From Groundwater to Streamflow: Exploring the Science, Projects, and Policies to Manage Groundwater Resources to Support Streamflows for Salmon and Public Trust Resources

A Concurrent Session at the 41st Annual Salmonid Restoration Conference
Santa Rosa, California, March 26-29, 2024

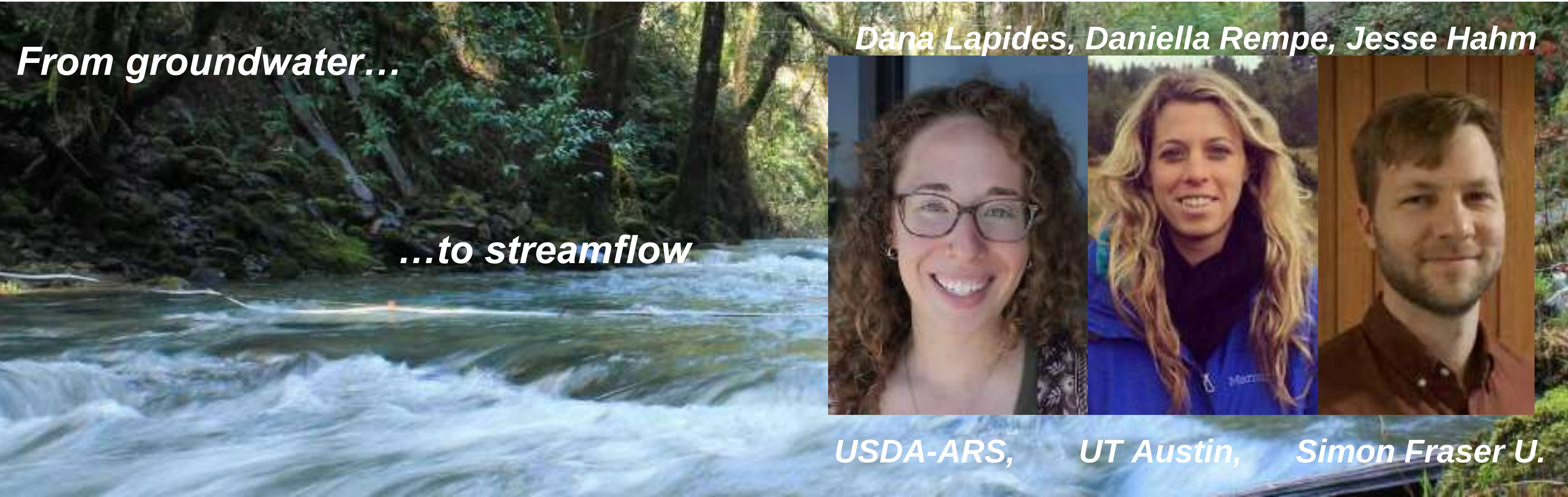
Session Coordinators: Monty Schmitt, The Nature Conservancy; **Matt Clifford**, JD, Trout Unlimited; and **David Dralle**, Ph.D., U.S. Forest Service, Pacific Southwest Research Station

Groundwater contributions to instream flows, particularly in the dry season, are essential for the restoration of rivers and the recovery of salmonid populations. Historic logging practices, changes in land use, the legacy of fire exclusion, and increasing well diversions have all contributed to depleted streamflows. Efforts to manage groundwater resources, like the Sustainable Groundwater Management Act and recent efforts by county planning departments, have yet to address the complex technical and regulatory issues associated with avoiding or mitigating existing cumulative impacts and permitting for new wells. Additionally, existing state-wide legislation manages groundwater only in large groundwater basins like the Central Valley, neglecting the essential role of hillslope groundwater systems in the small headwater watersheds that support salmon populations. Increasingly, groundwater infiltration and recharge projects are being proposed, but securing permits for restoration actions and predicting the benefits of actions are not always straightforward. This session will address three main challenges and explore solutions regarding groundwater modeling of streamflow depletion in diverse (geology, biome, etc.) landscapes; designing and permitting infiltration and flood recharge projects; and efforts to develop county groundwater well ordinances to protect public trust resources.

Presentations

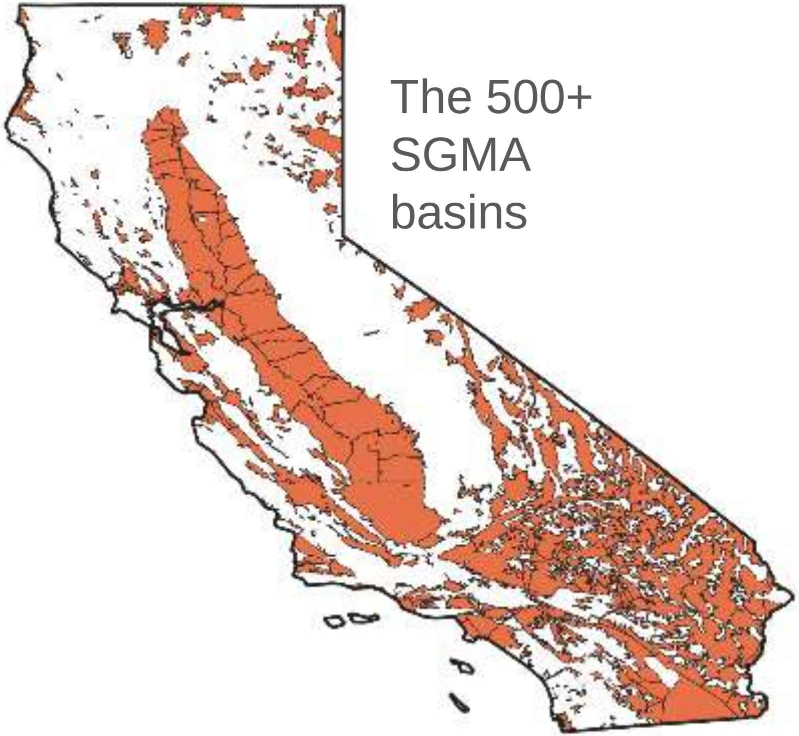
Process controls on low flows in headwaters: What do we know (and not know, but could) that can help inform management?

David Dralle, USDA Forest Service Pacific Southwest Research Station
Salmonid Restoration Federation Conference 2024



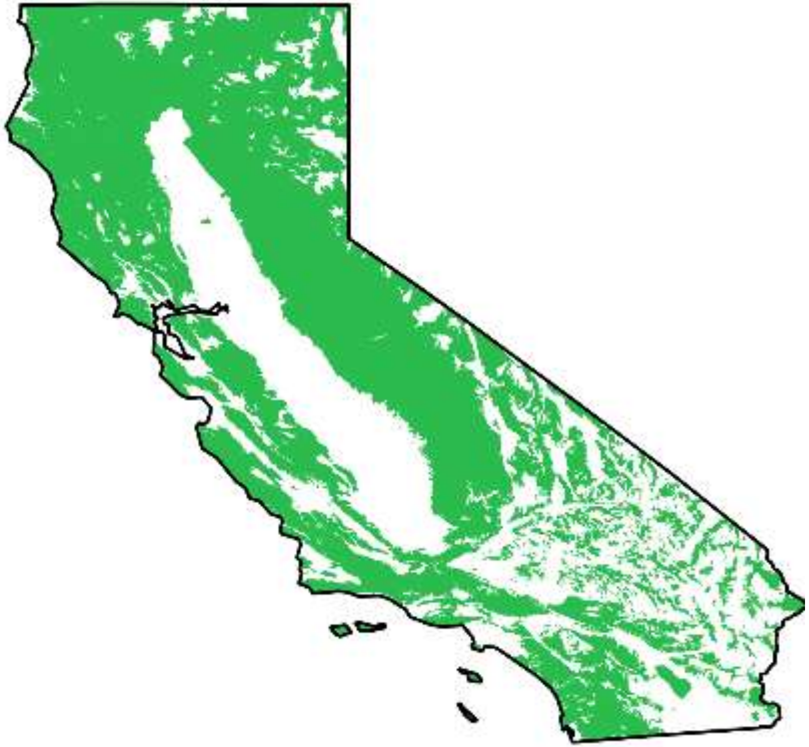
Groundwater in California

where we manage for it…



The 500+
SGMA
basins

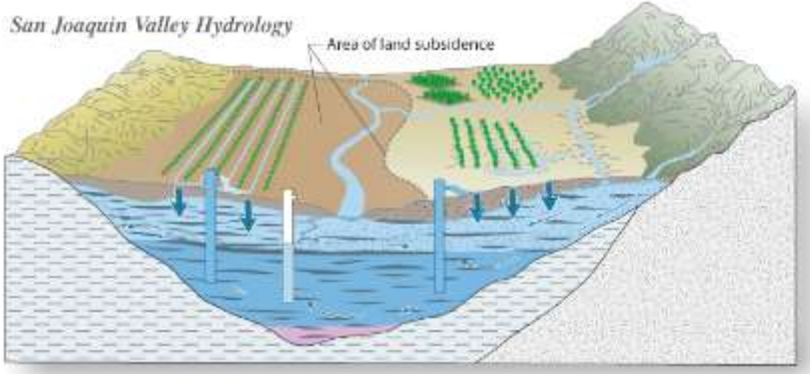
and where we don’t….



Where is groundwater?

where we manage for it…

and where we don't….



Today’s talk

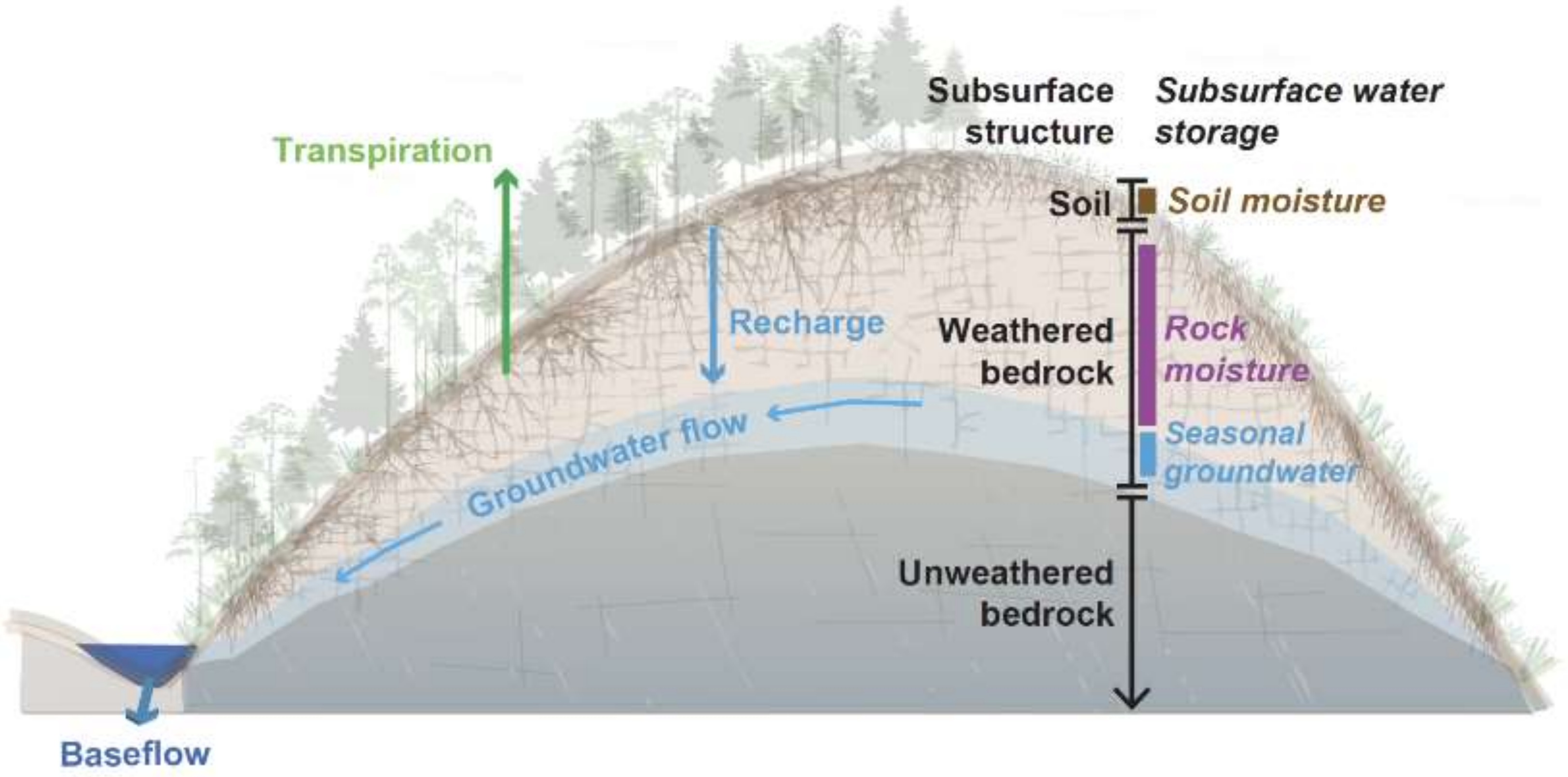
Where is groundwater?

How does groundwater drain and produce flow?

How is groundwater refilled?

Pressing management questions?

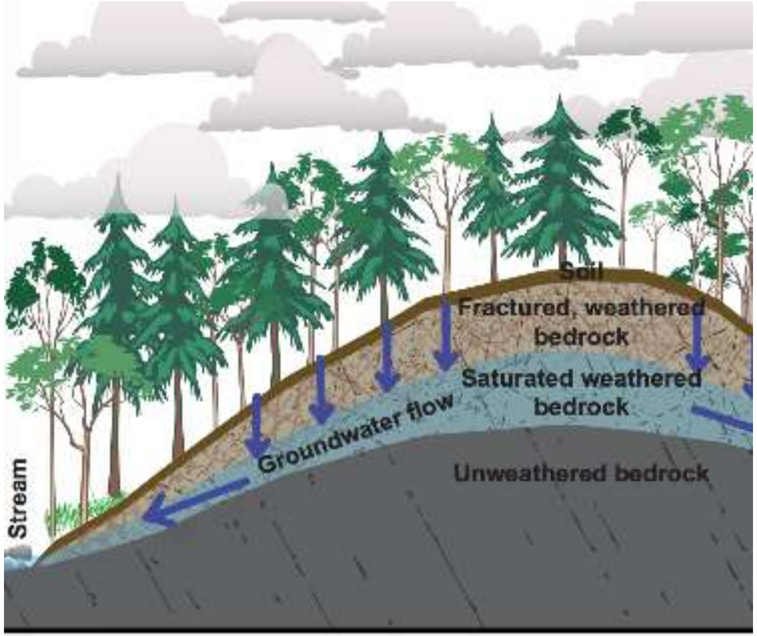
Where is groundwater?



Dupuit 1863, Freeze 1974, Salve et al 2012, Troch et al 2013, Rempe and Dietrich 2018, Hahm et al 2019

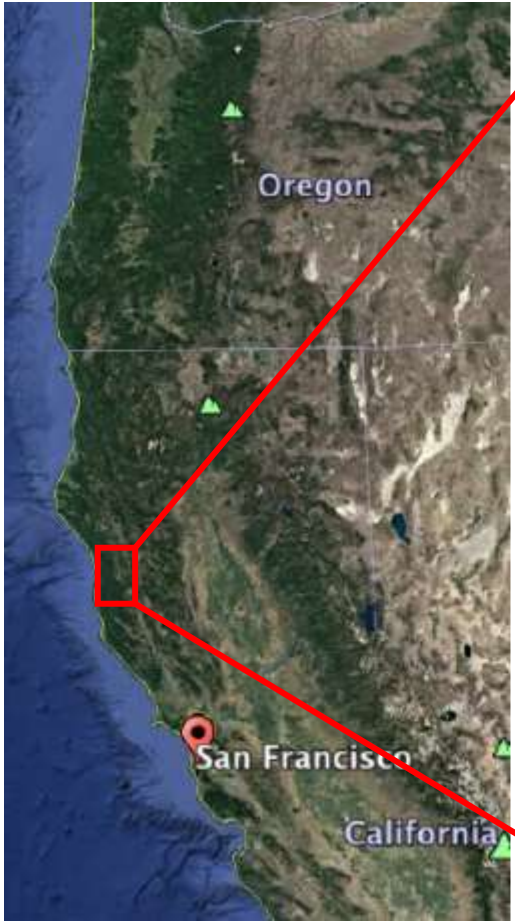
General observations of hillslope groundwater systems:

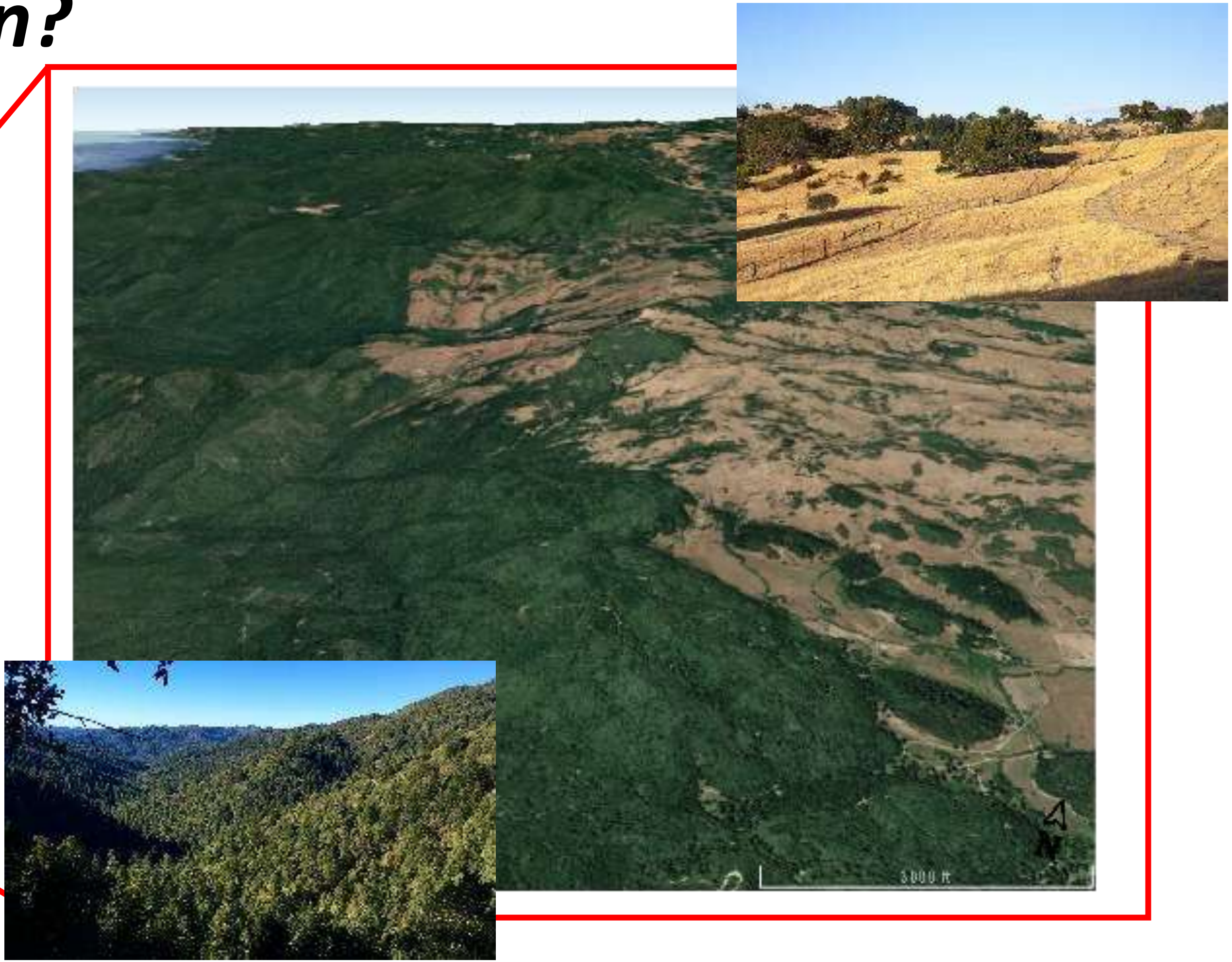
- Saturated “slab” atop fresh bedrock that slopes and drains toward streams
- Resides within fractured rock, not soil
- Deepest at the ridge
- Drives most or all of streamflow generation (even during very wet periods), especially during the dry season
- Highly responsive to individual storms (quick to drain)
- May or may not be recharged in a given year, depending on precipitation
- By volume (e.g. mm), smaller than unsaturated root zone storage

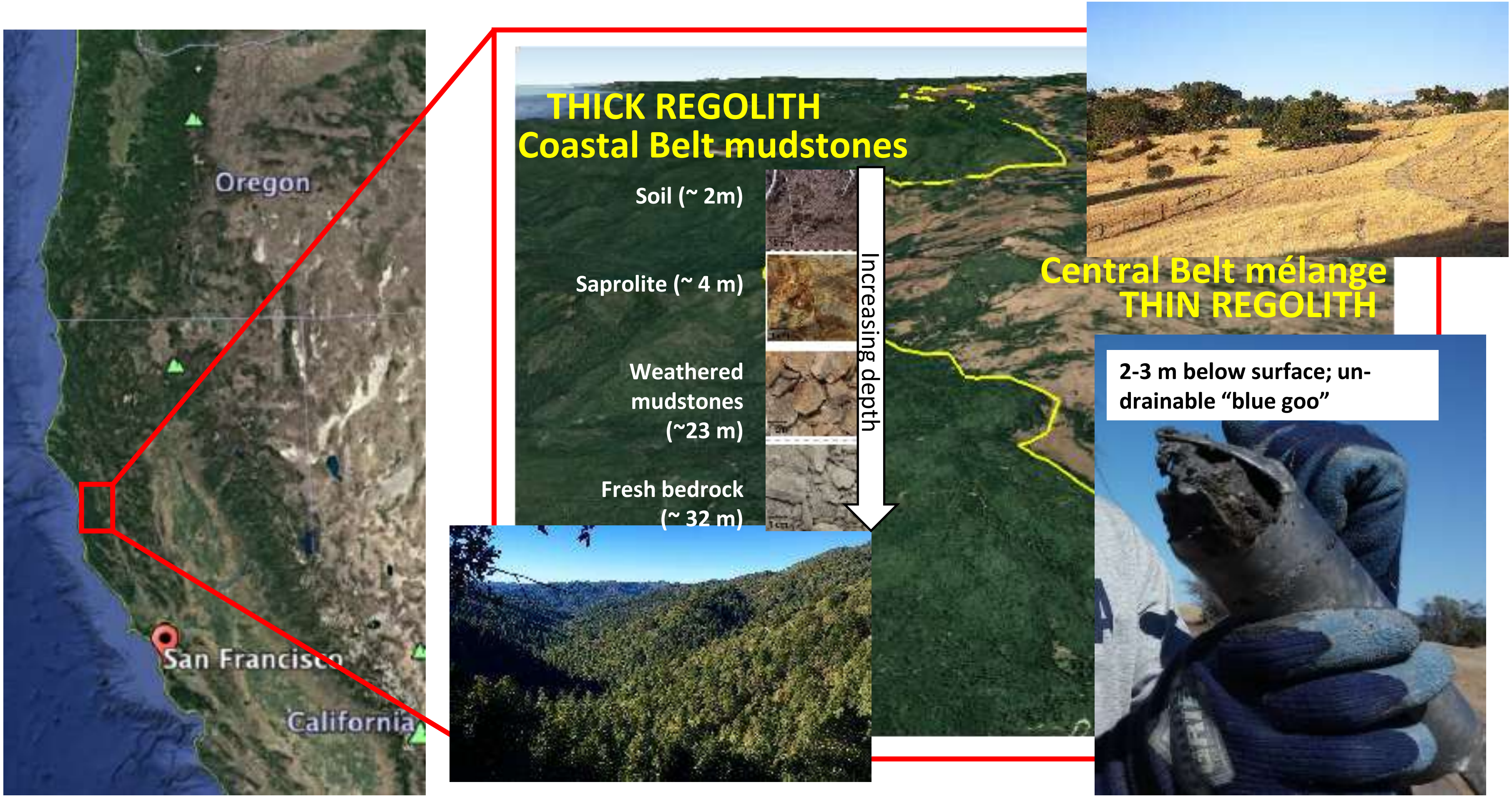


Conceptual diagram modified from original by Daniella Rempe

How does it drain?

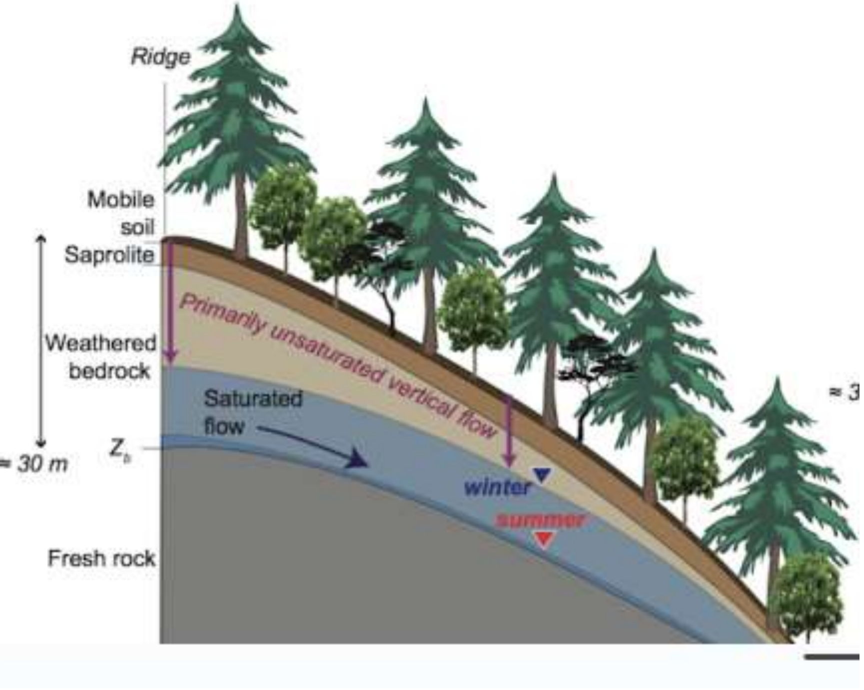


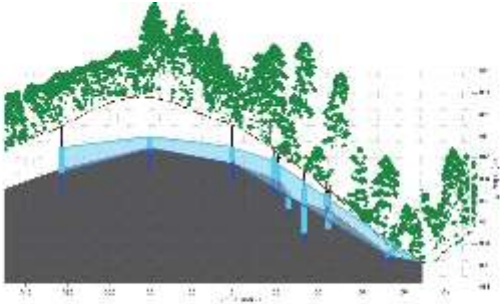


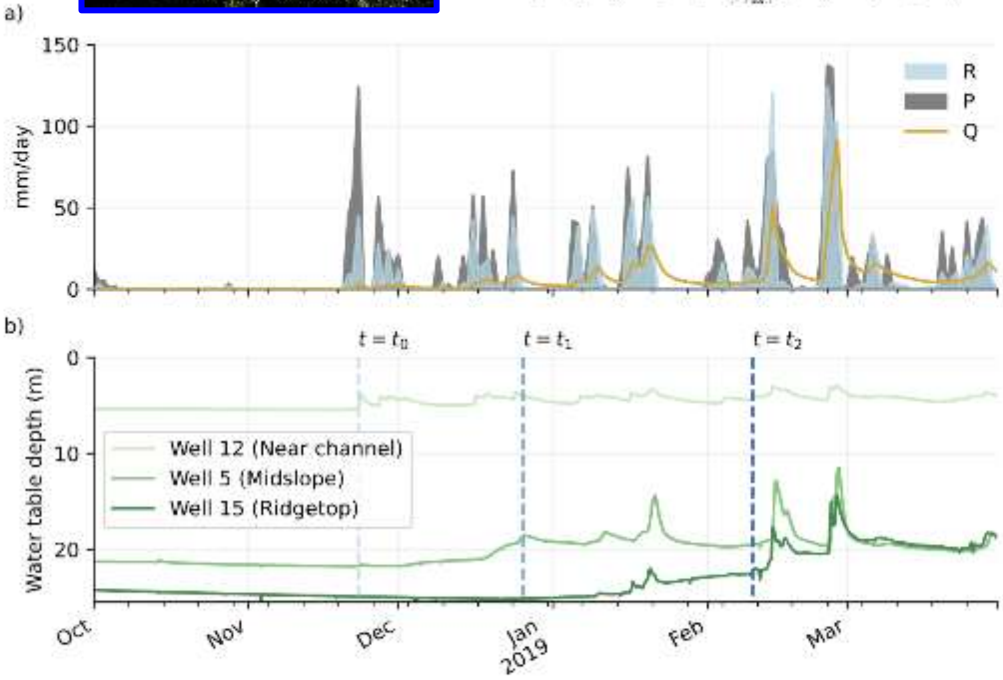


Hahm, Rempe, Dralle, et al, *Water Resources Research*, 2019

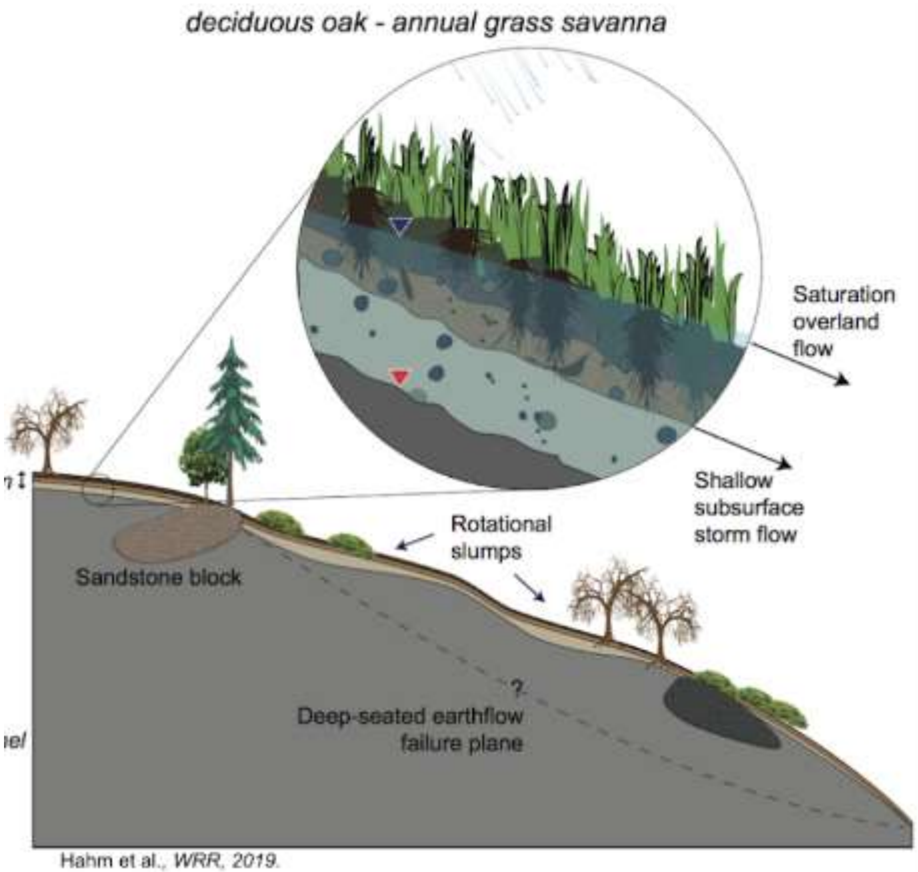
Lateral, subsurface flow

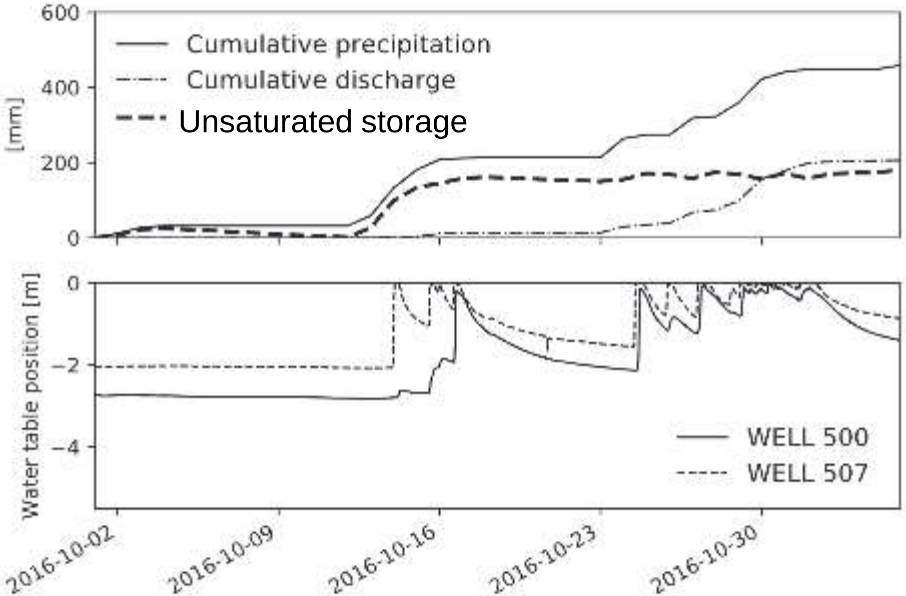






Saturation overland flow

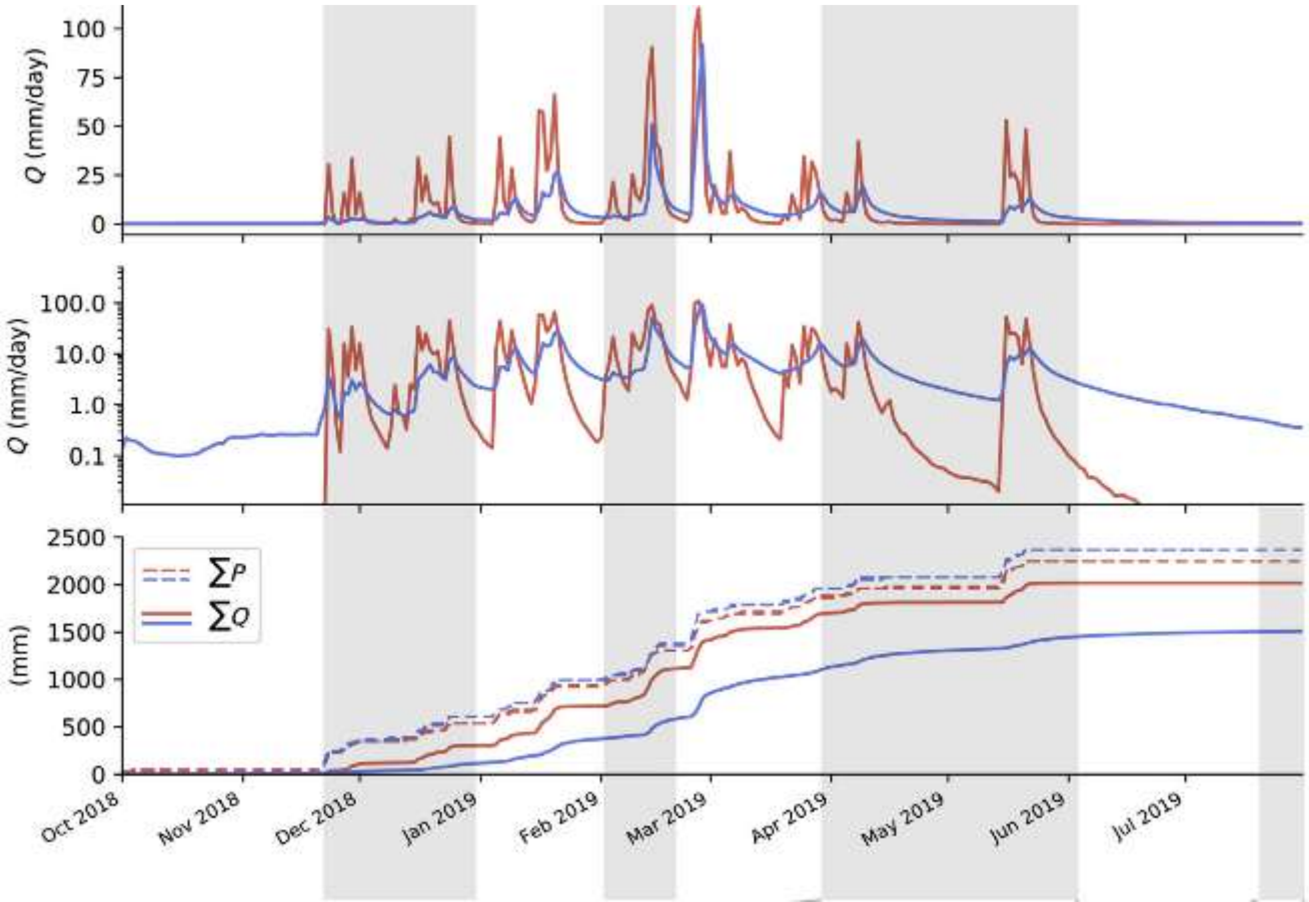


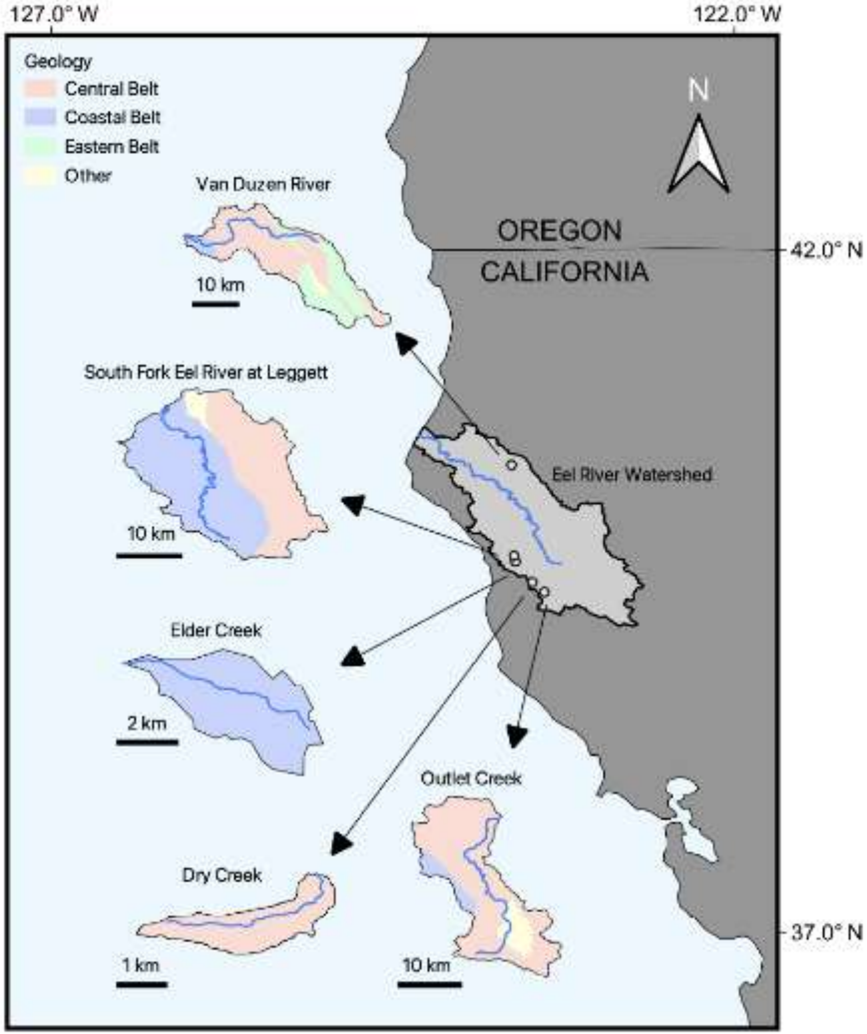


In both cases, groundwater mediates all aspects of flow regime (see Dralle et al 2023, “Salmonid and the subsurface…”)

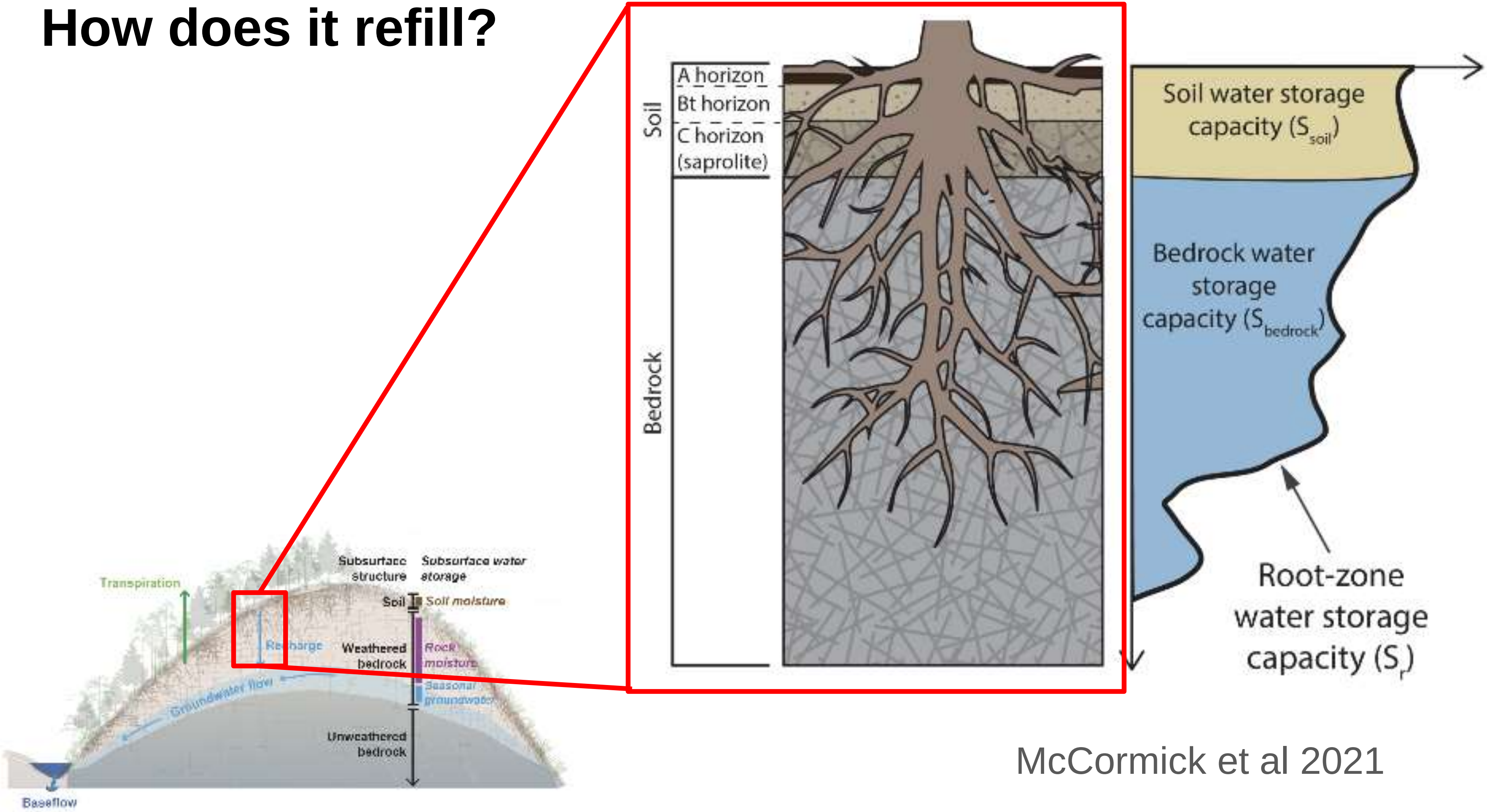
Low storage

High storage




127.0° W
122.0° W
Geology
Central Belt
Coastal Belt
Eastern Belt
Other
N
Van Duzen River
10 km
OREGON
CALIFORNIA
42.0° N
South Fork Eel River at Leggett
10 km
Eel River Watershed
Elder Creek
2 km
Outlet Creek
Dry Creek
1 km
10 km
37.0° N

How does it refill?

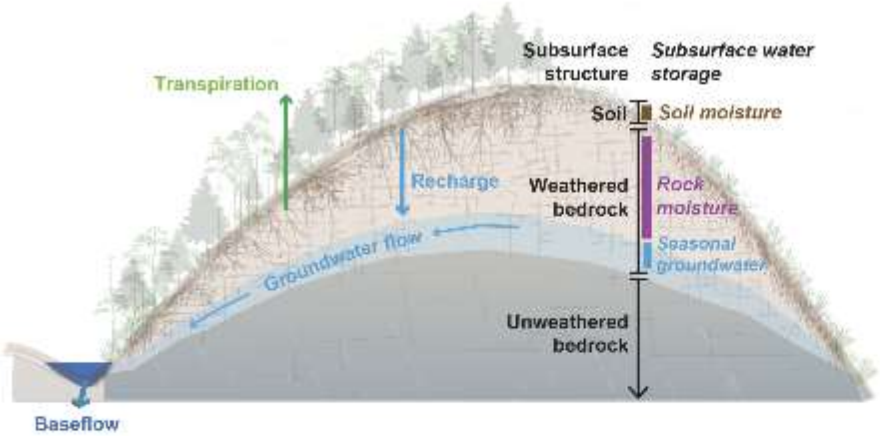


McCormick et al 2021

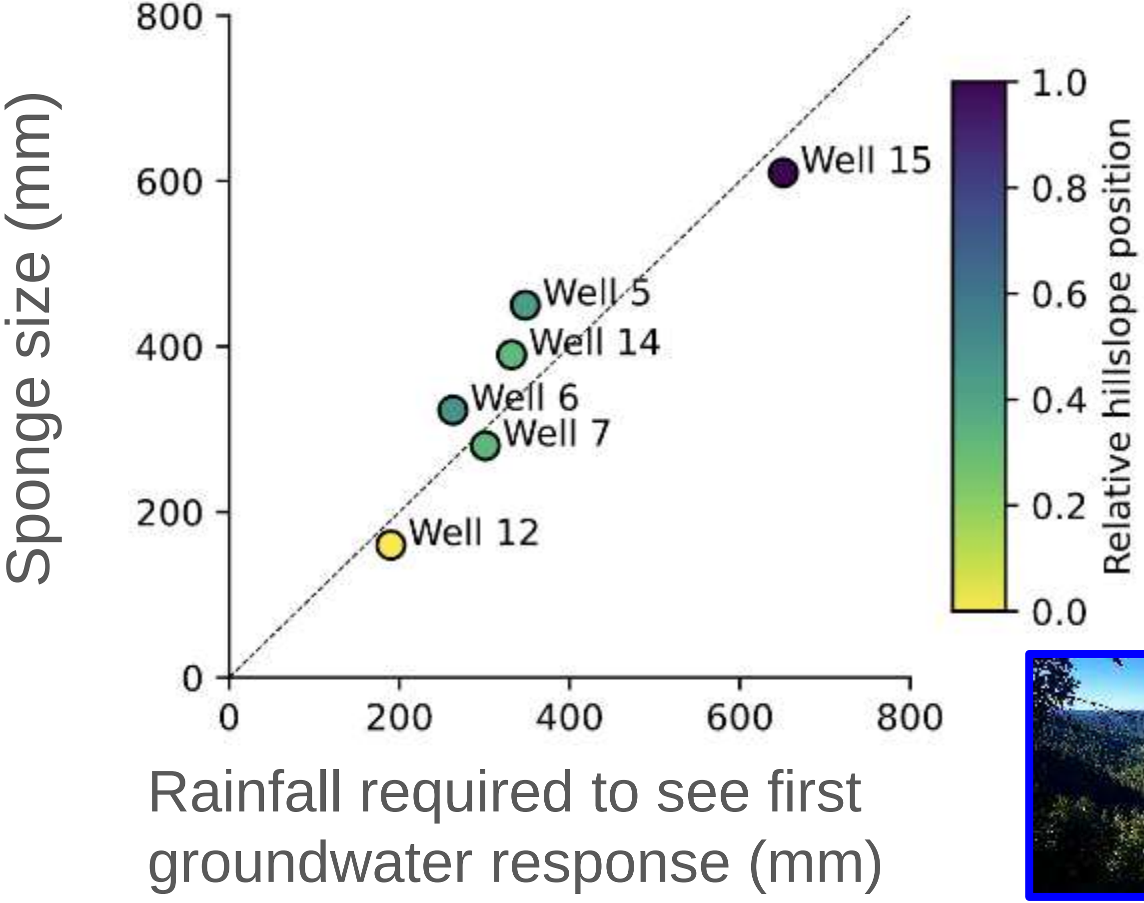
 ≈ 

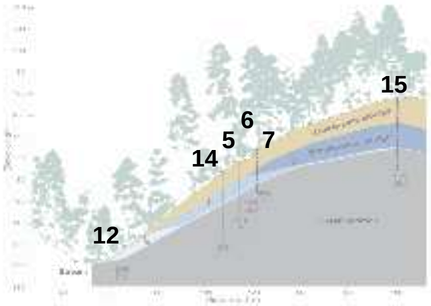
Wisdom of the ***unsaturated*** sponge

Wet sponge drips excess water, and stays wet



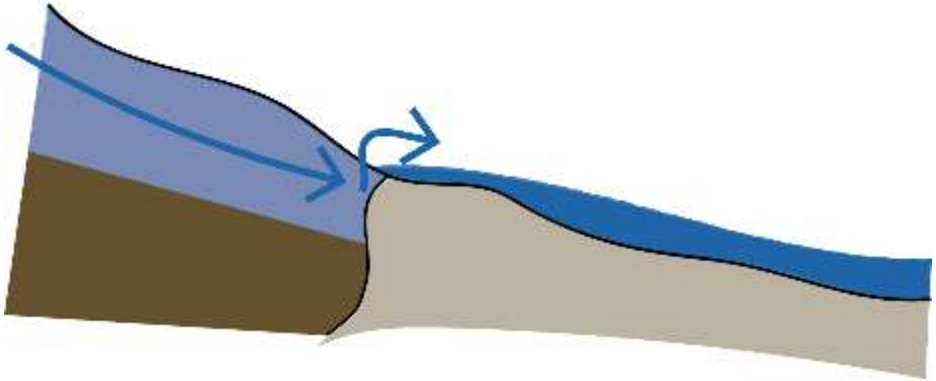
Evaporation fully dries the wet sponge


Sponge size (mm)
800
600
400
200
0
0
200
400
600
800
Well 15
Well 5
Well 14
Well 6
Well 7
Well 12
1.0
0.8
0.6
0.4
0.2
0.0
Relative hillslope position
Rainfall required to see first groundwater response (mm)

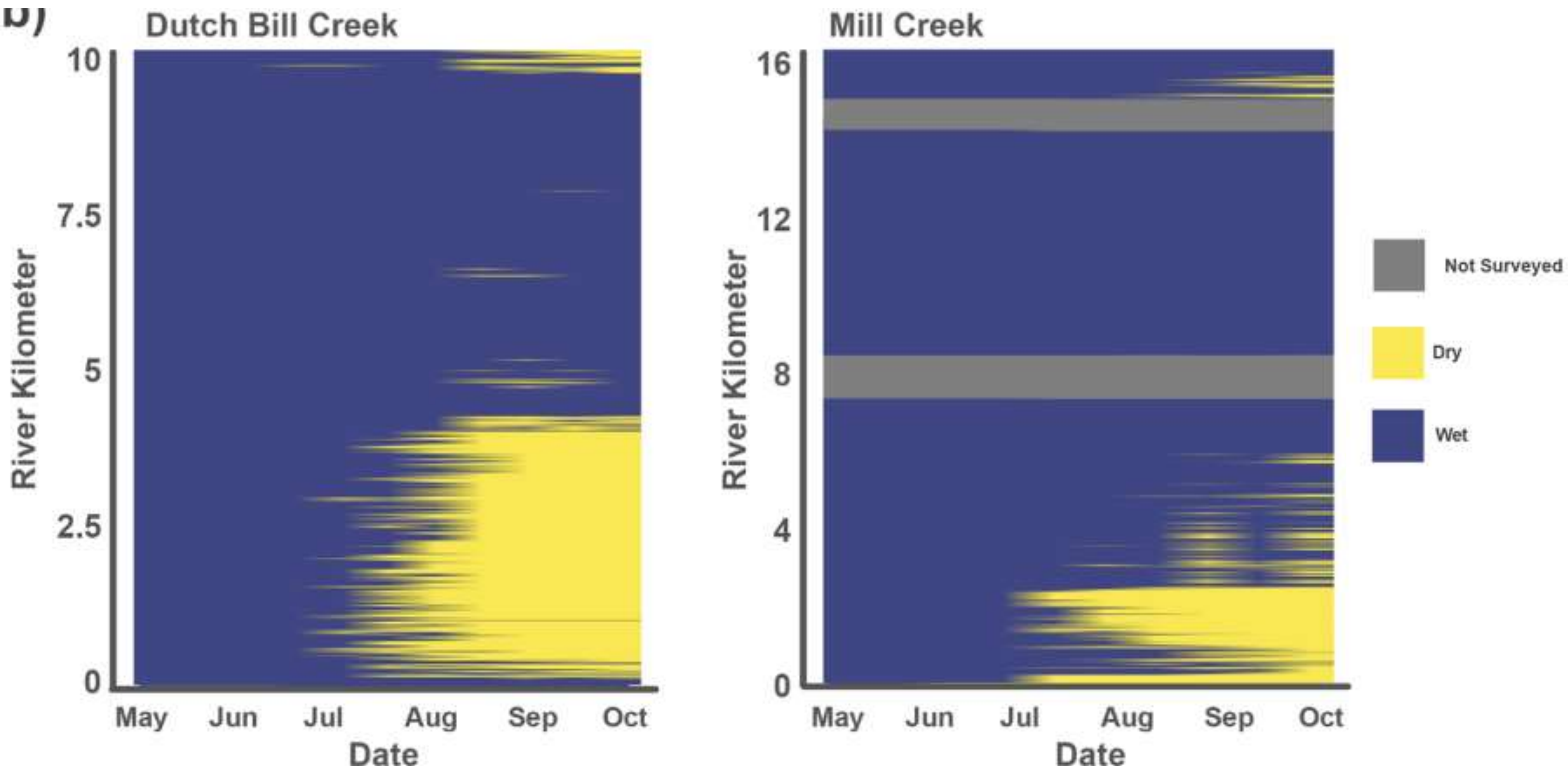

15
6
5
7
14
12

Channel conditions really matter at low flows

Surface flow appears where flow from upstream exceeds the capacity of the subsurface

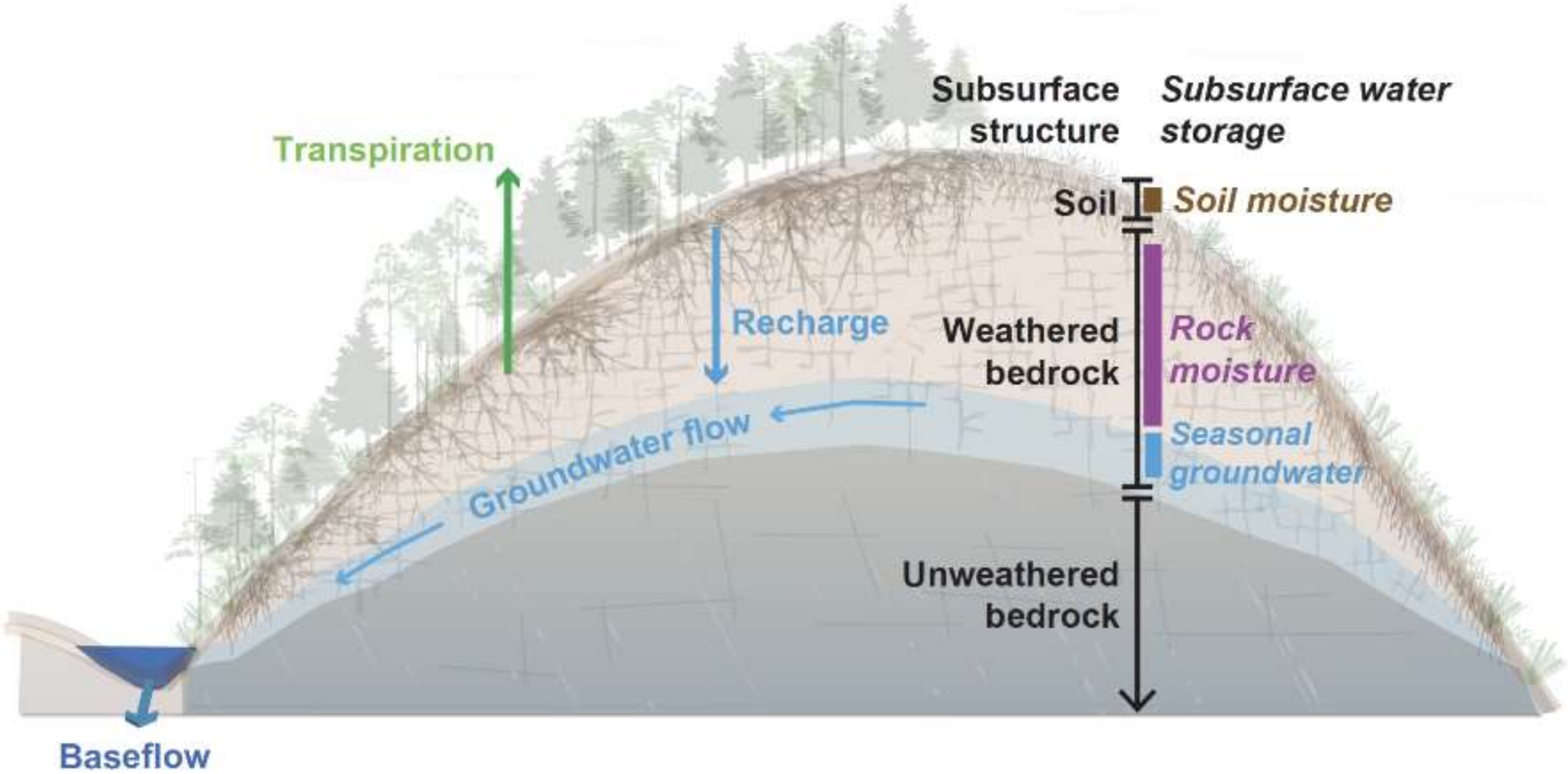


Godsey and Kirchner. Hydrological Processes, 2014.



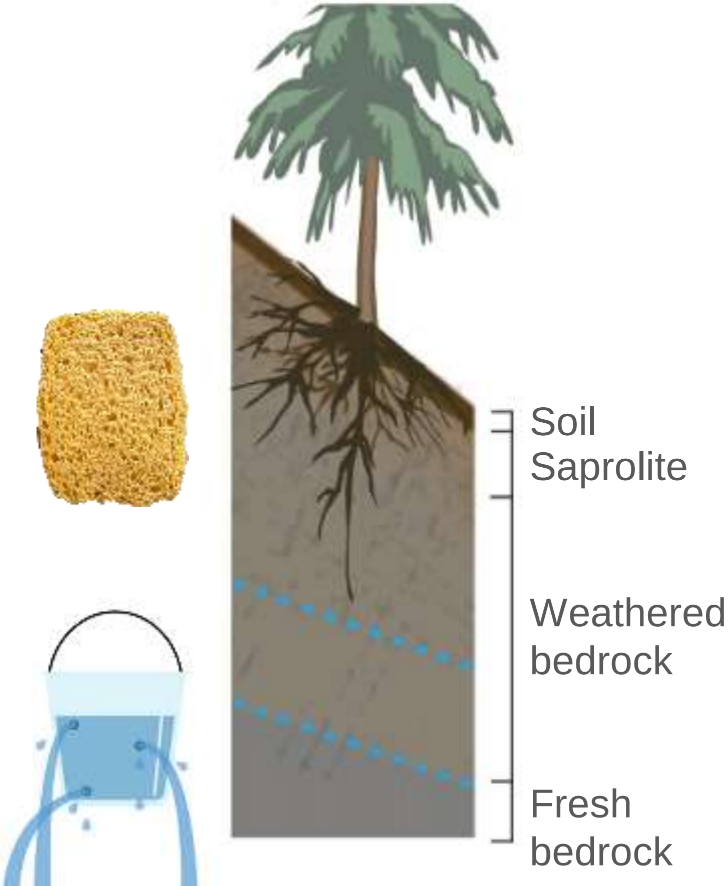
Moidu et al 2021

What are key unanswered questions?



How should I manage vegetation to increase low flows?

Where do roots get water? Unsaturated “sponge” vs. groundwater



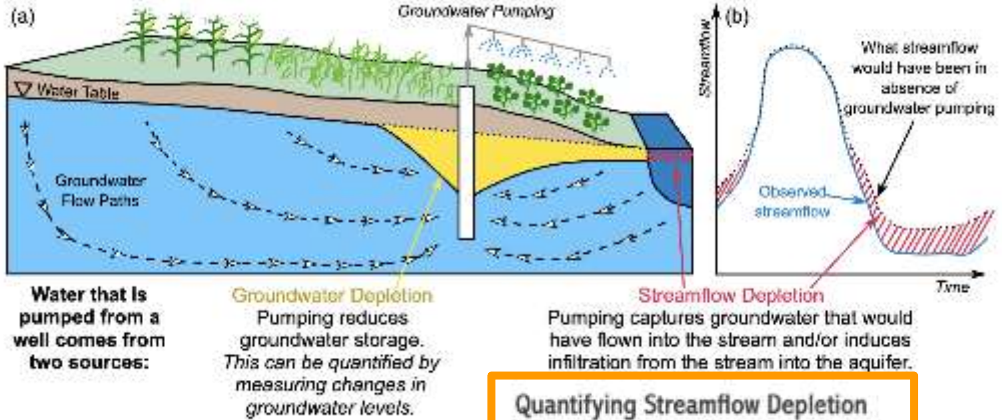
Roots in the unsaturated sponge primarily affect recharge (drippy sponge)
=> Indirect impact on low flows

Roots in the saturated bucket “pump” groundwater
=> Direct impact on low flows

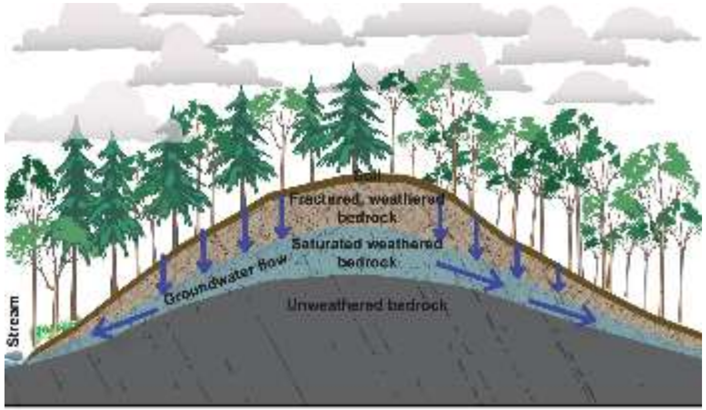
The Other Water Users:
How Plant and Human Water Use Impact Streams
Dana A Lapides, USDA-ARS
SW Watershed Research Center

How does pumping impact flows?

Adapt existing models, develop some new ones?



e.g. Zipper et al 2019



Conceptual diagram modified from original by Daniella Rempe

Quantifying Streamflow Depletion from Groundwater Pumping Using Storage-Discharge Functions in Headwater Catchments
Phil Georgakakos, Ph.D., UC Berkeley

Unified Modeling Approaches to Estimating Streamflow Depletion Due to Groundwater Pumping, Nick Murphy, The Nature Conservancy

Approaches for Evaluating Streamflow Depletion; Shedding Some Light on the Secret, Occult, and Concealed Nature of Surface Water/Groundwater Interactions, Jeremy Kobor, MS, PG, OEI, Inc

Effects of Short-Term Flow Reductions on Juvenile *O. mykiss*: An Experiment at the Sierra Nevada Aquatic Research Lab
Kelly Goedde-Matthews, UC Davis, Center for Watershed Sciences

Can I slow down groundwater drainage and get more later?

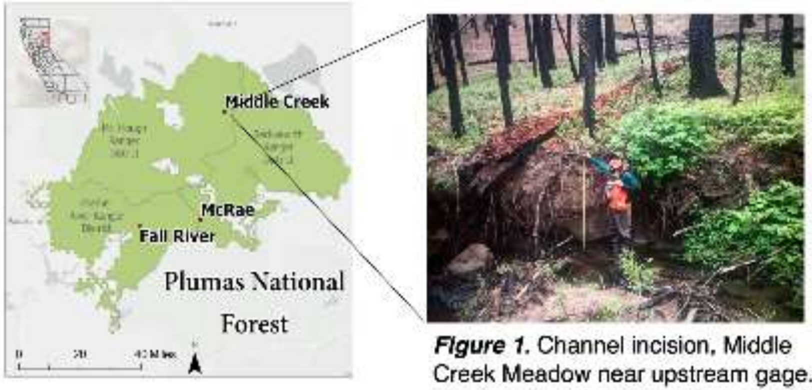
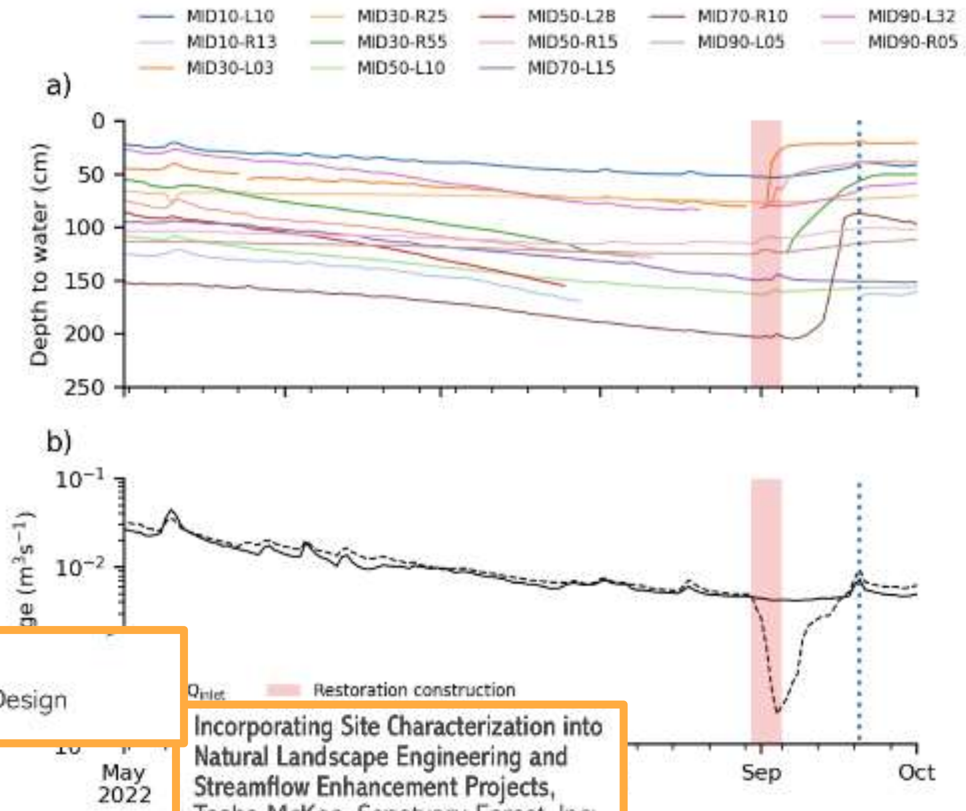


Figure 1. Channel incision, Middle Creek Meadow near upstream gage.
Map Credit: Adam Cummings, PSW



Short-Term Hydrologic Responses to Process-Based Restoration
Emma Sevier, MS, Cal Poly Humboldt

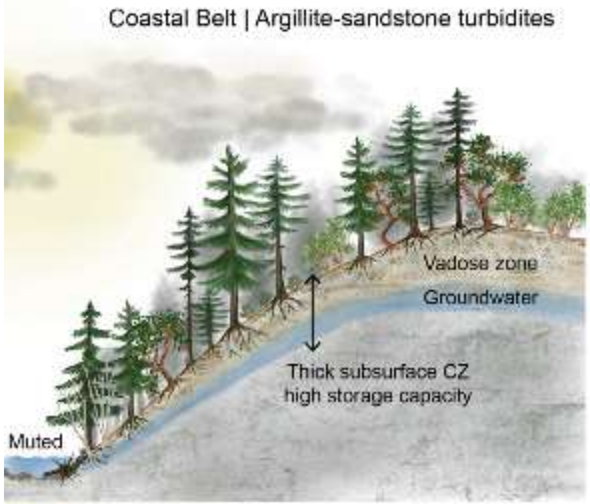
Process-Based Restoration in Burned Headwater Meadows: Exploring Potential for Sediment Storage and Floodplain Reconnection
Kate Wilcox, USDA Forest Service, Pacific Southwest Research Station

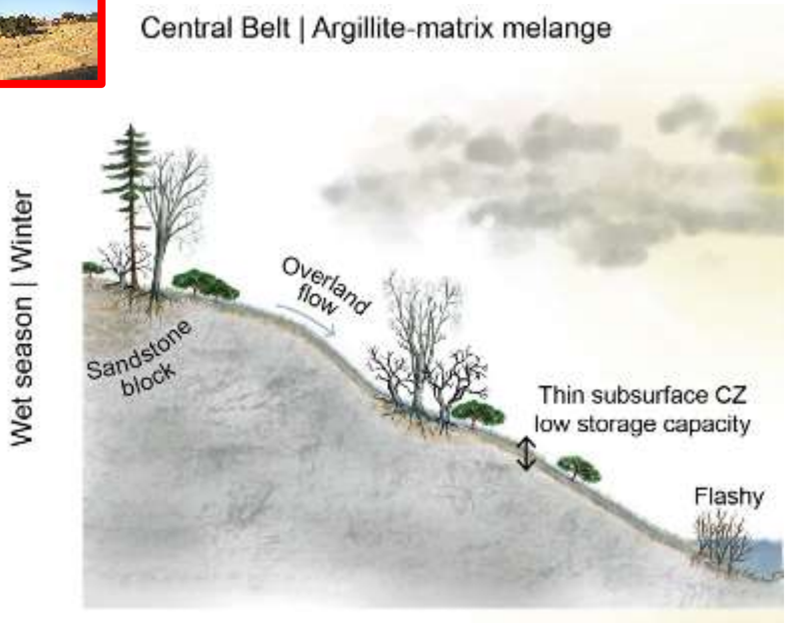
Well? Did it Work?
Kevin Swift, Swift Water Design

Incorporating Site Characterization into Natural Landscape Engineering and Streamflow Enhancement Projects,
Tasha McKee, Sanctuary Forest, Inc; and Wyeth Wunderlich, EBA Engineering

t al, in review

Can we increase low flows by increasing recharge?





Small-Scale Groundwater Recharge Opportunities for Streamflow Augmentation, Little Mill Creek, Navarro River Watershed

Christopher Woltemade, Ph.D.,
Prunuske Chatham, Inc.

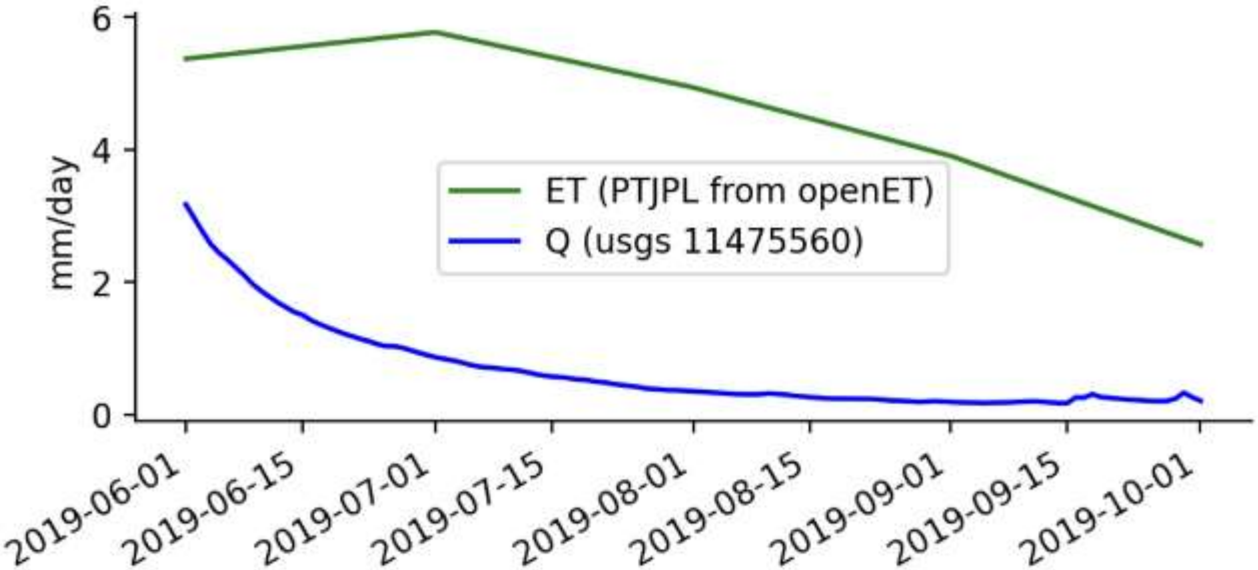
Presentation:
https://bit.ly/49kyEv8

THANKS!

Please feel free to email:
david.dralle@usda.gov

Pacific Southwest Research Station

Important: this dynamic storage is primarily depleted by plants in summer



summer transpiration (50 - 130 mm/month) >> runoff (5-10 mm/month)

(in Coastal Belt)

The Nature Conservancy

Unified Modeling Approaches to Estimating Streamflow Depletion due to Groundwater Pumping

The Nature Conservancy, University of Kansas, O'Connor Environmental Inc., Foundry Spatial

Nicholas Murphy, PhD – 3/29/24


Why do we care?
Image Credit © DAVID VARGAS F/TNC Photo Contest 2022
The Nature Conservancy

UNCHARTED WATERS

America Is Using Up Its Groun[d...]
Like There's No Tomorro[w]

CALIFORNIA DEPAR[TMENT...]
SUSTAINABI[LITY...]

SANTA CRUZ COUNTY
ENVIRONMENTAL HEALTH

About Us | Program[s]

Well Ordinance Up[date]

NEW HOME > PROGRAMS > WATER RESOURCES > WELL ORDINANCE UPDATE

Meeting Materials

Meeting 3

Agenda

Stream and Well Impact Considerations Memo

Public Trust Protection Comments and Response

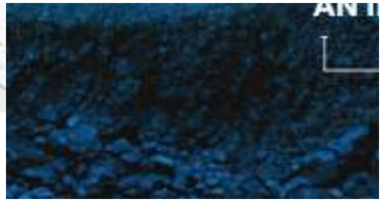
Santa Cruz County Environmental Health staff are conveni[...]
(Well TAC) to provide County Staff with guidance, recomm[...]
policy matters pertaining to the update of the Water Wells [...]
Cruz County Code:

Water Wells Chapter (7.70)

Individual Water Systems Chapter (7.73)

Goal and Objectives

The goal of the TAC is to help staff develop an ordinance t[...]
well construction and use, while not creating an undue bur[...]



FOR IMMEDIATE RELEASE

Board of Supervisors gives initial approval to Well Ordinance update

Santa Rosa, CA | April 05, 2023

The Board of Supervisors on Tuesday gave initial approval to amendments to the county's Well Ordinance, which would create a new regulatory process for approving well permits.

Under the amendments, before a well permit may be approved, potential adverse impacts on public trust resources in navigable waterways, such as the Russian River, would be analyzed and mitigated to the extent feasible. The amendments were created to reflect the county's responsibilities under California's public trust doctrine regarding natural resources such as waterways.

See full Press Release on Permit Sonoma Website>>

Russian Riverkeeper (RRK) and our state association, California Coastkeeper Alliance, recently filed a challenge to the Sonoma County Well Ordinance update. While the new ordinance started the conversation around what is needed, the final amendment is too vague and has not analyzed whether it will protect fish and other resources as claimed. The stakes are too high to not take the time to get this policy right.

The Well Ordinance update was in response to a prior lawsuit against the County for failing to protect endangered fish and other resources from county-permitted wells. Existing wells are known to pump streams so low, and oftentimes even dry, that fish and other species become trapped and die. Beyond fish impacts, many families and small farms have had their wells go dry and are experiencing reduced water quality due to the recent drought and increased groundwater use. It is clear we have an issue now —unrestrained groundwater pumping cannot continue as it has.

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- Environmental Justice (12)
- Events (3)
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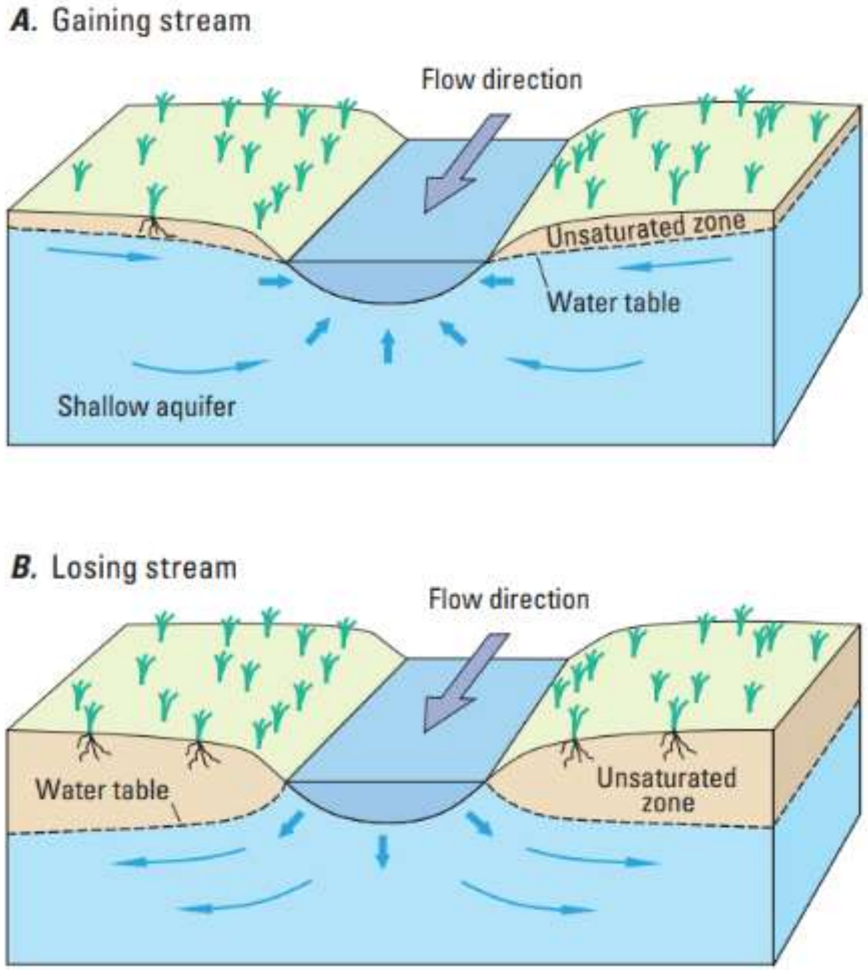
The Nature Conservancy

Interconnected Surface Water

“Surface water that is hydrologically connected at any point by a continuous saturated zone to the underlying aquifer…”

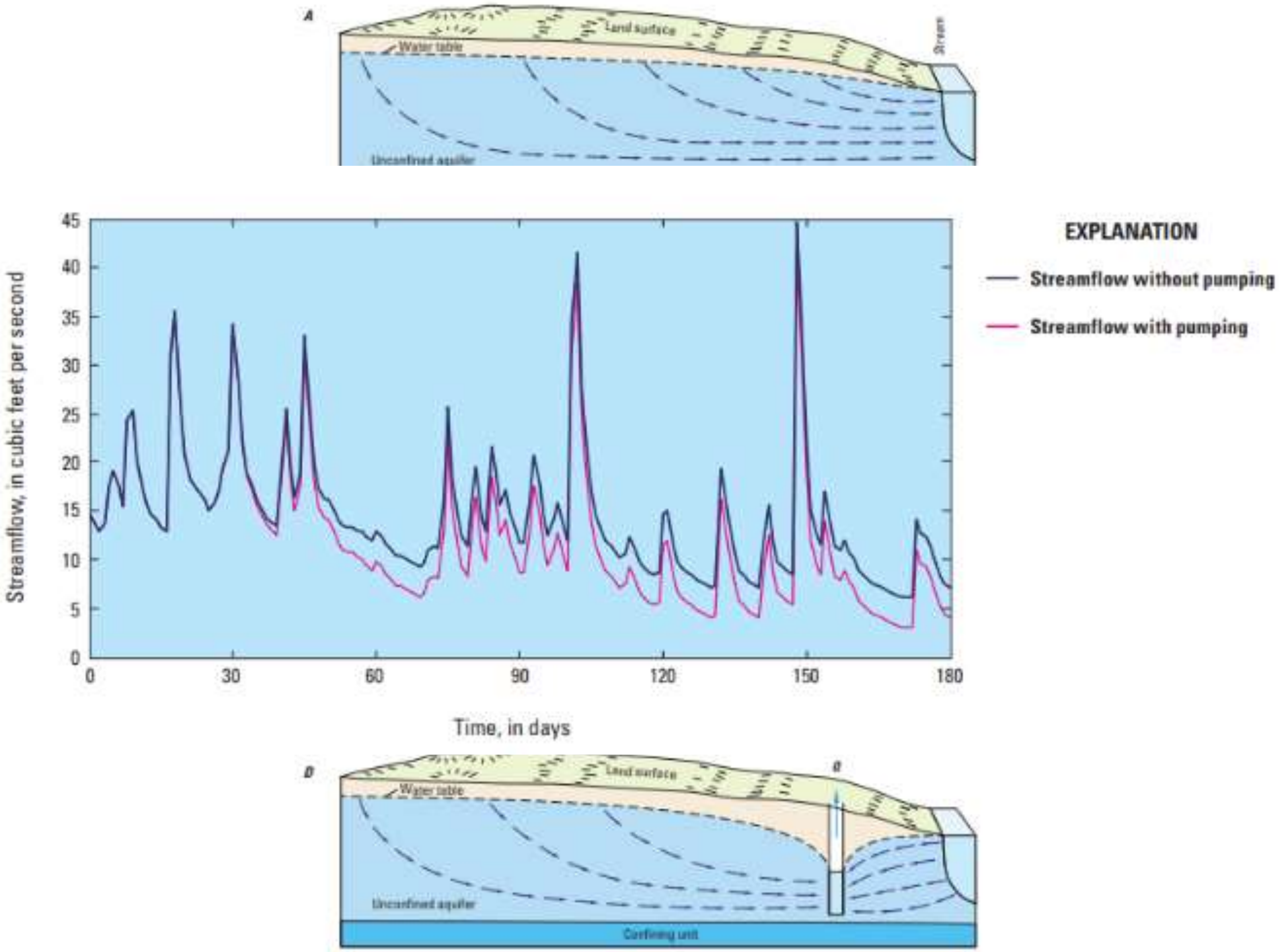
-Title 23 CA Code of Regulations



Barlow & Leake, 2012

Streamflow Depletion

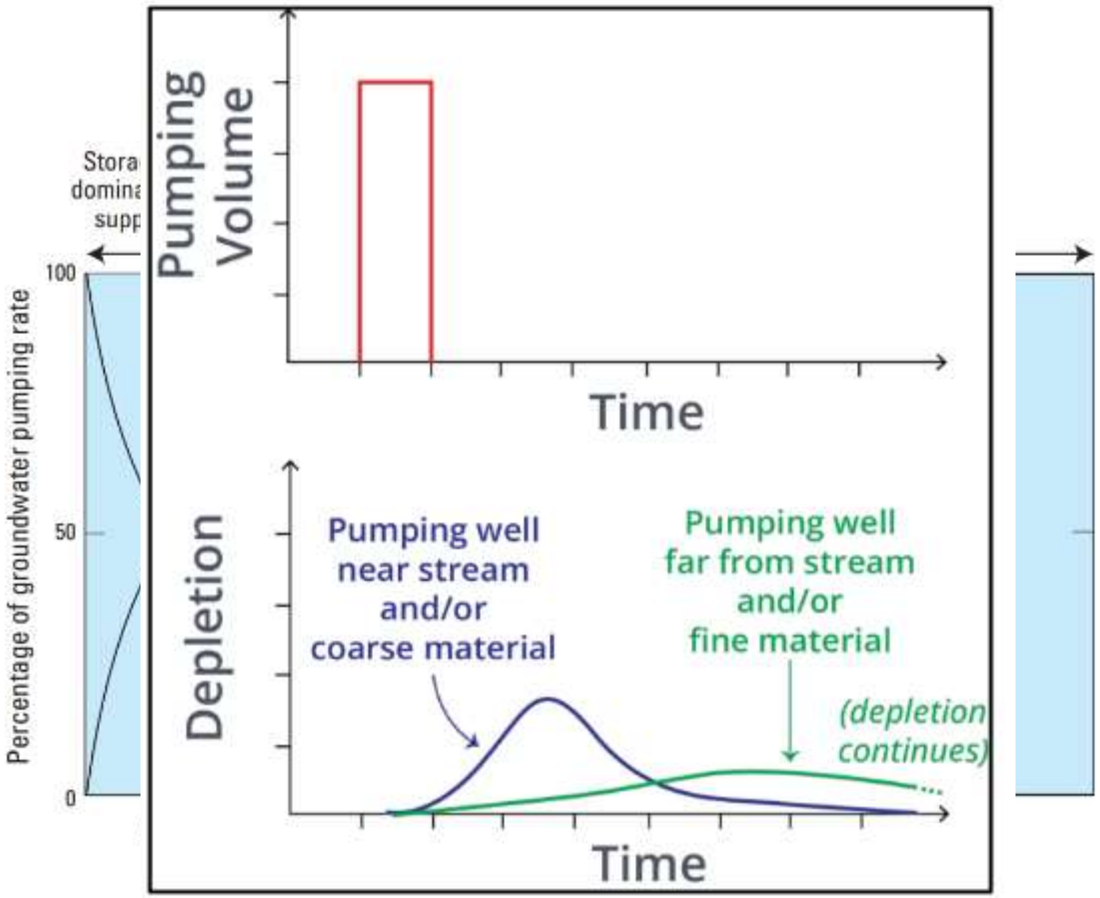
- Groundwater pumping results in streamflow depletion (reduction in flow and water level) of interconnected surface waters
  - Streamflow depletion occurs due to groundwater pumping, regardless of pumping volume or rate



Barlow & Leake, 2012

Streamflow Depletion

- Hydraulic properties of the aquifer systems influence system response to groundwater pumping
- Timing, location and magnitude of groundwater pumping is key to our understanding of streamflow depletion dynamics
- Over long timescales, a majority of pumped water comes from streamflow depletion



Barlow & Leake 2012, DWR 2024

The Nature Conservancy

Where are we working?

Image Credit © Bridget Besaw

The Nature Conservancy

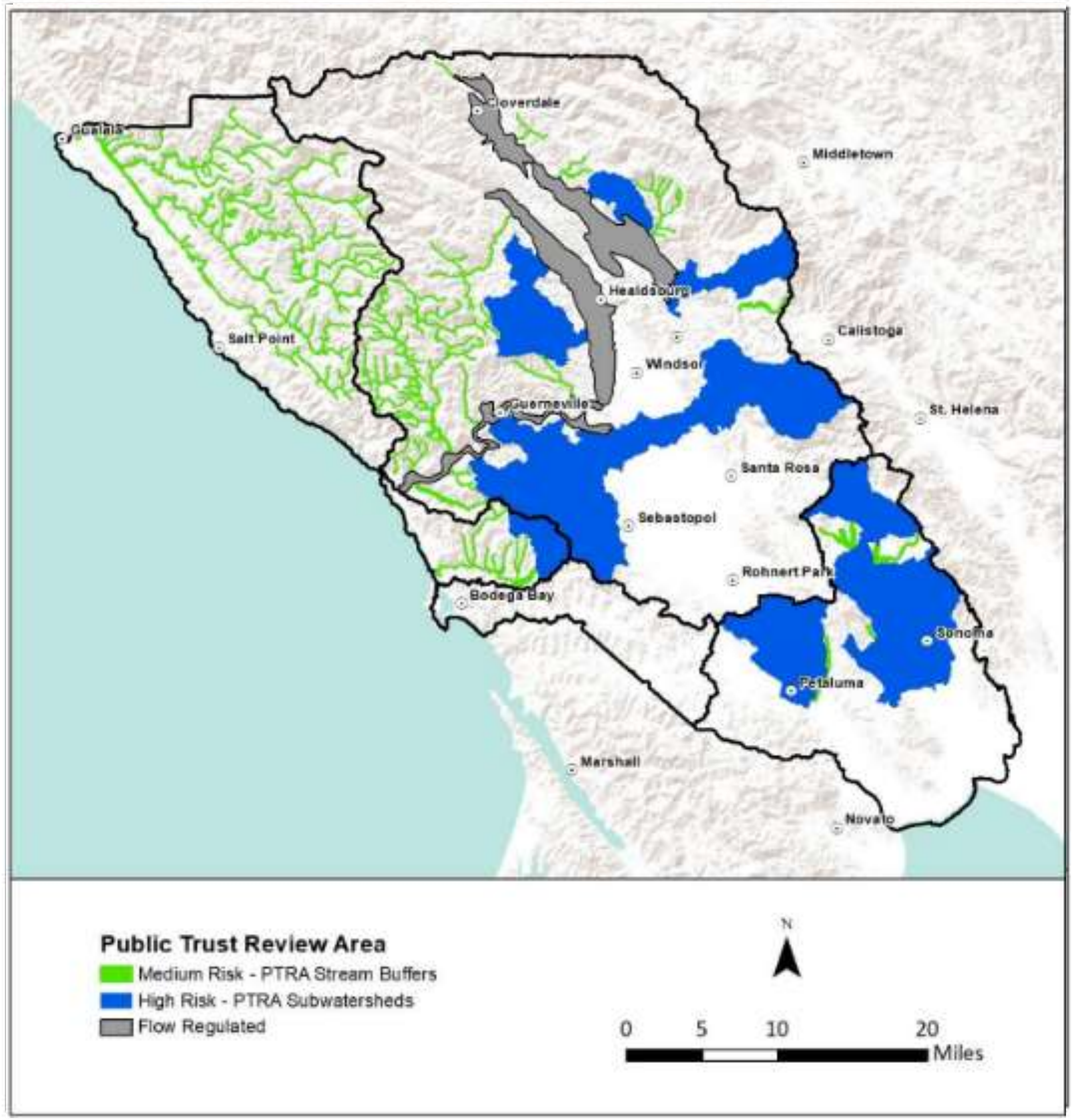
With respect to well ordinance revisions…

Sonoma County

Public trust resource impact analysis requires –

- Mapping habitat value
- Mapping existing and potential streamflow depletion impacts
- Development of a well-permitting framework based upon the best available science, informing policy

Working with partners on adaptive management plants to improve the protection of public trust resources



OEI & Permit Sonoma, 2023

Sonoma County

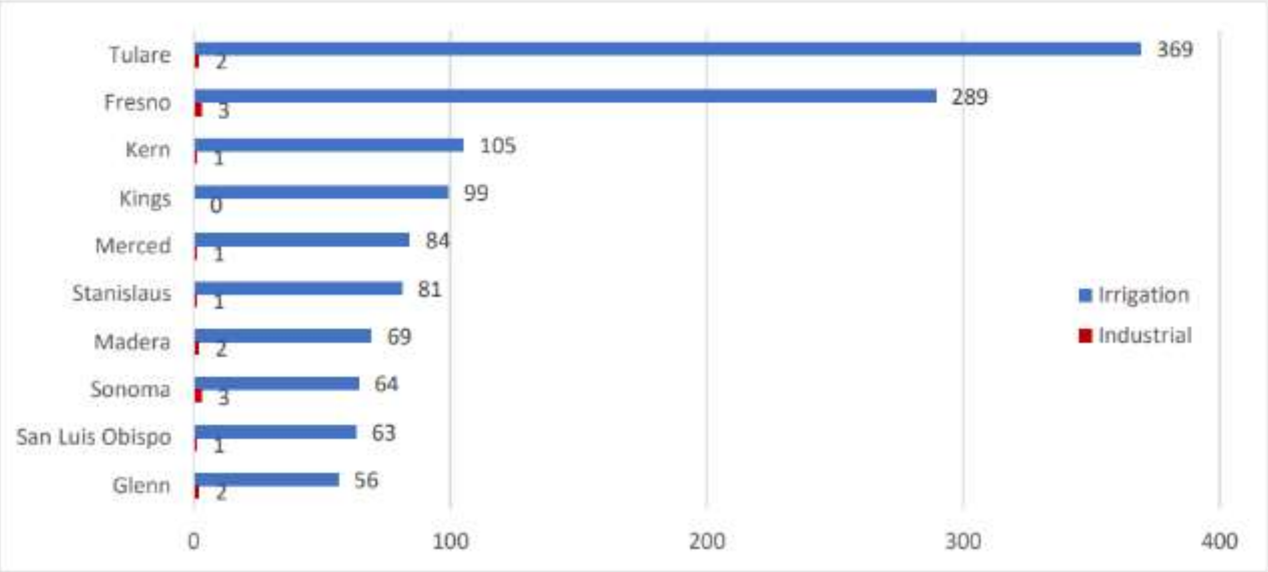
Top 10 counties statewide –

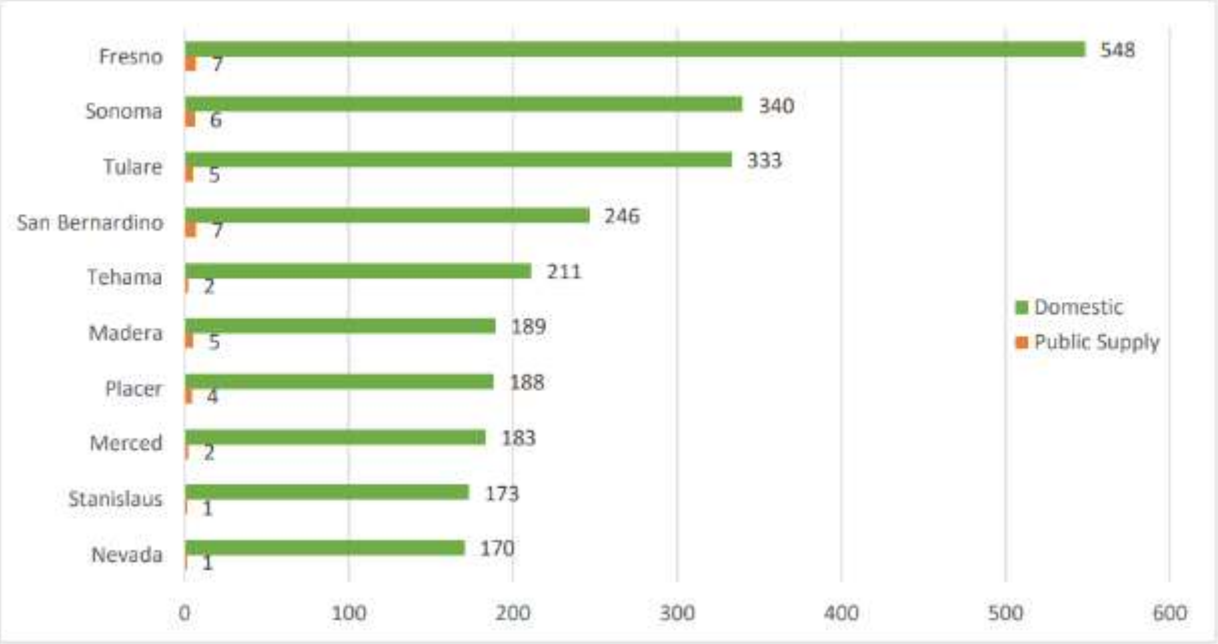
wells installed since 3/28/22

Sonoma County

8th most irrigation wells installed

2nd most domestic wells installed



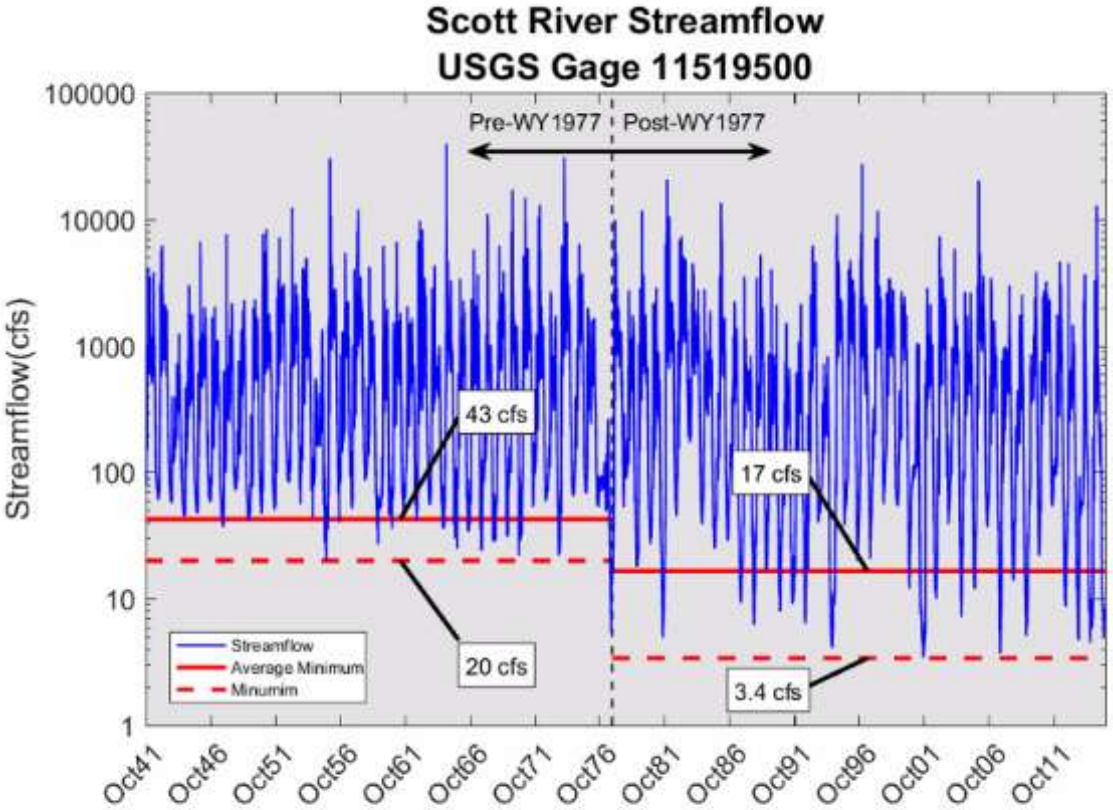


DWR, 2024

The Nature Conservancy

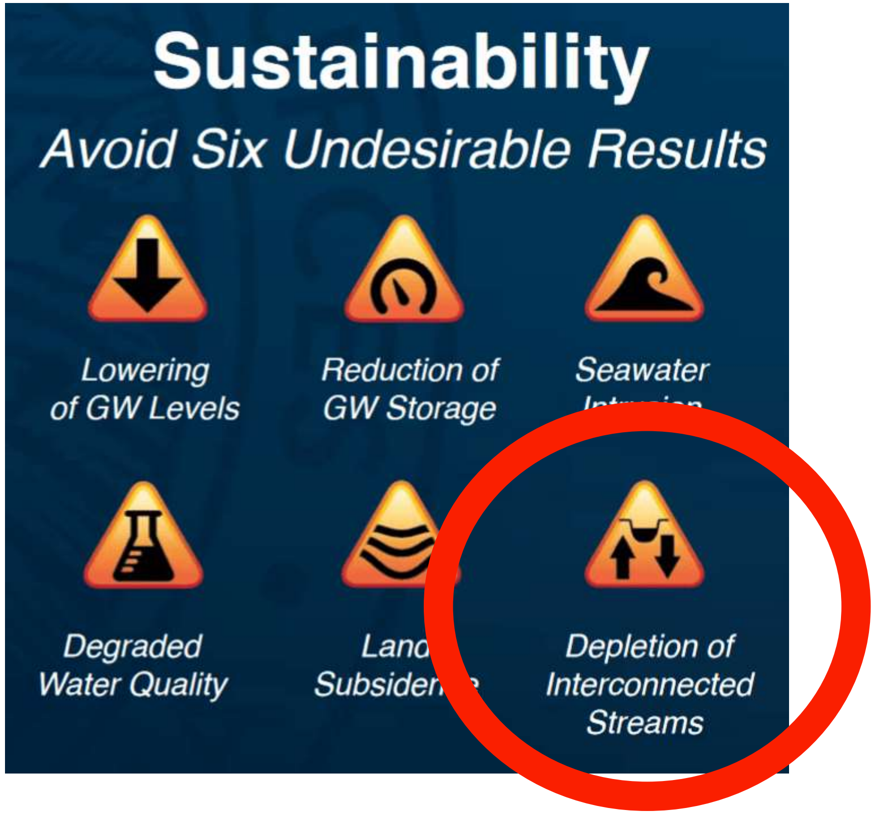
Siskiyou County

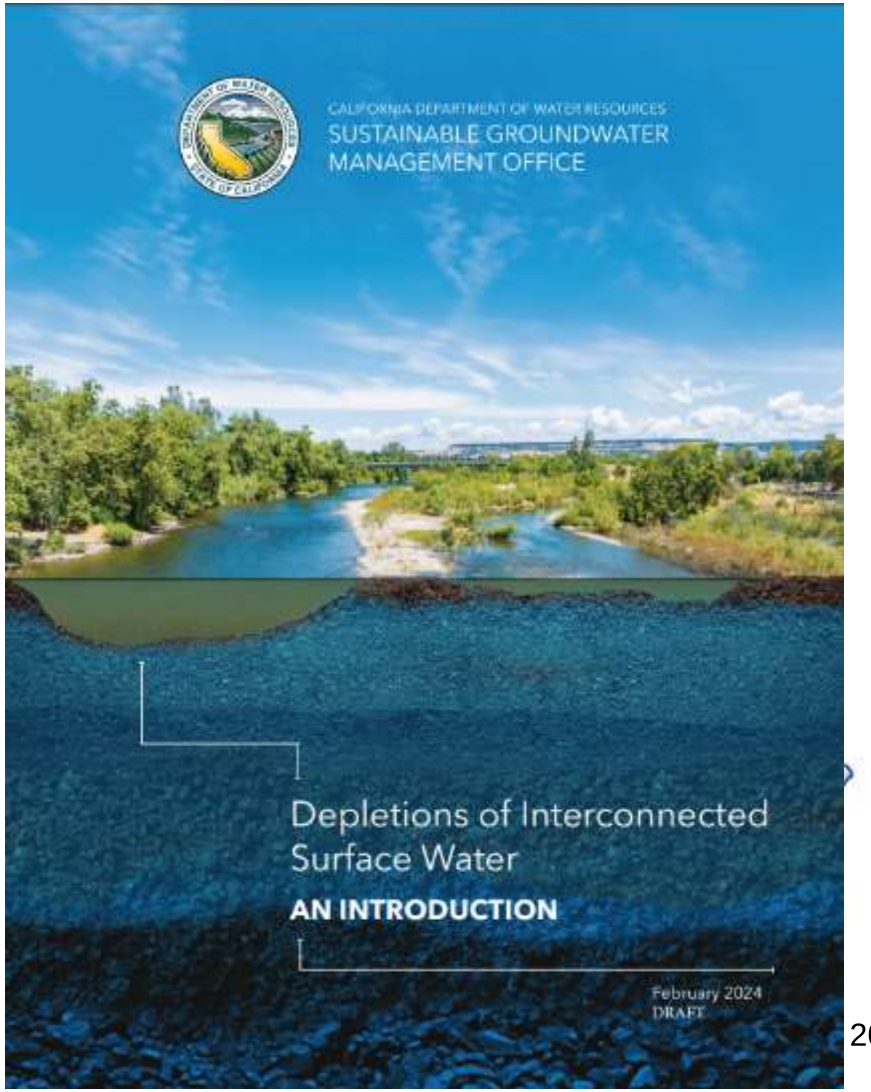
- Mid-summer to fall streamflow mainly depends on baseflow from the valley aquifer
- In the 1970s, late-summer streamflow decreased by ~50%
- Likely driving factors -
- Switch from surface water to groundwater irrigation
- Additional cutting of alfalfa



and more counties!

Statewide – Sustainable Groundwater Management Act (SGMA) Implementation





2018

The Nature Conservancy


What are we doing?
The Nature Conservancy
Image Credit © Bridget Besaw

Streamflow depletion cannot be measured directly…”

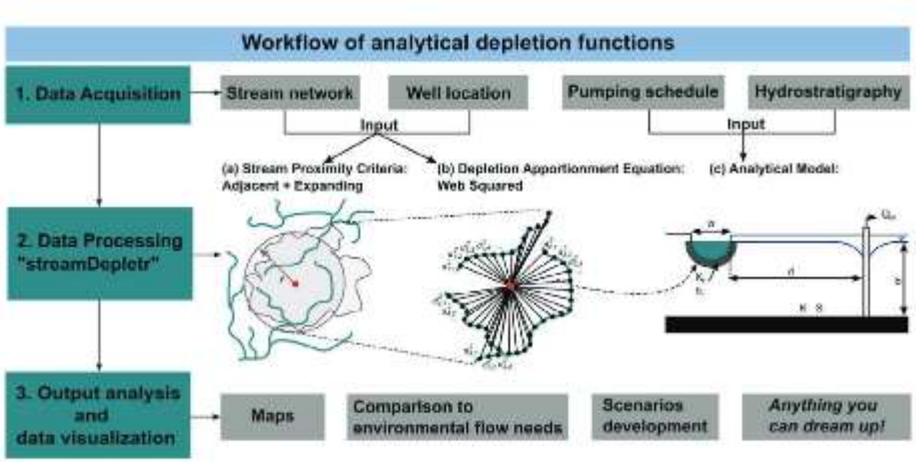
“

Zipper et al. 2022

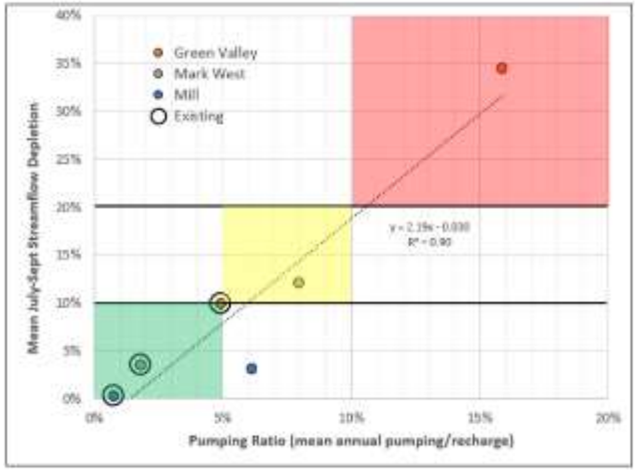
The Nature Conservancy

Modeling Streamflow Depletion

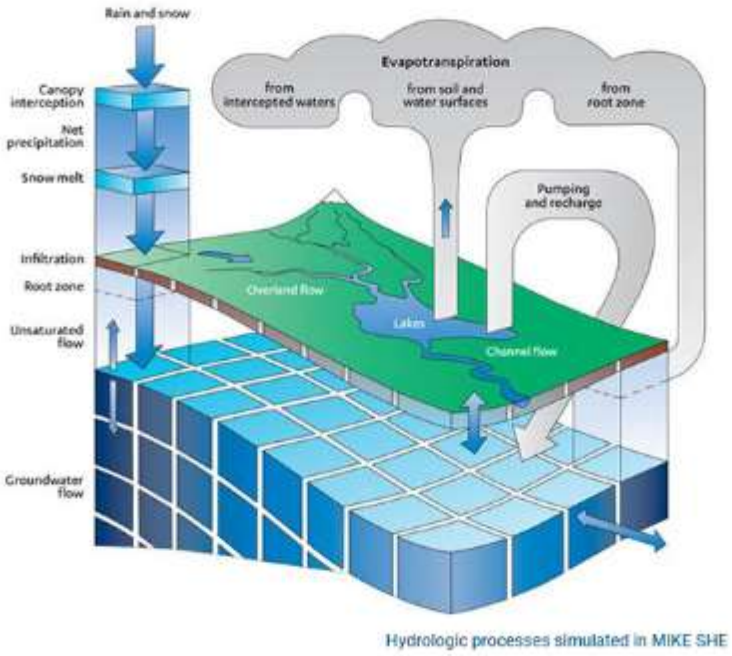
Analytical Models



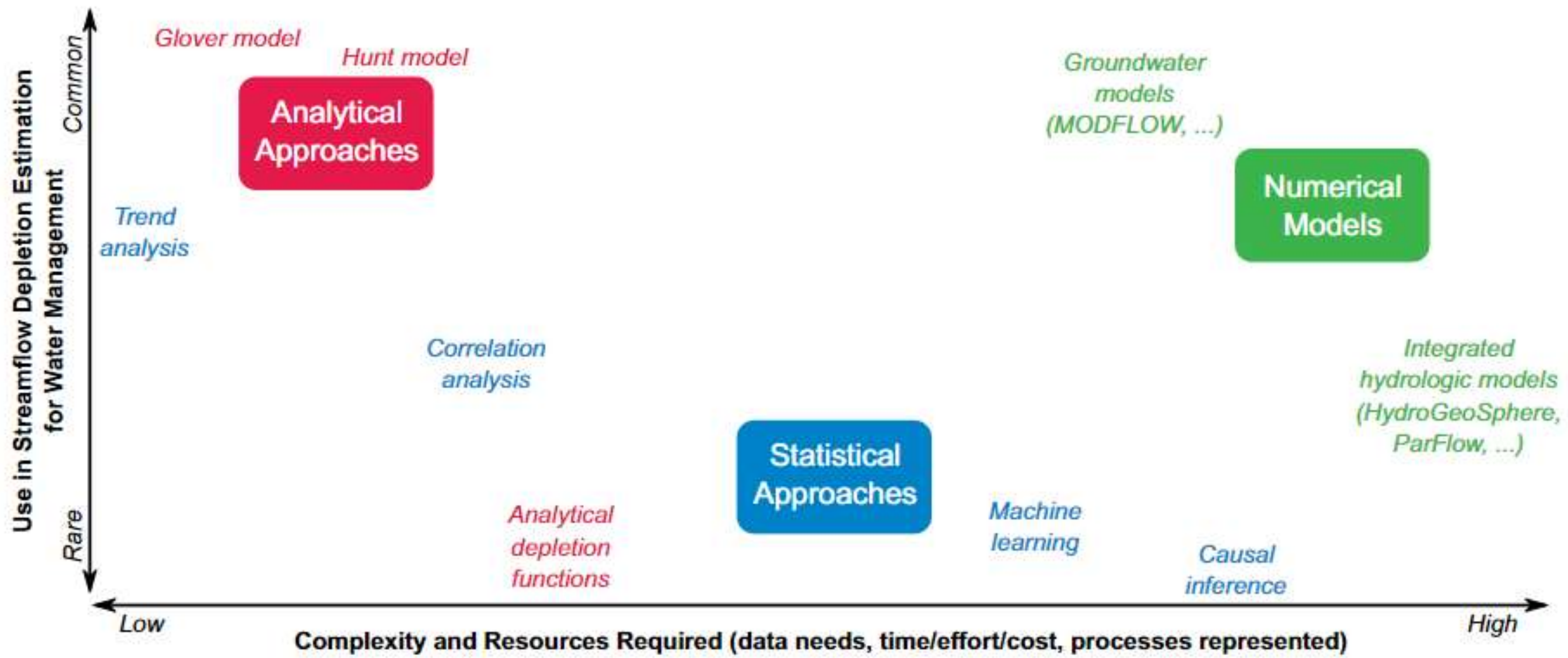
Statistical Models



Numerical Models

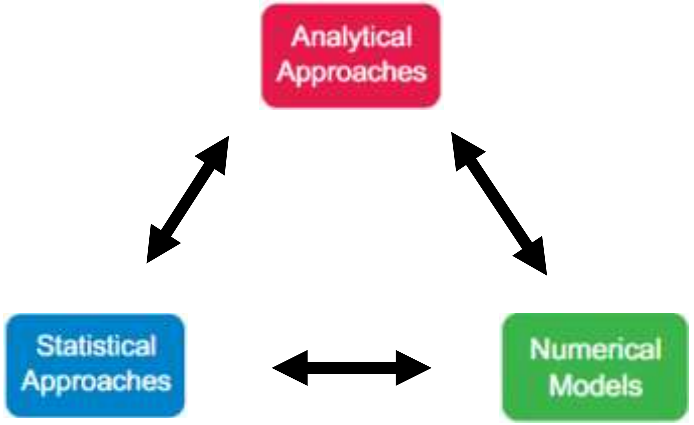


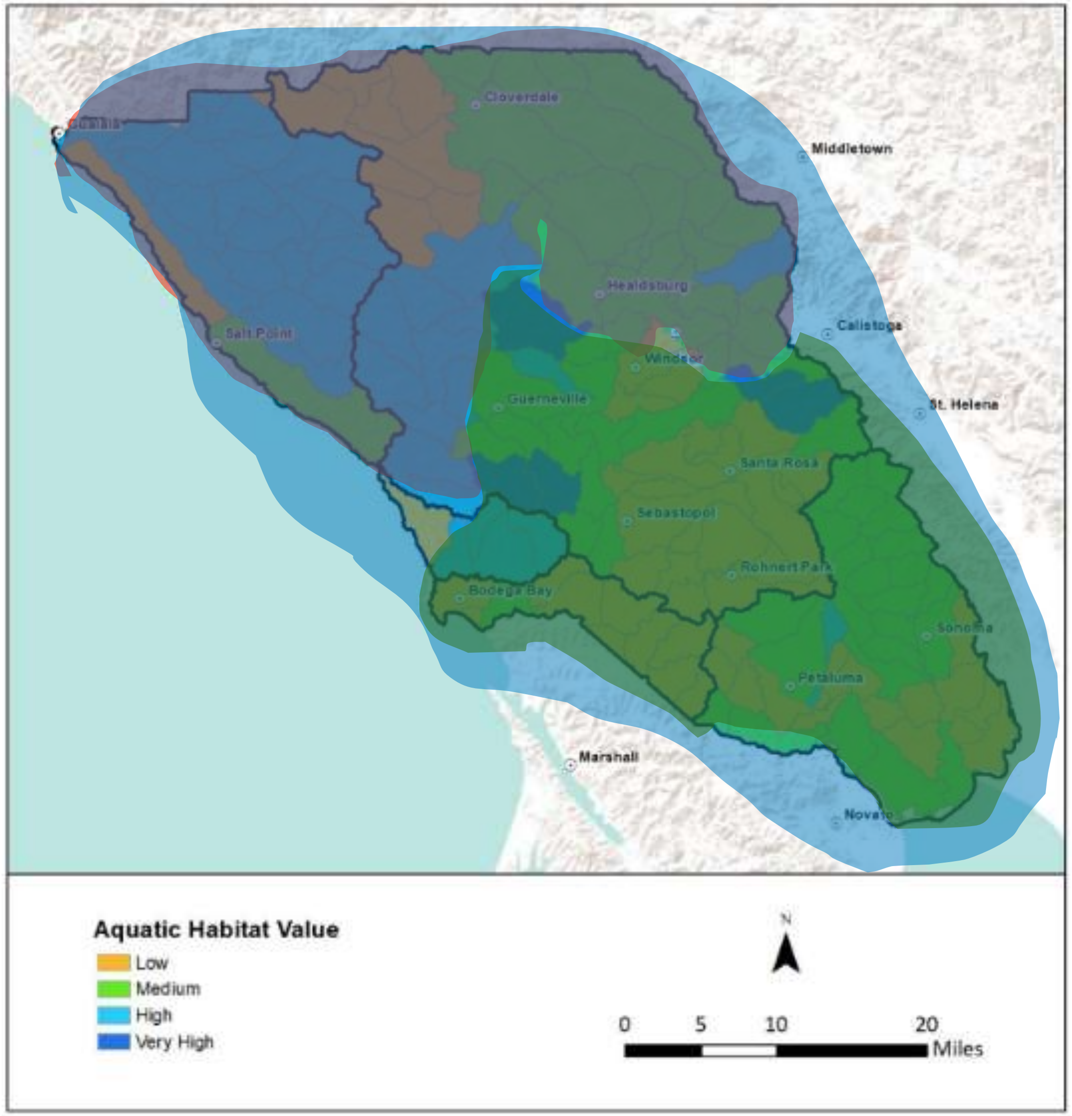
Modeling Streamflow Depletion



Zipper et al. 2022

Why a ‘unified modeling approach’ ?

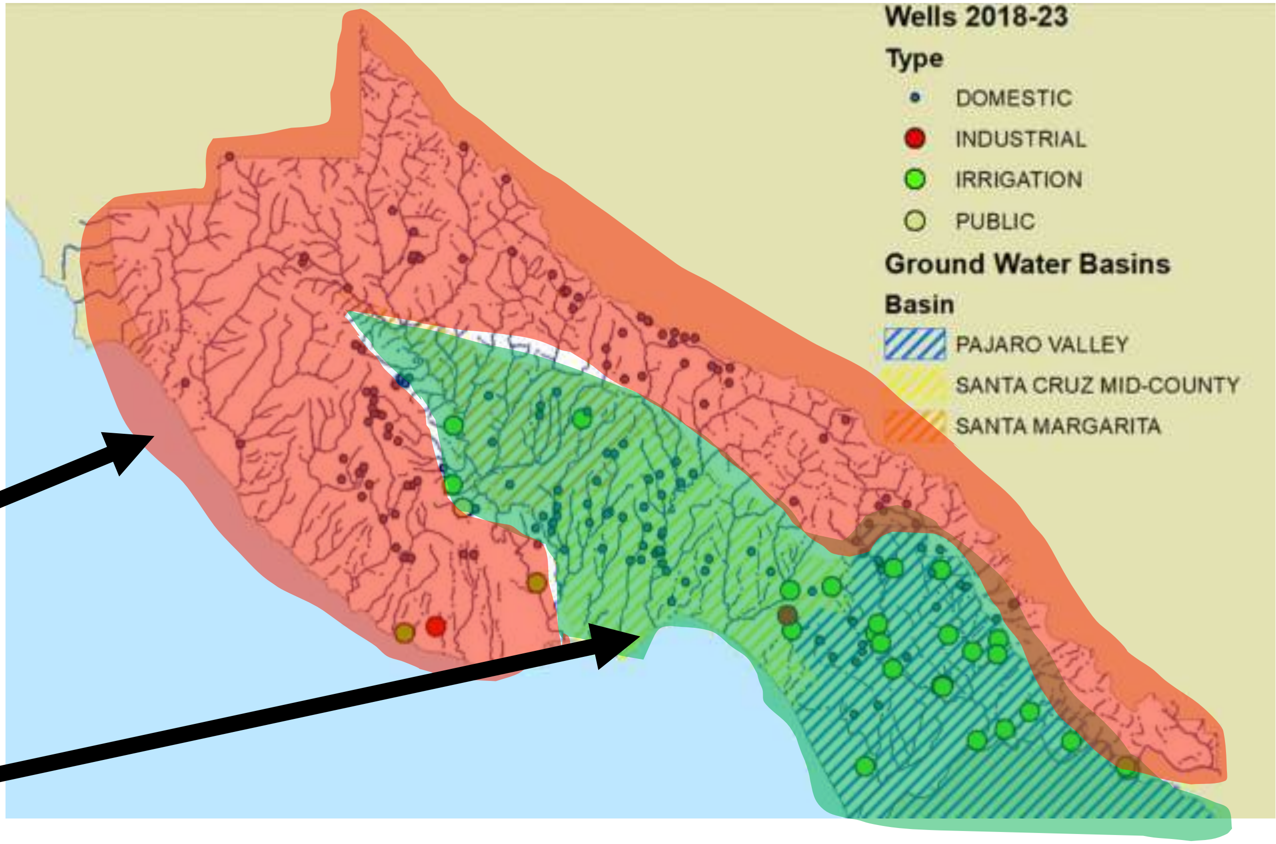




The Nature Conservancy

Why a ‘unified modeling approach’ ?

Fill in the gaps!



Analytical Approaches

Numerical Models

The Nature Conservancy

Unified Modeling Approach to Streamflow Depletion

Goal: Develop a suite of modeling approaches to evaluate streamflow depletion caused by groundwater pumping

Case Studies: Sonoma County & Scott Valley, CA

Analytical Modeling

- Develop analytical depletion function (ADF) models for both geographies
- Estimate regional-scale cumulative streamflow depletion due to existing groundwater pumping
- Modeling comparison studies to evaluate analytical vs. numerical modeling use cases

Numerical Modeling

- Explore methodologies to apply numerical modeling estimates of streamflow depletion to a well permitting framework
- Exchange of site-specific hydrogeologic data to inform analytical model development

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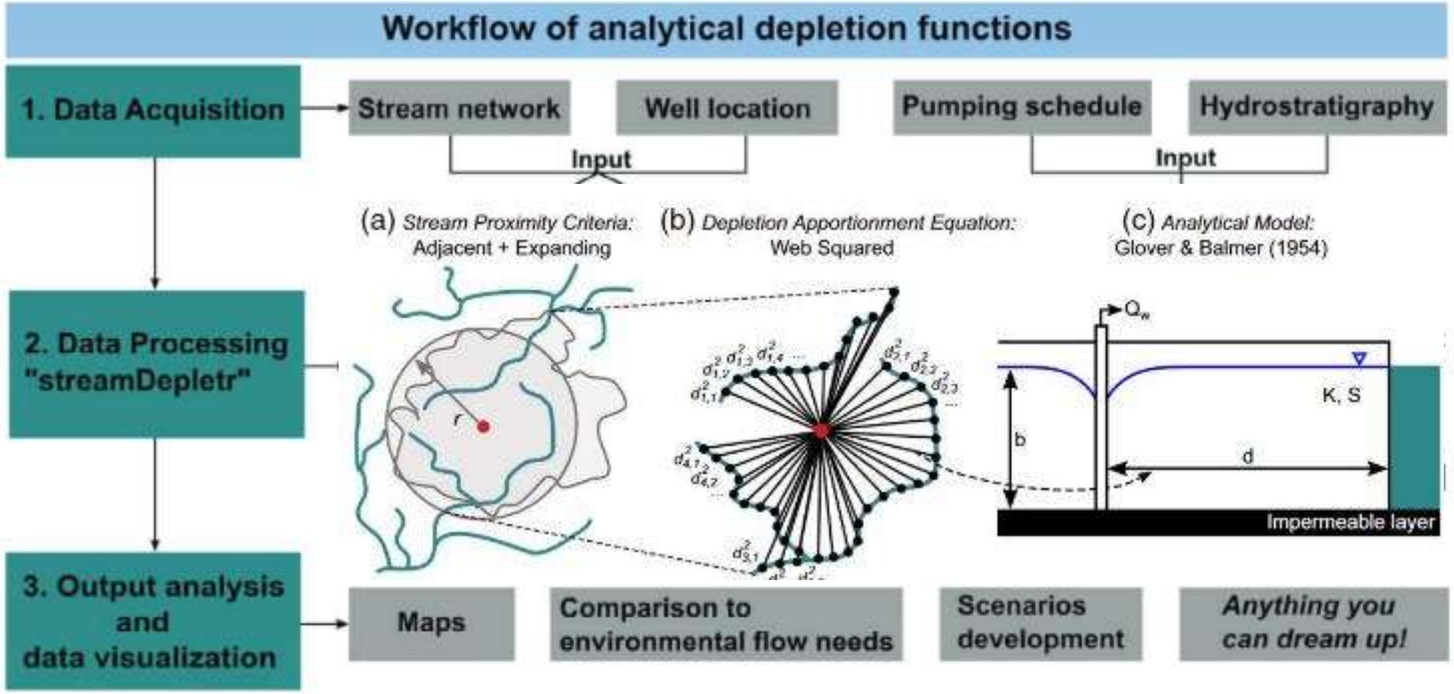
ADF Model Workflow

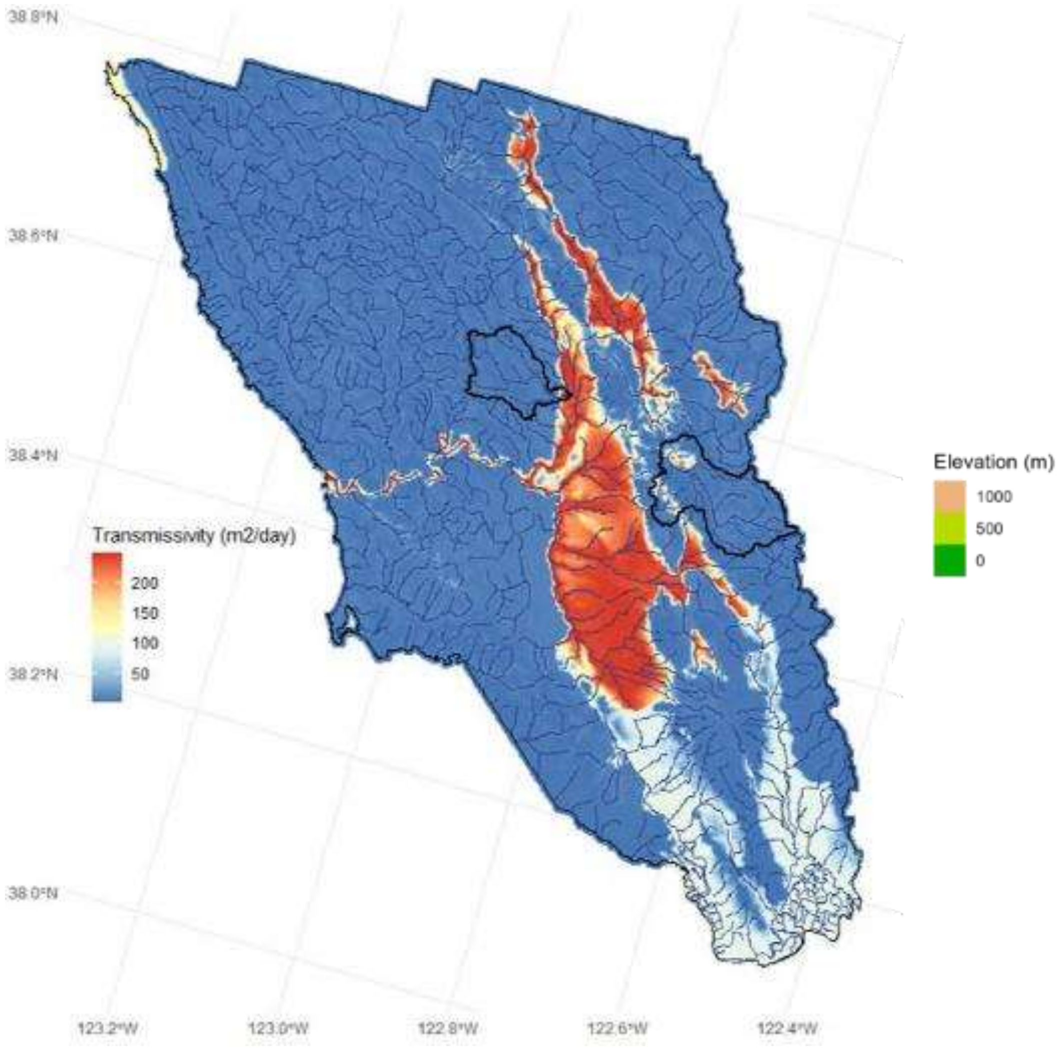


Zipper et al. 2022

Stream network
• Source: NHDplusv2

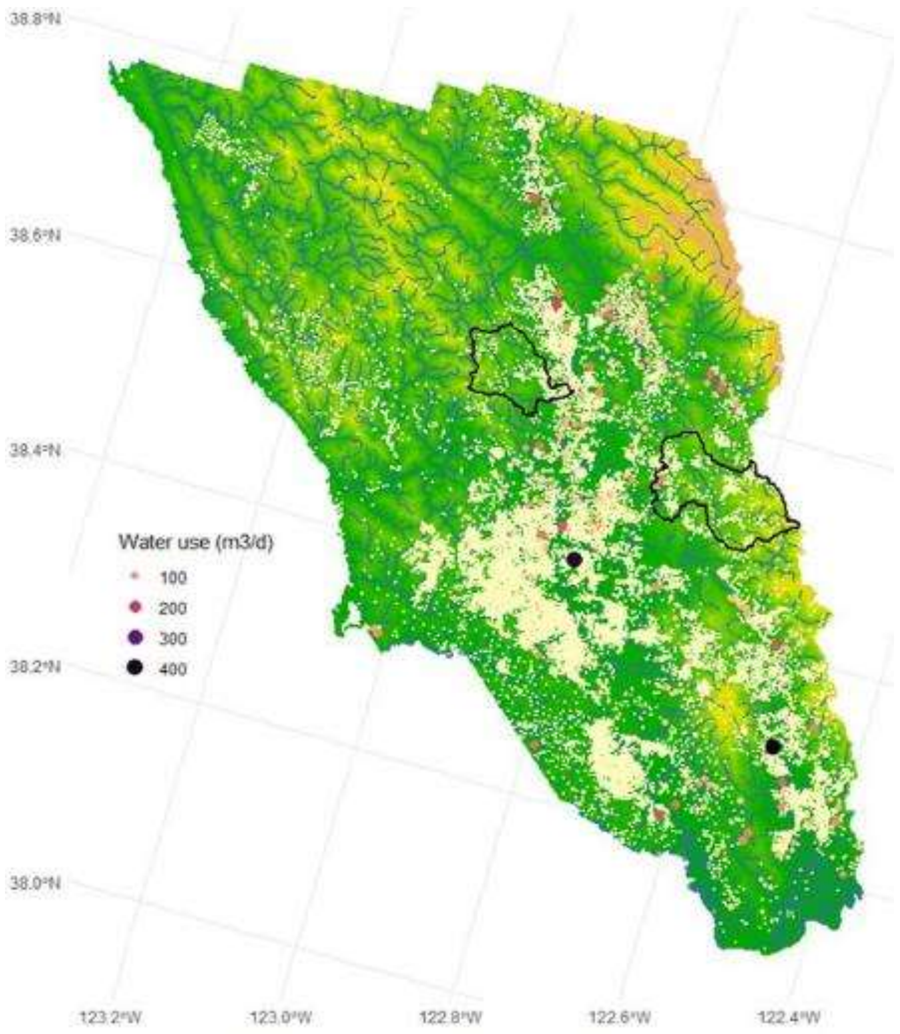
Hydrogeologic data needs- Transmissivity

- Source: Zell and Sanford, 2020
- From CONUS-scale MODFLOW models



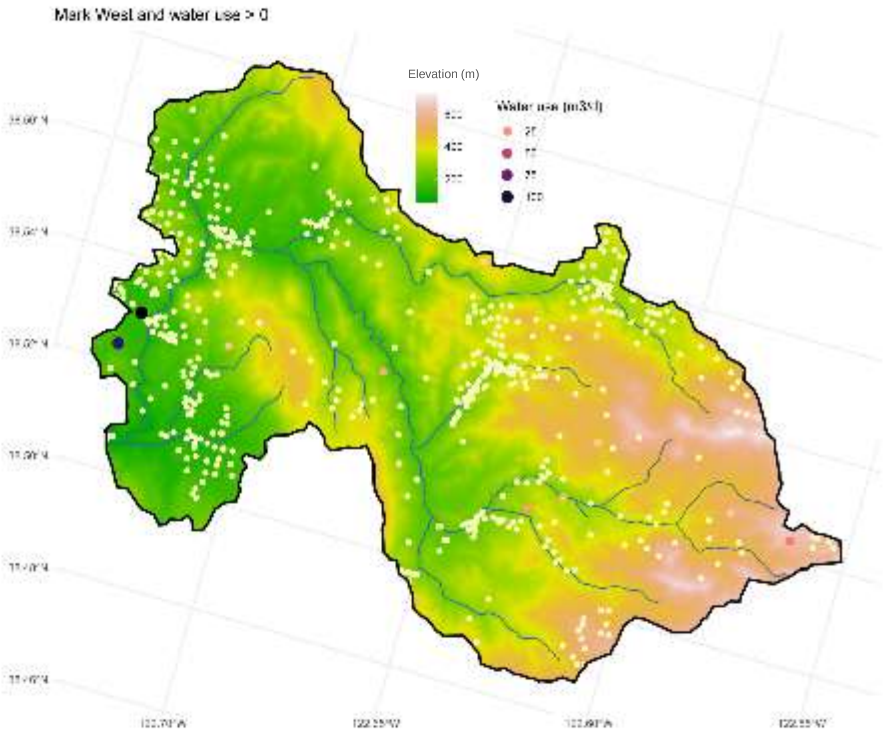
ADF Model Workflow

- Parcel centroids
- Any parcel with estimated GW use > 0
- Parcel dataset: Sonoma County
- Annual water use by parcel: Sonoma County
- Disaggregated annual estimates to monthly rates based on % of total in each month from OEI schedule
- Split into 'Agricultural' and 'Non-Ag' use

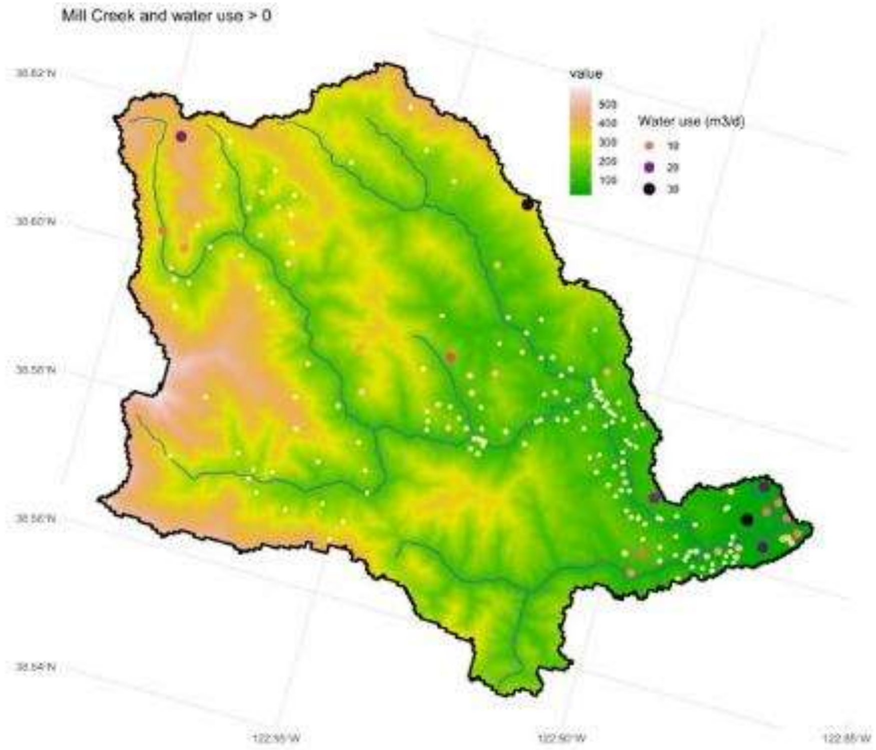


ADF Model Workflow

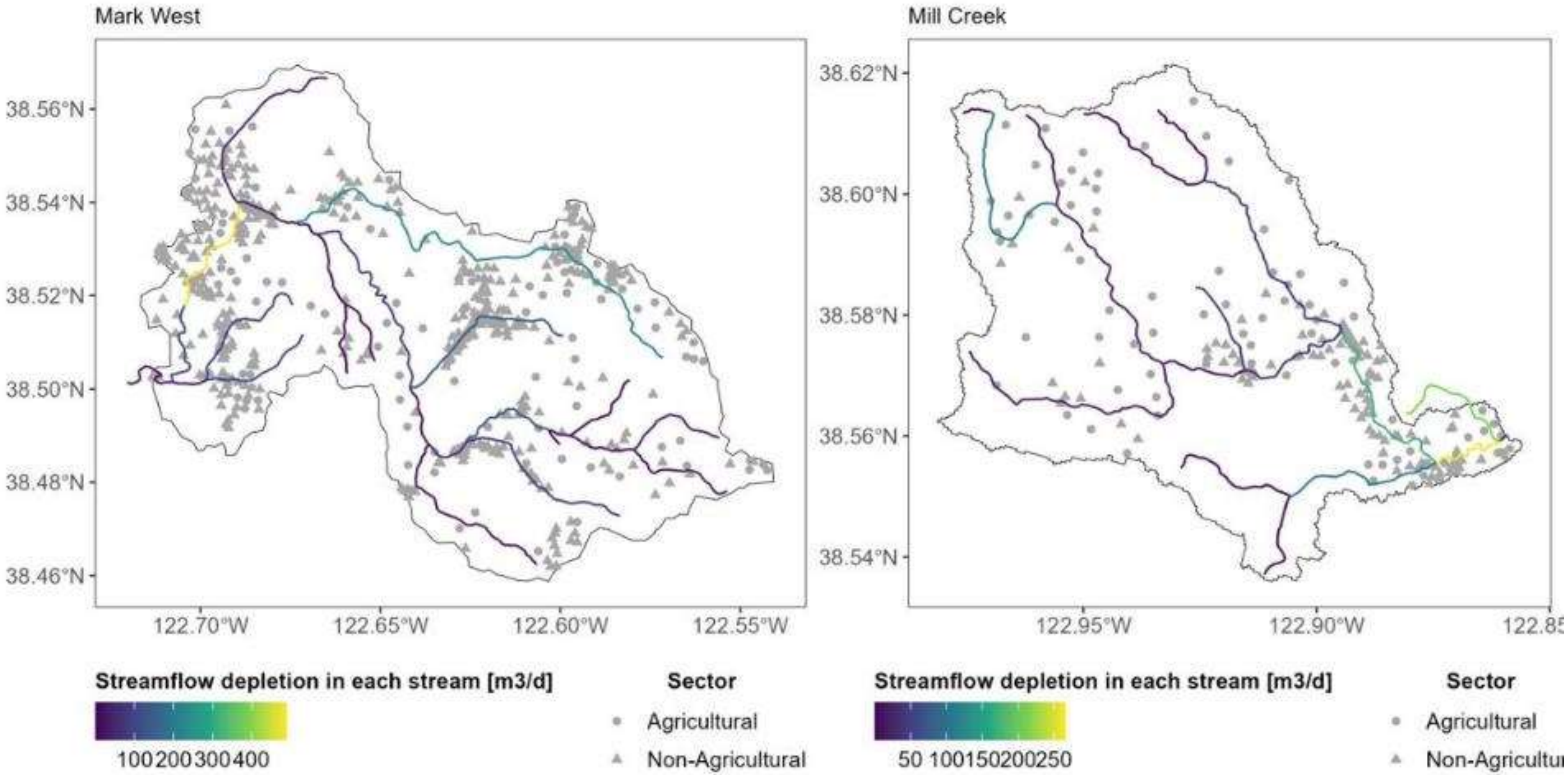
Mark West Creek



Mill Creek



ADF Model Workflow



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t = 7200 days (September, year 20)

KU HEAL, Zipper Lab Group

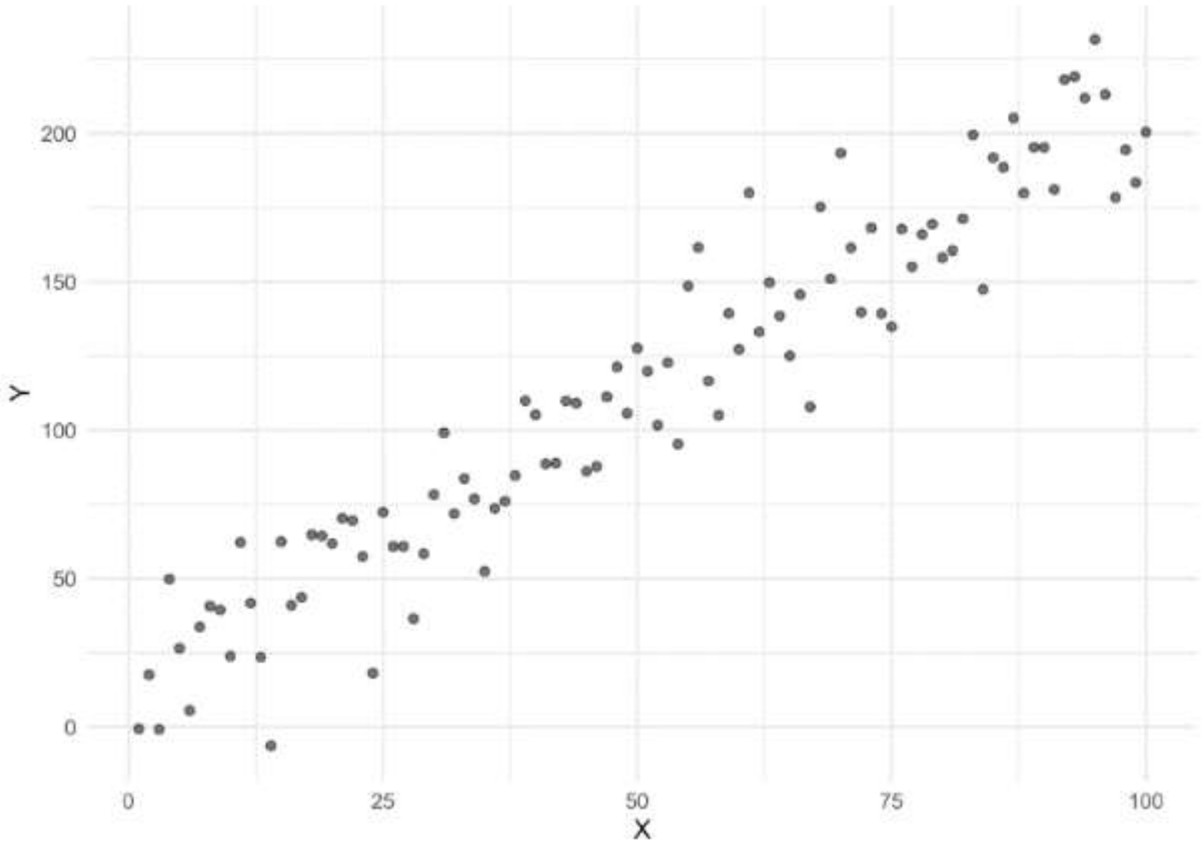
Modeling Comparison Considerations

Model Agreement

- estimates of streamflow depletion,
- timing, location and magnitude of streamflow depletion simulated
- estimates of streamflow depletion ***impact to environmental flows*** ***within a well permitting framework***
- *do different models arrive at the same conclusion, when applied as a well permitting decision-support tool?*

Model Complexity

- data requirements
- technical expertise
- computational requirements



Next steps – Future research

Model Comparison Studies
- Sonoma County
- Siskiyou County (Scott Valley to start)

Decision-support tool development
- Guidance for the unified modeling of streamflow depletion through the lens of a well permitting framework

Acknowledgements

- Partners –
- O’Connor Environmental Inc.
- University of Kansas
- Foundry Spatial
- Salmon and Steelhead Coalition (The Nature Conservancy, CalTrout, Trout Unlimited)

The Nature Conservancy


Thank You
The Nature Conservancy
Image Credit © Bridget Besaw

All water discharged from wells is balanced by a loss of water somewhere.”

“

Charles V. Theis, 1941

Sonoma County

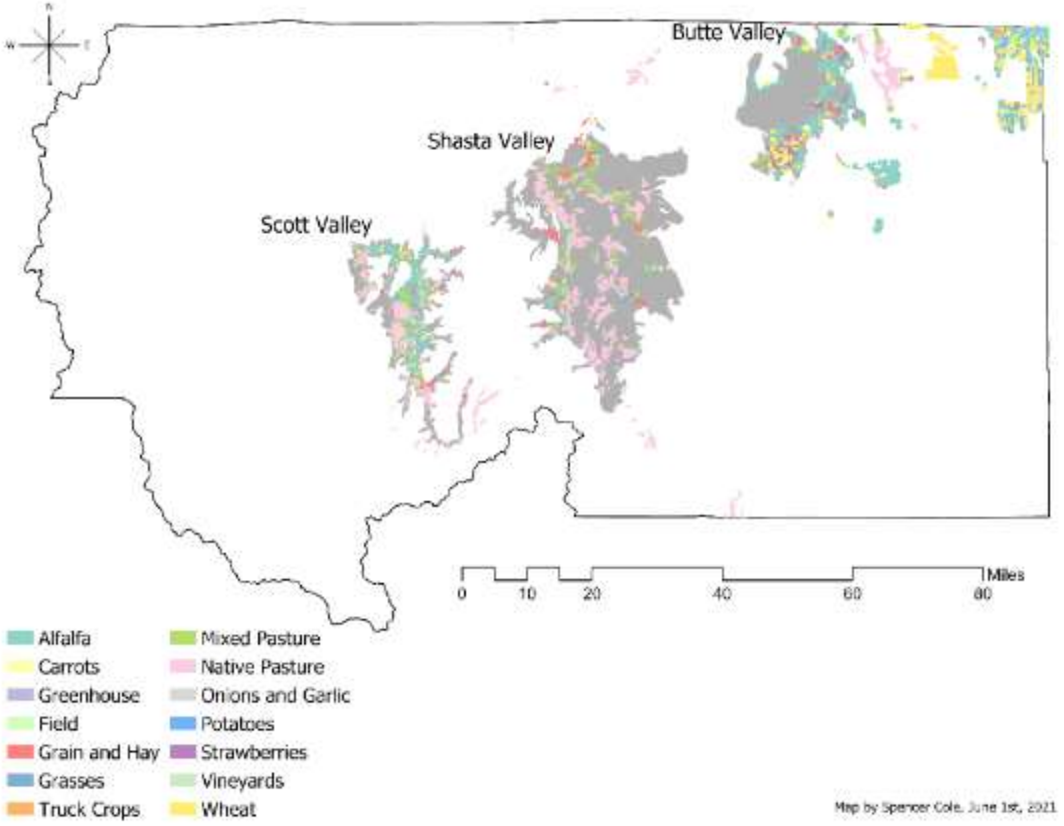
- Well ordinance revisions driving a need for technical modeling capacity, at the county scale –

- Estimates of existing cumulative streamflow depletion
- Estimates of acute, point-source streamflow depletion potential from proposed wells

The Nature Conservancy

Siskiyou County

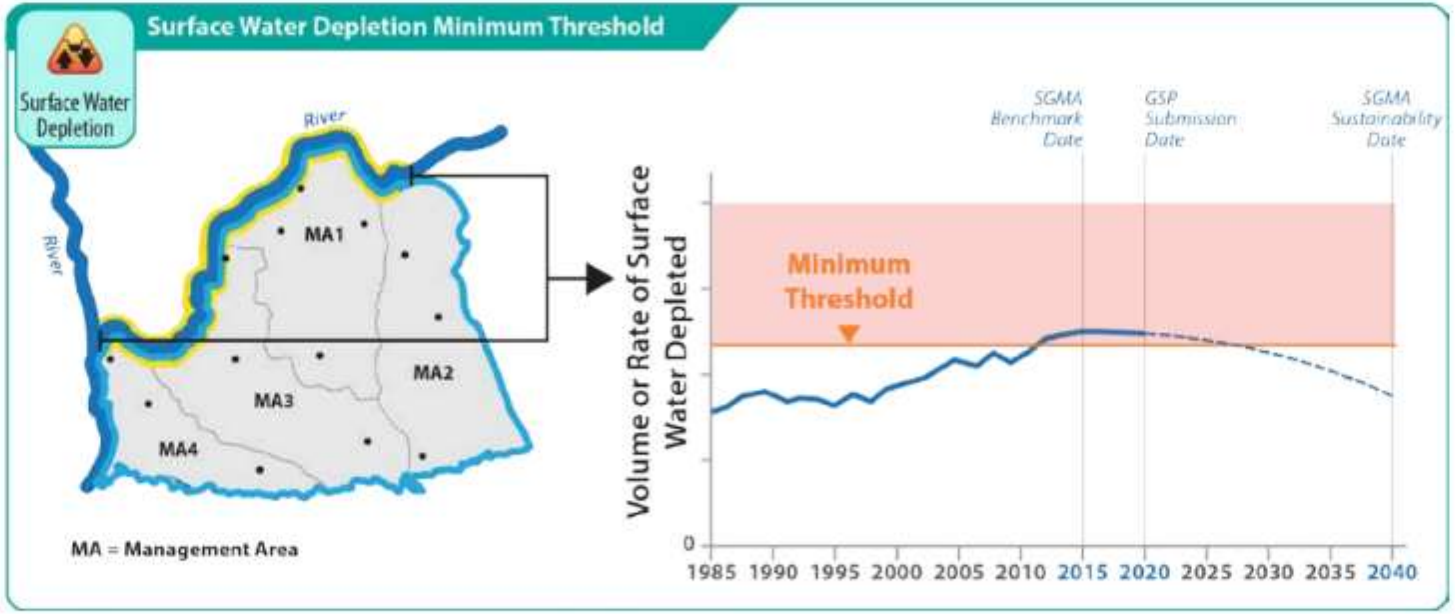
- Range of development stages for existing numerical models
- Need for modeling tools of with varying resolution, complexity and COST



Cole, 2021

Statewide – Sustainable Groundwater Management Act (SGMA) Implementation

- Unclear how the regulatory benchmark of SGMA (2015) conditions will shape ISW management under SGMA
- Developing ISW guidance presents an opportunity to work with state agencies to develop consistent modeling approaches

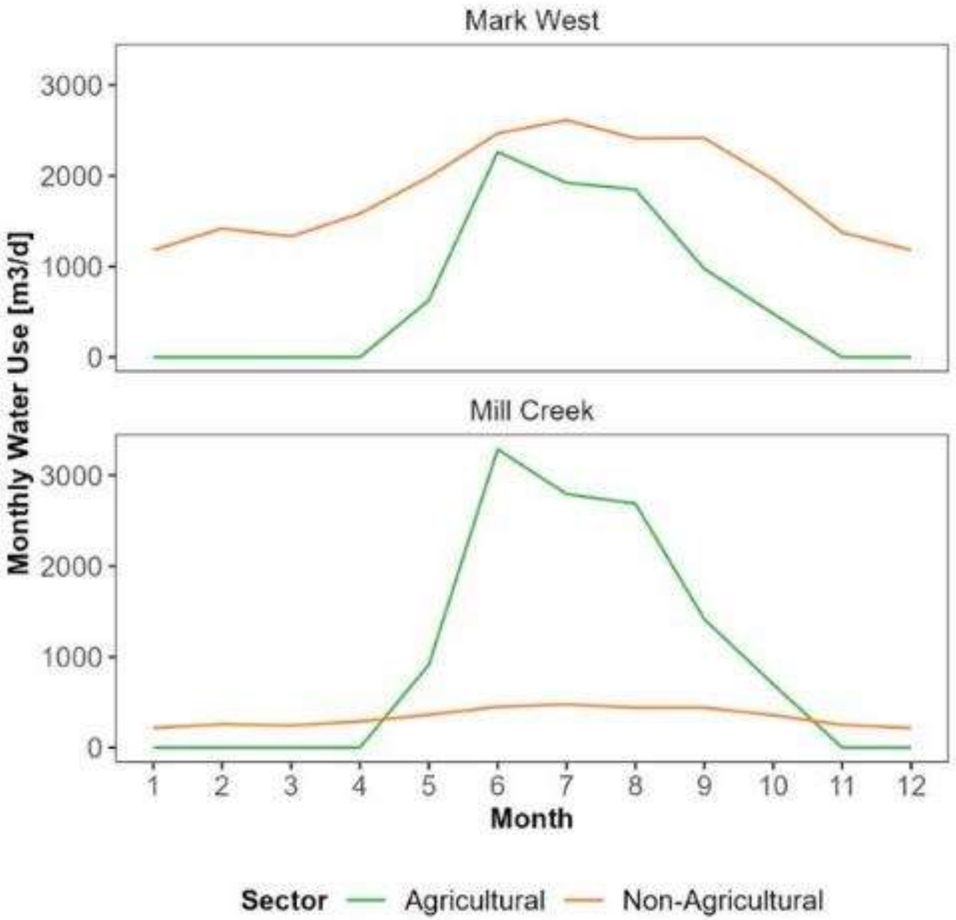


DWR, 2018

Water Use

- Grouped into "Agricultural" and "Non-agricultural"
- Agricultural = Seasonal pattern expected
  - Agriculture, School/Golf, Winery/Vines
- Non-agricultural = Year-round use expected
  - Commercial, Residential, MultiFamily

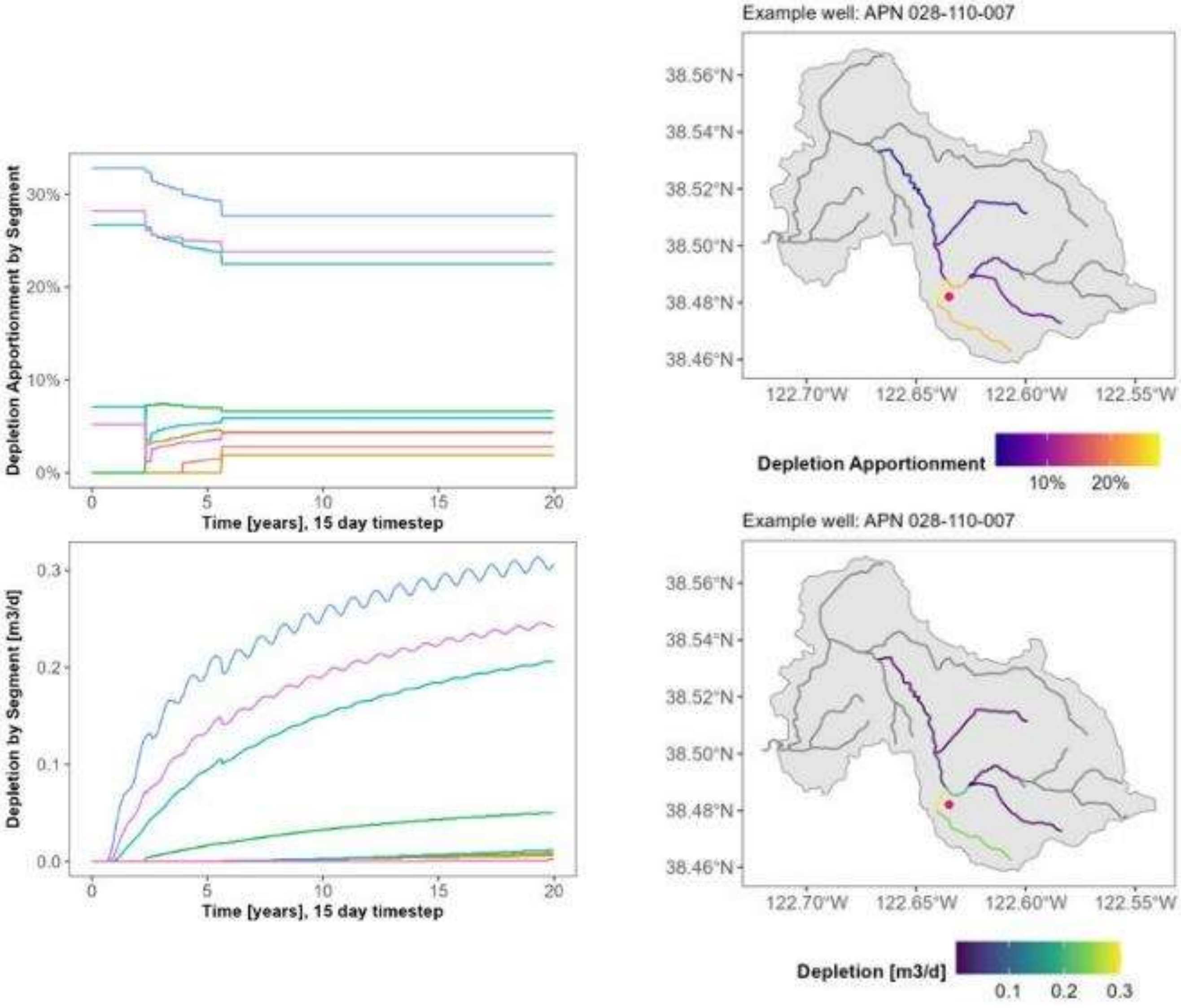
•Disaggregated annual estimates to monthly rates based on % of total in each month from OEI schedule



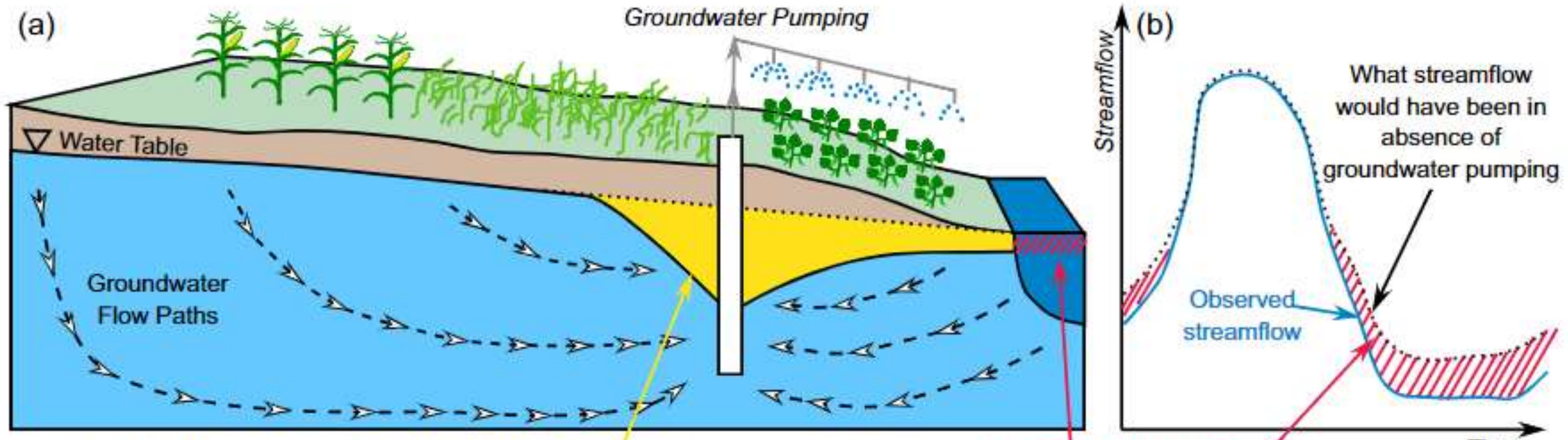
Example – Agricultural Well in Mark West Creek

- Apportionment reflects adjacent + expanding criteria
  - Start of time – adjacent streams only
  - More streams affected with time
- Different seasonal depletion amplitudes depending on stream affected
  - But, no streams are fully recovering every year

- t = 7200 (~20 years, September)
- Impacts greatest in nearby segments
- However, some impacts even quite far away – realistic?



Streamflow Depletion



Water that is pumped from a well comes from two sources:

Groundwater Depletion

Pumping reduces groundwater storage.
This can be quantified by measuring changes in groundwater levels.

Streamflow Depletion

Pumping captures groundwater that would have flown into the stream and/or induces infiltration from the stream into the aquifer.
This cannot be directly measured and is challenging to estimate.

The other water users: how plant and human water use impact streams

Dana Lapides[1], Jesse Hahm[2], David Dralle[3], Daniella Rempe[4], John Hammond[5], Sam Zipper[6,7]

1 - USDA-ARS Southwest Watershed Research Center
2 - Simon Fraser University
3 - US Forest Service Pacific Southwest Research Center
4 - University of Texas, Austin
5 - USGS
6 - Kansas Geological Survey
7 - University of Kansas, Lawrence

nature water

Article

https://doi.org/10.1038/s44221-023-00030-7

Future global streamflow declines are probably more severe than previously estimated

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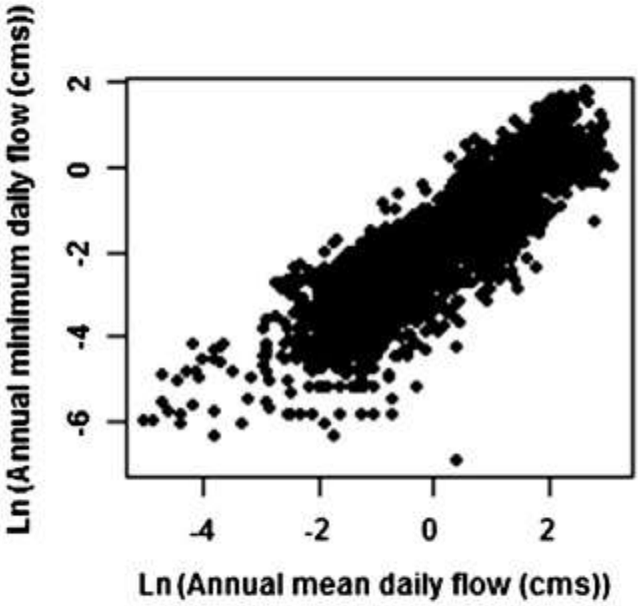
Check for updates

Yongqiang Zhang[1], Hongxing Zheng[2], Xuanze Zhang[1], L. Ruby Leung[3], Changming Liu[1], Chunmiao Zheng[4], Yuhan Guo[1], Francis H. S. Chiew[2], David Post[2], Dongdong Kong[5], Hylke E. Beck[6], Congcong Li[1,7] & Günter Blöschl[8]

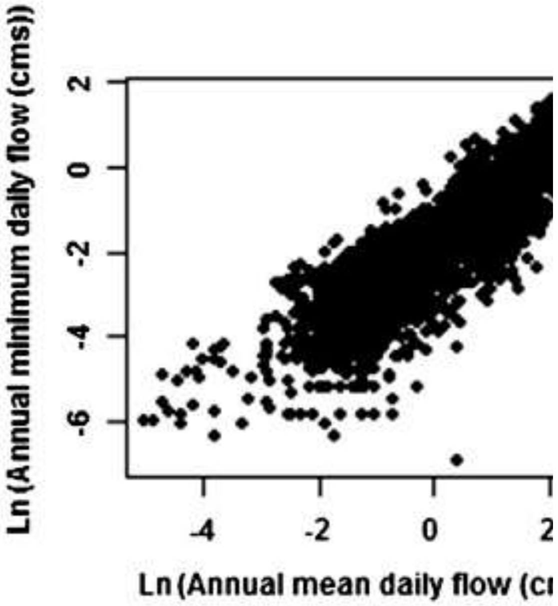
Climate change and increasing water use associated with socio-economic growth have exacerbated the water crisis in many parts of the world. Many regional studies rely on Earth System Models that, however, do not fully exploit streamflow observations. Here we offer an observation-based approach to predicting streamflow change on the basis of the elasticity of

Leading to lower low flows



Reynolds, Lindsay V., Patrick B. Shafroth, and N. LeRoy Poff. "Modeled intermittency risk for small streams in the Upper Colorado River Basin under climate change." *Journal of Hydrology* 523 (2015): 768-780.

Leading to lower low flows and summer flows



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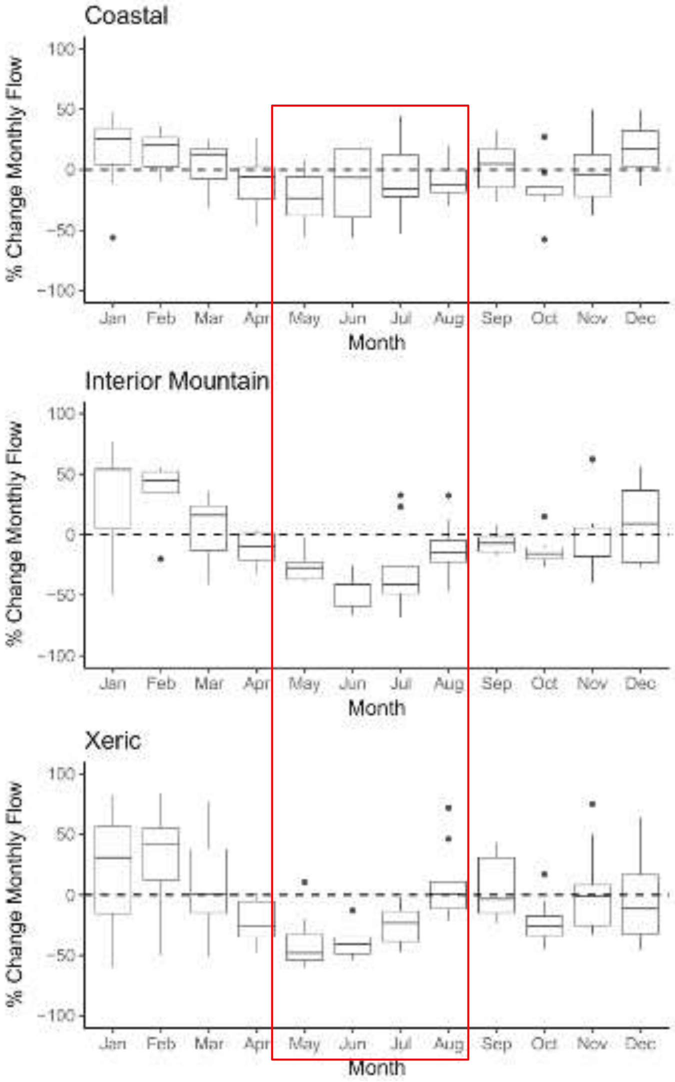
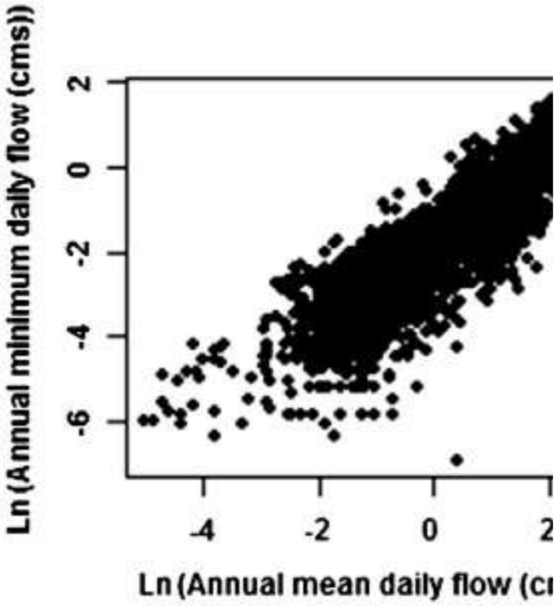


Grantham, Theodore EW, et al. "Sensitivity of streamflow to climate change in California." *Climatic Change* 149 (2018): 427-441.

Leading to lower low flows and summer flows and more intermittency



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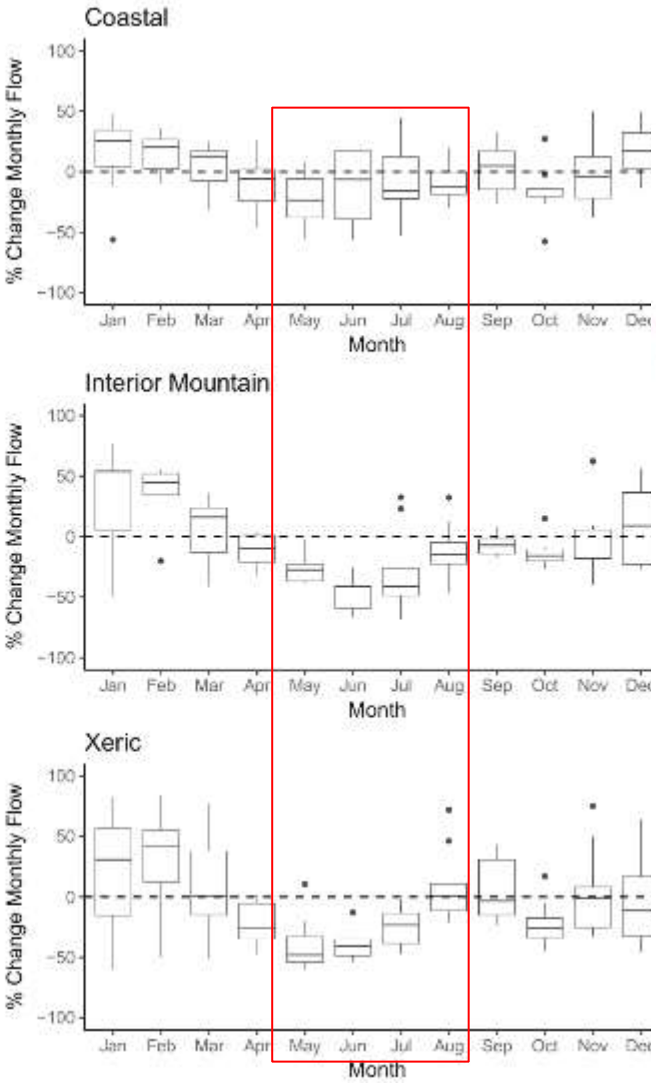

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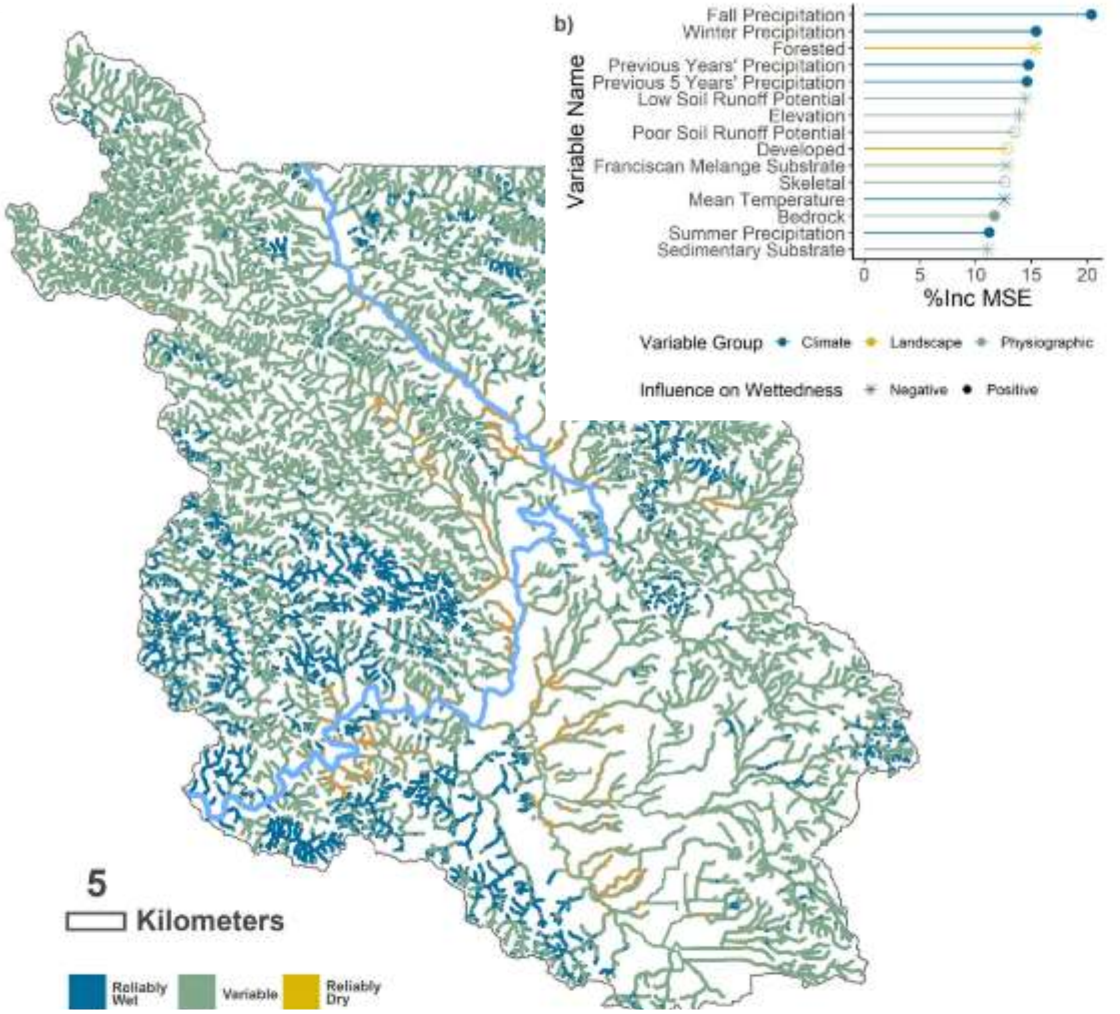
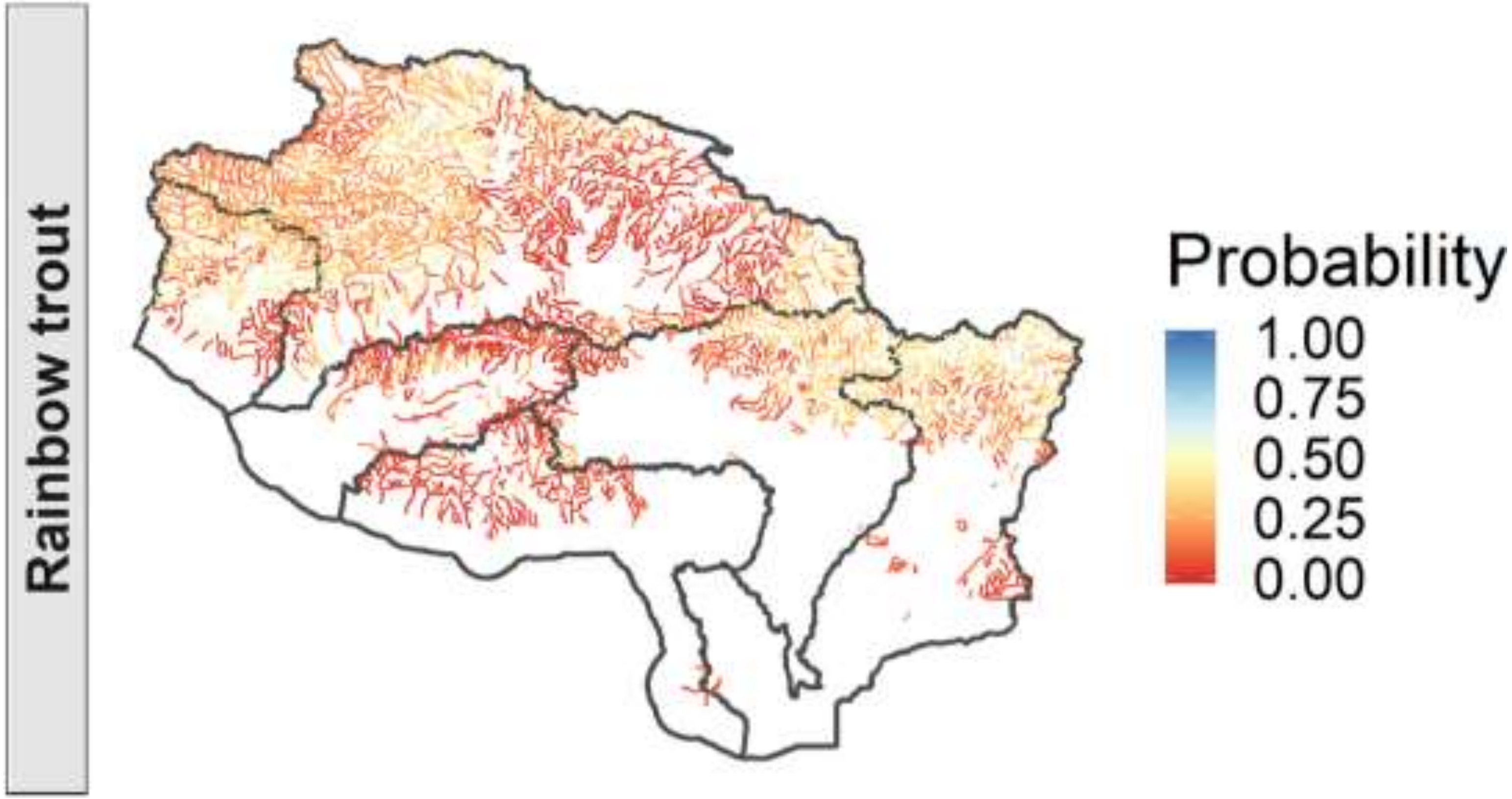


Moidu, H., et al. "Spatial patterns and sensitivity of intermittent stream drying to climate variability."
Water Resources Research 57.11 (2021): e2021WR030314.

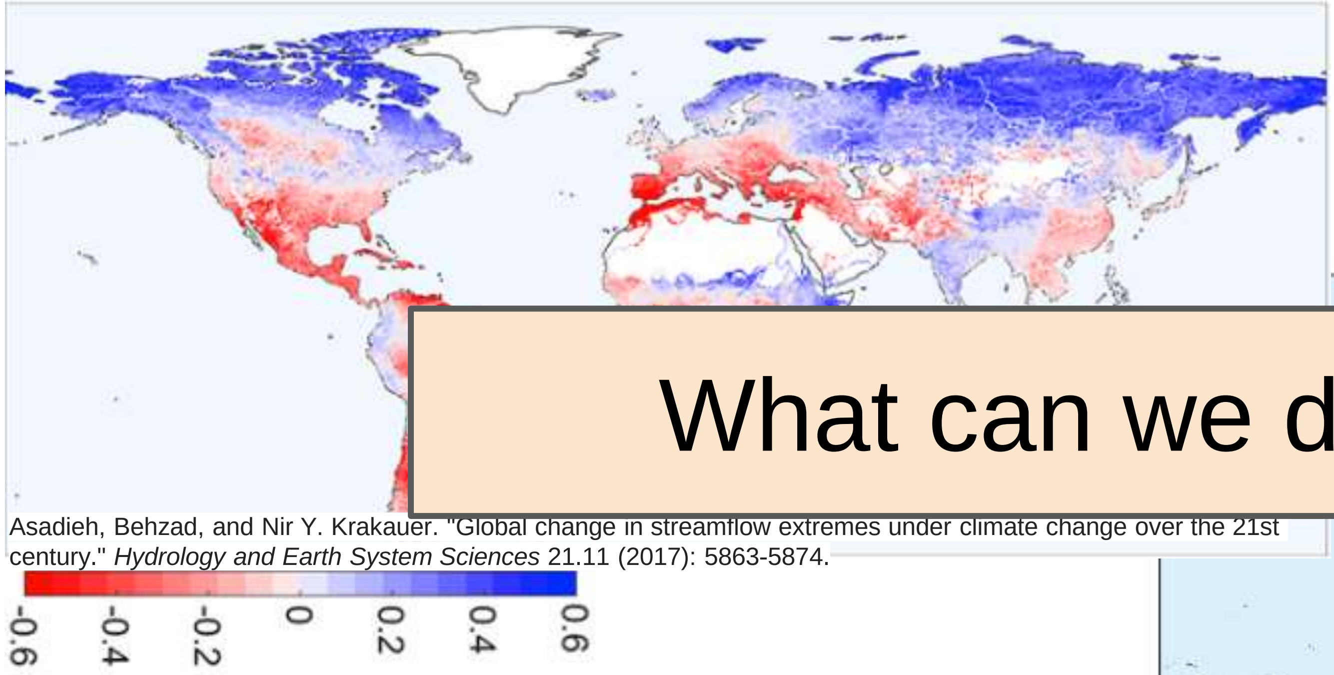
Reductions in streamflow threaten habitat for aquatic organisms and lead to decreasing populations or species loss



Rogers, Jennifer B., et al. "The impact of climate change induced alterations of streamflow and stream temperature on the distribution of riparian species." *PLoS One* 15.11 (2020): e0242682.

What’s causing streamflow declines?

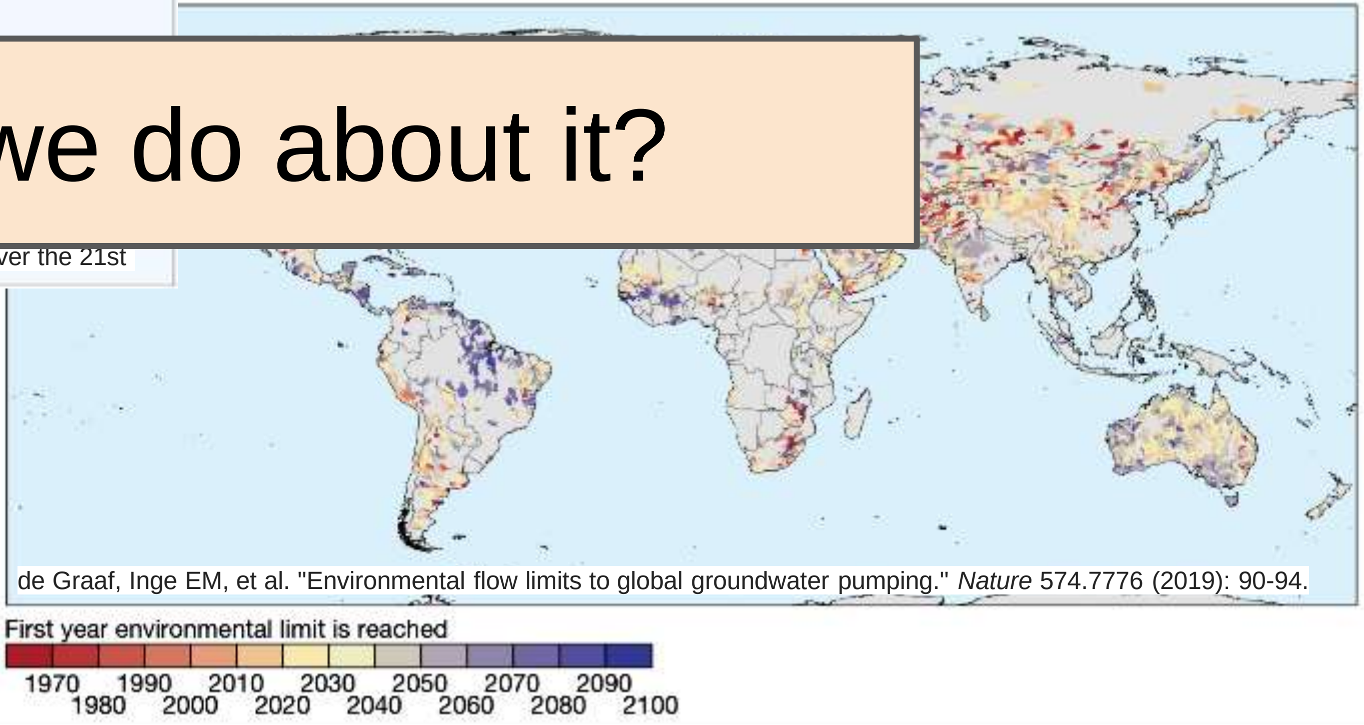
Climate change



Asadieh, Behzad, and Nir Y. Krakauer. "Global change in streamflow extremes under climate change over the 21st century." *Hydrology and Earth System Sciences* 21.11 (2017): 5863-5874.

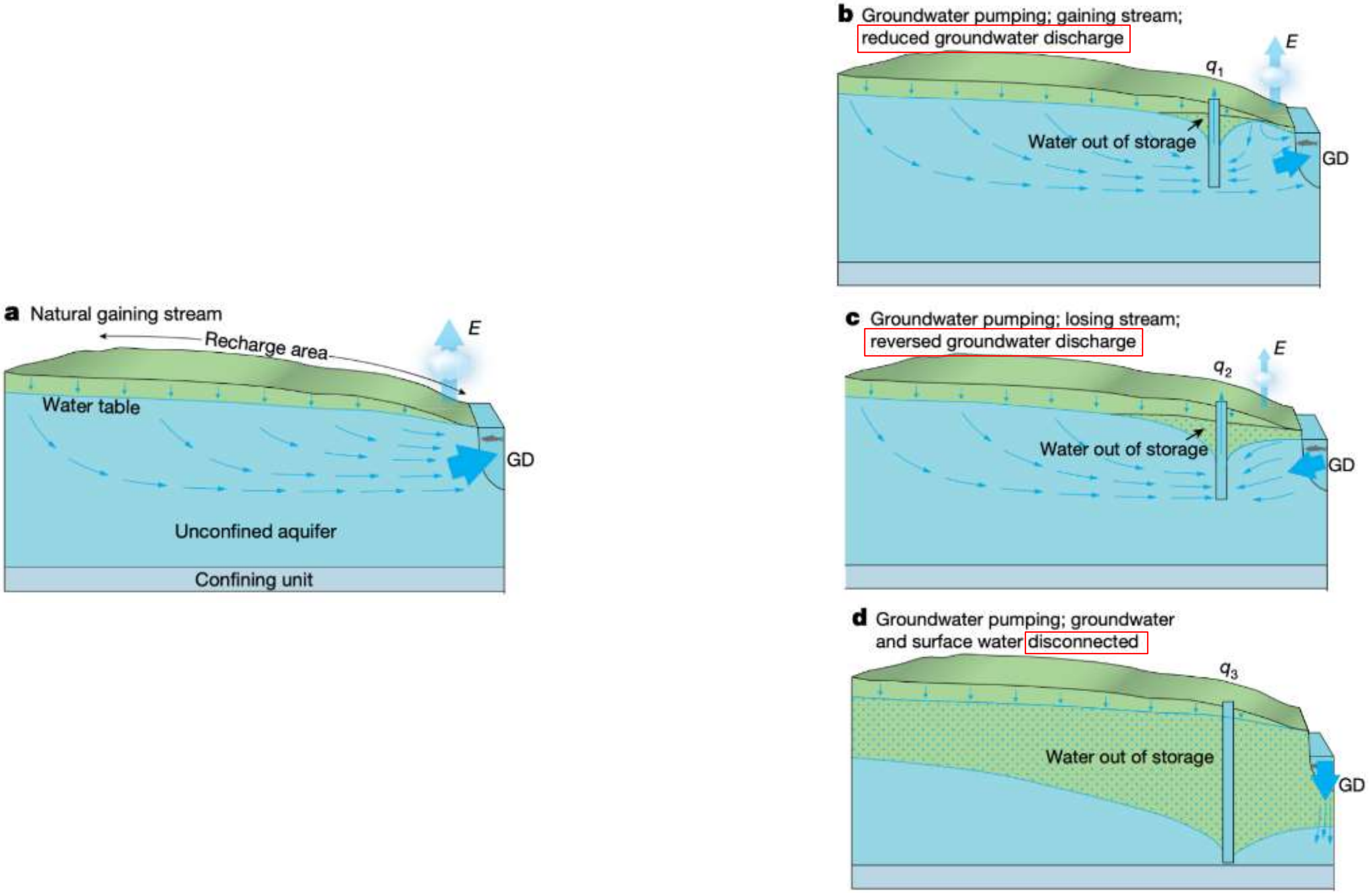
Normalized change in median streamflow projected with climate change

Groundwater pumping



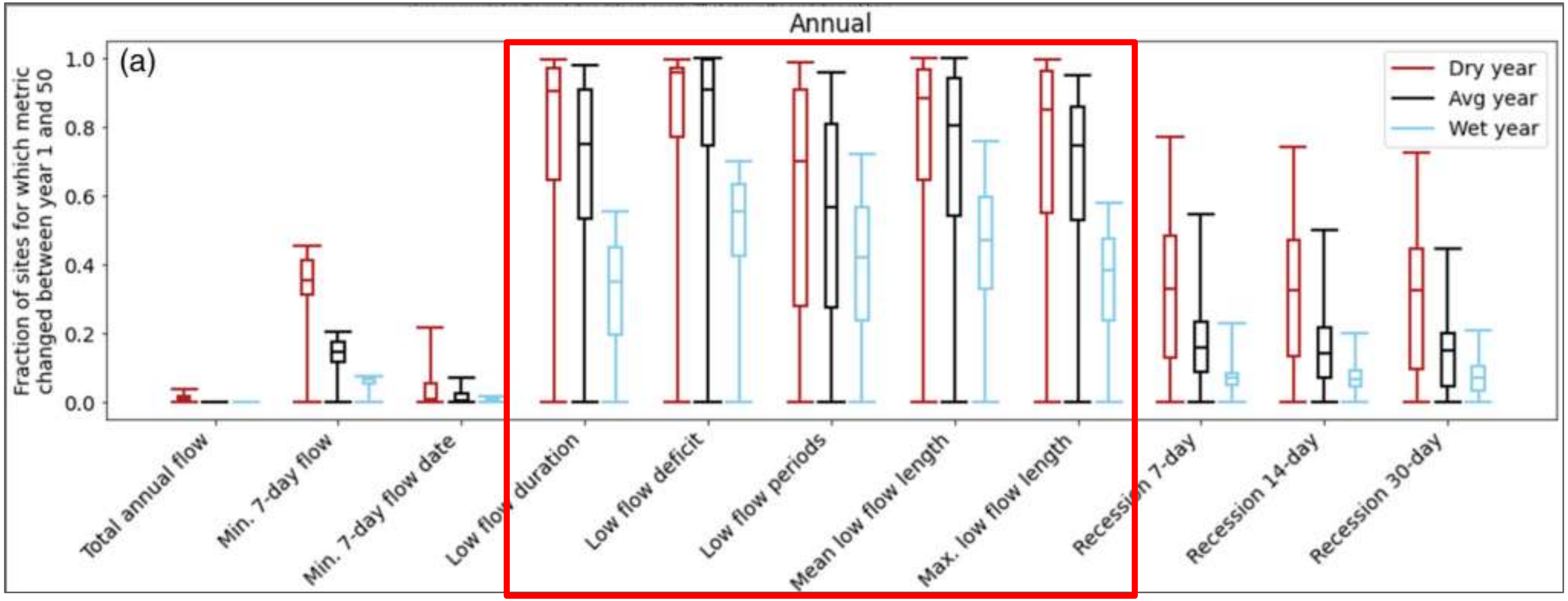
de Graaf, Inge EM, et al. "Environmental flow limits to global groundwater pumping." *Nature* 574.7776 (2019): 90-94.

What can we do about it?



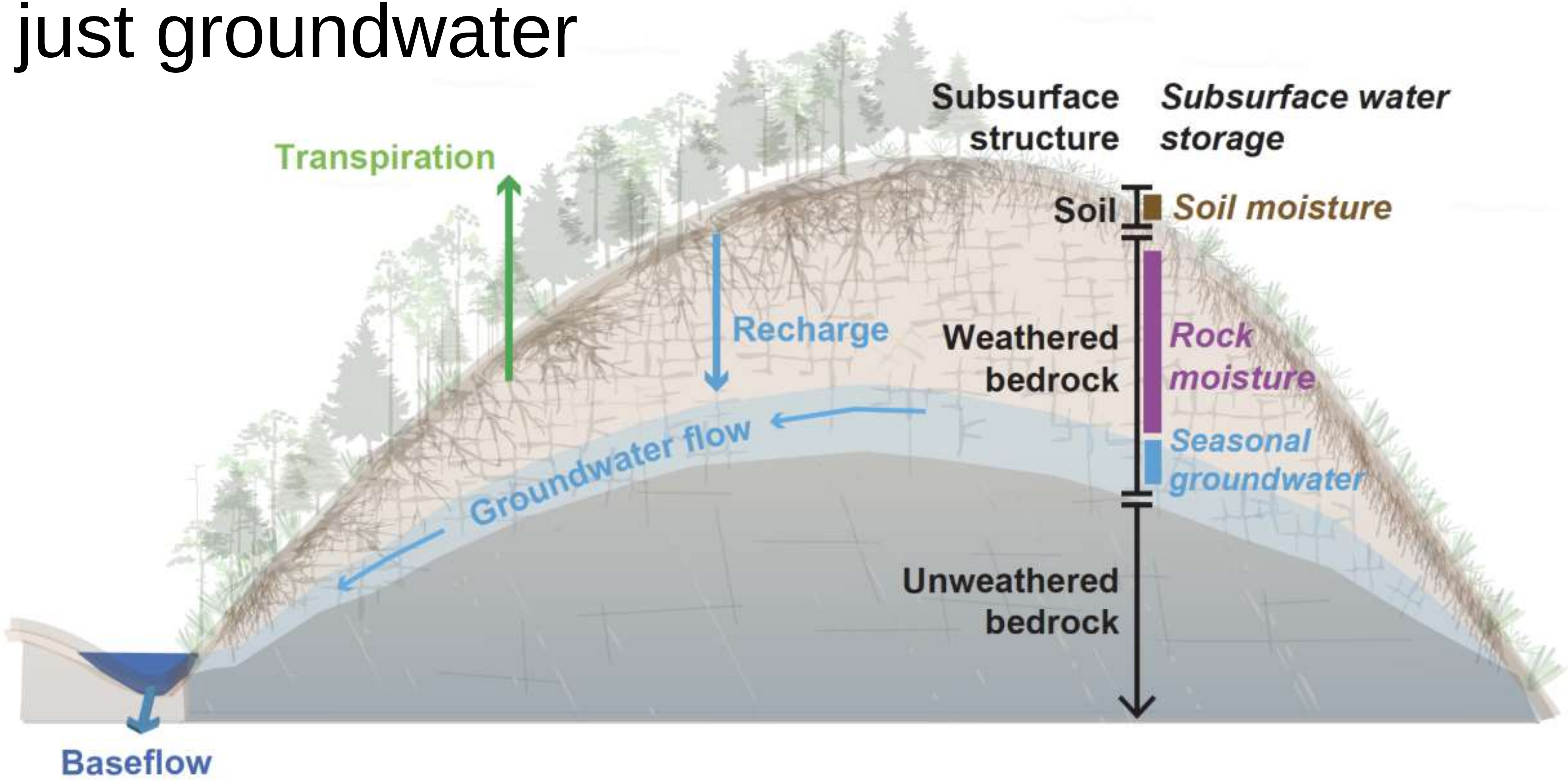
de Graaf, Inge EM, et al. "Environmental flow limits to global groundwater pumping." *Nature* 574.7776 (2019): 90-94.
Barlow, Paul M., and Stanley A. Leake. Streamflow depletion by wells--Understanding and managing the effects of groundwater pumping on streamflow. No. 1376. US Geological Survey, 2012.

These impacts particularly show up in low flows



Lapides, Dana A., Sam Zipper, and John C. Hammond. "Identifying hydrologic signatures associated with streamflow depletion caused by groundwater pumping." Hydrological Processes 37.4 (2023): e14877.

But there's more beneath the surface than just groundwater



Outline

1. What happens to water as it transits the unsaturated zone before it reaches the water table?
2. How do these plant-water interactions affect runoff in streams?

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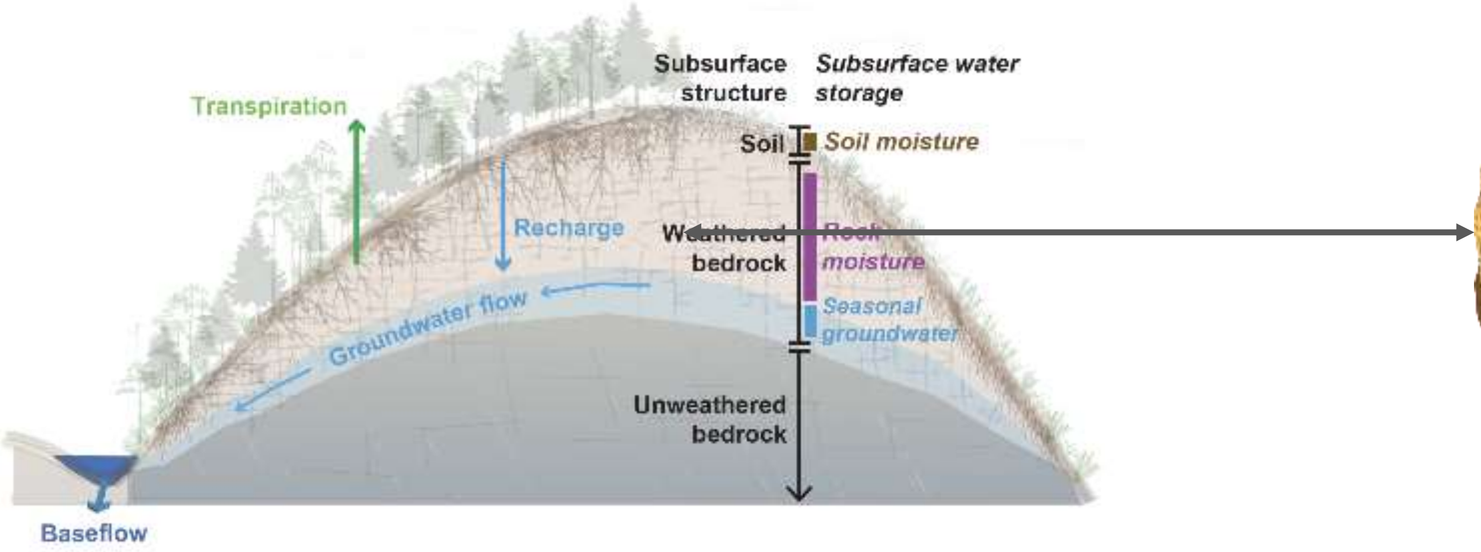
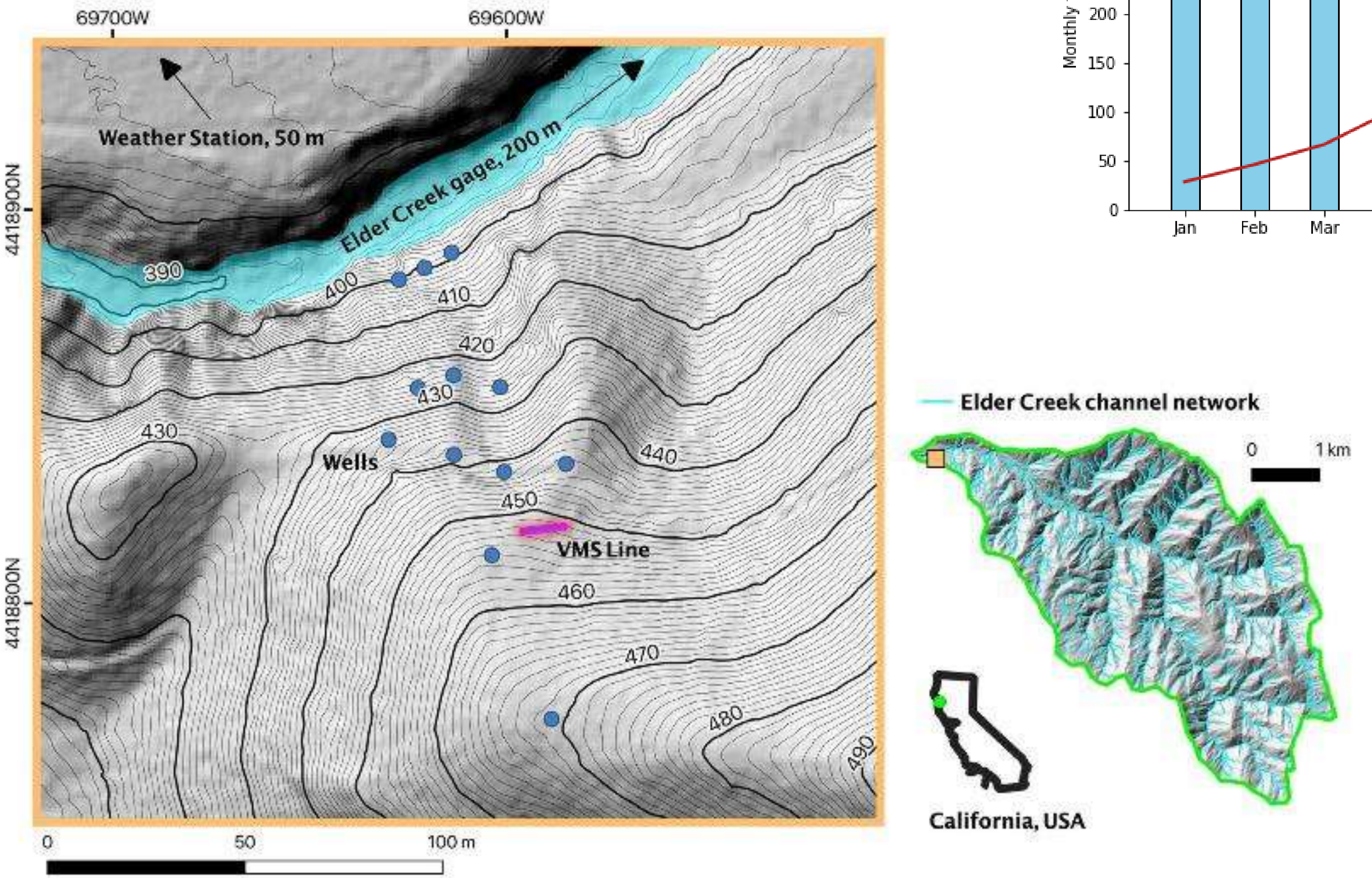
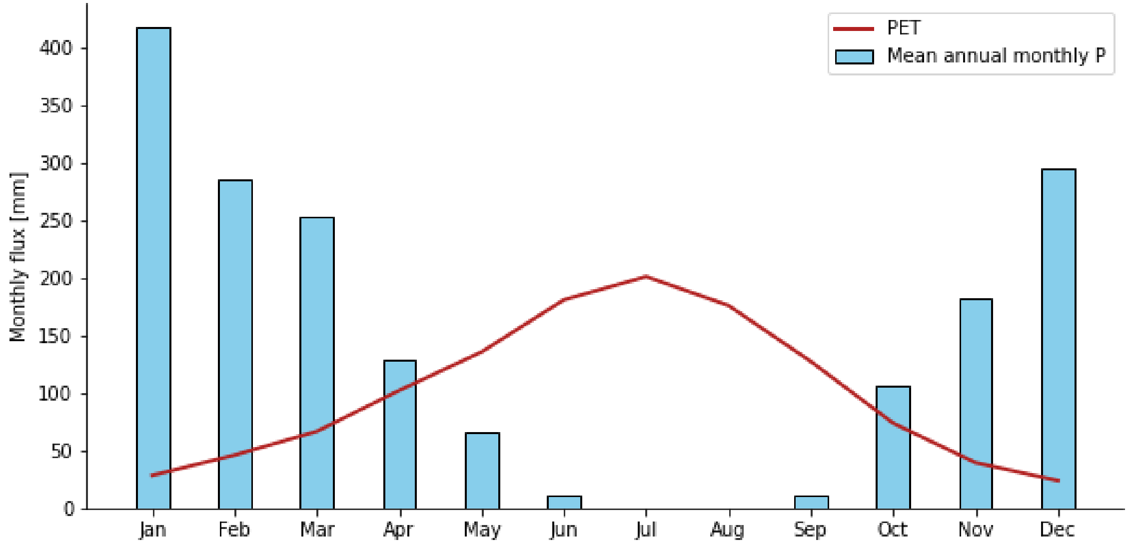
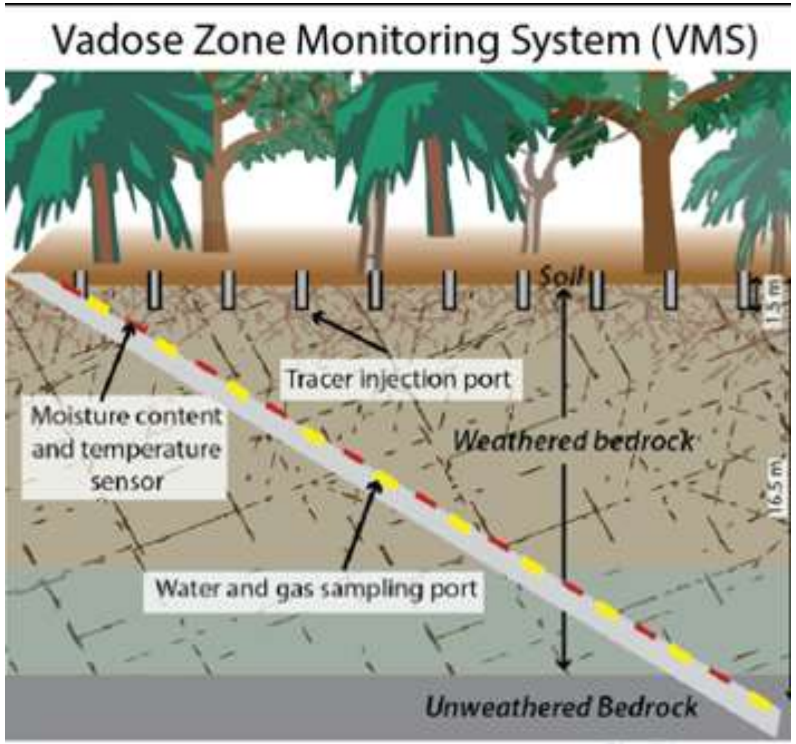


Elder Creek

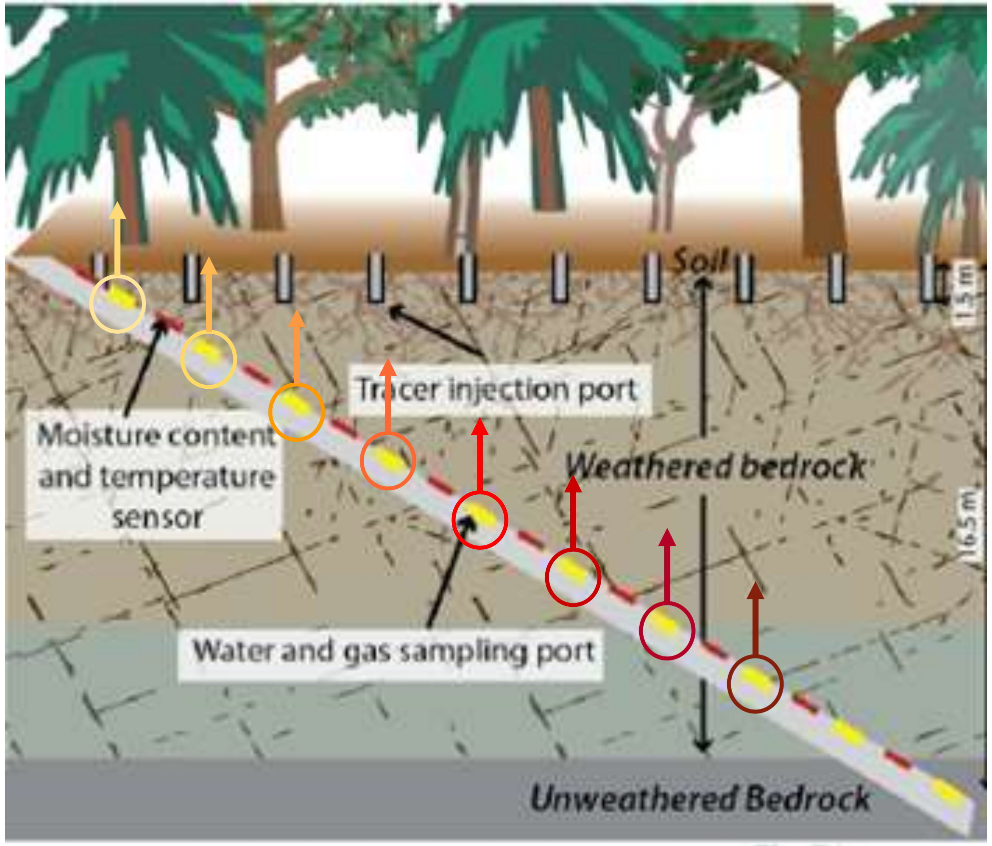


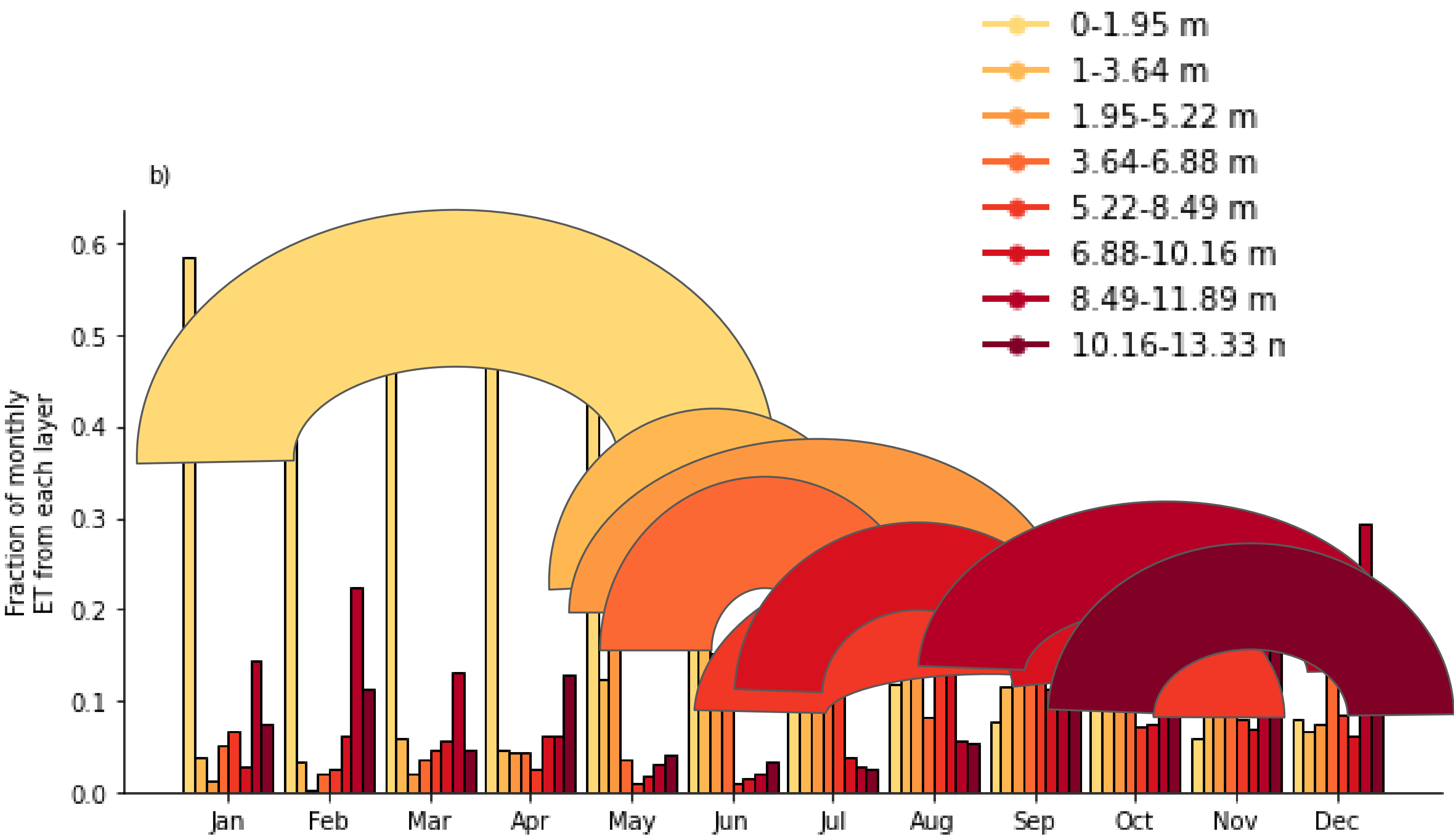




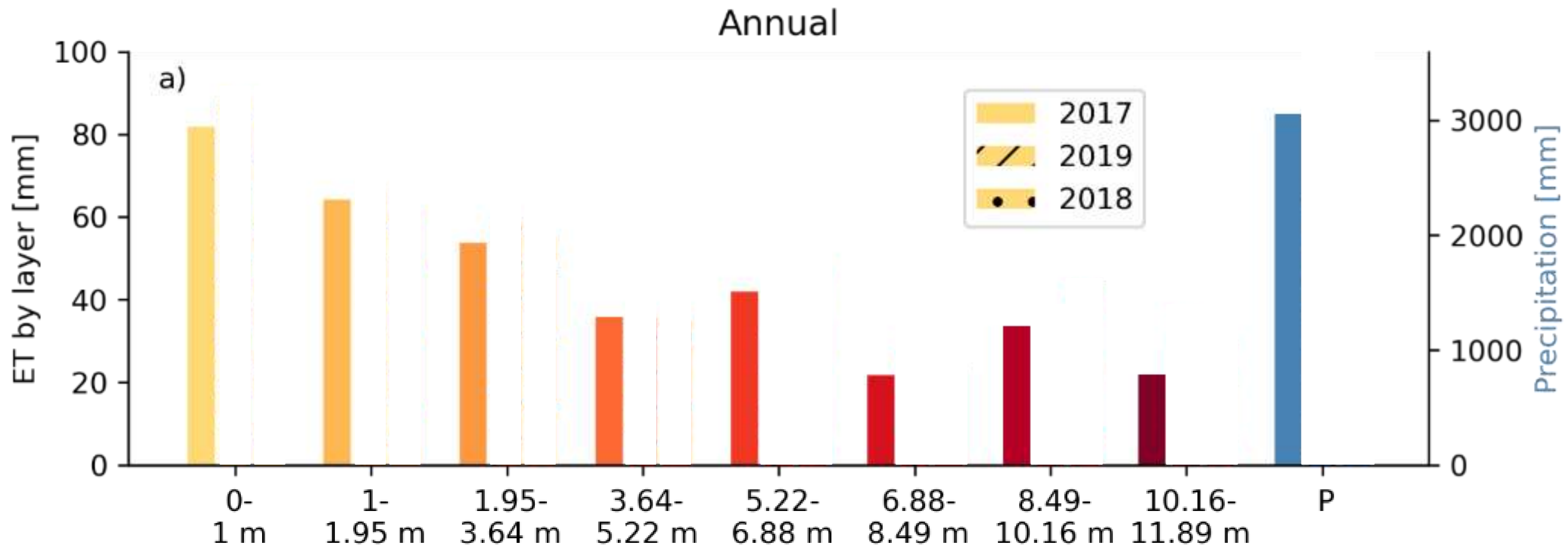
La Follette, Peter T., et al. "Multicriteria analysis on rock moisture and streamflow in a rainfall-runoff model improves accuracy of model results." Hydrological Processes 36.3 (2022): e14536.

Plants access water from deeper as the dry season progresses

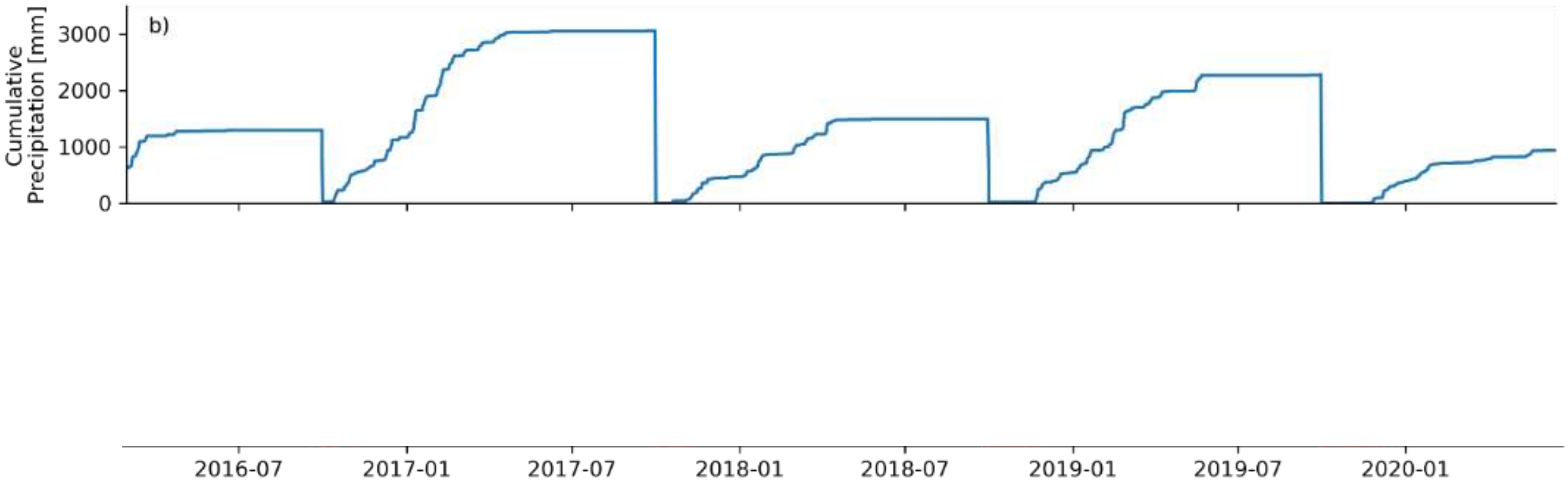




It’s pretty much the same pattern, regardless of precipitation



Drainage continues into the summer



What does it mean?

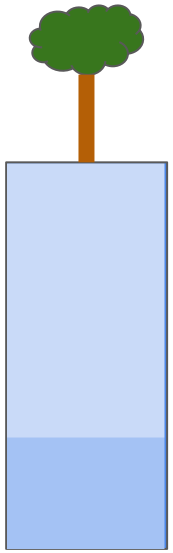
The unsaturated zone might be important for low flows

Outline

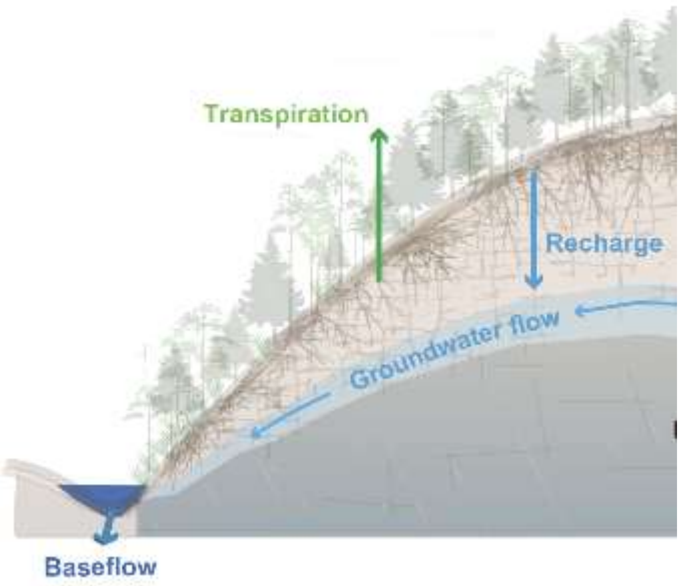
1. **What happens to water as it transits the unsaturated zone before it reaches the water table?**

Rain wets the sponge

Plants use water from the top down



Drainage continues through dry periods



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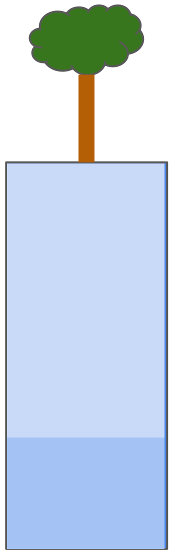

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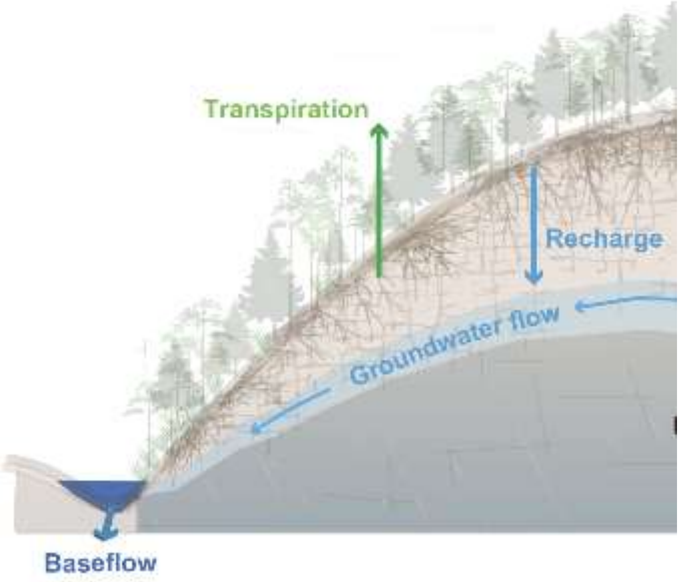
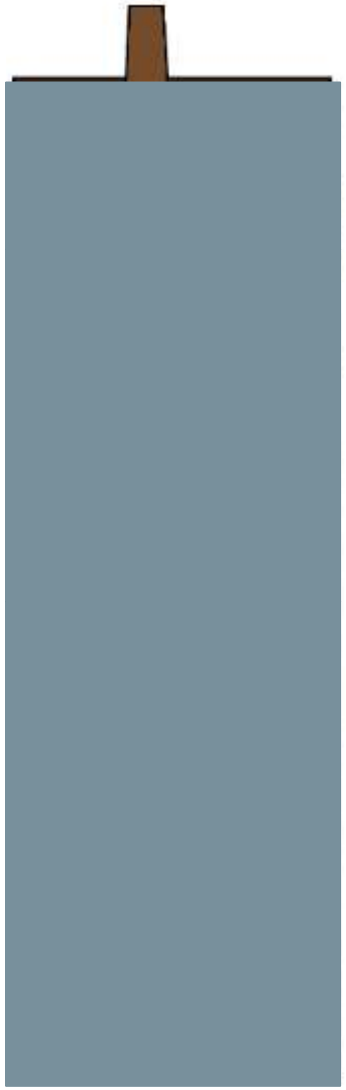
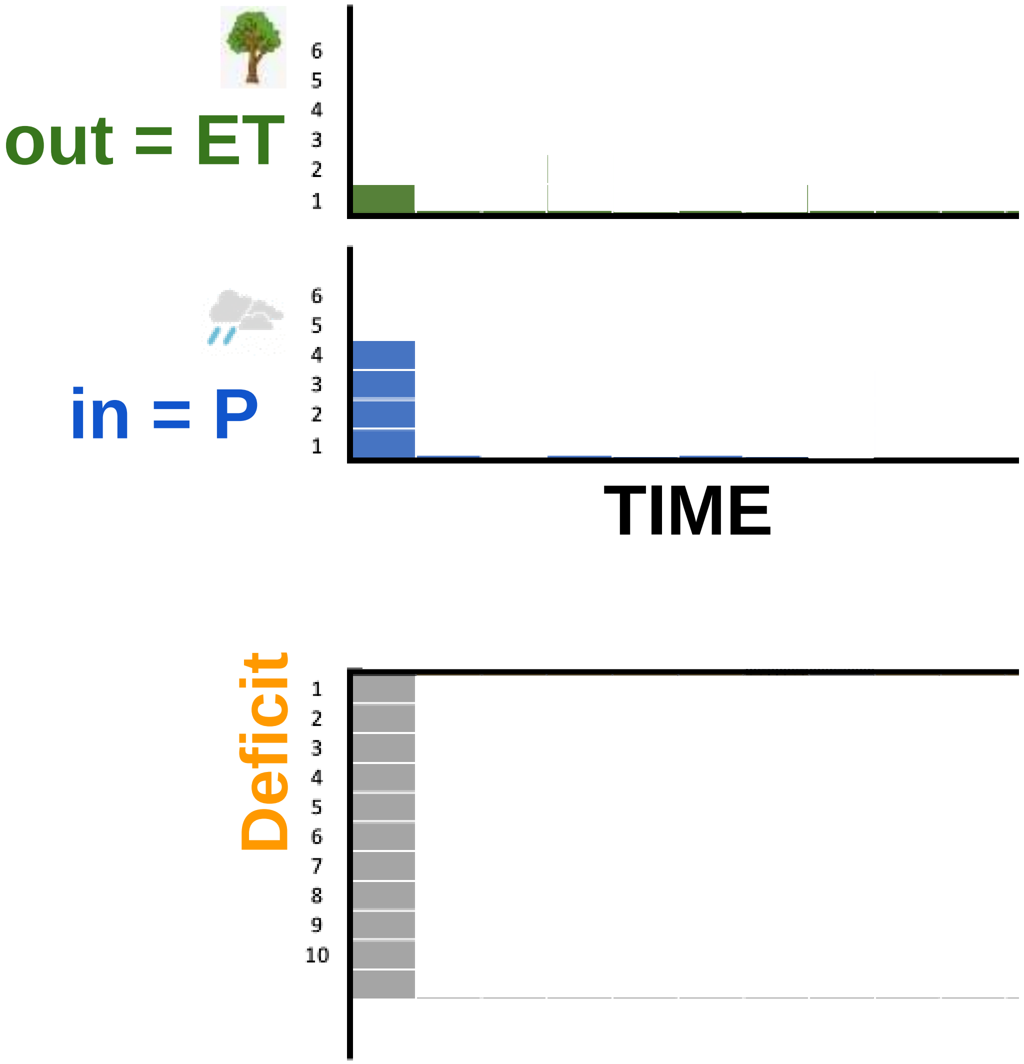


Let’s take what we learned at Elder Creek and try to generalize…how?

We can go big using distributed data products to sense what’s going on under the surface

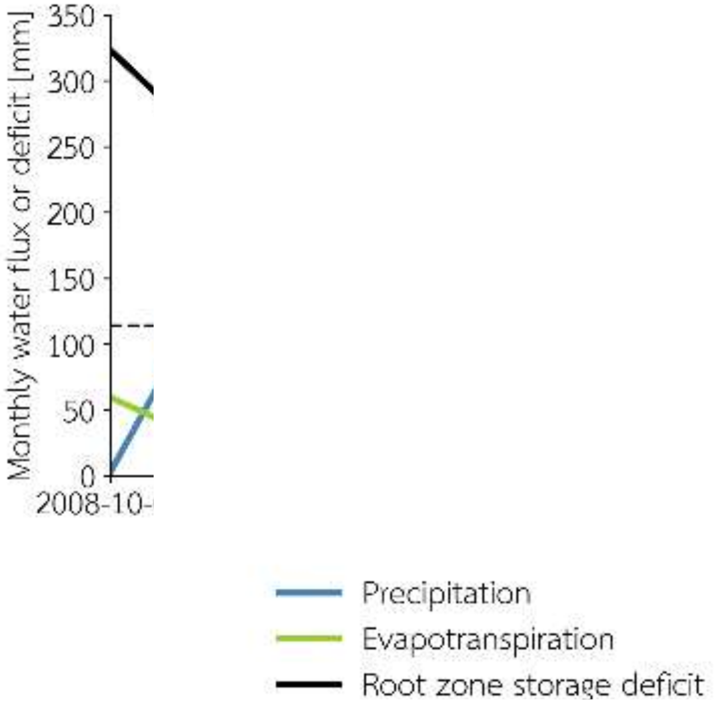


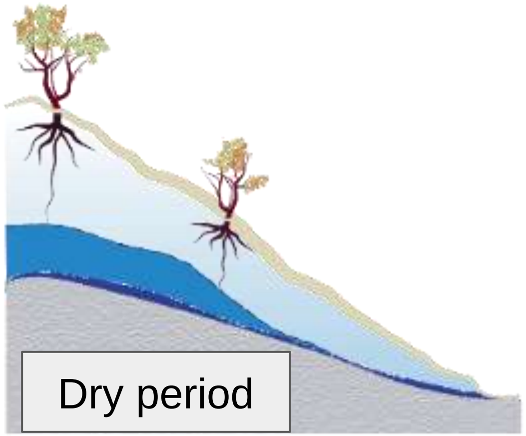


How dry?

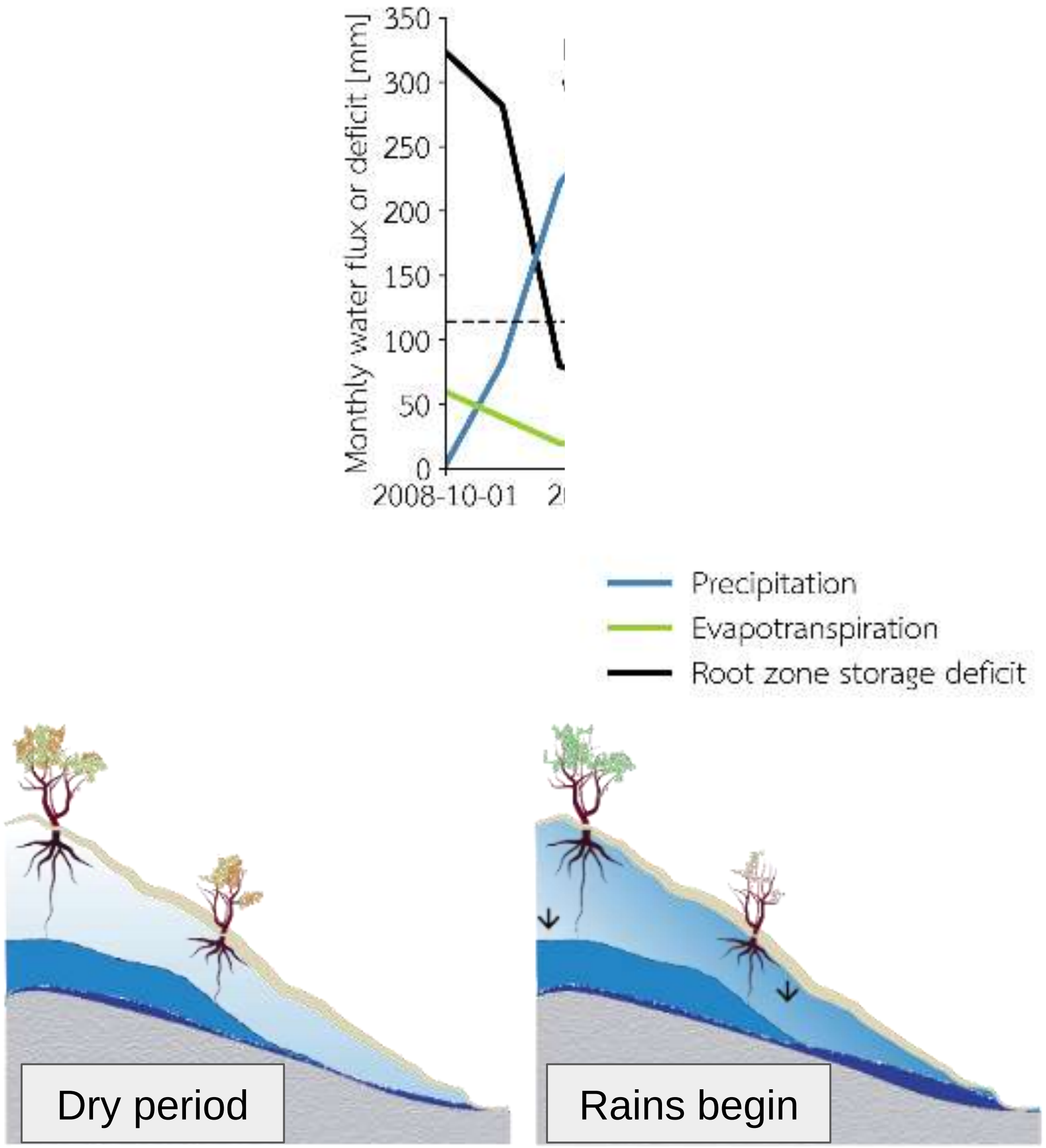
Dralle et al (2021), HESS   or Wang-Erlandsson et al (2016), HESS

The deficit at the start of the wet season sets the initial condition for the next year’s streamflow





The deficit at the start of the wet season sets the initial condition for the next year's streamflow



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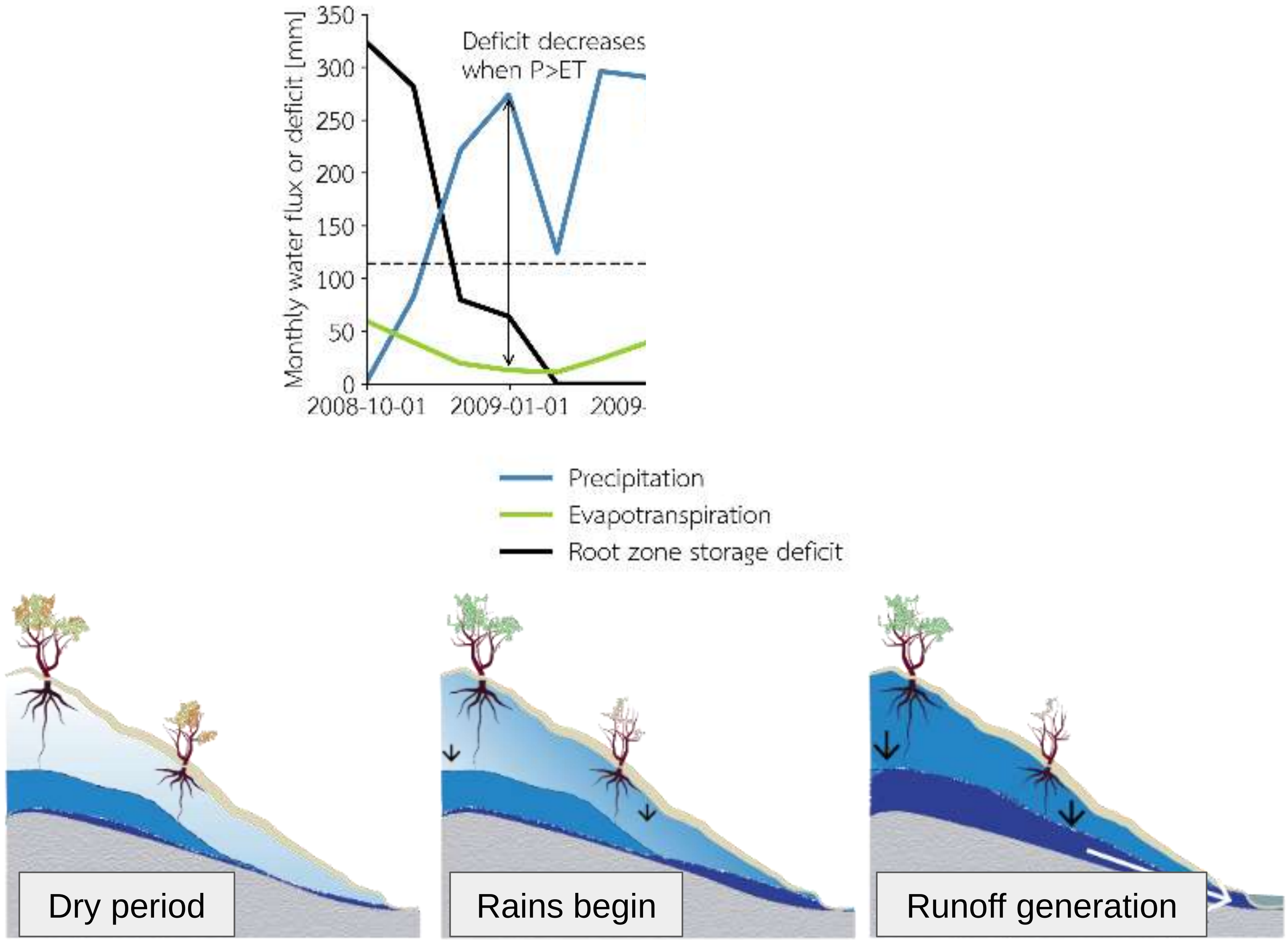

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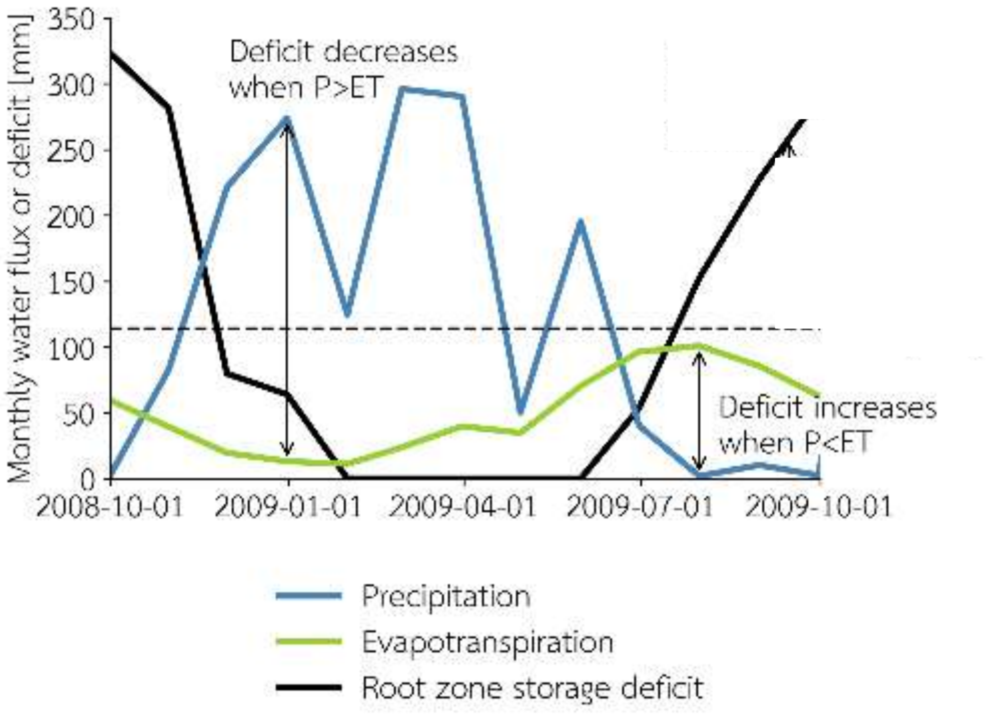
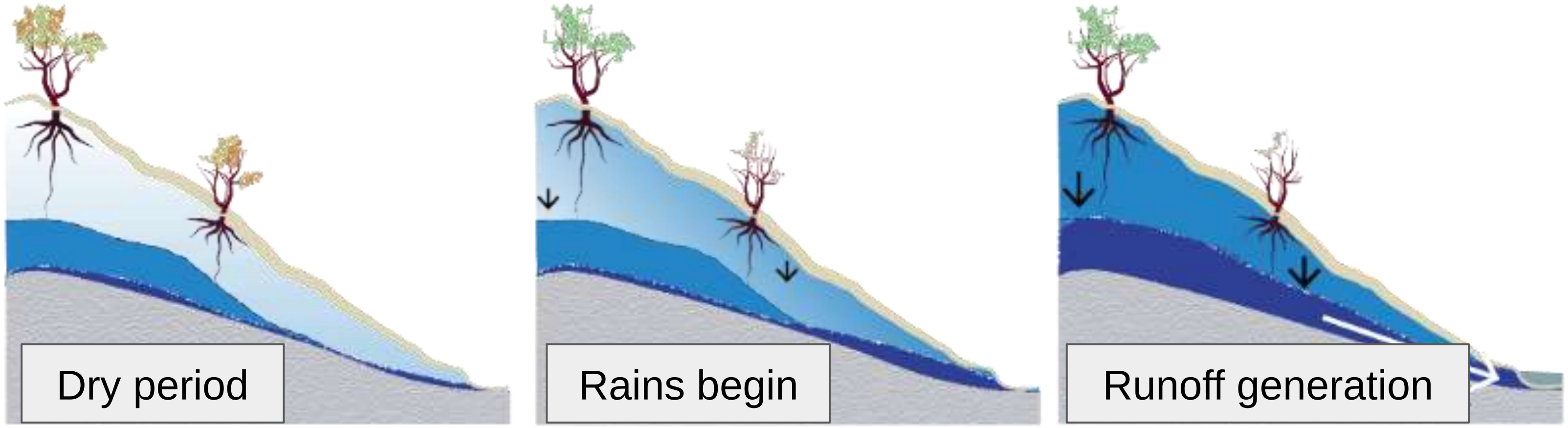
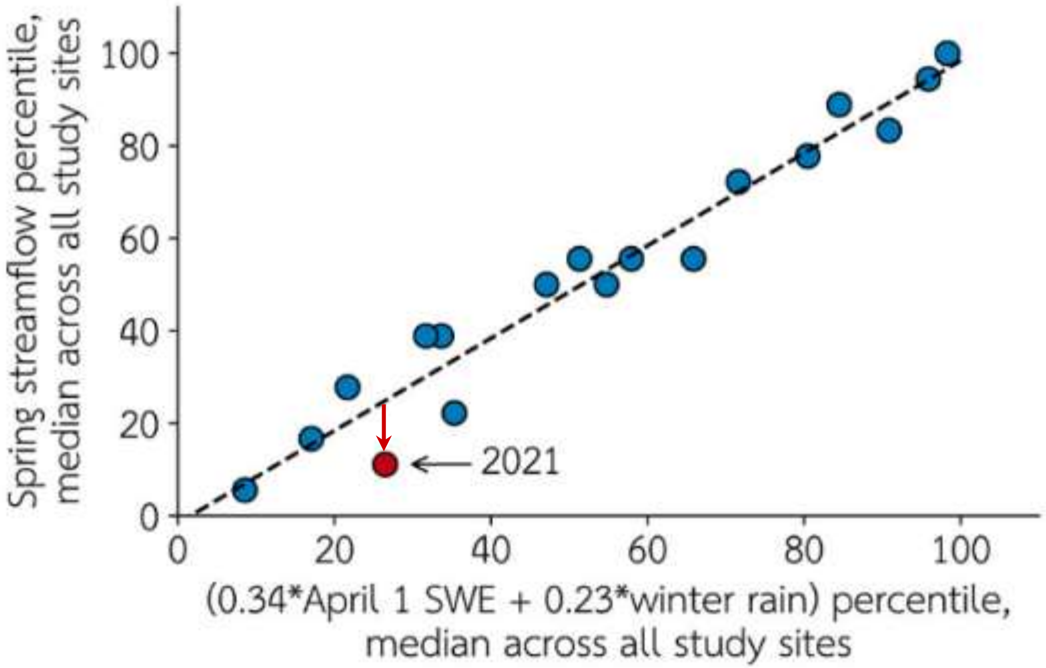


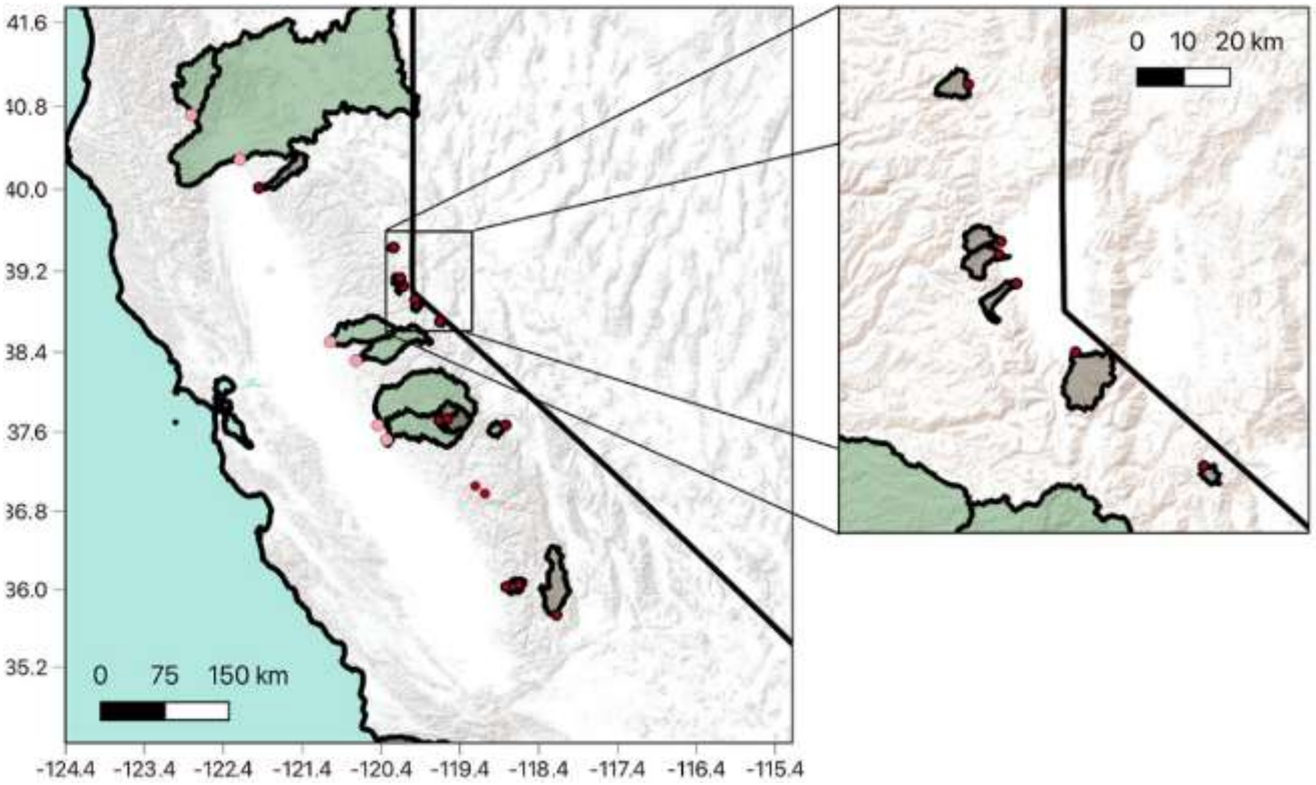


Runoff this year is a function of precipitation and ET this year…

But also the deficit at the end of last year



Spring streamflow percentile, median across all study sites
100
80
60
40
20
0
0
20
40
60
80
100
2021
(0.34*April 1 SWE + 0.23*winter rain) percentile, median across all study sites



41.6
40.8
40.0
39.2
38.4
37.6
36.8
36.0
35.2
0 75 150 km
-124.4
-123.4
-122.4
-121.4
-120.4
-119.4
-118.4
-117.4
-116.4
-115.4
0 10 20 km

Where did Sierra snow go this spring? Not into California rivers and water supplies

by Paul Rogers, Mercury News

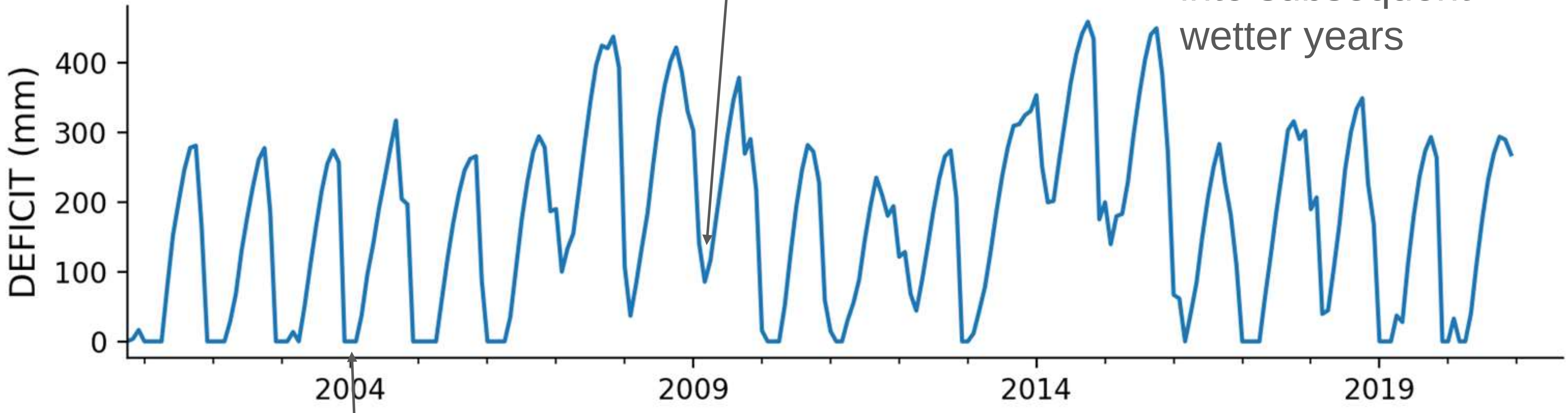
What was special about 2021?

It was a year following a multi-year drought period

On dry years, deficit may not be fully replenished, setting dry initial condition for following year

What does it mean?

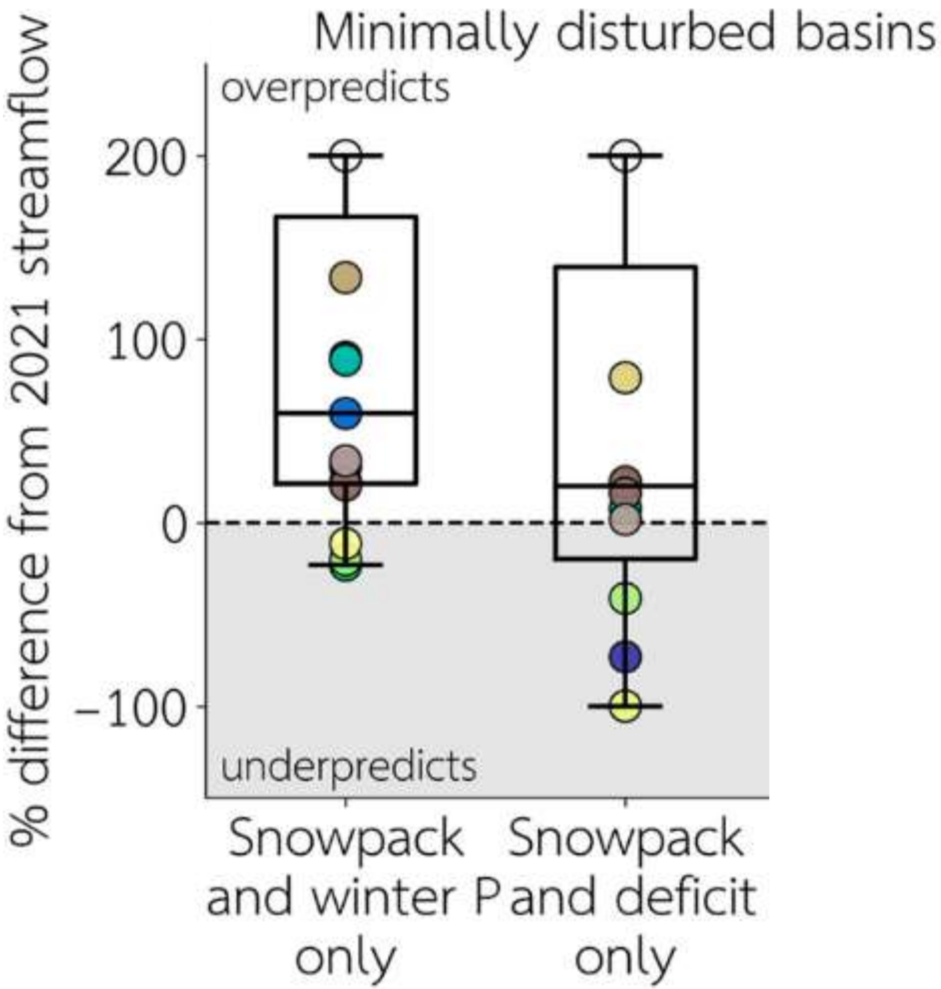
The deficit carries the signature of dry years into subsequent wetter years



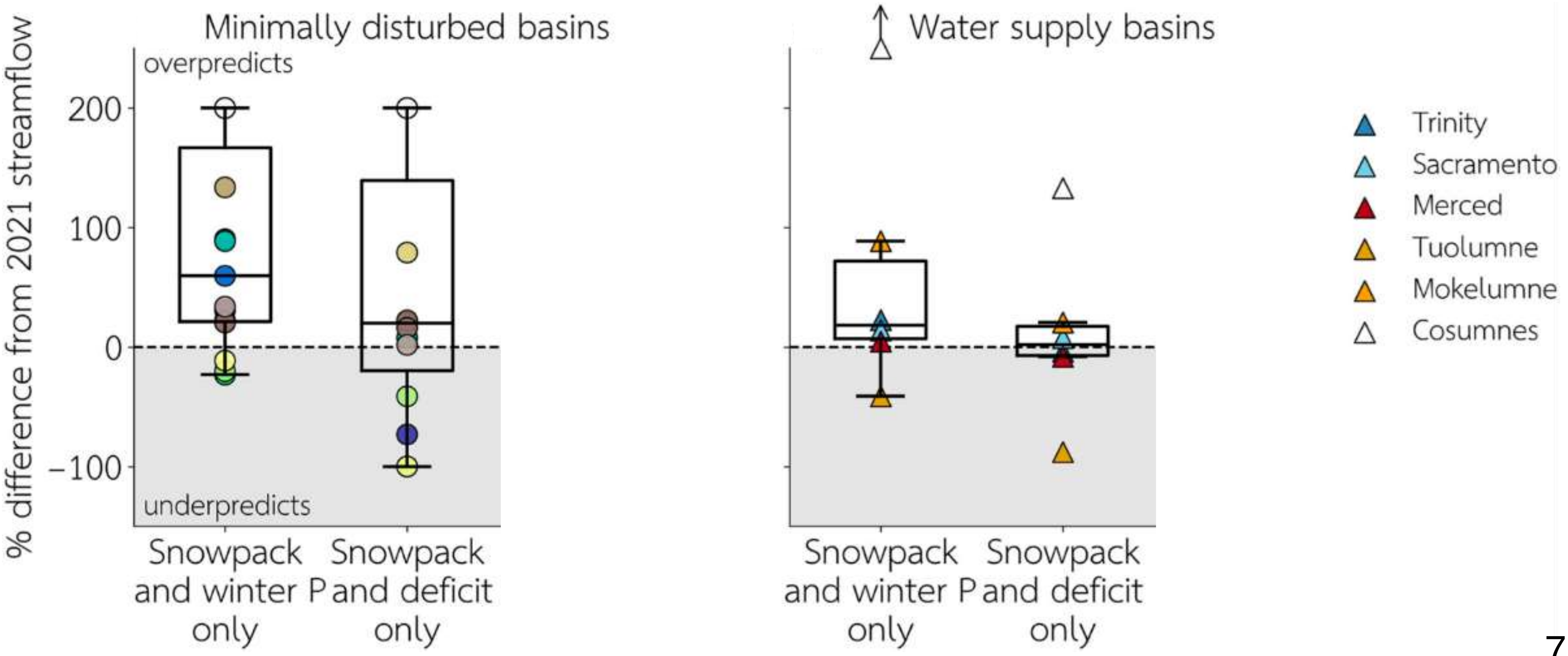
On wetter years, deficit is fully replenished

So if we add the deficit at the beginning of the year as a model predictor for streamflow…

Median error in 2021 forecast is reduced from 60% to 20% in minimally disturbed basins



Median error in 2021 forecast is reduced from 18% to 2% in basins essential to California's water supply

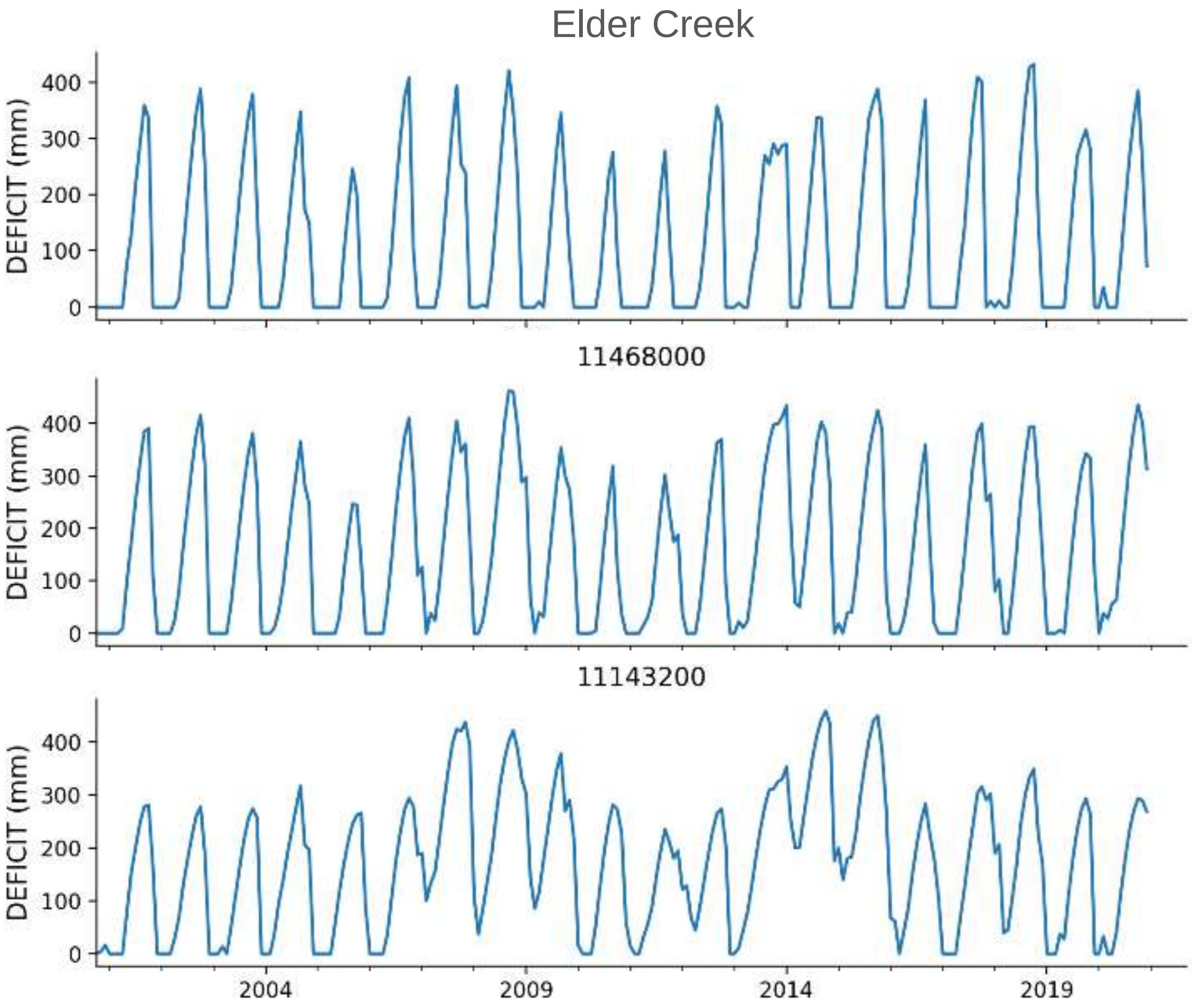


What does this teach us about how plants affect runoff at different places?

The deficit in the unsaturated zone affects streamflow, particularly in years following dry years.

These deficits are generated by plant water use.

Deficit behavior is different depending on local site behavior.

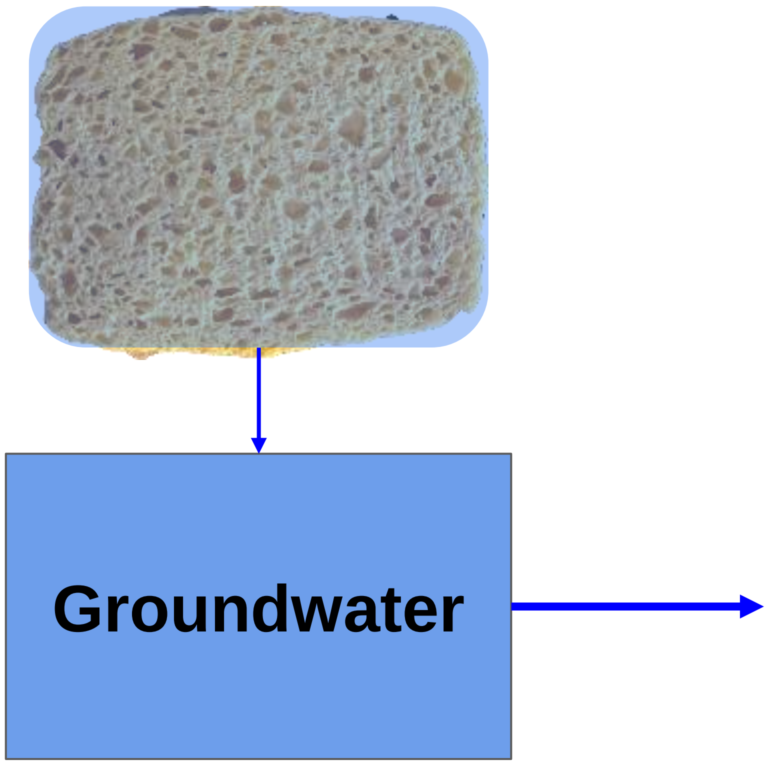


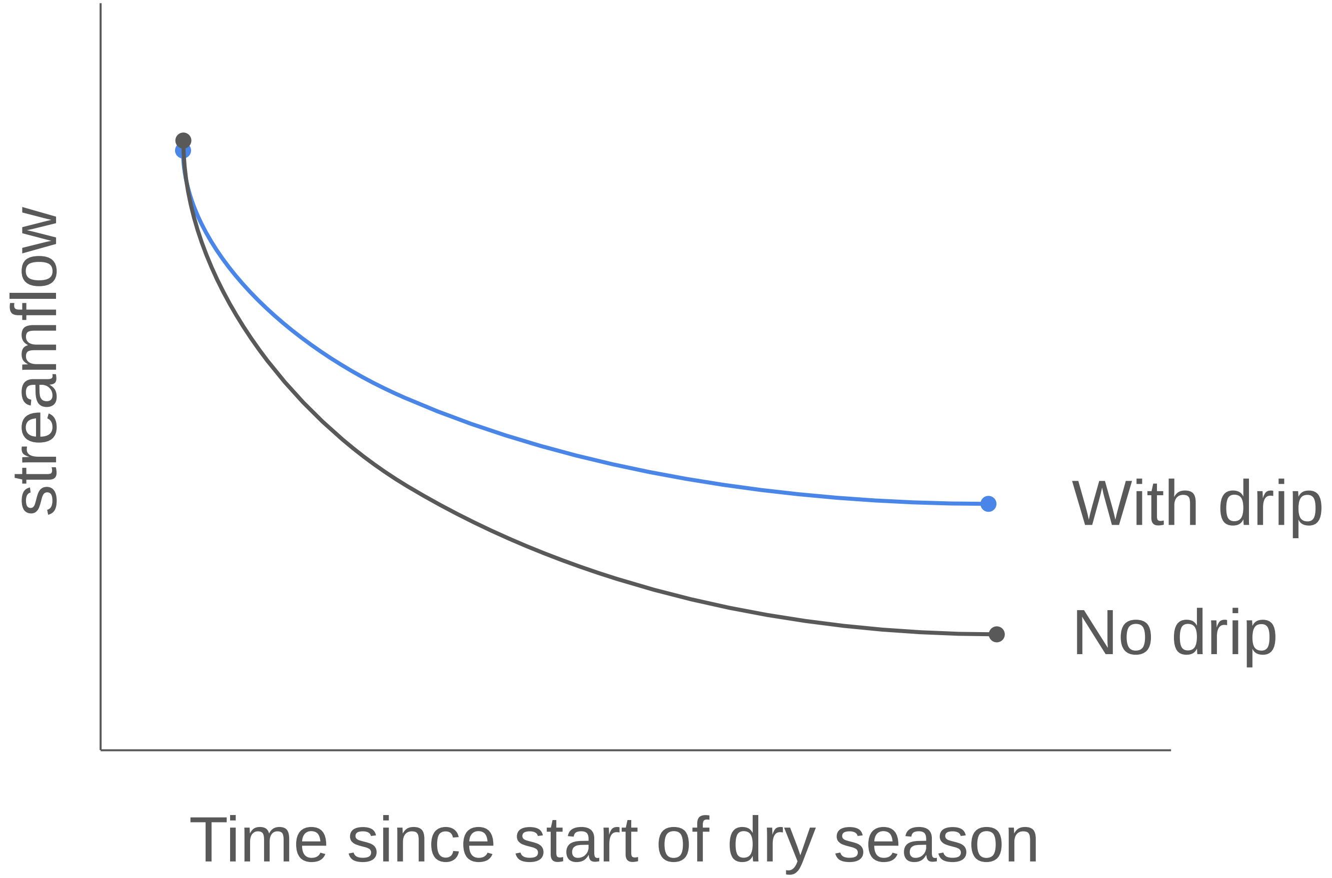
Deficit always replenished

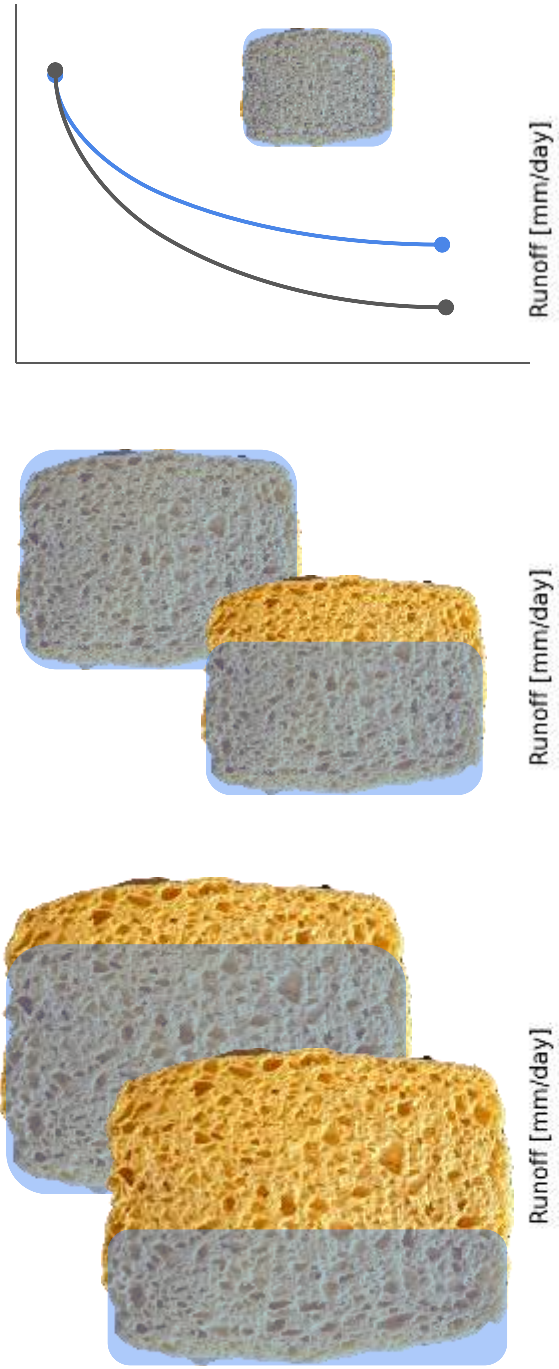
Deficit usually replenished

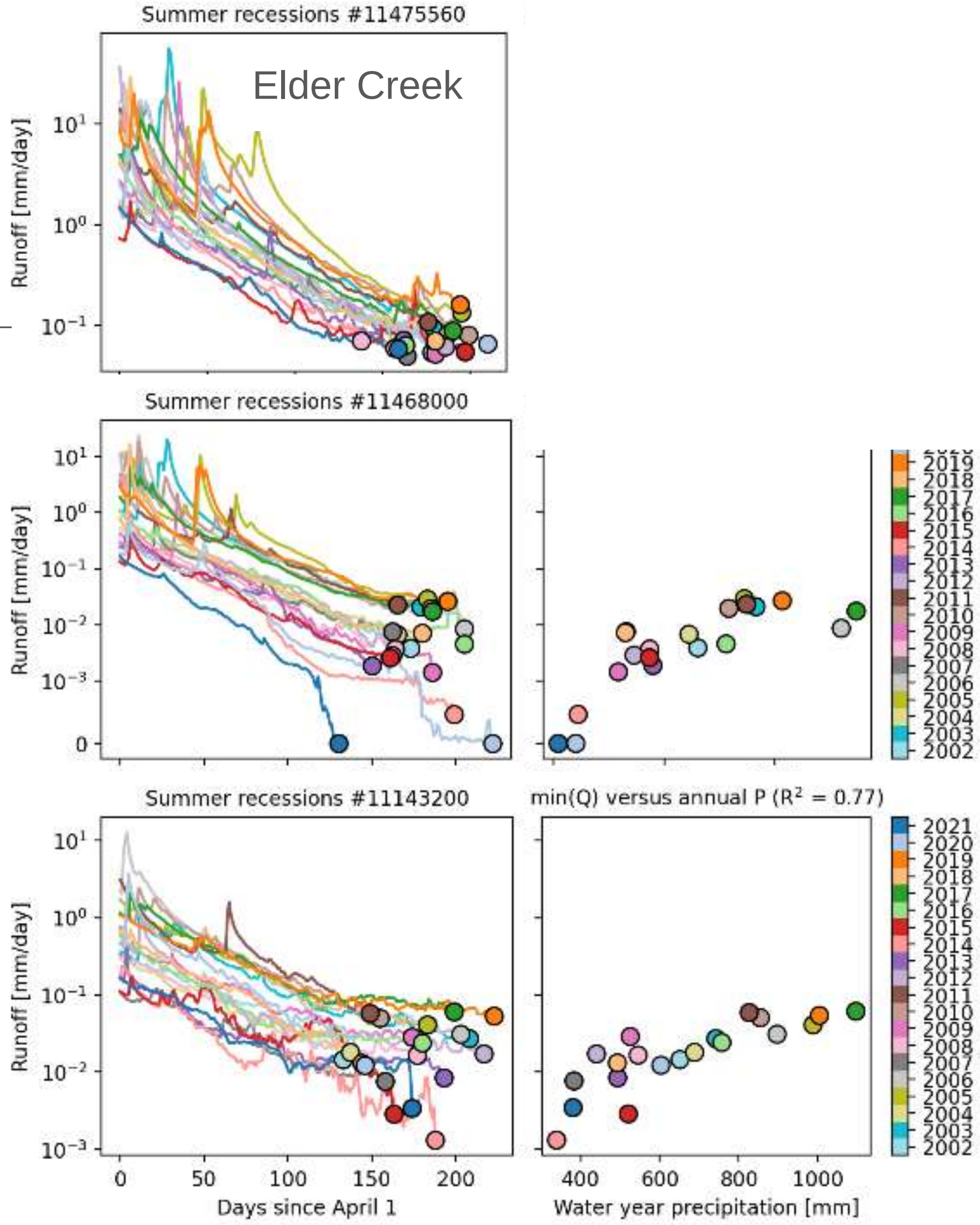
Deficit sometimes replenished

Low flows in streams









Low flows are nearly the same every year despite precipitation variability

Low flows depend to some degree on precipitation

Low flows depend strongly on precipitation

Outline

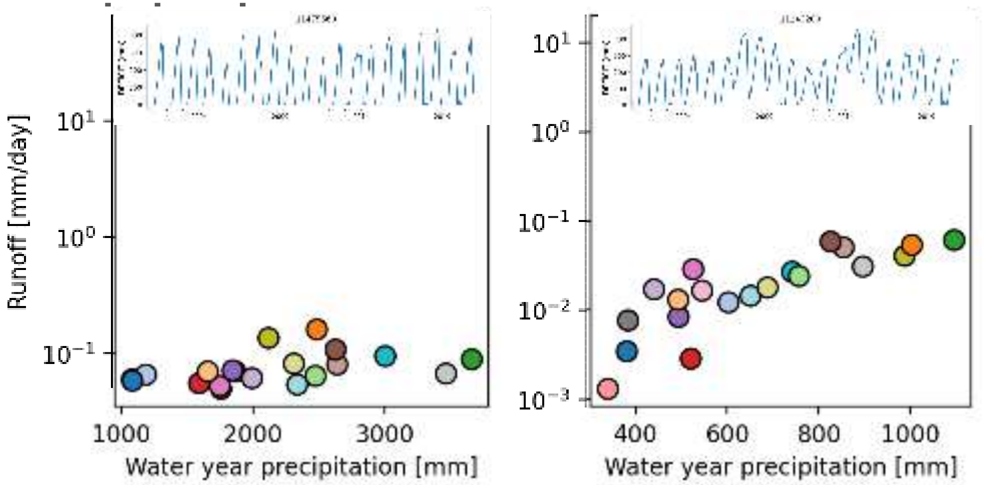
1. What happens to water as it transits the unsaturated zone before it reaches the water table?
2. **How do these plant-water interactions affect runoff in streams?**

Bigger deficits mean less streamflow


Where did Sierra snow go this spring? Not into California rivers and water supplies

by Paul Rogers, Mercury News

Deficit behavior determines whether low flows are coupled to



Final takeaways

Groundwater is stream water

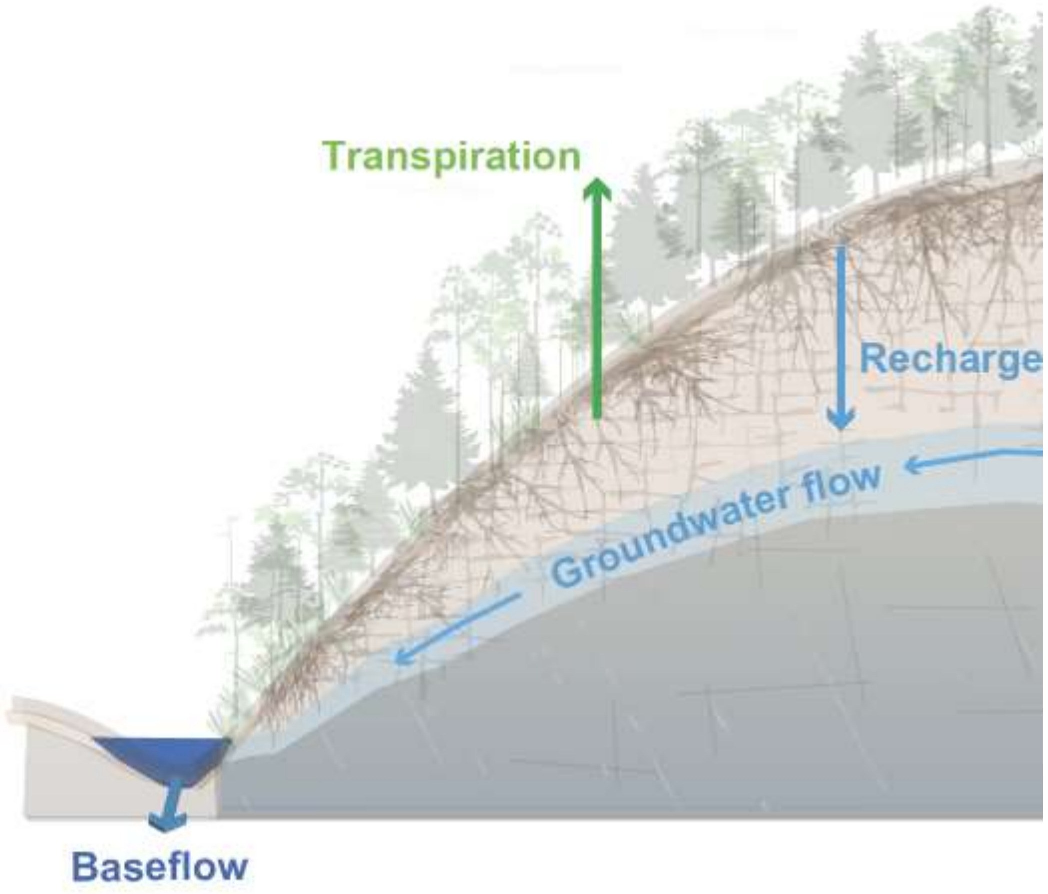
When water is withdrawn from groundwater, supply to streams is reduced

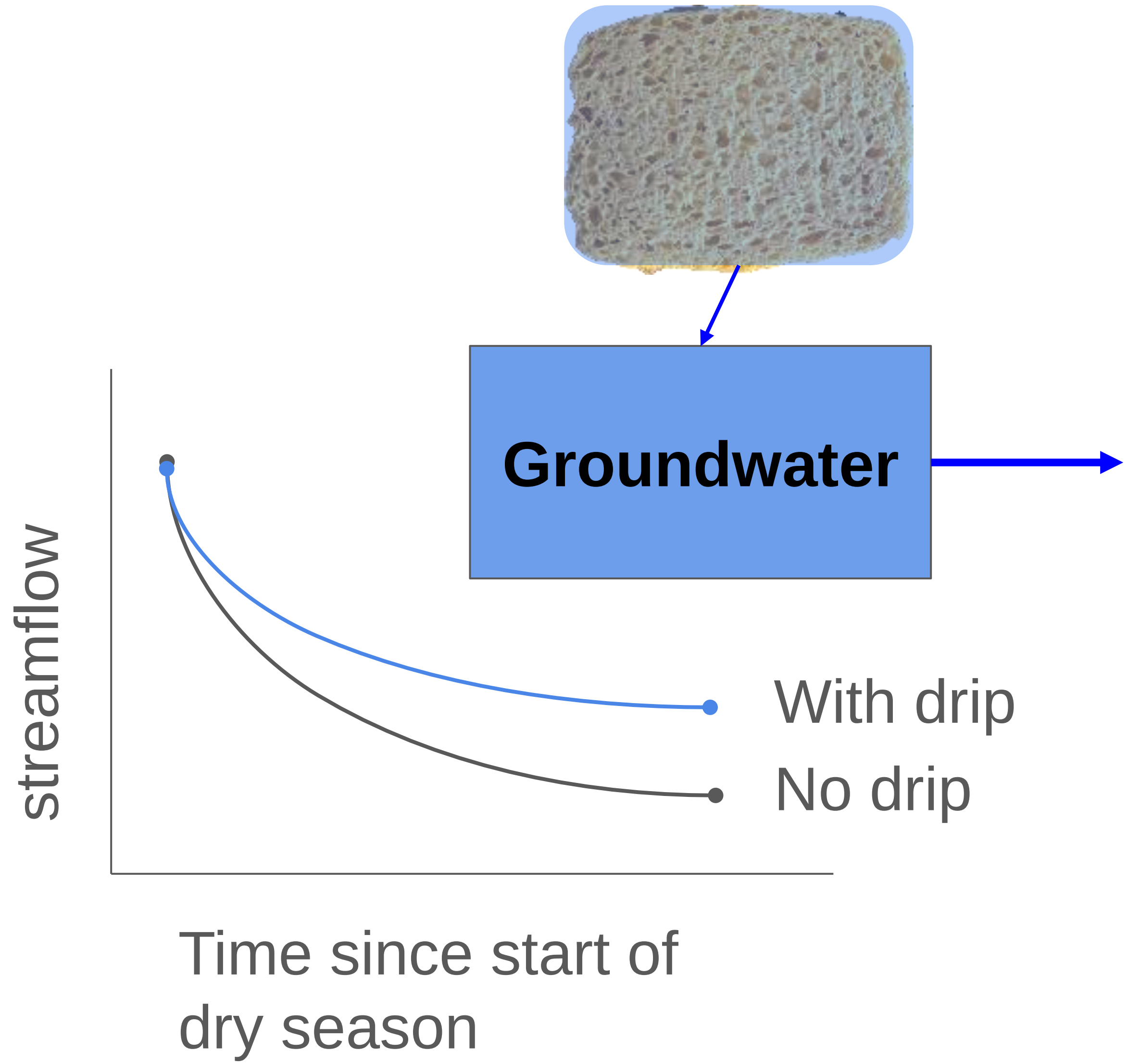
Anything we do at the surface has to filter through the unsaturated zone before it impacts groundwater

Different landscapes have different responses due to their geological and ecological structure (e.g., different deficit behavior and low flow behavior)

The unsaturated zone plays an important role in determining how landscapes respond to different conditions

Questions?


Transpiration
Recharge
Groundwater flow
Baseflow


Groundwater
streamflow
With drip
No drip
Time since start of dry season

Quantifying Streamflow Depletion from Groundwater Pumping Using Storage-Discharge Functions in Headwater Catchments

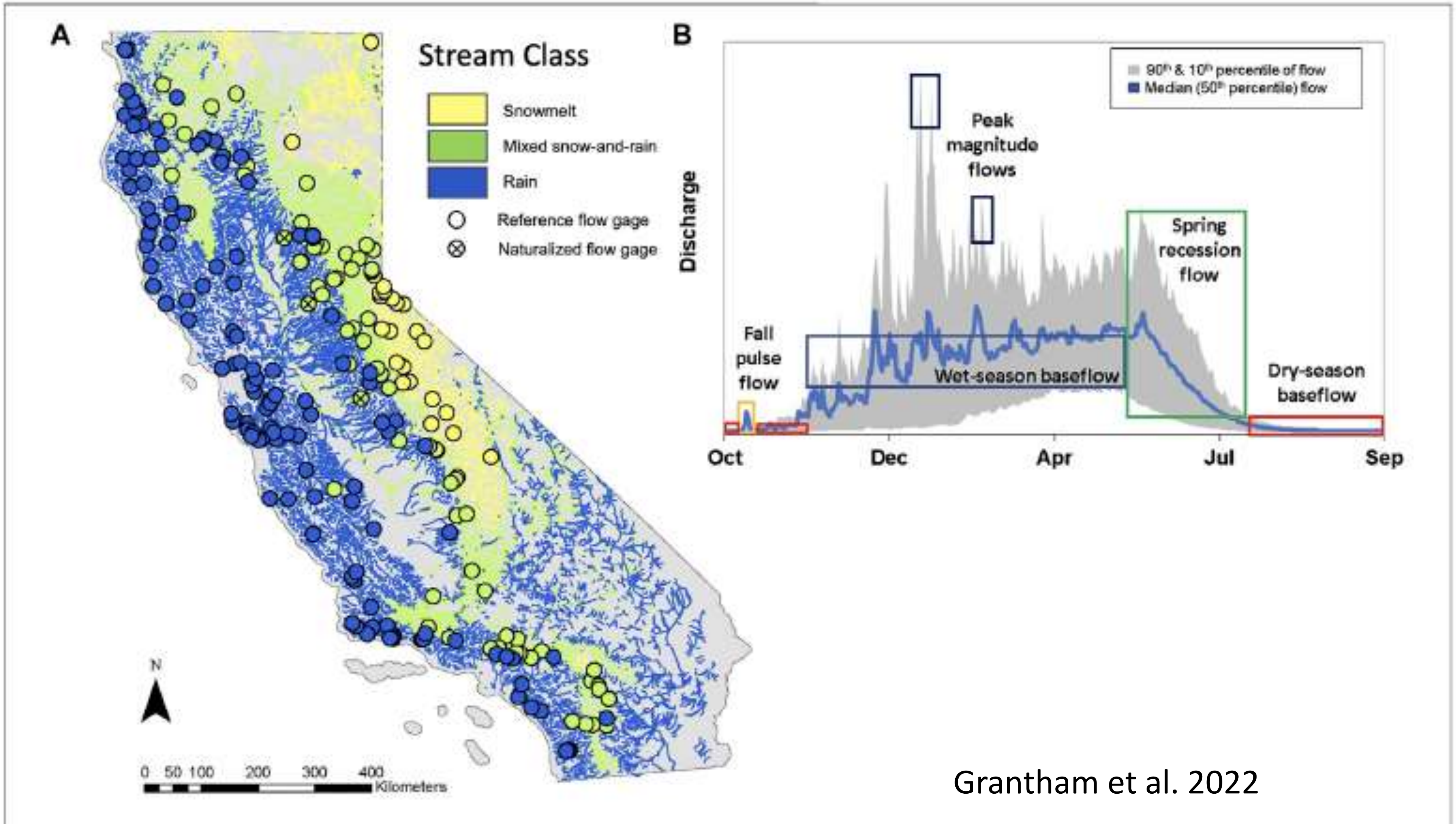
Phil Georgakakos, Chris Dillis, David Dralle,
Jesse Hahm, Dana Lapides, Ted Grantham

SRF 2024

Groundwater's impact on streamflow is hard to measure, especially in headwater catchments

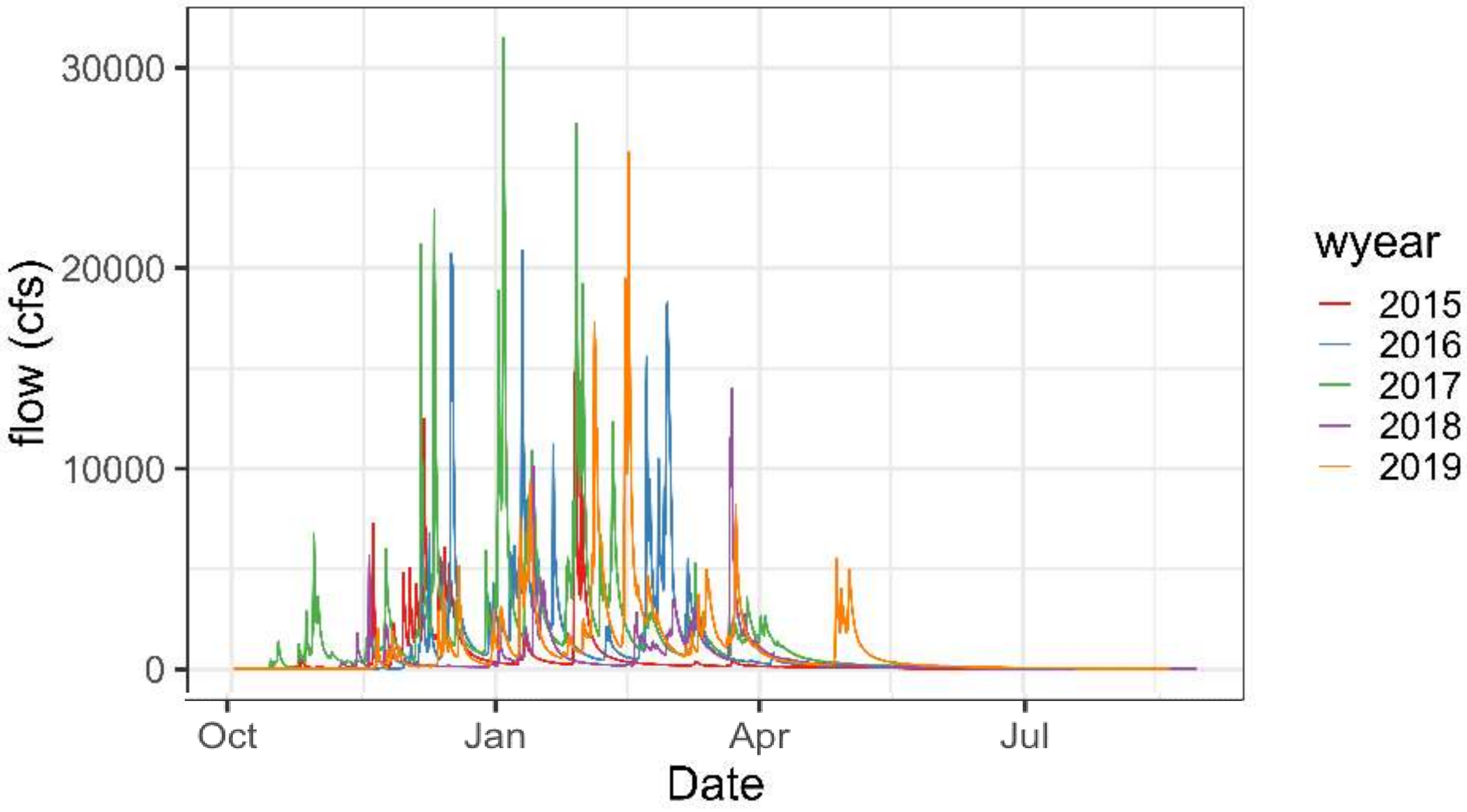
- Cannot directly observe groundwater
- Wells are point sources on hillslopes and expensive
- Time lags between water withdrawals and impacts to streamflow
- Individual basins can be mixed lithology
- Complicated subsurface dynamics
- Headwater catchments differ from lowland systems with large aquifers

Rain and groundwater are particularly important in Coastal California



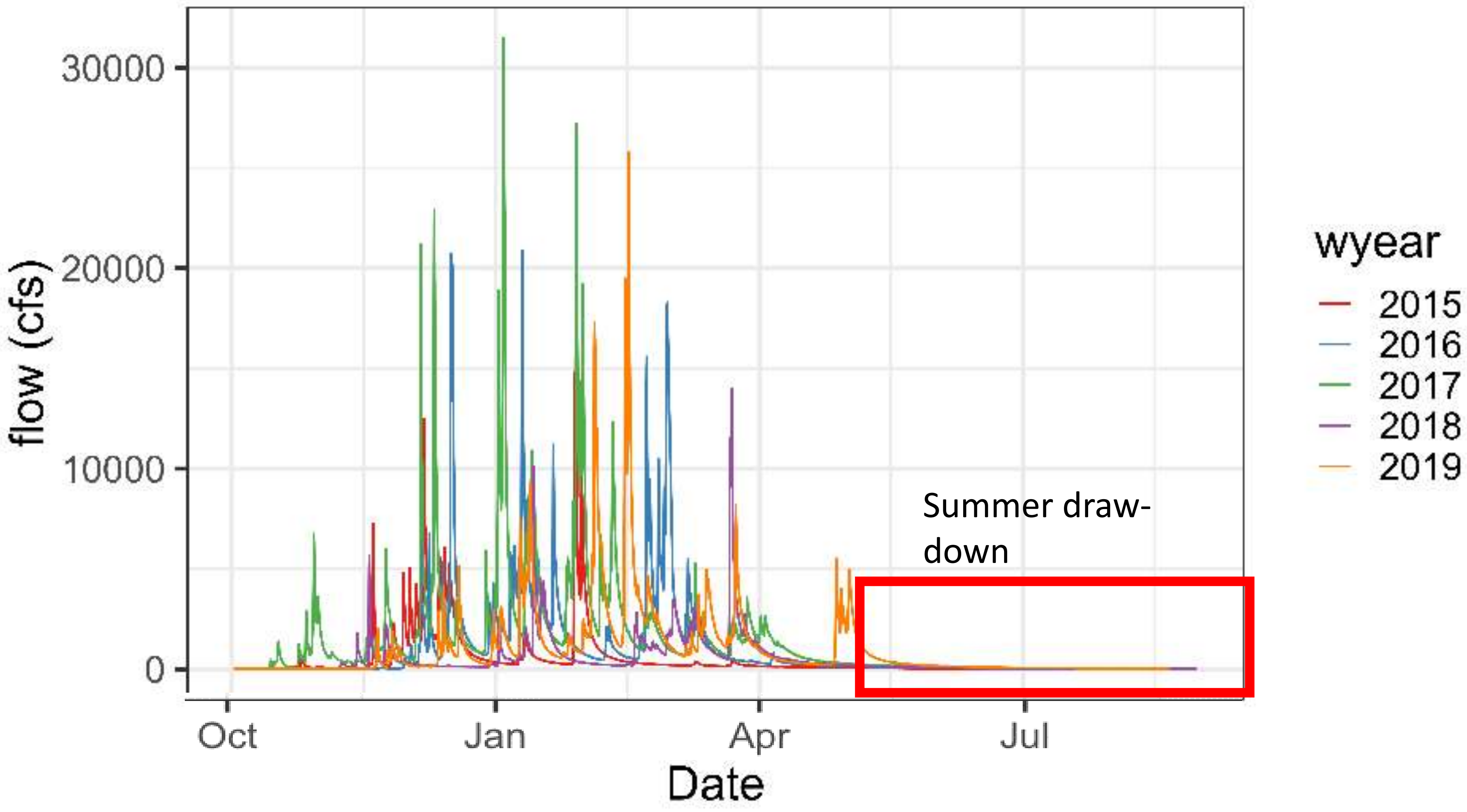
Grantham et al. 2022

Groundwater drives streamflow in summer



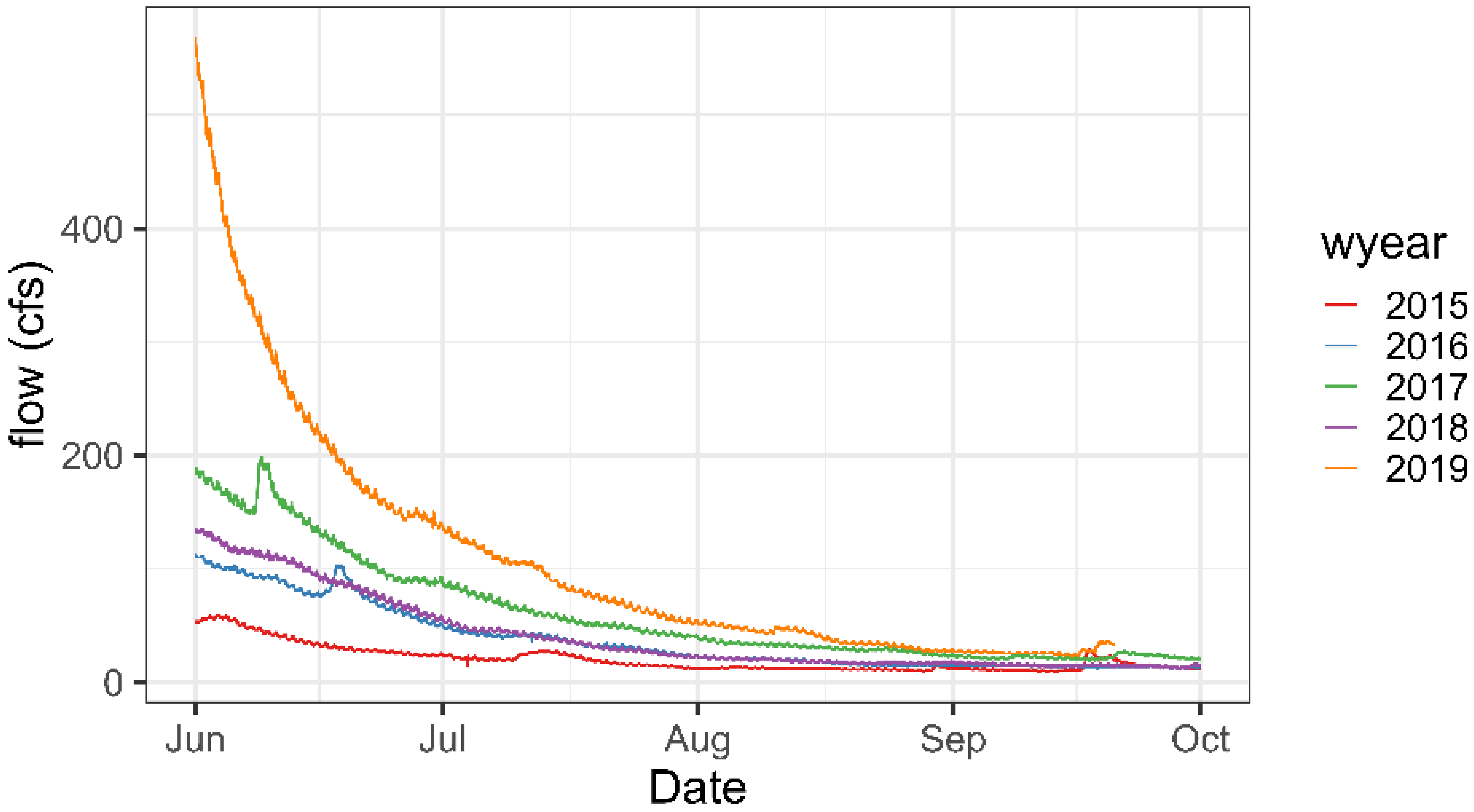
USGS stream gauge 11475800. Legget, CA

Groundwater drives streamflow in summer

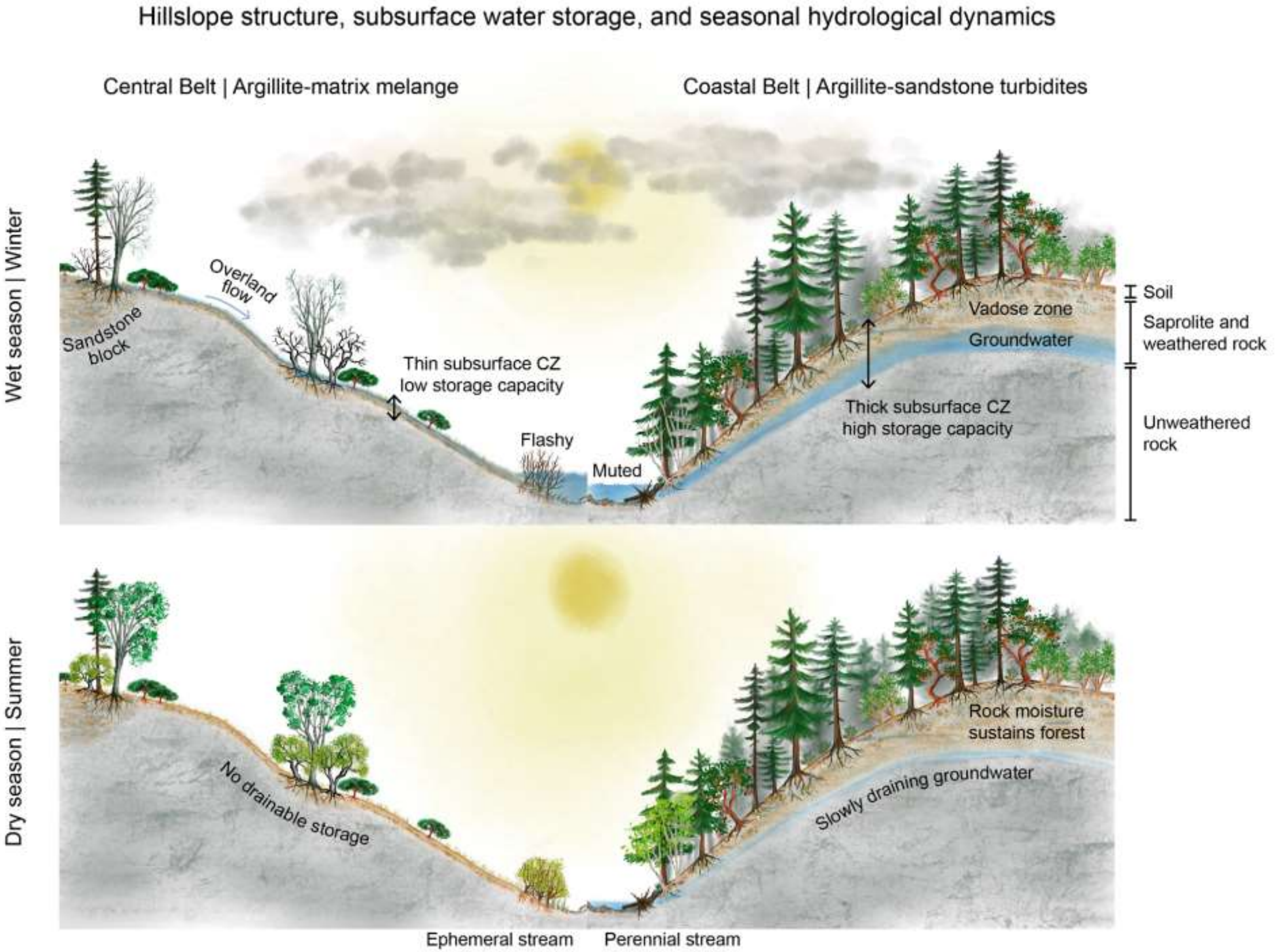


USGS stream gauge 11475800. Legget, CA

Groundwater drives streamflow in summer



USGS stream gauge 11475800. Legget, CA



Dralle et al. 2023

Storage capacity decouples rainfall and streamflow

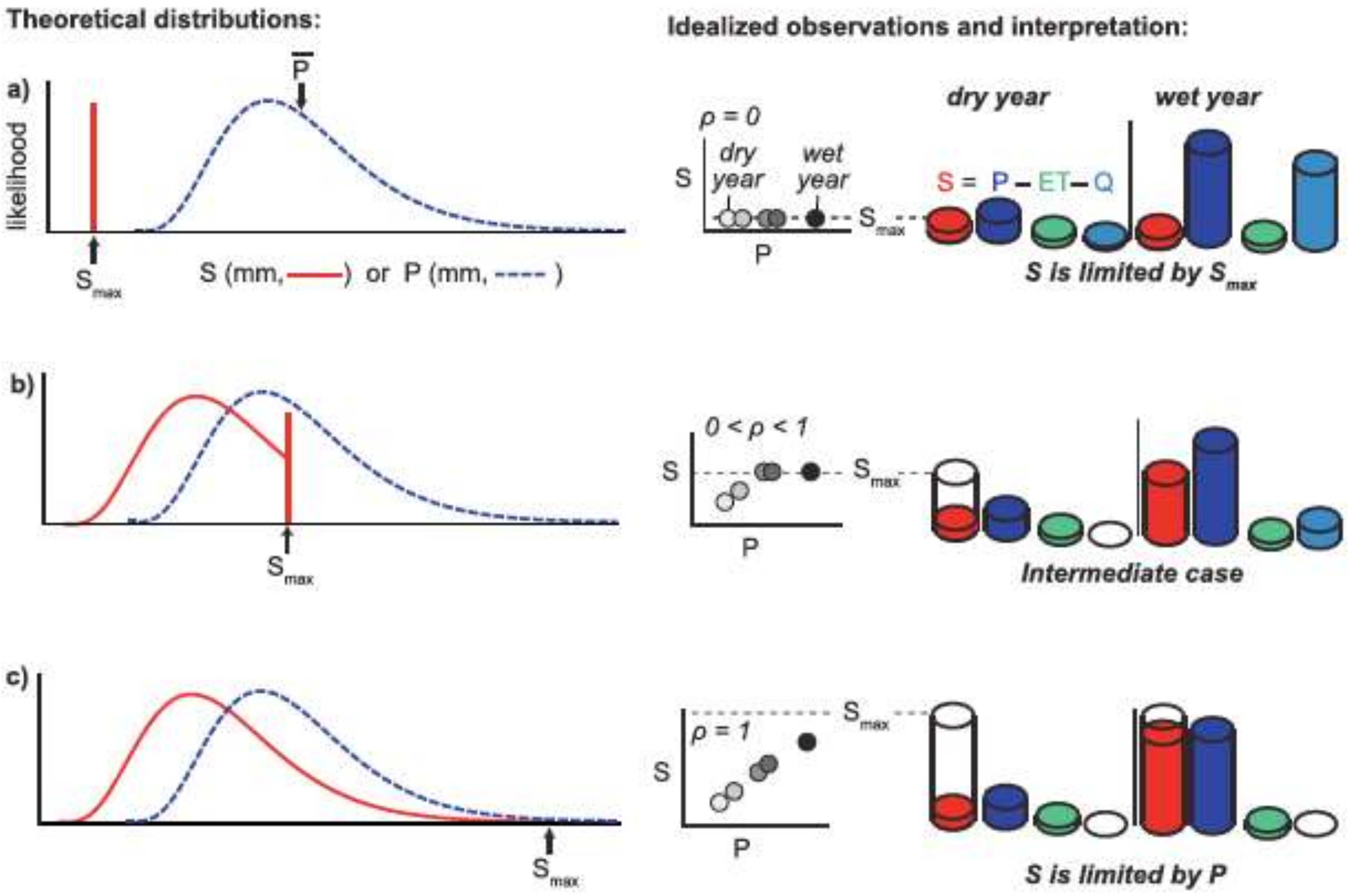


Figure 1, Hahm et al. 2019

Storage capacity decouples rainfall and streamflow

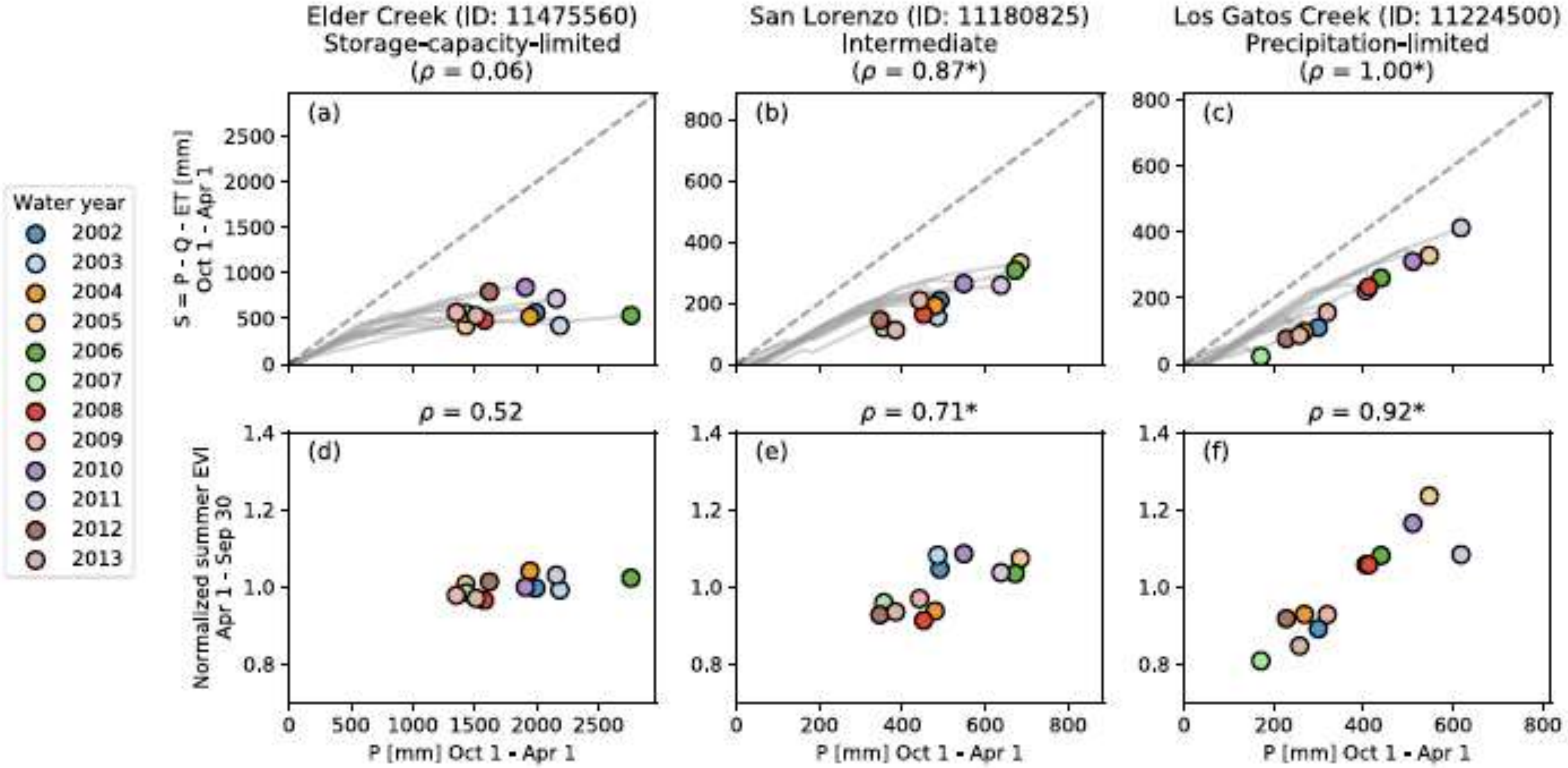


Figure 2, Hahm et al. 2019

Storage-discharge sensitivity functions to estimate streamflow

Storage-discharge sensitivity functions (Kirchner 2009)

- Watershed storage can be quantified by looking at changes in discharge using a storage-discharge sensitivity function g(Q)
- dS/dt = P - Q – E
  - P = Precipitation, Q = Discharge, E = Evapotranspiration

- g(Q) quantifies how much discharge will change for a given change in storage

- dQ/dt = -g(Q)(W +Q)

  - W = groundwater withdrawals, effectively a negative groundwater recharge term

- This is a first order differential equation for Q, which can be solved under natural (i.e. W = 0) and pumped/impacted (i.e. W > 0) scenario

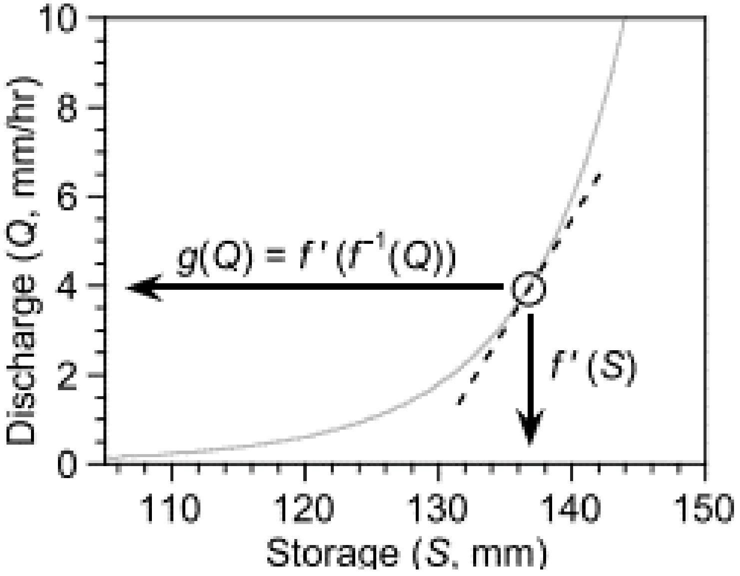


Figure 3, Kirchner 2009

Storage-discharge sensitivity functions to estimate streamflow

- Storage-discharge sensitivity functions (Kirchner 2009)
- Quantify mountain block recharge (Ajami et al. 2011)
- Quantify storage that does not drive streamflow streamflow (Dralle et al. 2018)
- Infer hillslope groundwater recharge (Dralle et al. 2023)

- Notes and assumptions**
  - Important to make inferences at the scale of the analysis (watershed scale)
  - Water is assumed to be extracted instantly and evenly across the watershed

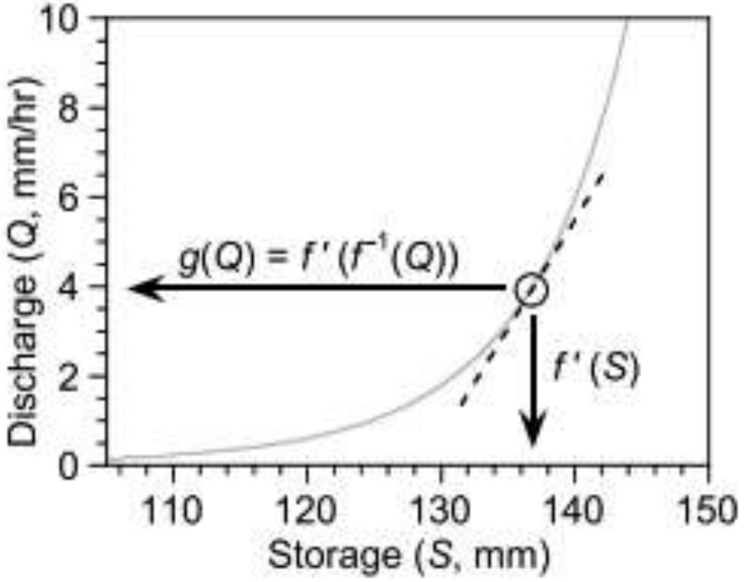
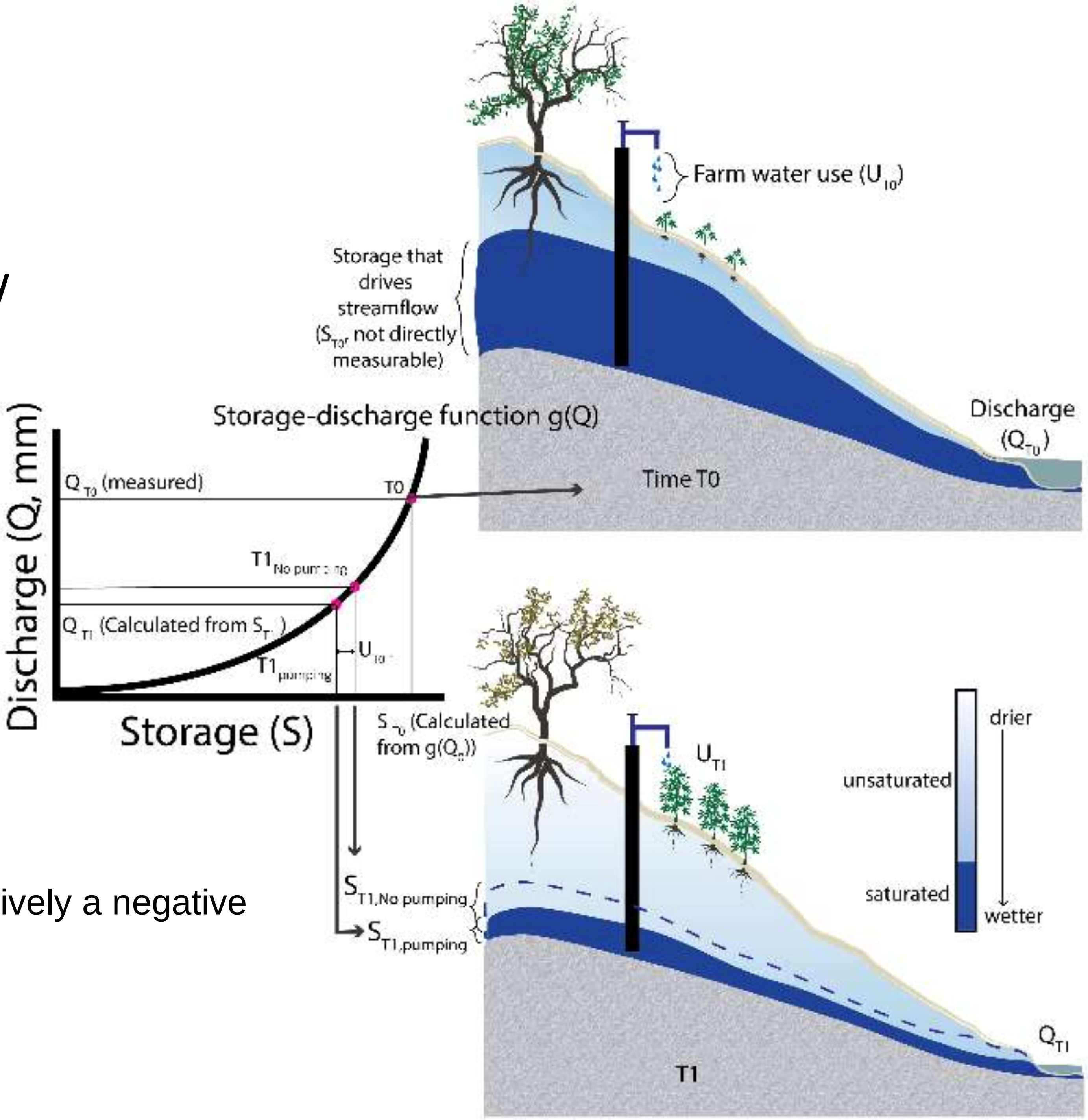


Figure 3, Kirchner 2009

Storage-discharge functions to estimate streamflow depletion

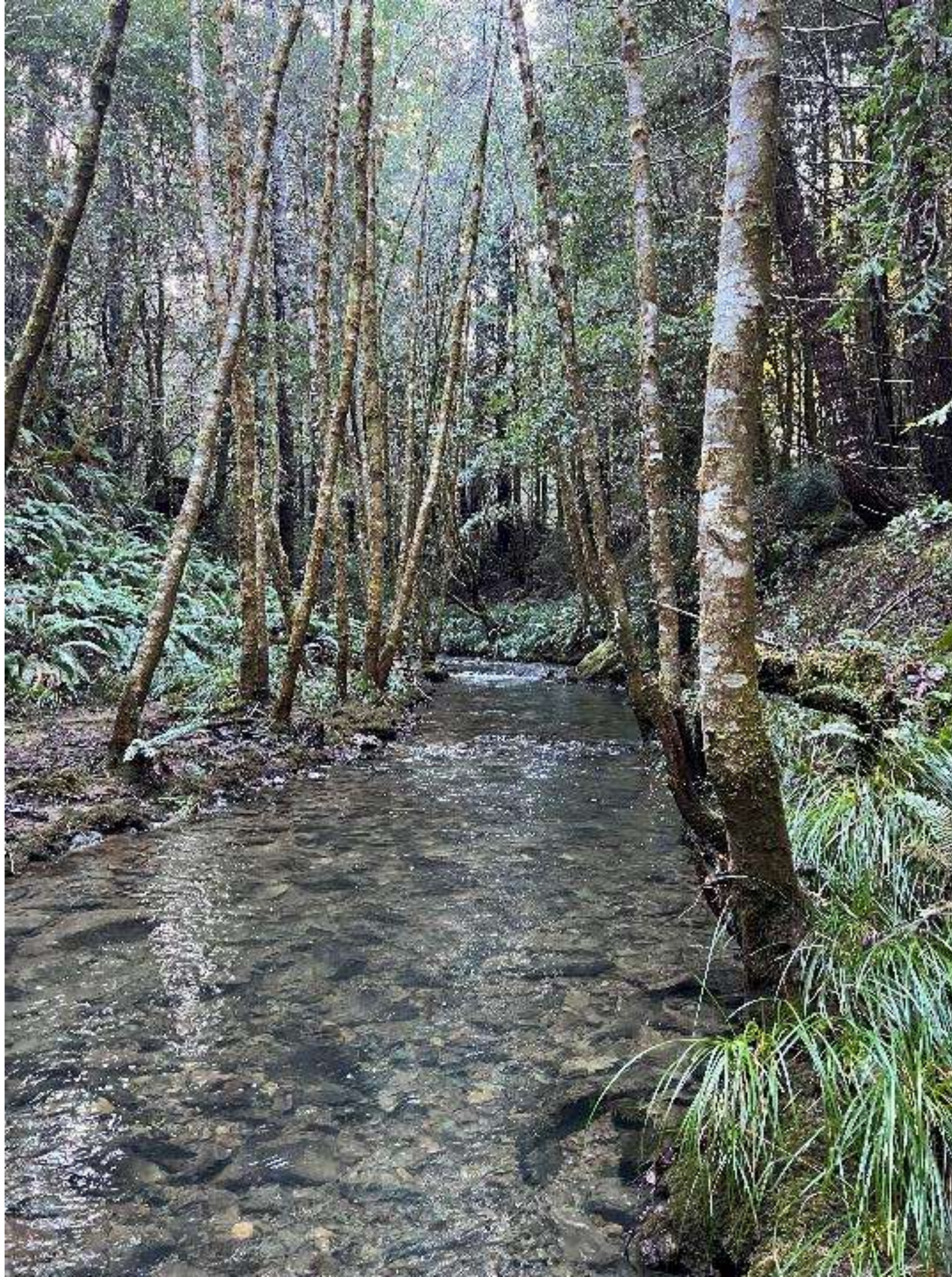


$$dQ/dt = -g(Q)(W + Q)$$

W = groundwater withdrawals, effectively a negative groundwater recharge

Case study

How does water extraction for cannabis cultivation influence headwater streamflow?



Does cannabis cultivation impact streams in Northern CA?

- Bauer et al. 2015 & Carah et al. 2015 suggest diversions for cannabis irrigation from streams are a serious threat to North Coast streams

Cannabis grows in Northern CA

Laytonville area, Mendocino, CA. July 2021. Google Earth

Greenhouse grow, photo by Scott Bauer

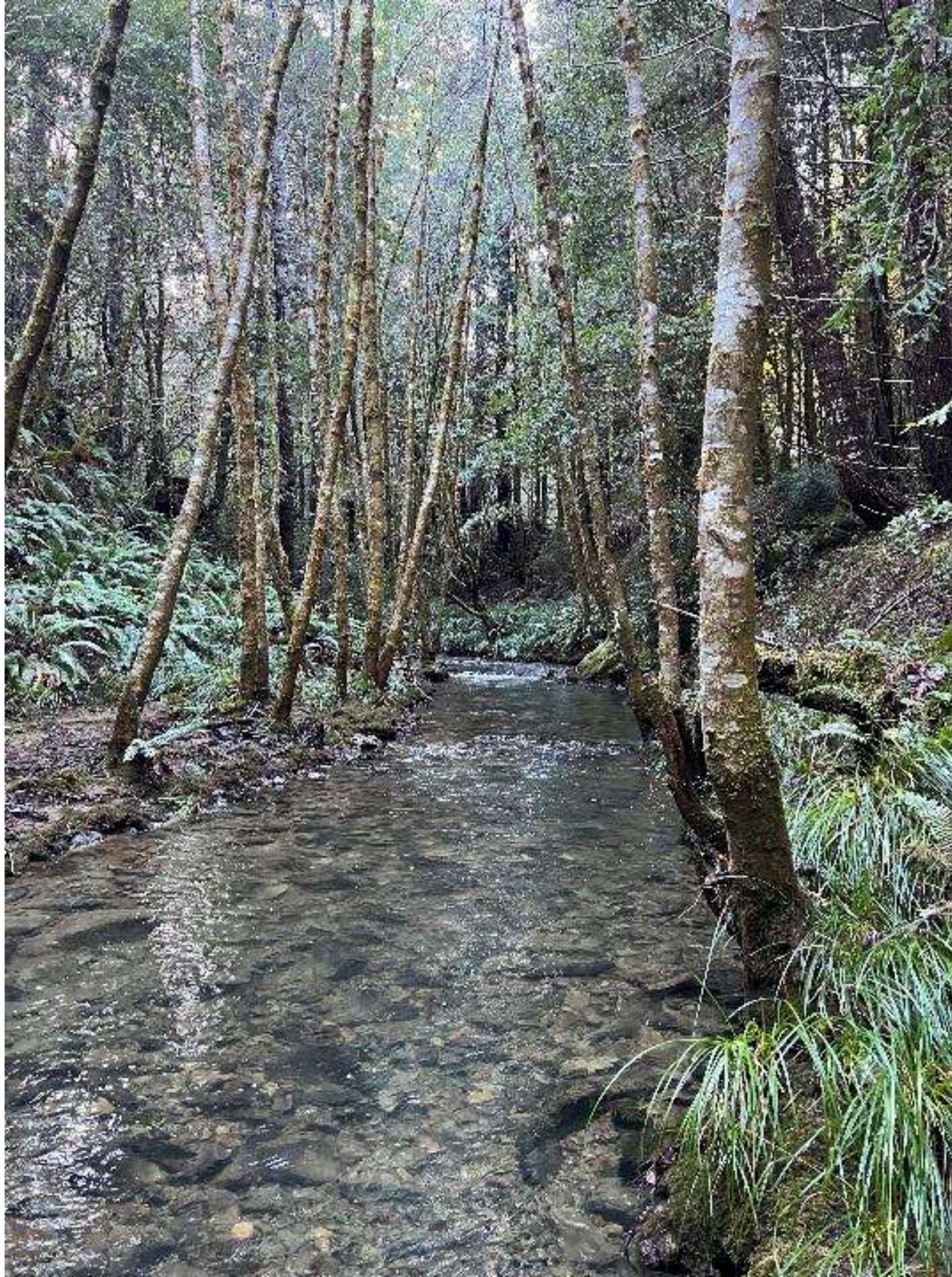
Hunter's Pool, South Fork Eel,
September 9, 2020

Merganser, South Fork Eel,
July 4, 2020

Cast study

- Use storage-discharge sensitivity functions to model streamflow from groundwater storage at the small watershed scale
- Create hypothetical scenarios that represent combinations of parameters
  - Water source
    - Groundwater pumping or Surface diversion
  - Farm water use efficiency
    - 50, 75, 90, 95 percentile of water users
  - Area of cannabis farms
    - 0.1, 0.25, 1, 2.5, 4.5 %
  - Lithologies
    - Elder and Dry Creek
  - Water year
    - Initial conditions 0.1mm/day to 10mm/day

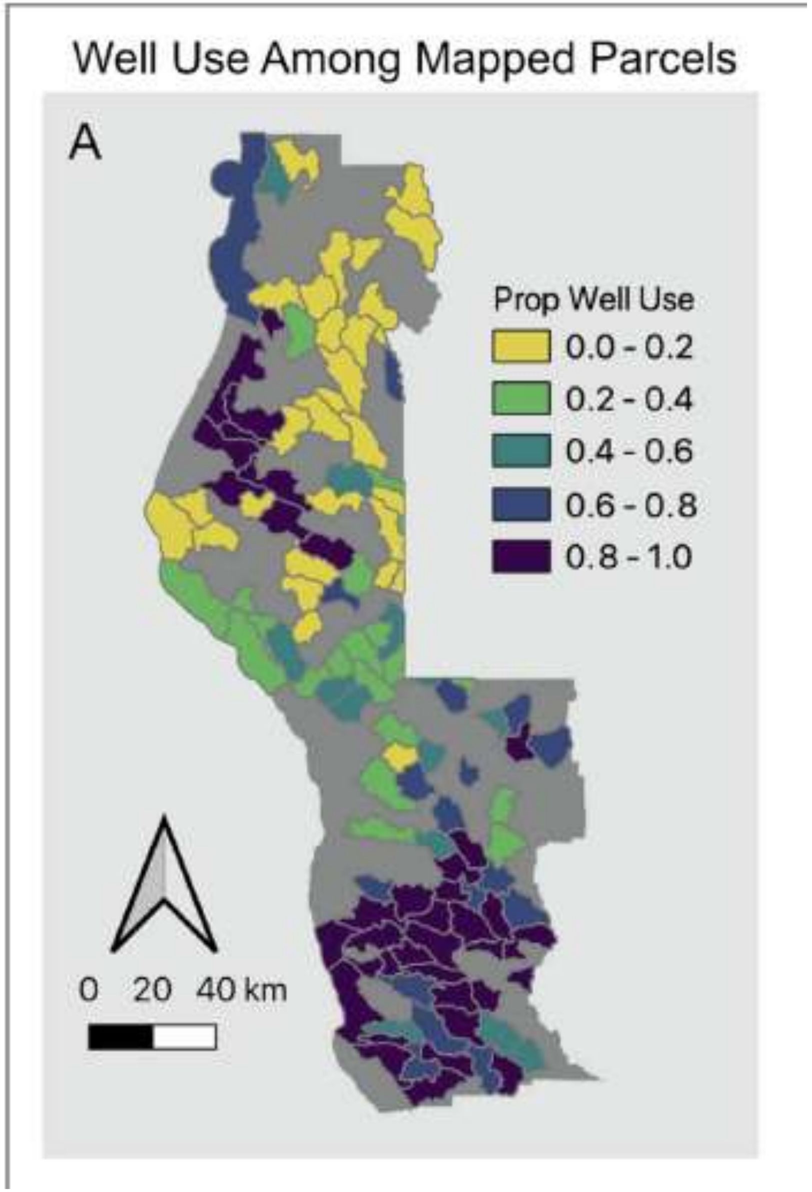
336 combinations scenarios result from the combination of these factors



Water source

Cannabis farms in Mendocino and Humboldt predominantly use well to irrigate crops

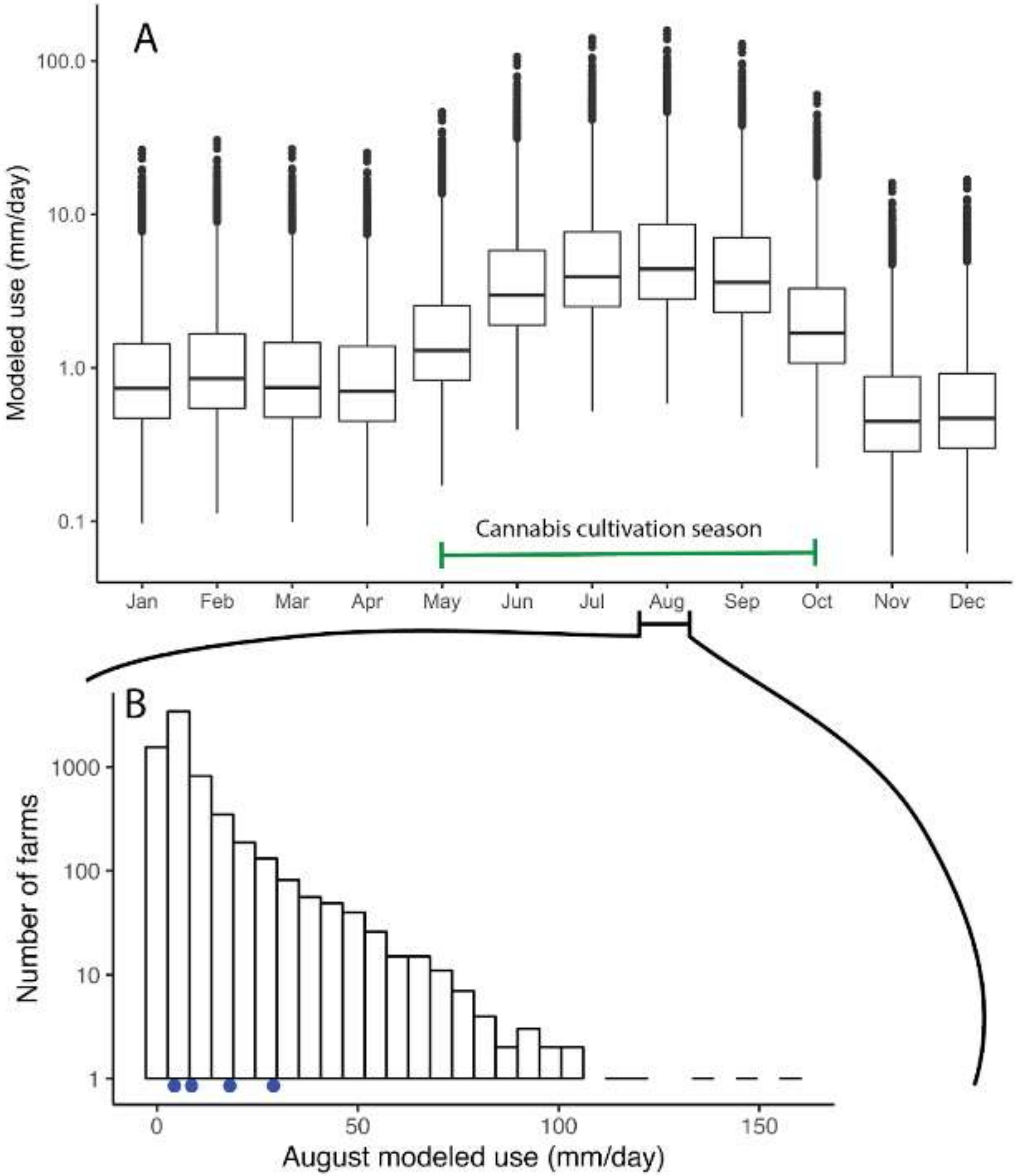
	Baseline well use prediction
Overall	0.60
Humboldt County	0.38
Mendocino County	0.71



Dillis et al. 2021

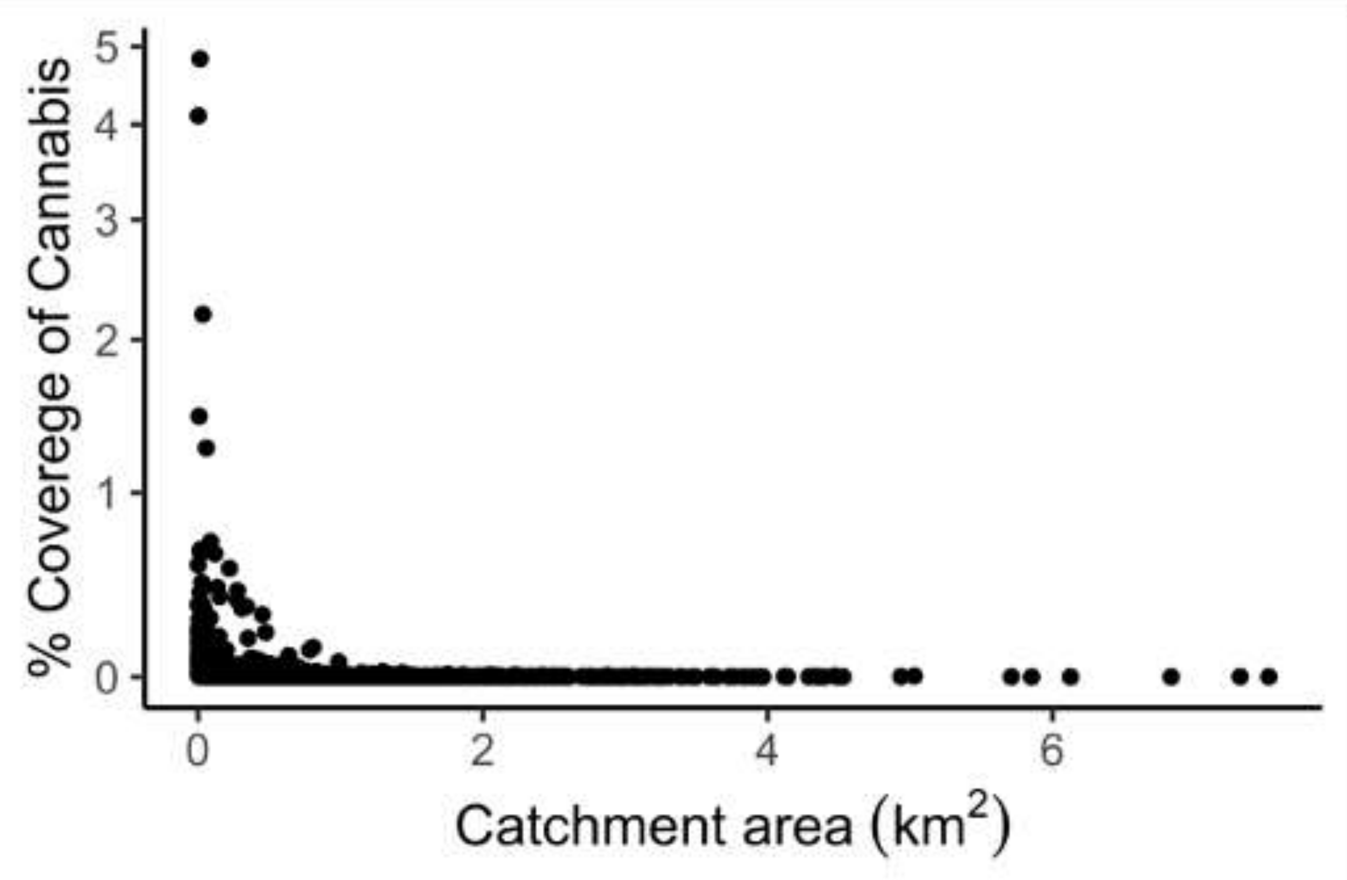
Farm water use efficiency

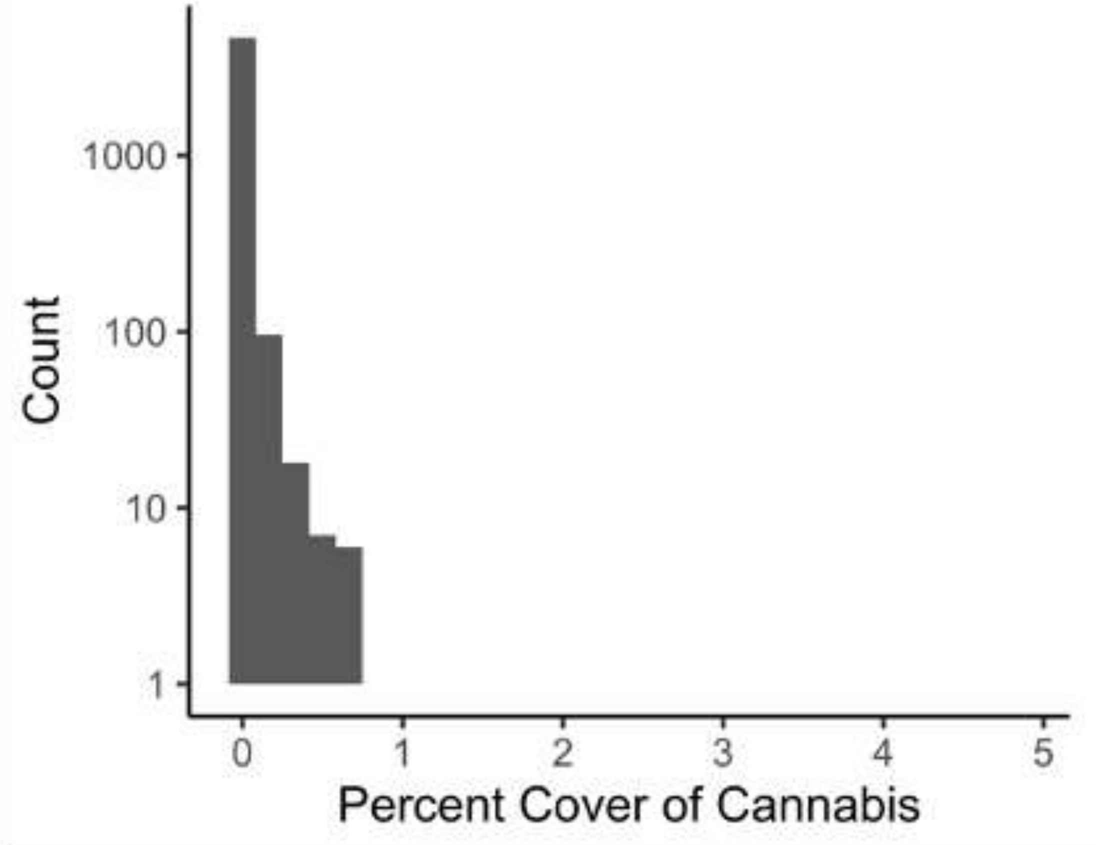
Modeled data from Dillis et al. (2023)
50, 75, 90, 95 percentile of water users



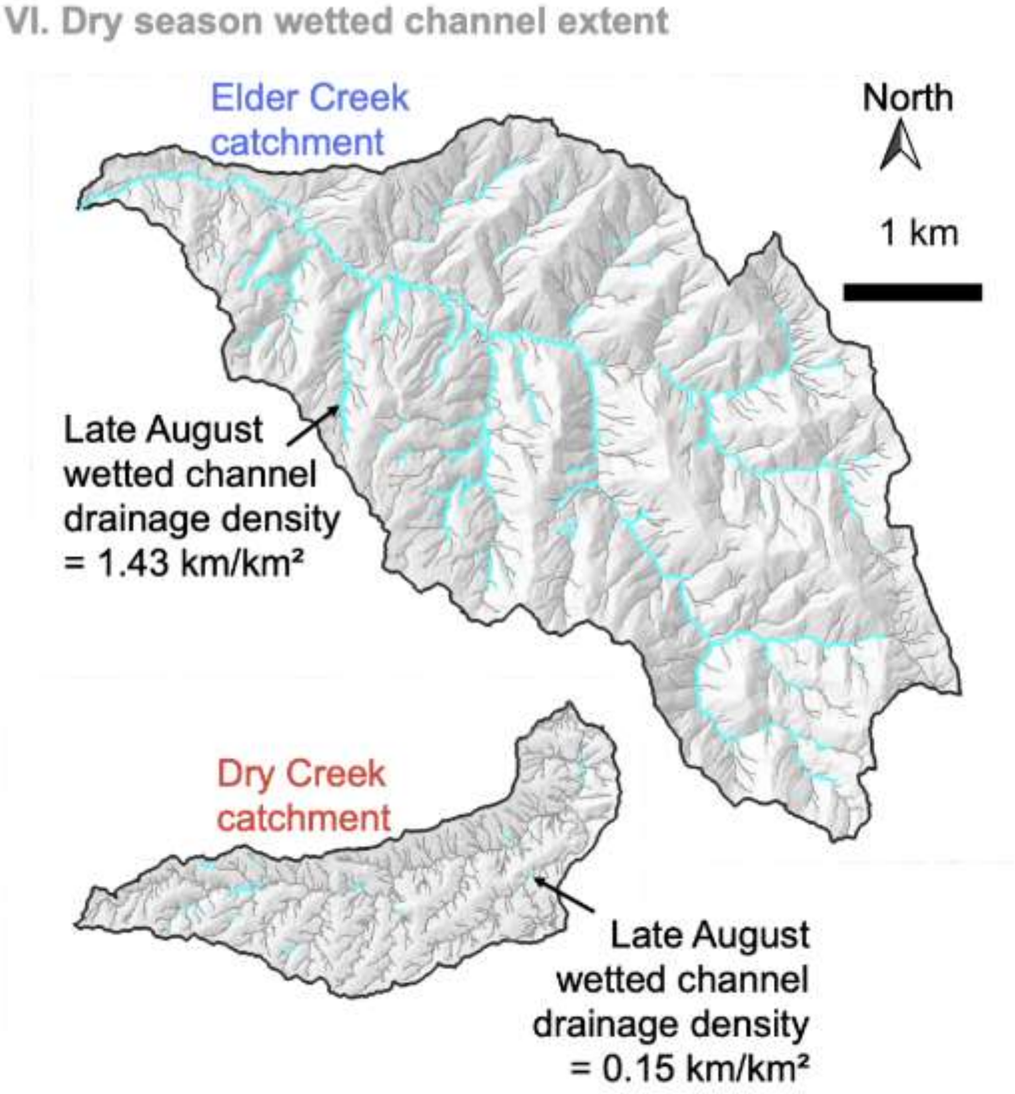
Areal coverage of cannabis agriculture

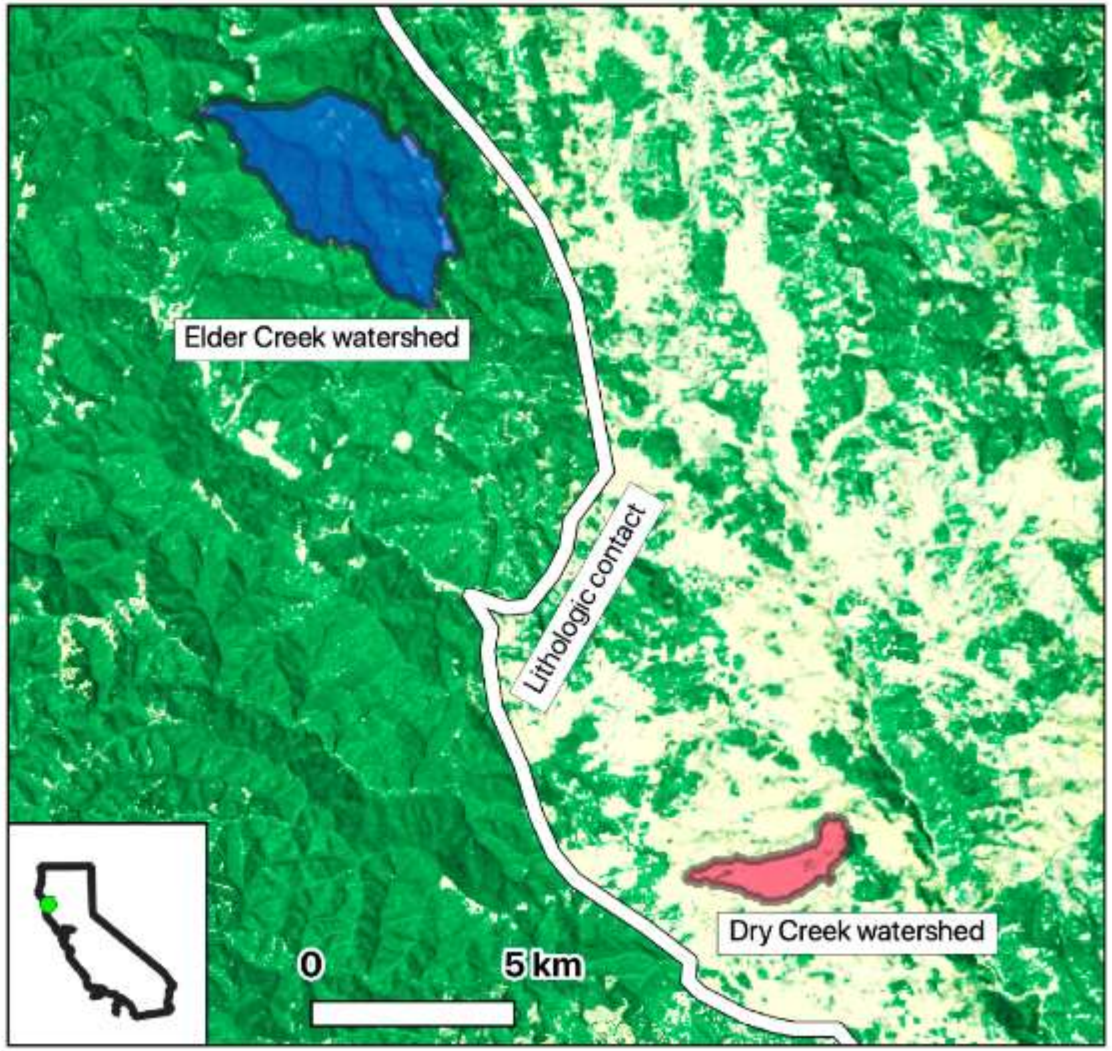
0.1, 0.25, 1, 2.5, and 4.5 %



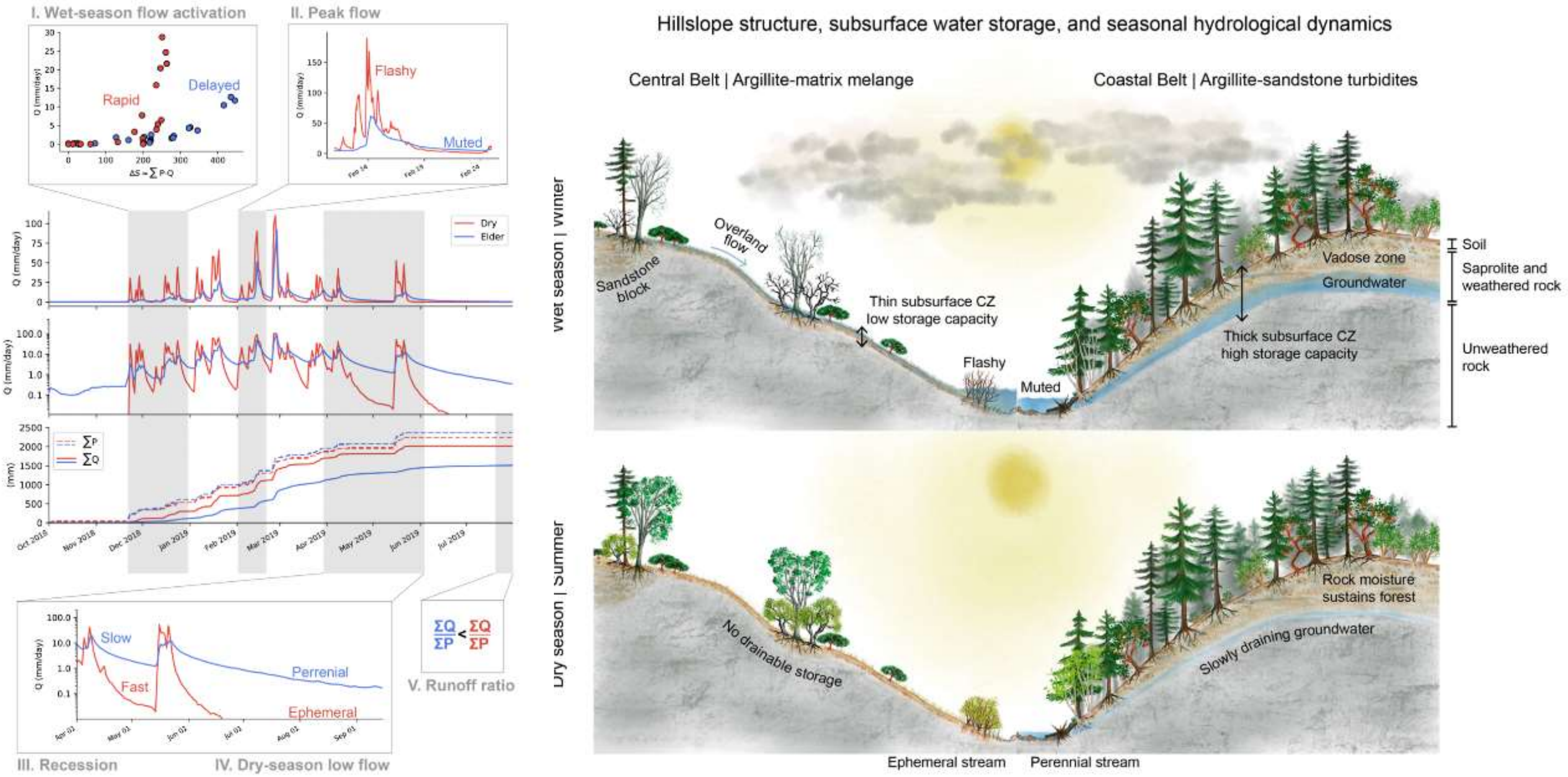


Lithology: two different streams





Dralle et al. 2023



Dralle et al. 2023

Cast study

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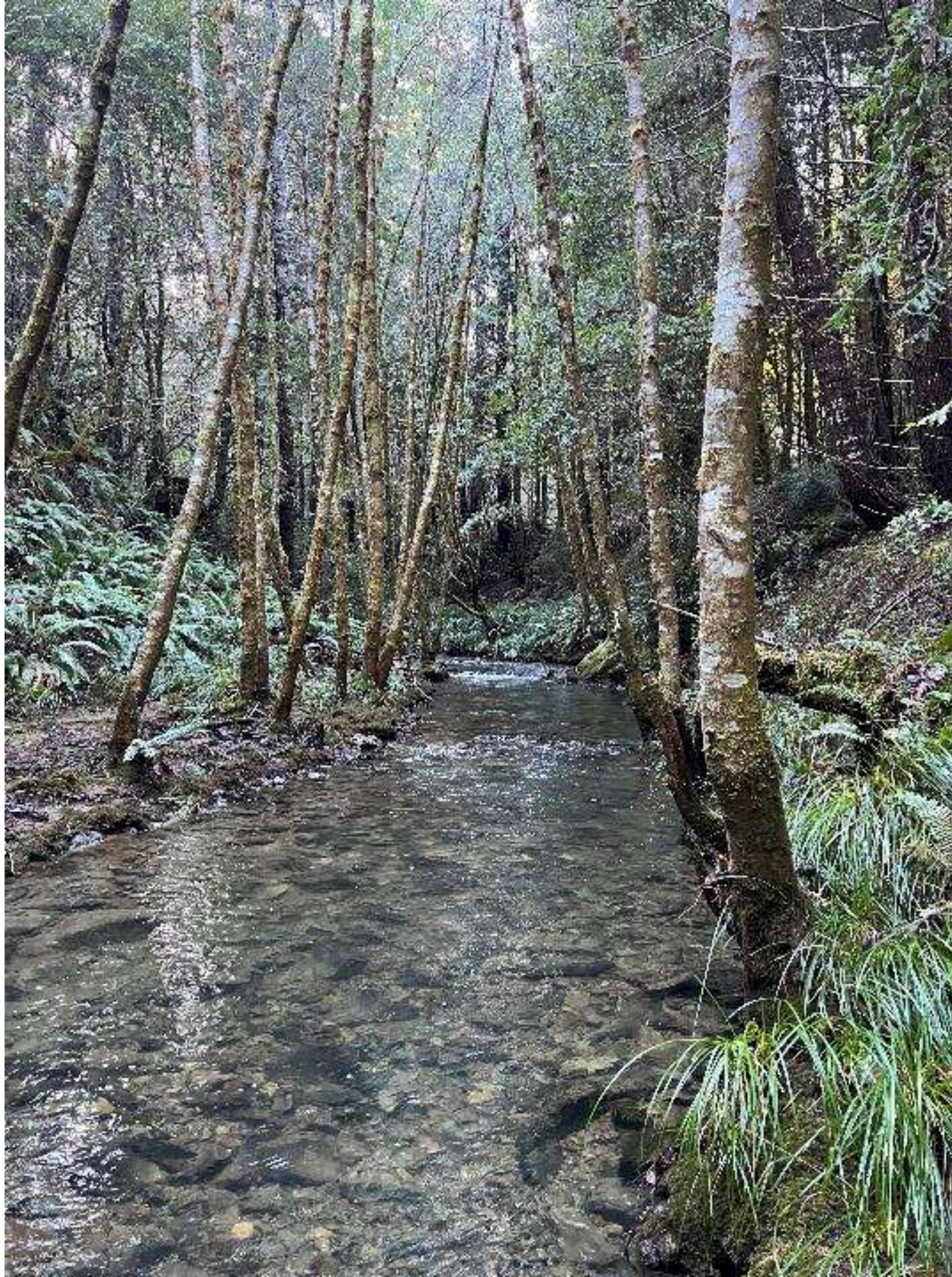
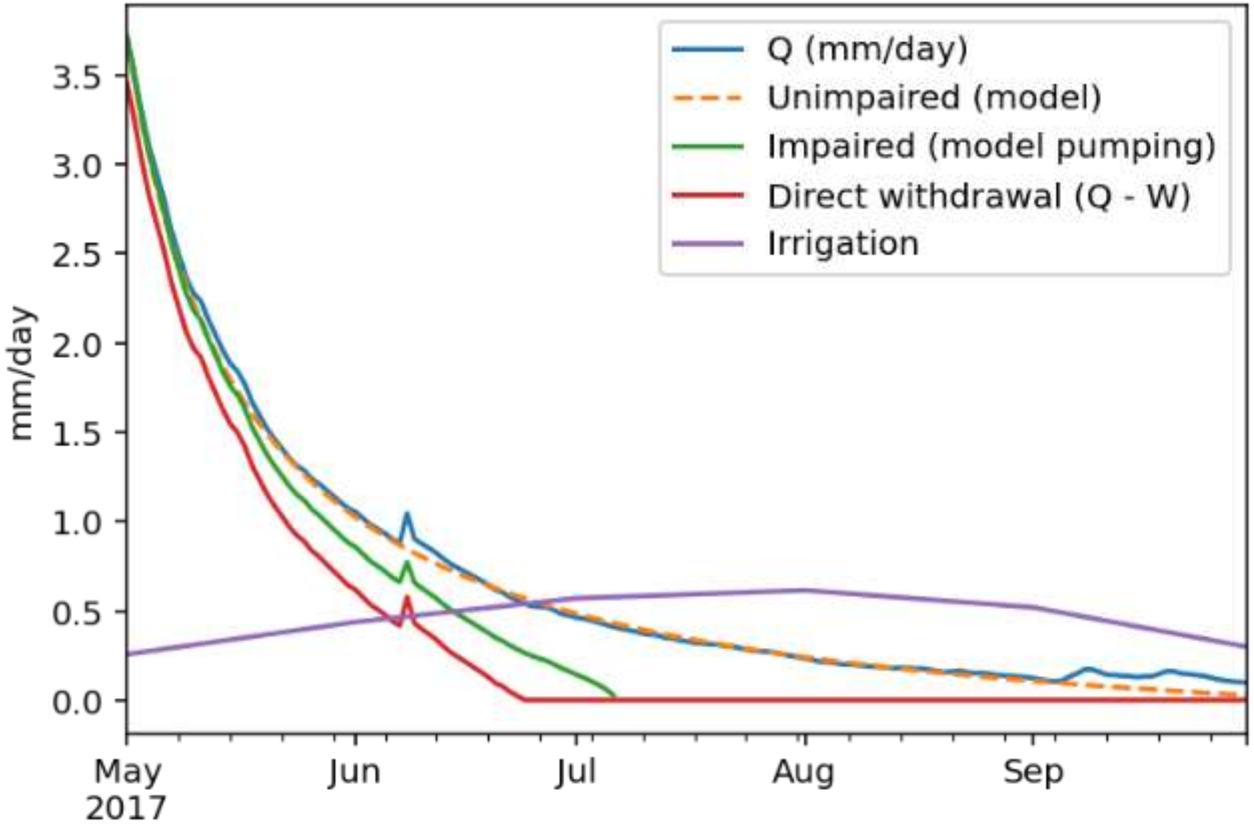


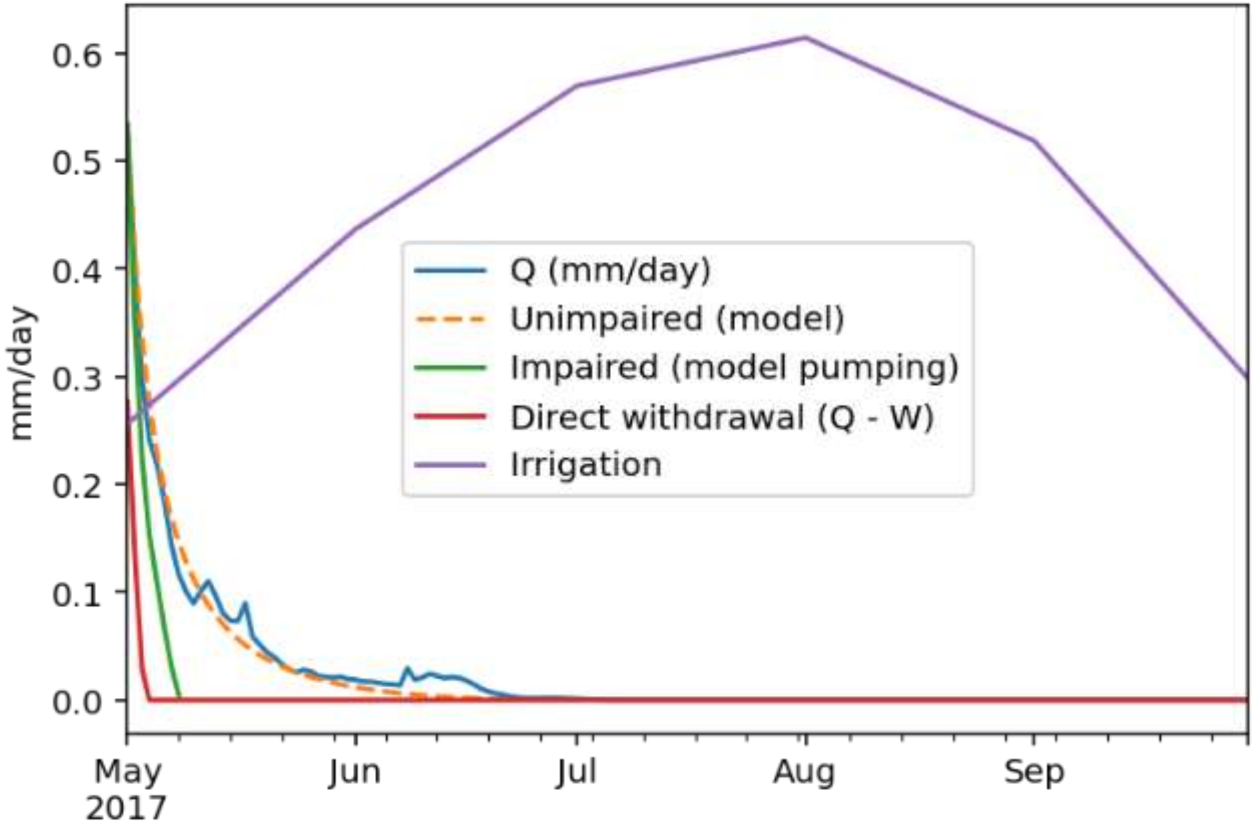
Impacts on Streamflow

2017, median water use rate, 2.5% cover

Elder

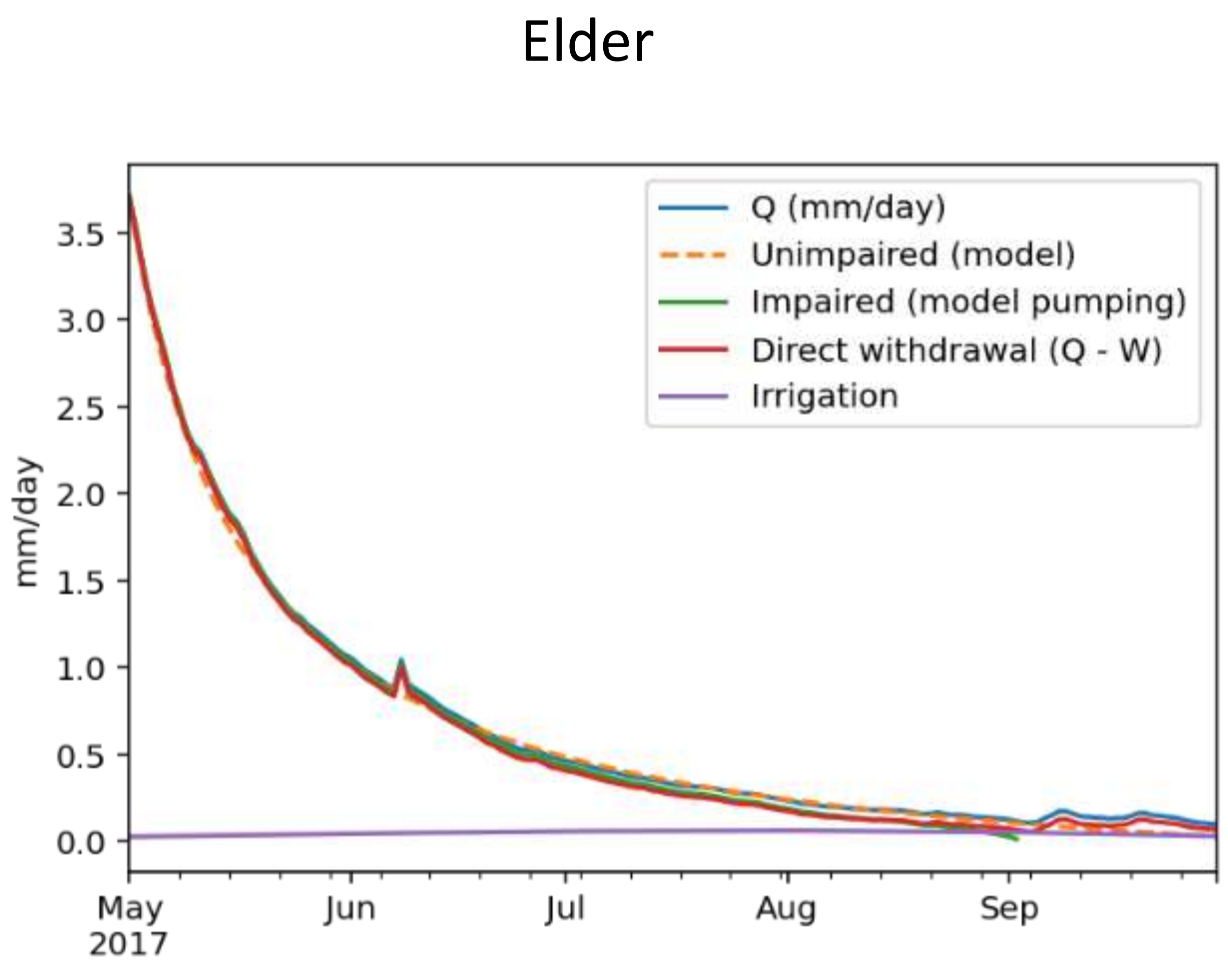


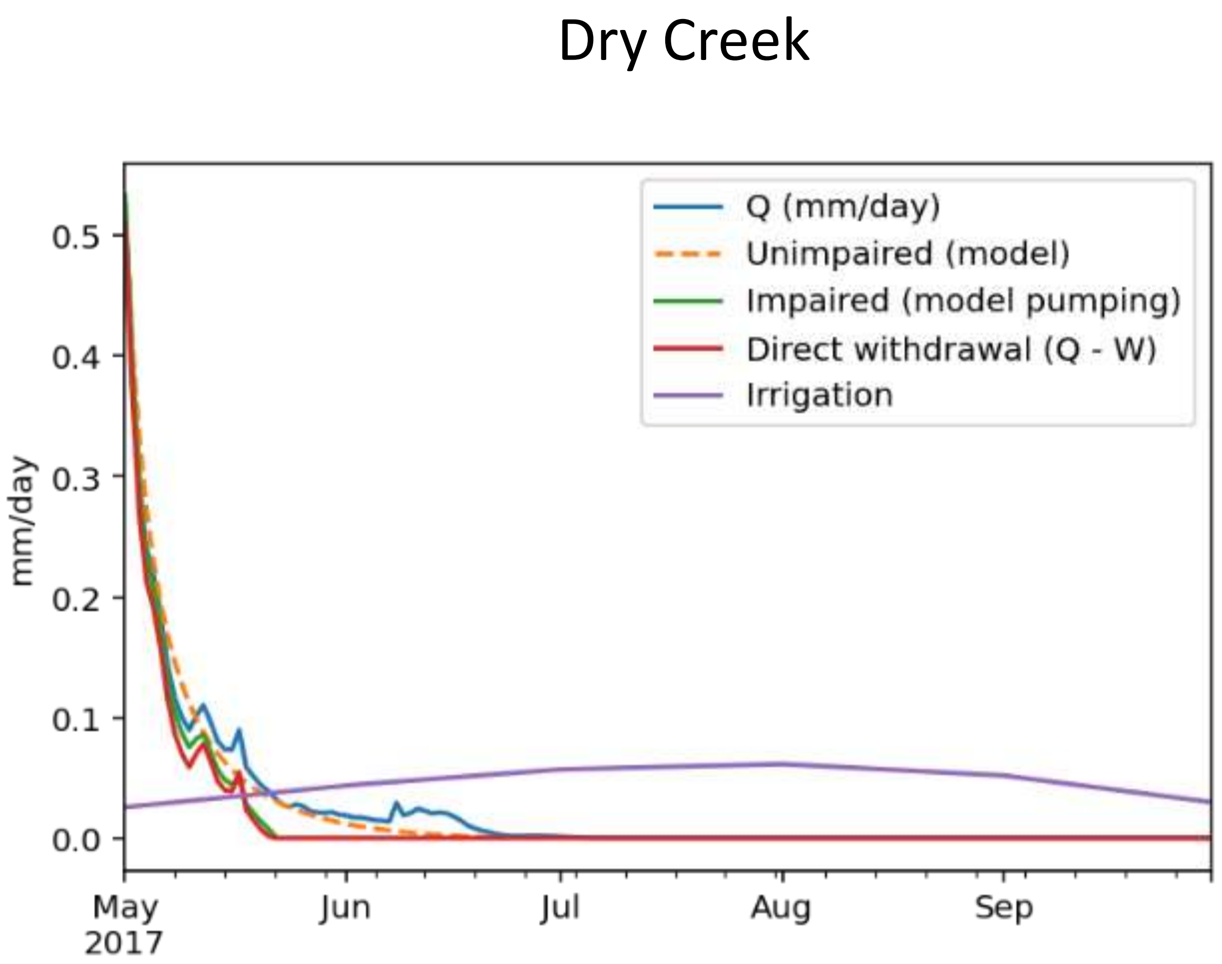
Dry Creek



Impacts on Streamflow

2017, median water use rate, 0.25% cover

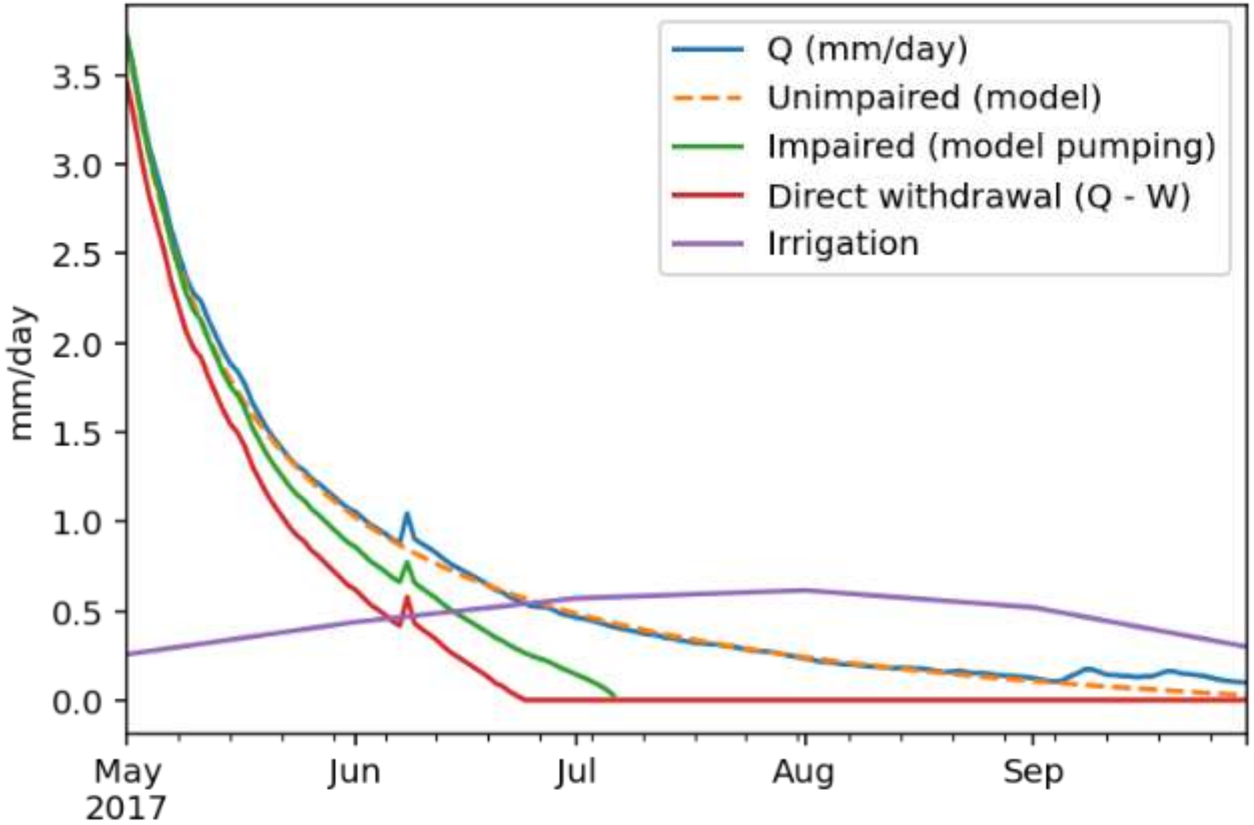




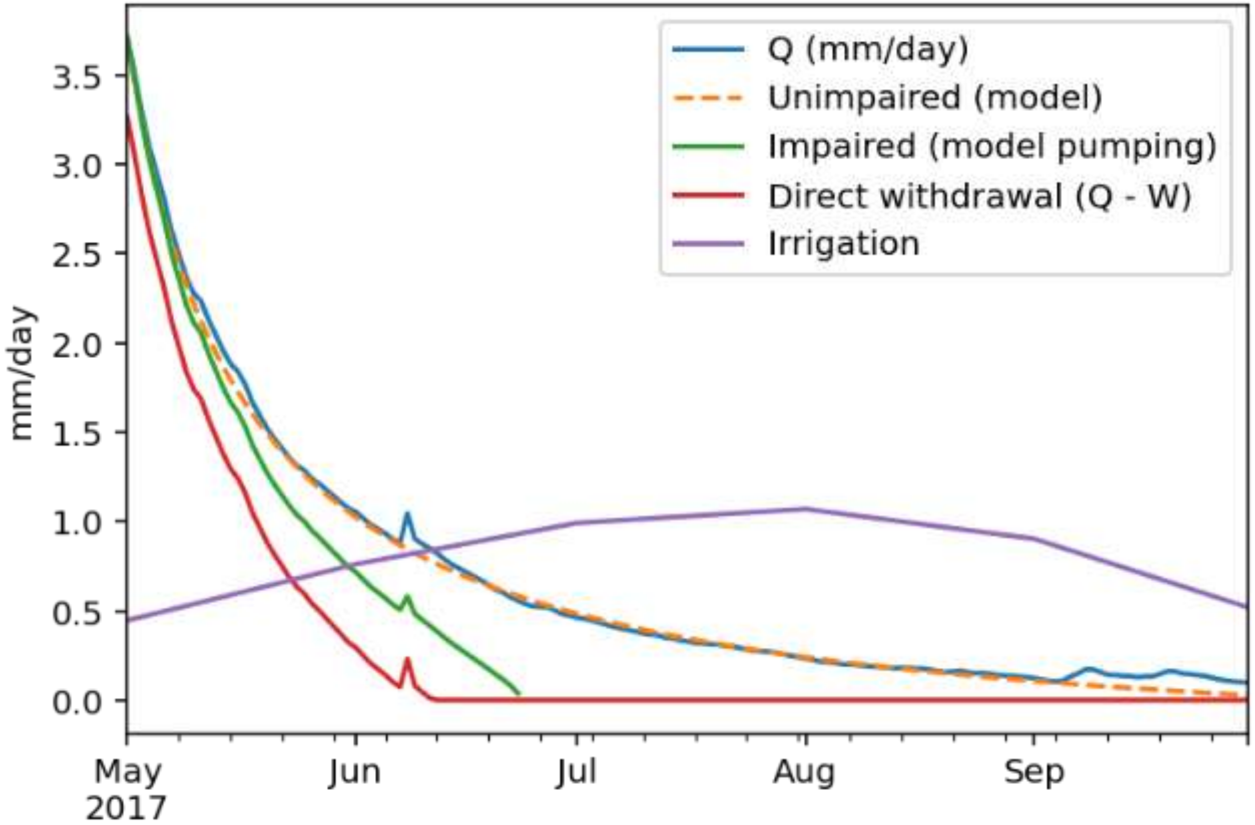
Impacts on Streamflow

2017, water user contrasts, 2.5% cover

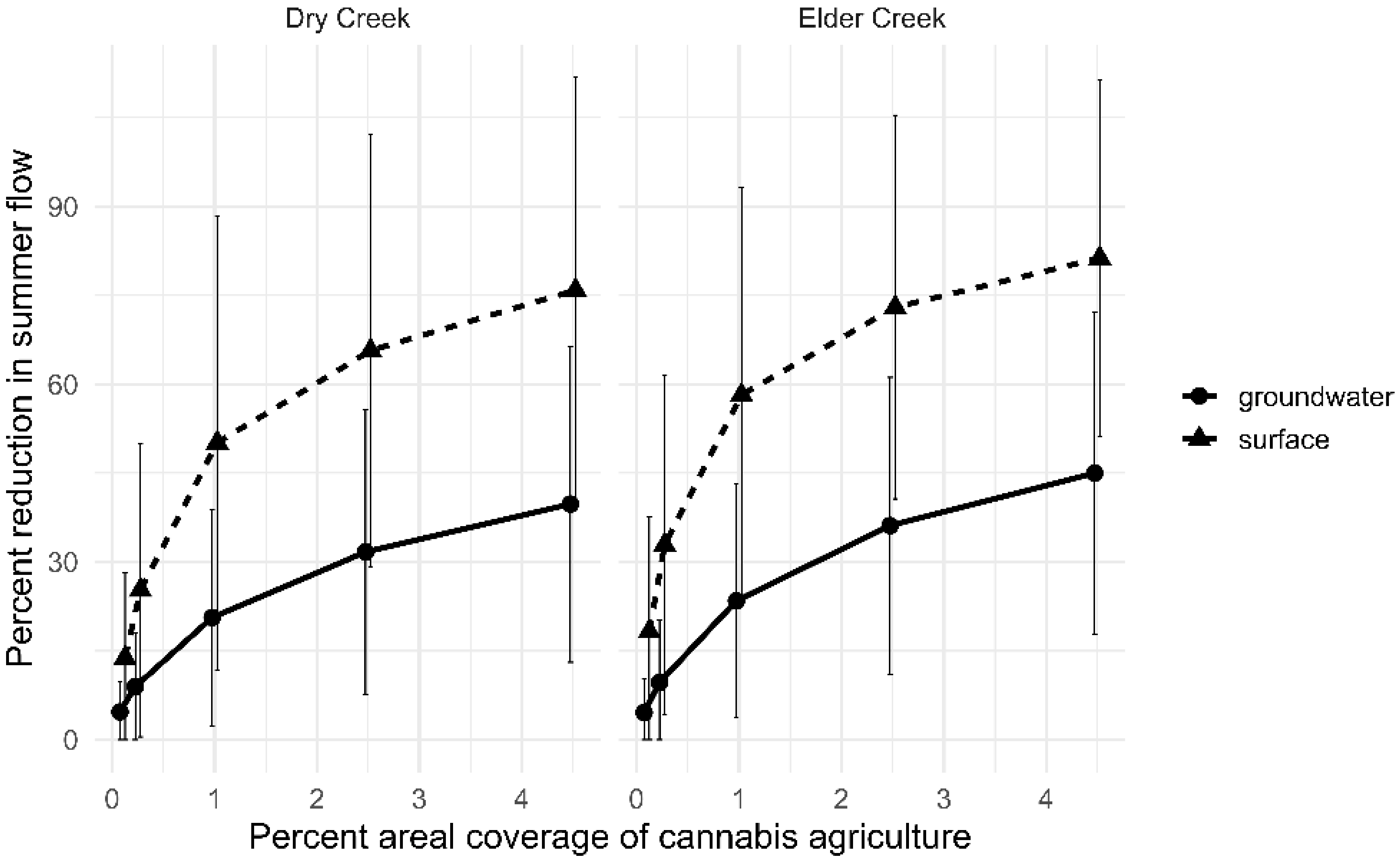
Elder, median user



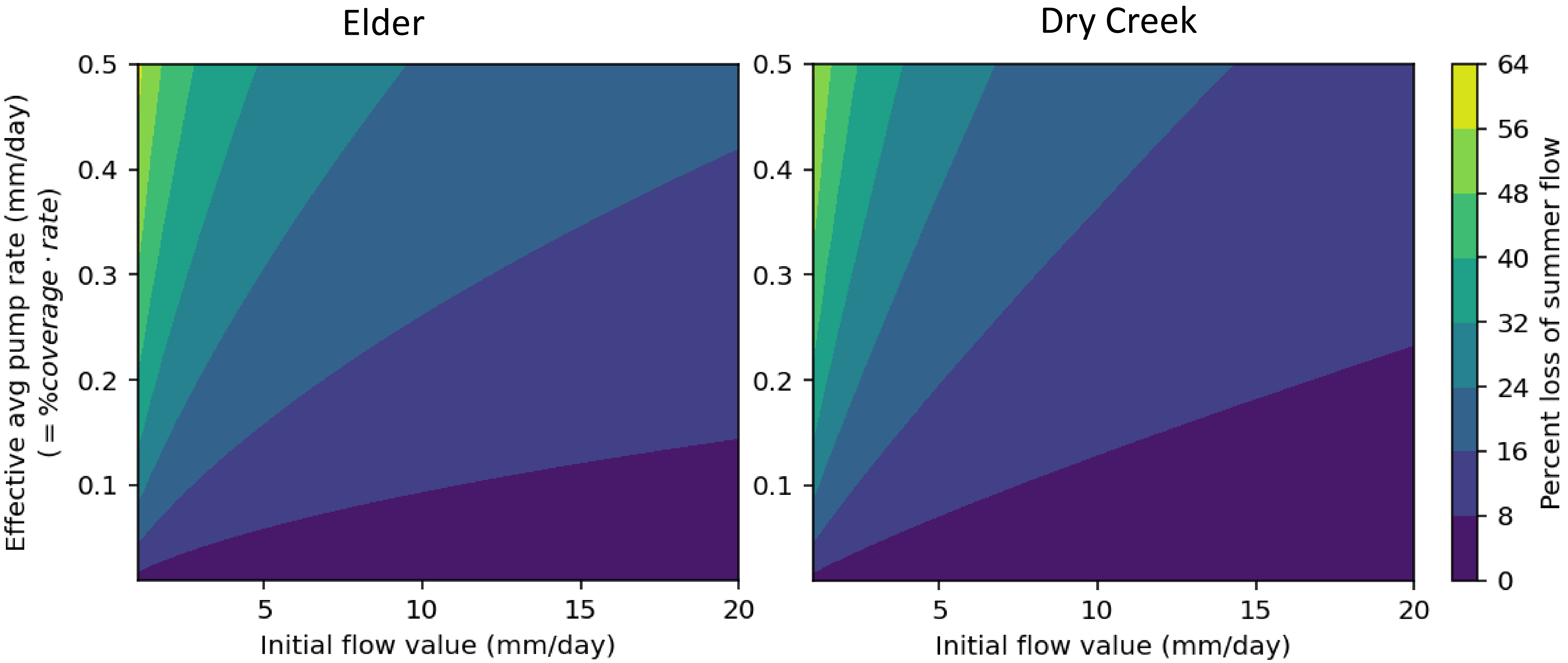
Elder, 95th percentile user



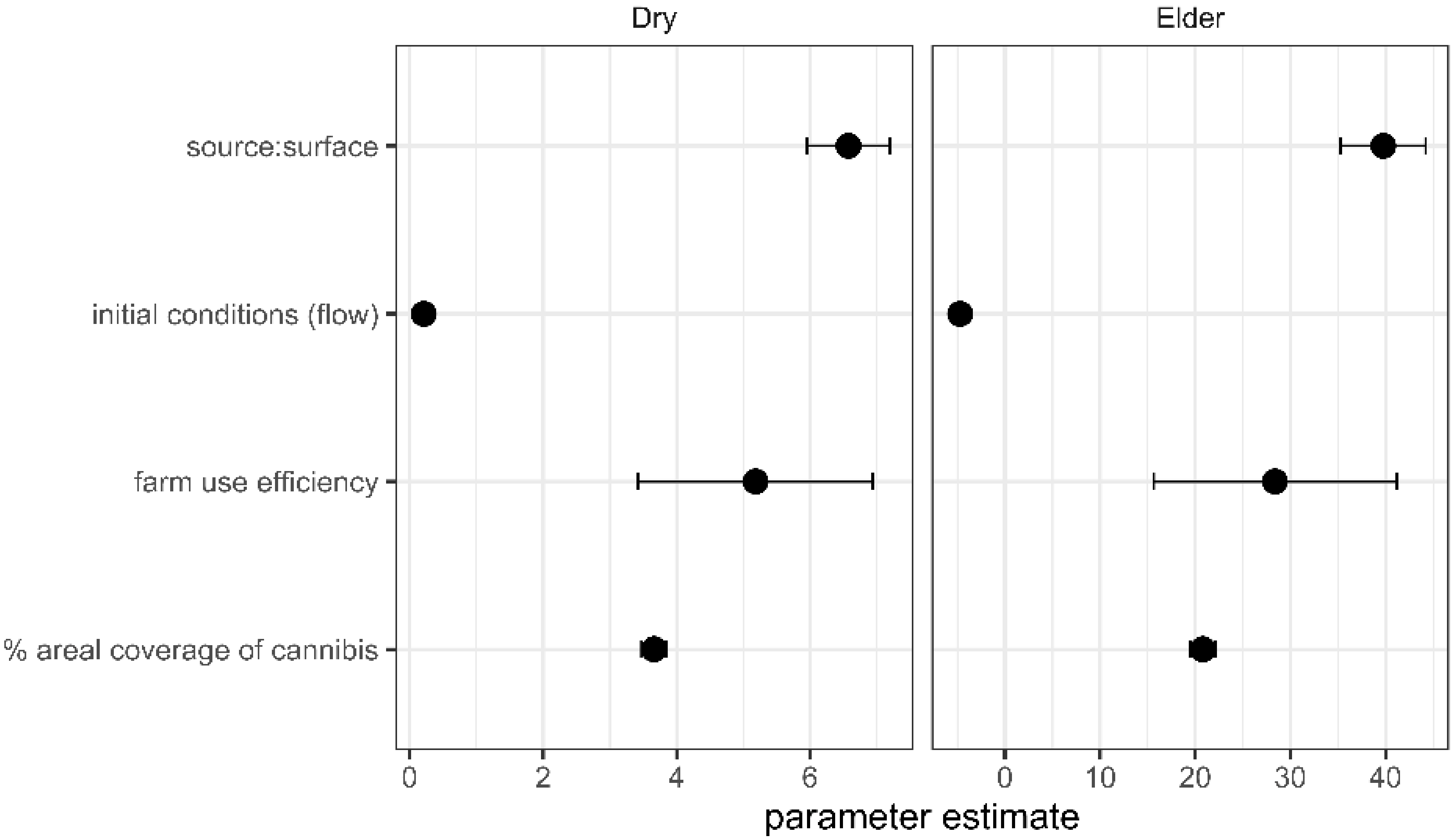
Percent reduction in summer flow



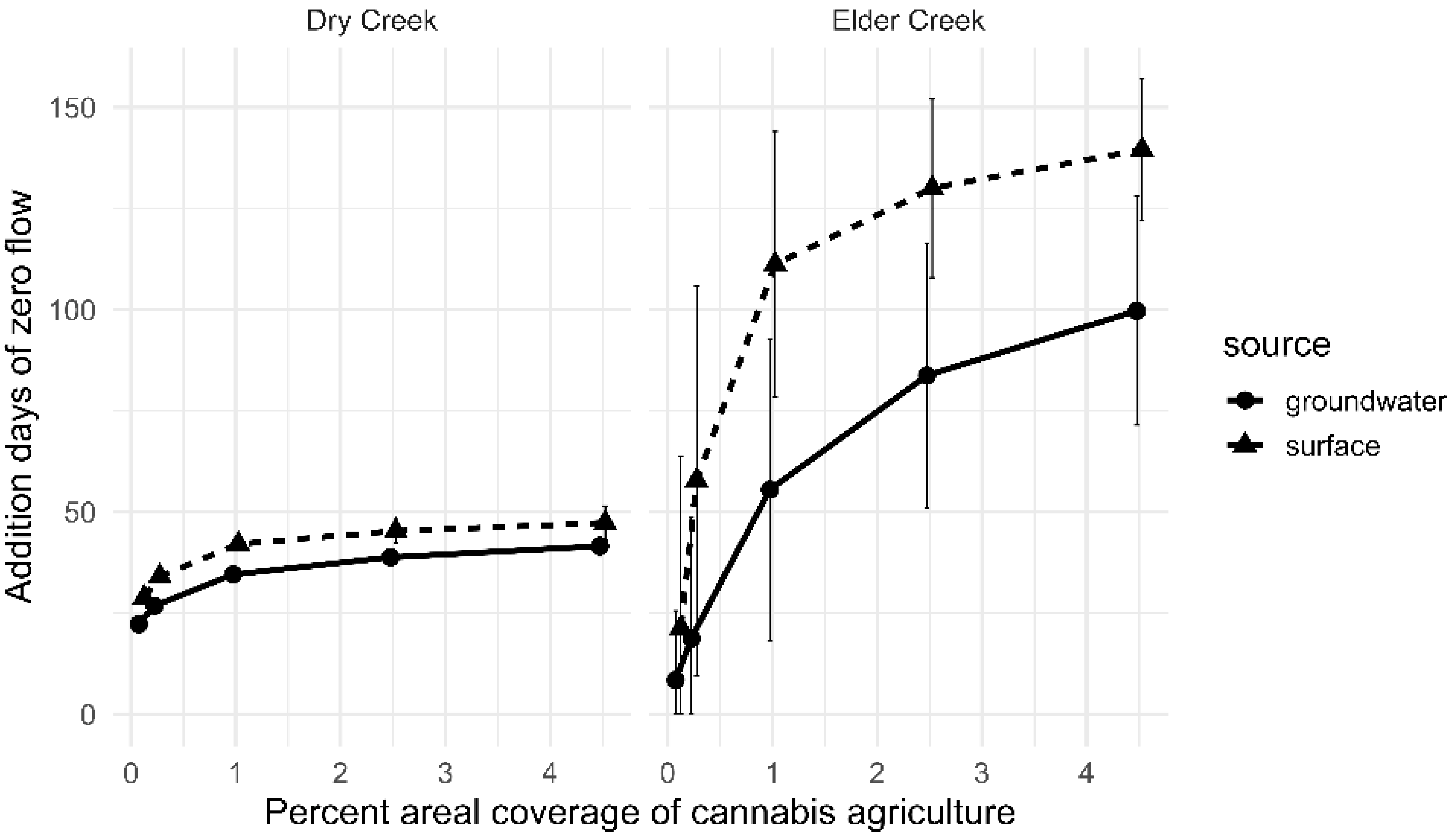
Percent reduction in summer streamflow



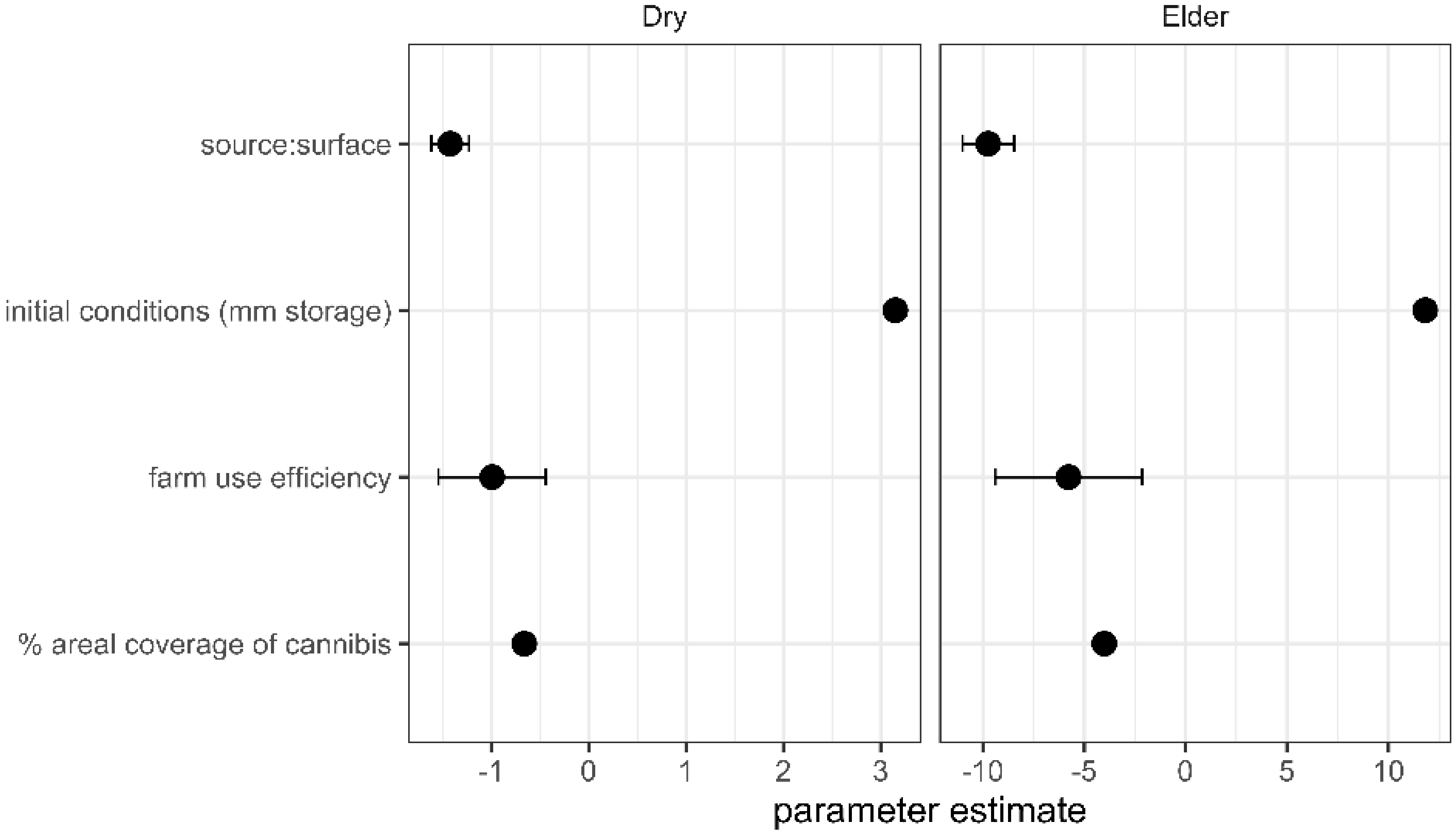
Effect sizes of predictor percent reduction in summer flow



Additional Zero-flow days



Effect sizes of predictor on additional zero-flow days



Conclusions

- Storage-discharge sensitivity functions can be useful for estimating effects of groundwater pumping at the scale of headwater streams
- Lower initial conditions (dry years), higher coverage of cannabis, higher pumping rates, and extraction from surface water rather than wells all lead to lower summer discharge and more days of zero flow
- Mélange streams more sensitive (with regard to discharge) to withdrawal
  - Accelerated drying
  - Greater impact at similar withdrawal rate
- Wide variation in cannabis irrigation rate, more efficient watering and onsite storage could have a large impact
- Pumping's effect on streamflow is expected to be delayed relative to surface water diversions but can still be substantial.
  - Spatial distribution of farms and wells in a watershed matters
  - May impact other aspects of the ecosystem more than direct water withdrawals

Acknowledgments

- University of California Natural Reserve System
- Department of Cannabis Control
- Eel River Critical Zone Observatory
- Berkeley Cannabis Research Canter

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Questions?

pgeorgakakos@Berkeley.edu

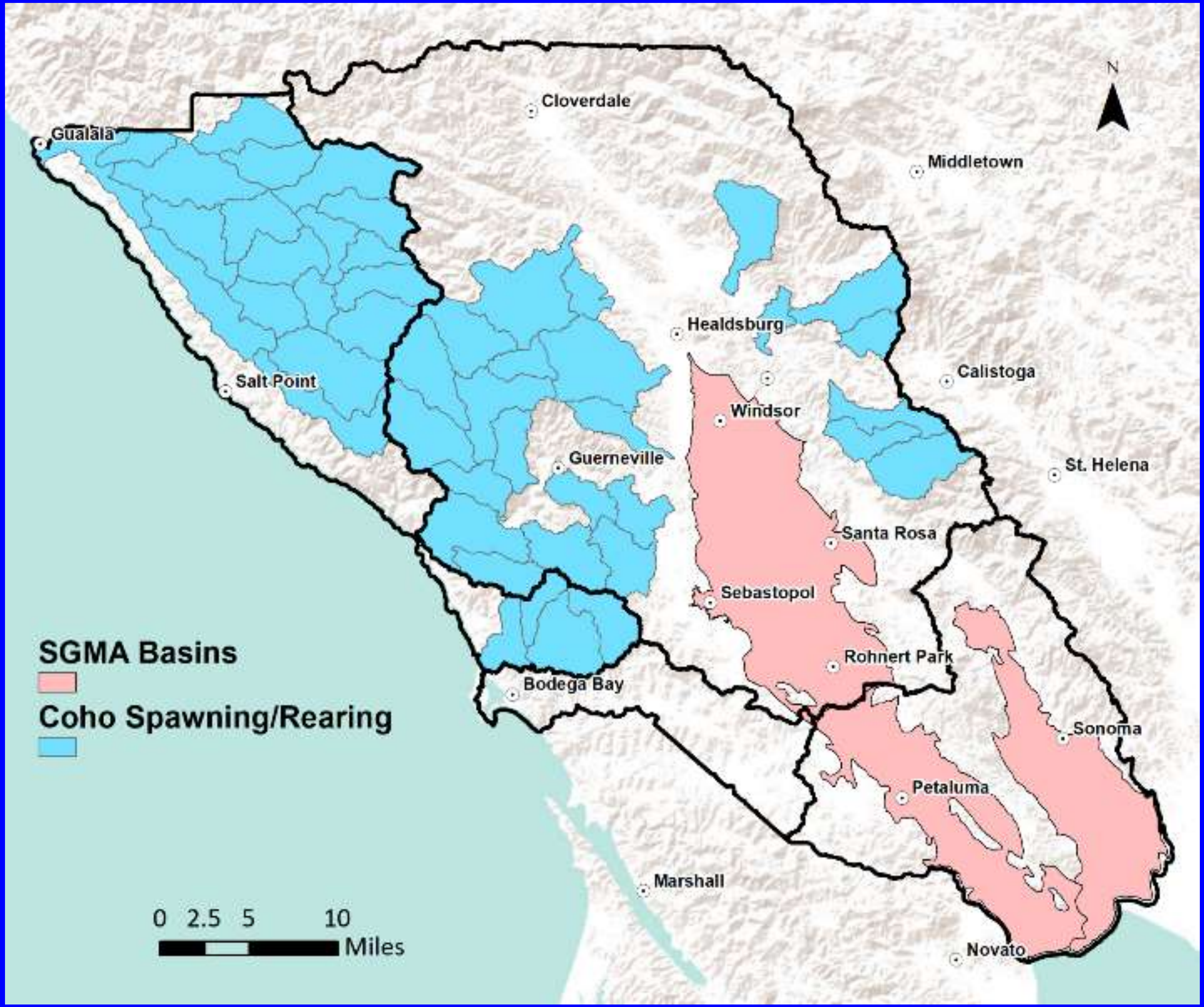
Approaches for Evaluating Streamflow Depletion;

Shedding Some Light on the Secret, Occult, and Concealed Nature of Surface Water/Groundwater Interactions

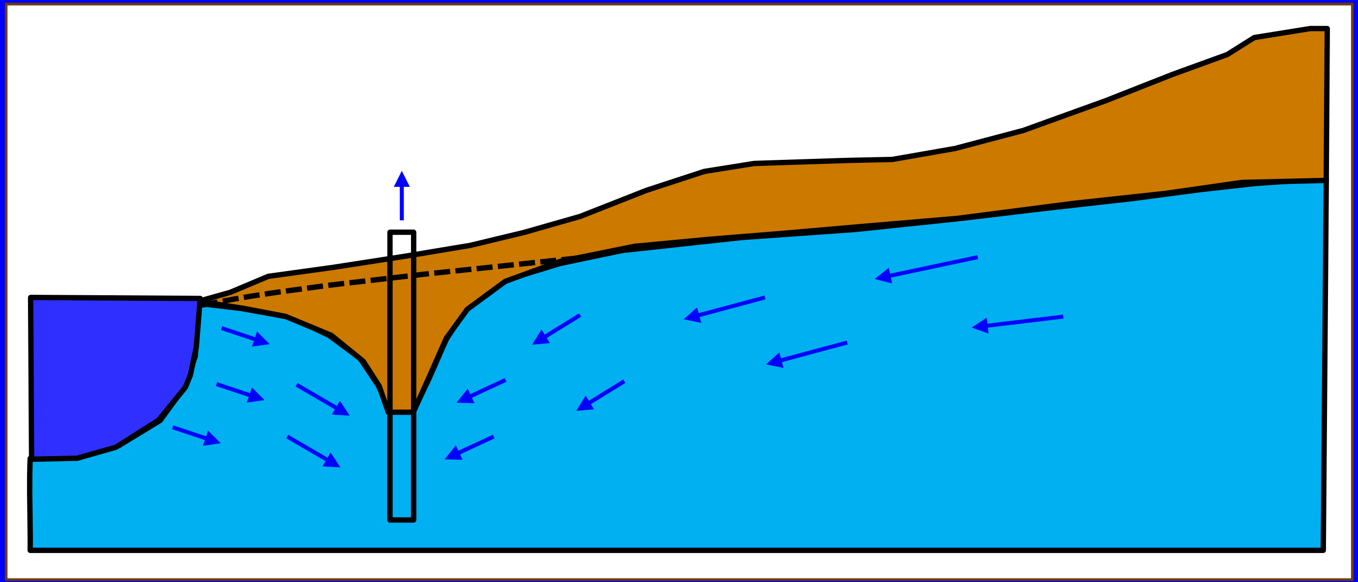
March 2024

Jeremy Kobor, MS, PG

The SGMA/Coho Mismatch



Types of Streamflow Depletion



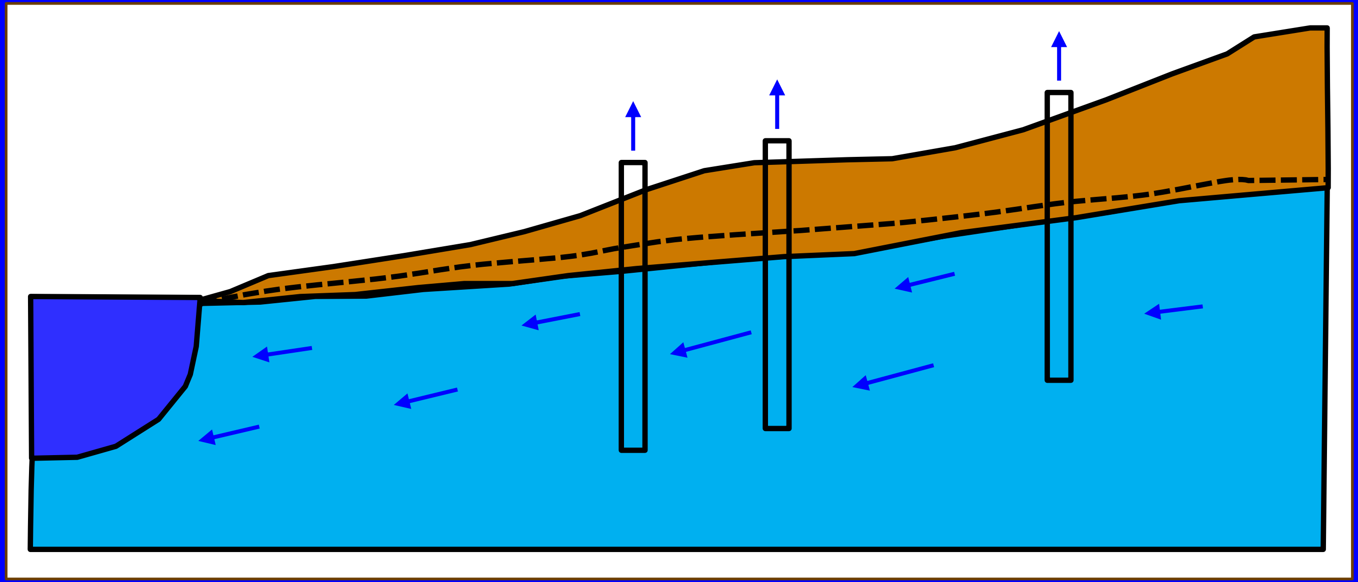
<u>Acute</u>

Short response time

Alluvial

Shallow/near-stream

'It's about the well'



<u>Cumulative</u>

Long response time

Any geology

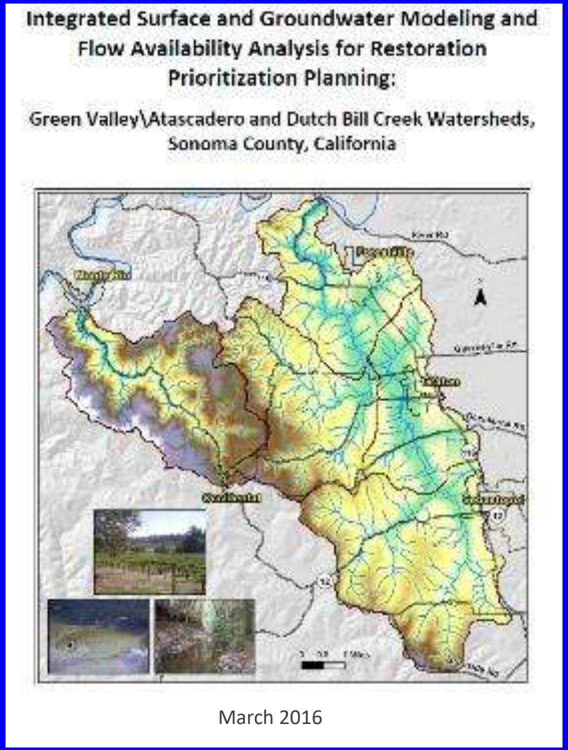
Any well completion

'It's about the water balance'

Streamflow Depletion Approaches

- Integrated Numerical Models
  - Generally considered the 'gold standard'
  - Physically-based representation of all relevant hydrologic processes
  - Can calibrate to streamflow & groundwater observations
- Analytical Models
- Statistical Models

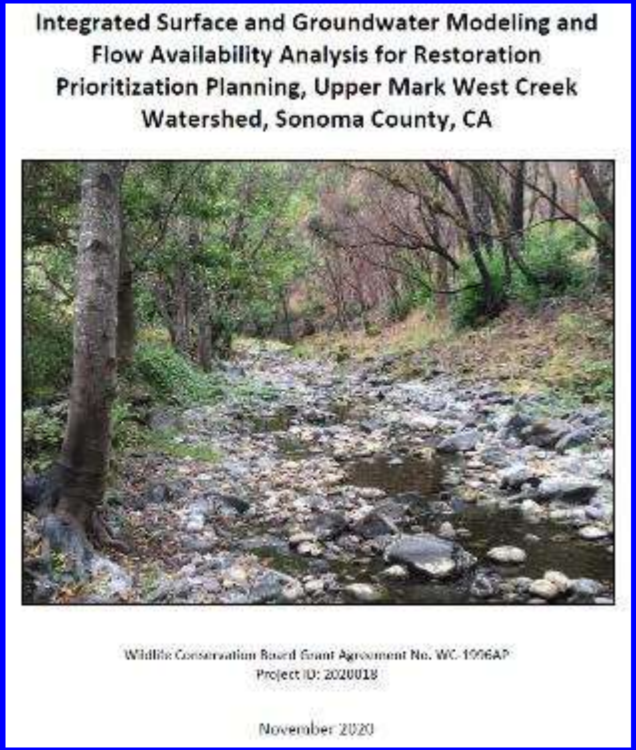
Existing Integrated Numerical Models



Integrated Surface and Groundwater Modeling and Flow Availability Analysis for Restoration Prioritization Planning:

Green Valley\Atascadero and Dutch Bill Creek Watersheds, Sonoma County, California

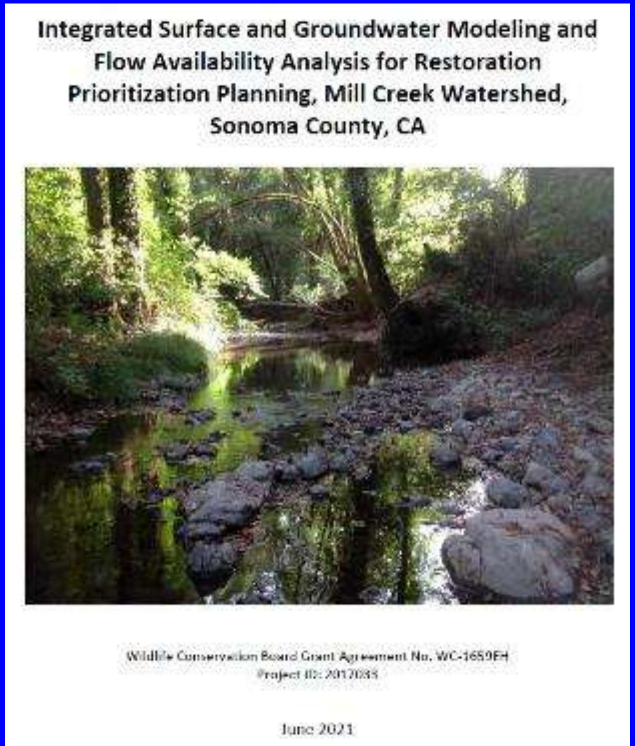
March 2016



Integrated Surface and Groundwater Modeling and Flow Availability Analysis for Restoration Prioritization Planning, Upper Mark West Creek Watershed, Sonoma County, CA

Wildlife Conservation Board Grant Agreement No. WC-1996AP
Project ID: 2020018

November 2020



Integrated Surface and Groundwater Modeling and Flow Availability Analysis for Restoration Prioritization Planning, Mill Creek Watershed, Sonoma County, CA

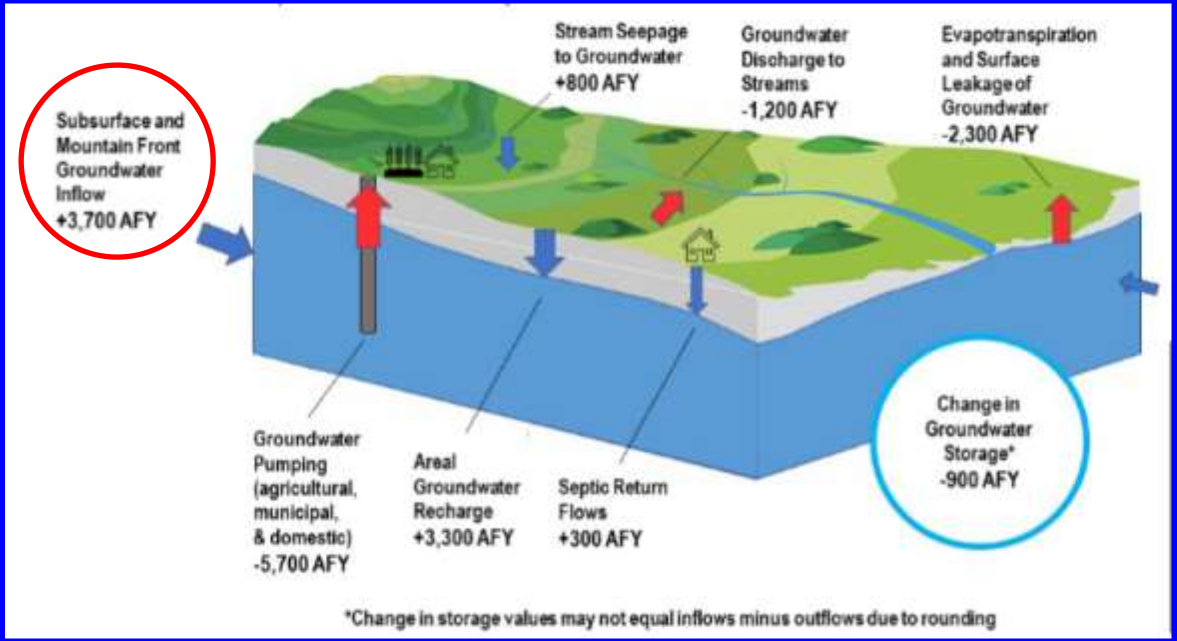
Wildlife Conservation Board Grant Agreement No. WC-1659EH
Project ID: 2017035

June 2021

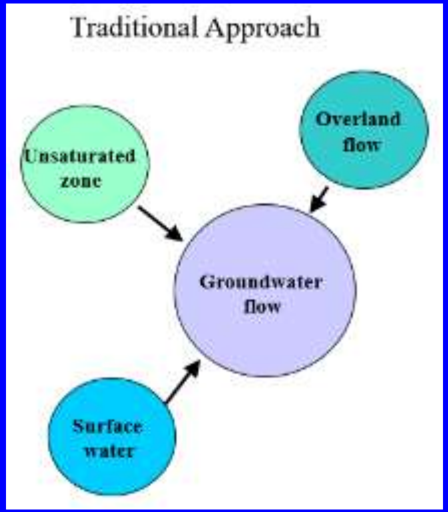
- CDFW & WCB Funded
- Coast Range Watershed Institute, OEI, Sonoma RCD, Gold Ridge RCD, Pepperwood Preserve, Trout Unlimited, FMWW, County Parks

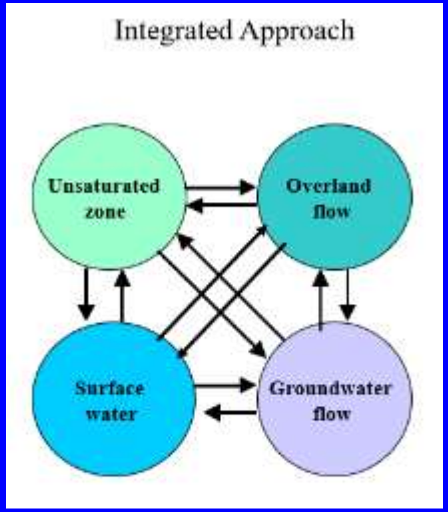
Integrated Model Considerations

- Represents all relevant processes/feedbacks?
- Appropriate scale and spatial extent?
- Based on quality input data?
- Well calibrated/validated?



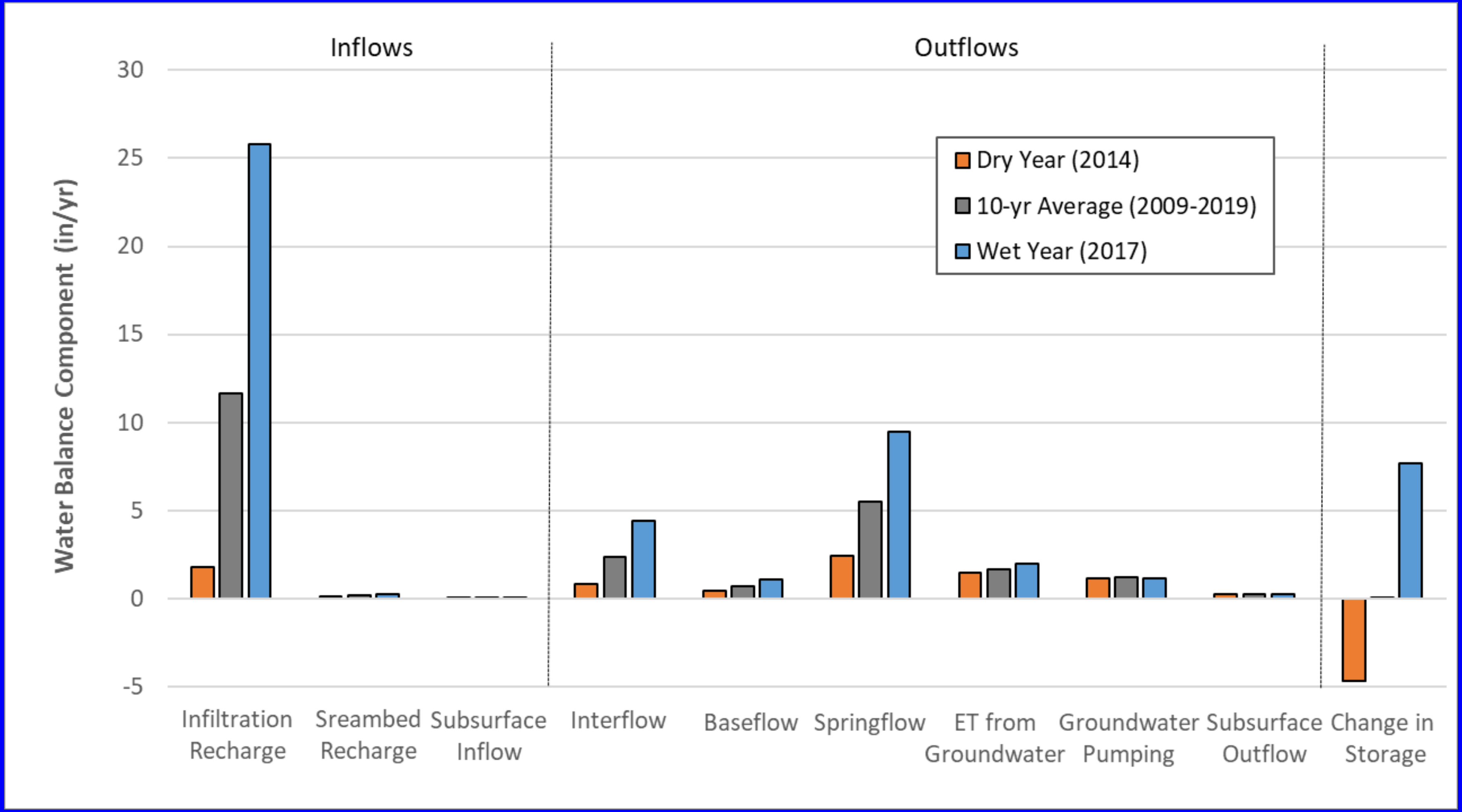
C/O Sonoma Valley GSP

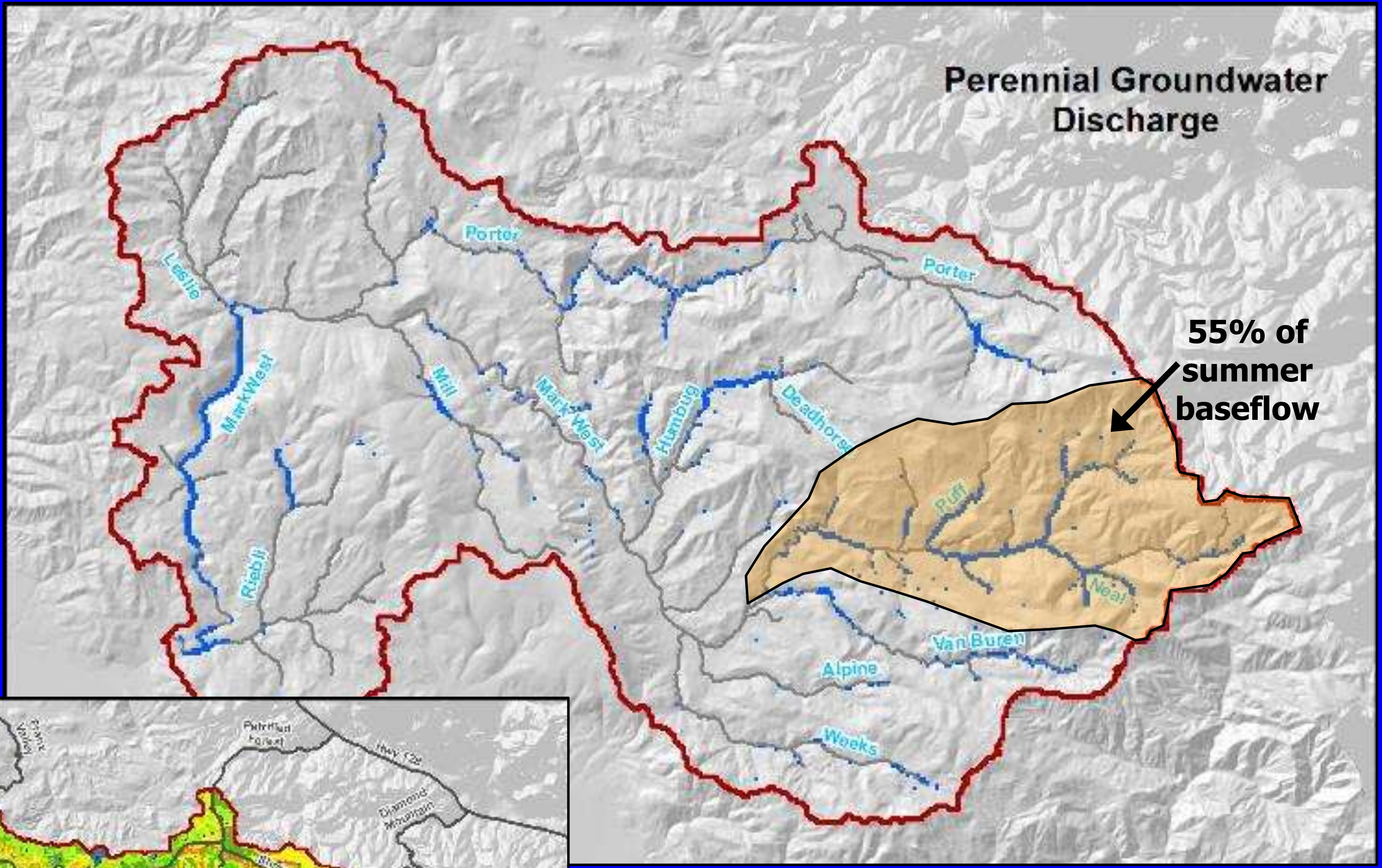


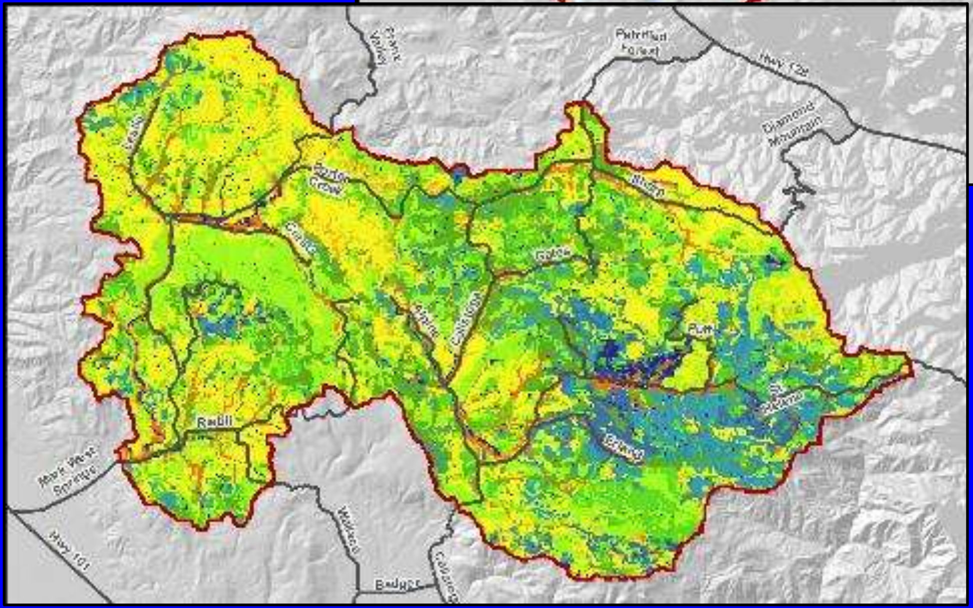


Water Balance

- Atascadero/Green Valley Creek





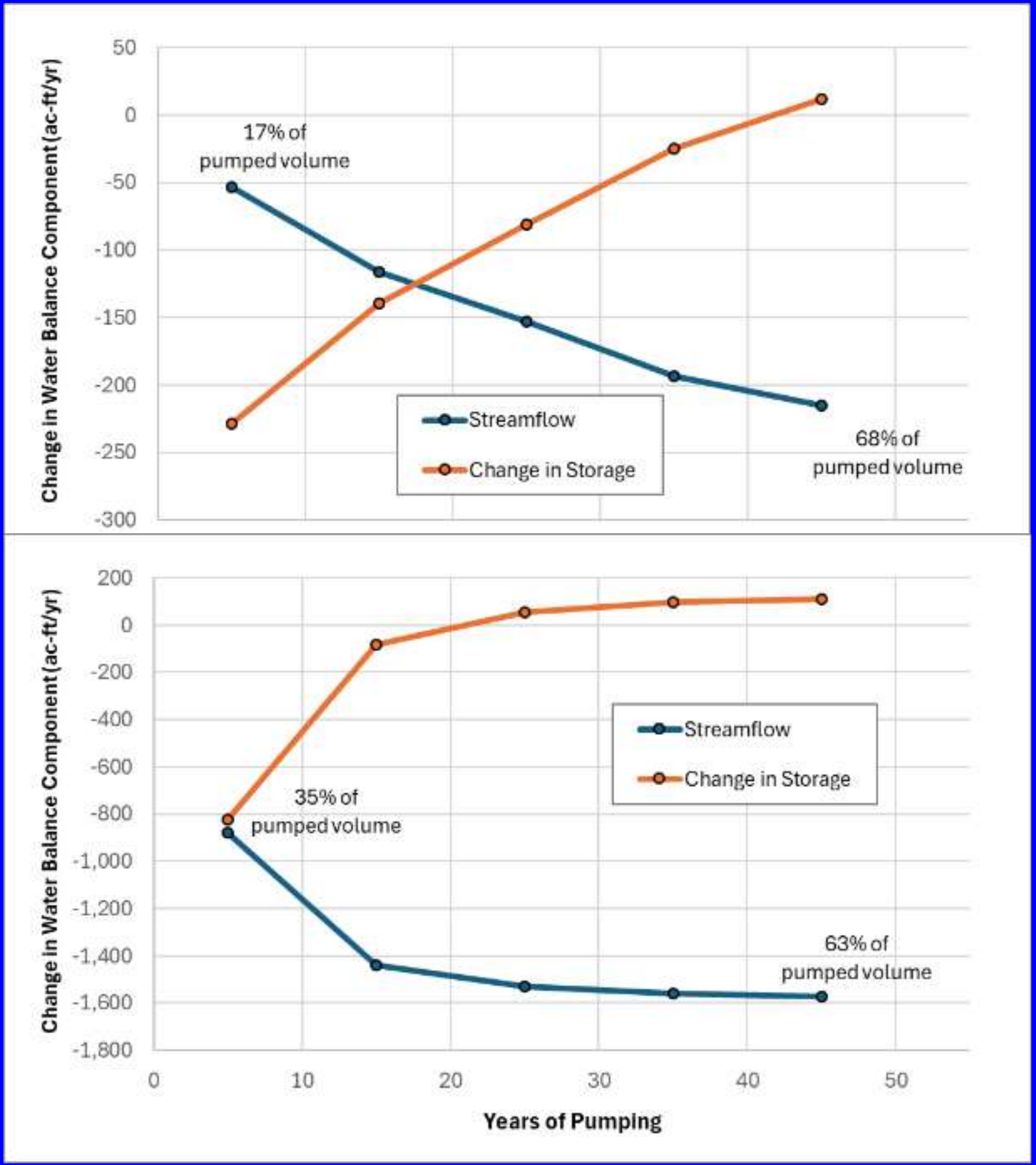


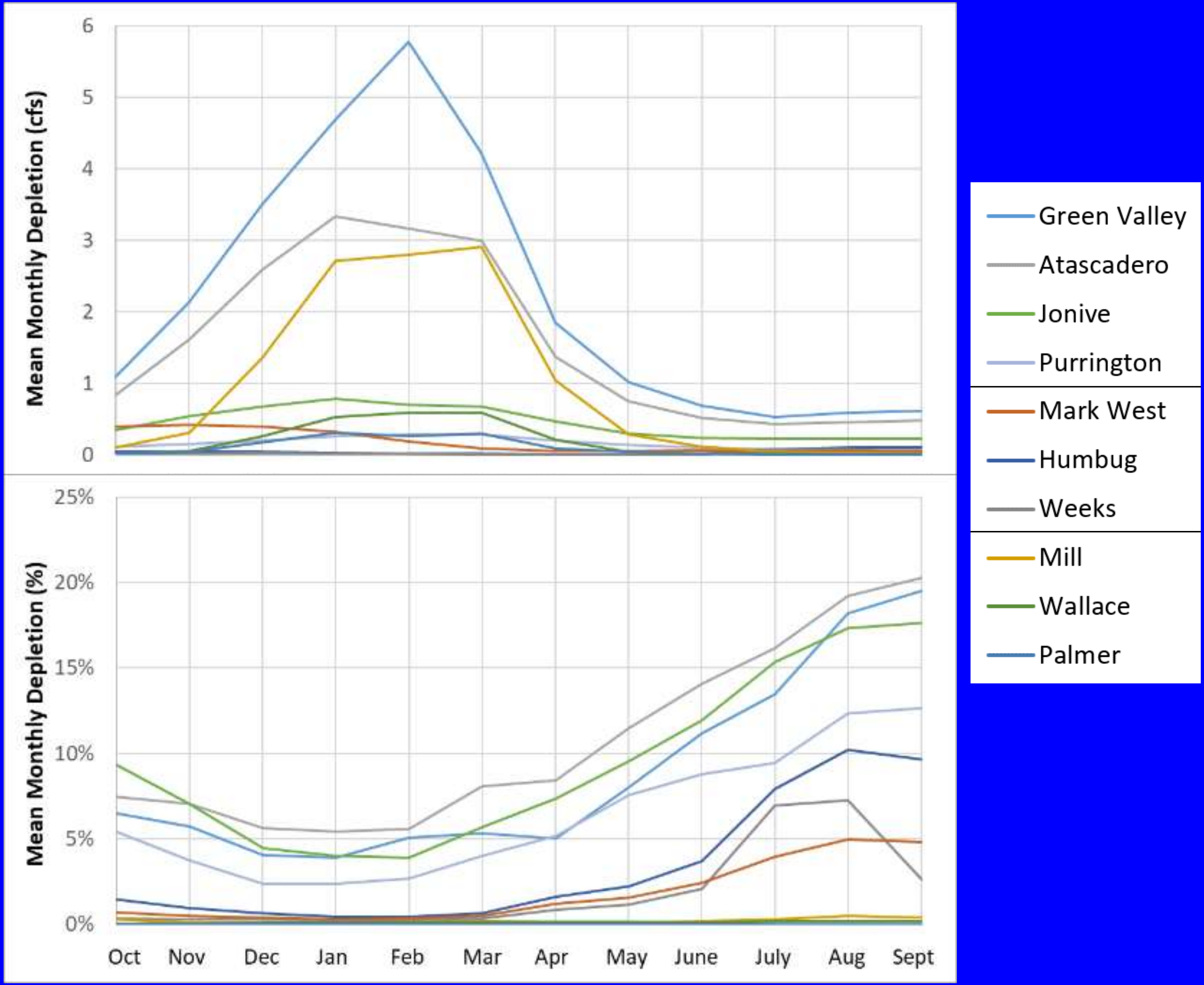
Infiltration Recharge (in/yr)

-4 to -2	6 to 8
-2 to 0	8 to 10
0 to 2	10 to 14
2 to 4	14 to 18
4 to 6	18 to 22

Mark West Creek

Atascadero/ Green Valley Creek

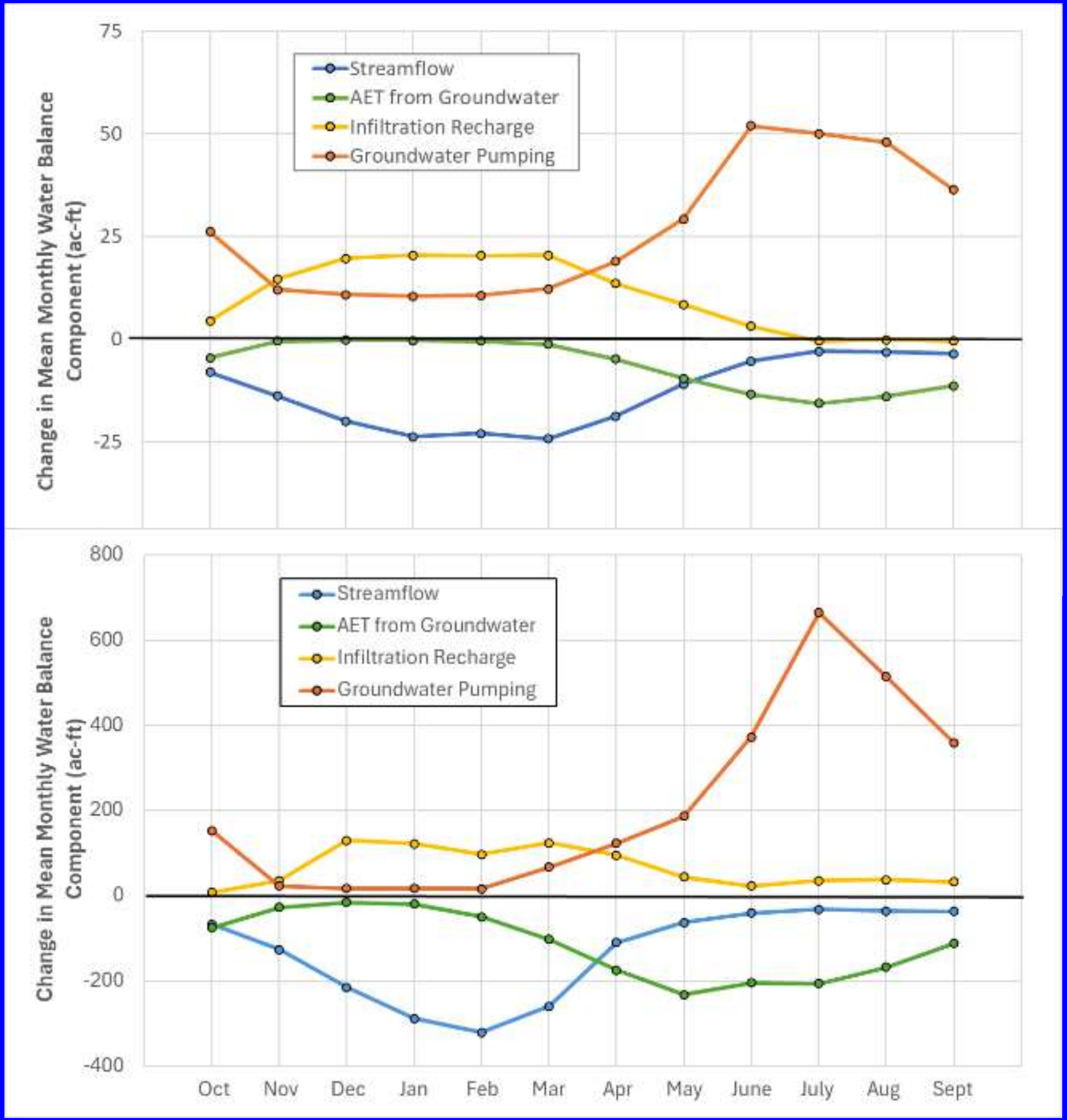




Mean Monthly Depletion (cfs)
0
1
2
3
4
5
6
Mean Monthly Depletion (%)
0%
5%
10%
15%
20%
25%
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Green Valley
Atascadero
Jonive
Purrington
Mark West
Humbug
Weeks
Mill
Wallace
Palmer

Mark West Creek

Atascadero/ Green Valley Creek



Sonoma County Well Ordinance
Subbasin Prioritization

- Designed as a screening tool to aid in identifying a public trust review area
- Characterizes the degree of cumulative groundwater use relative to groundwater availability
- Not designed to address individual well impacts

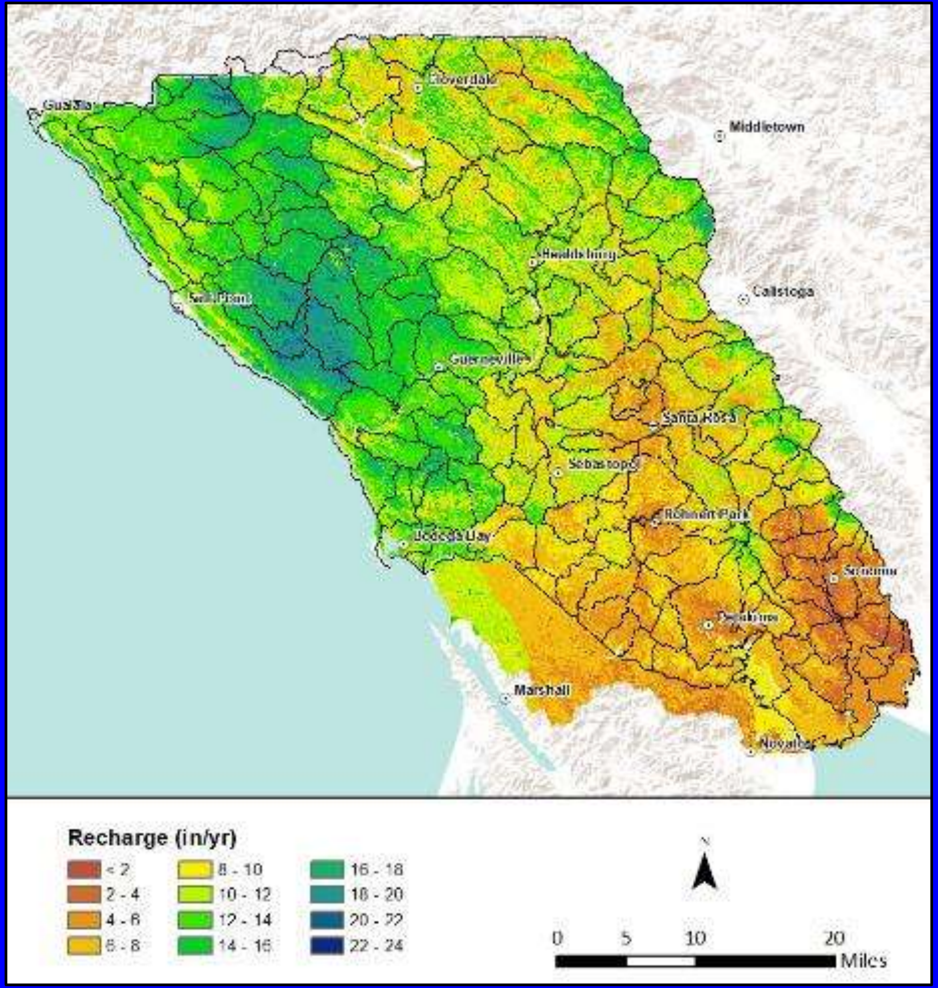
Pumping Ratio Rationale

Recharge + GW Inflow = Streamflow + GW ET + Pumping + GW Outflow +/- Δ Storage

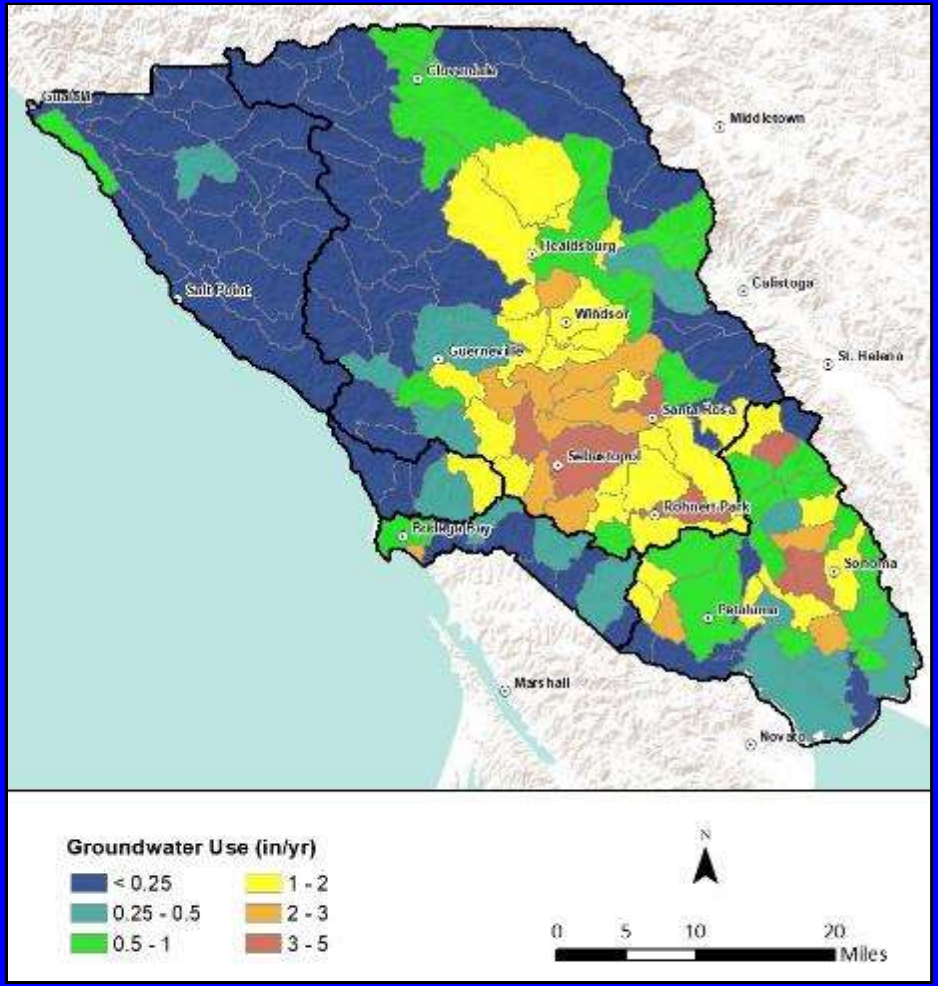
Recharge ≈ Streamflow + Pumping

- Ratio of pumping to recharge provides an approximation of relative cumulative streamflow depletion

Recharge (Soil Water Balance Model)

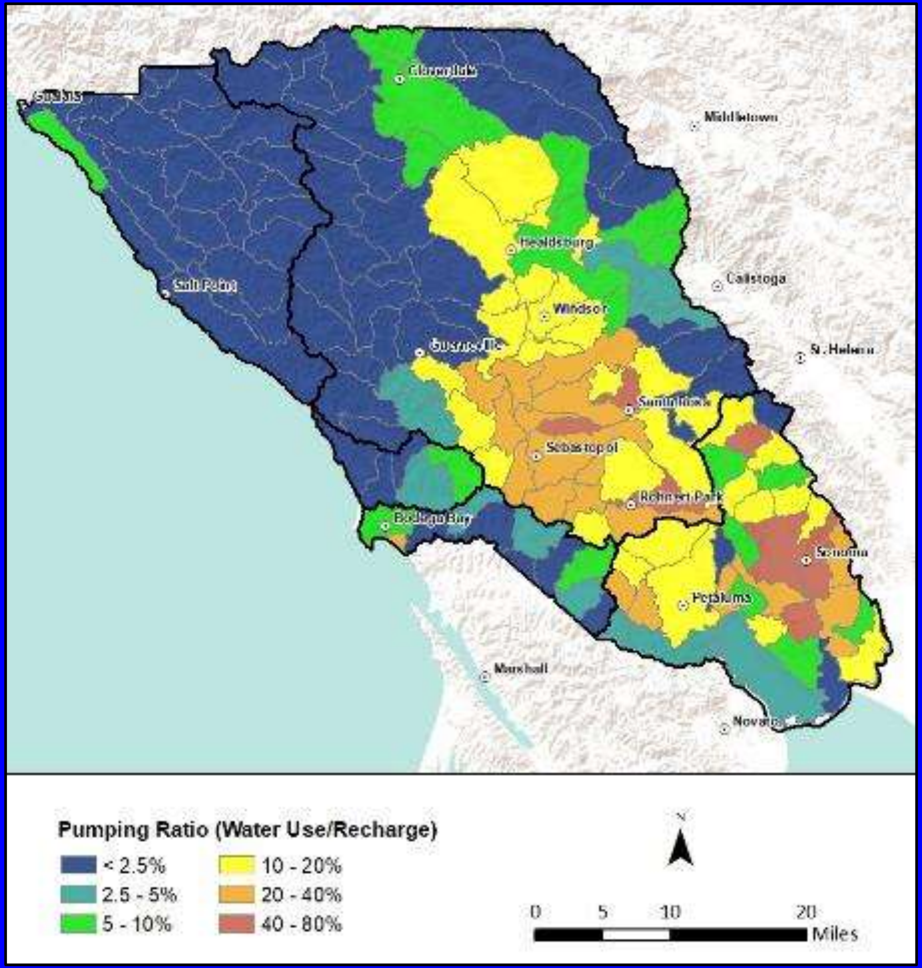


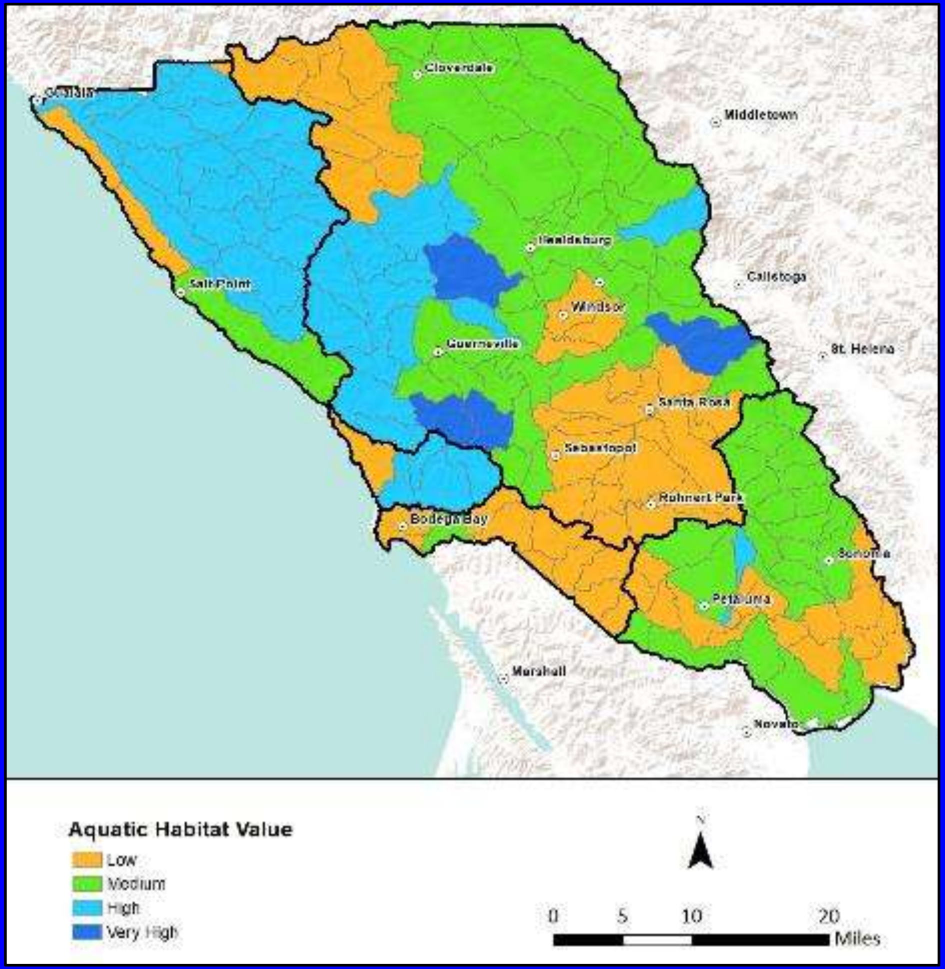
Cumulative Groundwater Use

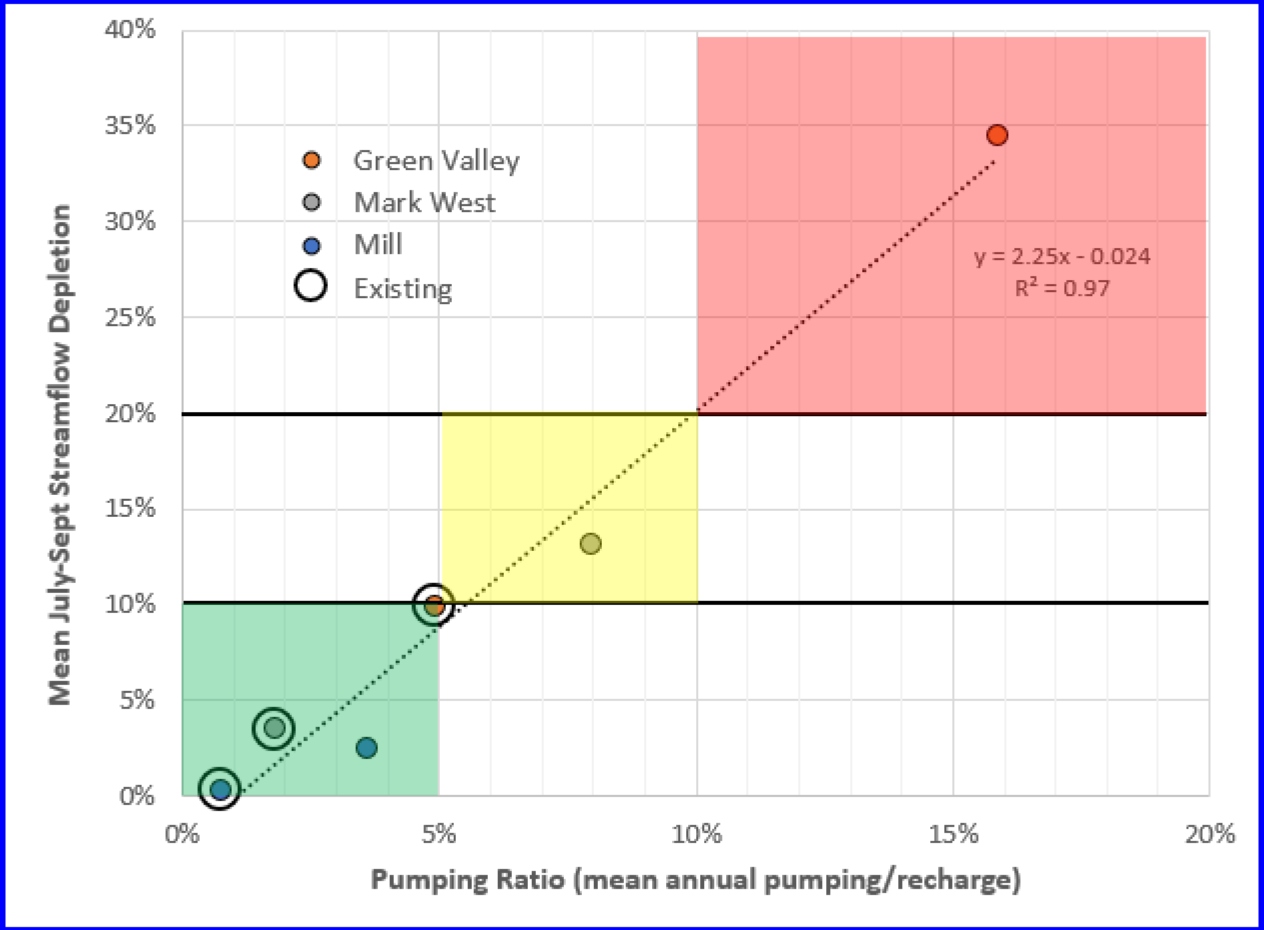


Pumping Ratio

Aquatic Habitat Value







Impact Thresholds

- Richter et al. (2012)
- Gleeson & Richter (2018)

Low SFD (<10%) – pumping ratio <5%

Medium SFD (10-20%) – pumping ratio 5-10%

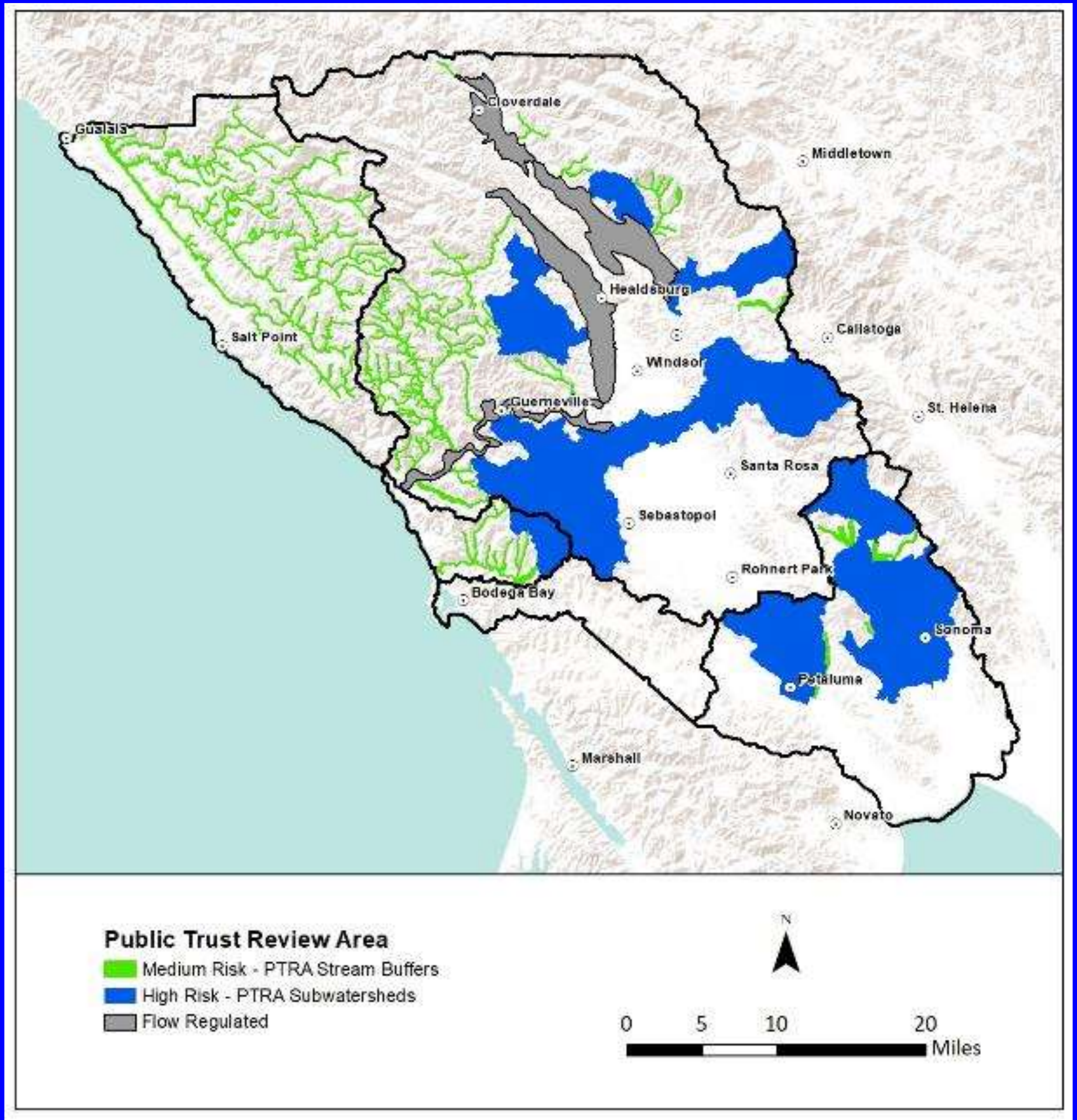
High SFD (>20%) – pumping ratio >10%

Classification Matrix

	Low SFD (0 – 10%)	Medium SFD (10 – 20%)	High SFD (>20%)
Low Habitat Value	Low Risk Area Not included in PTRA	Low Risk Area Not included in PTRA	Low Risk Area Not included in PTRA
Moderate Habitat Value	Low Risk Area Not included in PTRA	Moderate Risk Area Stream buffers	High Risk Area Sub-watershed
High Habitat Value	Moderate Risk Area Stream buffers	High Risk Area Sub-watershed	High Risk Area Sub-watershed
Very High Habitat Value	High Risk Area Sub-watershed	High Risk Area Sub-watershed	High Risk Area Sub-watershed

Public Trust Review Area

- combines resource sensitivity & existing level of depletion



Takeaways

- Regional Screening Level Analysis
  - Pumping Ratio/Analytical Models
- Local Detailed Analysis
  - Numerical Models
  - Monitoring & Subsurface Characterization
- Tailor Study/Regulation to Type of Depletion
  - Acute depletion – setbacks/storage & forbearance
  - Cumulative depletion - volume caps


Thank You

Effects of short-term flow reductions on juvenile rainbow trout (*Oncorhynchus mykiss*)

Kelly Goedde-Matthews, UC Davis Graduate Group in Ecology

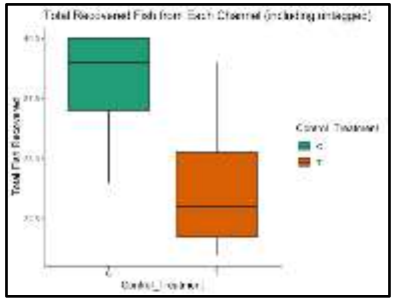
Rob Lusardi: UC Davis Department of Wildlife, Fish, and Conservation Biology

Bob Hawkins: California Department of Fish and Wildlife

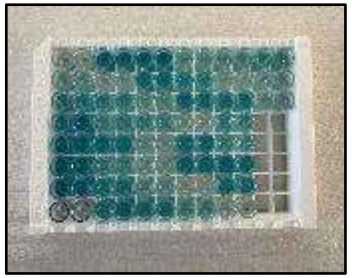
Effects of Short-Term Flow Reductions on Juvenile Rainbow Trout

1. Background

2. Question and Experimental Approach



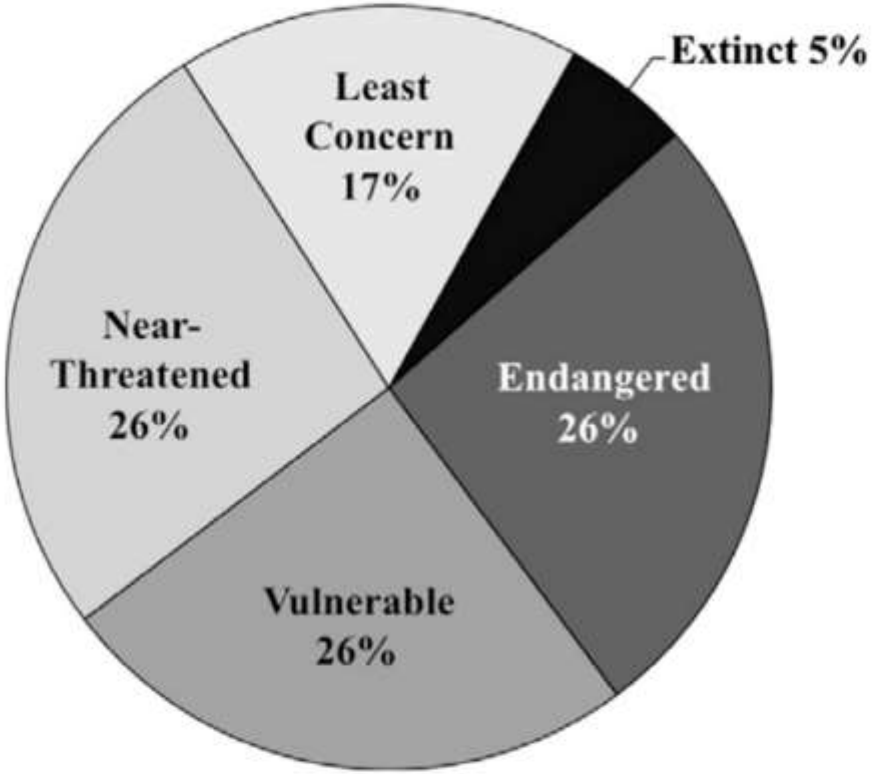
3. Results



4. Next Steps

5. Conclusions

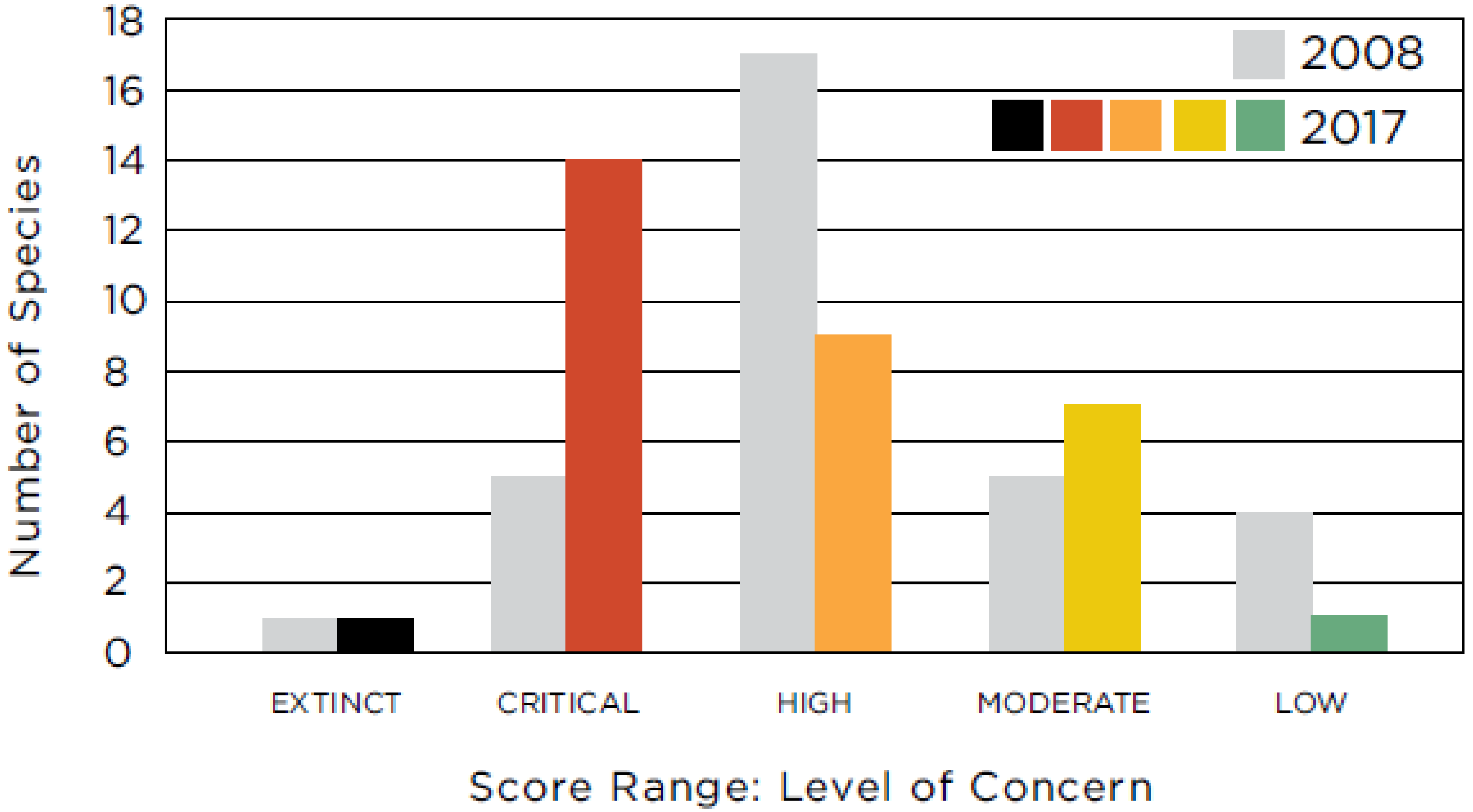
California's Fish Are Not Doing Well



Status of fishes (N = 129) native to inland waters of California in 2010.

Moyle et al. 2011, *Biological Conservation*

California’s Fish Are Not Doing Well



Change in Level of Concern in California’s native salmonids, 2008 vs. 2017.

State of Salmonids, Moyle et al. 2017

Long-Term Flow Reductions Negatively Affect Fish

Mortality

Emigration

Stress

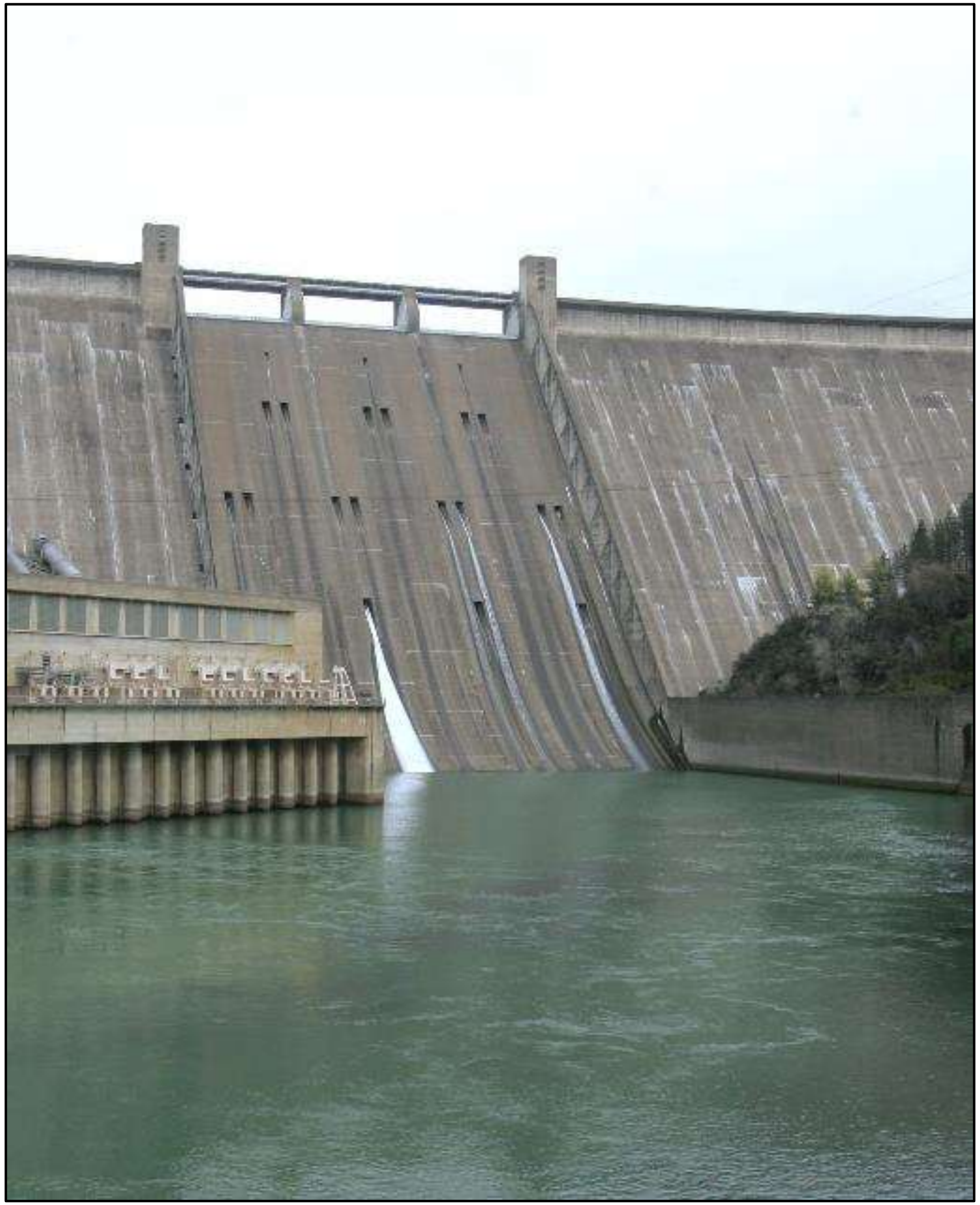
Growth Rates

Prey Availability

Armstrong et al. 1998, Arnekleiv et al 2004, Benejam et al. 2010, Flodmark et al 2002, Hakala and Hartman 2004, Harvey et al. 2006, Krimmer et al 2011, McIntosh et al. 2008, McKay and King 2006, Nislow et al. 2004, Riley et al. 2009, Spina et al. 2009

Repeated, Short-Term Flow Alterations

- Hydroelectric power
- Recreation



Pumping Causes Repeated, Short-Term Flow Reductions

- Dust Abatement
- Cannabis Irrigation

Pumping Standards to Protect Fish

- Very few laws limit short-term pumping
- Effectiveness of such laws is largely unknown

California Fish and Game Code section 5937

“good condition”

California Fish and Game Code sections 1600, *et seq.*

“substantially”

Burden on diverters to notify

“Water Drafting Specifications” Technical Memorandum

Does not have the force of law

California Code of Regulations, Title 14, Section 923.7(l)

Timber operations

Watersheds with CESA-listed anadromous salmonids

Effects of Short-Term Flow Reductions on Juvenile Rainbow Trout

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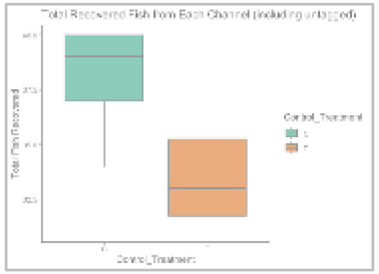
2. Question and Experimental Approach



3. Results

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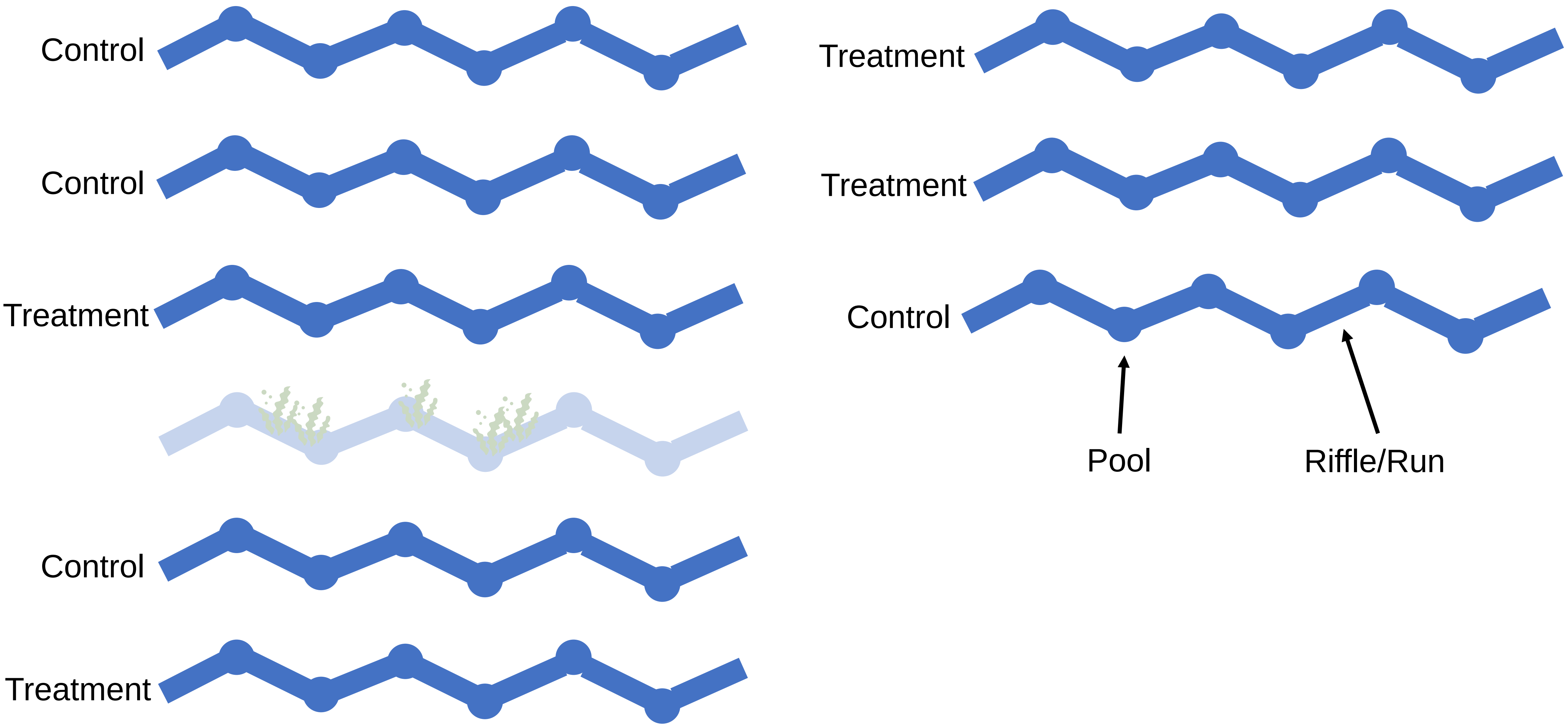
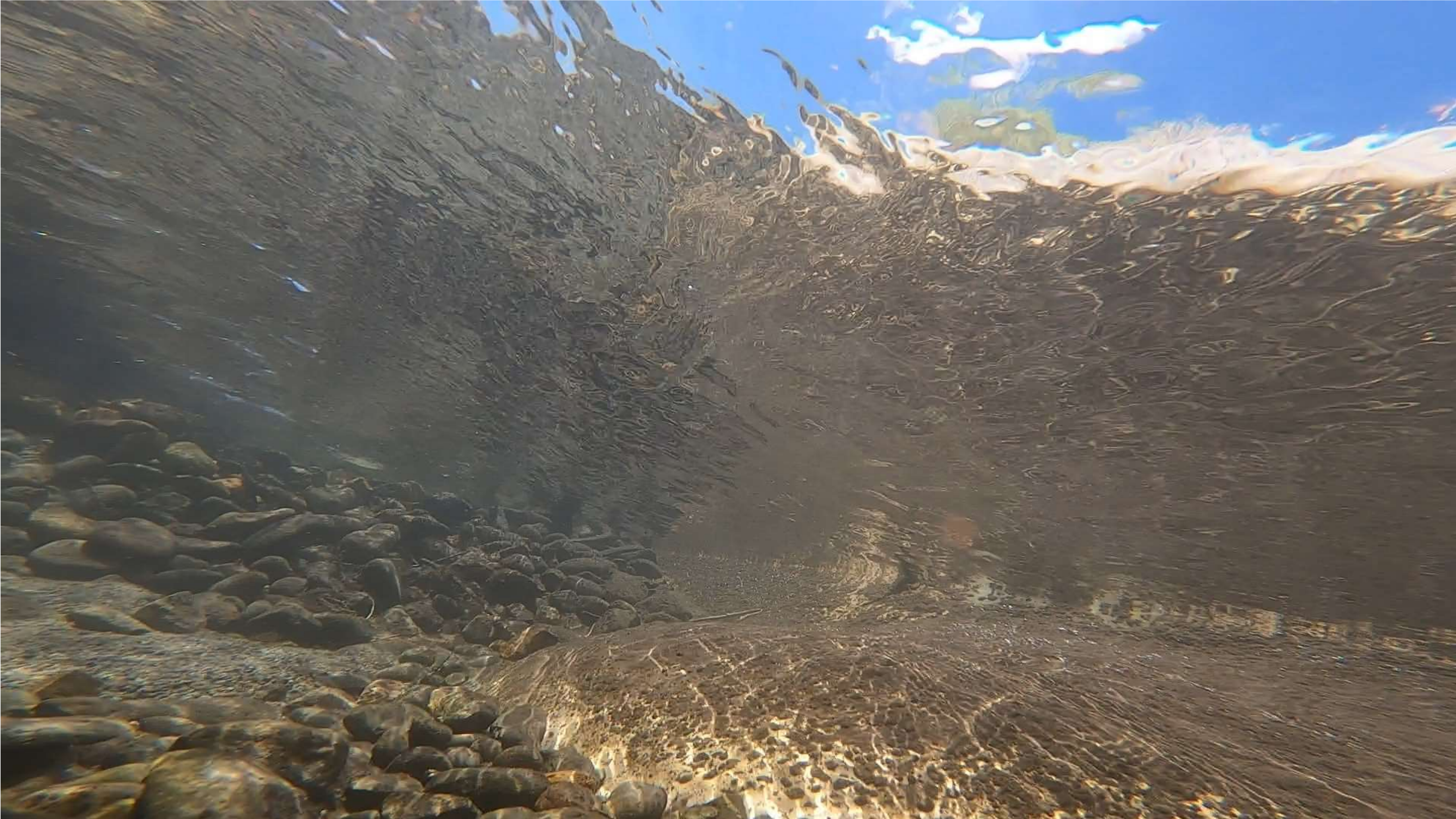
How do repeated short-term flow reductions affect juvenile *O. mykiss*?

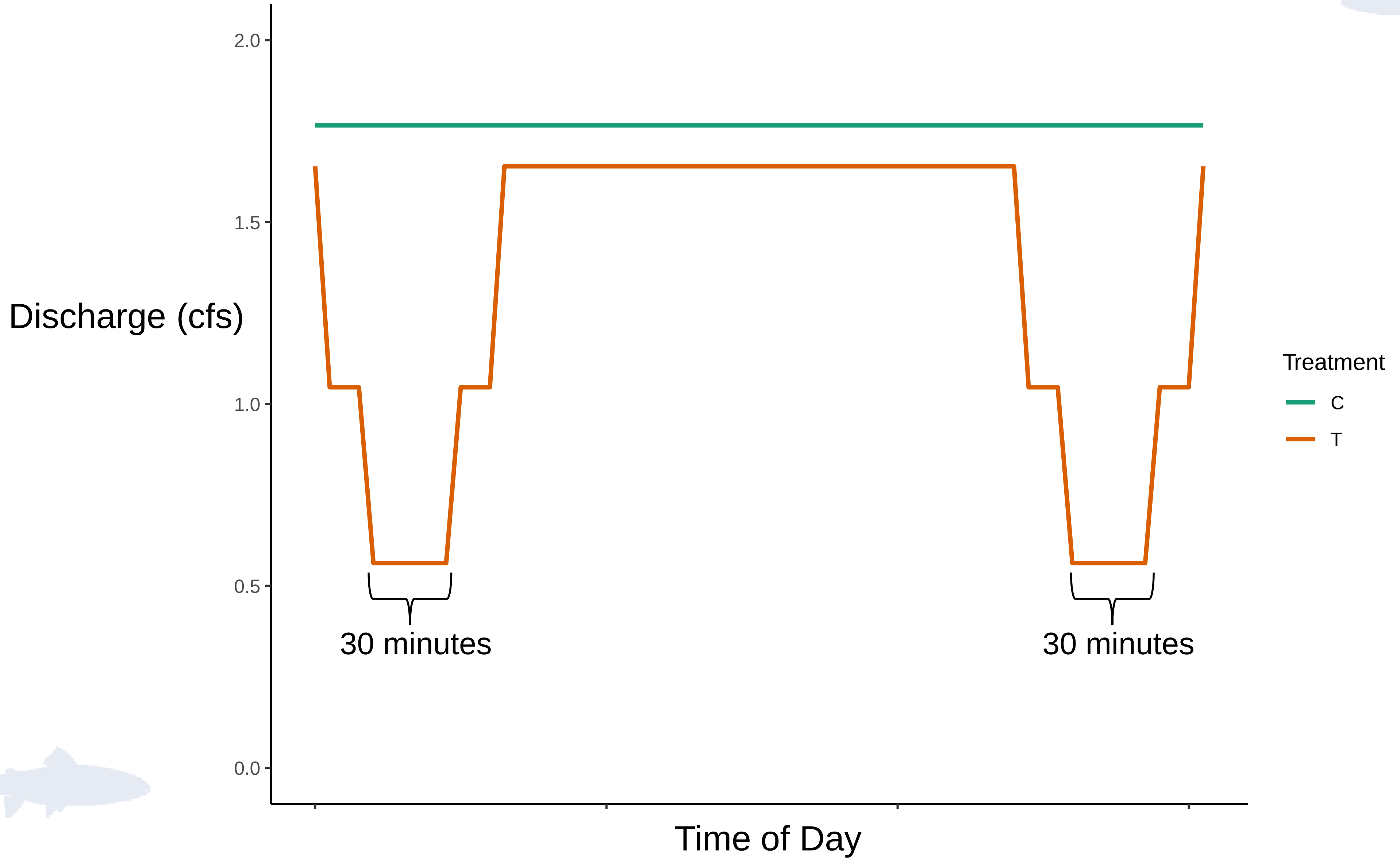
Sierra Nevada Aquatic Research Lab (SNARL)

Sierra Nevada Aquatic Research Lab (SNARL)


Control
Control
Treatment
Control
Treatment
Treatment
Treatment
Control
Pool
Riffle/Run



Average Daily Hydrograph



Effects of Short-Term Flow Reductions on Juvenile Rainbow Trout

Direct Effects:

- Mortality/Survivorship
- Growth
- Movement Behavior
- Stress (cortisol)
- Energy Storage (liver glycogen)

Indirect Effects:

- Habitat (water depths, velocities, temperature)
- Benthic macroinvertebrates

Predicted Effects of Repeated Short-Term Flow Reductions

Water Temperature

Mortality

Movement

Stress

Water Depth

Water Velocity

Growth

Liver Glycogen

Macroinvertebrate Density

Effects of Short-Term Flow Reductions on Juvenile Rainbow Trout

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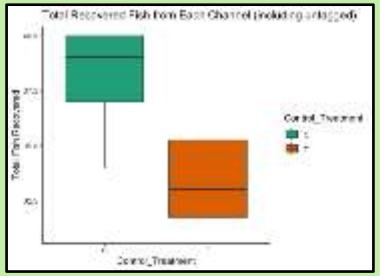

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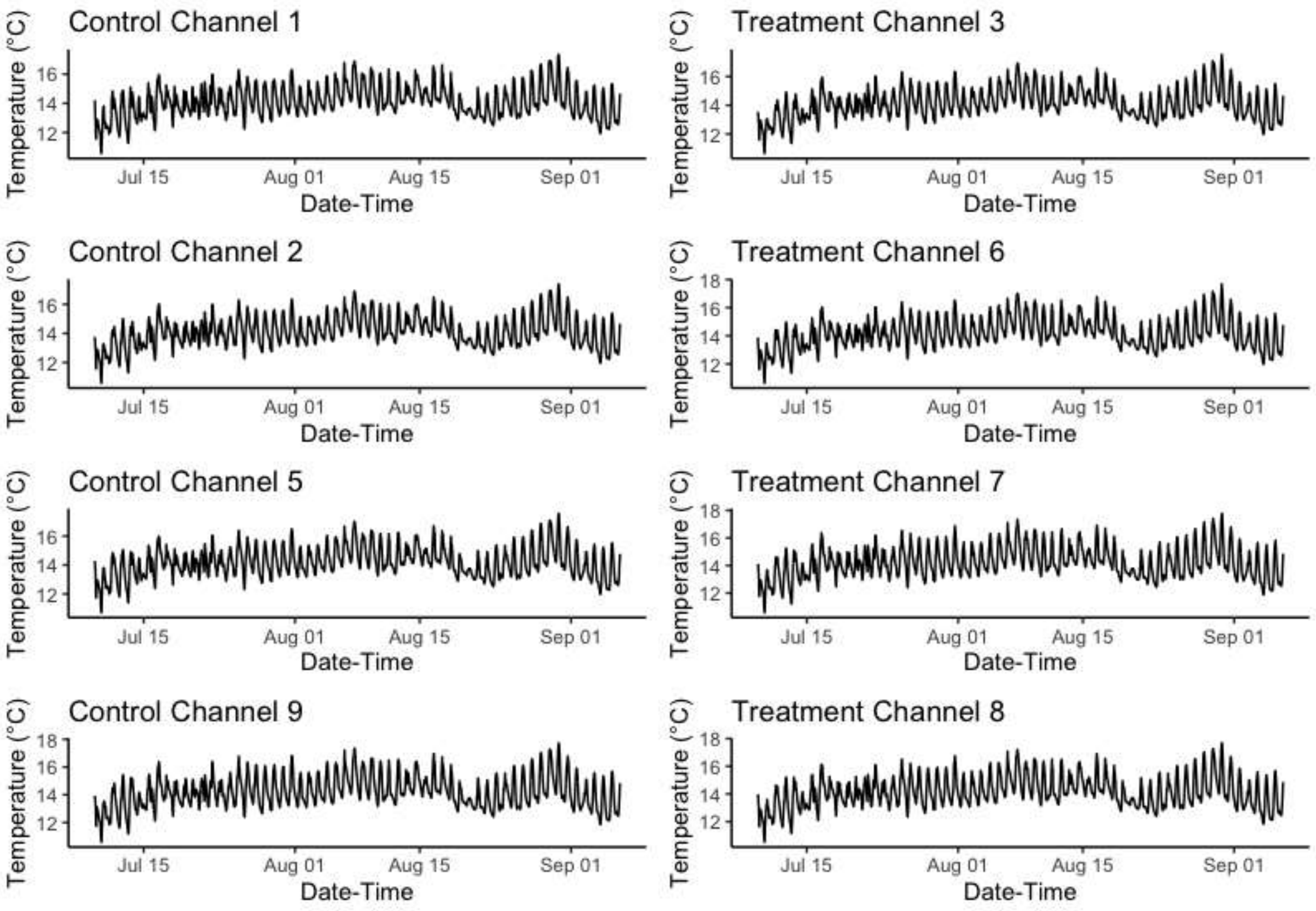
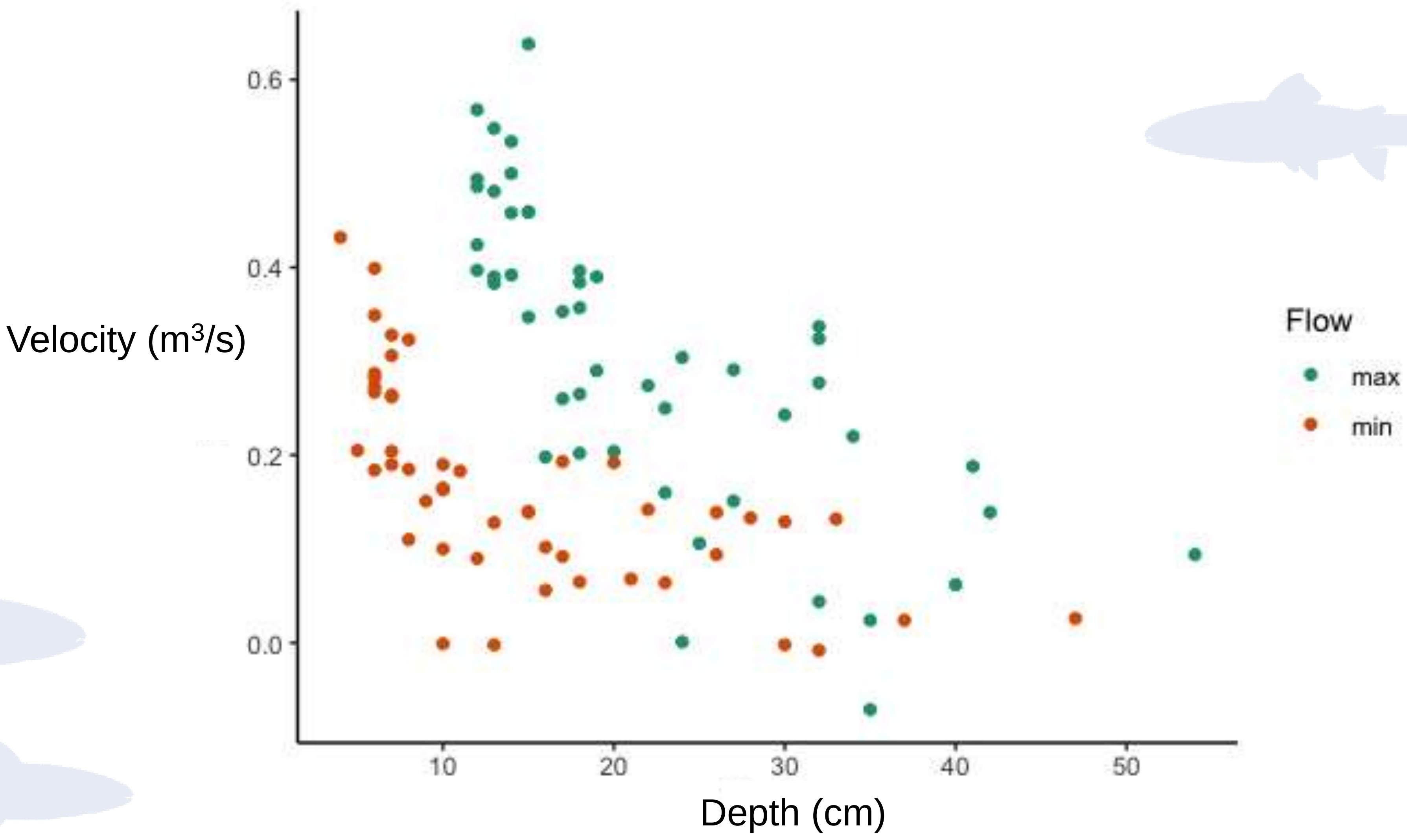
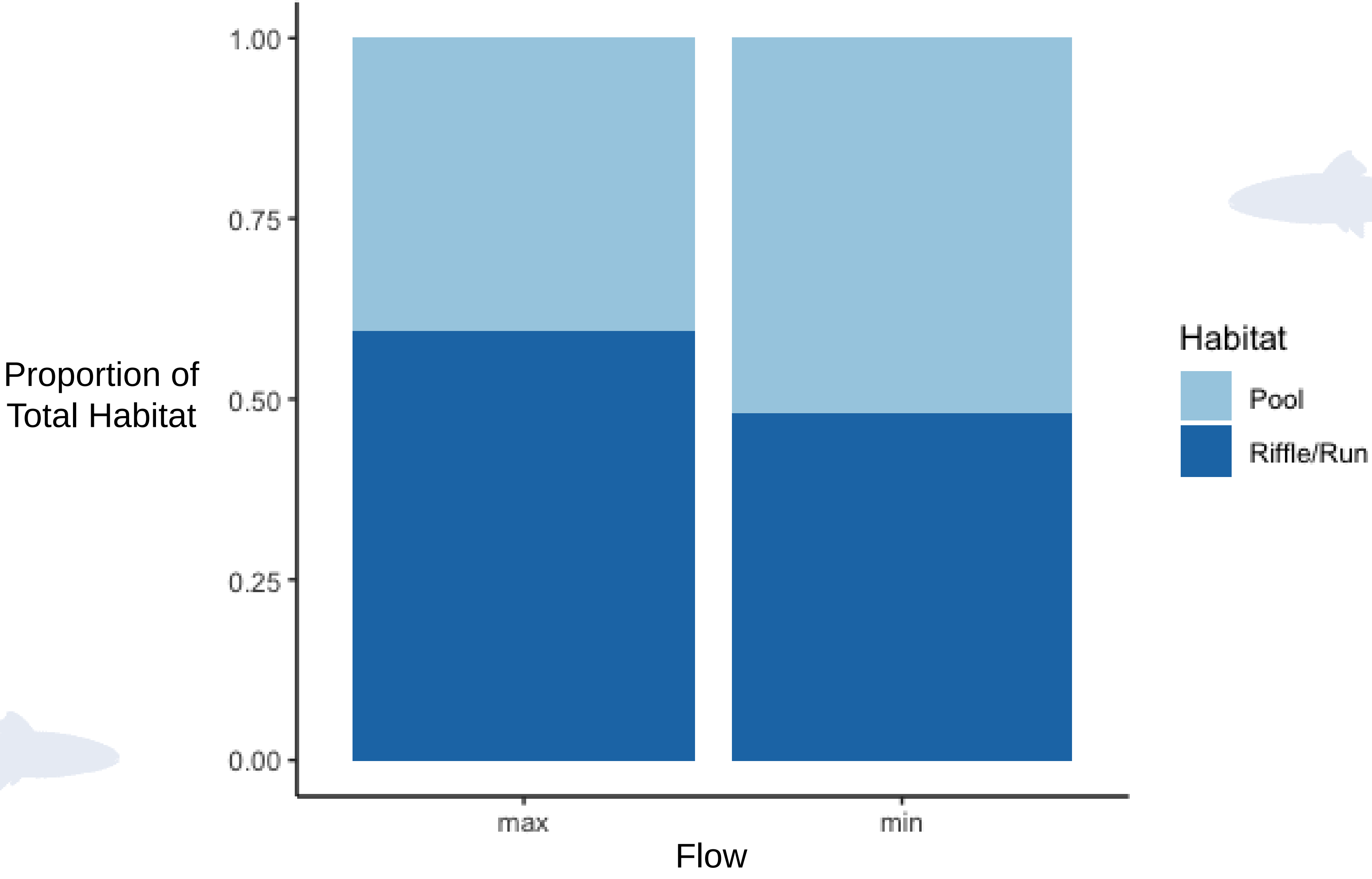
No Difference in Temperature



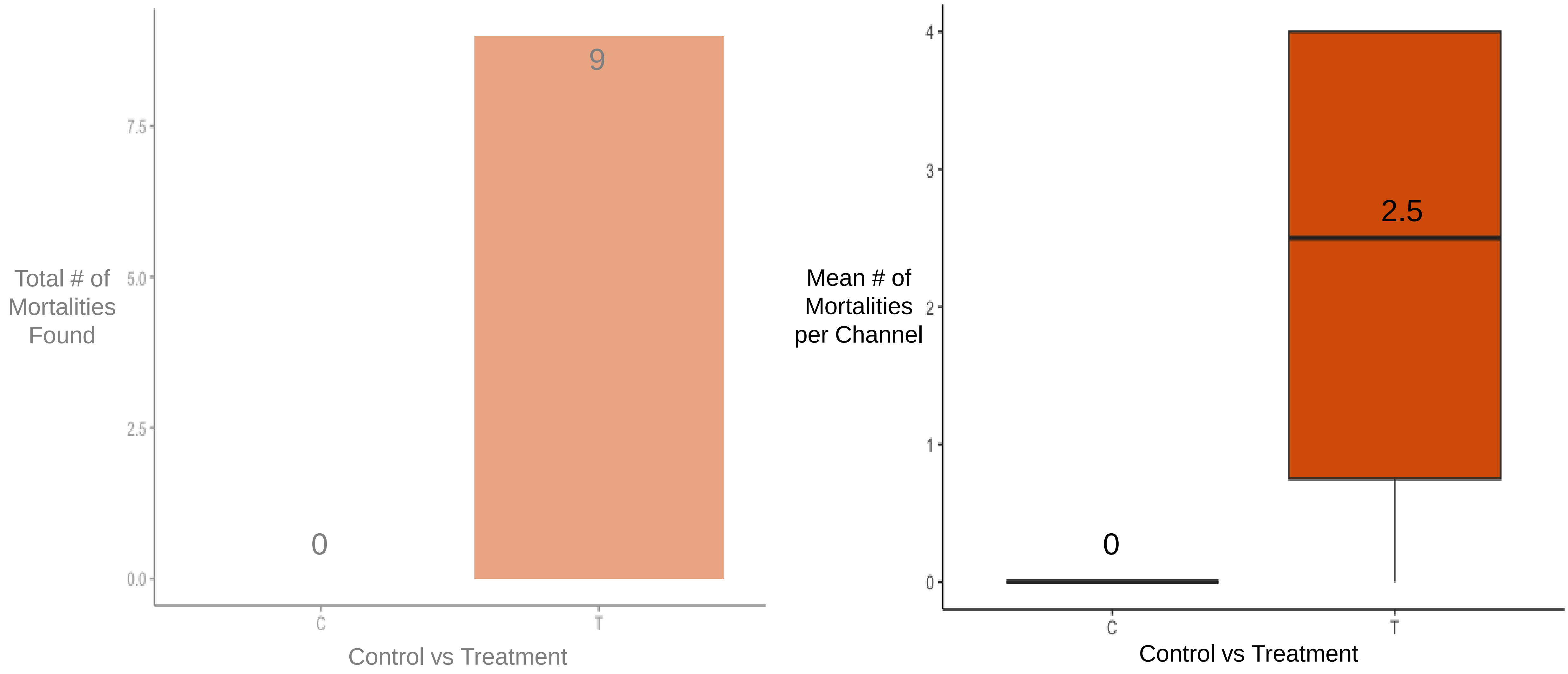
Reduced Depths and Velocities at Treatment Flow



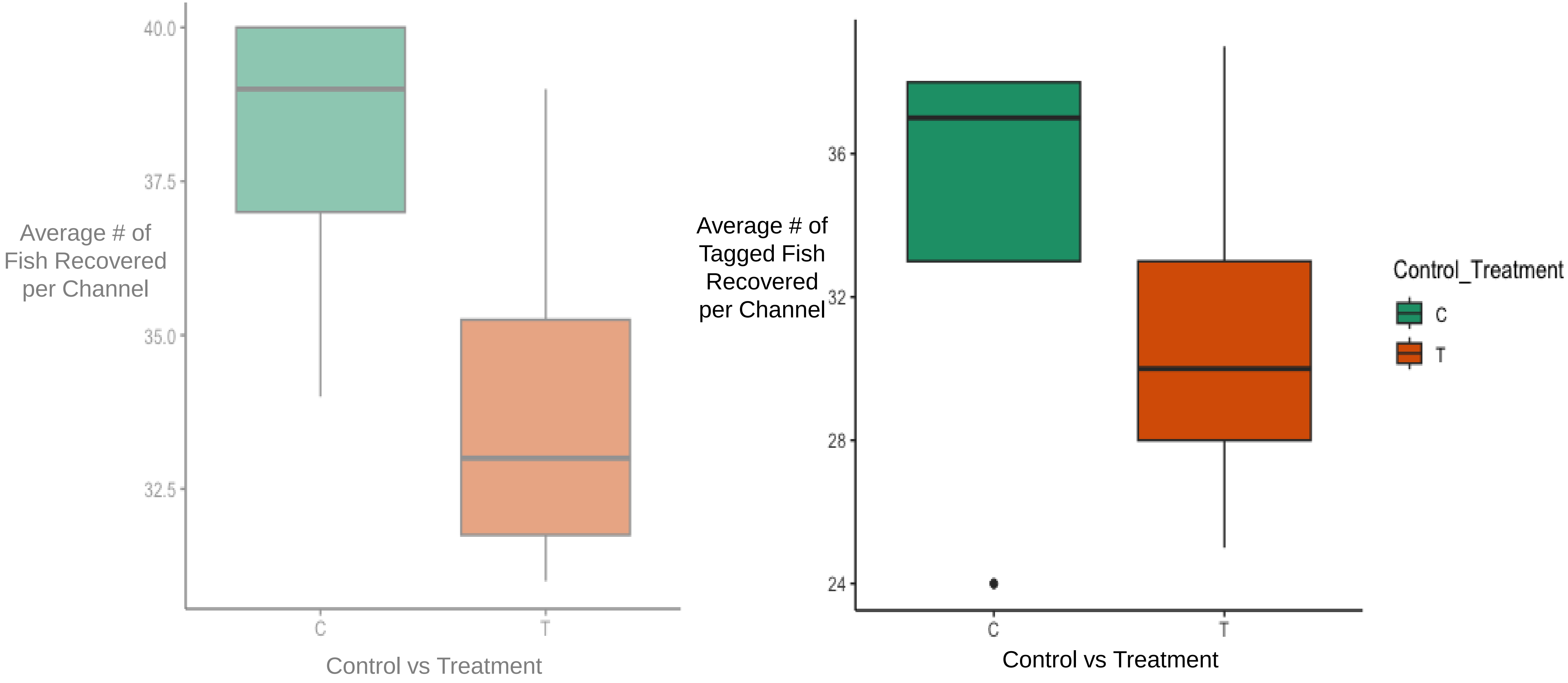
Reduced Riffle/Run Habitat at Treatment Flow



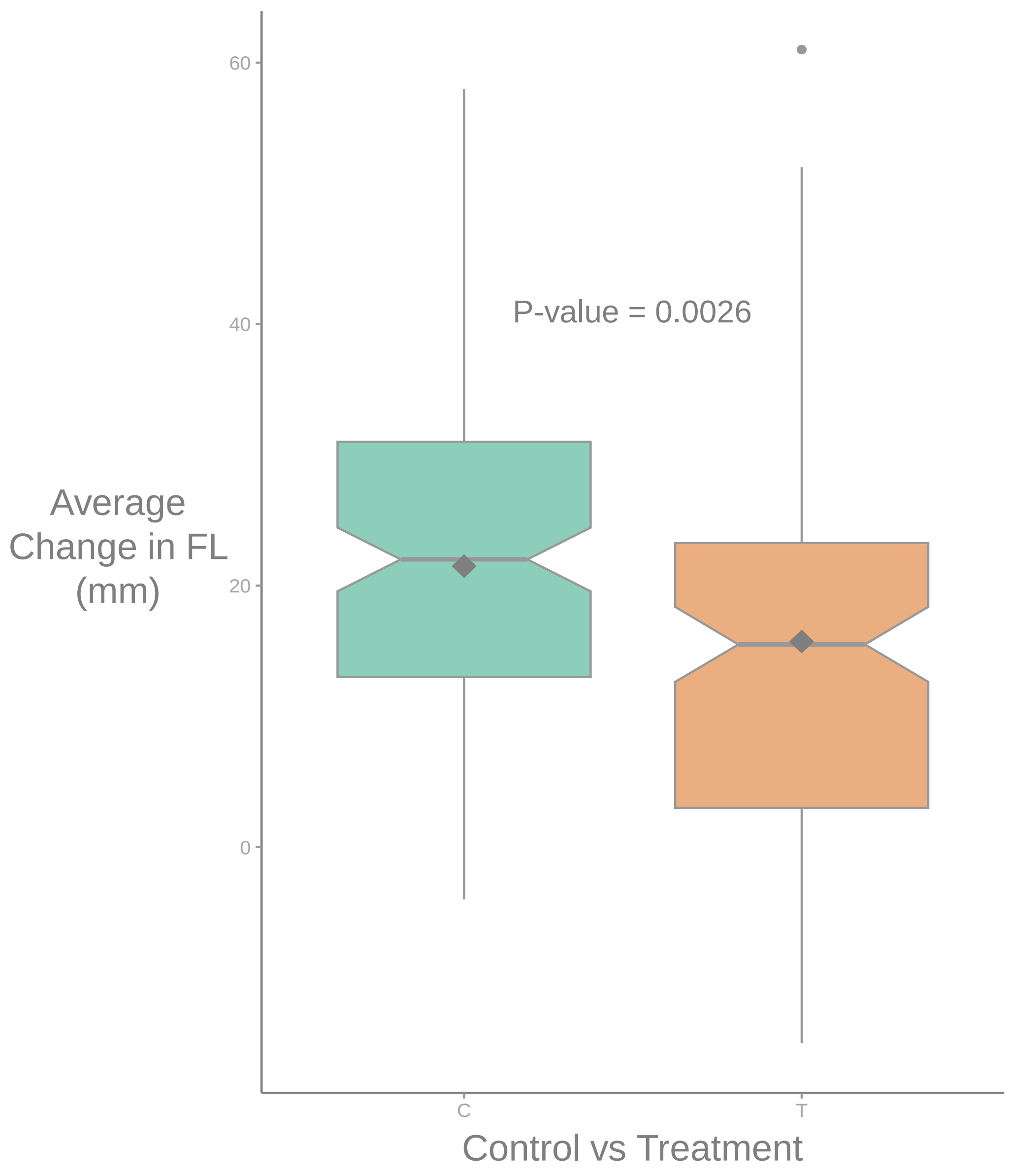
More Mortalities in Treatment Channels

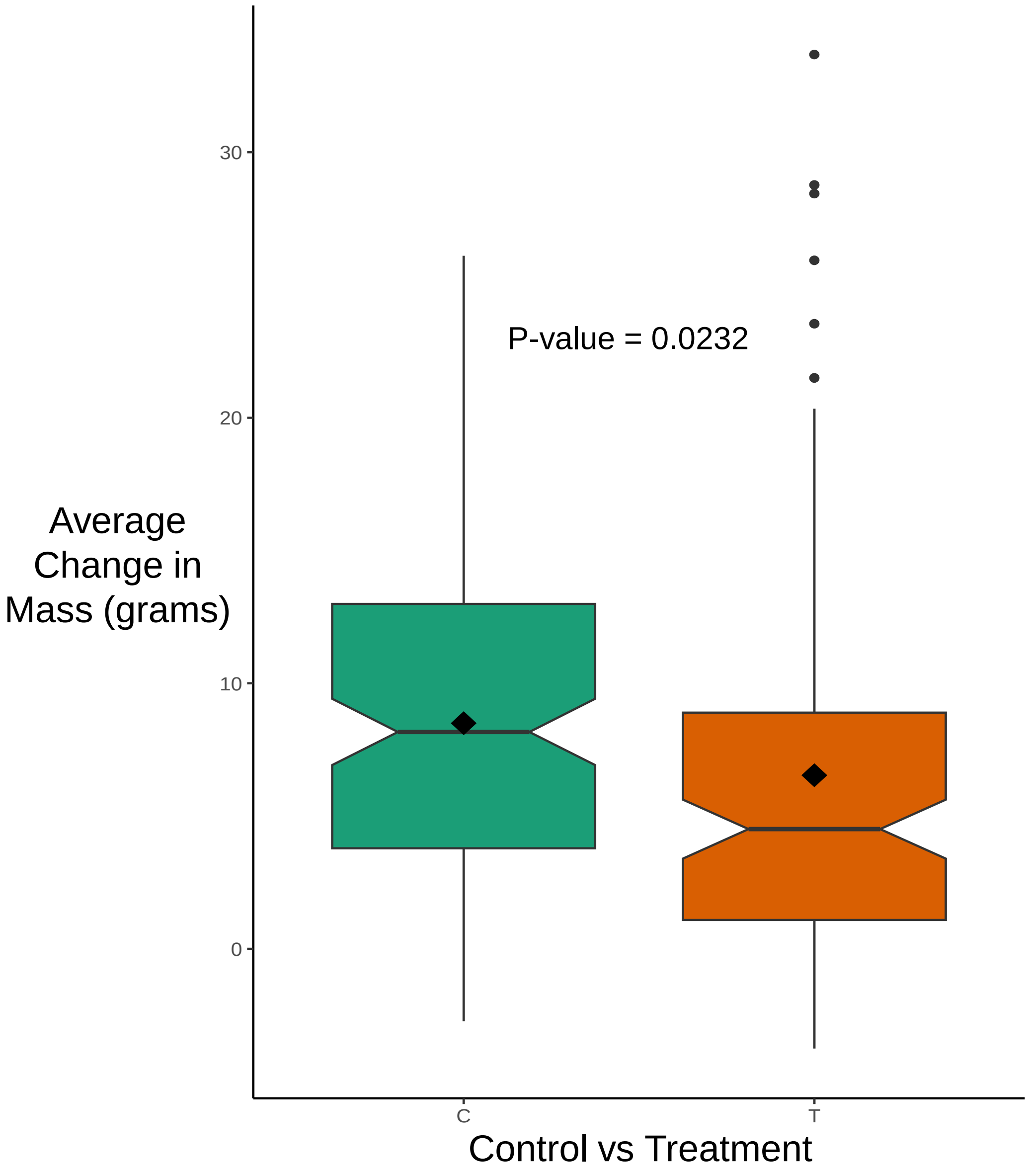


Fewer Recovered Fish from Treatment Channels

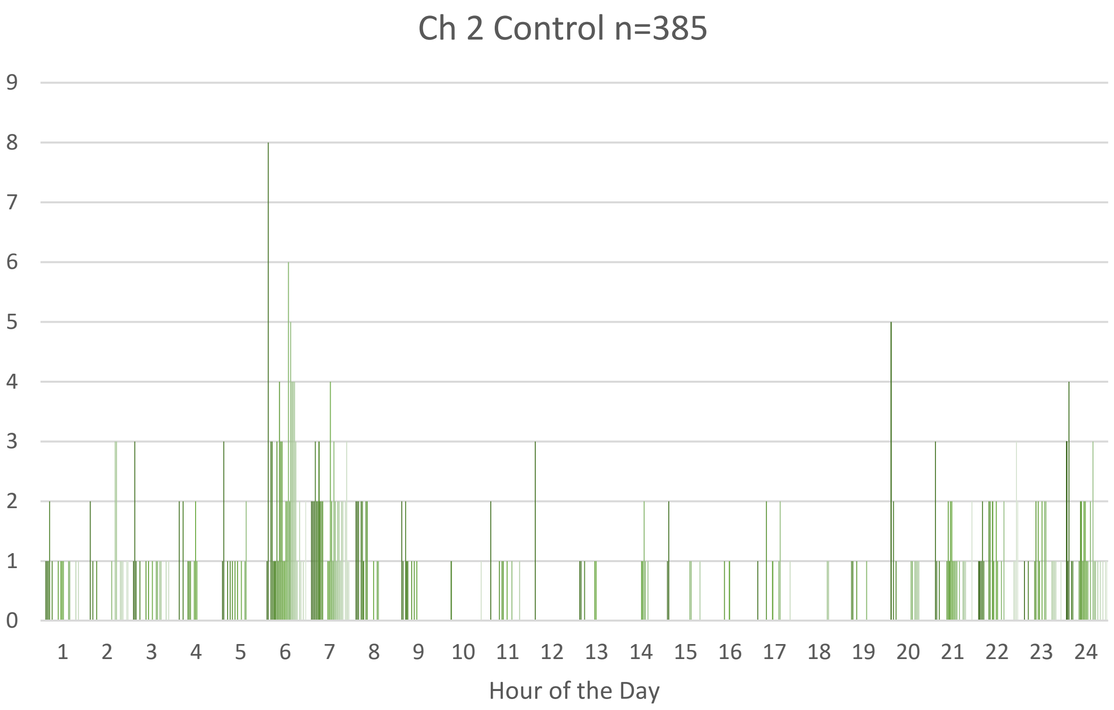


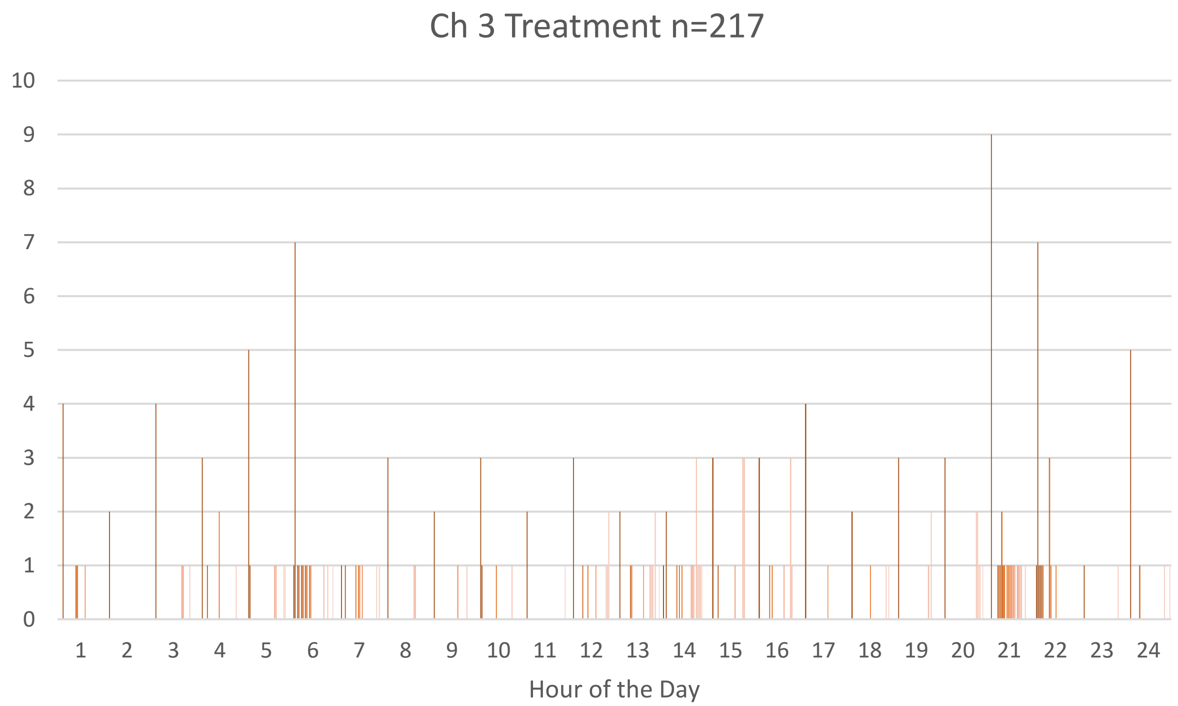
Reduced Growth in Treatment Channels





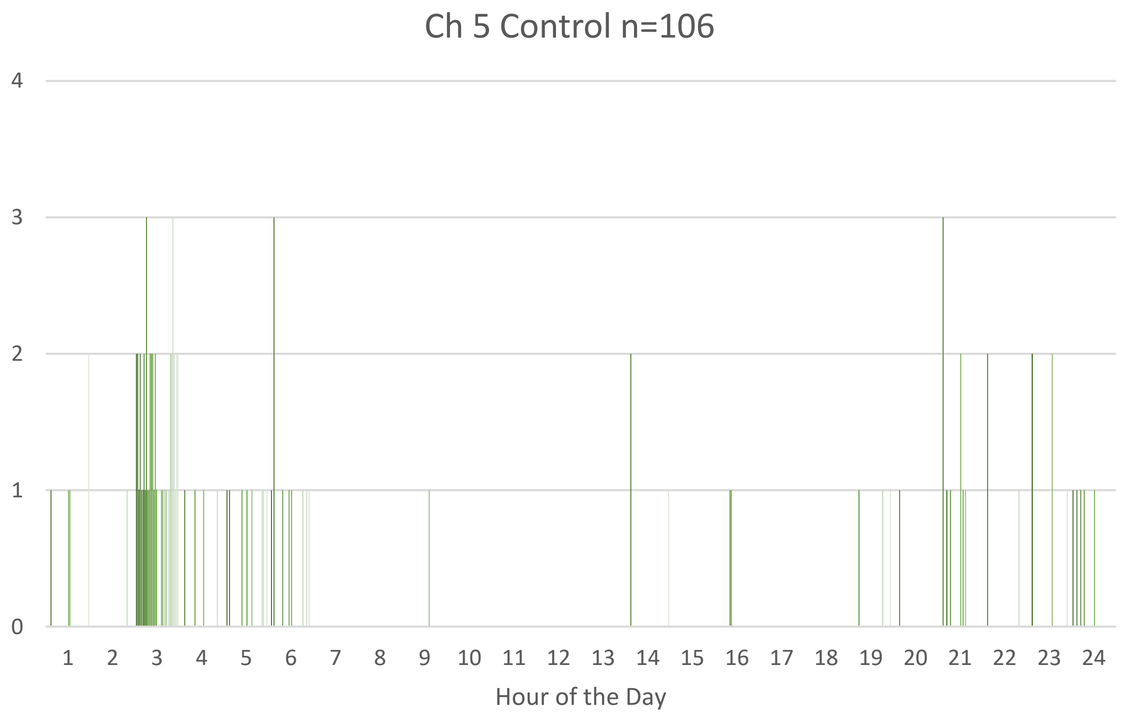
Preliminary Movement Patterns

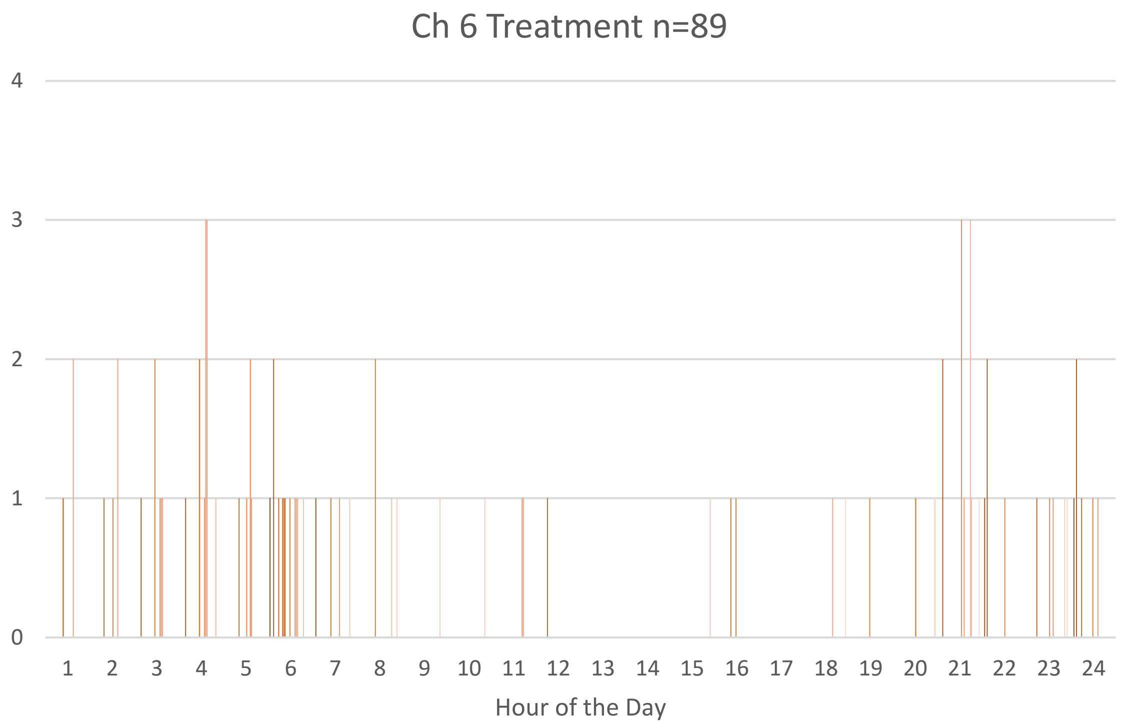




Chris Adams, PhD
Michigan Technological University

Preliminary Movement Patterns





Chris Adams, PhD
Michigan Technological University

Effects of Short-Term Flow Reductions on Juvenile Rainbow Trout

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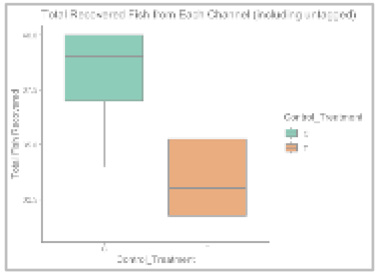
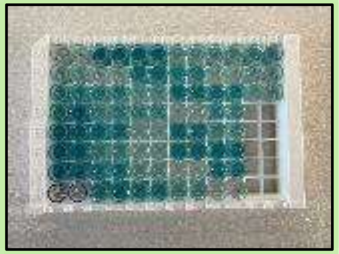
2. Question and Experimental Approach



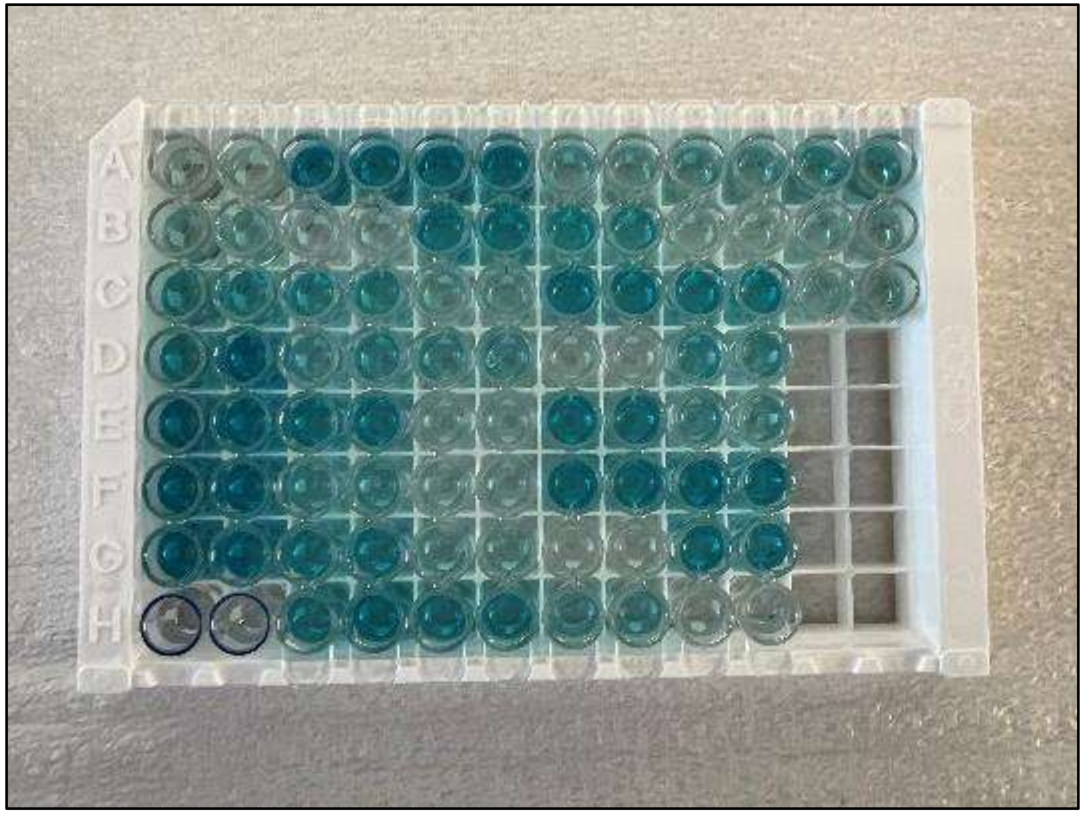
3. Results



4. Next Steps

5. Conclusions

Whole-Body Cortisol



Nick Hudson
MS Student at UC Davis

Liver Glycogen

Aquatic Macroinvertebrates

Effects of Short-Term Flow Reductions on Juvenile Rainbow Trout

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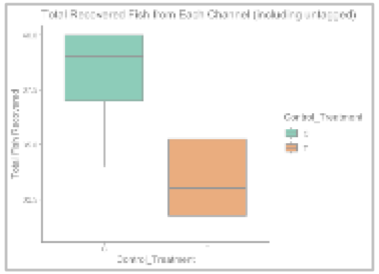

3. Results

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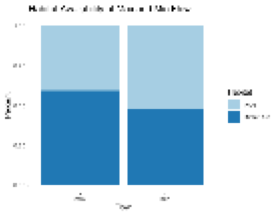
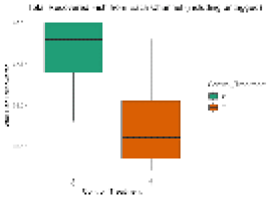
How do repeated short-term flow reductions affect juvenile *O. mykiss*?

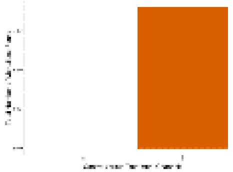
Reduced riffle/run habitat



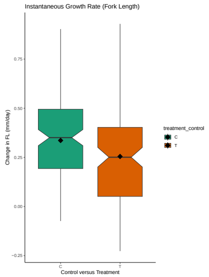
Reduced survival



Increased mortality



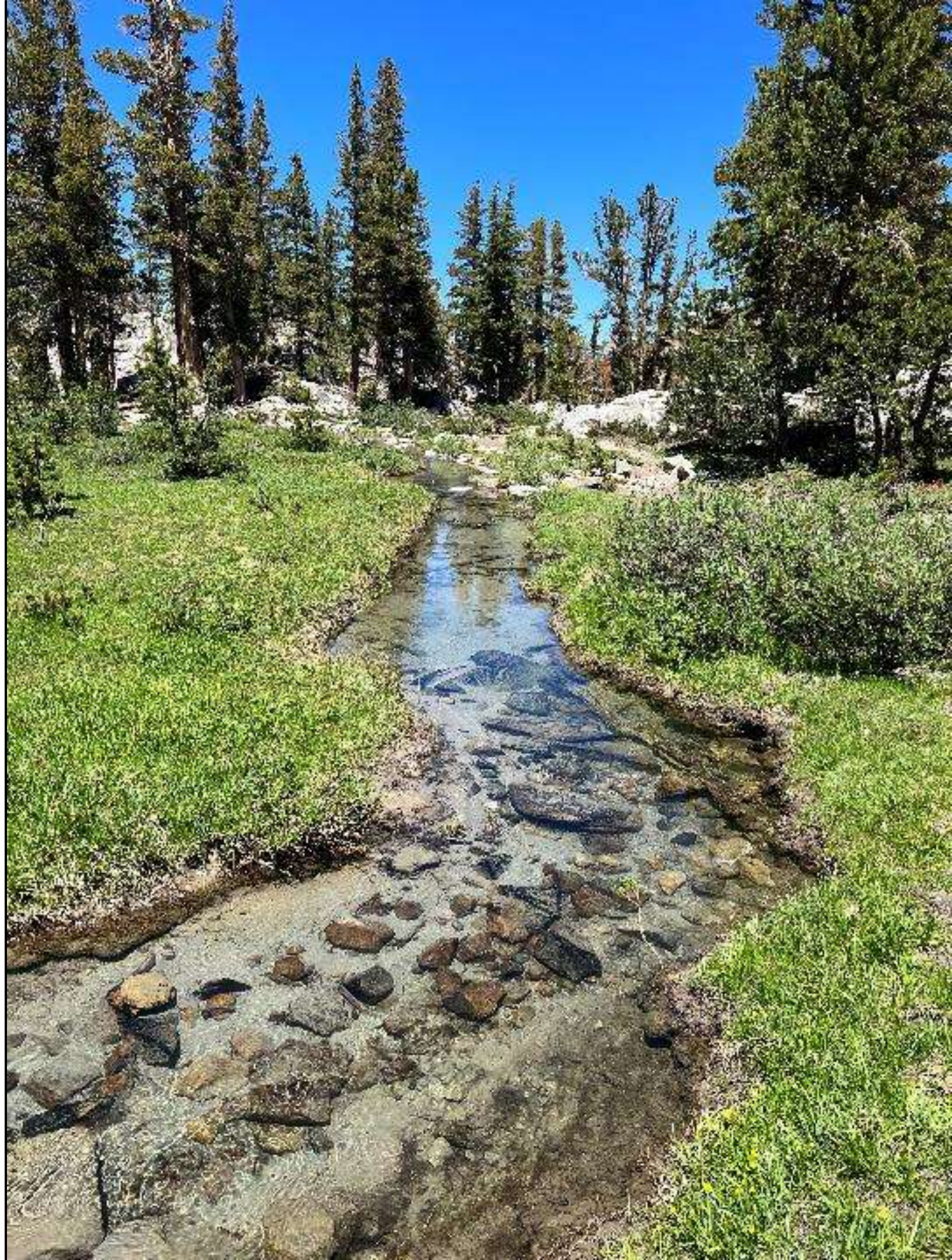
Reduced growth rates



Impacts

- Inform conservation and management practices

- Ensure continued protection of freshwater habitats and the species that depend upon them



Acknowledgements

- Rob Lusardi at UC Davis
- Bob Hawkins and the California Department of Fish and Wildlife
- Freshwater Ecology Lab at UC Davis – Claire Inouye, Alex Johanson, Sarah Howe, Kiliana Kato, Caroline Gengo
- Chris Adams
- Nick Hudson
- Nann Fangue
- Sarah Yarnell
- Andrew Rypel
- California Fly Fishers Unlimited
- Diablo Valley Fly Fishing Club
- Images created using BioRender

Thank You! Questions?

kgoeddem@ucdavis.edu