Climate Change Impacts on Groundwater Recharge

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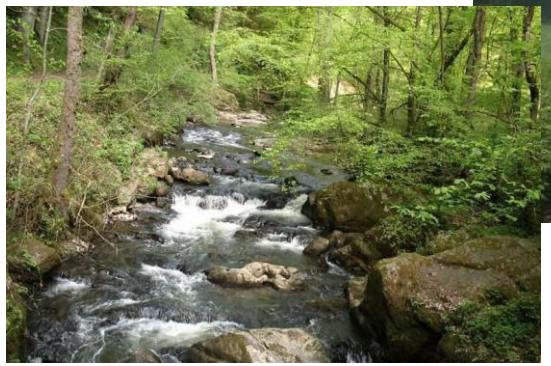
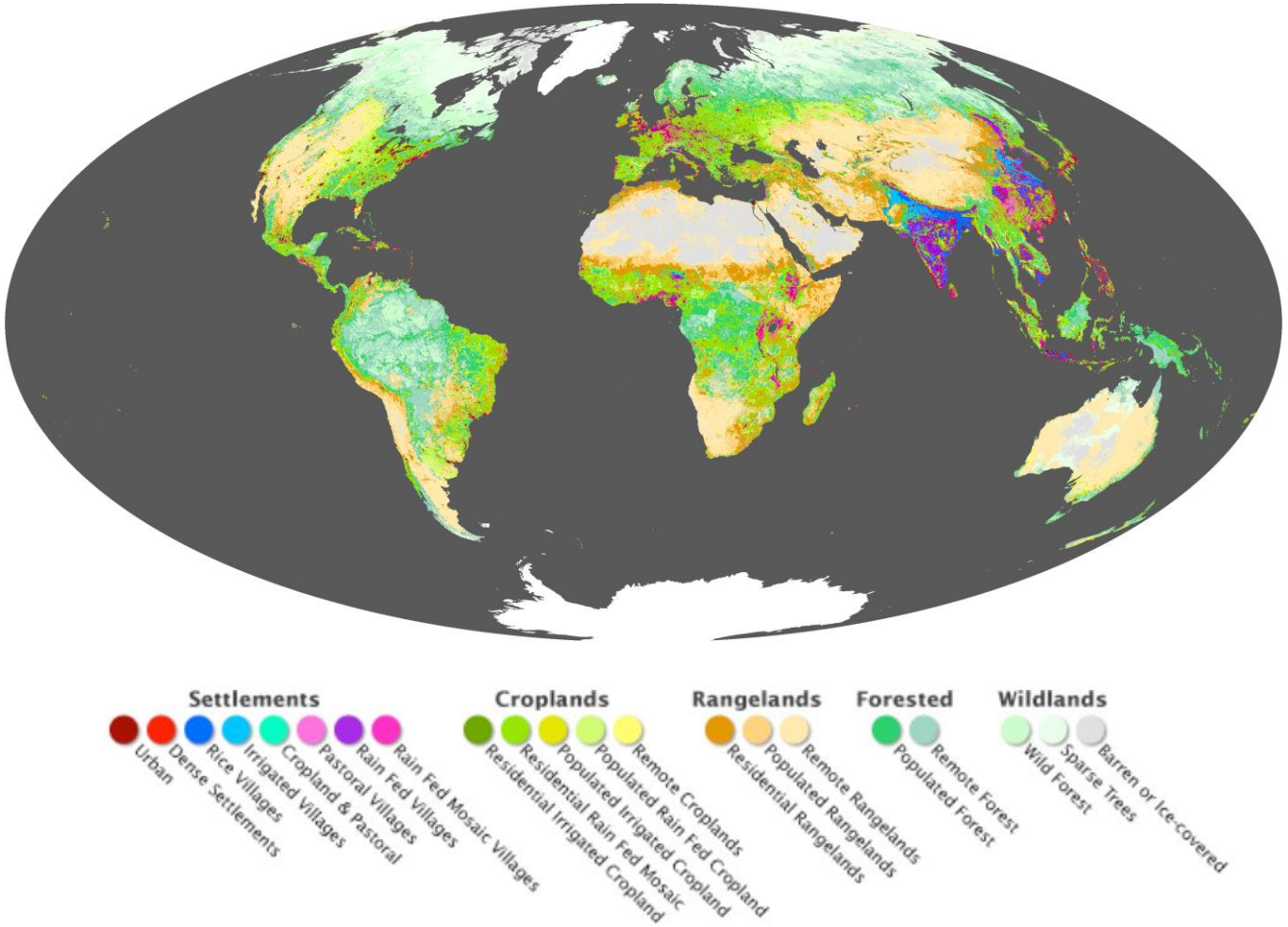


Upper San Pedro Partnership Technical Committee Meeting **May 17, 2023**

Human alterations to terrestrial ecosystems have created "anthropogenic biomes".

Human activities are shaping ecosystem dynamics in addition to geology and climate.



https://earthobservatory.nasa.gov/images/40554/human-ecosystems

(Ellis and Ramankutty.2008. *Front. Ecol. Environ*)

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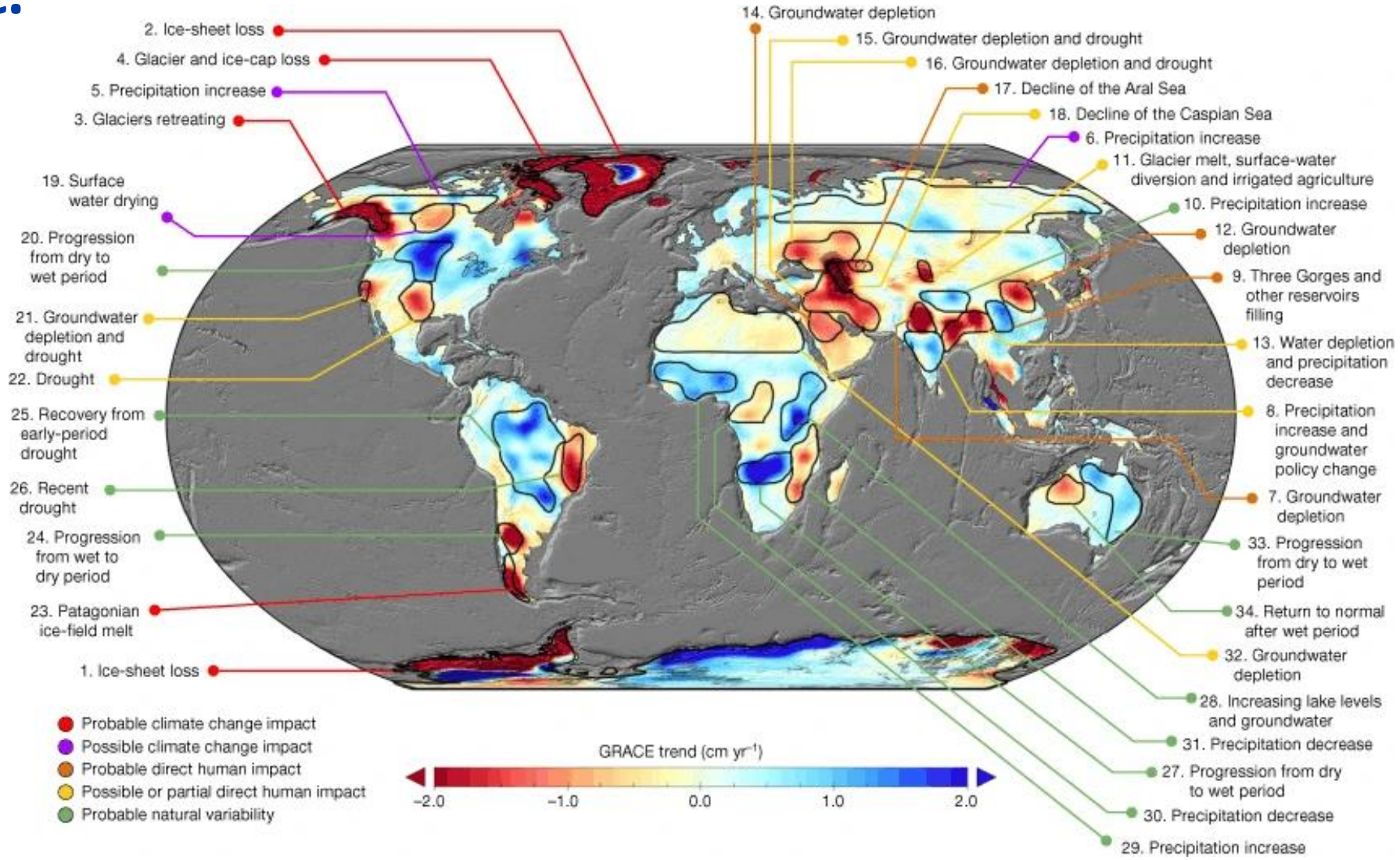
Freshwater availability is impacted by human activities and climate change.

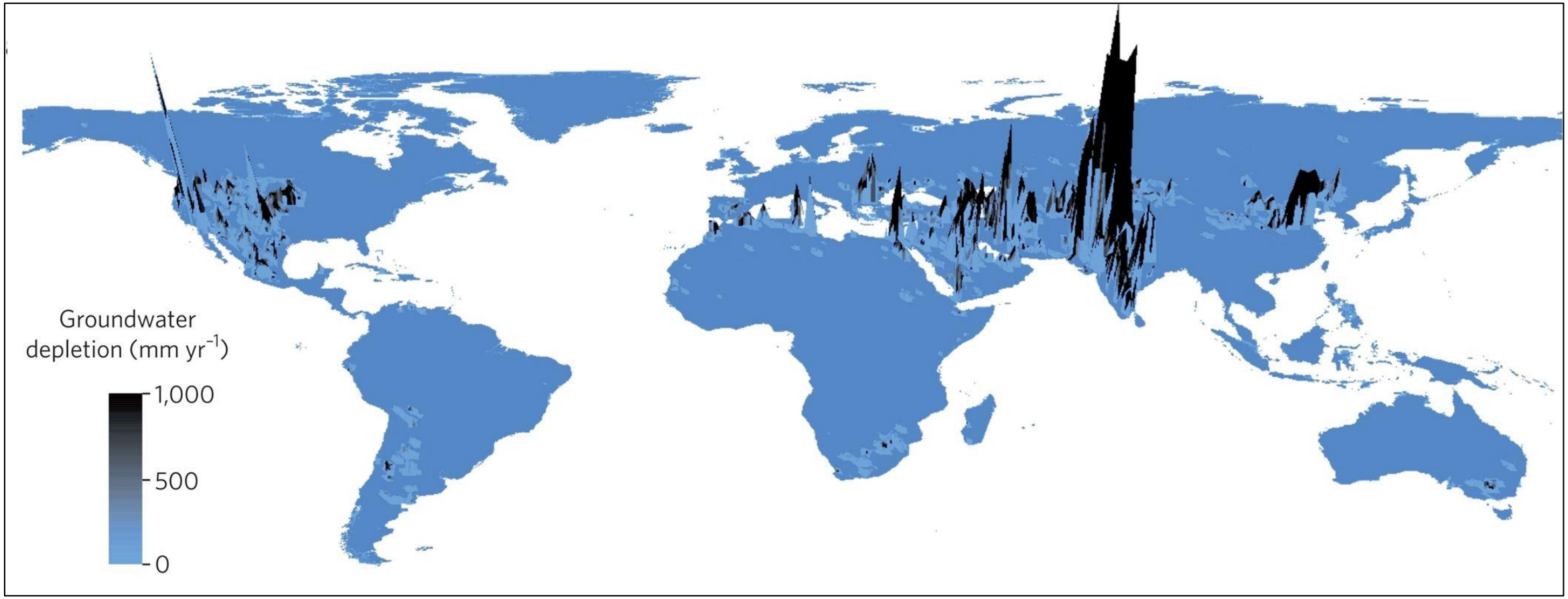


Trends in TWS (in cm/yr) from GRACE observations (April 2002 to March 2016).

Rodell et al.2018. *Nature*

Water extraction for irrigation is the main cause of groundwater depletion.

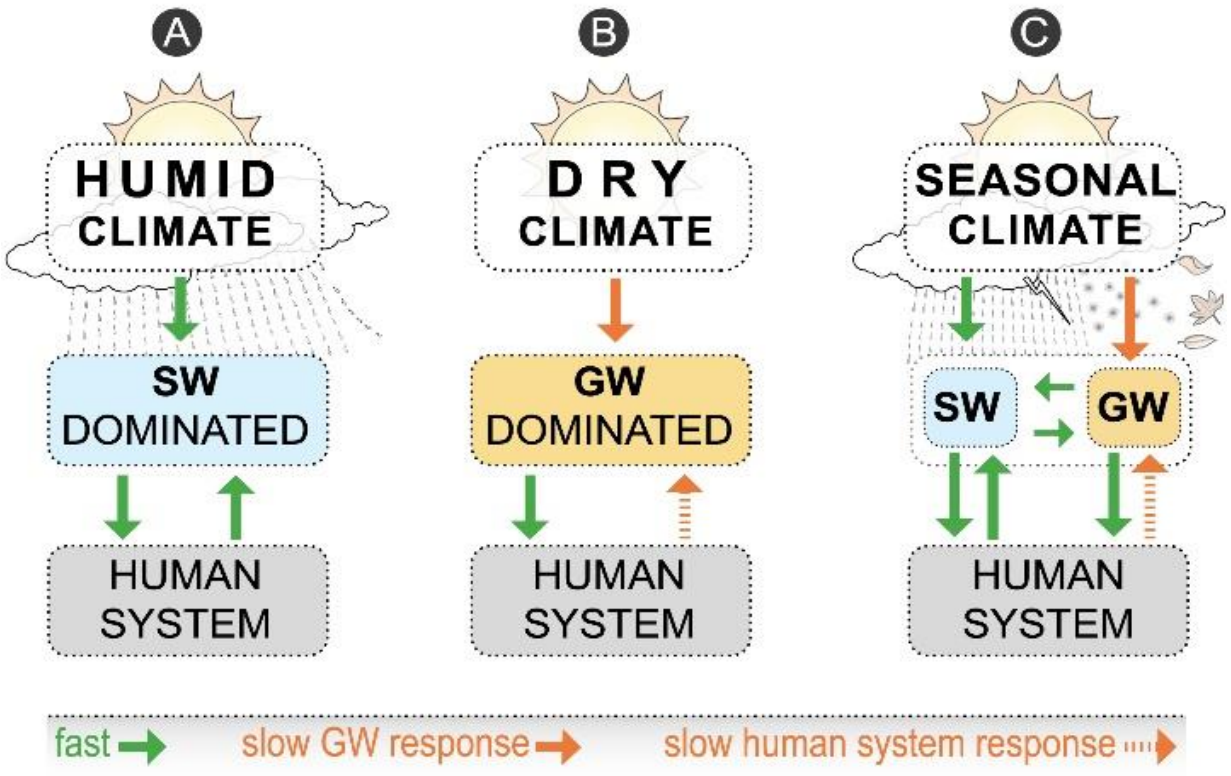
Global distribution of groundwater depletion



Aeschbach-Hertig and Gleeson.2012. *Nature Geoscience*

Understanding climate-groundwater feedbacks in coupled natural-human systems are complex.

- Groundwater flow is slow and aquifers have long residence times.
- Detection of climate and human-induced stresses on groundwater resources are challenging.
- Degree of surface water-groundwater connectivity determines system response.



Ajami et al. *In Preparation*

Holman.2006. *Hydrogeology Journal*; Konikow.2015. *Ground water*; Green et al. 2011. *Journal of Hydrology*

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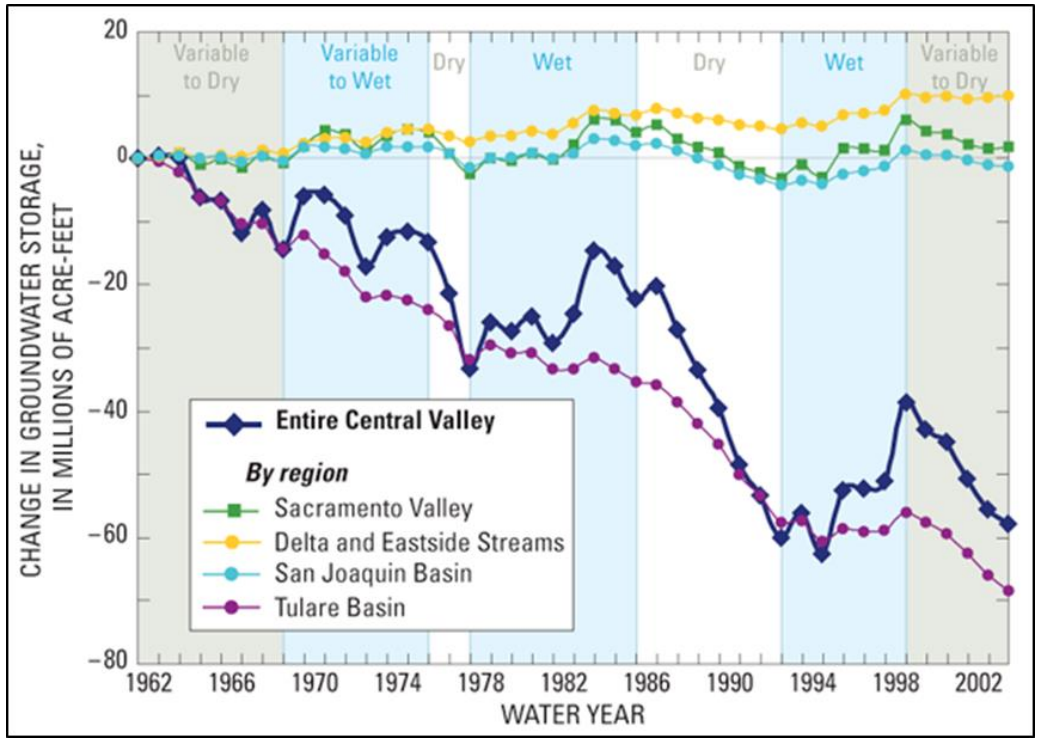
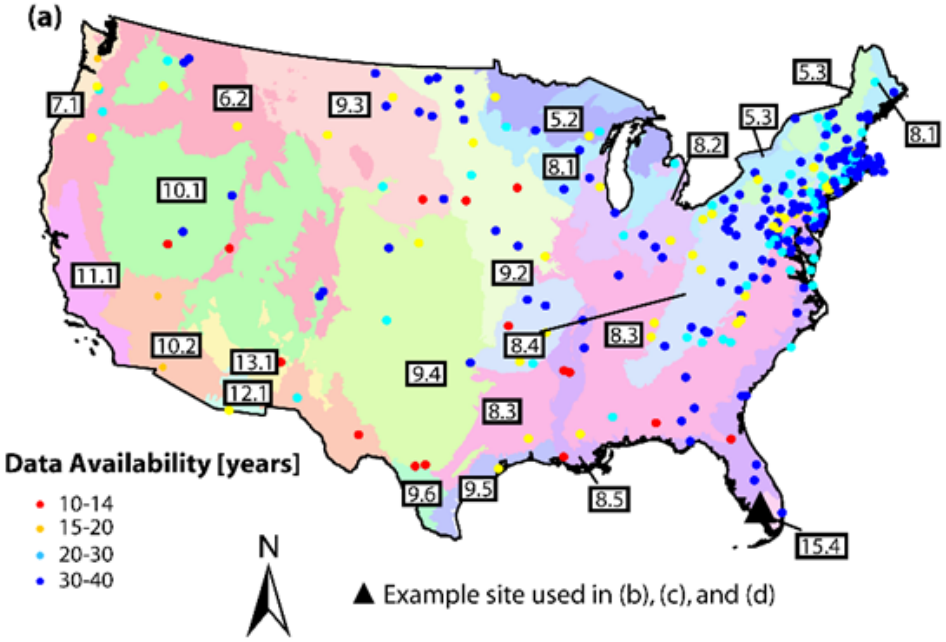
Understanding meteorological drought impacts on groundwater response time is important.

- What is the time lag between precipitation drought and groundwater drought?
- How do watershed properties control the time lag?
- How long does it take for aquifers to recover from a drought?



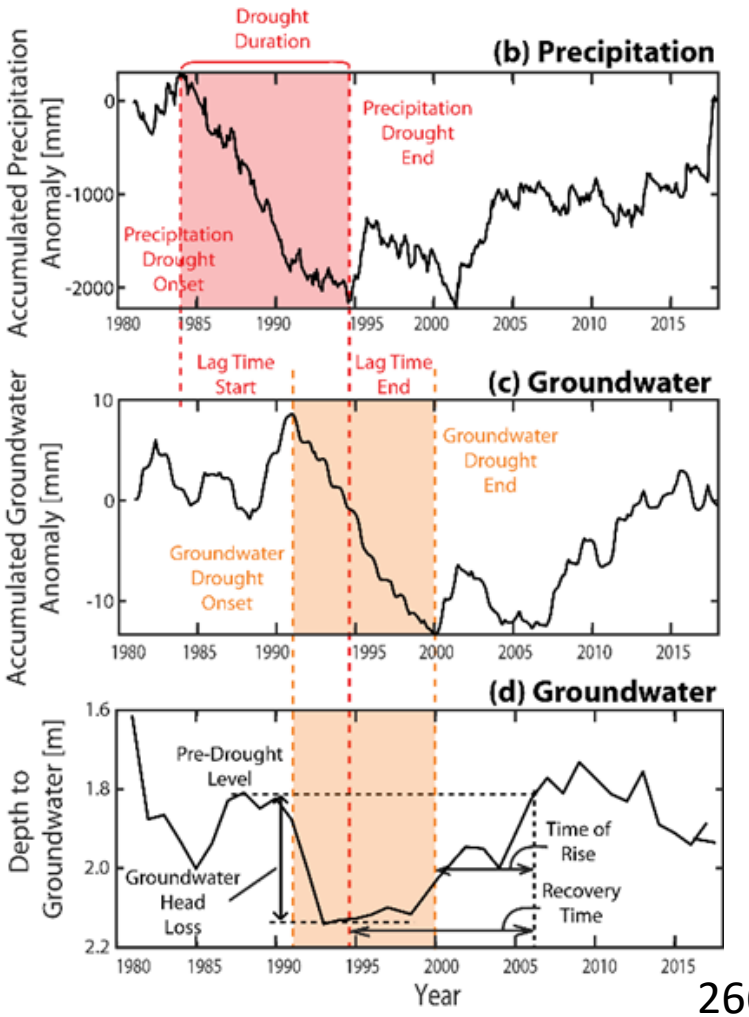
Faunt.2009. *USGS*

Matching a precipitation drought with a corresponding drought in groundwater level data remains a challenge.



Ecoregions

- 5.2 Mixed Wood Shield
- 5.3 Atlantic Highlands
- 6.2 Western Cordillera
- 7.1 Marine West Coast Forest
- 8.2 Central USA Plains
- 8.3 Southeastern USA Plains
- 8.4 Ozark-Appalacian Forests
- 8.5 Mississippi and Southeastern USA Plains
- 9.2 Temperate Praries
- 9.3 West-Central Semiarid Praries
- 9.4 South-Central Semiarid Praries
- 9.5 Texas-Louisiana Coastal Plain
- 9.6 Tamaulipas-Texas Semiarid Plain
- 10.1 Cold Deserts
- 10.2 Warm Deserts
- 11.1 Mediterranean California
- 12.1 Western Sierra Madre Piedmont
- 13.1 Upper Gila Mountains
- 15.4 Everglades



Groundwater Level

- Observation wells in Climate Response Network (USGS)
- Unconfined aquifers
- Not impacted by pumping or other human activities
- Multiple years of data

Precipitation

- PRISM dataset
- Daily precipitation totals

266 observation wells with 10 years of data

Schreiner-McGraw & Ajami. *2021. Journal of Hydrology*

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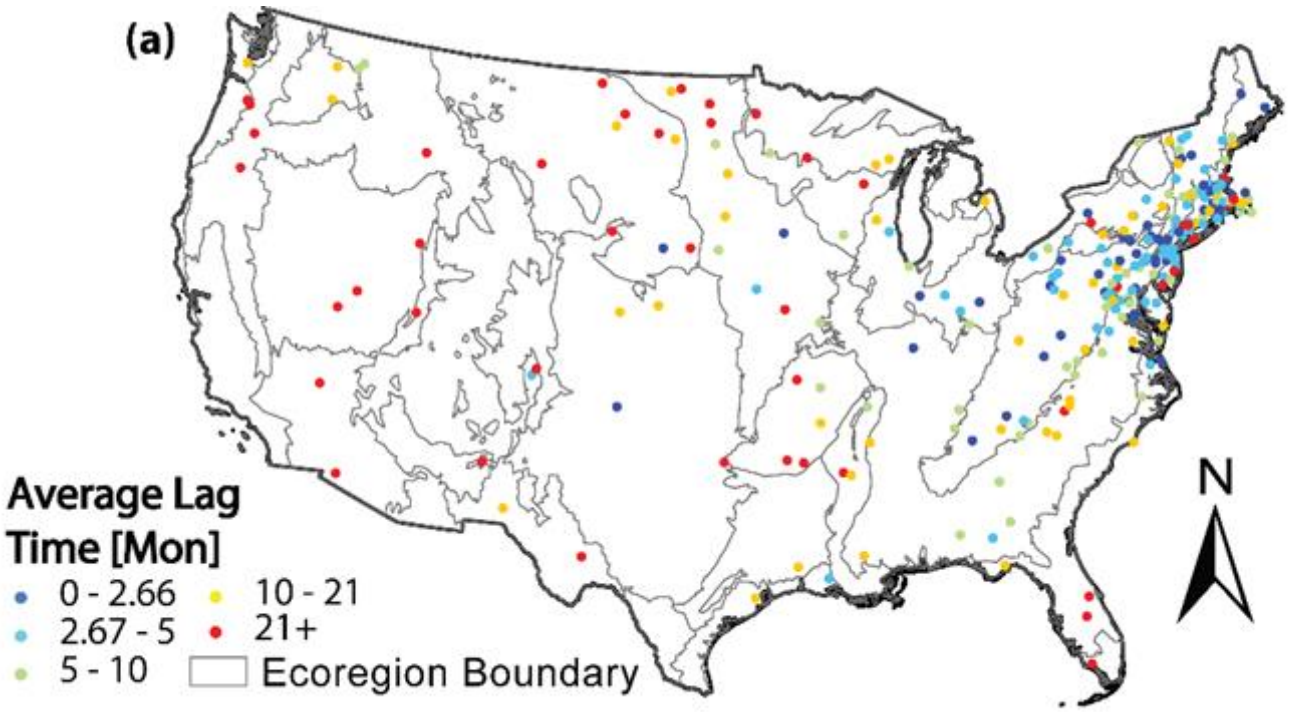
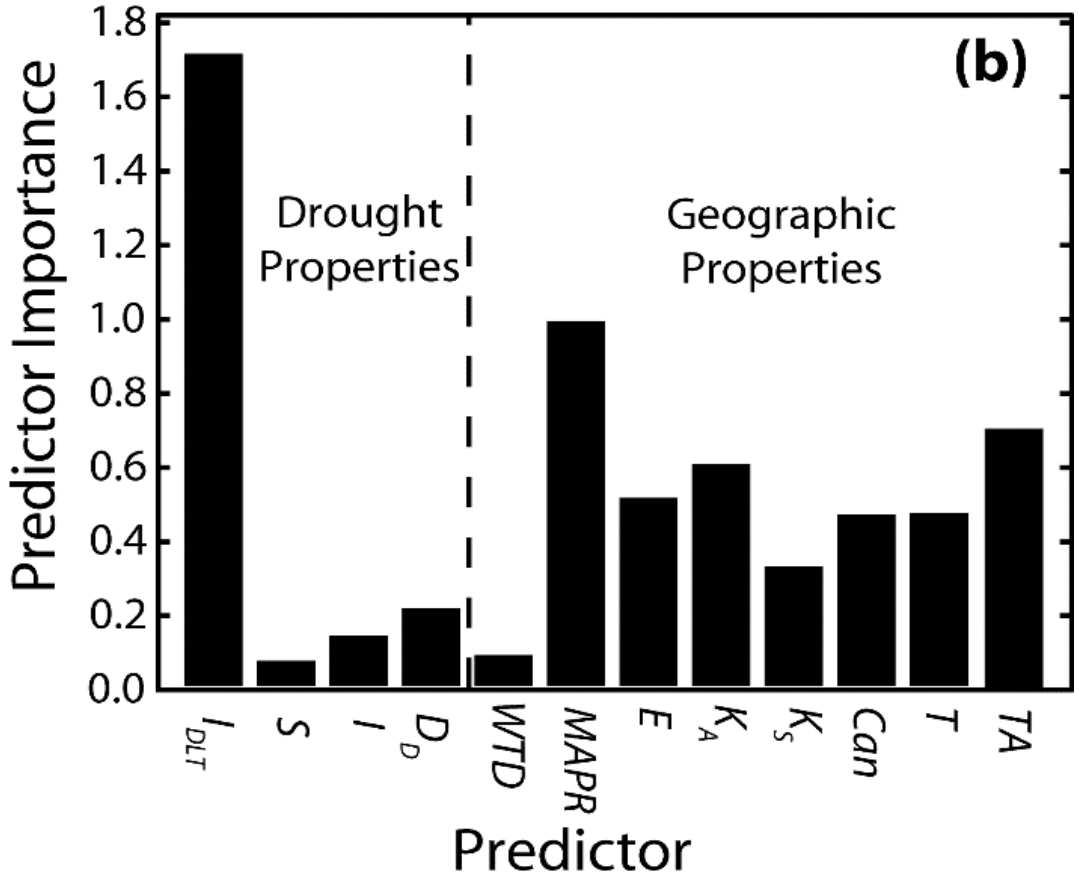
The lag time between changes in precipitation and groundwater level is highly variable.



- Lag time at the start of a drought ranges from 1 to 185 months (mean = 20 months).
- Majority of wells have relatively short lag time (<24 months).
- Lag times are shorter in the eastern US.

Schreiner-McGraw & Ajami. *2021. Journal of Hydrology*

A random forest model is developed to identify important factors controlling groundwater lag time.



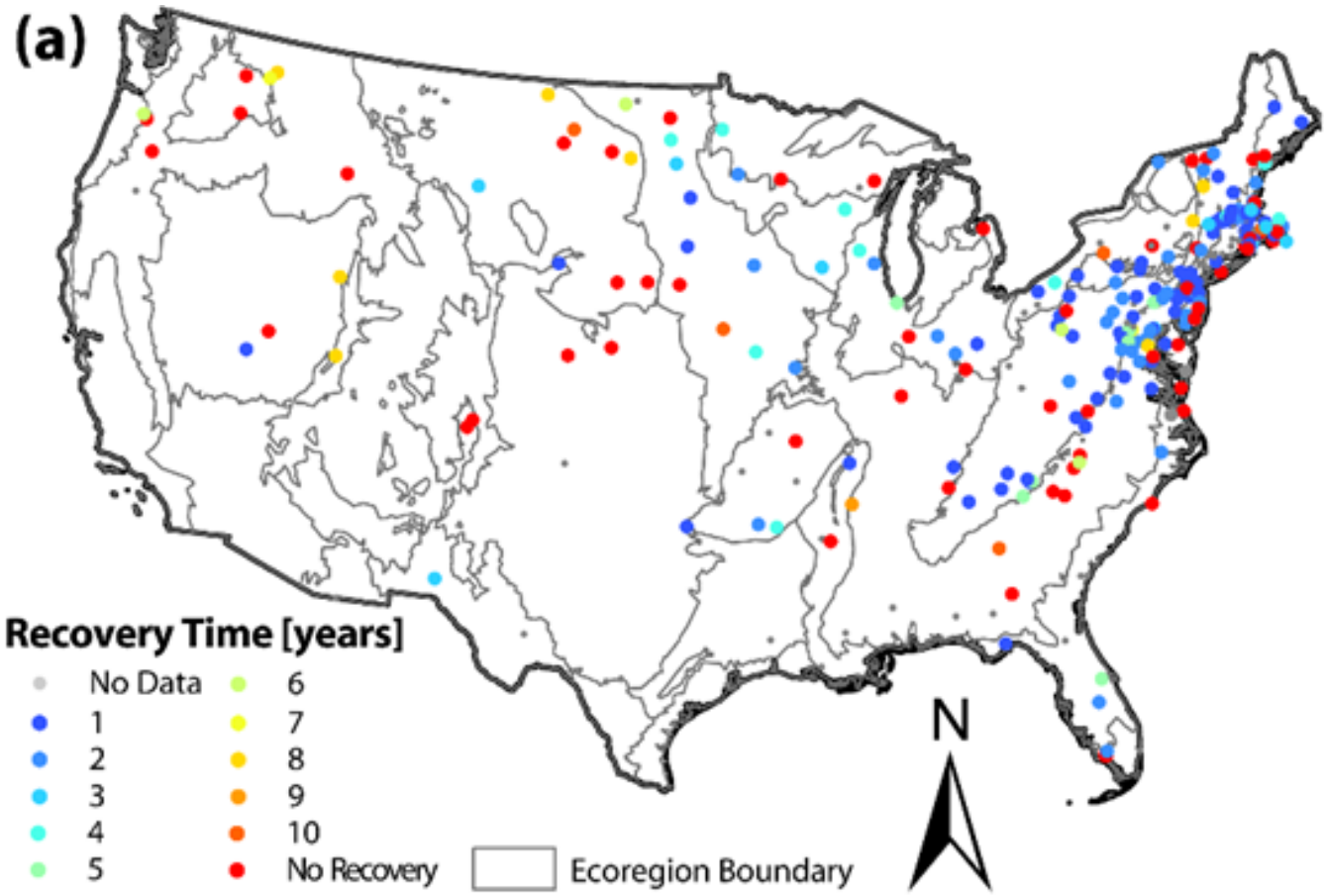
Drought intensity during lag time (I_{DLT})
Drought severity (S)
Drought intensity (I)
Drought duration (D_D)

Depth to Water Table (WTD)
Mean annual recharge (MAPR)
Elevation (E)
Hydraulic conductivity - aquifer (K_A)
Hydraulic conductivity - soil (K_S)
Canopy cover (Can)
Transmissivity (T)
Air temperature (TA)

Schreiner-McGraw & Ajami. *2021. Journal of Hydrology*

Average groundwater recovery time is 3 years.

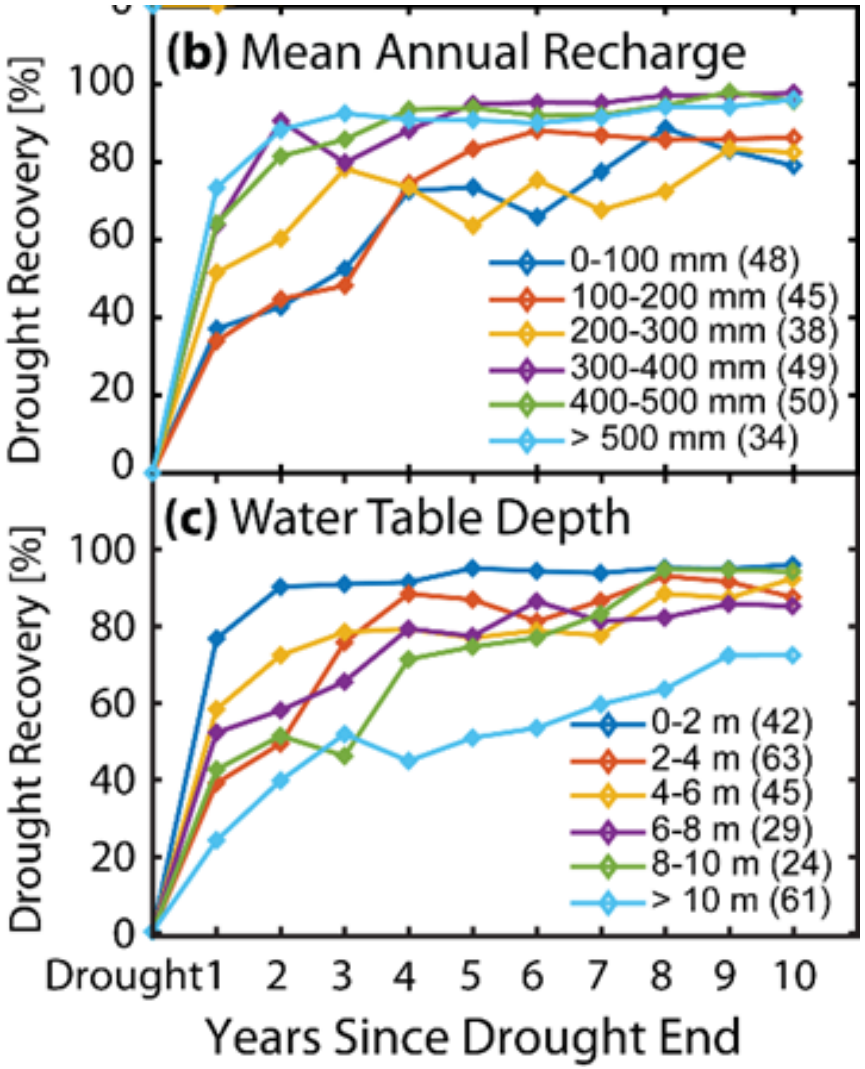
- For 85% of droughts, groundwater recovers within 10 years.



Schreiner-McGraw & Ajami. *2021. Journal of Hydrology*

Groundwater recovery pathways are controlled by mean annual recharge and average water table depth.

- At sites with MAPR < 200 mm/yr: recovery is less than 50% in the first three post-drought years.
- Greater WTD alters the recovery trajectory and increases the groundwater recovery time with increased vadose zone thickness.



Schreiner-McGraw & Ajami. *2021. Journal of Hydrology*

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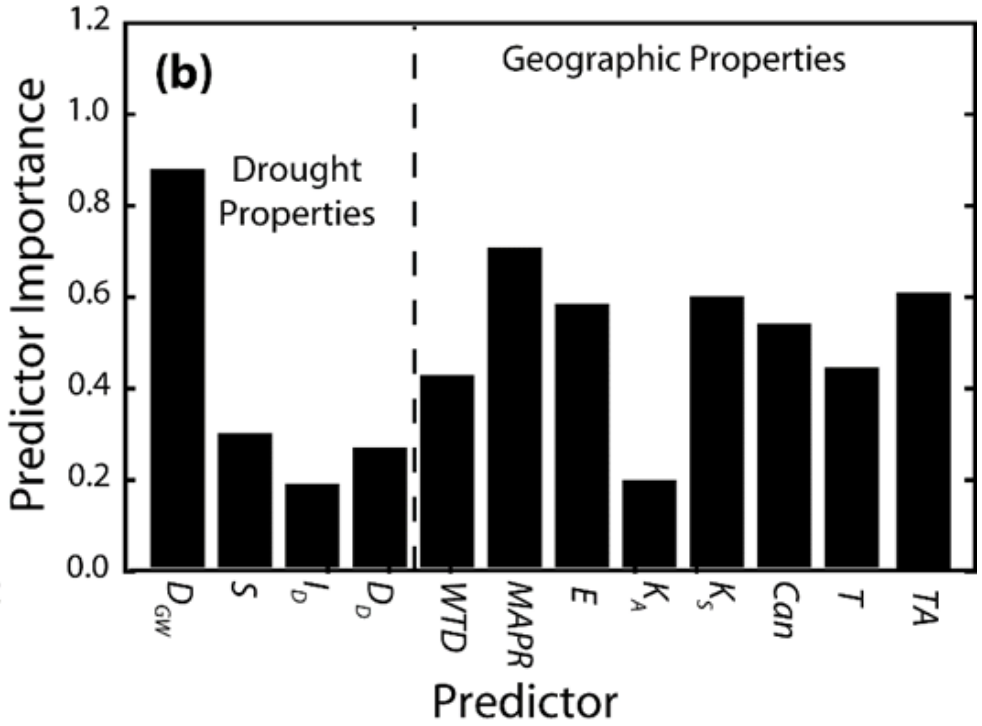
Magnitude of groundwater depletion during drought controls recovery time.

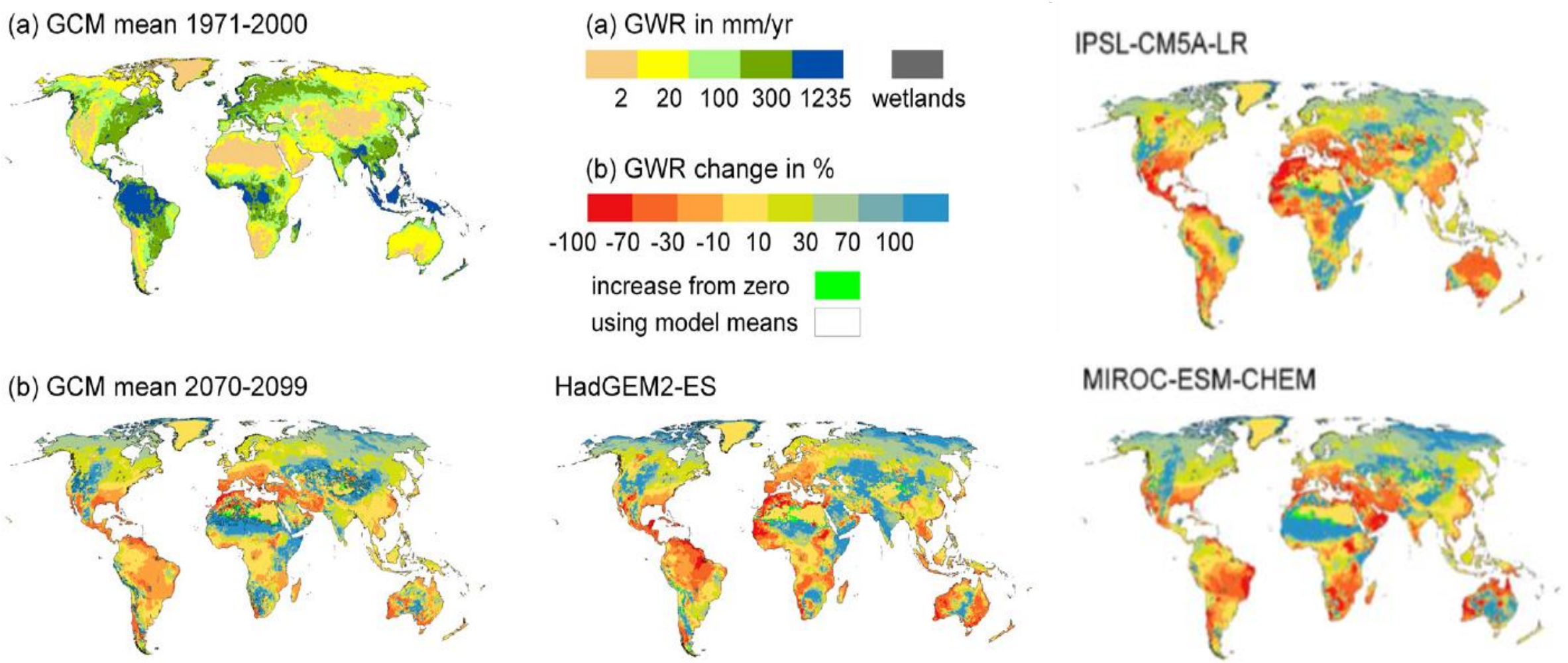


- Groundwater depletion is controlled by drought severity.
- If climate change increases drought severity, aquifer recovery will increase in the future, although potential increases in extreme precipitation may offset the impact.

Schreiner-McGraw & Ajami. *2021. Journal of Hydrology*

Accurate estimates of groundwater recharge is key in determining groundwater recovery process.

Groundwater recharge-WaterGAP model



Portmann et al.2013. *Environmental Research Letters*

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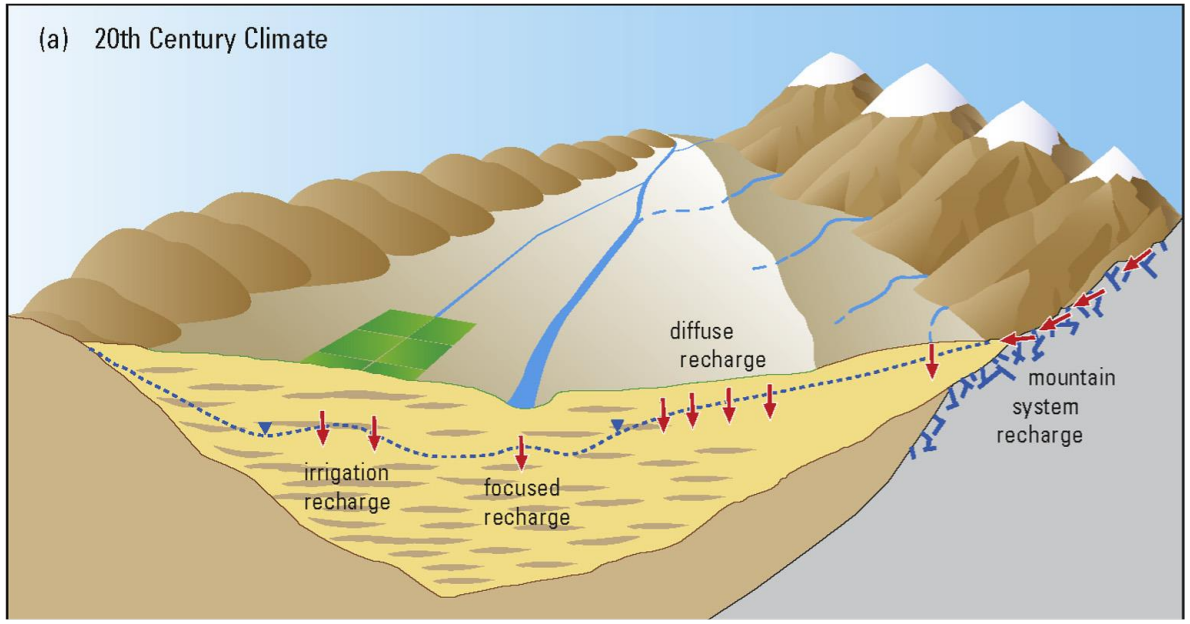
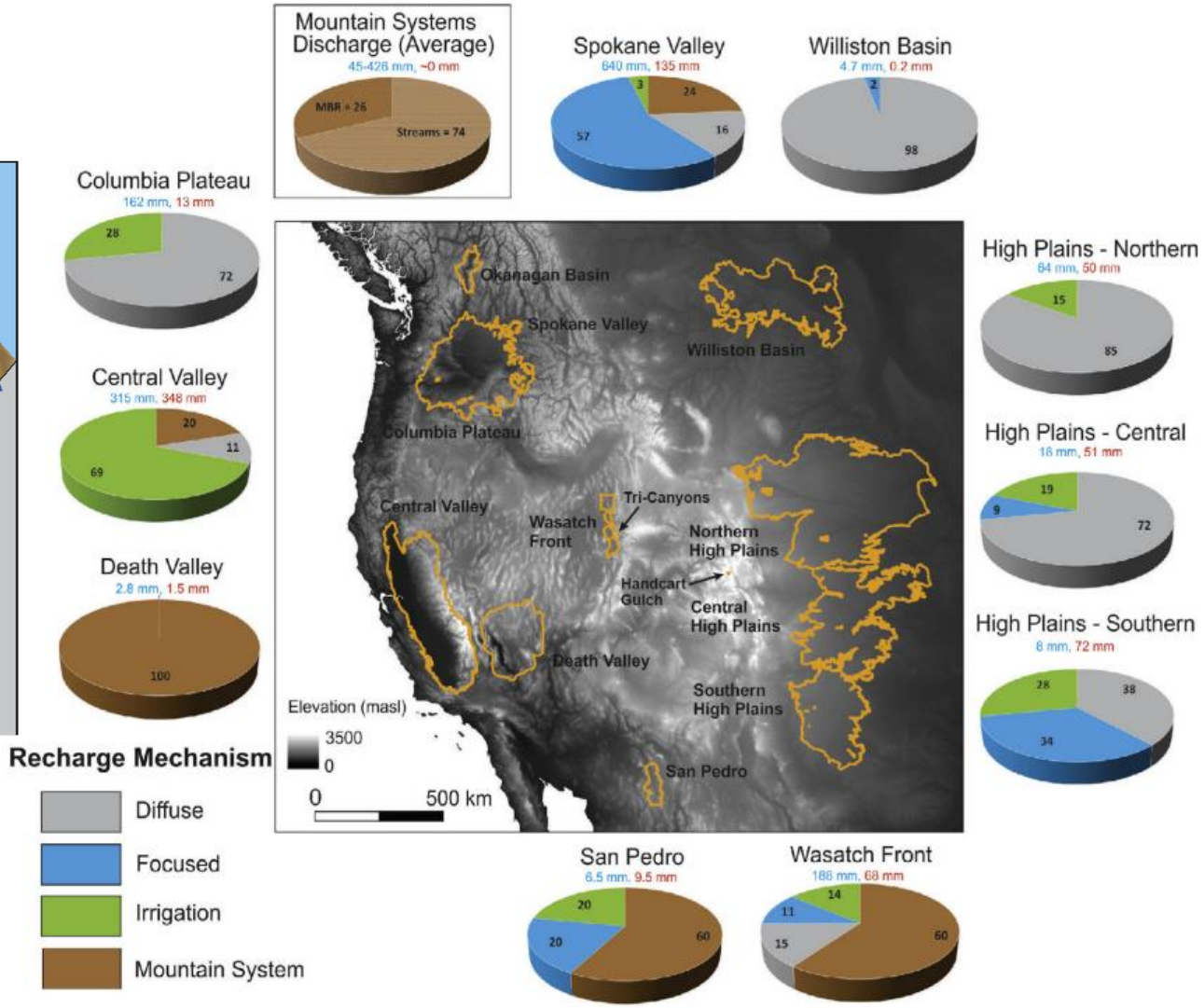
Groundwater recharge partitioning varies among major aquifers.





Meixner et al.2016. *Journal of Hydrology*

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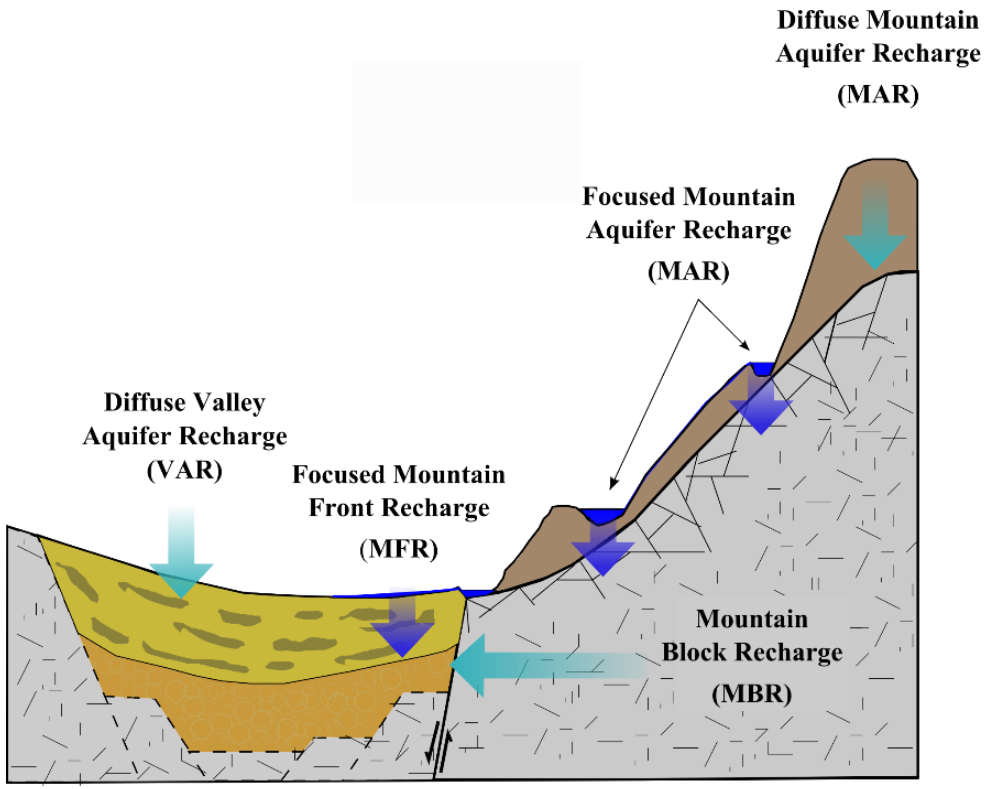
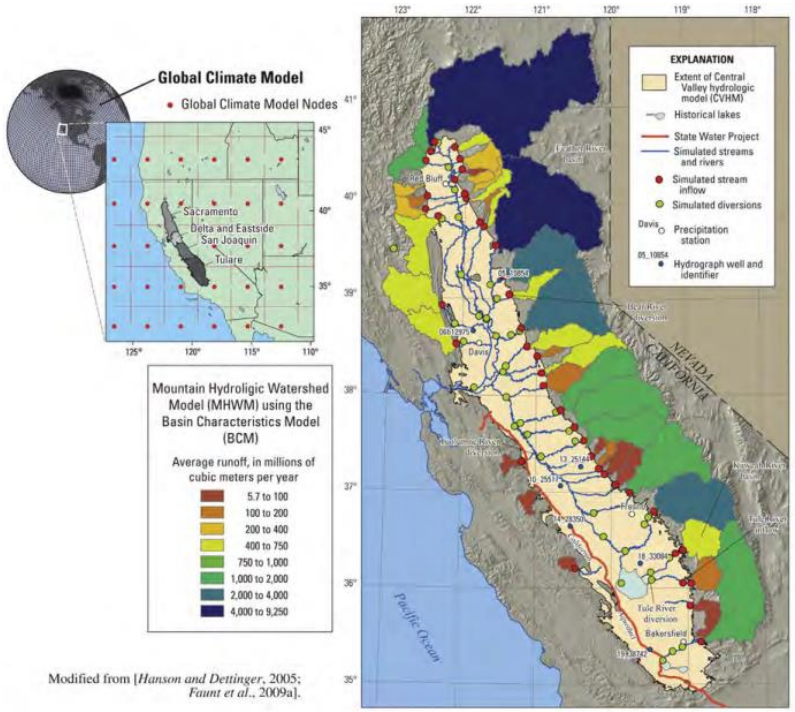
Mountain system recharge (MSR) contribution to valley-fill aquifers is uncertain.



Armengol et al. (In revision)



Hanson et al. (2012)

Mountain-Valley Systems

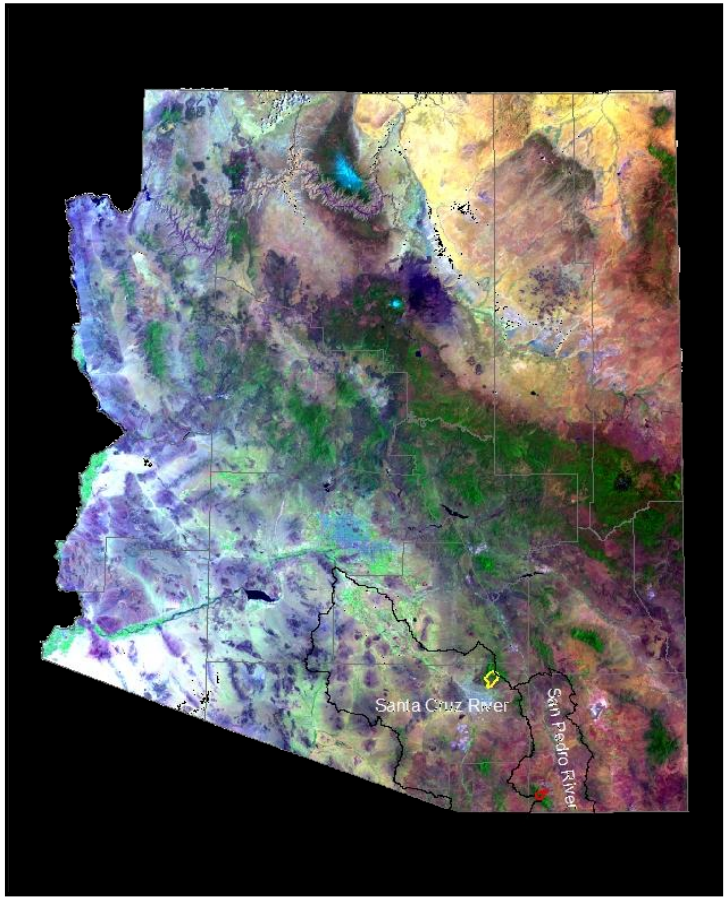
- Poorly understood
- Lack of monitoring
- Uncertain MFR/MBR

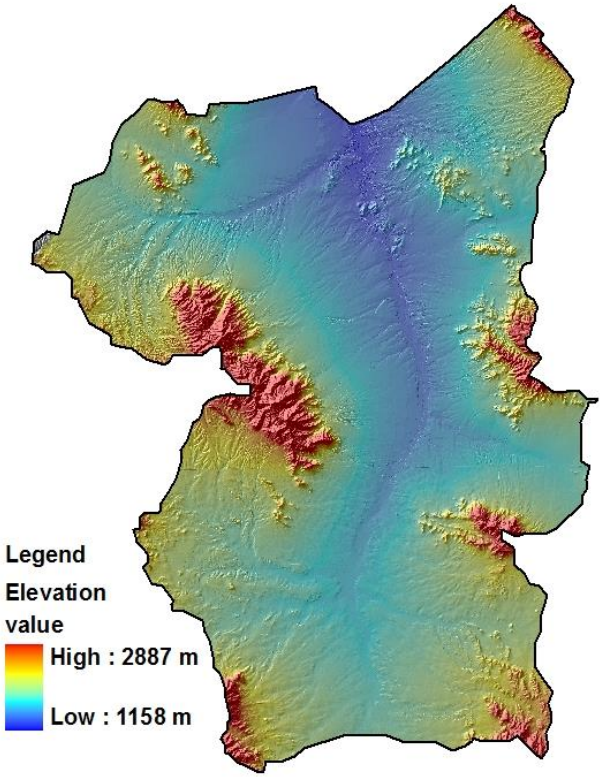
Armengol et al. *In Review*

Previous Approaches

- Empirical equations
- Valley-distributed
- Mountain-lumped

Case Study: Upper San Pedro Basin, Arizona





The Upper San Pedro basin is about 4500 km^2.

Mean annual precipitation is 41 cm.

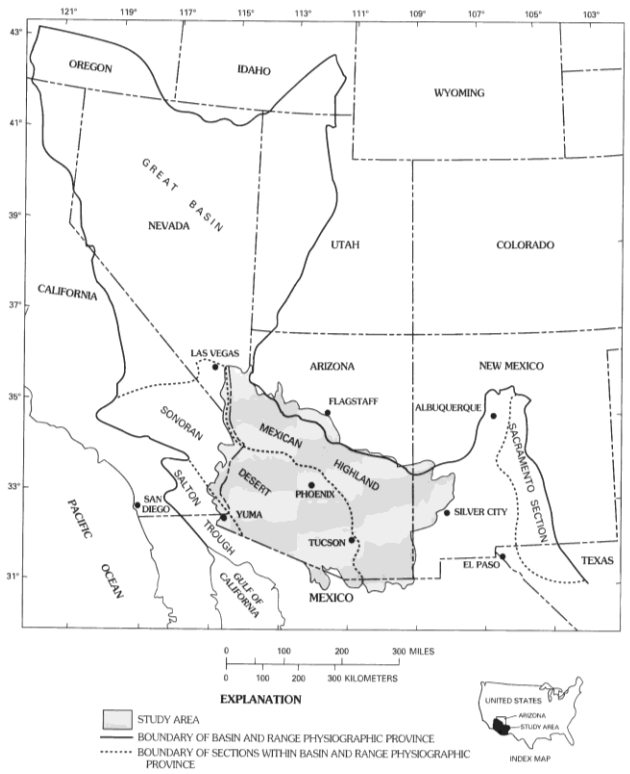
July through September are the wettest months.

Estimating MSR using empirical equations

Anderson Equation (1992):

$$MSR_a = 0.042(P_a - 203)^{0.98}$$

MSR_a: Annual recharge (mm/yr)
P_a: Annual precipitation (mm/yr)



Seasonalize MSR using existing models and data?

How to seasonalize annual MSR?

Seasonal MSR Ratios

(Isotopic data)

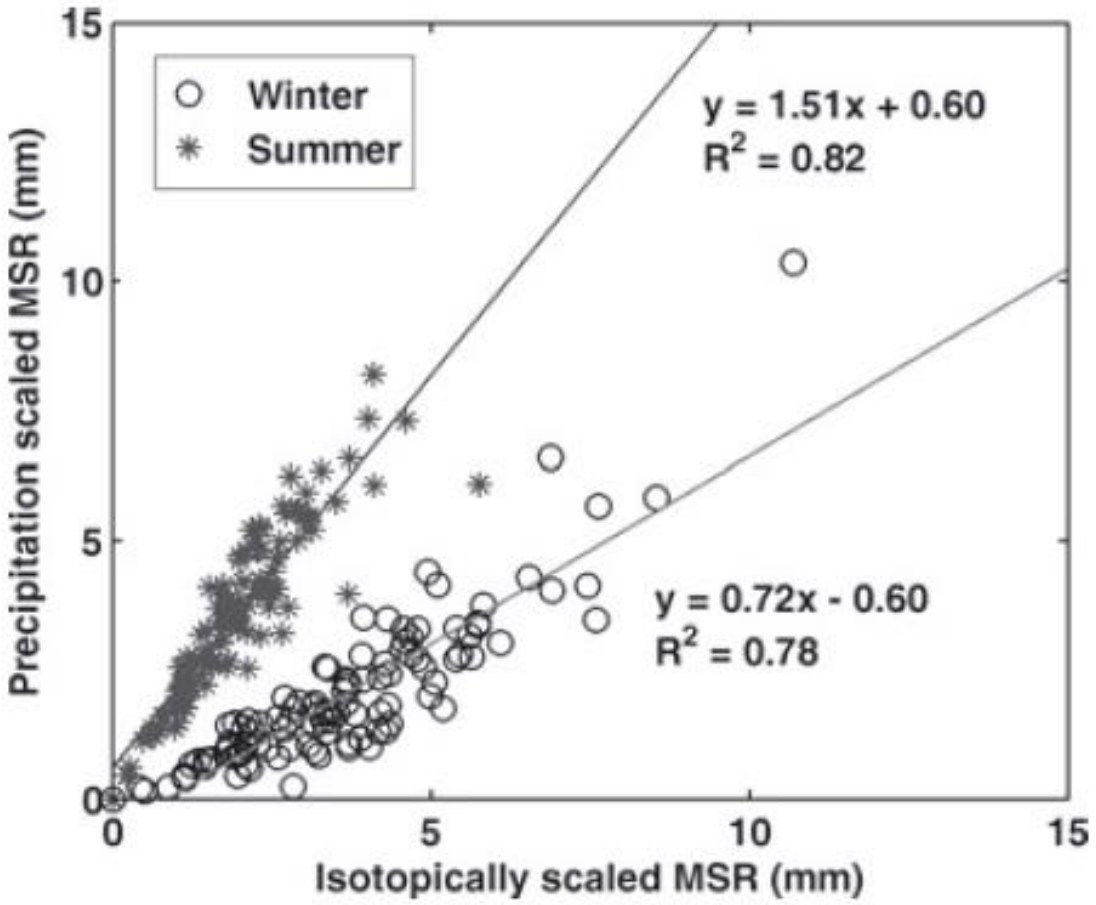
70% of MSR winter

(Wahi et al., 2008)

↓

Seasonal MSR Ratios

Seasonal precipitation ratios



Overestimates summer recharge

Ajami et al.2012. Groundwater

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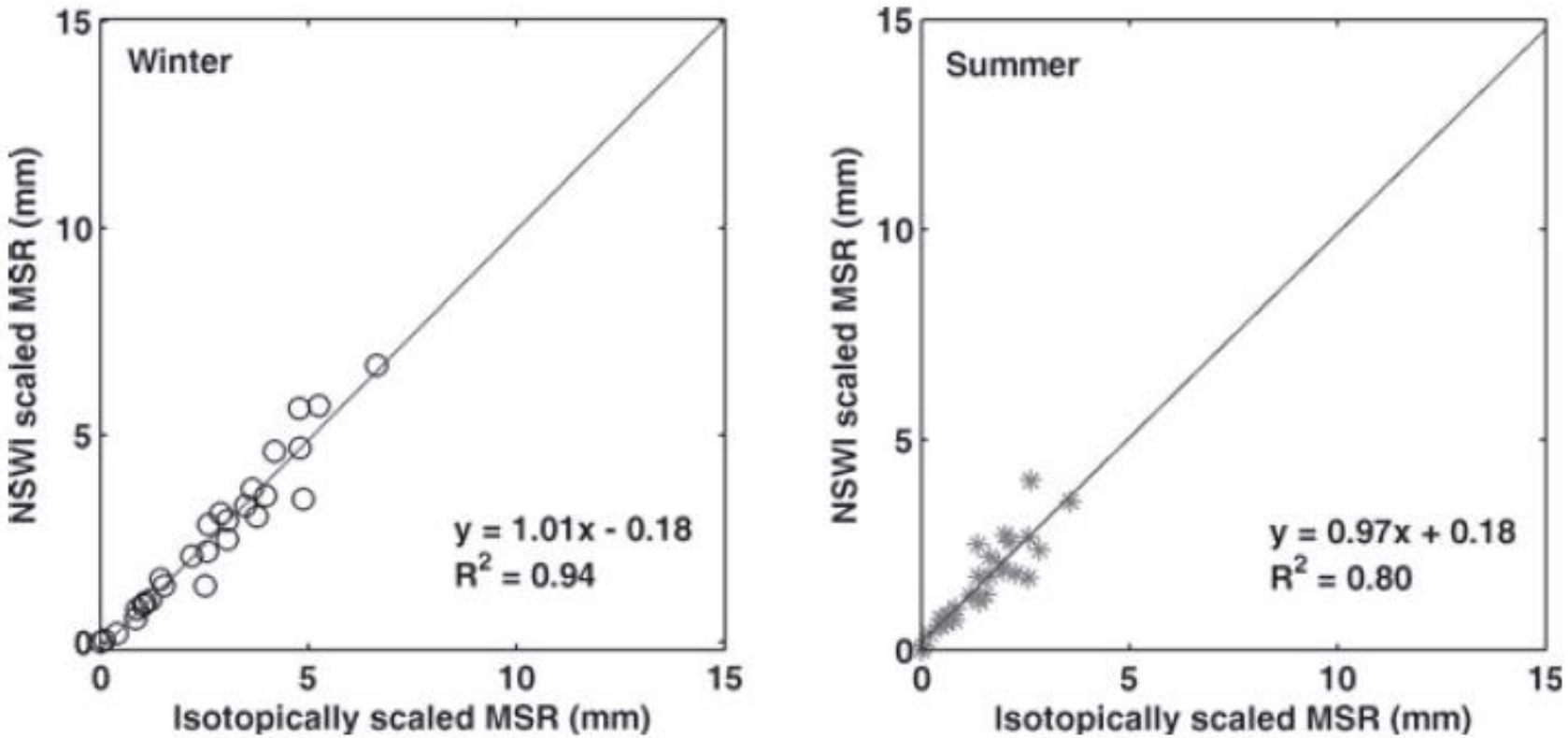
Normalized Seasonal Wetness Index



$$NSWI_{winter} = \frac{\left(\frac{P_{winter}}{AET_{winter}}\right)}{\left(\frac{P_{winter}}{AET_{winter}} + \frac{P_{summer}}{AET_{summer}}\right)}$$

Incorporating AET values improved MSR predictions especially in summer season.

Ajami et al. 2012. Groundwater

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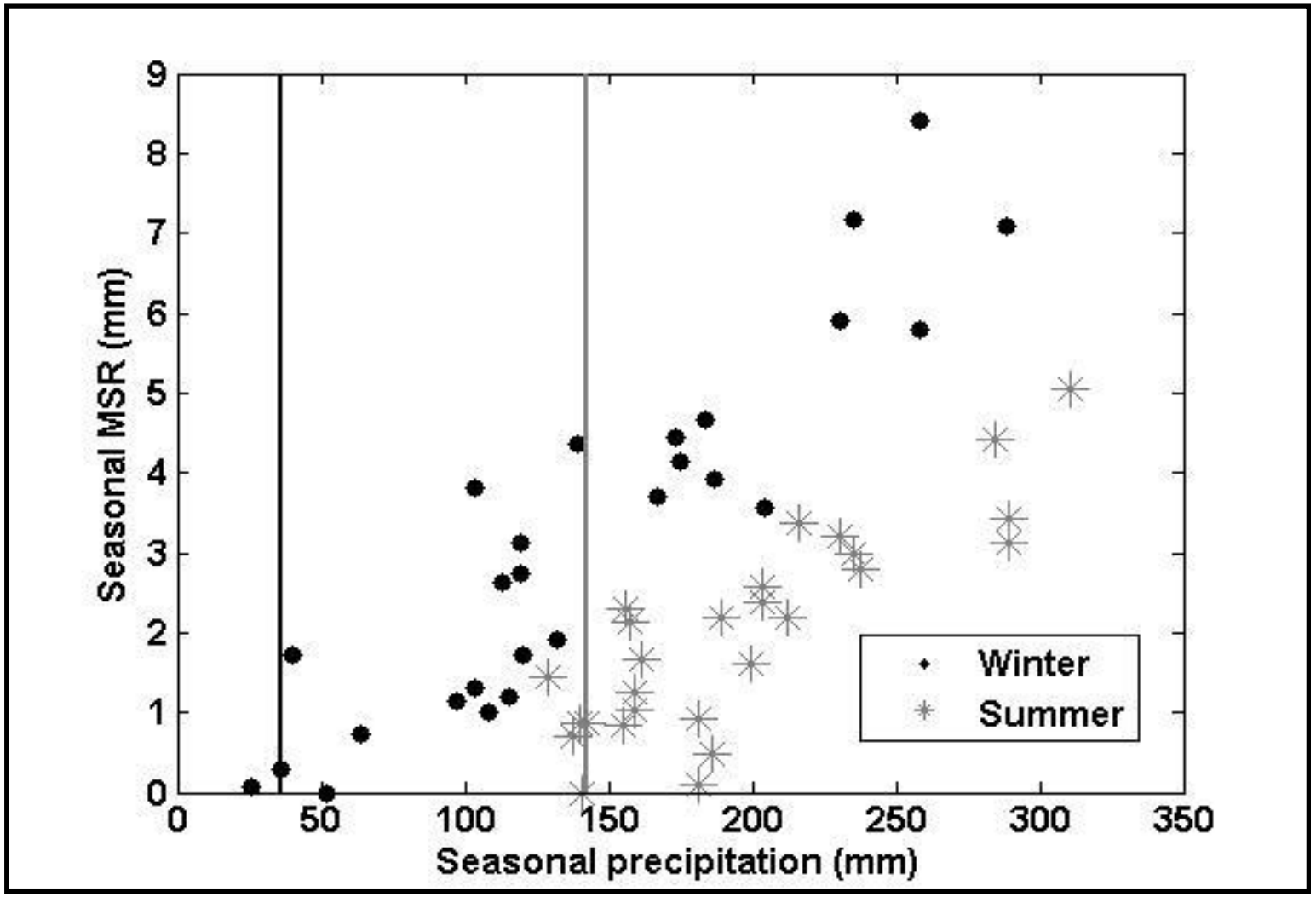
Seasonal precipitation thresholds in the USPR



Smaller precipitation thresholds in winter

Ajami et al. 2012. Groundwater

Climate change impacts on recharge depends on precipitation projections.

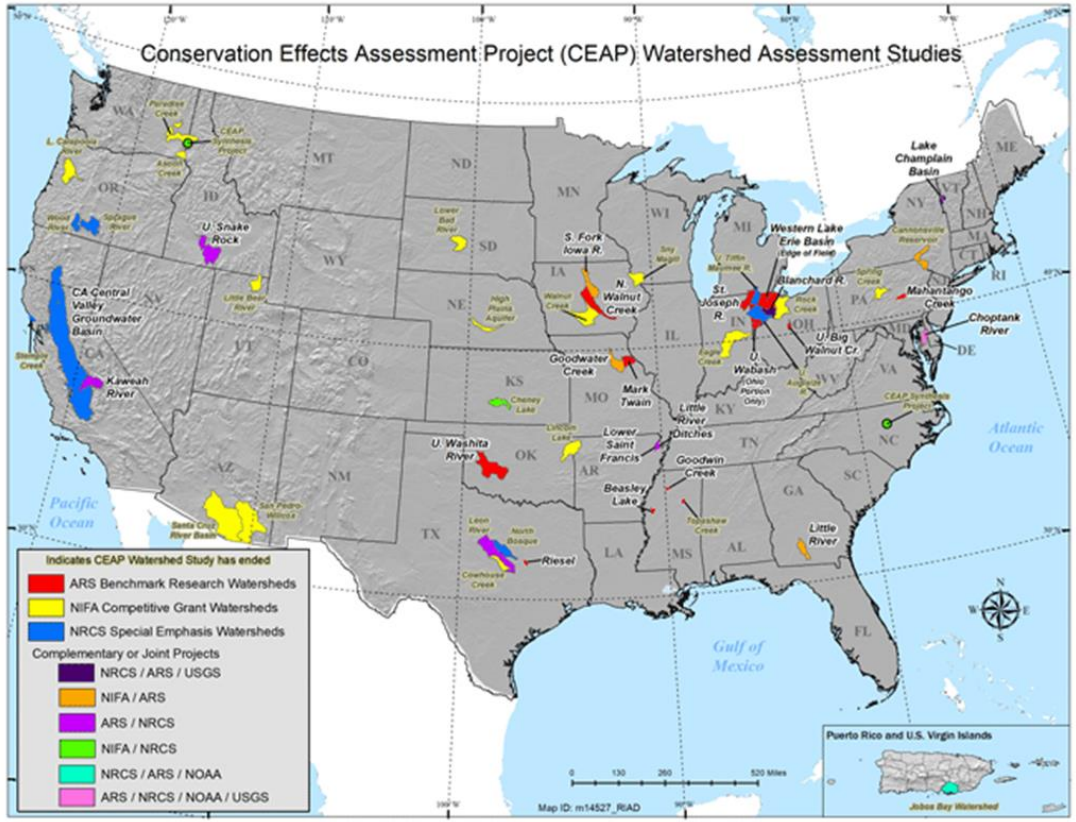
Table 3
Percent Change in Potential Evapotranspiration, Precipitation, and Recharge Based on Change Between Historic Mean (1950–2000) and Predicted Mean (2050–2099)

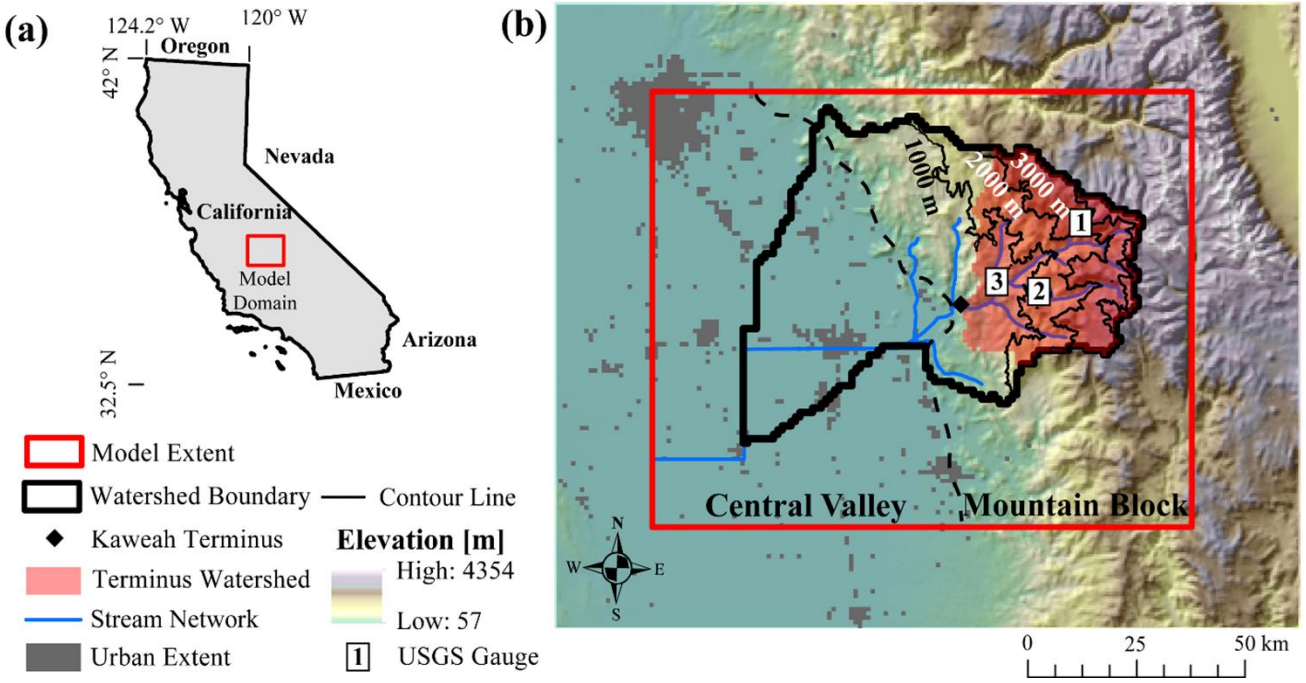
Scenarios	PET_a	P_a	MSR_a	PET_w	P_w	MSR_w	PET_s	P_s	MSR_s
ECHAM5-A1B	24*	−14*	−27*	32*	−1	−23*	20*	−21*	−32*
ECHAM5-A2	24*	−10*	−20*	32*	−2	−18	20*	−15*	−23*
ECHAM5-B1	18*	−5	−9	23*	5	−6	15*	−10*	−13
HadCM3-A1B	22*	0	0	29*	−7	−8	18*	4	8
HadCM3-A2	23*	7	15	29*	5	8	20*	9*	22*
HadCM3-B1	17*	−5	−10	23*	−9	−13	14*	−3	−6

*Mean difference between historic and predicted values are statistically significant ($p < 0.05$).

Ajami et al. 2012. Groundwater

Kaweah River watershed is part of the CEAP watershed network.





Watershed area: 4000 Km^2

USDA NRCS
United States Department of Agriculture
Natural Resources Conservation Service

Schreiner-McGraw & Ajami. *2020. Water Resources Research*

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Accurate estimates of recharge depends on meteorological forcing.

Water Resources Research

RESEARCH ARTICLE
10.1029/2020WR027639

Key Points:
- Uncertainty in simulated groundwater storage change is a result of topographic redistribution of uncertainty in precipitation forcing
- Subsurface flow pathways in both soil and deeper bedrock control watershed response to variable precipitation input
- Merging multiple precipitation data sets provides better results than merging simulated fluxes, due to high model sensitivity to changes in precipitation

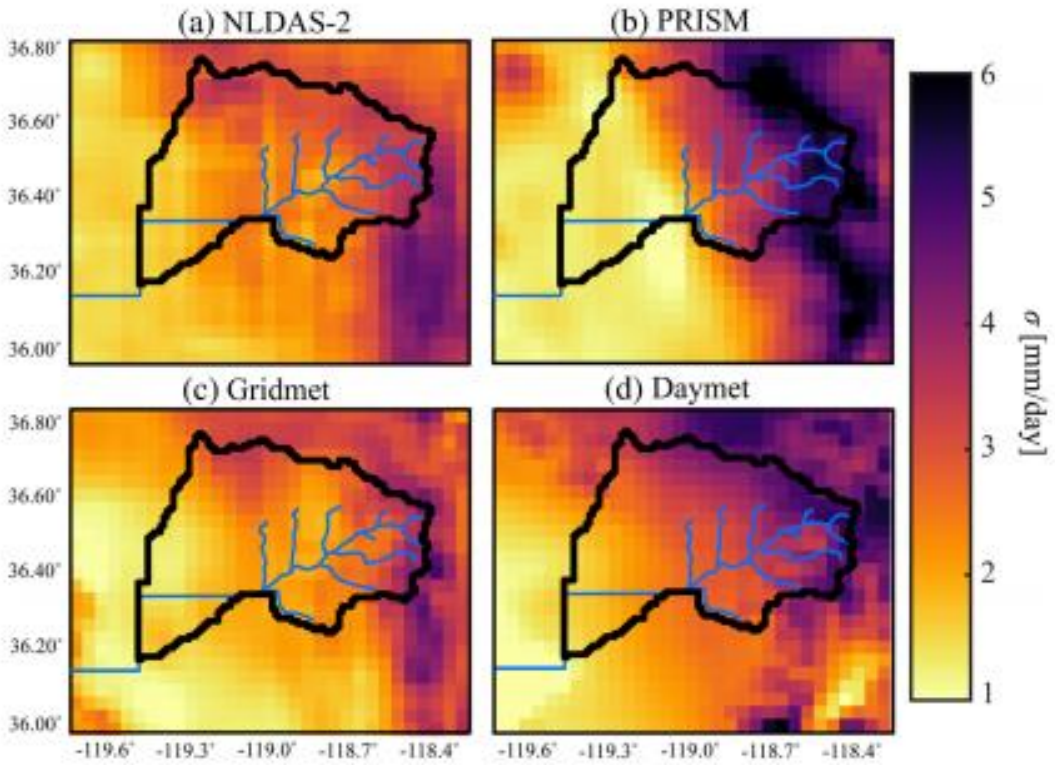
Supporting Information:
- Supporting Information S1

Impact of Uncertainty in Precipitation Forcing Data Sets on the Hydrologic Budget of an Integrated Hydrologic Model in Mountainous Terrain

Adam P. Schreiner-McGraw[1] and Hoori Ajami[1]

[1]Department of Environmental Sciences, University of California, Riverside, CA, USA

Abstract Precipitation is a key input variable in distributed surface water-groundwater models, and its spatial variability is expected to impact watershed hydrologic response via changes in subsurface flow dynamics. Gridded precipitation data sets based on gauge observations, however, are plagued by uncertainty, especially in mountainous terrain where gauge networks are sparse. To examine the mechanisms via which uncertainty in precipitation data propagates through a watershed, we perform a series of numerical experiments using an integrated surface water-groundwater hydrologic model, ParFlow. CLM. The Kaweah River watershed in California, USA, is used as our virtual catchment laboratory to characterize watershed response to variable precipitation forcing from headwaters to groundwaters. By applying the three-cornered hat method, we quantify the spatially distributed uncertainty in four publically



Uncertainty as predicted from the 3CH method for daily precipitation forcing data sets at 4-km spatial resolution.

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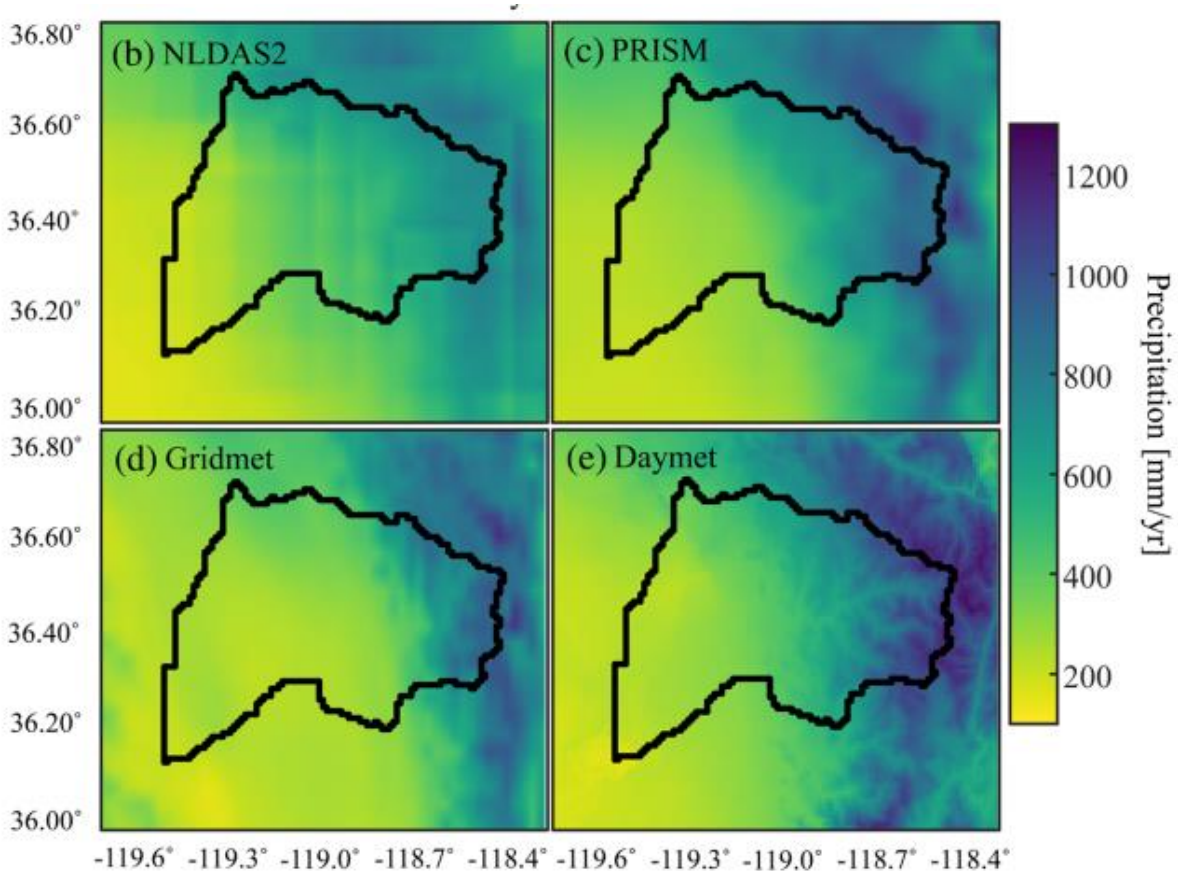
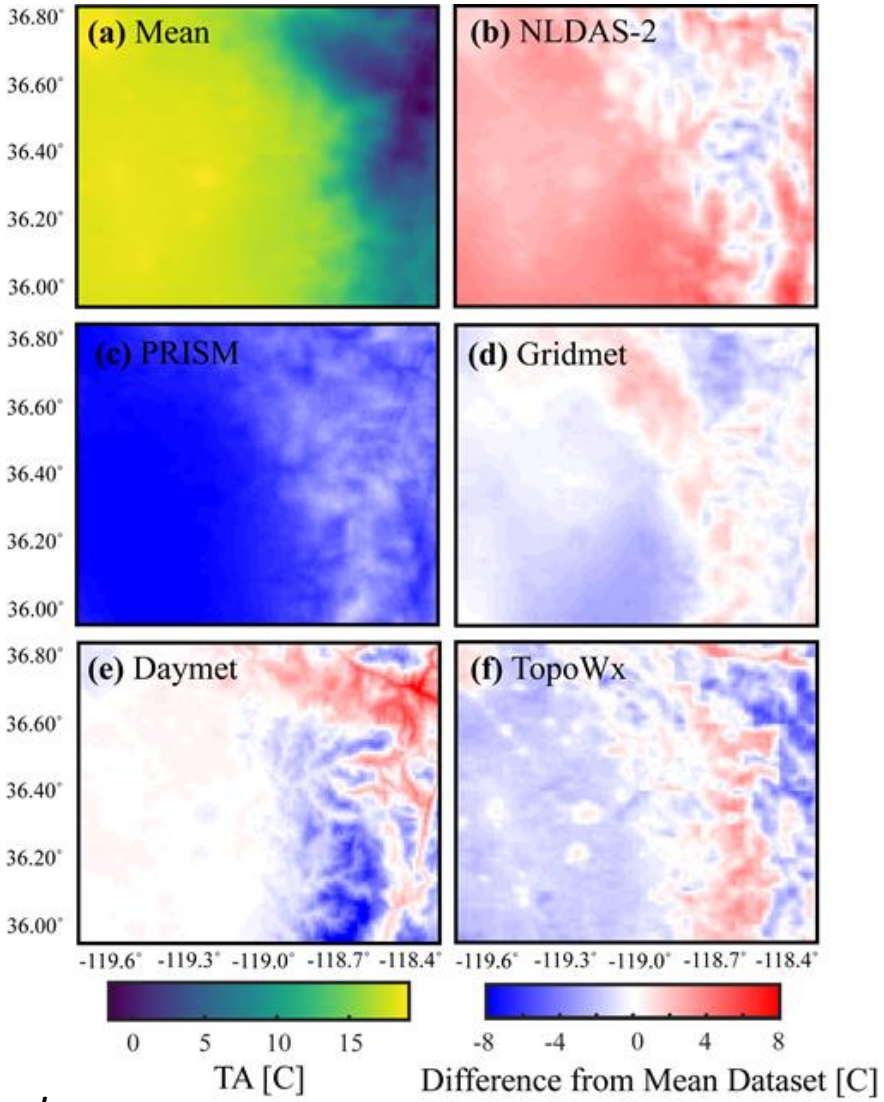
Large differences in annual average precipitation and mean daily air temperature exist among multiple gridded products.





Schreiner-McGraw & Ajami. *2020. Water Resources Research*

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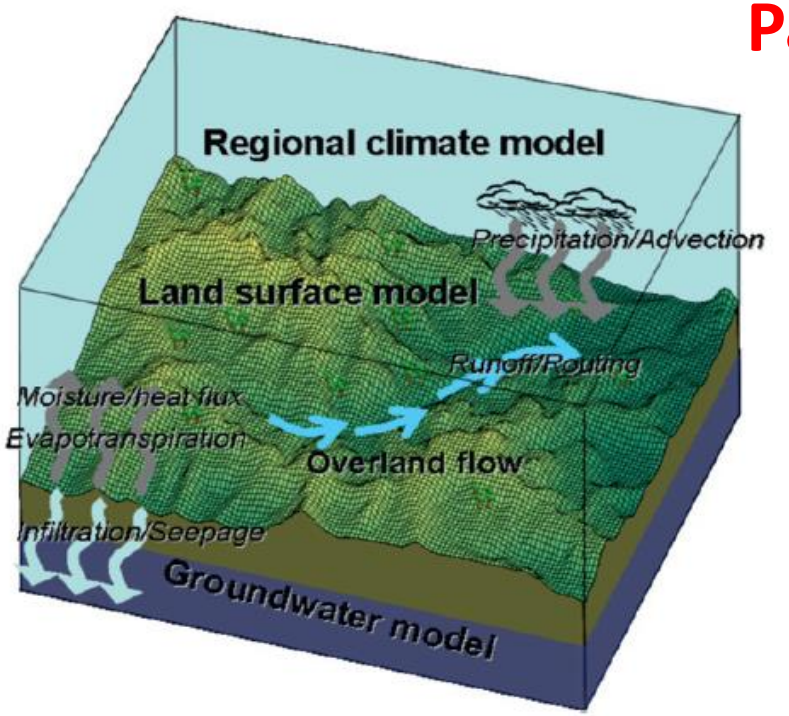
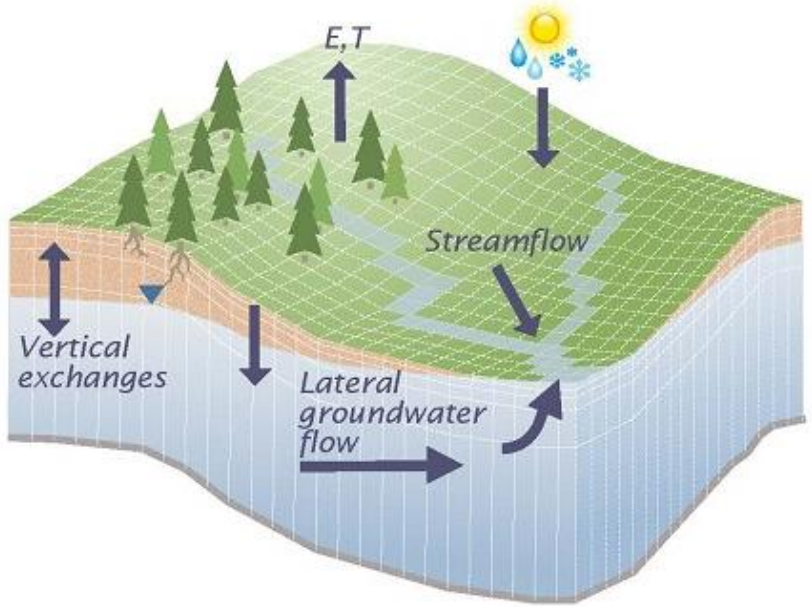
Utilized an integrated surface-subsurface hydrology model to simulate surface water-groundwater interactions.

ParFlow Modeling Package



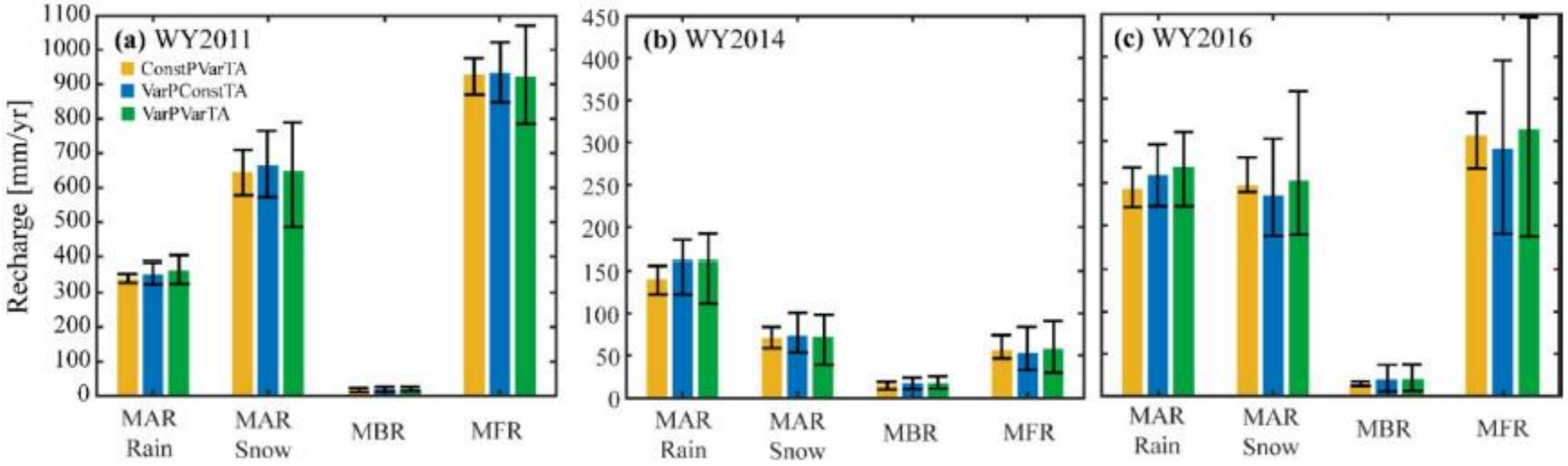


Integrated Hydrologic Models

- Integrated Groundwater-Land Surface-Atmospheric Model
- 3D variably saturated groundwater flow model
- Fully integrated overland flow process
- Coupled to the Common Land Model (CLM)

Kollet and Maxwell. 2008. *Water Resources Research*

Contrasting findings on MFR & MBR relative contribution to valley aquifers

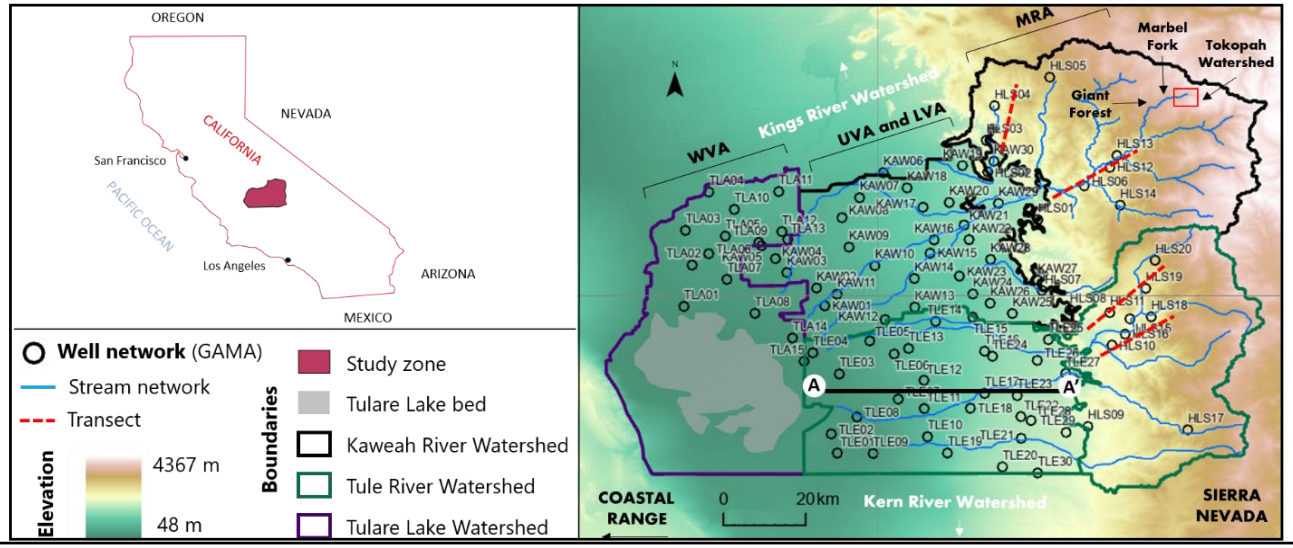


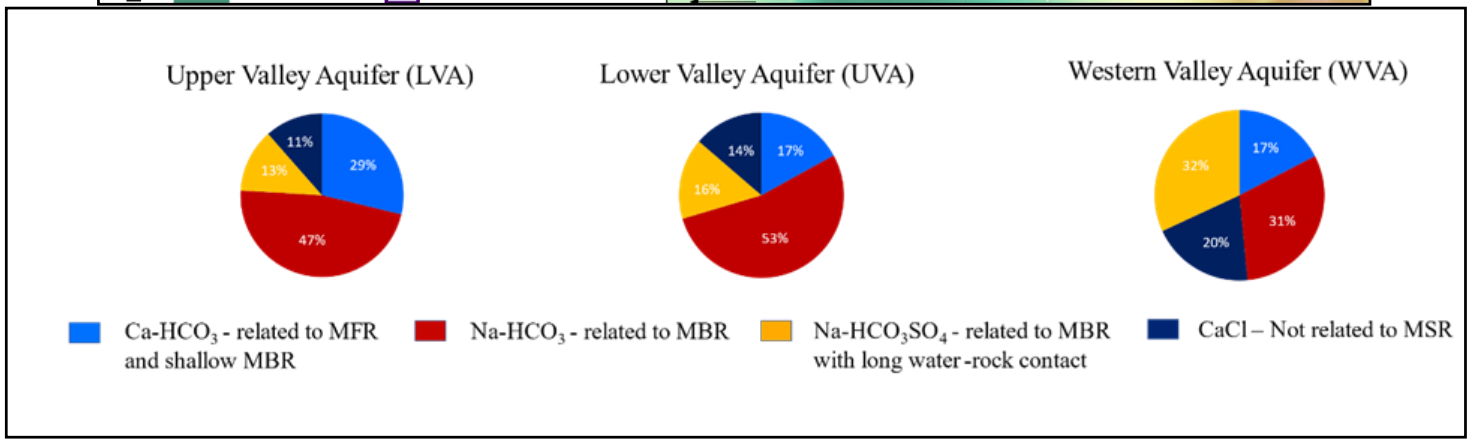
MBR: less significant pathway (up to 15%) recharging the Central Valley

Schreiner-McGraw & Ajami. 2022. *HESS*

Isogeochemical characterization of mountain system recharge processes in the Sierra Nevada

CA GAMA Data





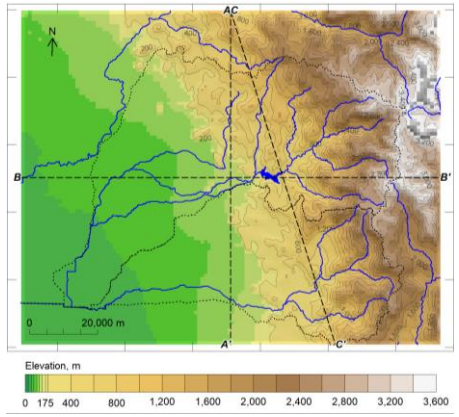
MBR: primary pathway (>50%)

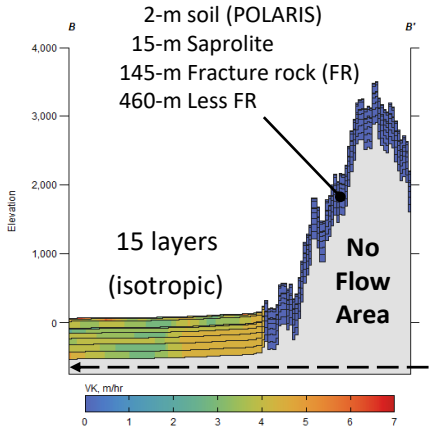
Armengol et al. *In Review*

Integrating water chemistry and isotope data with numerical modeling

01 Former model setup

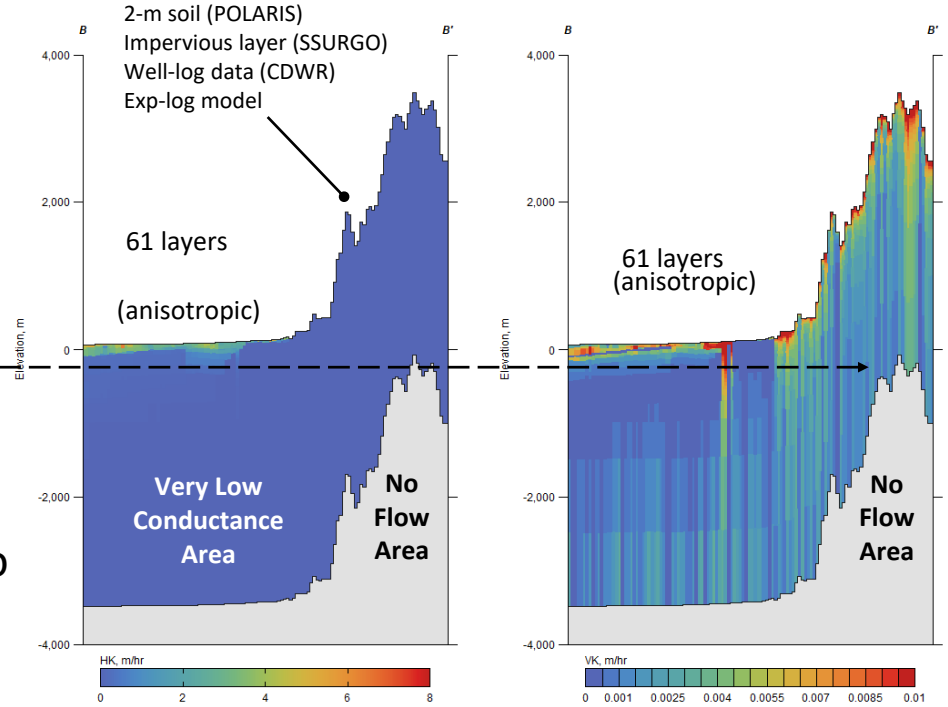
Simplified USGS CVHM + fixed geologic structure





02 New model setup

Detailed USGS CVHM + multidata geologic structure



Isogeochemical-derived MFR/MBR ratio

Validate new model setup by quantifying MFR/MBR contribution to valley aquifer under predevelopment.

Isotope-derived water age/fluxes

Constrain the system using isotope-derived fluxes at given depths.

Acero et al. *In preparation*

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Summary

- Lag time of up to 15 years exist between meteorological drought and groundwater drought.
- Average groundwater recovery time is about 3 years.
- Groundwater recovery time increases with increasing drought severity.
- MSR processes are complex and accurate estimate of recharge requires integrating **geochemical tracers with hydrometric observations** and numerical models.



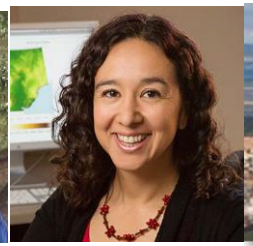


Acknowledge Co-authors & Funding Agencies



Dr. Adam Schreiner-McGraw
Dr. Juan Sebastian Acero Triana
Dr. Sandra Armengol Vall
Postdoctoral fellows at UC Riverside






Professor Thomas Meixner
Professor Thomas Maddock III
Professor Francina Dominguez
Dr. James Hogan

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STATE OF CALIFORNIA ENERGY COMMISSION

Advanced Statistical-Dynamical Downscaling Methods and Products for California Electricity System Climate

NSF

CAREER: Characterizing Mountain System Aquifer Recharge in the Sierra Nevada Mountains of California

USDA ARS

NRCS Natural Resources Conservation Service

A Modeling Assessment of Agricultural Land Groundwater Recharge in the Kaweah River Watershed, California

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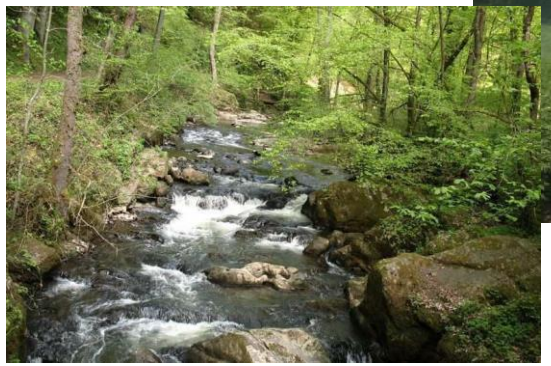
Climate Change Impacts on Groundwater Recharge

THANK YOU

Questions: hooria@ucr.edu



Upper San Pedro Partnership Technical Committee Meeting **May 17, 2023**

UC RIVERSIDE NSF USDA NIFA USDA ARS NRCS Natural Resources Conservation Service CALIFORNIA ENERGY COMMISSION