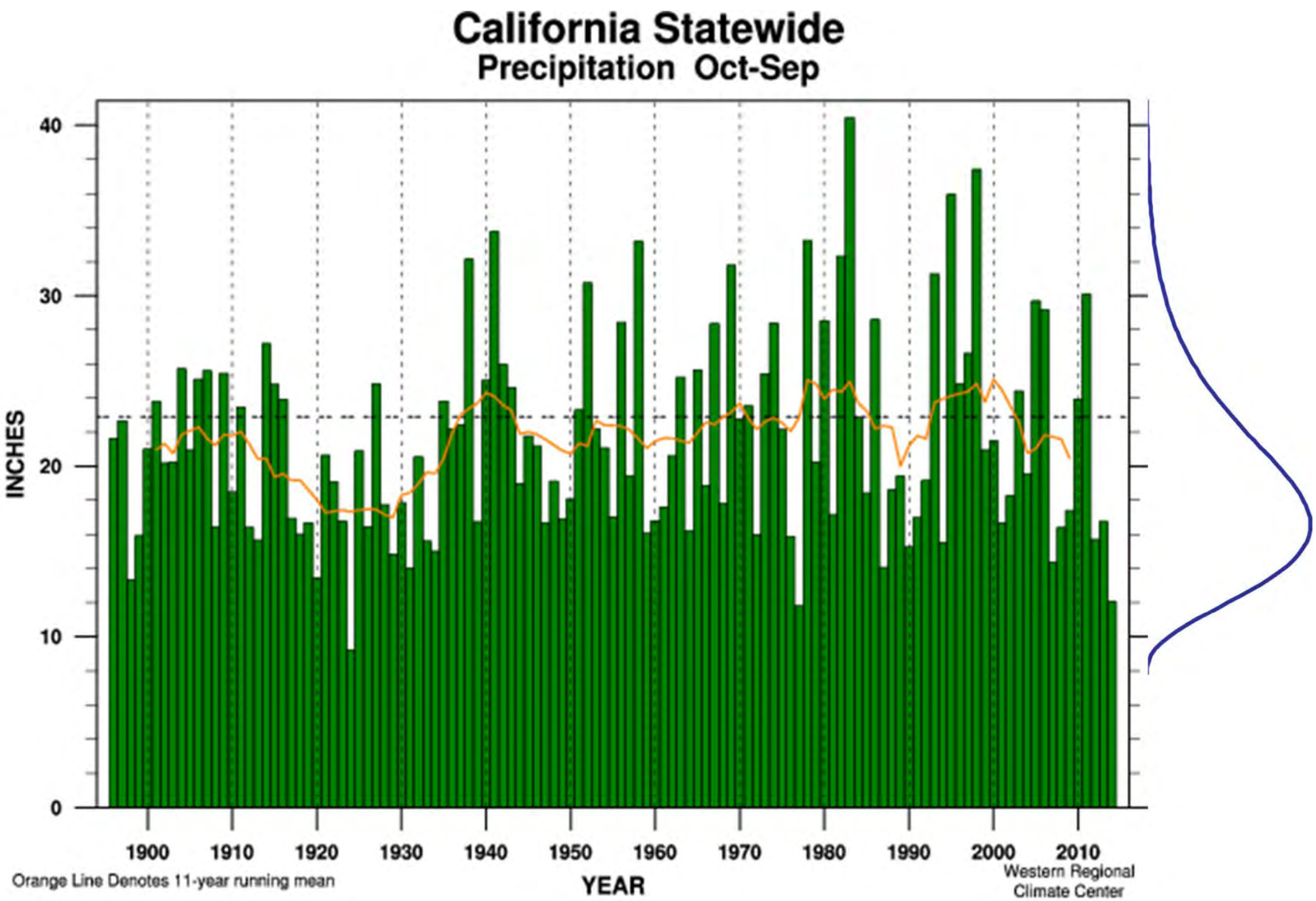
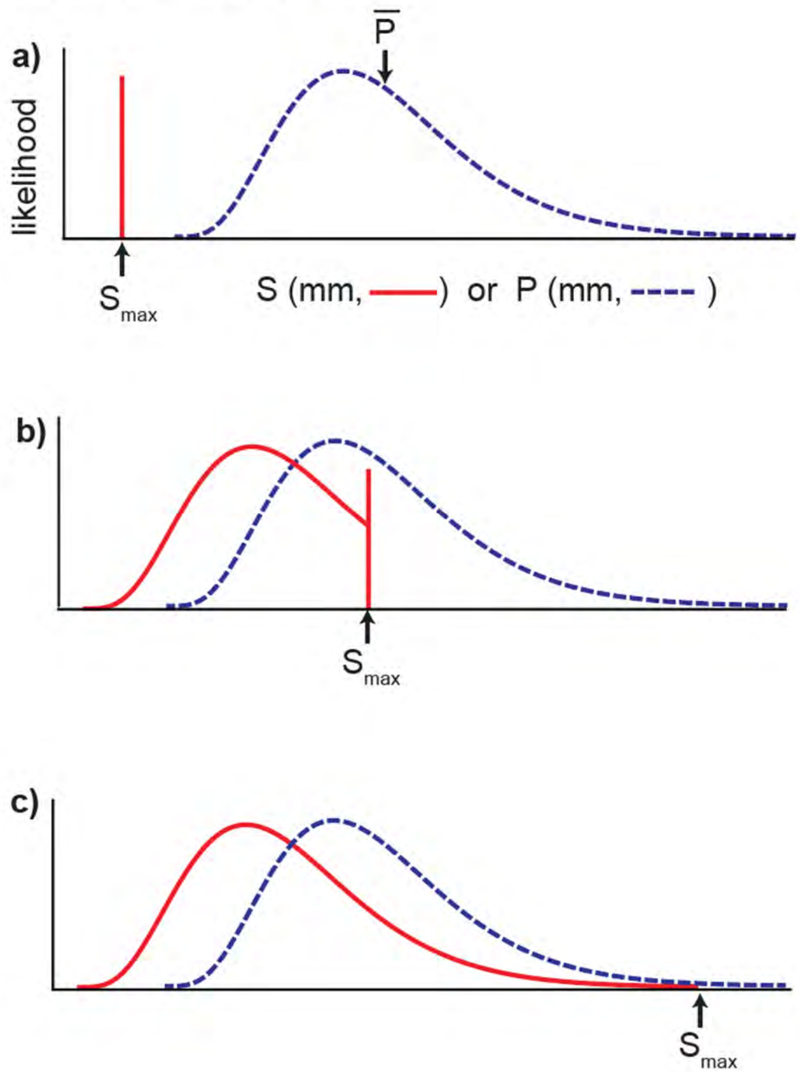
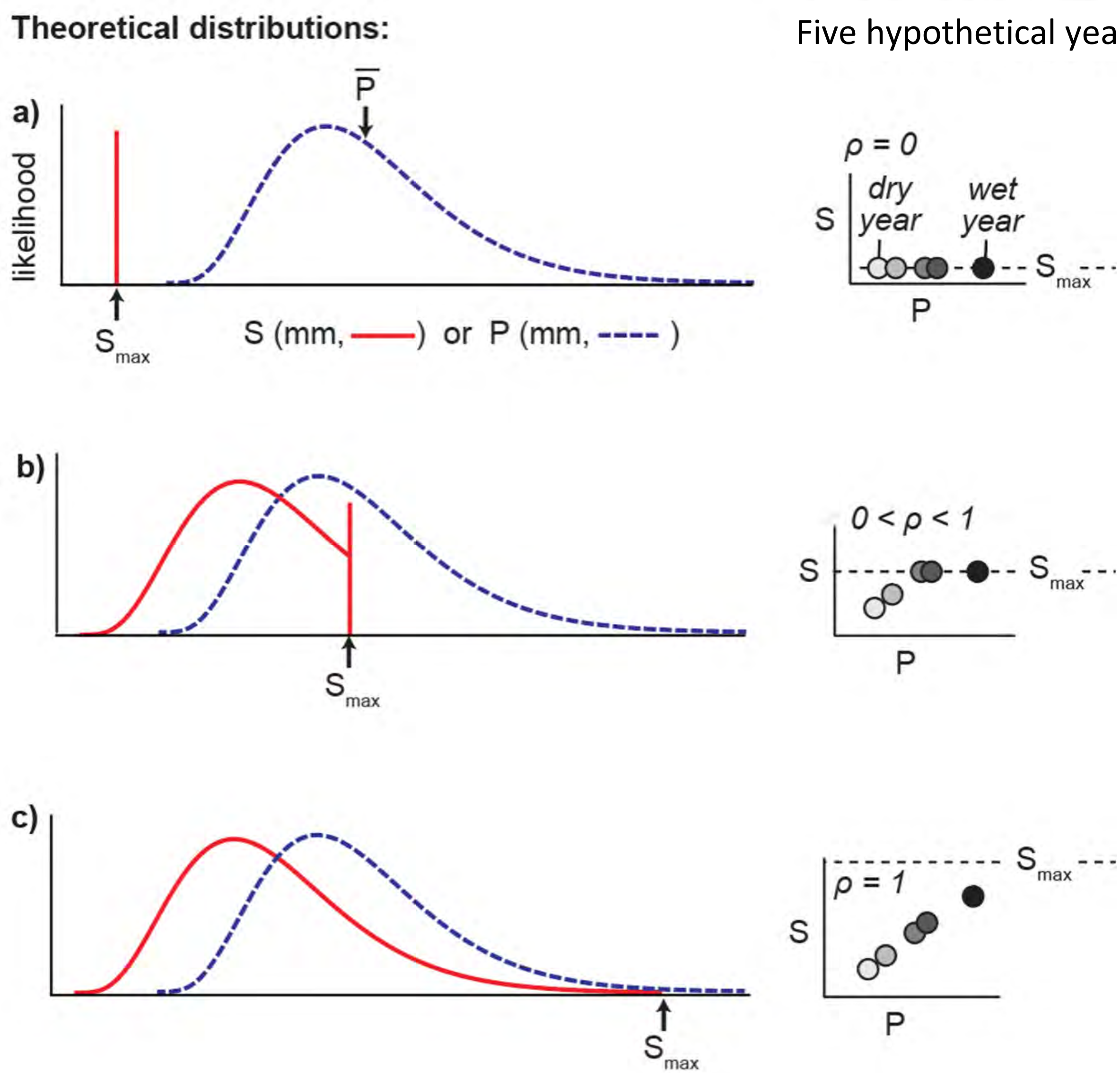


Total precipitation can be modeled as a random gamma-distributed variable

Theoretical distributions:





Theoretical distributions:
Five hypothetical years
a)
likelihood
P̄
S_{max}
S (mm, ——) or P (mm, - - - -)
ρ = 0
S
dry year
wet year
S_{max}
P
b)
S_{max}
0 < ρ < 1
S
S_{max}
P
c)
S_{max}
S_{max}
ρ = 1
S
P

Contours are strength of correlation between end-of-wet season storage and cumulative rainfall