Spatio-Temporal Modeling of Groundwater Flow Dynamics Under Extensive Irrigation in the San Joaquin Valley

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May 2025, Folsom, CA, USA

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2025 CWEMF Annual Meeting

Background

- Competition for water resources is growing throughout California, particularly in the Central Valley.
- Drought, and the ecological crisis in the Sacramento–San Joaquin Delta have created an intense demand for water
- The San Joaquin Valley has experienced declining groundwater levels and accompanying depletion of groundwater storage.

California Department of Water Resources (Water Plan Update, 2023)

Objectives

Main Objective:

To understand the spatio-temporal dynamics of groundwater flow under intensive pumping in the San Joaquin Valley (Modesto-Turlock-Merced)

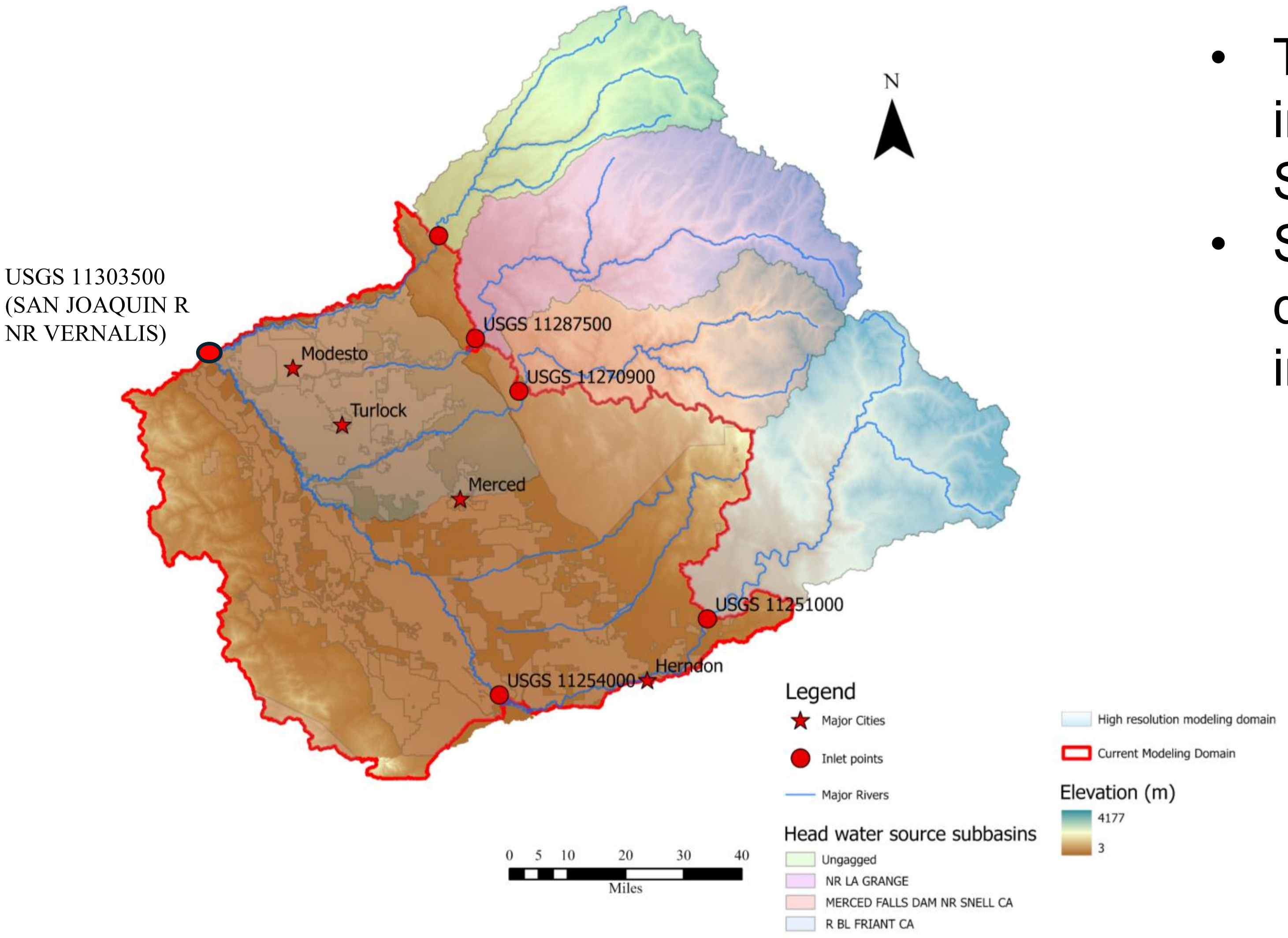
Specific Objectives:

1. Evaluate the ability of the SWATPlus-GWFLOW model to represent groundwater flow dynamics under intensive pumping.
2. Estimate the annual dropdown rate of groundwater levels and annual groundwater storage changes?
3. Compare the amount of annual pumping rate with annual natural recharge

Research Questions

- Is SWATPlus-GWFLOW model capable of predicting the groundwater flow dynamics?
- Can we provide reasonable water flux partitioning and water balance components of Modesto-Turlock-Merced area using SWATPlus-GWFLOW model?
- How do the SWATPlus-GWFLOW simulation outputs compare with other models?

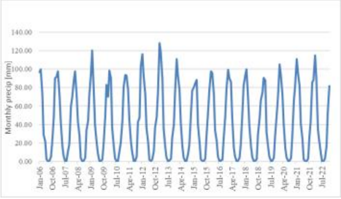
Study area

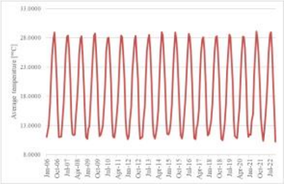


- The San Joaquin River originates in the high-elevation Eastern Sierra Nevada mountain range
- SWATPlus-GWFLOW model developed for the intensively irrigated areas:
  - Area = 5932 mile^2
  - HRUs = 118,372
  - 5 inlet points (contribute 21 m^3/s) representing the head water sources
  - Active grid cells = 945168
  - Water districts = 151

Model inputs

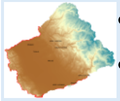
Hydroclimate input data:
- Daily precipitation, maximum and minimum temperature (PRISM)
- Daily streamflow (USGS)

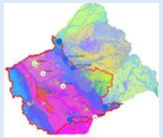


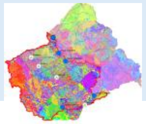


SWAT+
Bieger et al. (2017)

Spatially distributed input data:
- USGS DEM (10 m resolution)
- Land use/cover (NLDC)
- Soil (SSRUGO), 1 to 8 layers, maximum depth reaches to 2.14 m







SWAT+GWFLOW
Bailey et al. (2020)

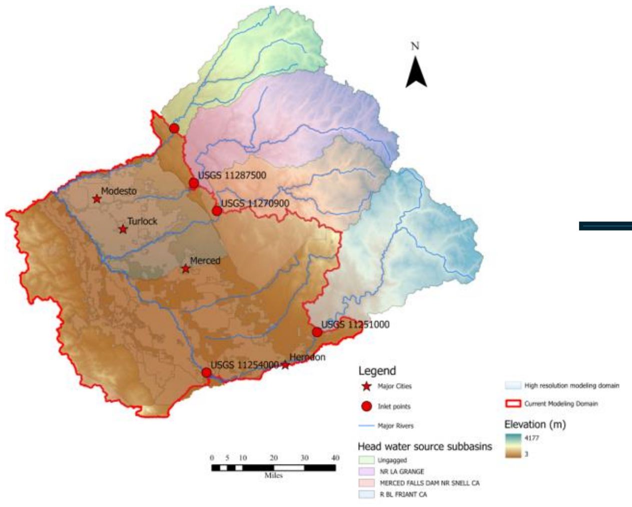
- Stream network, HRUs, Landscape unit
- Aquifer thickness (272 to 432 m),
- Hydraulic conductivity (0.0063 to 81 m/day)

Parametrization & uncertainty analysis

SWAT+ model outputs:
- Streamflow, surface runoff, lateral flow
- Groundwater recharge,
- Actual ET, Potential ET

SWAT+GWFLOW outputs:
- GW recharge, gw storage, gw head, depth to water table
- GW-SW exchange, saturation excess flow
- Groundwater deficient

Model Configration and Boundary conditions



- Applying recall module to represent the flows at the upstream section
- Catchment discretization into square grid cells (cell size = 300)

- Create hrus & grid cell intersection
- Create aquifer zones based on hydraulic conductivity and aquifer thickness
- **Define initial conditions** (stream thickness = 7.5 m, Groundwater ET extinction = 3.5, streambed hydraulic conductivities, groundwater pumping)

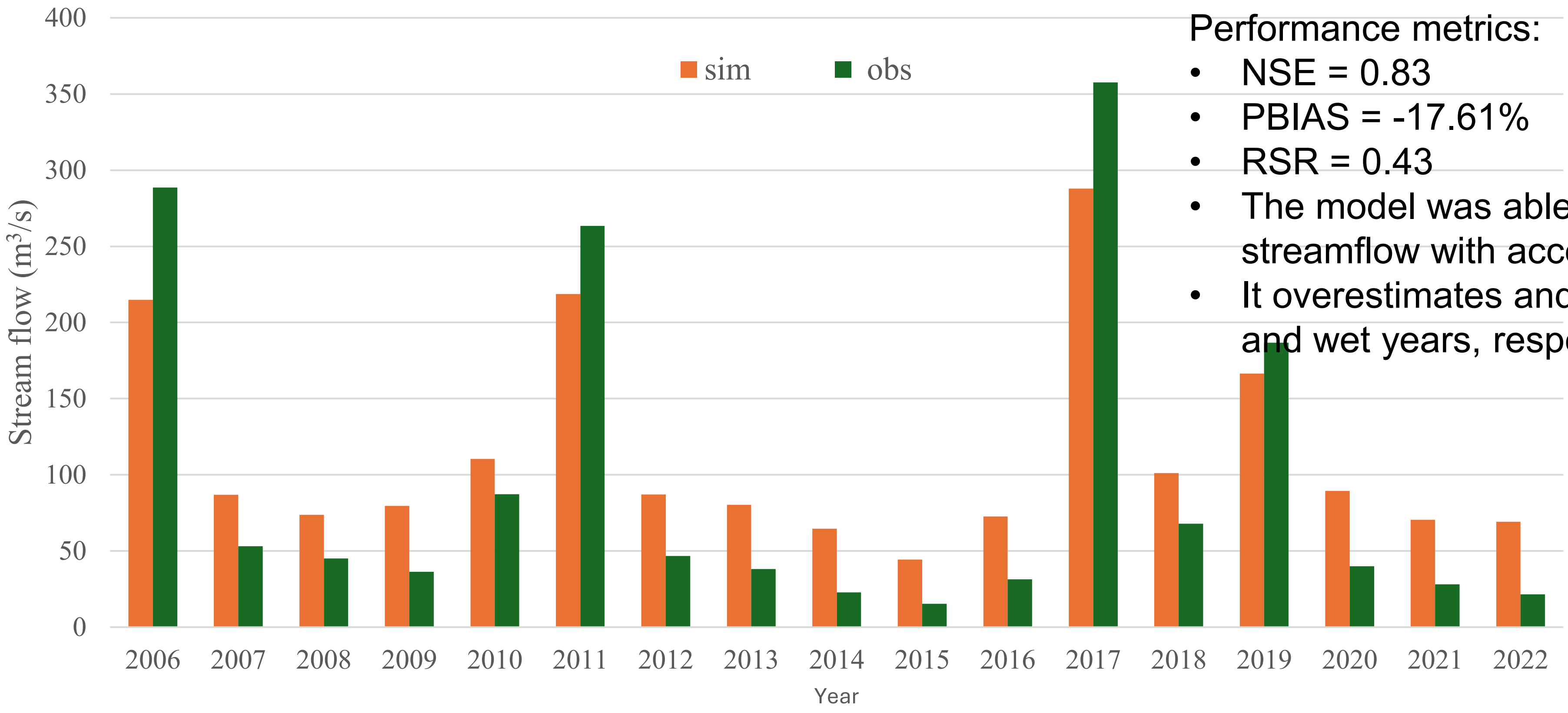
Use water allocation decision tables to trigger groundwater pumping based on plant water stress:

i. Identify HRUs in irrigated areas
ii. Intersect hrus with groundwater cells
iii. Prepare demand and source tables
iv. Assumption: the sources for irrigation water demand are precipitation & groundwater

Parameterize and run the model to simulate hydrological processes

Analyze and interoperate results

Results: 1) Annual mean streamflow



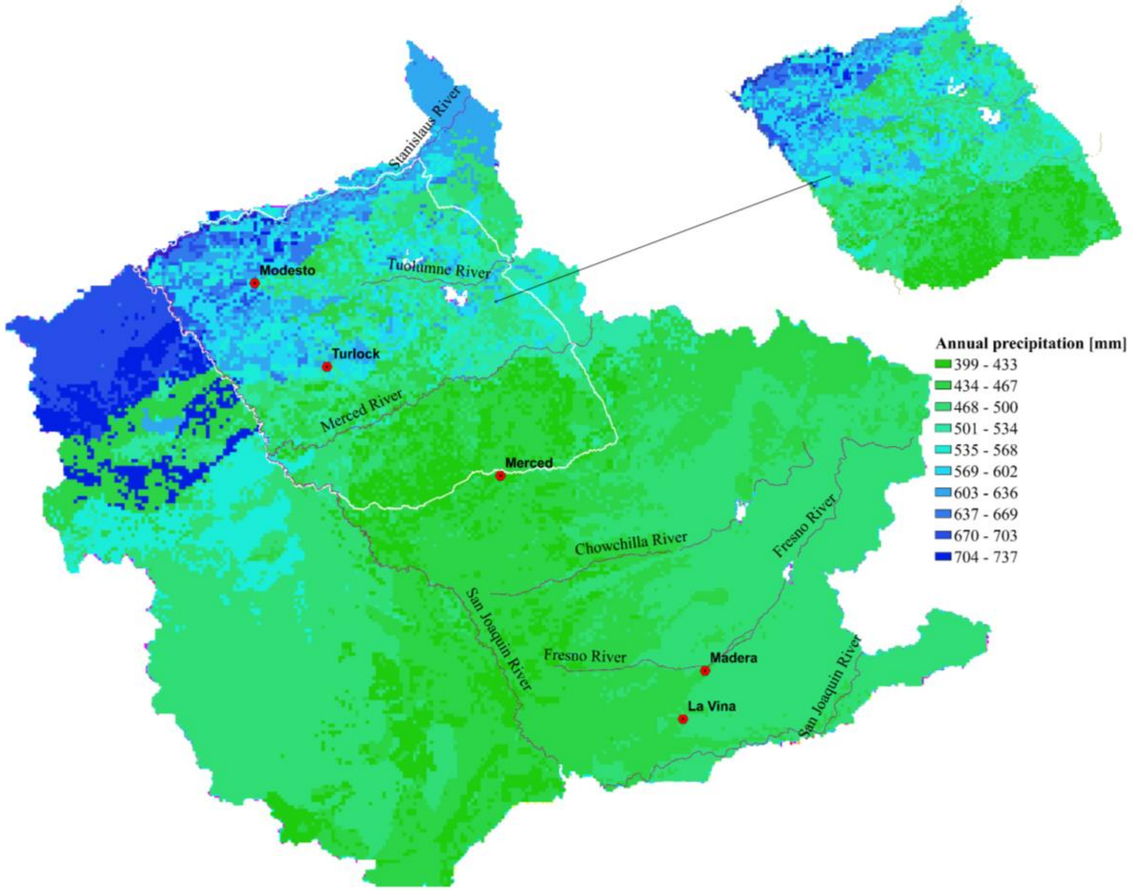
Annual mean:

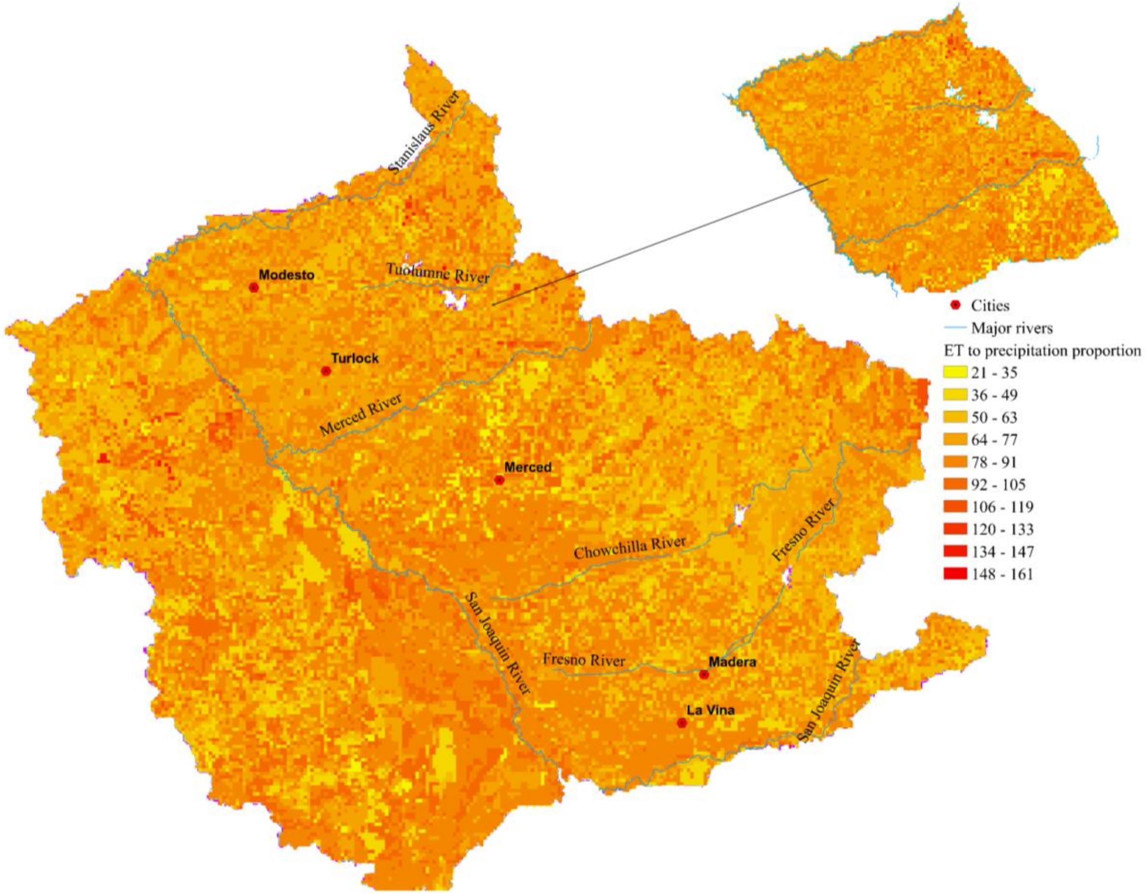
- simulated =112 m^3/s
- observed = 96 m^3/s

Performance metrics:

- NSE = 0.83
- PBIAS = -17.61%
- RSR = 0.43
- The model was able to simulate the annual streamflow with acceptable error boundary
- It overestimates and underestimates the dry and wet years, respectively.

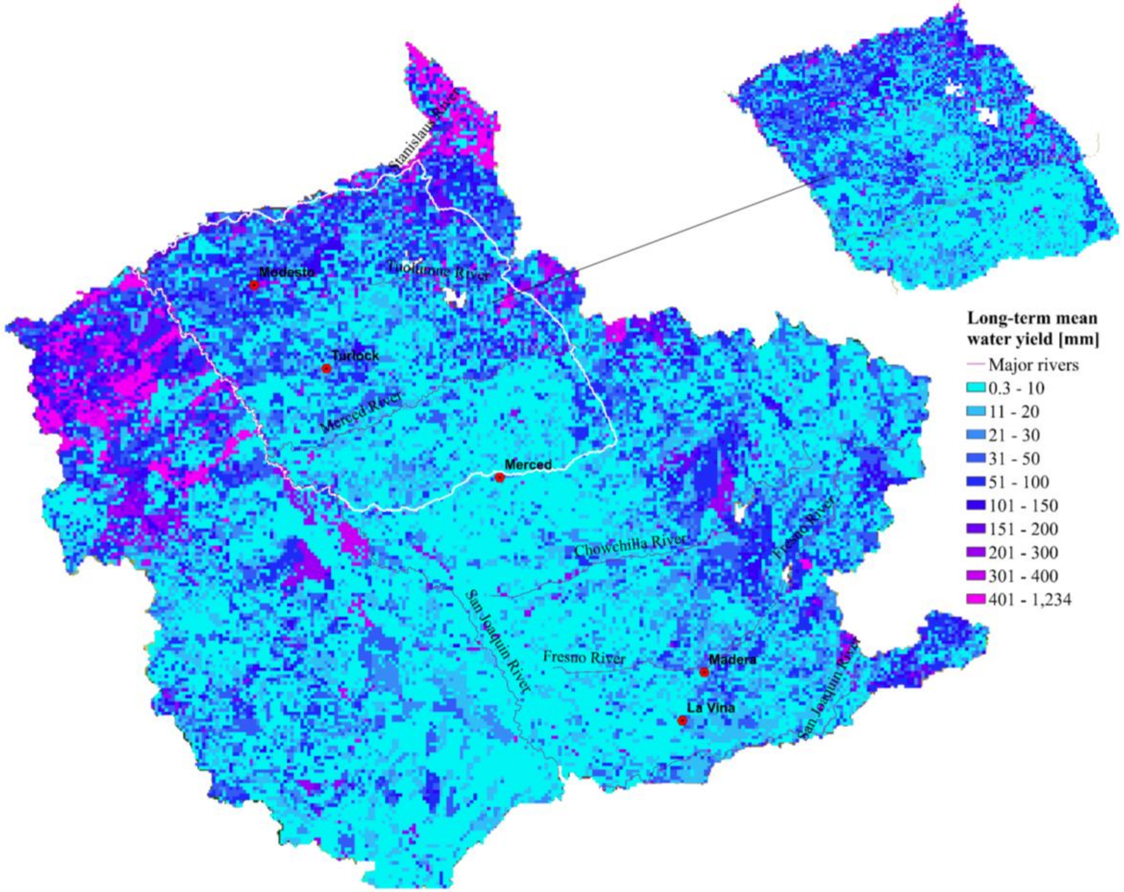
Results: 2) Annual average precipitation and actual ET distribution

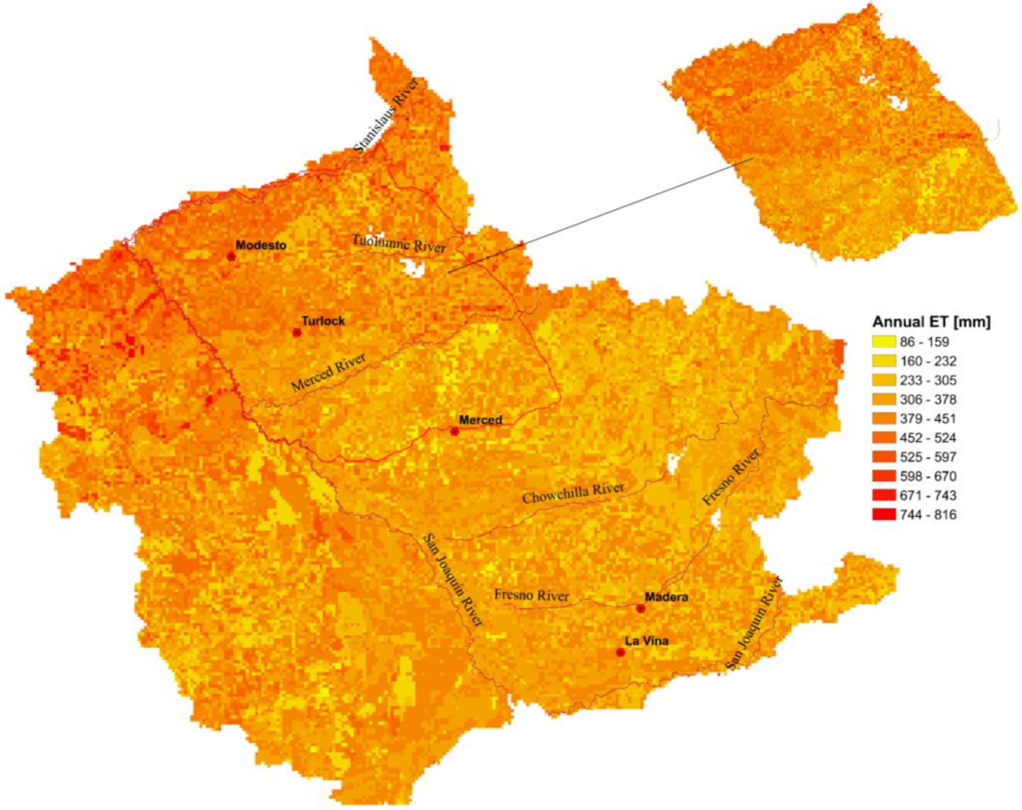




- The annual average precipitation and actual ET distribution show North-West to South-East gradient
- The average precipitation is about 495 mm
- Average ET to precipitation proportion varies between 21 to 161% with overall average of 73% comparable with (Baldocchi et al. 2019)
- The ET percentage distribution shows higher proportion to the southern part of the valley due to the higher temperature

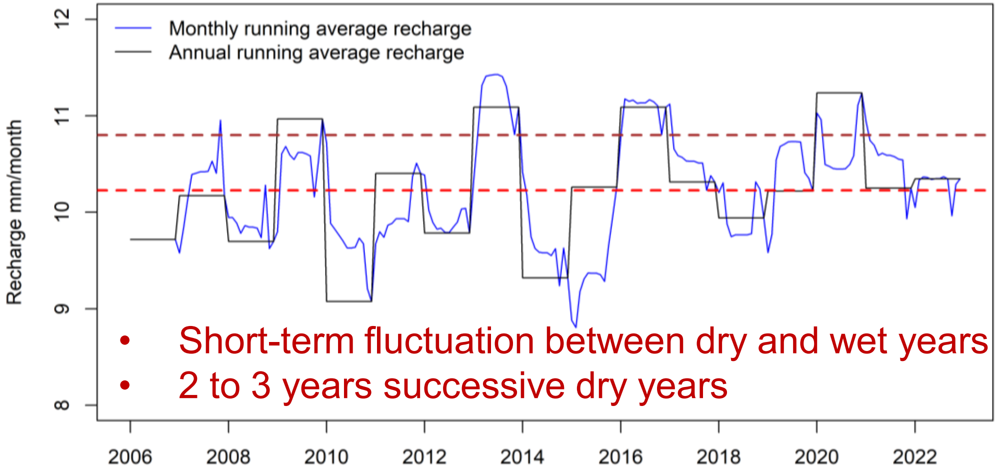
Results: 3) Spatial distribution of water yield and ET



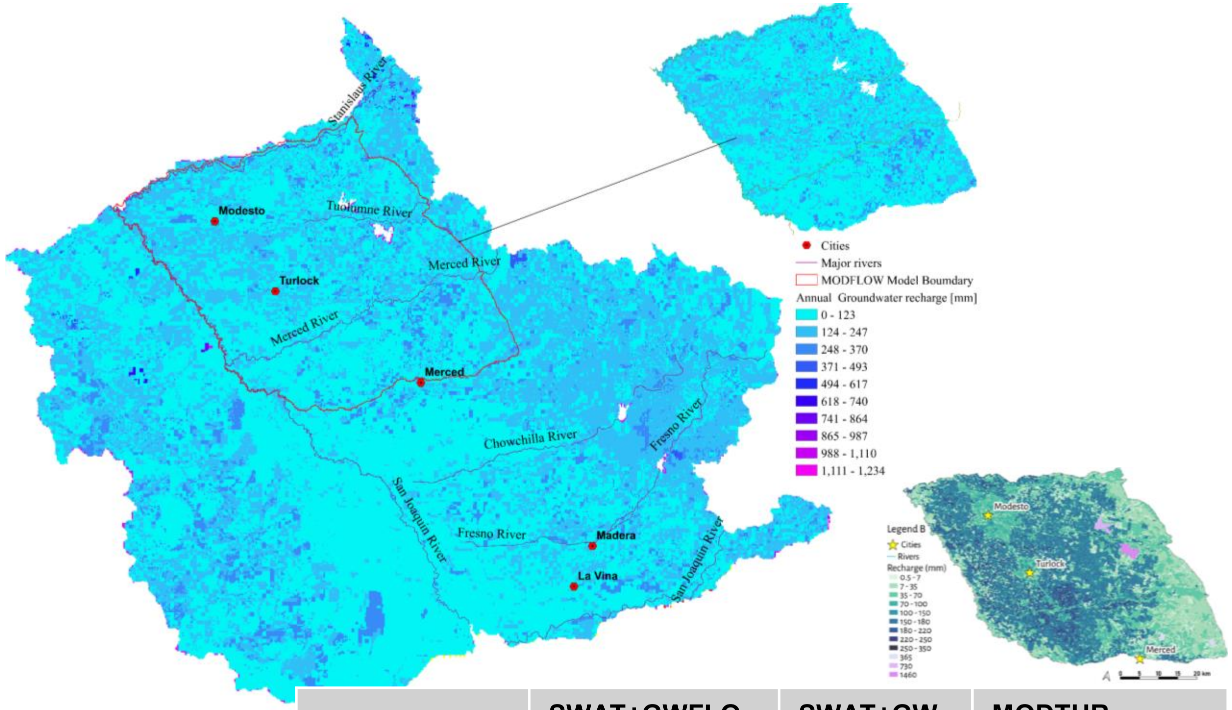


- The catchment water yield is smaller compared to ET
- The northern part and the highlands have higher magnitude of water yield, whereas the southern part and the valley have lower magnitudes due to differences in the amount of precipitation as well as topographic influence
- The average water yield to precipitation is 12%

Results: 4) Basin average and spatial distribution of groundwater recharge



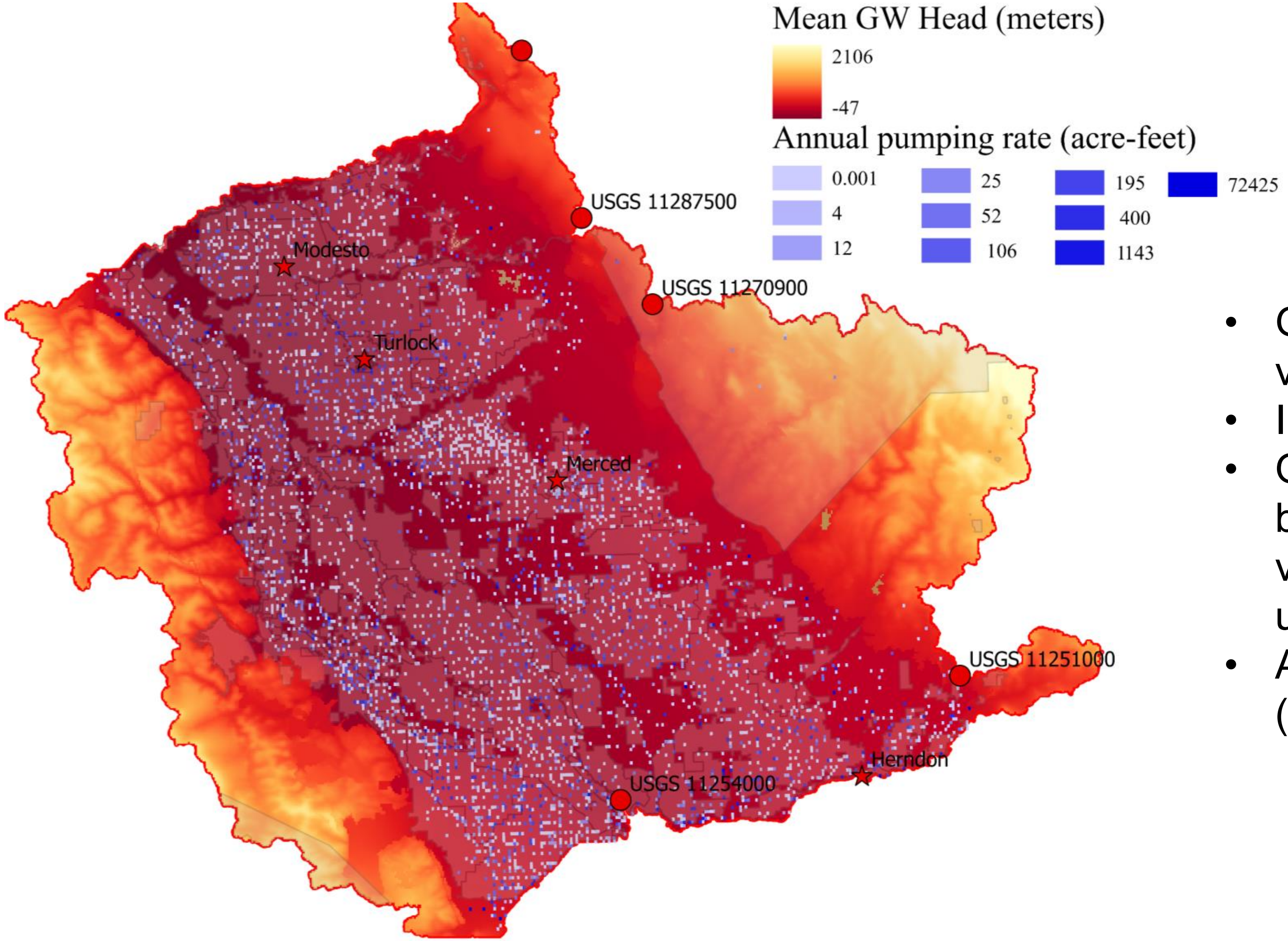
- Short-term fluctuation between dry and wet years
- 2 to 3 years successive dry years



	SWAT+GWFLOW (large scale)	SWAT+GWFLOW (mall scale)	MODTUR (Casilas et al. 2025)
Annual average recharge (mm)	120	121	135
Monthly average recharge (mm)	10.2	10.3	10.8
Cumulative recharge (mm)	2463what m	2783	2800
Spatial variation	0.1 to 1234	1 - 740	0.5 - 1460

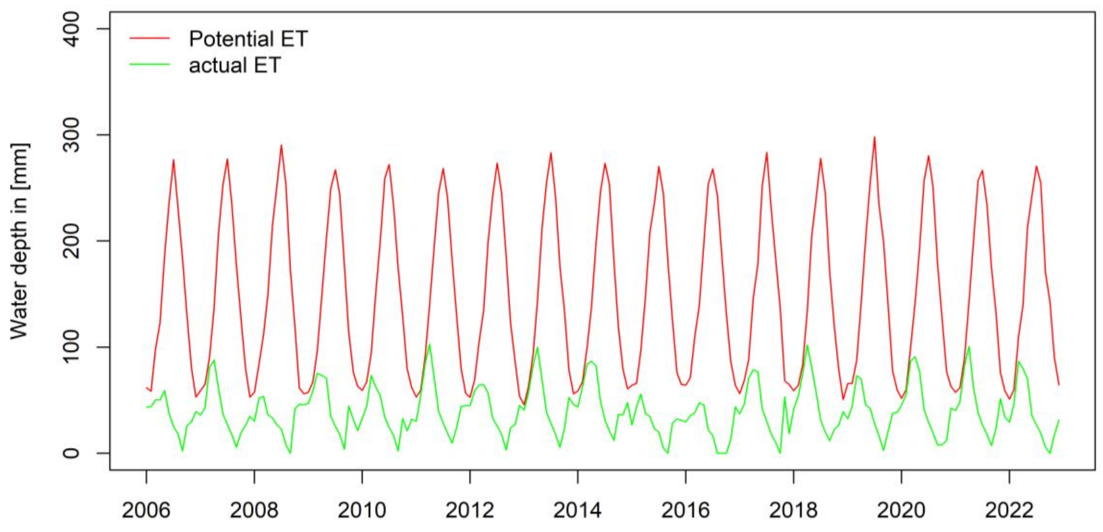
- The monthly running average recharge ranges 8.8 to 11.43 mm (which compares closely with (Casilas et al. 2025)
- The lowest average recharge observed in 2015, and the highest in 2014
- The groundwater recharge reflects the seasonal and temporal dynamics of precipitation
- The groundwater recharge seasonal pattern follows the precipitation dynamics similar to the finding of Hanak et al. (2018).

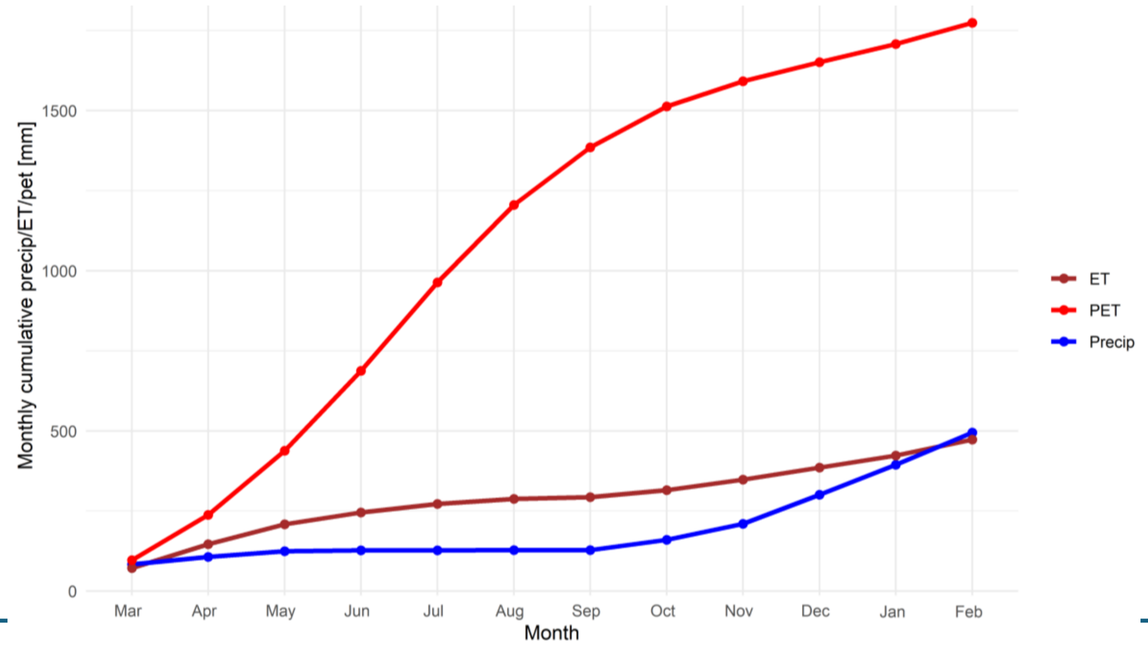
Results: 5) Groundwater head and withdrawal variabilities over space

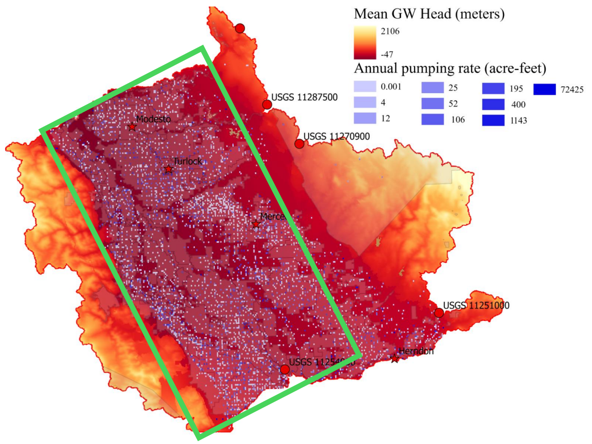


- Groundwater head decreases towards the valley floor
- Intense pumping to the southern part
- On average the groundwater level drops by 0.98 ft/year (comparable to literature values and DWR's Water plan update, 0 up to ≥ 2.5 ft)
- Annual mean pumping is about 267 mm (630 acre-feet)

Results: 6) Water budget distribution in irrigated hrus

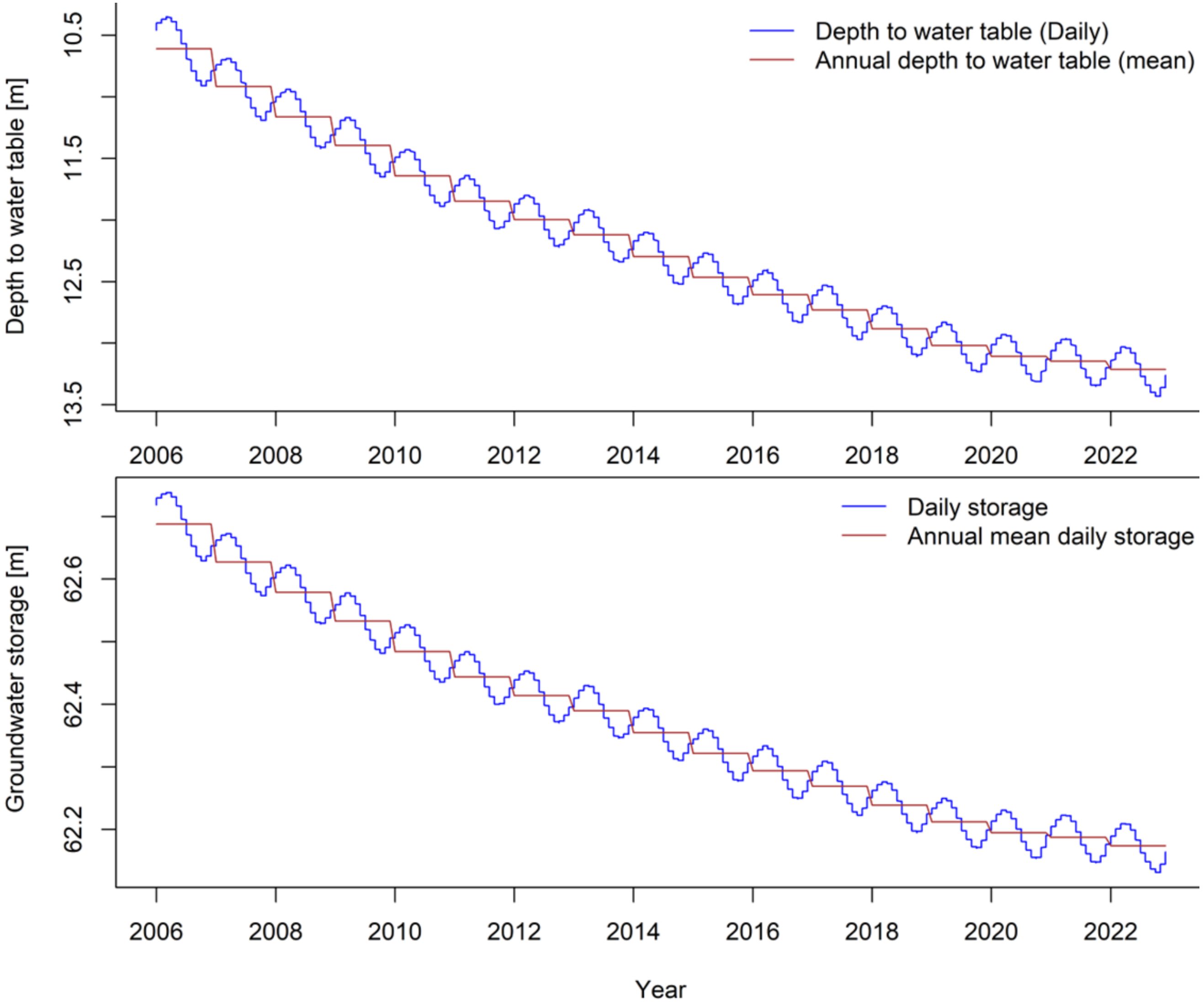






- Actual ET increases during summer due to groundwater pumping for irrigation
- Pumping from the aquifer occurs when there is plant water stress
- The deficit varies between 3 to 243 mm
- The highest pumping occurs in the month of June and the deficit reaches 99%
- April, May, June, July, and Aug are months with plant water stress
- June experiences the highest plant water stress
- Annual mean ET counts 73% of precip and comparable with Baldocchi et al. (2019); Szilagyi and Jozsa (2018)

Results: 7) Groundwater overdraft in the San Joaquin Valley



- Groundwater level steadily drops due to over pumping
- On average the groundwater level drops by 0.98 ft/year comparable to Famiglietti et al. (2021) and Massoud et al. (2018).
- The over pumping accounts to 121% of the modeled recharge, leading to a steady decline of groundwater storage
- On average, the groundwater storage declines by about 450175 acre-feet annually
- The annual average groundwater flux added to the aquifer at the watershed boundary is 460 mm

Take home and general conclusions

- The annual average irrigation pumping was approximately 267 mm, which is inline with the California Water Board’s estimation for Eastern San Joaquin (265 mm) (https://www.waterboards.ca.gov/).
- The monthly average groundwater recharge was about 10.2 mm, which is consistent with the findings of Casillas-Trasvina et al. (2025).
- Groundwater levels and storage volumes show a continuous decline, confirming a persistent imbalance between natural recharge and pumping. The change in the groundwater level is comparable with DWR report (Bulletin 2020, Water Plan Update 2023).
- This model would be suitable for evaluating the relative impacts of different climate and water management scenarios.

Thank you!

Questions?

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