Agricultural Managed Aquifer Recharge (Ag-MAR) – A Method for Sustainable Groundwater Management

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UC DAVIS DEPARTMENT OF LAND, AIR AND WATER RESOURCES

The New York Times

Nearly half the sites have declined significantly over the past 40 years as more water has been pumped out than nature can replenish.

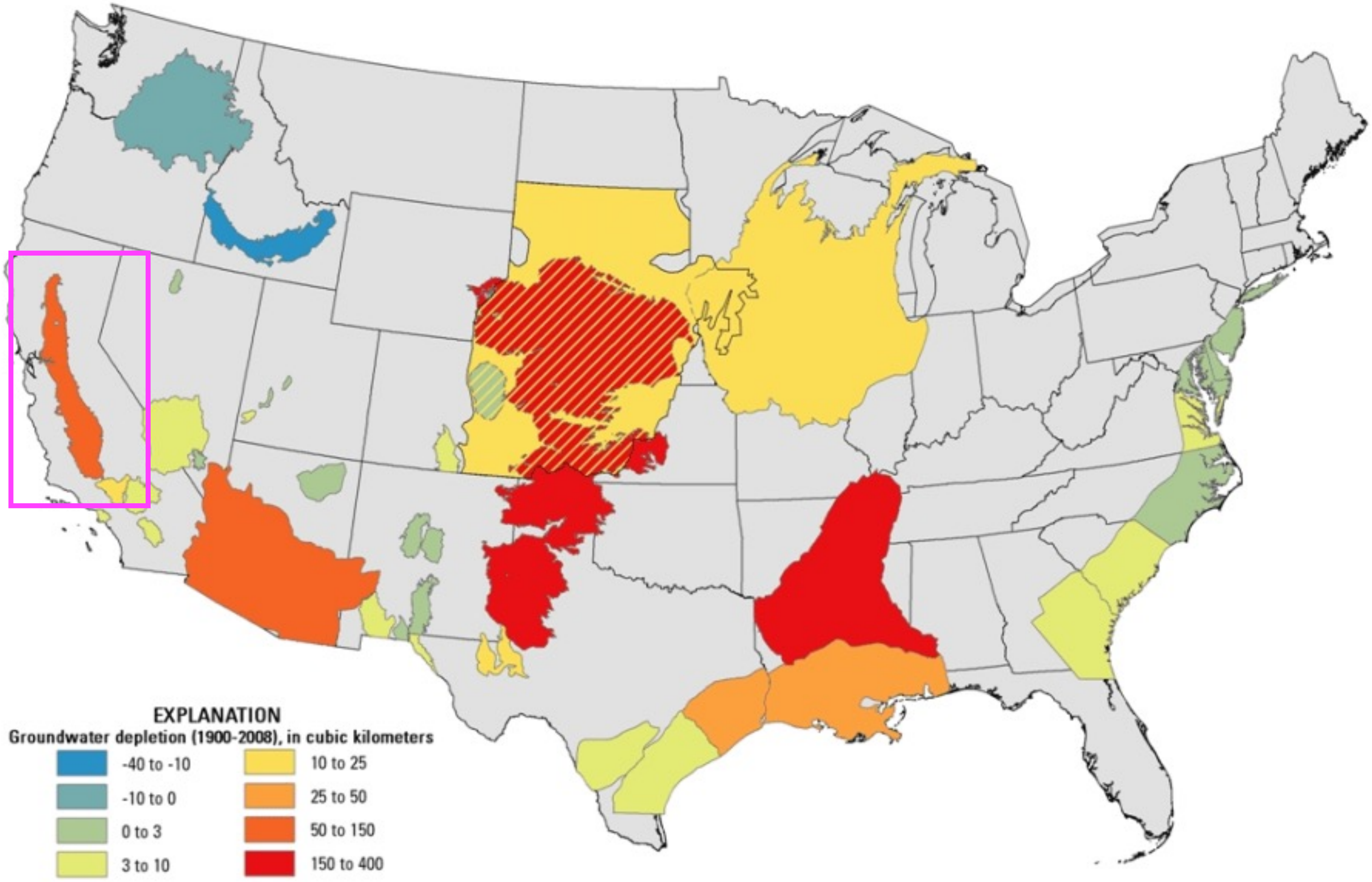
Sites with falling water levels since 1980

UNCHARTED WATERS

America Is Using Up Its Groundwater Like There's No Tomorrow

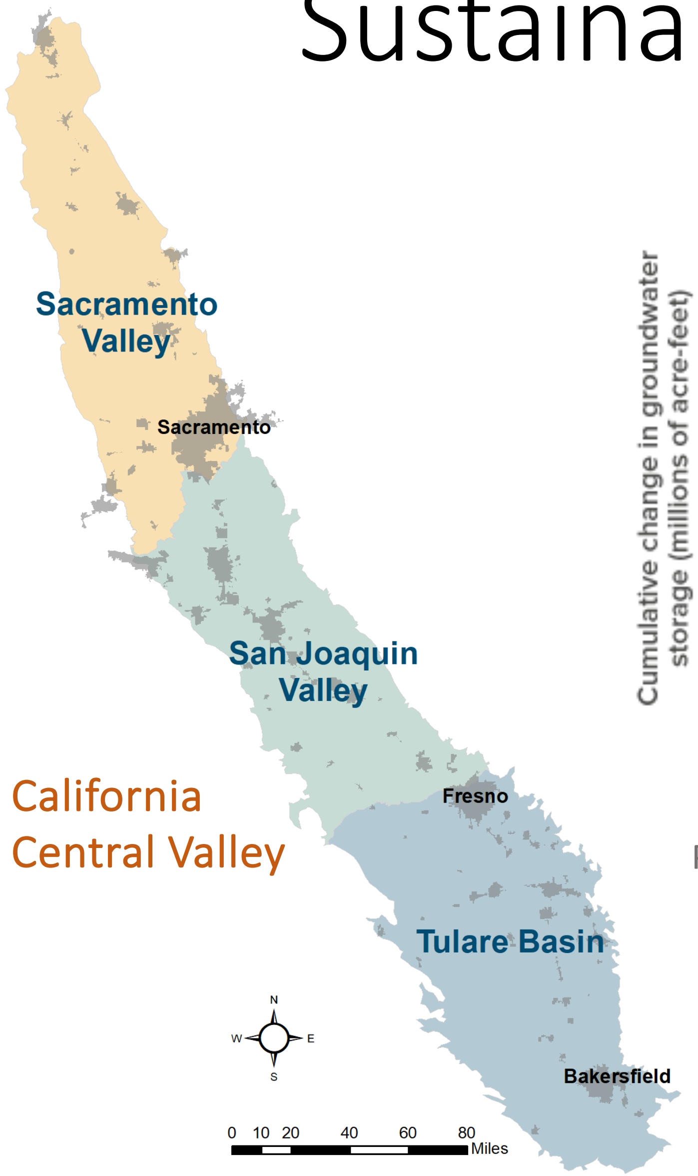
Overuse is draining and damaging aquifers nationwide, a New York Times data investigation revealed.

Groundwater Depletion 1900-2008

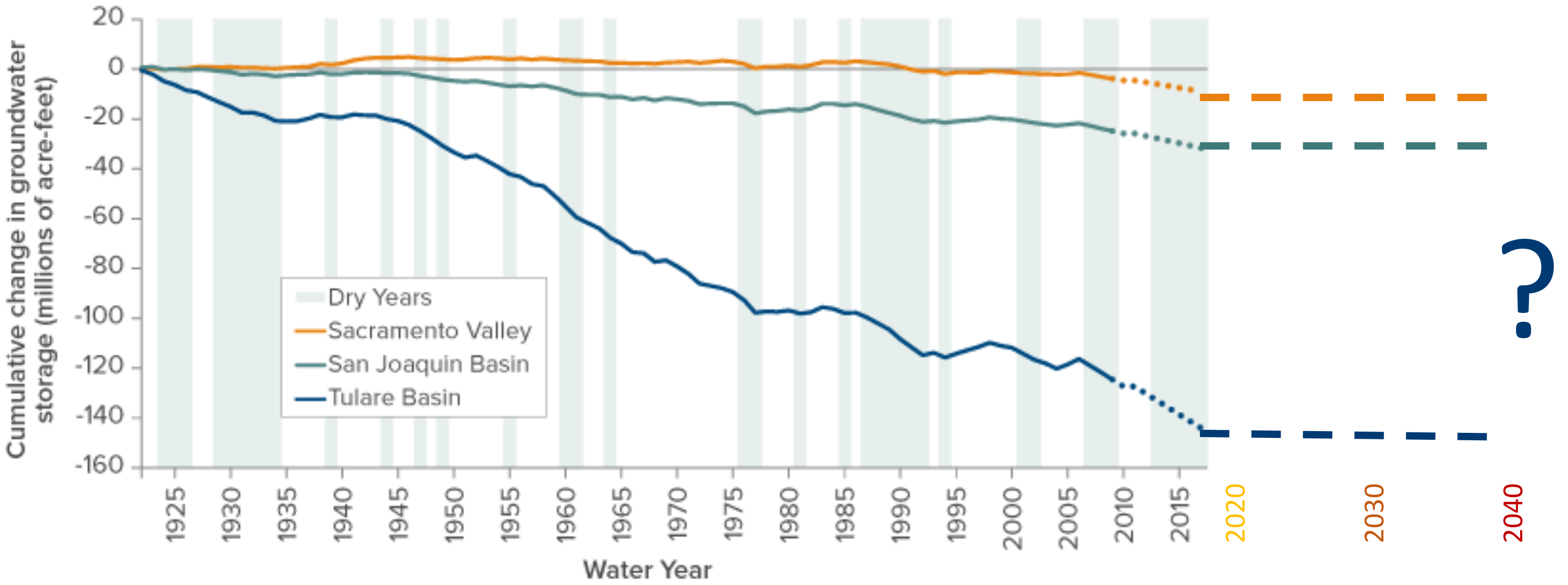


Konikow, 2013

Sustainable groundwater management



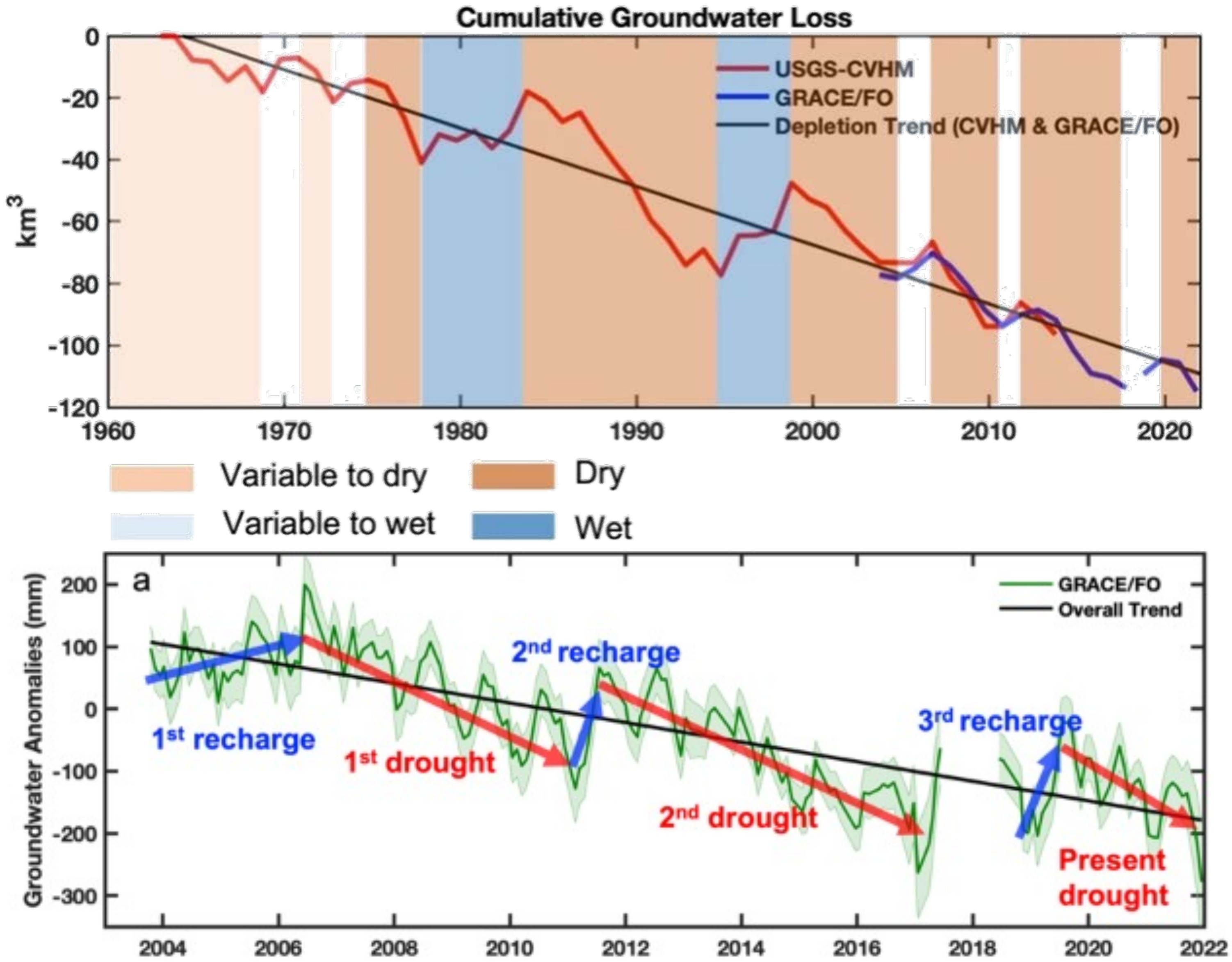
California Central Valley



PPIC, 2015

Undesirable results of groundwater overdraft

Groundwater overdraft – recent trends



Central Valley overdraft rates:

1961–2021: 1.51 MAF/yr

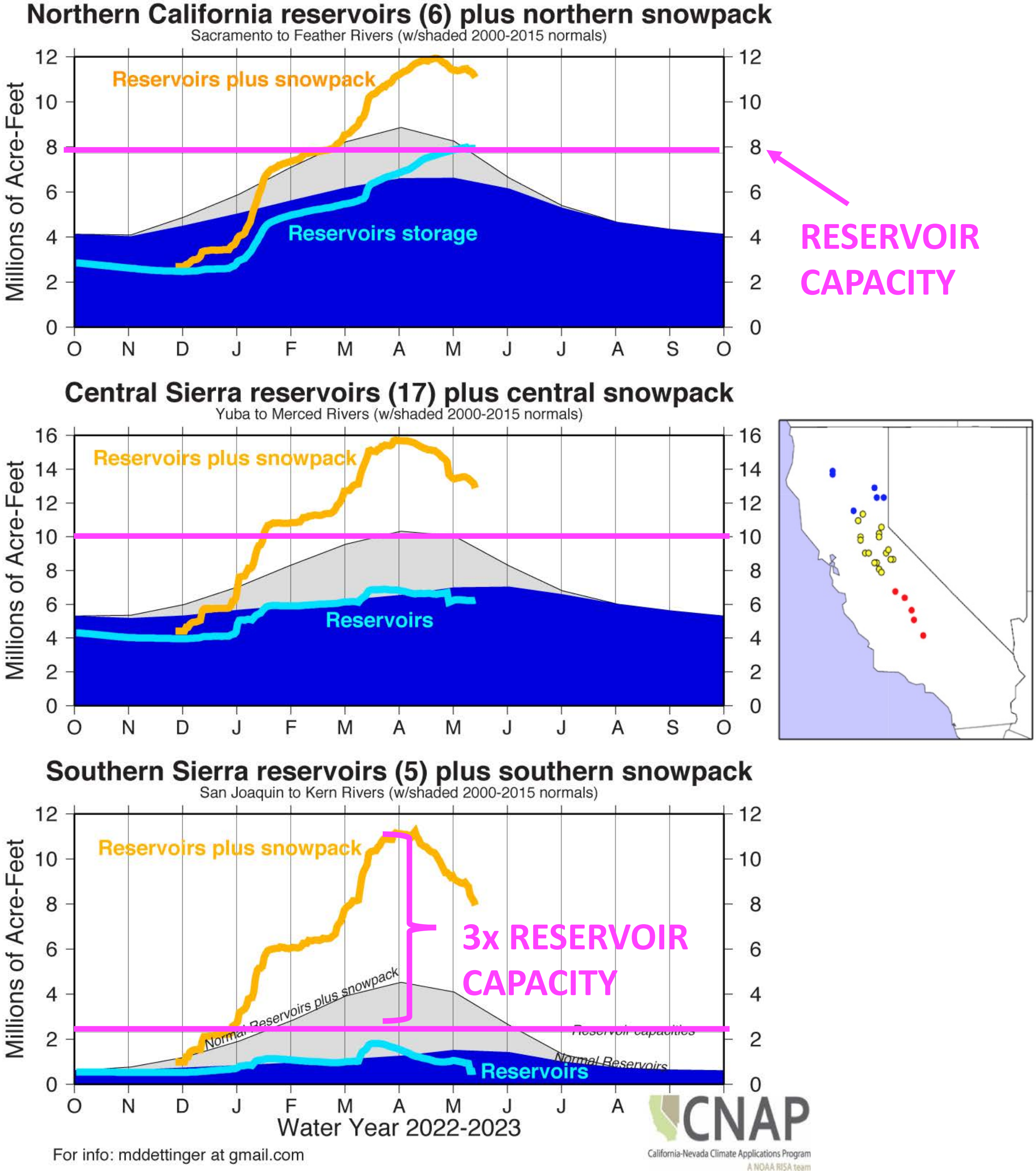
2003–2021: 1.95 MAF/yr

2019–2021: 6.95 MAF/yr

Liu et al., 2022, Nature Communications

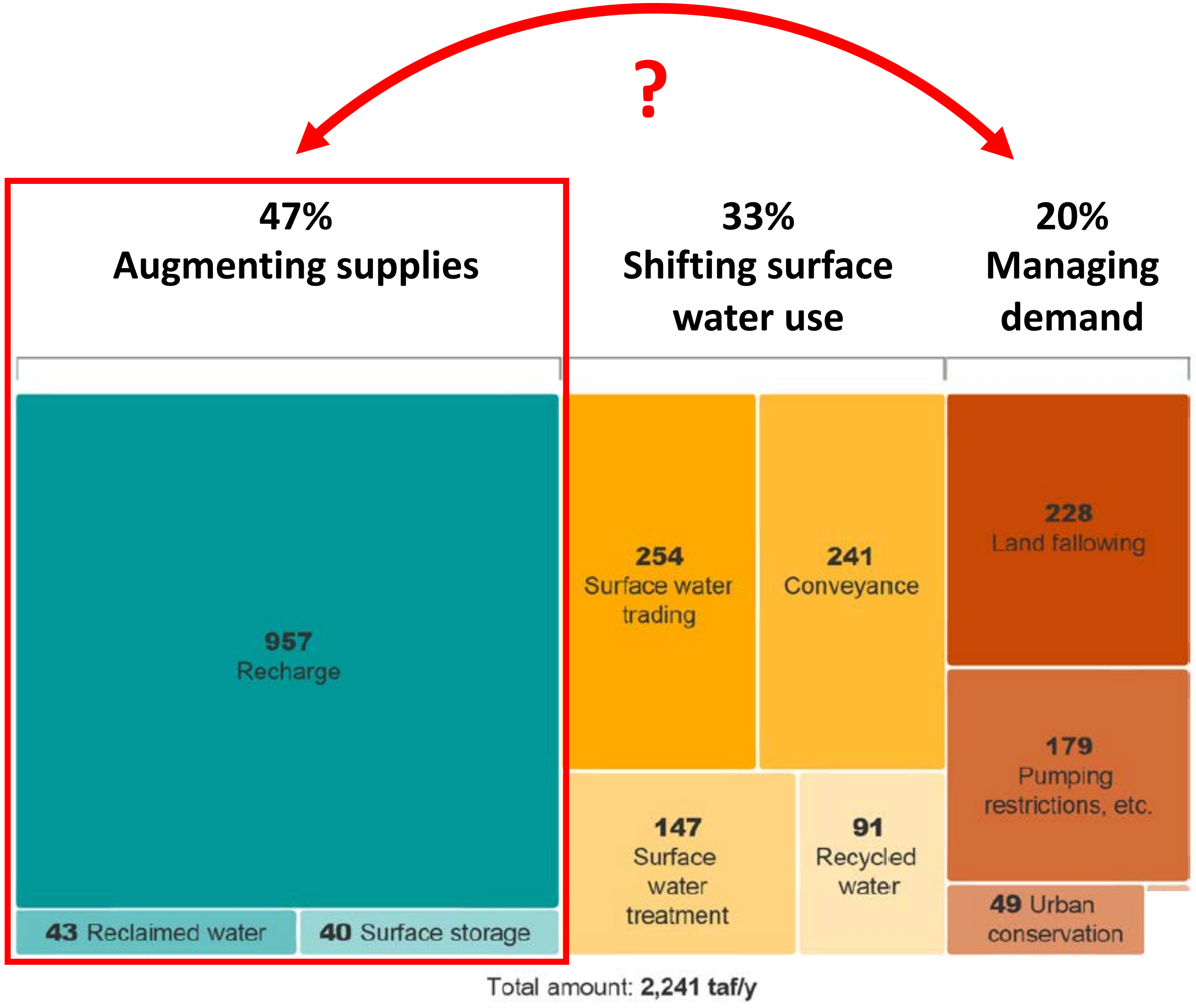
➢ Data as of May 16, 2023

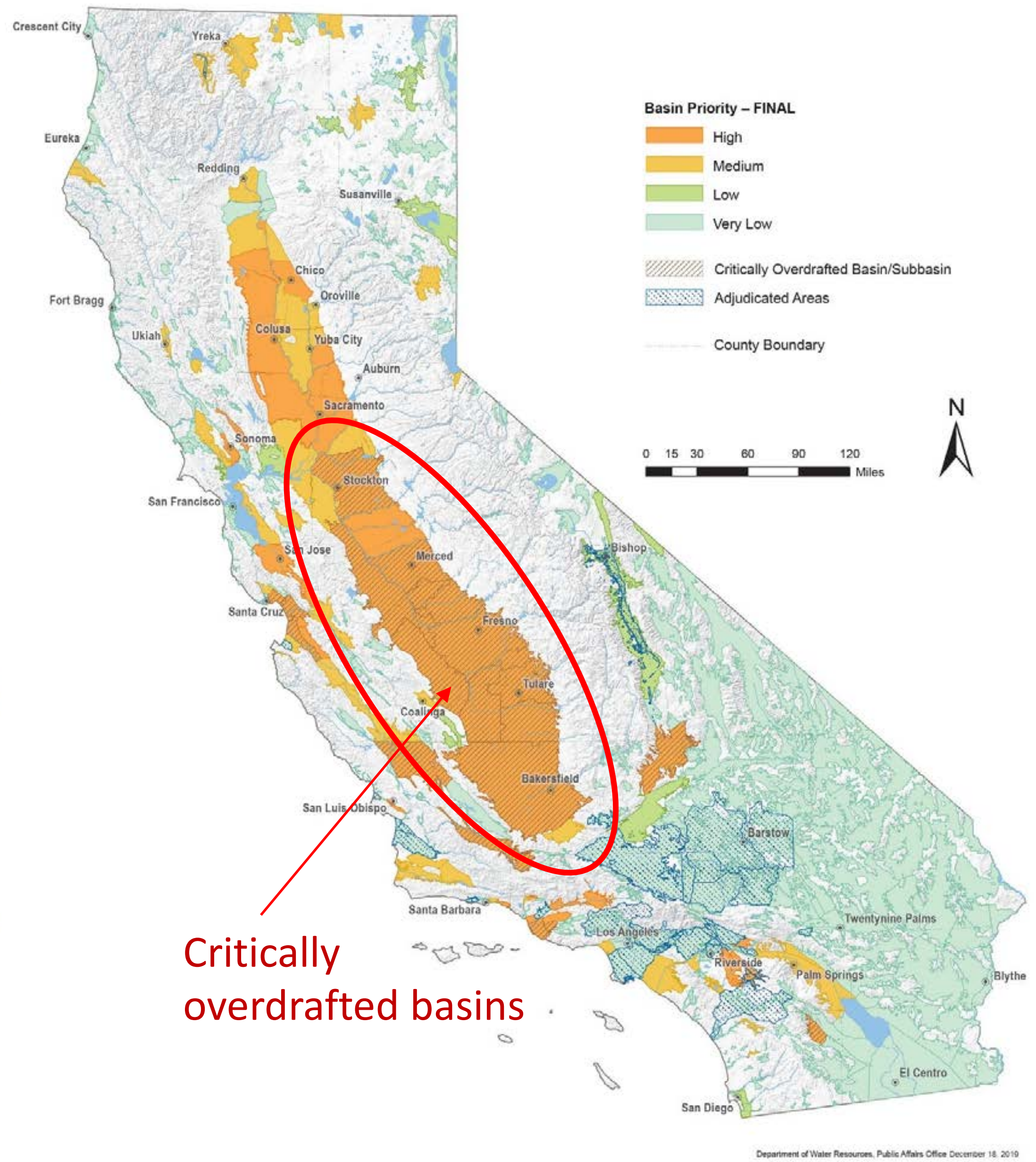
https://cdec.water.ca.gov/reportapp/javareports?name=swccond.pdf
https://cnap.ucsd.edu/storage_in_sierra_ucrb/



How to address 2-3 million acre-feet per year of groundwater overdraft in the Central Valley?

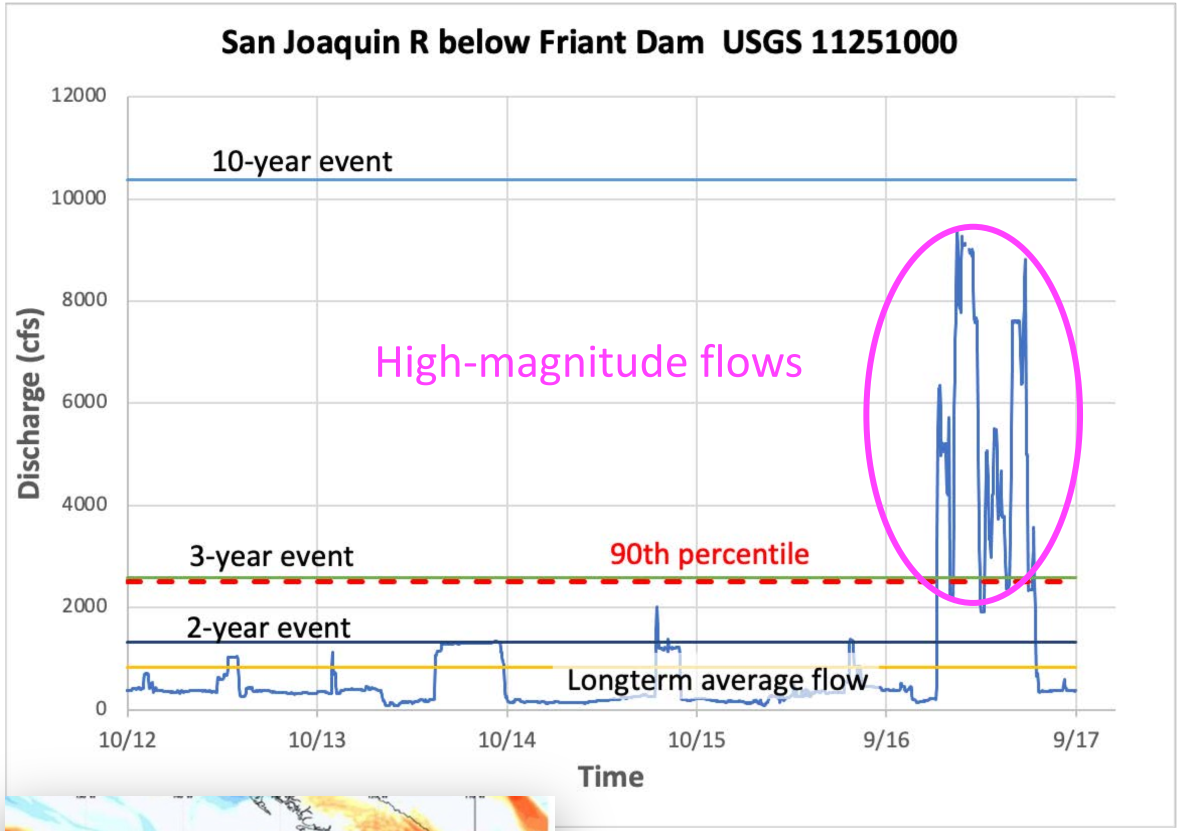
Current plans to address groundwater overdraft





PPIC, 2020, A Review of San Joaquin Valley Groundwater Sustainability Plans

Capture high-magnitude flows



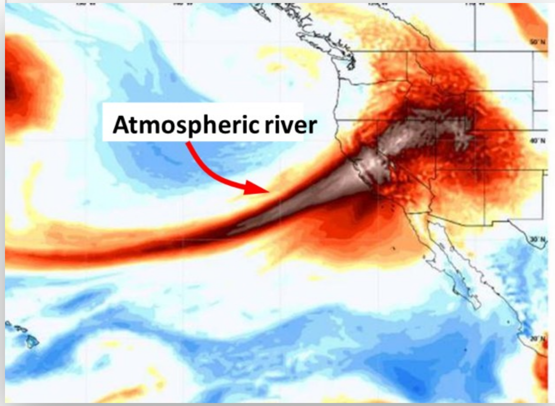
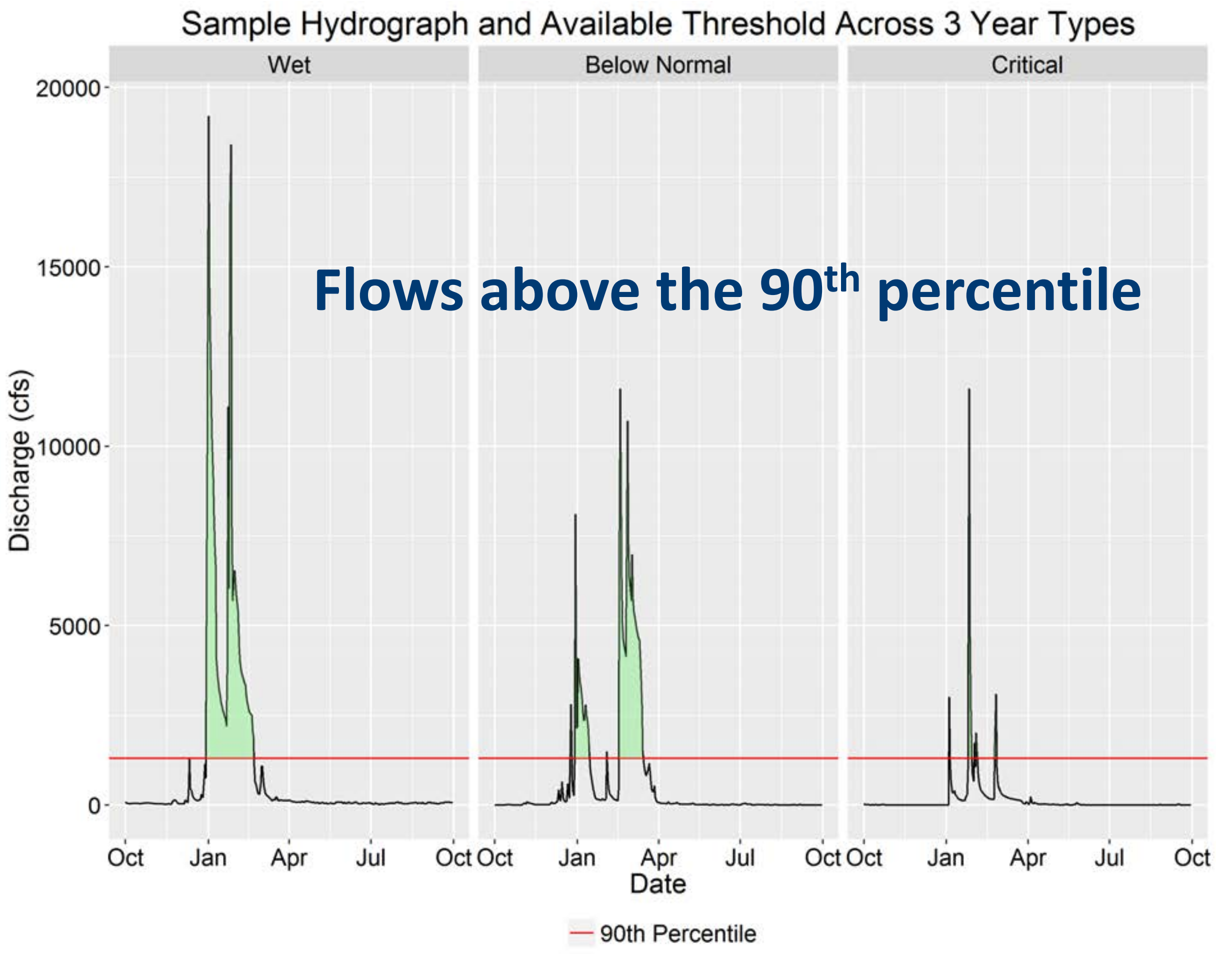


Photo credit: Sustainable Conservation

High-magnitude flows



Average total flow above 90th percentile

Outlet	Dec-Feb	Nov-Apr
Sac Valley	1.15 MAF	1.88 MAF
SJ Valley	0.5 MAF	0.97 MAF

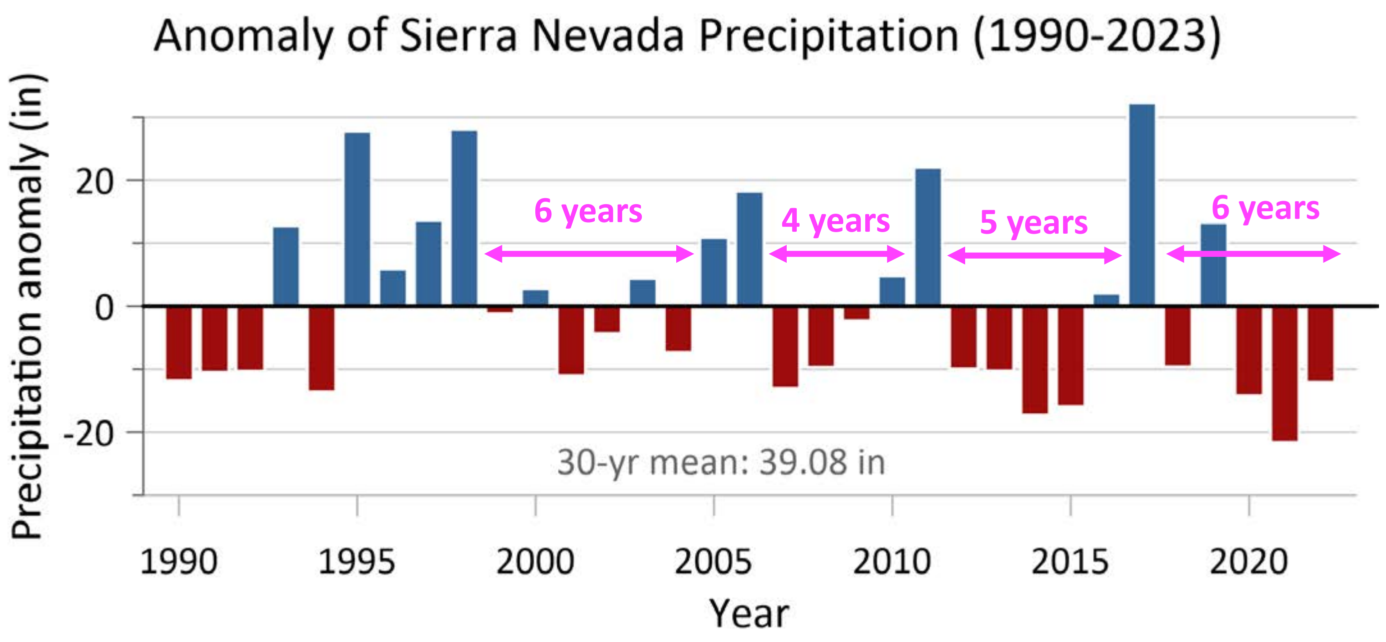
Average flow above 90th percentile during wet years

Outlet	Dec-Feb	Nov-Apr
Sac Valley	1.75 MAF	3.01 MAF
SJ Valley	0.65 MAF	1.21 MAF

Averages were calculated over period 1970-2015

Kocis & Dahlke, 2017, *ERL*

High-magnitude flows



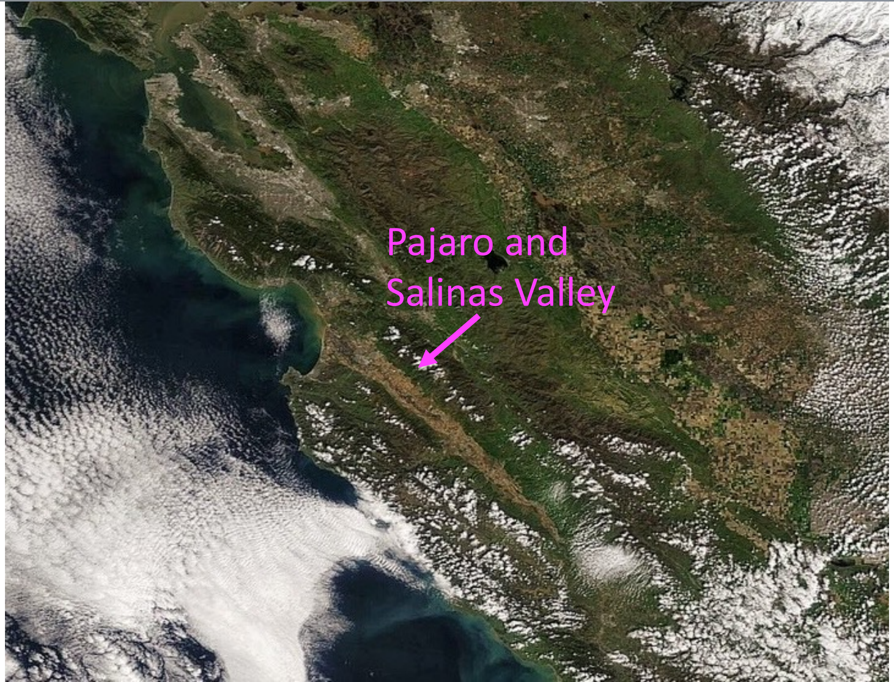
- HMF availability is 4.5 out of 10 years in San Joaquin Valley and 7/10 in Sacramento Valley.
- On average we see 20-40 days with HMF in San Joaquin Valley and 30-50 days of HMF in Sacramento Valley.

Wet years provide 50% to 125+% more flow than average years.
To capture infrequent HMF, we need large recharge areas…

HMF = high-magnitude flow


How do we capture large amounts of water in a short time?

UNMANAGED RECHARGE

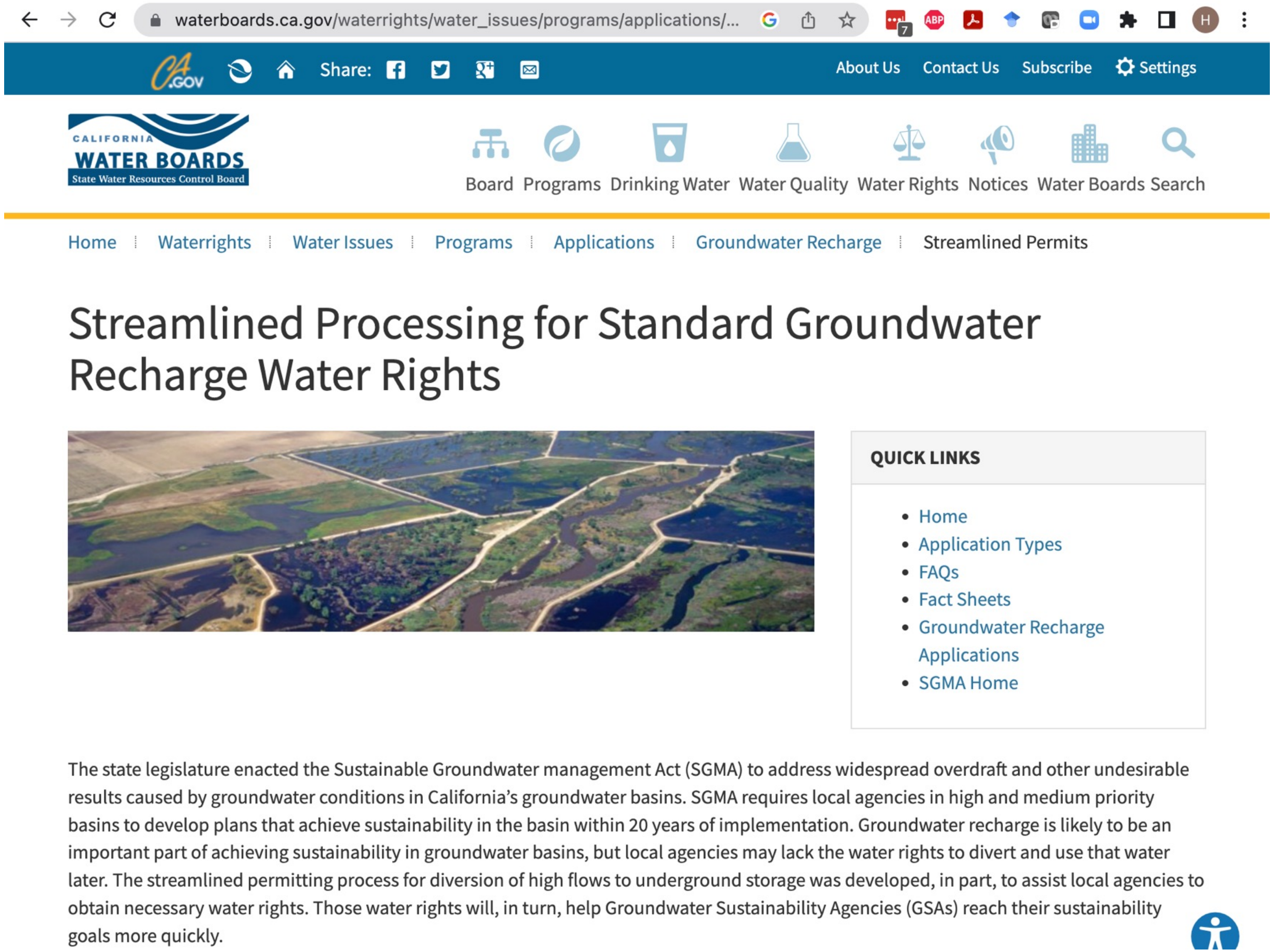


MANAGED RECHARGE

Photo credit: Sustainable Conservation

Photo credit: Tulare Irrigation District

California Flood-MAR program


waterboards.ca.gov/waterrights/water_issues/programs/applications/...

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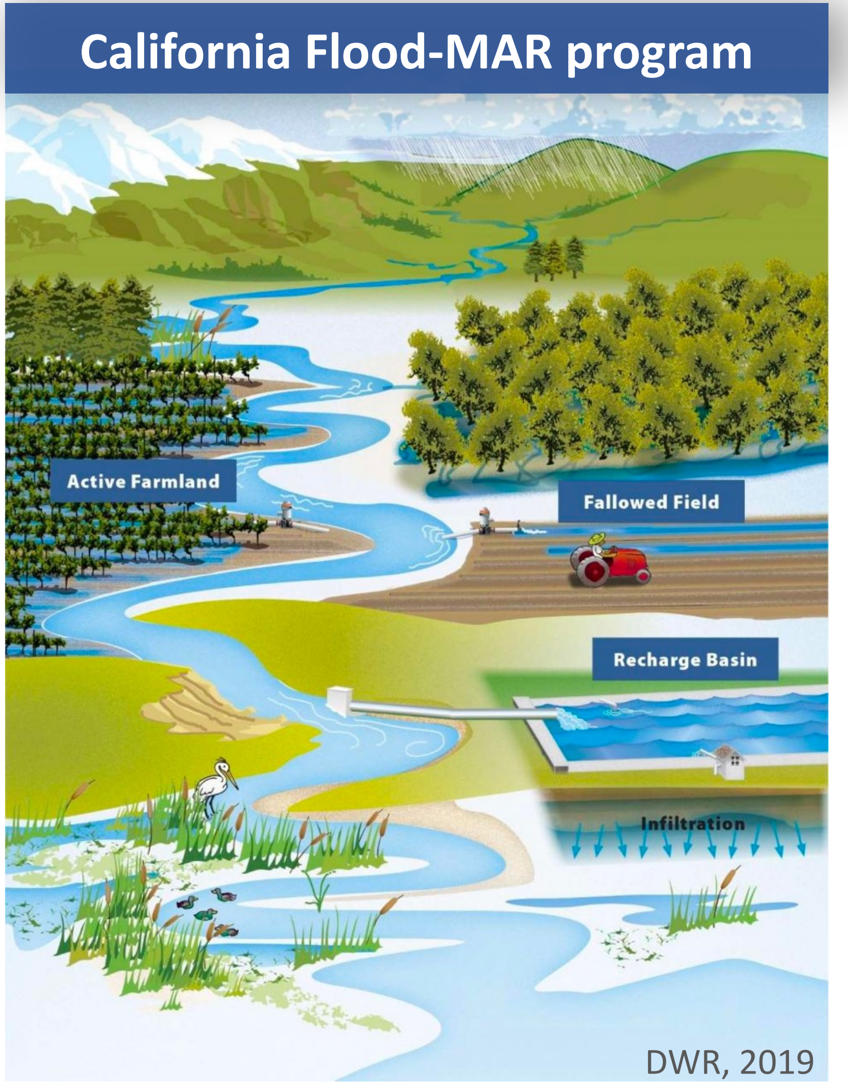
Streamlined Processing for Standard Groundwater Recharge Water Rights

QUICK LINKS

- Home
- Application Types
- FAQs
- Fact Sheets
- Groundwater Recharge Applications
- SGMA Home

The state legislature enacted the Sustainable Groundwater management Act (SGMA) to address widespread overdraft and other undesirable results caused by groundwater conditions in California's groundwater basins. SGMA requires local agencies in high and medium priority basins to develop plans that achieve sustainability in the basin within 20 years of implementation. Groundwater recharge is likely to be an important part of achieving sustainability in groundwater basins, but local agencies may lack the water rights to divert and use that water later. The streamlined permitting process for diversion of high flows to underground storage was developed, in part, to assist local agencies to obtain necessary water rights. Those water rights will, in turn, help Groundwater Sustainability Agencies (GSAs) reach their sustainability goals more quickly.



DWR, 2019

Photo credit: PPIC

Don Cameron, General Manager, Terranova Ranch

Bio-physical factors

- Crop tolerance
- Soil suitability
- Water availability
- Hydrogeology
- Conveyance capacity
- Water quality

Institutional factors

- Cost & incentives
- Water rights
- Permits
- Shared governance
- Ecosystem services and benefits

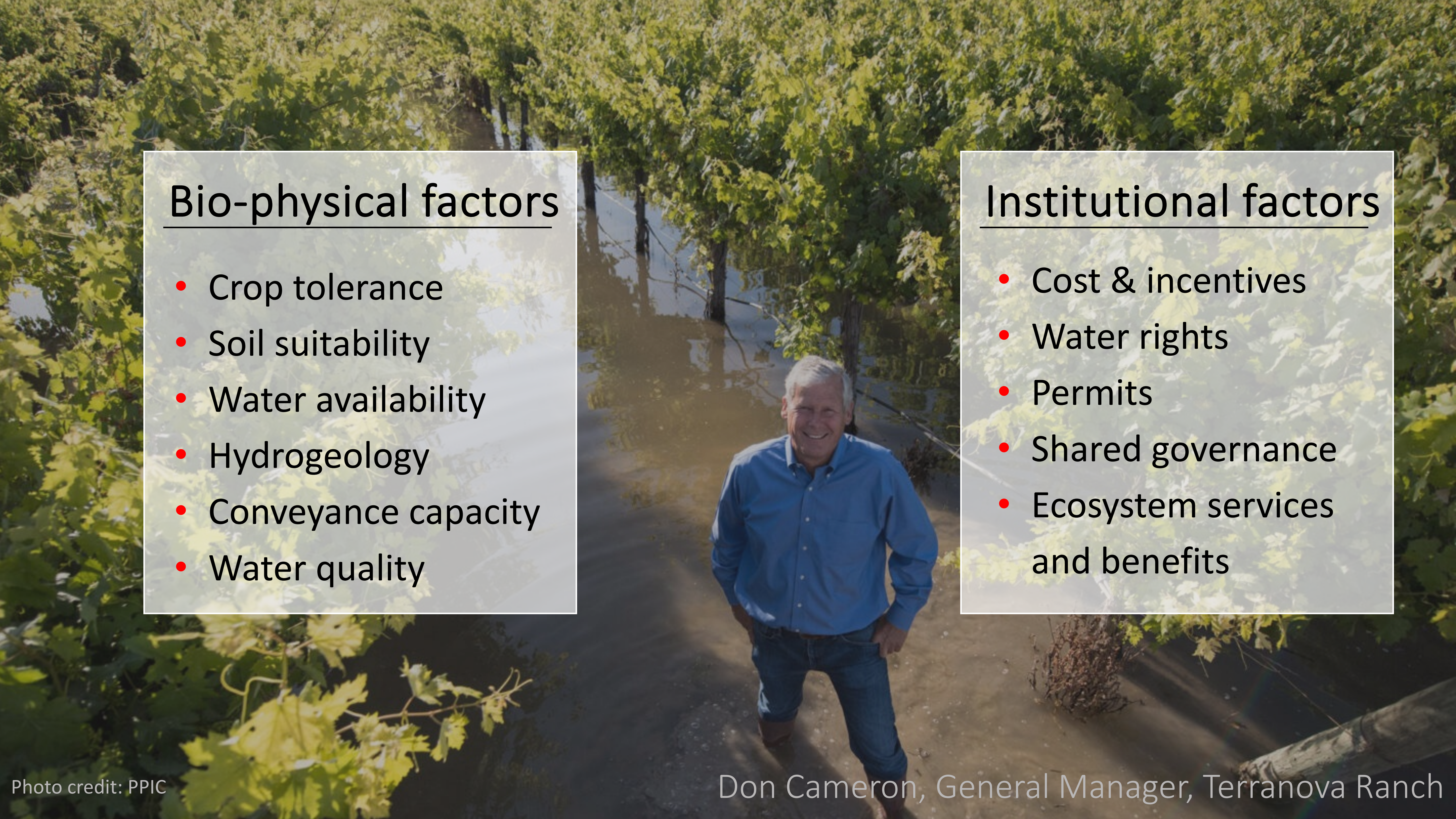
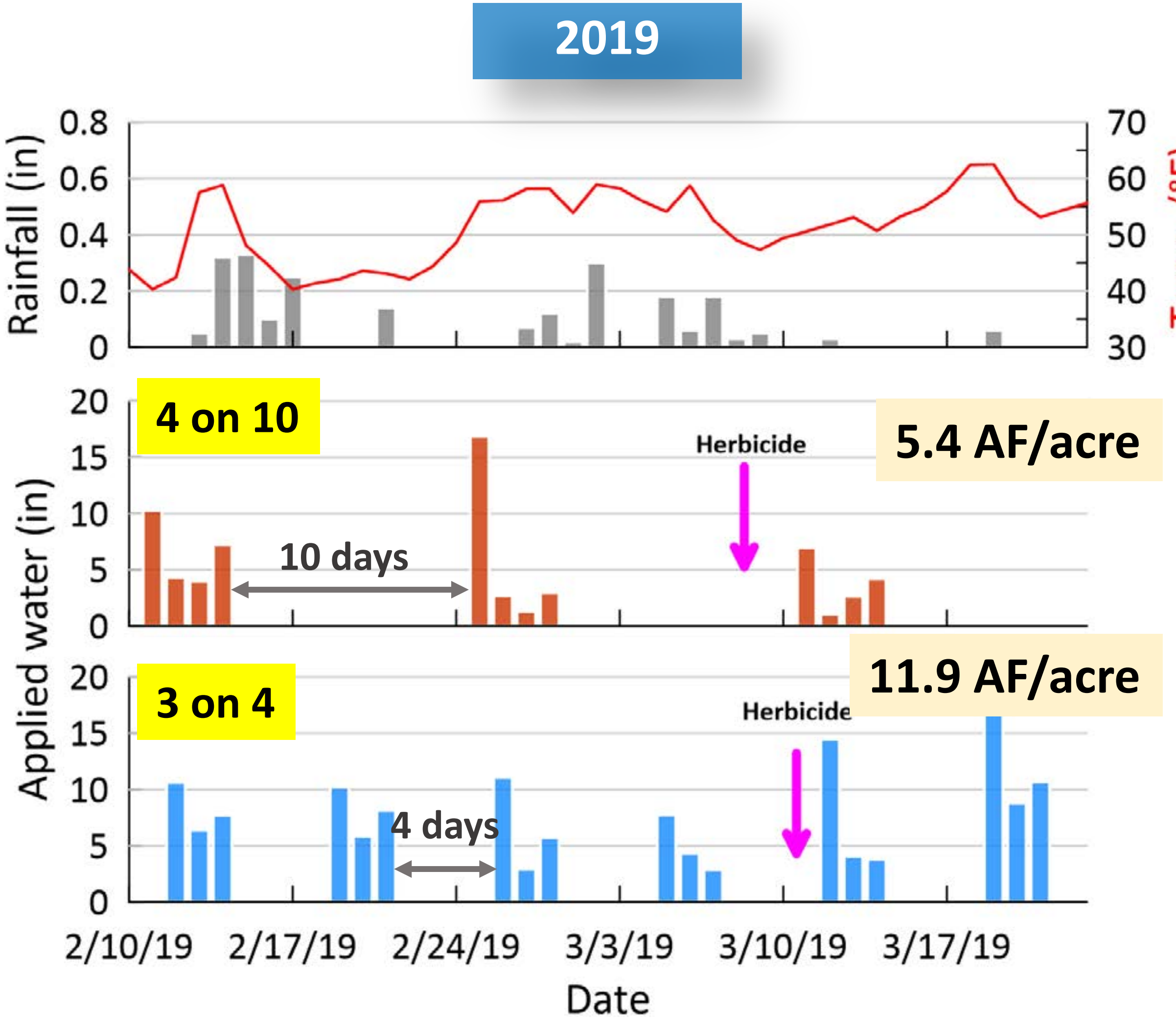


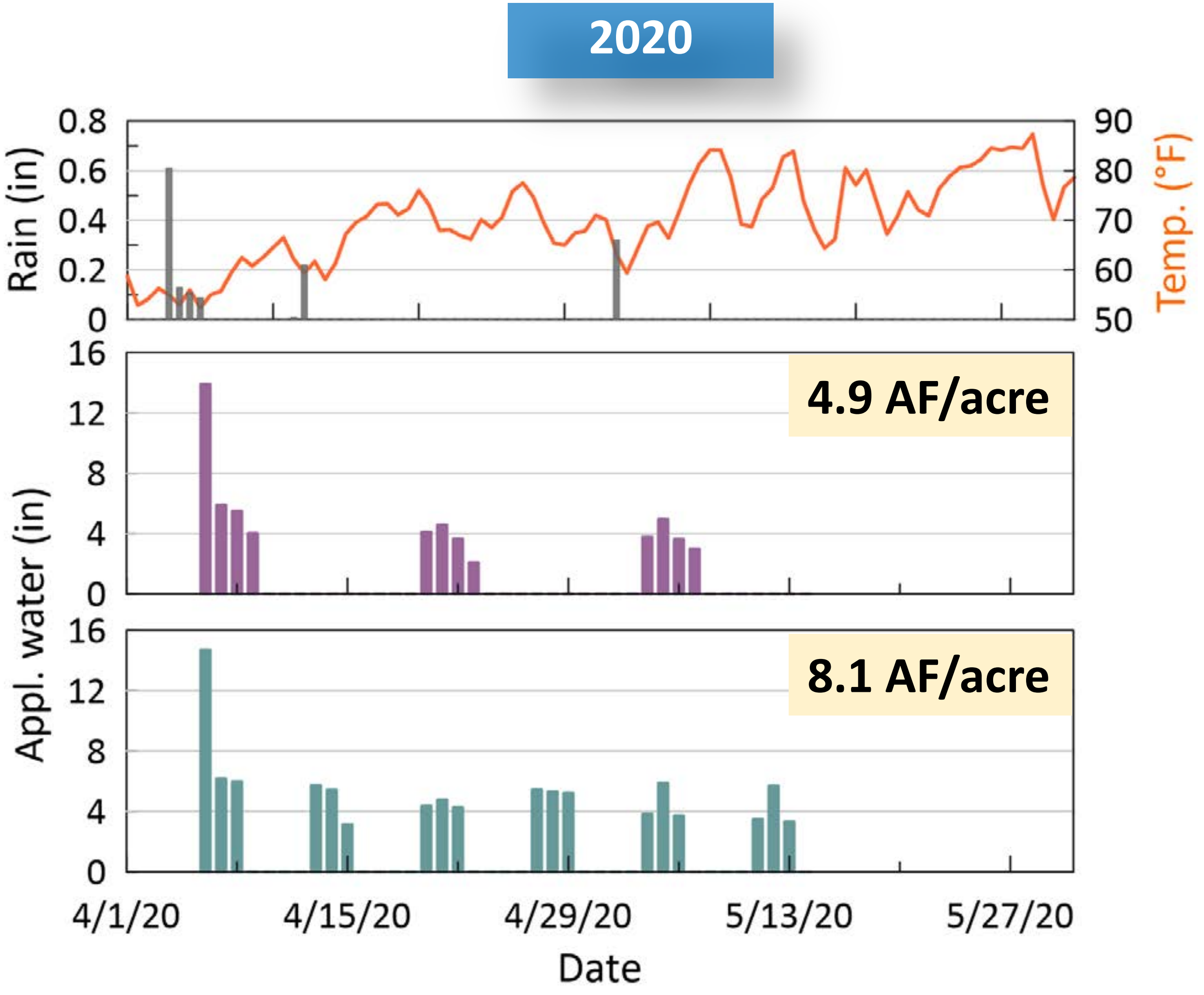
Photo credit: PPIC

Don Cameron, General Manager, Terranova Ranch


ALFALFA

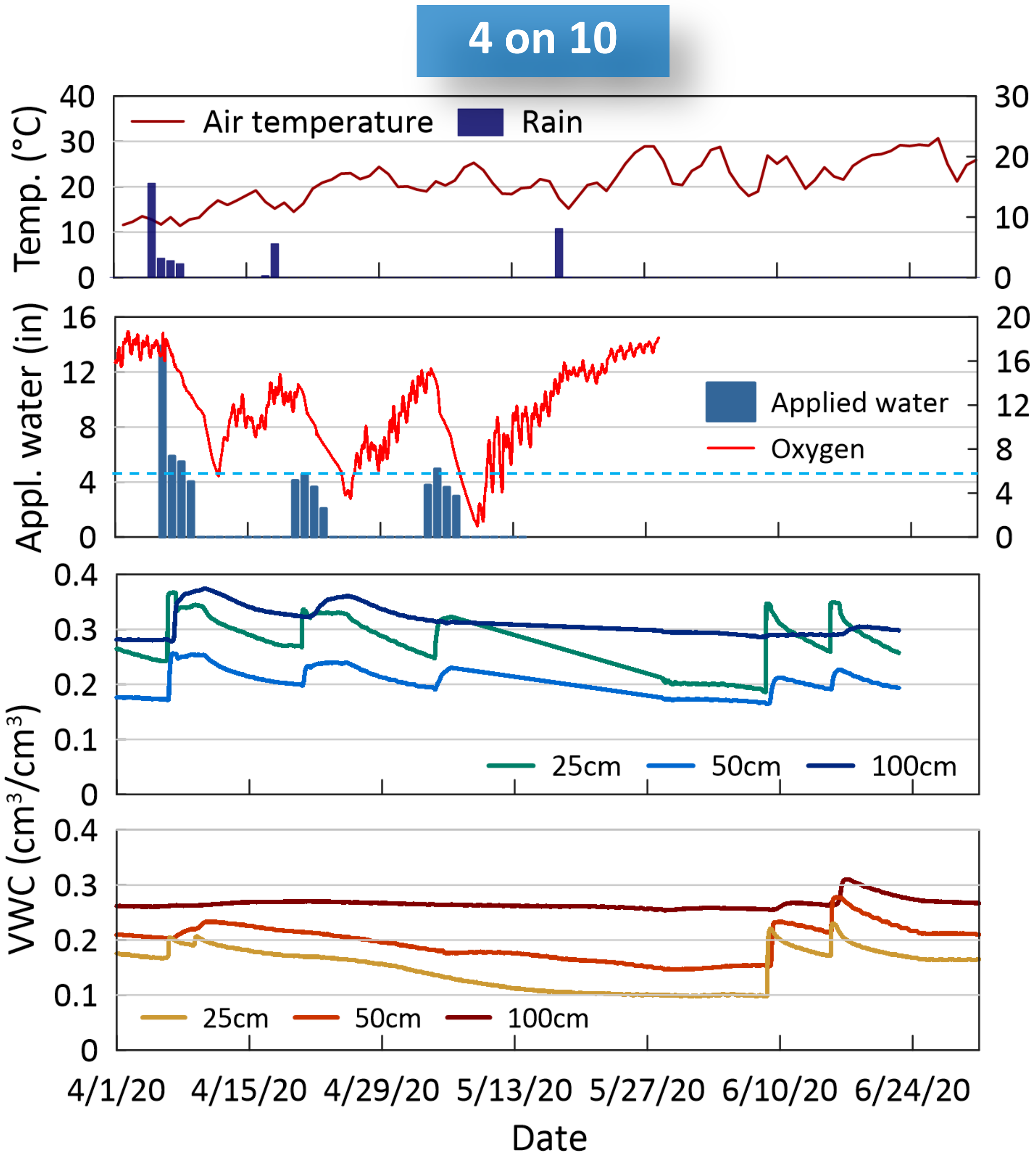
Treatments & Applied Water (2019 & 2020)

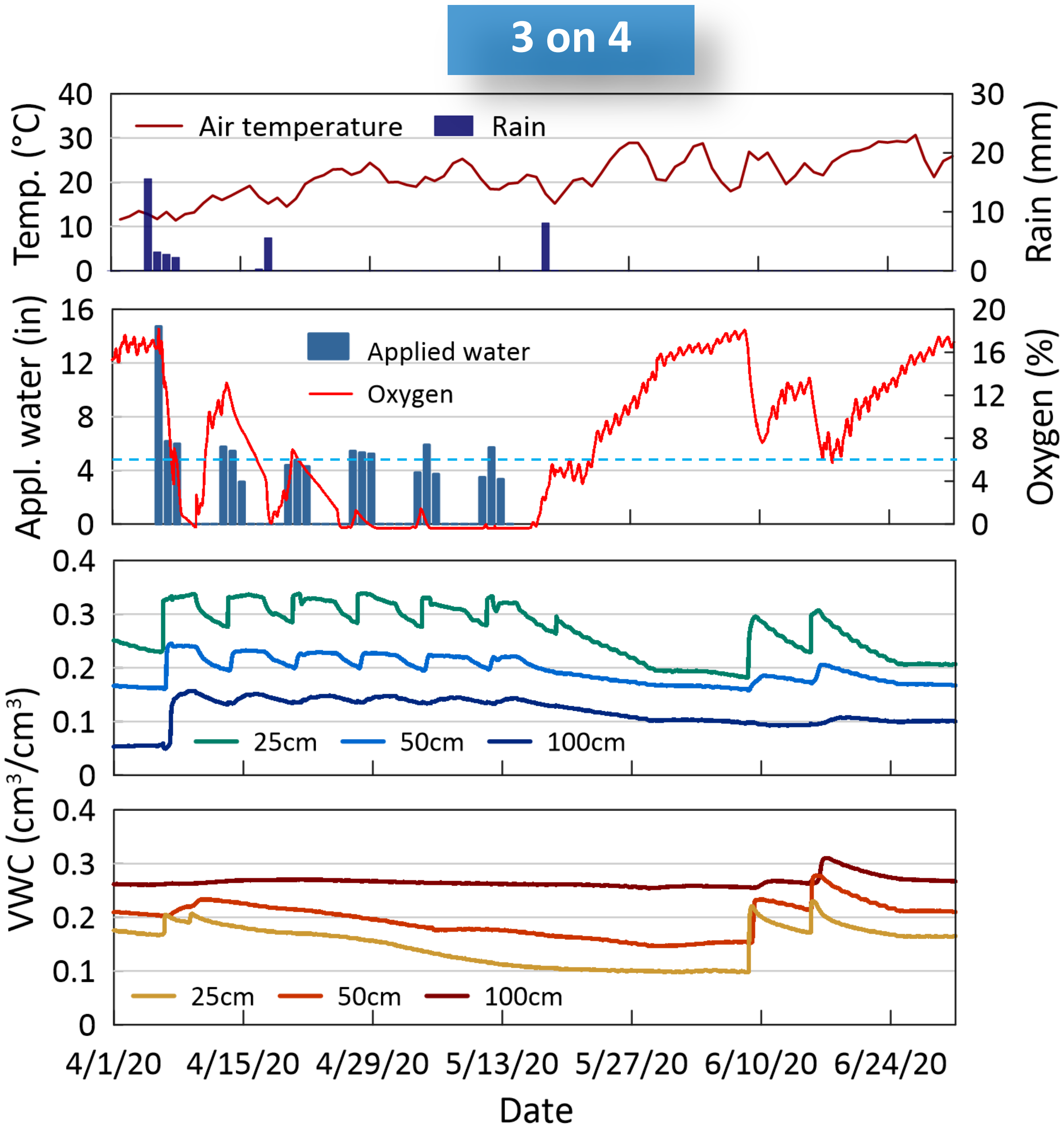




*Roundup and Poast (2.25 pt/ac) with a COC or MSO in mix

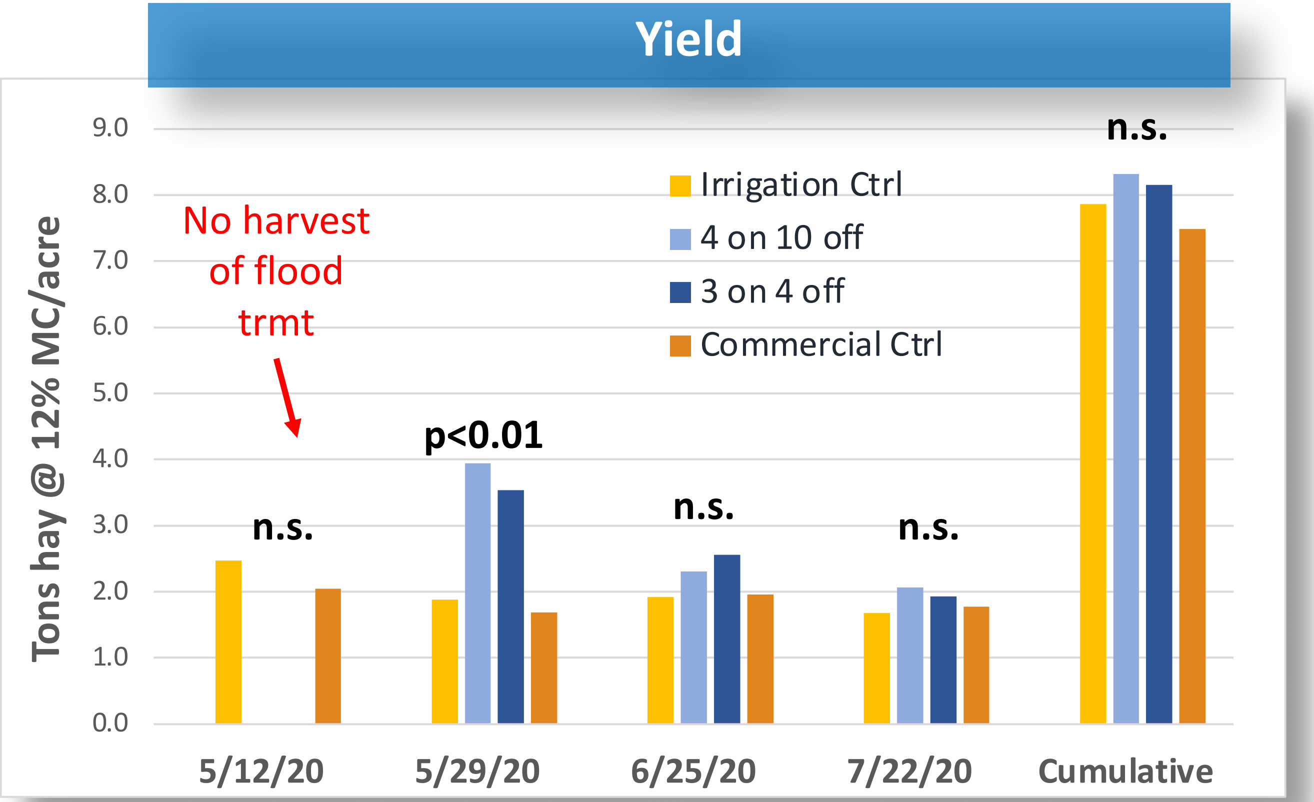
Soil oxygen & moisture content (2020)

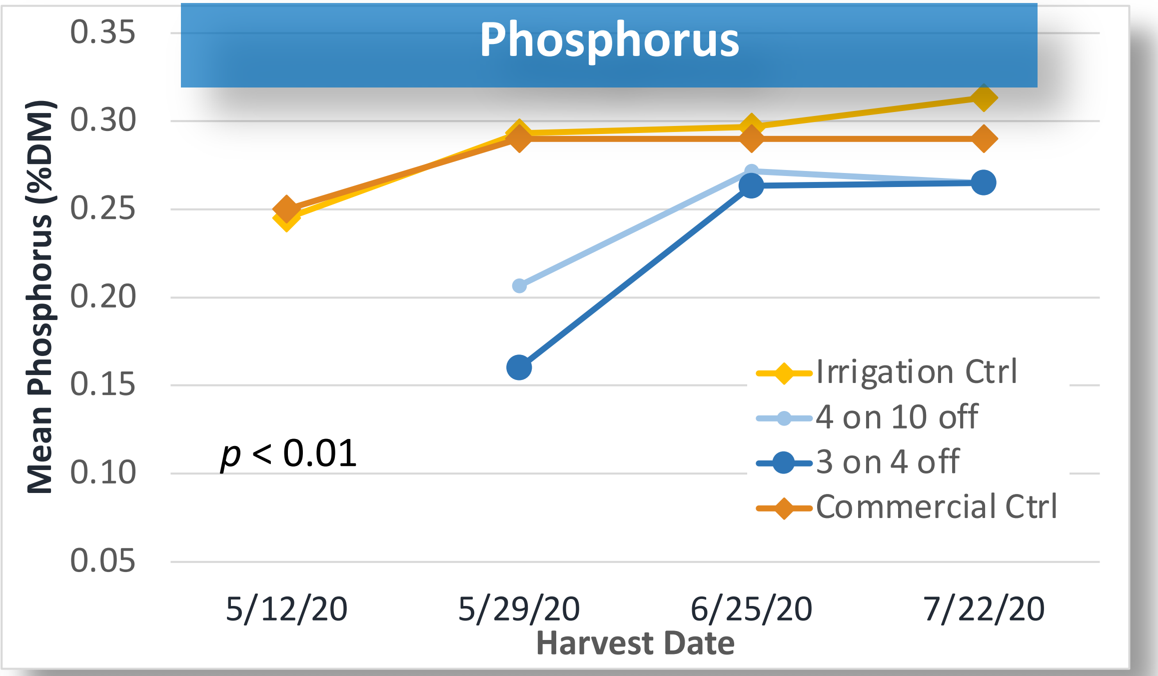


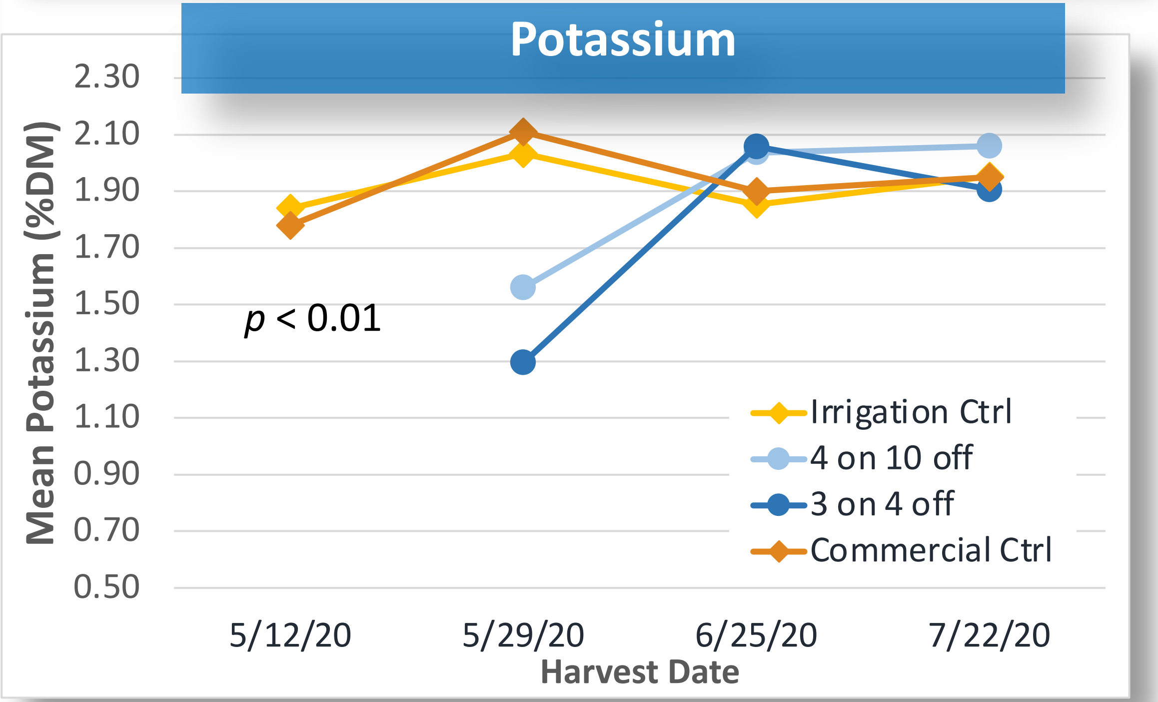


Yield

- Alfalfa in flood treatment could not be cut during 1st cutting → double yield during 2nd cutting
- 3rd and 4th cutting no statistical difference in yield







Forage Quality

aNDF = total insoluble fiber in feeds
ADF = least digestible fiber, subset of aNDF
Ash = total mineral content
CP = nitrogen content of alfalfa amino acids

Flooding did impact digestible fiber content

	Treatment	Amylase-treated neutral detergent fiber (aNDF)		Acid Detergent Fiber (ADF)		Ash		Crude Protein (CP)	
Commercial control	4	41 **Fair**	b	33.76 **Fair**	b	11.02 **High**	b	21.07 **Premium**	a
Irrigation control	1	42.2 **Fair**	b	35.02 **Fair**	b	13.22 **High**	a	22.22 **Supreme**	a
4 on 10 off	2	47.11 **Utility**	a	39.35 **Utility**	a	13.61 **High**	a	19.01 **Good**	b
3 on 4 off	3	48.28 **Utility**	a	40.03 **Utility**	a	13.29 **High**	a	18.11 **Good**	b
		$p < 0.001$		*$p < 0.001$*		*$p < 0.001$*		*$p < 0.001$*	

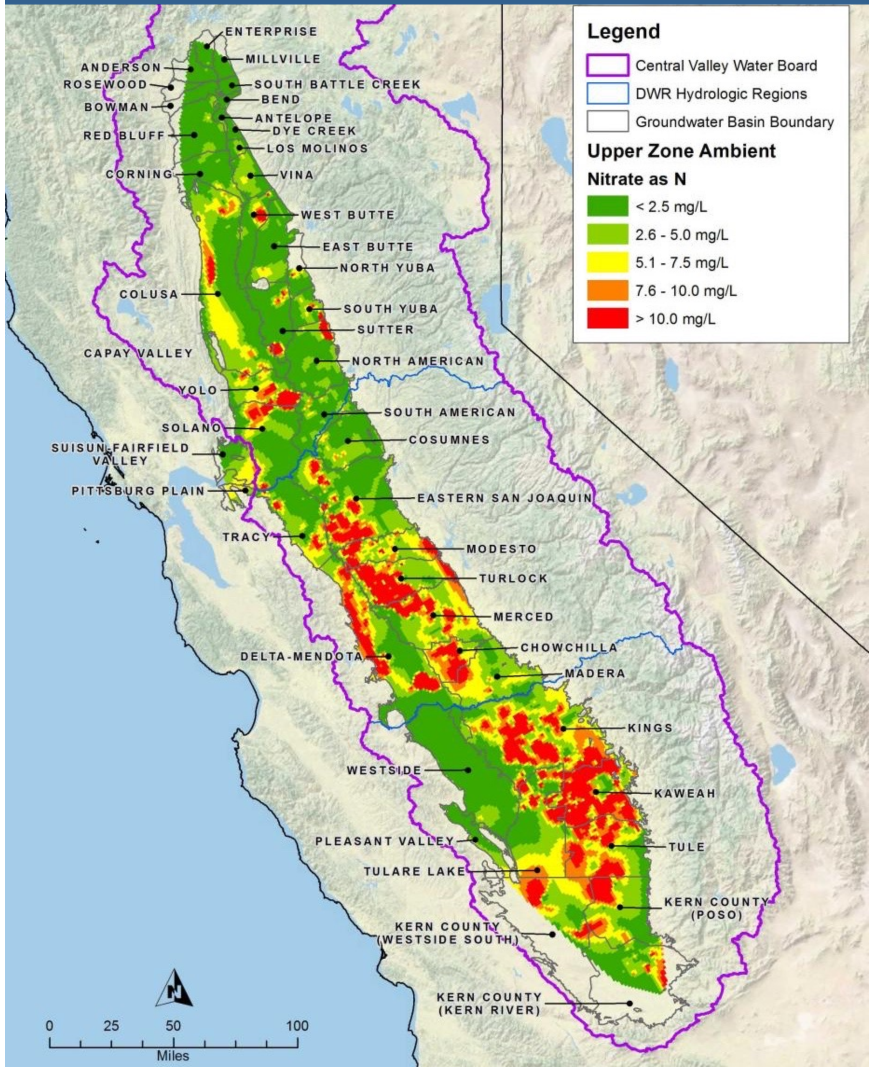
	ADF	NDF	RFV	TDN-100%	TDN-90%	CP-100%
Supreme	<27	<34	>185	>62	>55.9	>22
Premium	27-29	34-36	170-185	60.5-62	54.5-55.9	20-22
Good	29-32	36-40	150-170	58-60	52.5-54.5	18-20
Fair	32-35	40-44	130-150	56-58	50.5-52.5	16-18
Utility	>35	>44	<130	<56	<50.5	<16

ADF = Acid Detergent Fiber; NDF = Neutral Detergent Fiber; RFV = Relative Feed Value; TDN = Total Digestible nutrients. RFV calculated using the Wis/Minn formula. TDN calculated using the western formula. Values based on 100% dry matter, TDN both 90% and 100%.

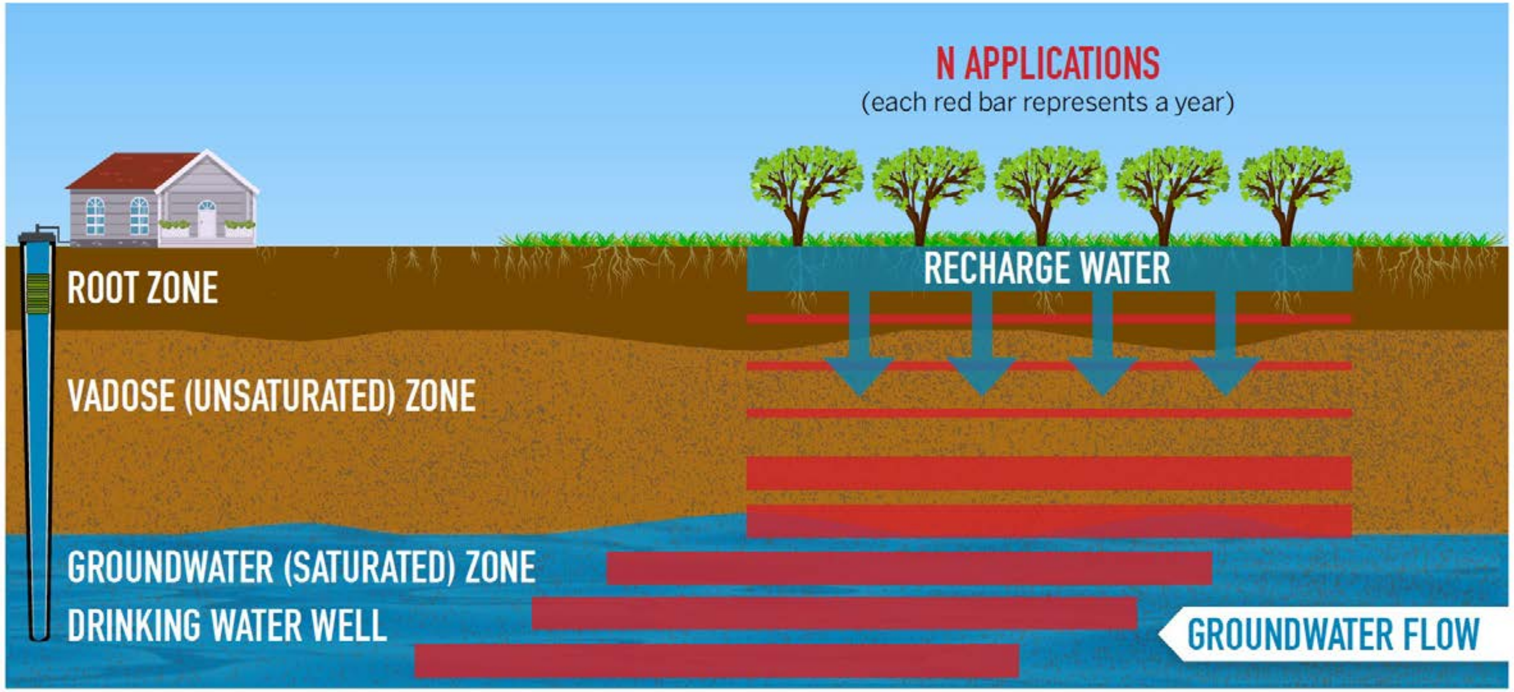

WATER QUALITY

Risk of groundwater contamination

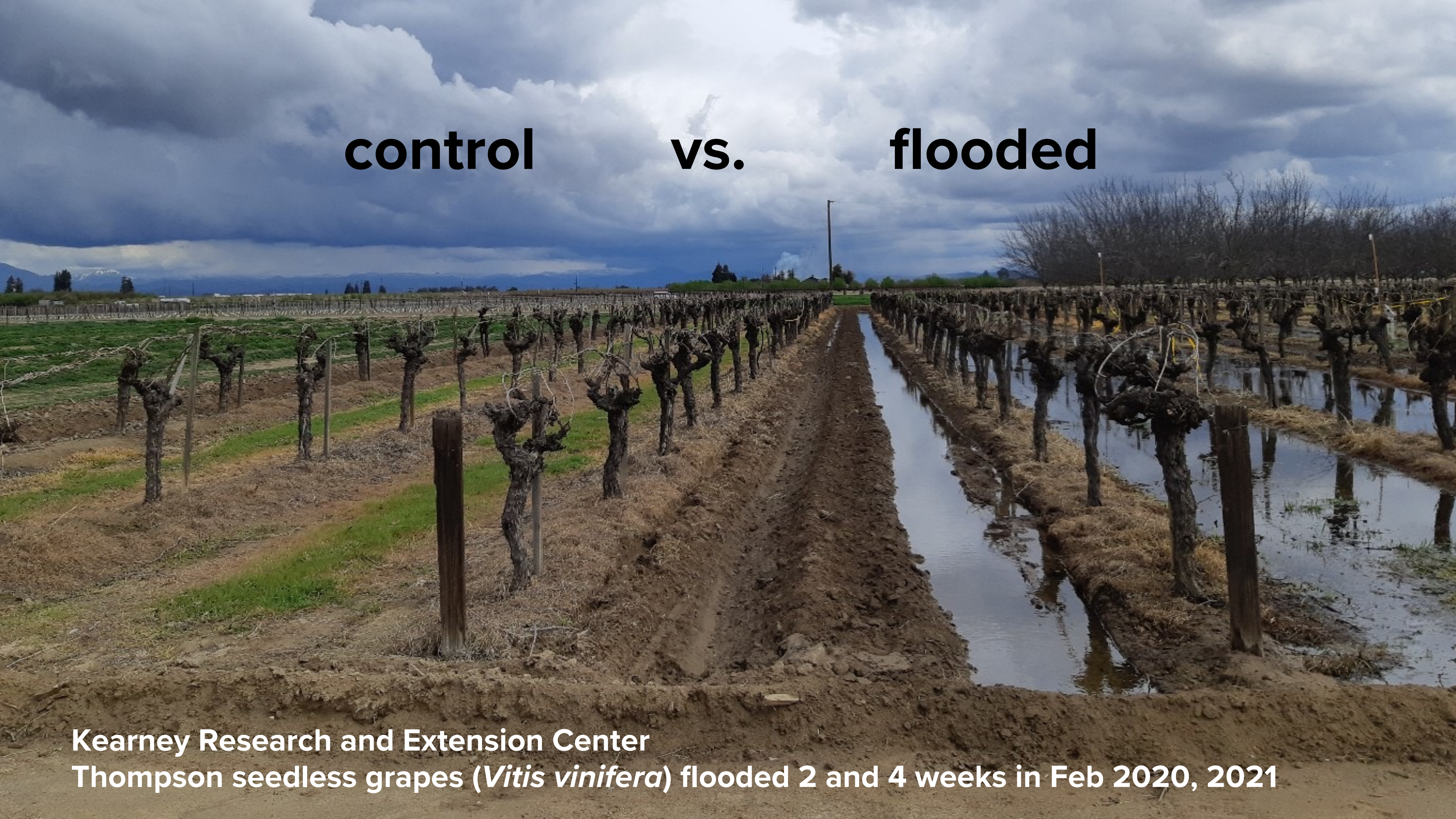
Nitrate in shallow groundwater



Source: CV-Salts Coalition



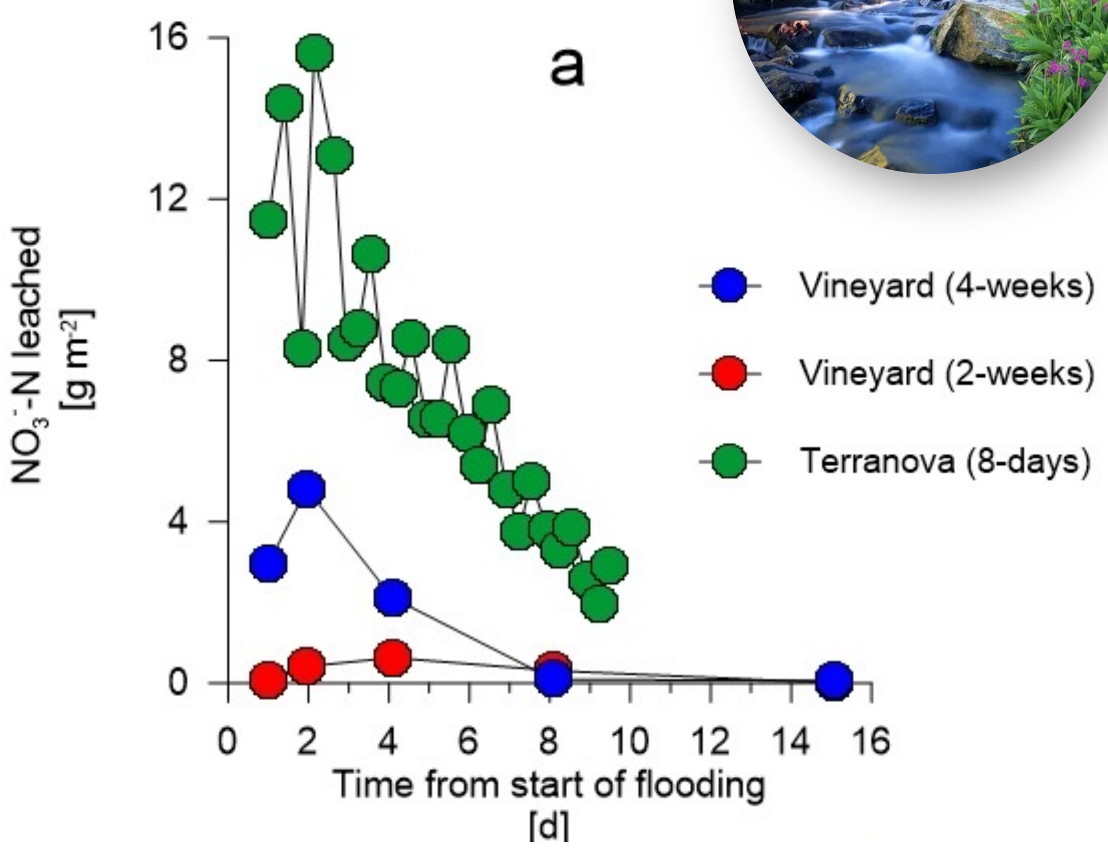
https://suscon.org/wp-content/uploads/2021/06/Protecting-Groundwater-Quality-While-Replenishing-Aquifers.pdf

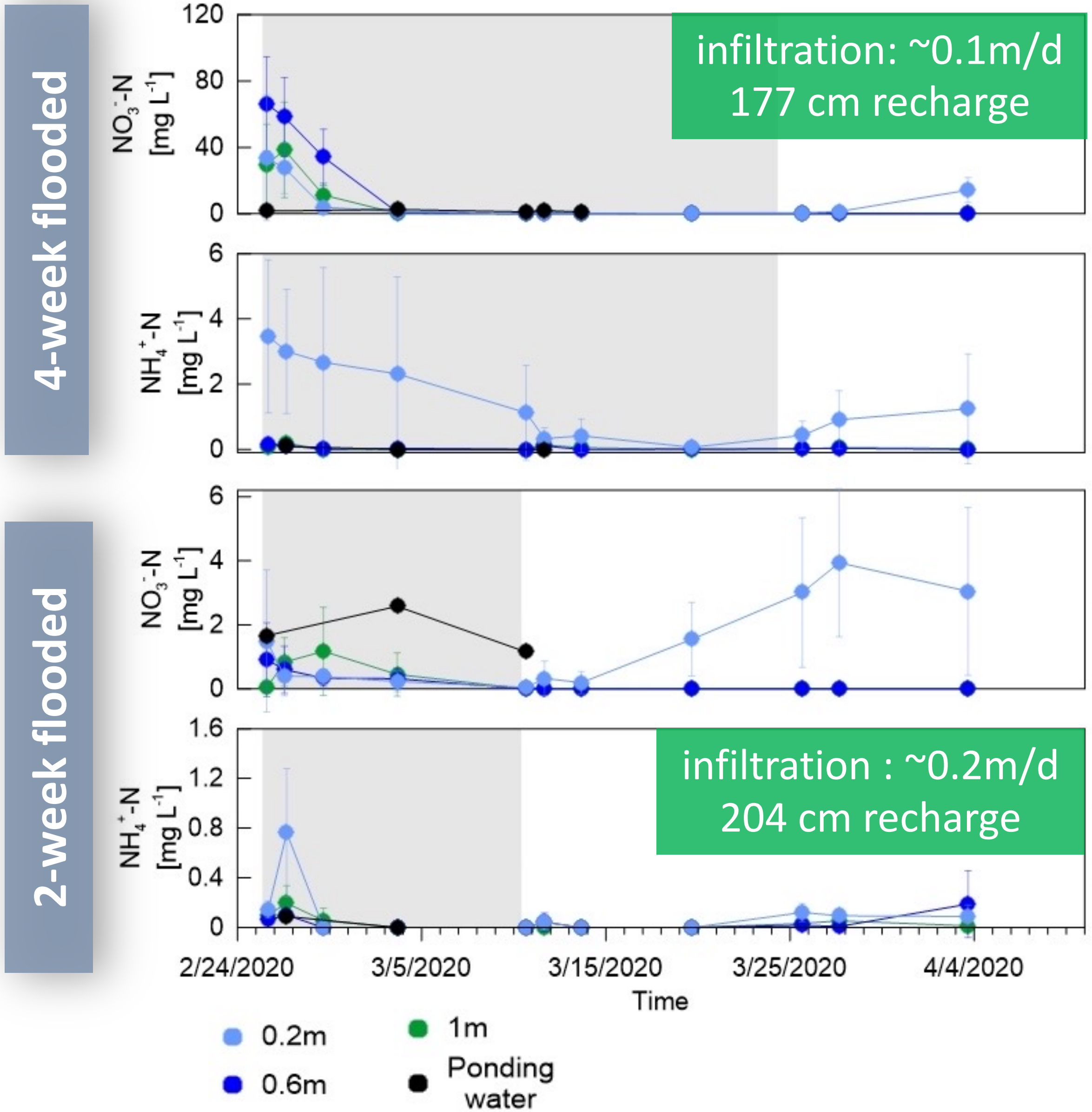


Kearney Research and Extension Center
Thompson seedless grapes (*Vitis vinifera*) flooded 2 and 4 weeks in Feb 2020, 2021

Site-specific nitrogen management

Low N source water

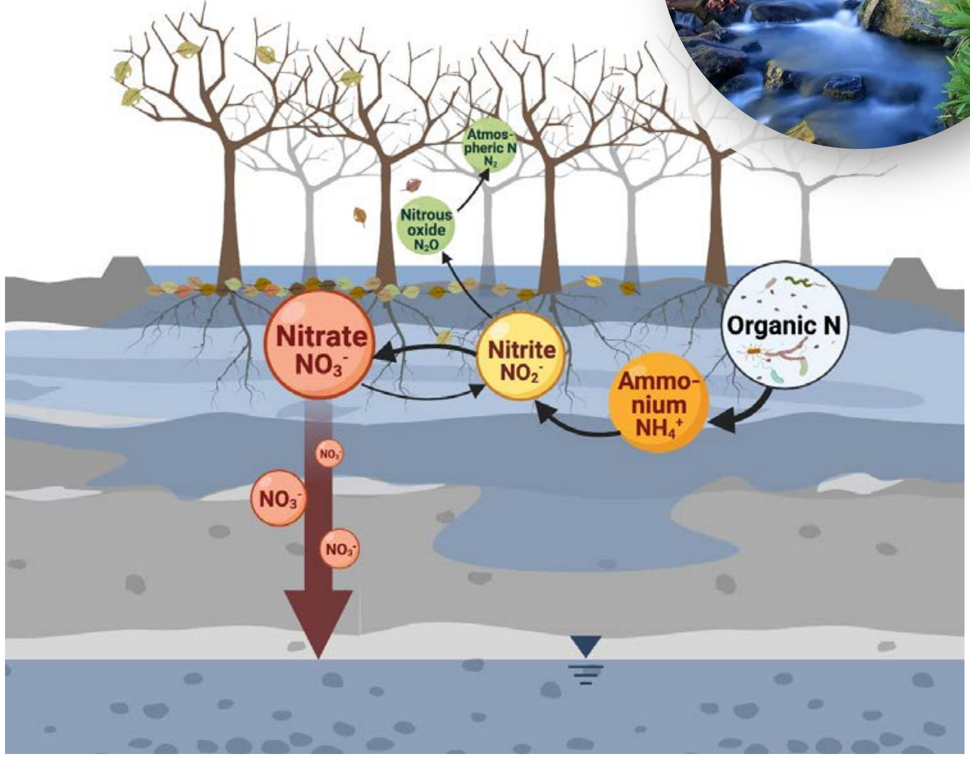


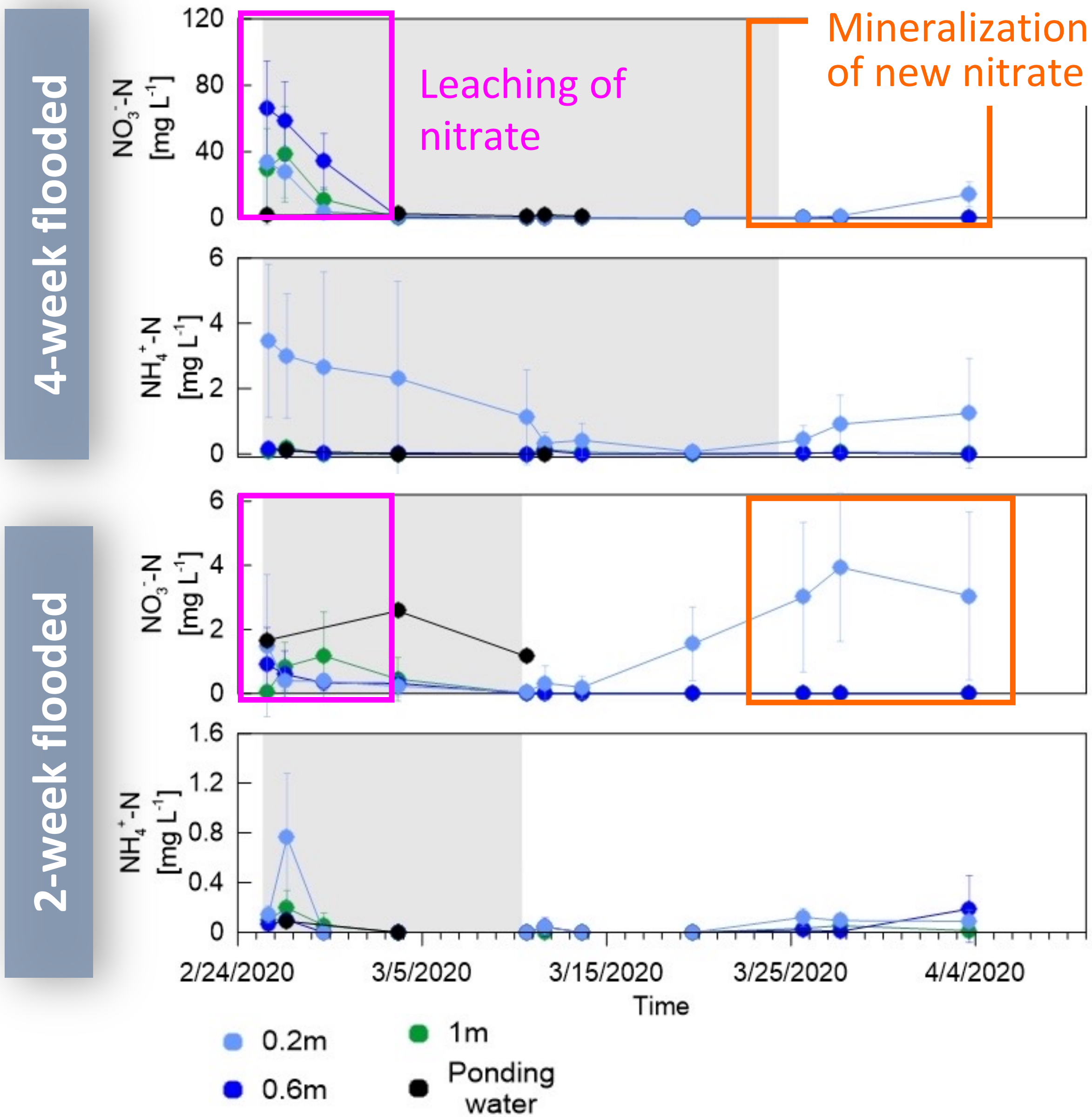


Levintal et al. 2022, *ES&T in prep*

Site-specific nitrogen management

Low N source water

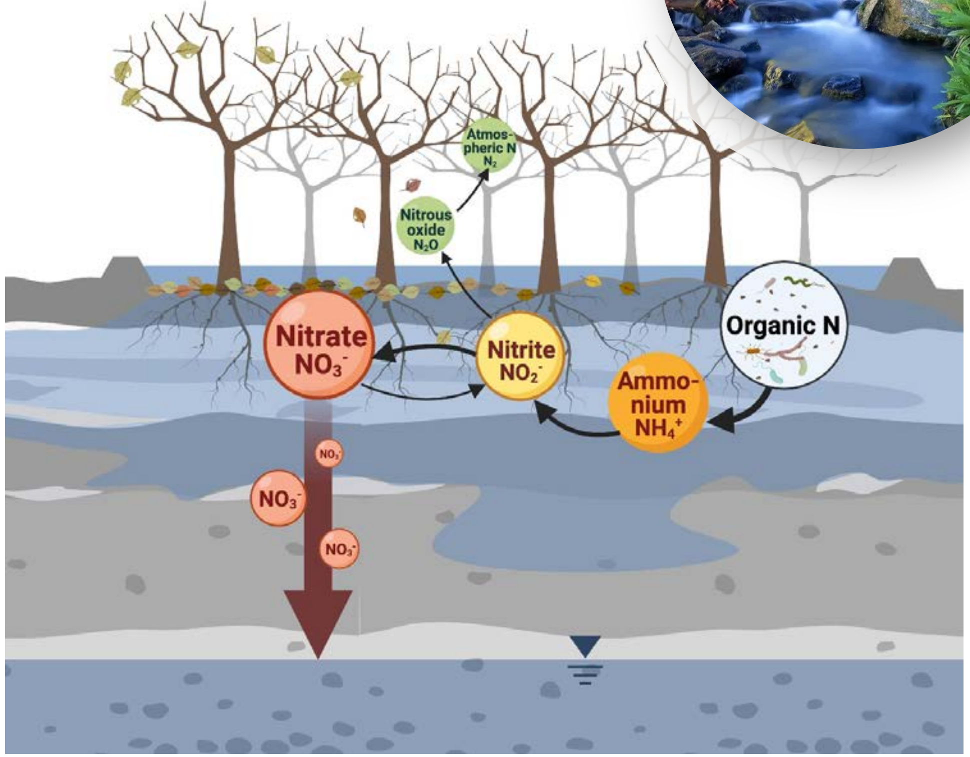




Murphy et al. 2021, *VZJ;* Levintal et al. 2022, *Crit. Rev ES&T*

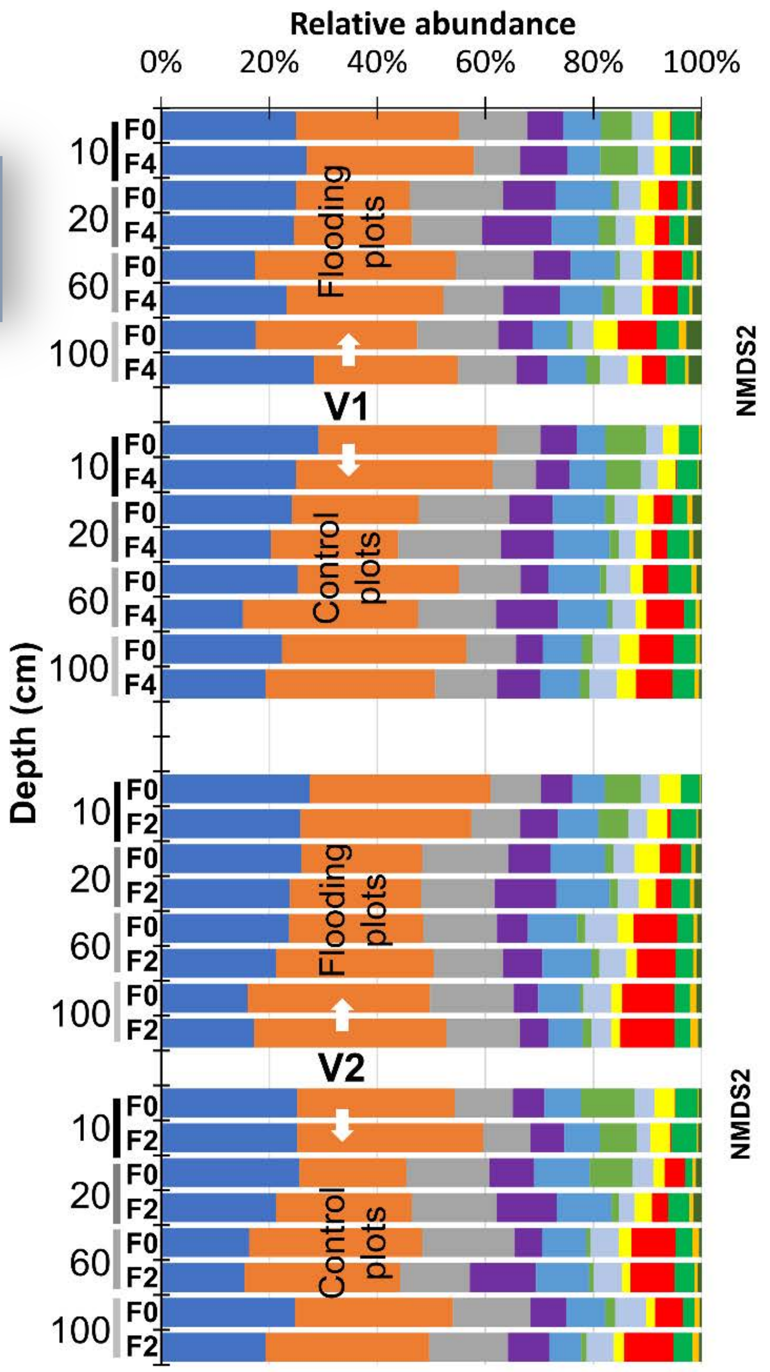
Nitrogen cycling processes

Low N source water



Soil microbial communities

- Proteobacteria
- Firmicutes
- Planctomycetota
- Crenarchaeota
- Actinobacteriota
- Chloroflexi
- Verrucomicrobiota
- Nitrospirota
- Acidobacteriota
- Bacteroidota
- Methylomirabilota
- Desulfobacterota

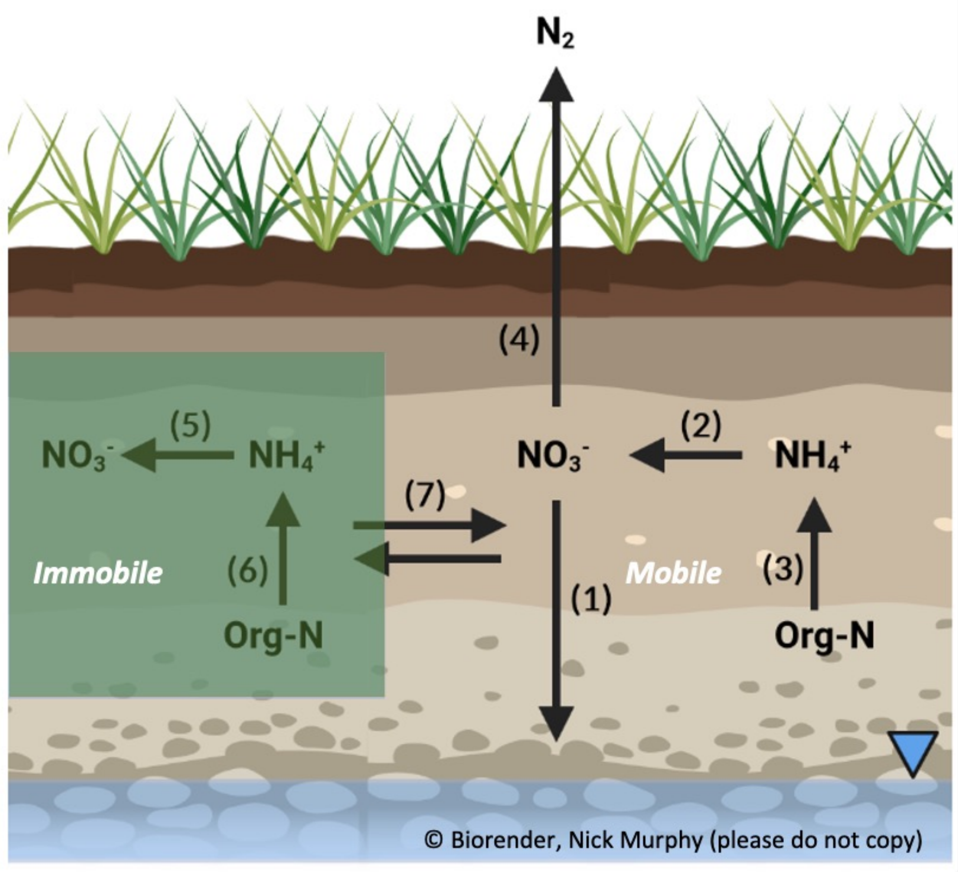


Murphy et al. 2021, *VZJ;* Levintal et al. 2022, *Crit. Rev ES&T*

Huang et al., ISMEJ, in review.

Reactive nitrate leaching transport modeling

- **Conditional kinetic HP1-MIM (HYDRUS-1D & PHREEQC Model)**
- Dual-porosity, mobile-immobile zone reactive nitrate transport model



Simulated Nitrogen Transformation processes

1. Leaching
2. Mobile Nitrification (1st order)
3. Mobile Mineralization (1st order)
4. Immobile Nitrification
5. Immobile Mineralization
6. Denitrification
7. Mass transfer (mobile- immobile phase)

Murphy et al. 2023, submitted

Reactive nitrate leaching transport modeling

HYDRUS-1D calculates

Water Flow (Richard's Eq.)

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S(h)$$

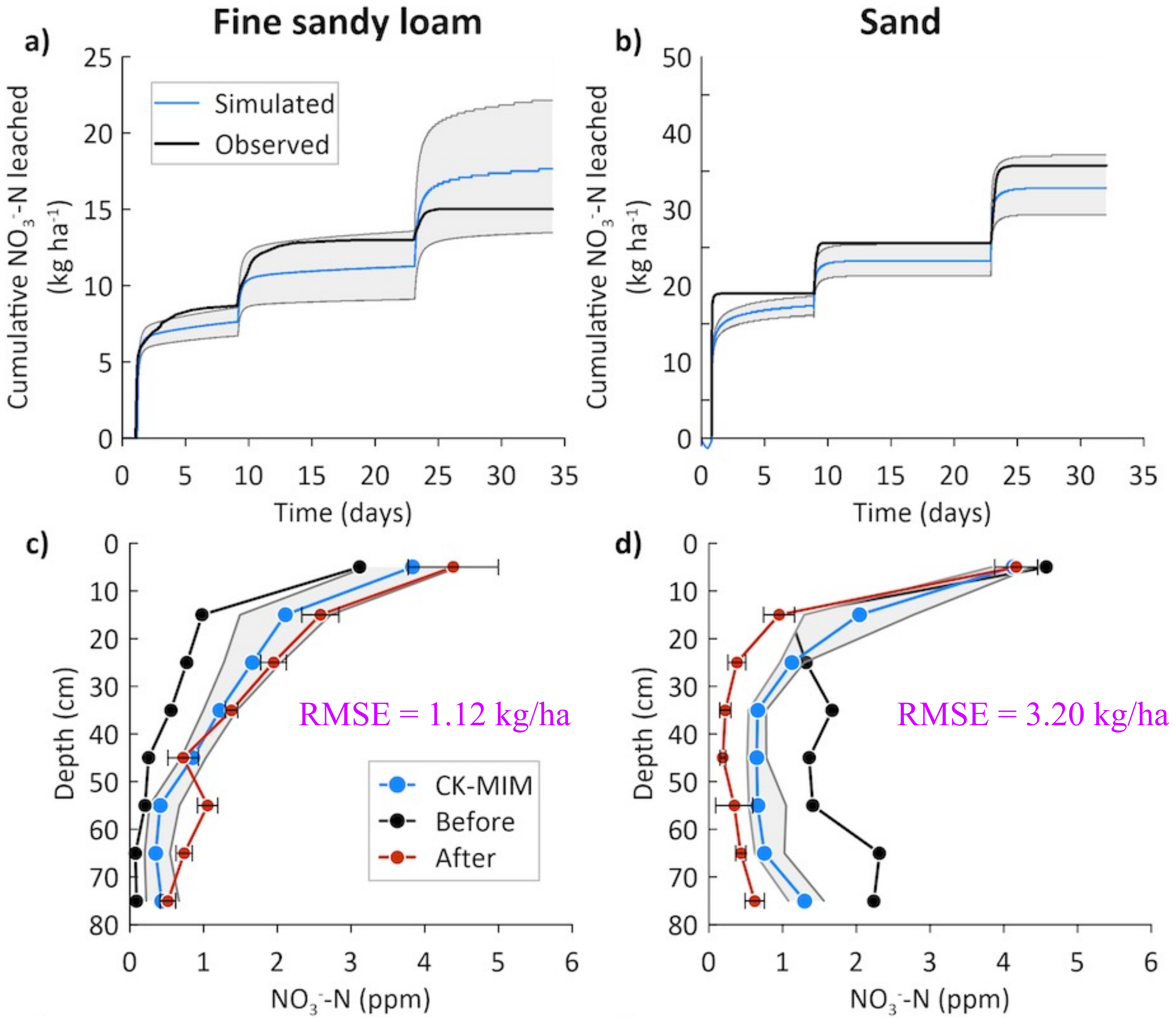
Solute Transport (ADE + Sinks + Biogeochemical Reactions)

$$\frac{\partial \theta c_i}{\partial t} = \frac{\partial}{\partial x}\left(\theta D_i^w \frac{\partial c_i}{\partial x}\right) - \frac{\partial q c_i}{\partial x} - S c_{r,i} + R_i$$

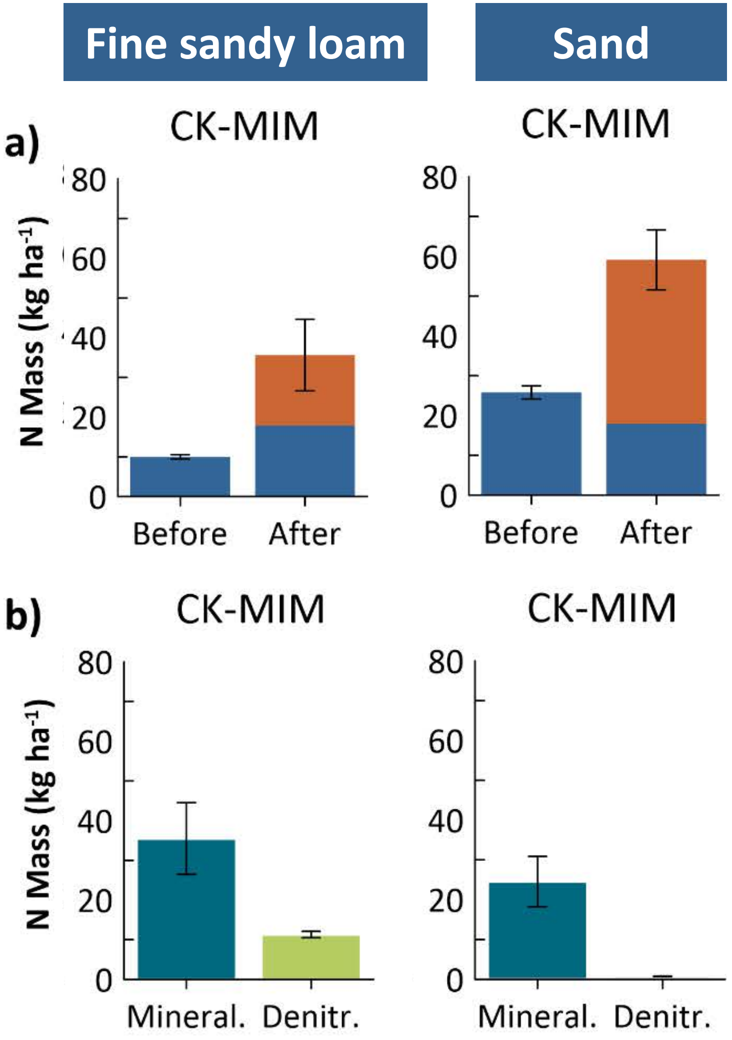
PHREEQC calculates

- Denitrification (zero-order kinetic reaction; rates estimated from lab incubation data, conditional on %PSF)
- Nitrification (first-order kinetic reaction; rates assumed to be non-limiting, conditional on %PSF)
- Mineralization (first-order kinetic reaction; rates estimated from lab incubation data, conditional on water content and temperature)
- Adsorption of org-N, org-C, ammonium (Freundlich Isotherm, parameters from literature)

Murphy et al. 2023, submitted



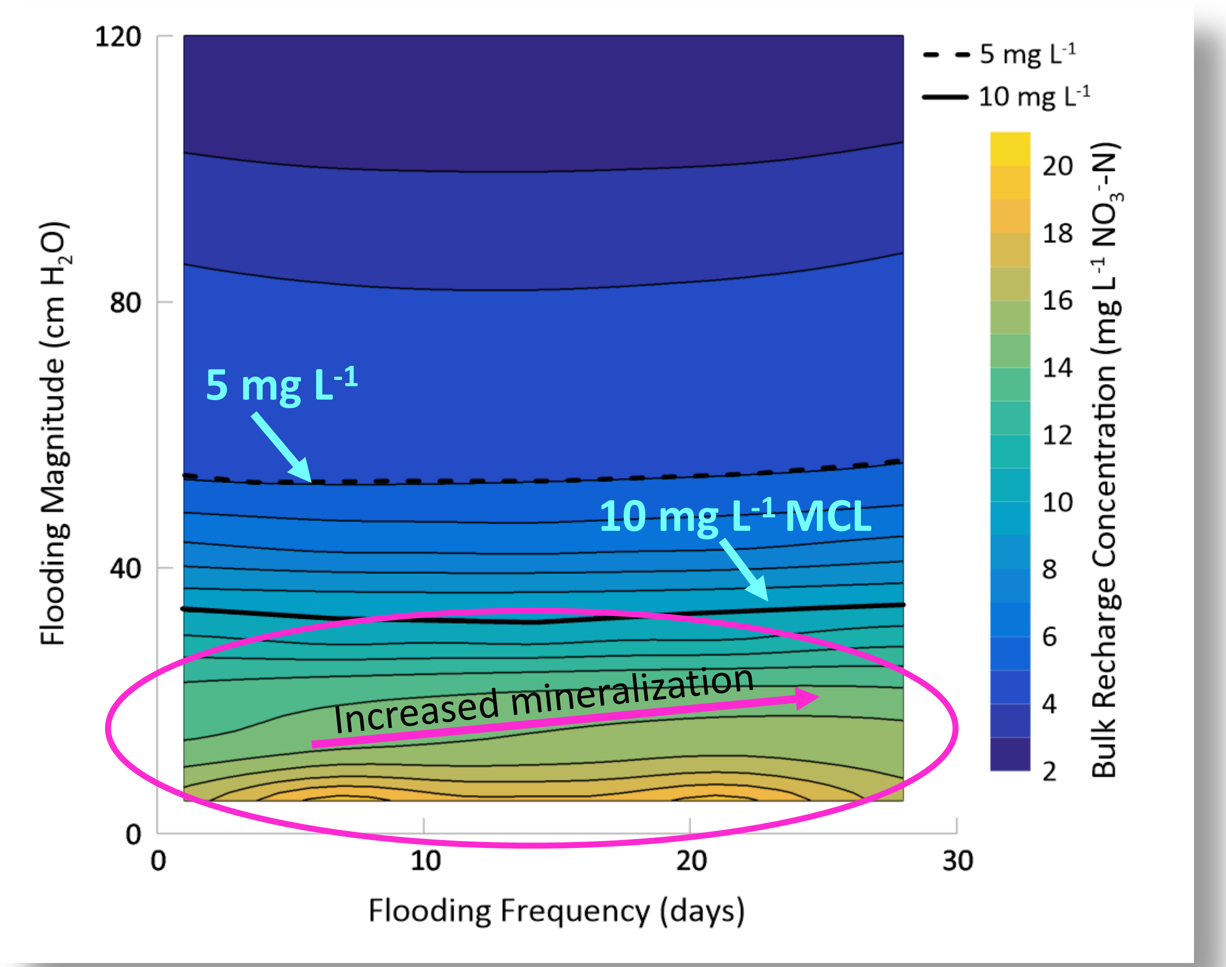
a)
Fine sandy loam
Simulated
Observed
Cumulative NO_3^--N leached (kg ha^{-1})
Time (days)
b)
Sand
c)
d)
Depth (cm)
NO_3^--N (ppm)
RMSE = 1.12 kg/ha
RMSE = 3.20 kg/ha
CK-MIM
Before
After



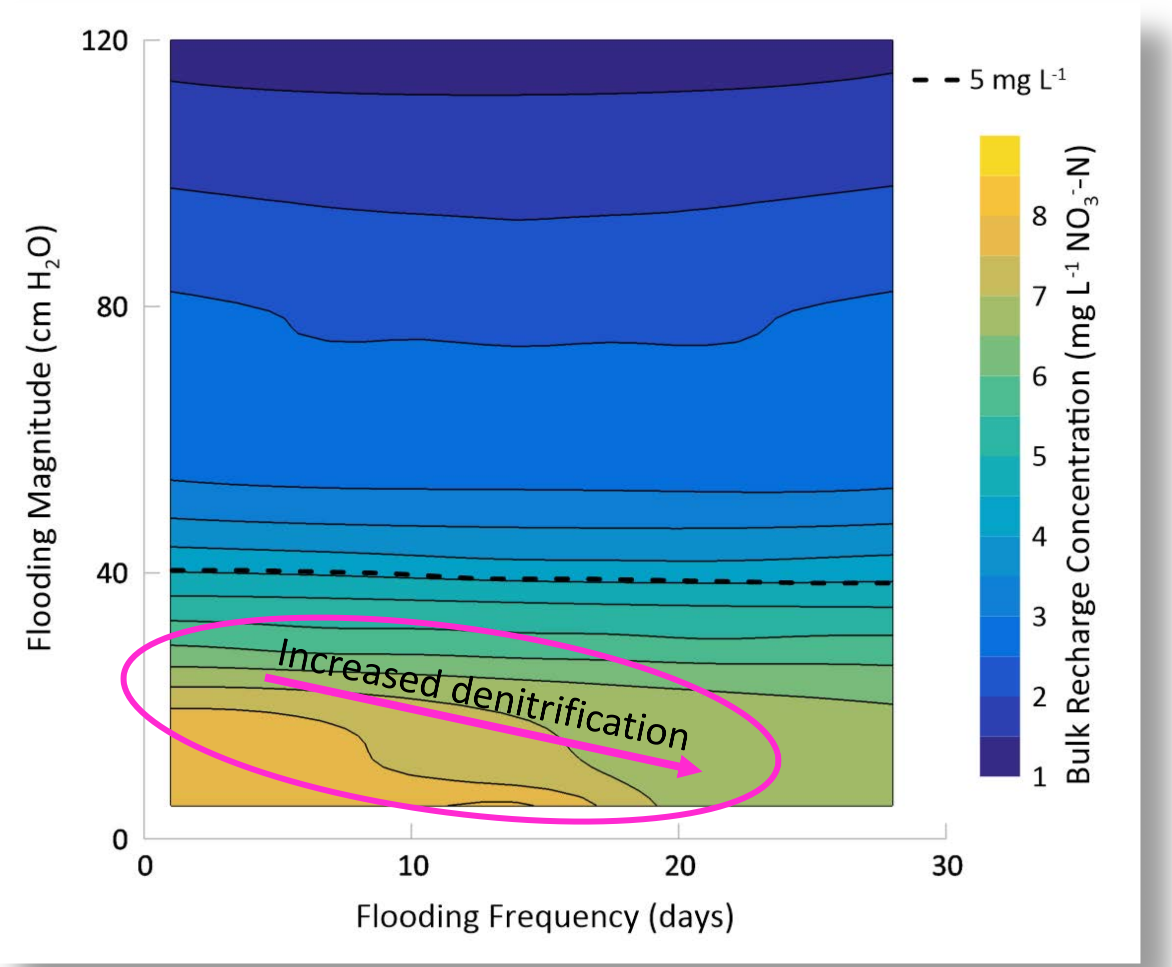
Fine sandy loam
Sand
a)
CK-MIM
N Mass (kg ha^{-1})
Before
After
b)
Mineral.
Denitr.

Role of flooding magnitude and frequency on nitrate leaching

Sand



Fine sandy loam



! Absolute values are influenced by initial soil nitrate concentrations…

Murphy et al. In Prep.


Effect of Ag-MAR on groundwater nitrate?

Nitrate leaching risk

Soil surface

Depth (ft)	Depth (m)
8 in	0.2 m
2 ft	0.6 m
3.3 ft	1 m
9.8 ft	3 m
16 ft	5 m

Flooding
- 4-weeks
- 3 plots, 7785 sqft each
- 10m average recharge

Sensors
- Soil moisture, EC, temperature
- O_2 (gaseous)
- Redox potential
- Ponding depth
- Water level

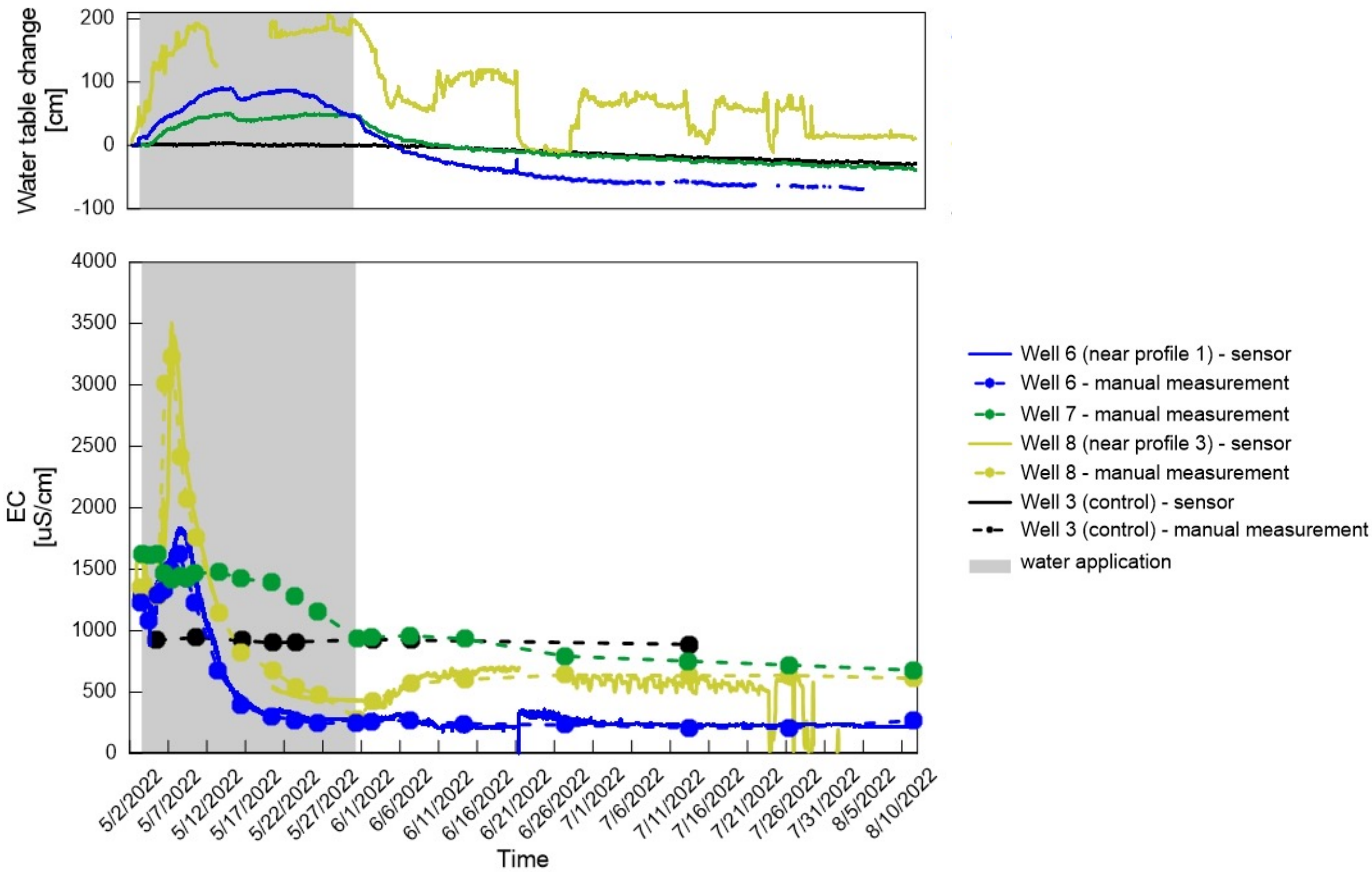
Sampling

Soil samples
Soil pore water
Groundwater

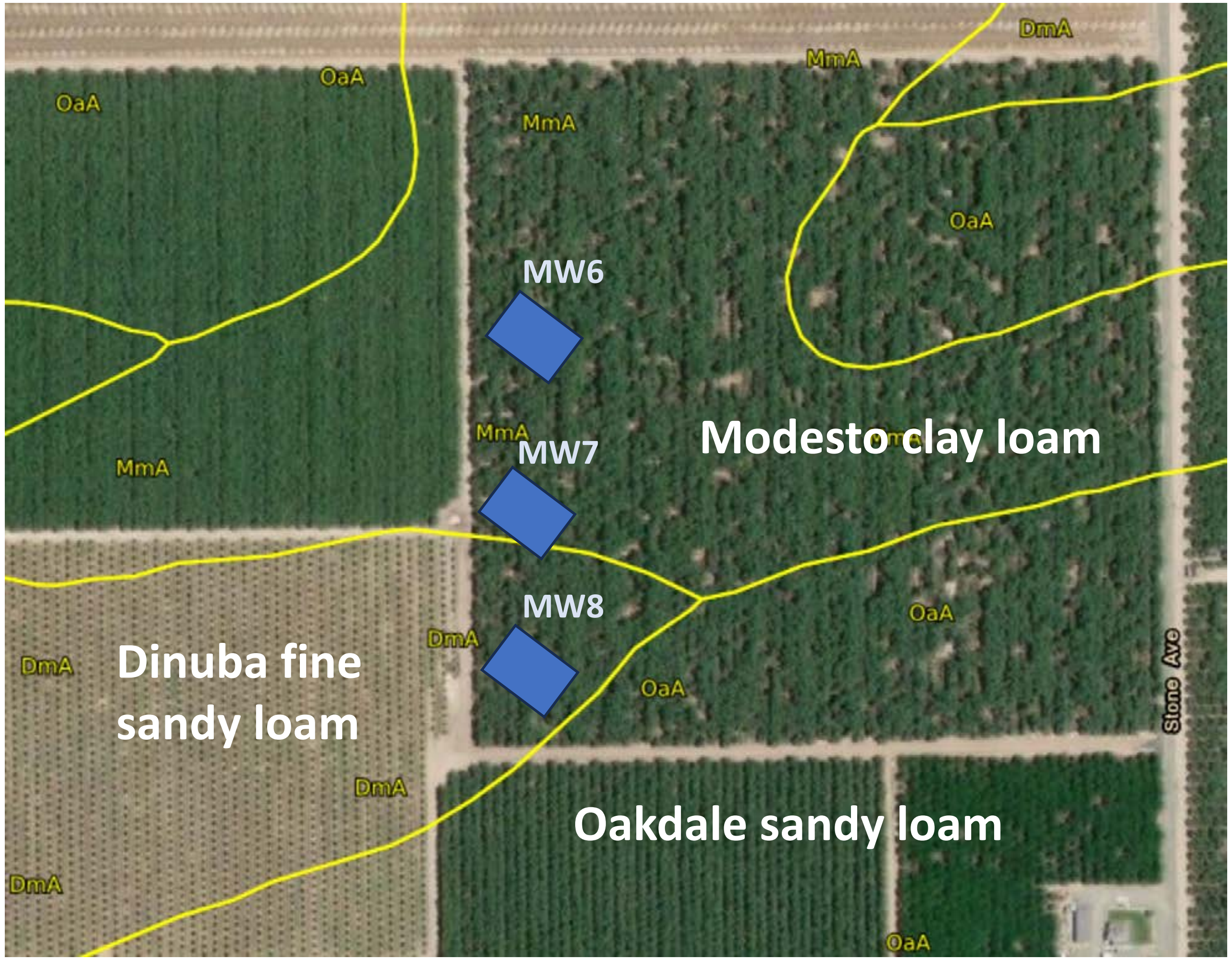
Groundwater table at 21 ft

Almond orchard - Modesto

Breakthrough of vadose zone contaminants



Subsurface heterogeneity



MW6 (Profile 1), MW7 (Profile 2), MW8 (Profile 3)

Depth (cm)	MW6	MW7	MW8
0-33	SC	SC	SC
33-66	SC	SC	SCL
66-100	SCL	SCL	SCL
100-133	SC	SCL	SCL
133-166	SCL	SiL	SCL
166-200	SCL	SiL	SCL
200-266	SCL	SC	FS
266-333	FS	FS	S
333-400	SCL	SCL	S
400-466	FS	FS	S
466-533	S	S	FS
533-600	S	S	FS
600-666	SCL	SCL	S
666-733	FS	S	SCL

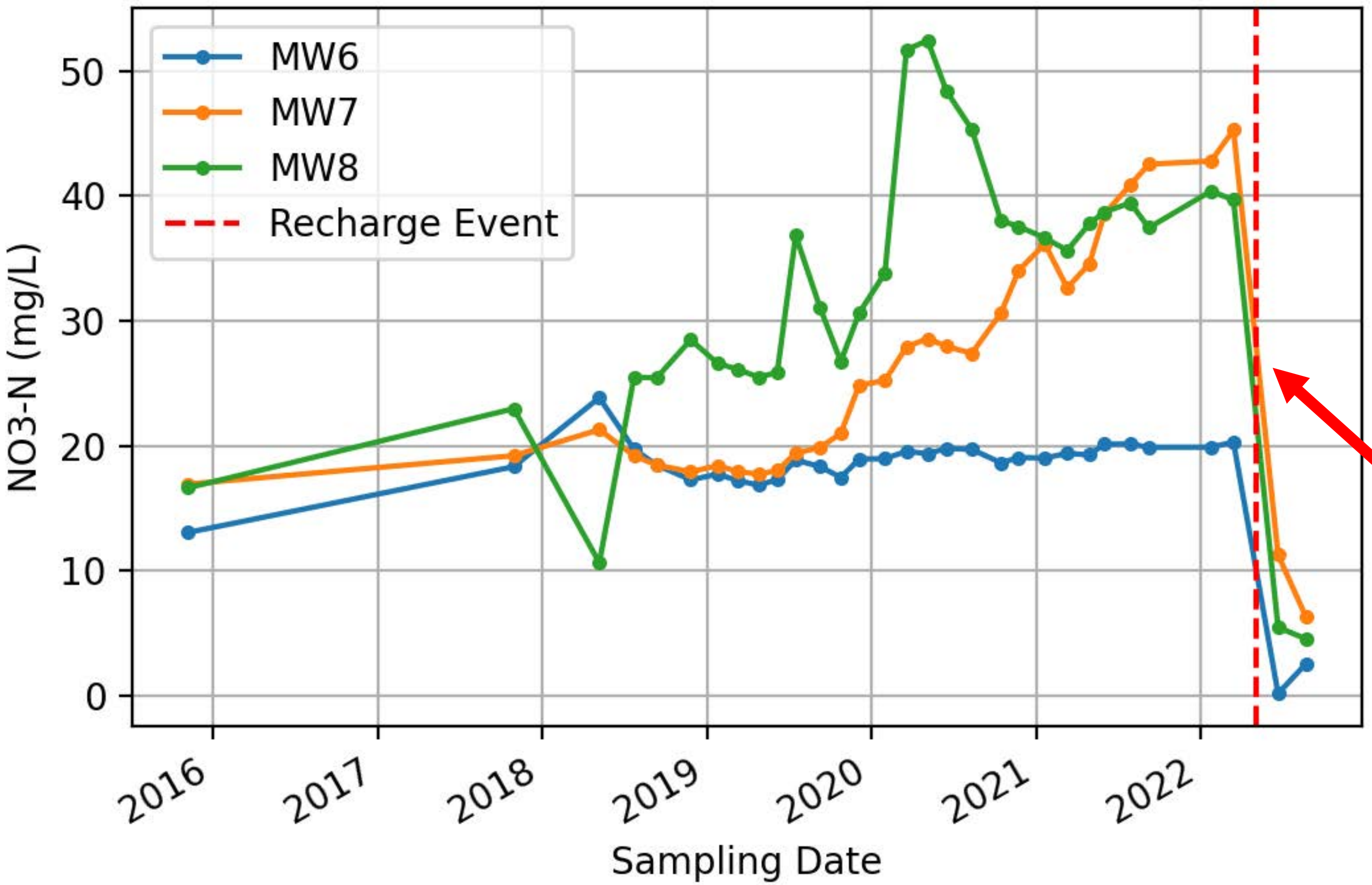
SC: silty clay, SCL: silty clay loam, SiL: Silt loam, FS: fine sand, S: sand

Impact of subsurface heterogeneity on recharge

Indicators	MW6	MW7	MW8	Mean	Variation percentage
Recharge efficiency (-)	87.8%	88.8%	89.80%	88.8%	-2.3%
Flow velocity (cm/day)	144.29	90.13	163.81	135	81.7%
Travel time of recharge (days)	3.47	4.99	2.63	3.69	32.3%
Oxidation-reduction potential (Eh)	-331.9	-200.7	-296.1	-276.2	65.30%

Zhou et al. 2023 submitted to WR

Nitrate leaching to groundwater

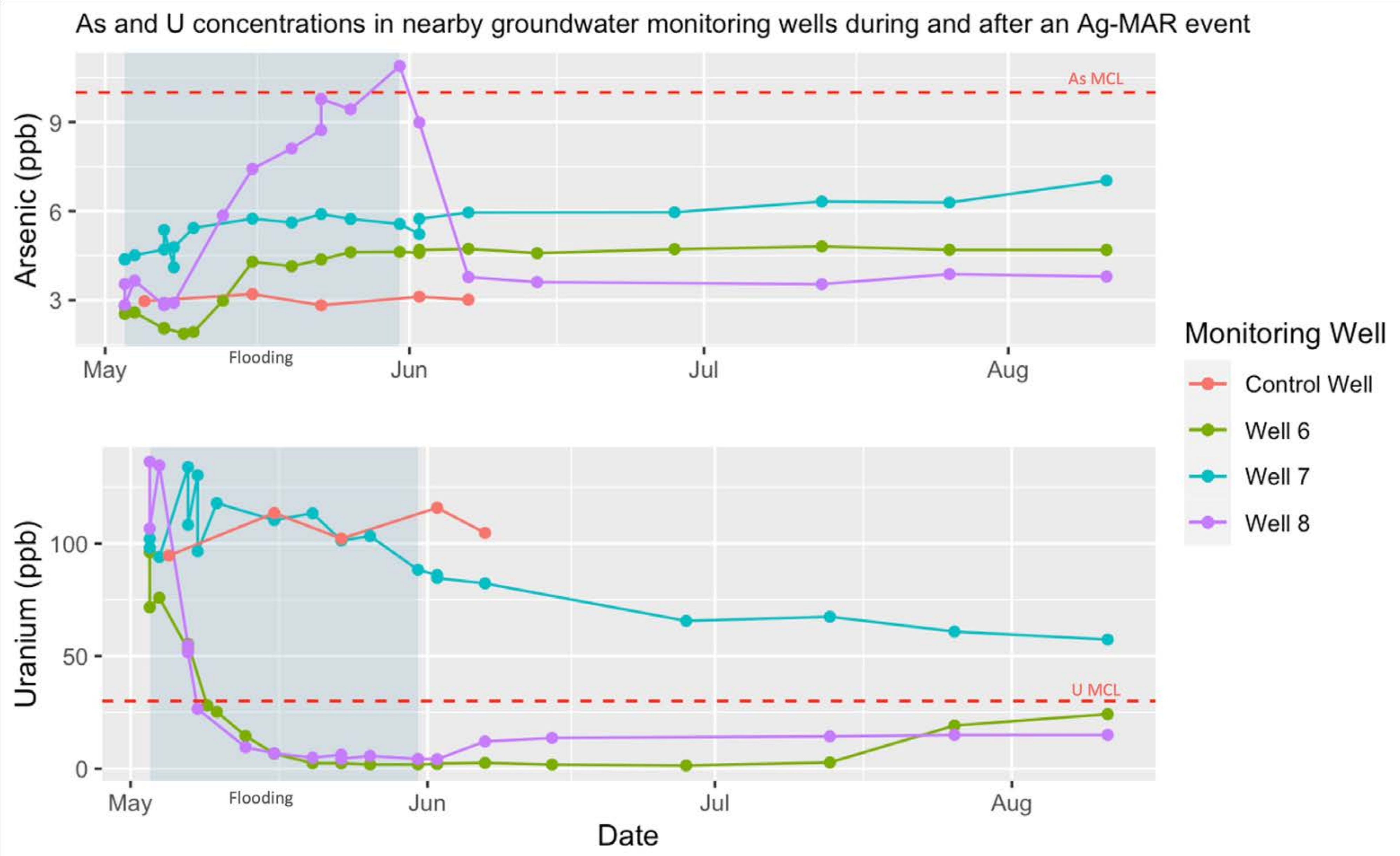


Groundwater nitrate concentrations in monitoring wells

On-farm recharge event

Data from Thomas Harter & Spencer Jordan

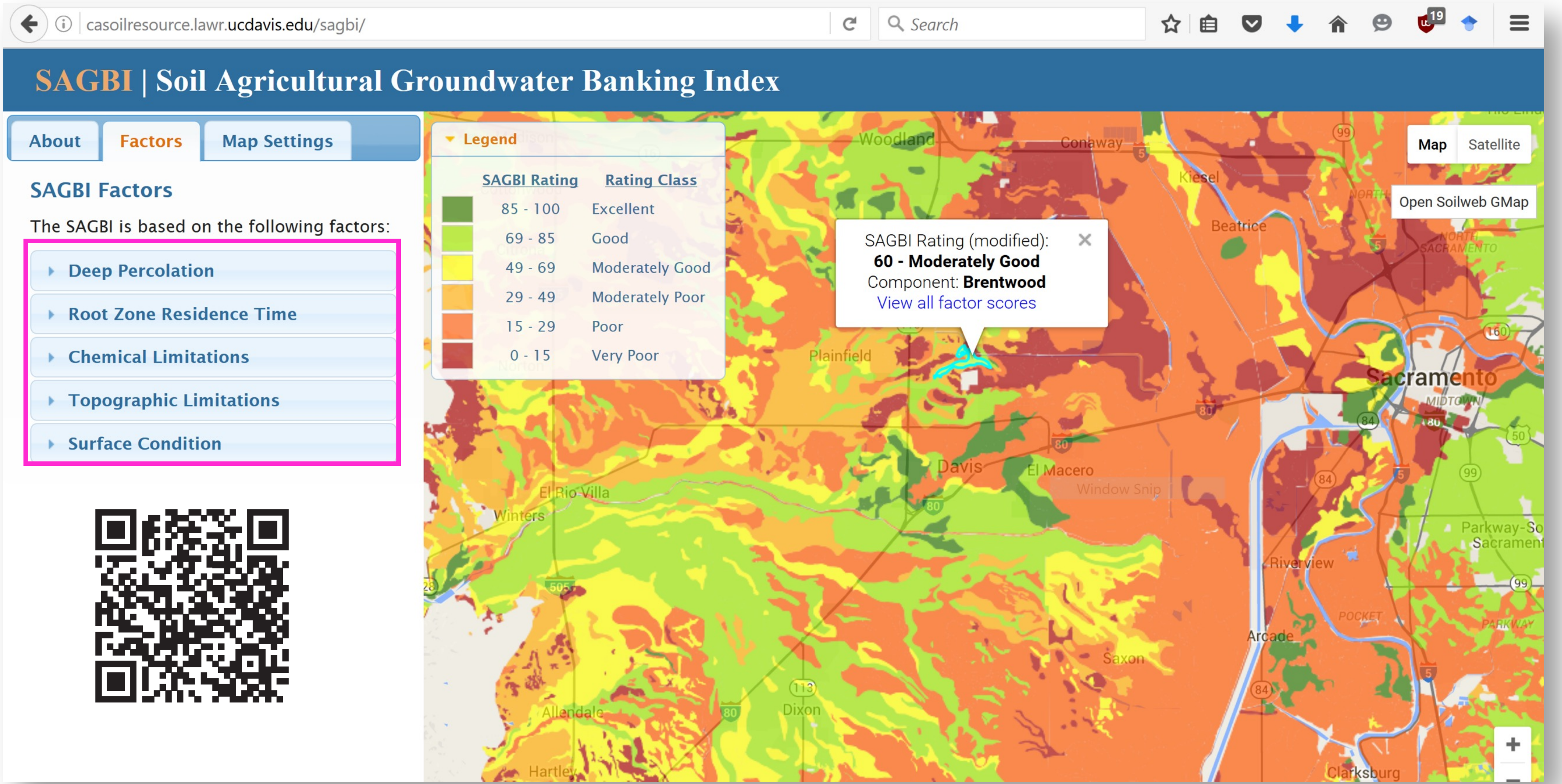
Mobilization of geogenic contaminants



DECISION SUPPORT TOOLS

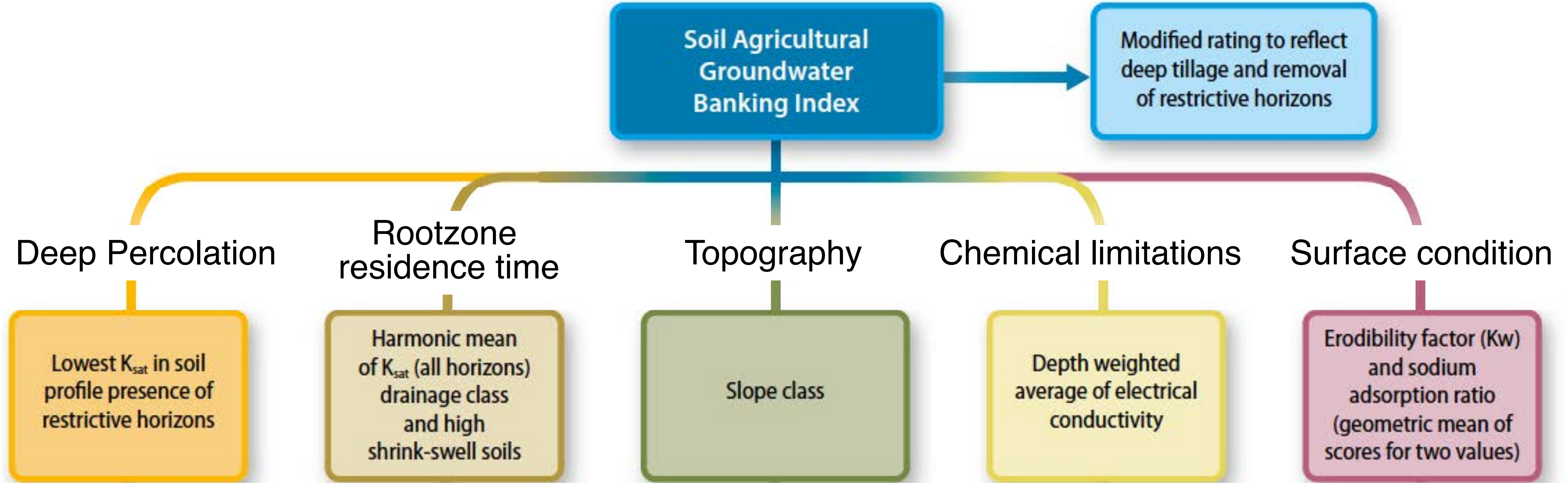
How to site the best Ag-MAR locations?

Decision support



O’Geen et al. 2015, CalAg

Soil agricultural groundwater banking index (SAGBI)



O’Geen et al. 2015, CalAg

https://casoilresource.lawr.ucdavis.edu/sagbi/

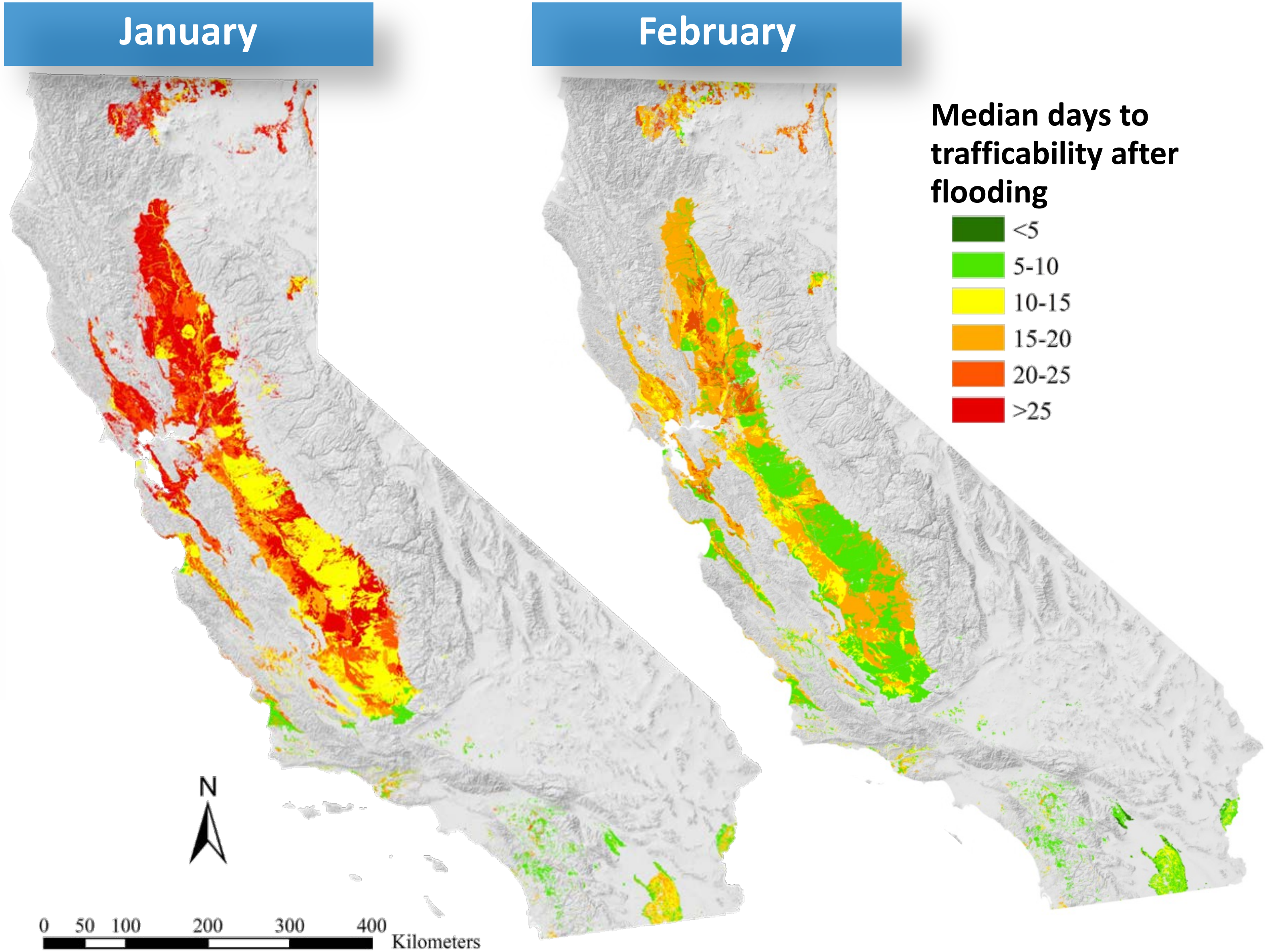
Soil-crop relationships

Crop	SAGBI rating	Soil texture	Infiltration rate (in/hr)	Water applied (ft)	Deep percolation (%)	Yield - compared to control (%)
Almond	Excellent	Dune land	13	2.1	99	125
Alfalfa	Good	Stoner gravelly coarse loam	3.9	28	99	90
Almond	Moderately good	Dinuba fine sandy loam	2.7	2	87	99
Tomato	Moderately poor	Traver fine sandy loam	0.24	1.95	85	125
Almond	Moderately poor	Tehama silt loam*	0.25	0.4	77	-
Grape	Poor	Hanford sandy loam*	0.32	6.7	98	88
Grape	Poor	Hanford fine sandy loam*	0.16	5.8	95	60

* Soil with hardpan

Soil trafficability after deep wetting

Trafficability and risk of soil compaction



Devine et al. 2021, J. of Soil & Tillage Research

Soil trafficability after deep wetting

Time-to-trafficability after deep soil wetting

ABOUT | SOIL TRAFFICABILITY

▲ Background

The *time-to-trafficability* SoilWeb product is intended to help California growers identify when fields are generally *trafficable* after *deep soil wetting* during crop dormancy or winter fallow periods. The tool applies to wetting situations such as managed aquifer recharge projects and large rain or flood events. The primary objective of the app is to help growers avoid physical soil damage by agricultural vehicles, so estimates are relatively conservative.

See the topics below to better understand this SoilWeb product.

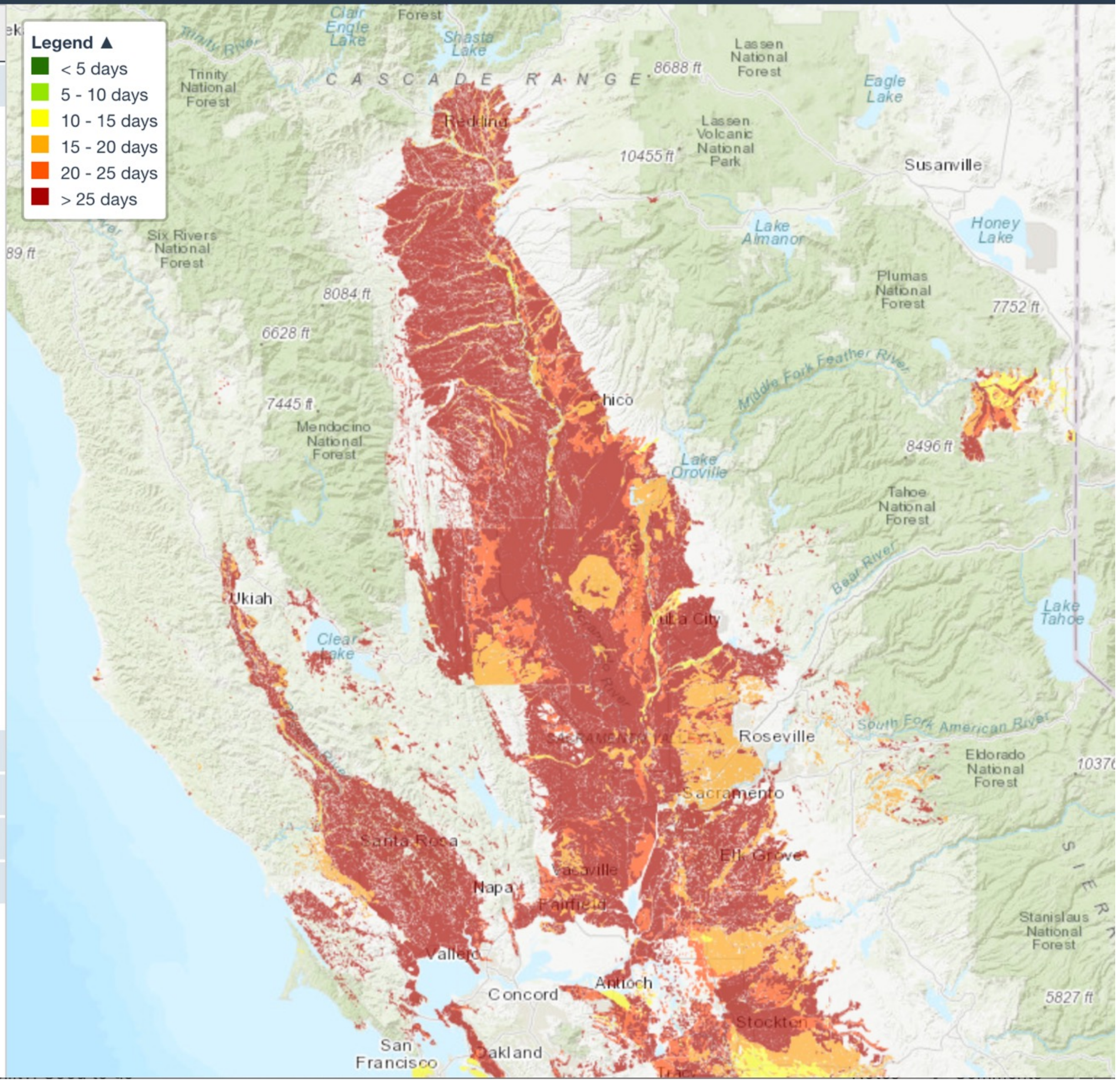
Use the "Soil Trafficability" tab to modify the trafficability estimate and map settings.

▼ Definitions

▼ How to Interpret

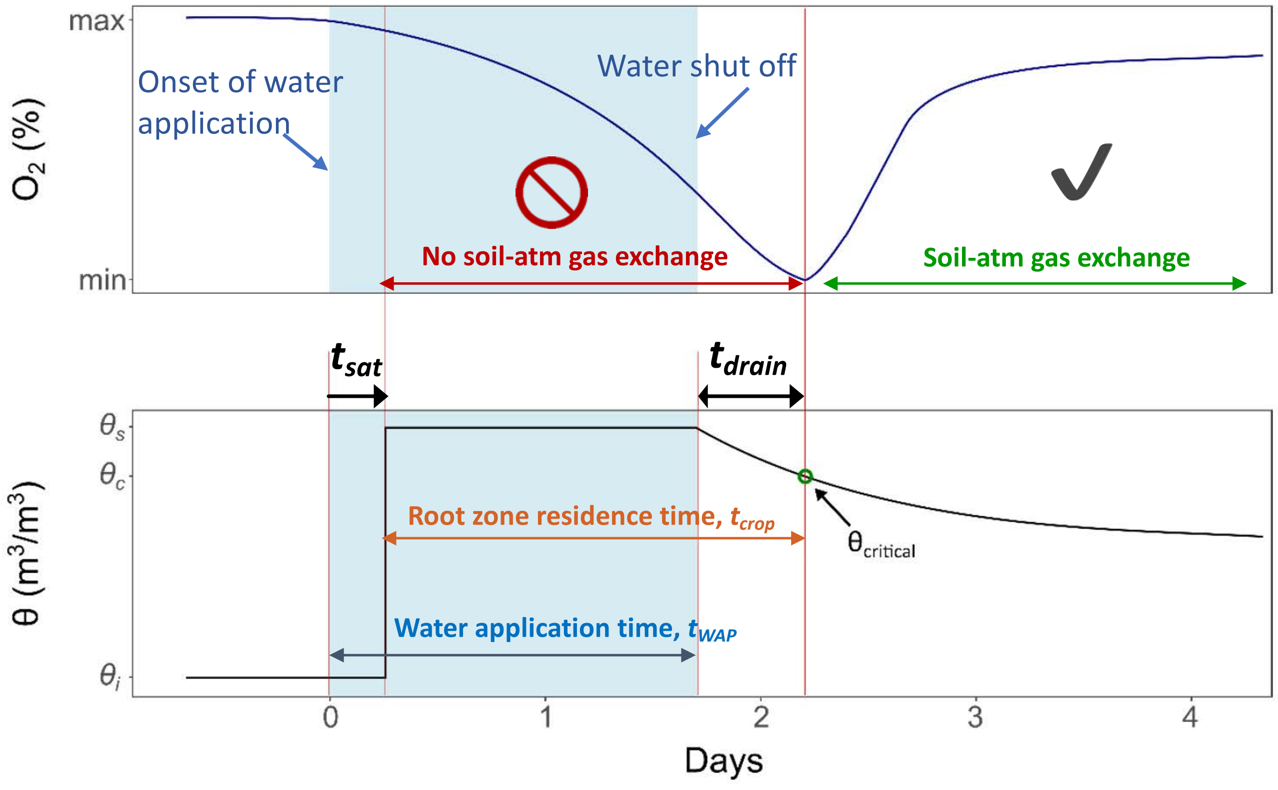
▼ Assumptions

▼ Feedback



https://soilmap2-1.lawr.ucdavis.edu/soil-trafficability/

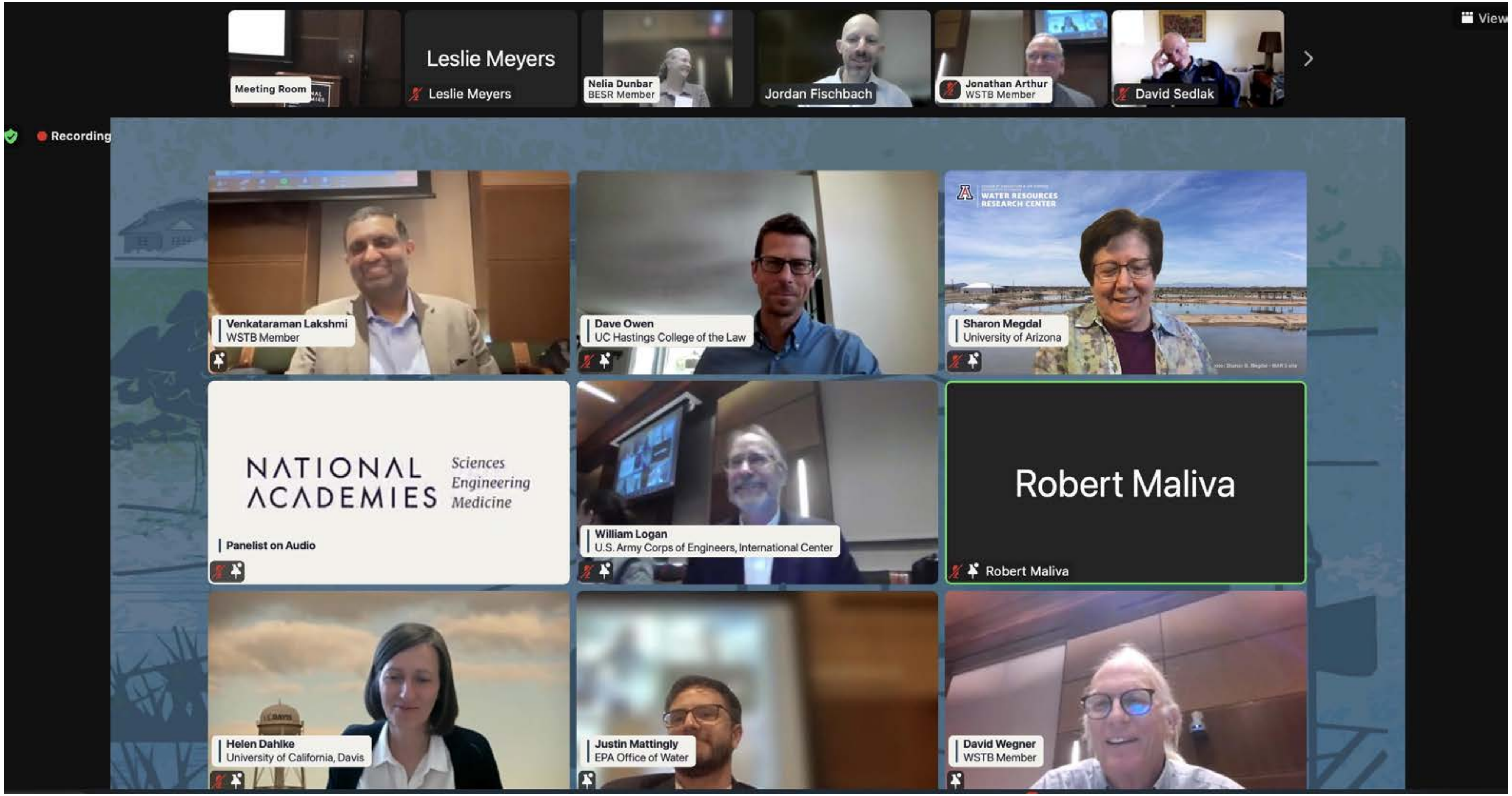
Safe water application calculator



Ganot & Dahlke, 2021 *AgWaterMgt*

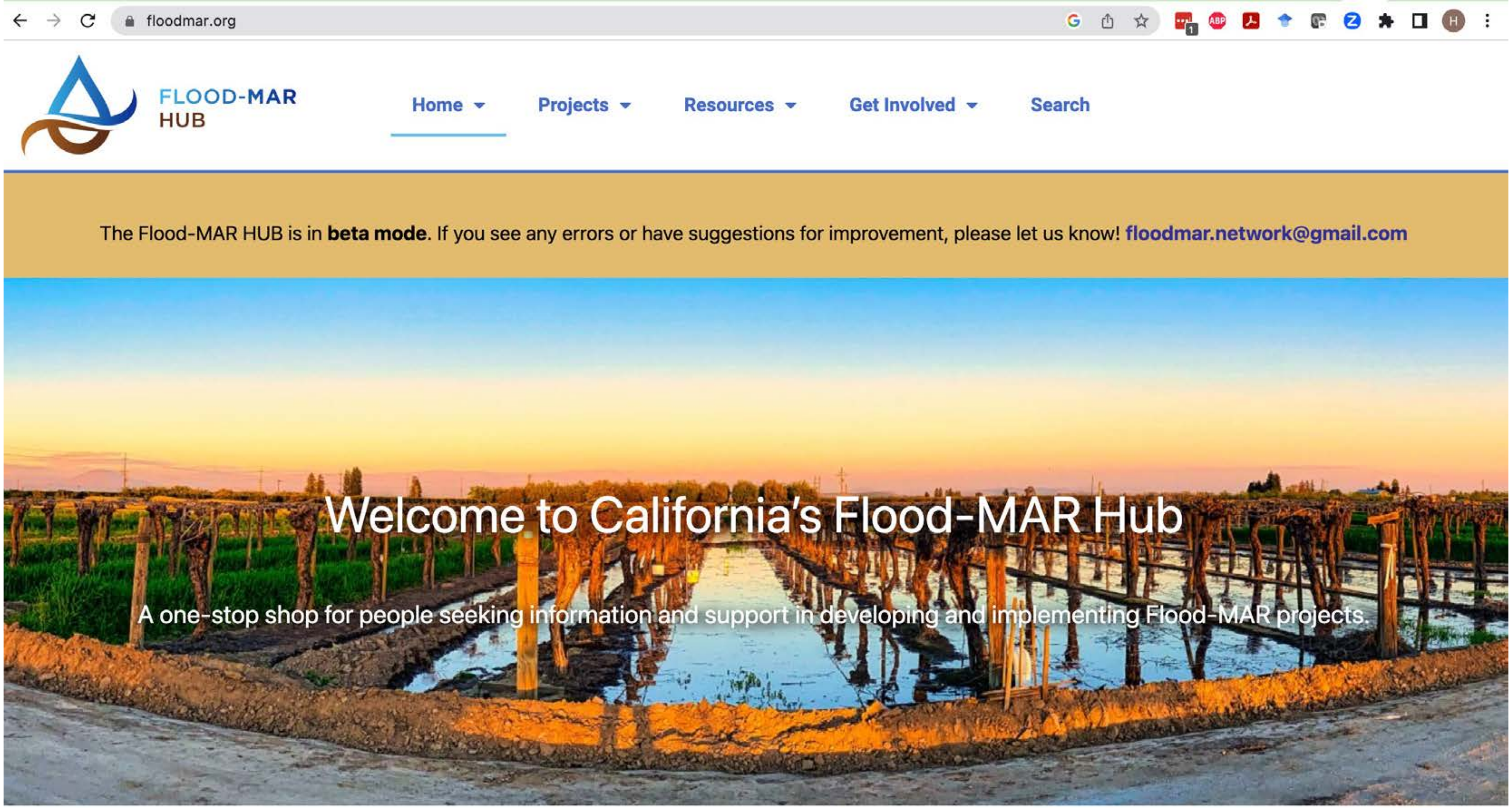
Resources

Future of Managed Aquifer Recharge in the U.S.



https://www.nationalacademies.org/event/05-10-2022/future-of-managed-aquifer-recharge-in-the-us

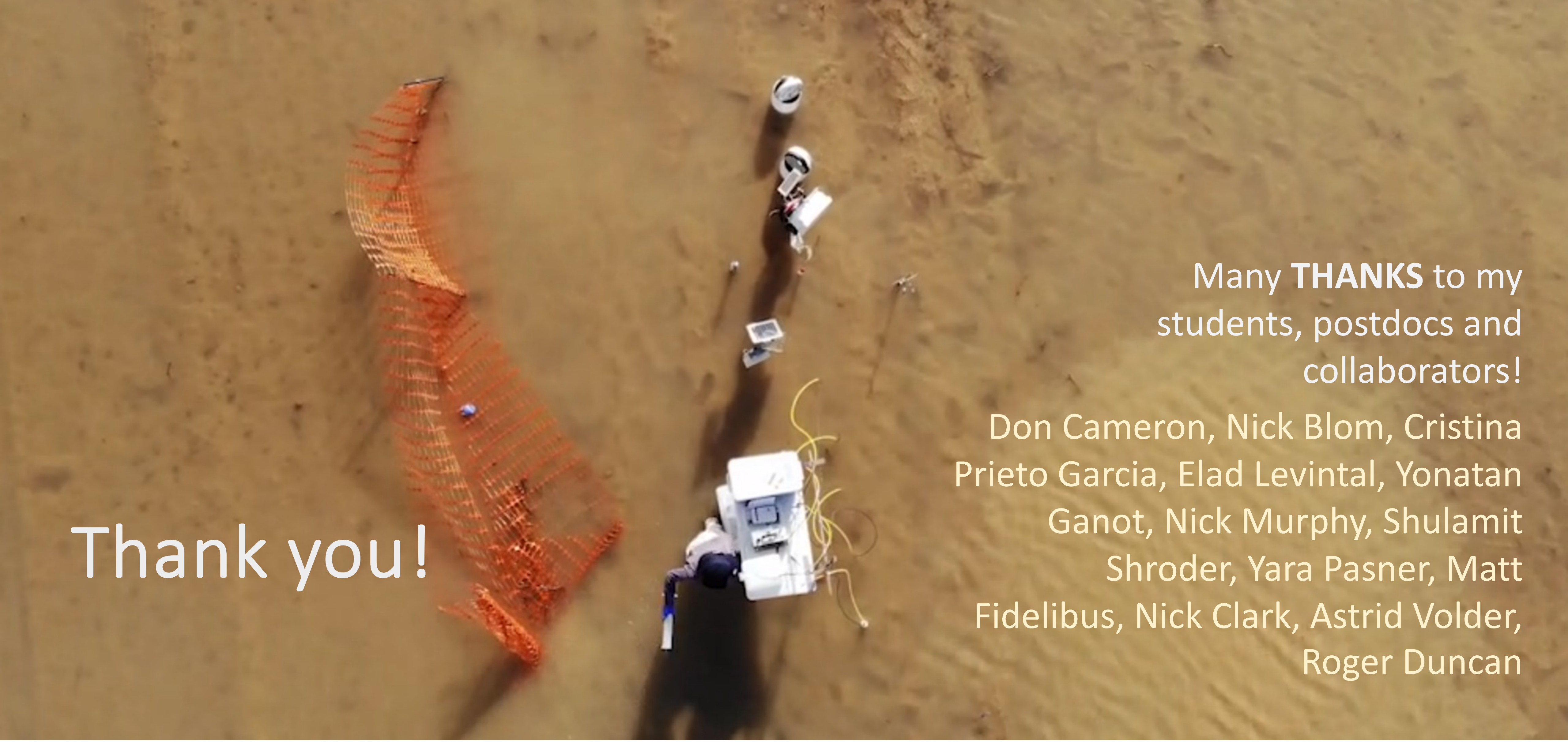
Join the Flood-MAR network



https://floodmar.org

Why should I consider Ag-MAR

- Increased groundwater storage for next drought
- Fill up soil profile prior to growing season
- Frequency of wet years is decreasing in southwestern US
- Additional moisture stimulate mineralization (natural production of nitrate in soils)
- Recharge with low nitrogen source water does dilute elevated groundwater nitrate concentrations
- Management of soil salinity



Thank you!

Many **THANKS** to my students, postdocs and collaborators!

Don Cameron, Nick Blom, Cristina Prieto Garcia, Elad Levintal, Yonatan Ganot, Nick Murphy, Shulamit Shroder, Yara Pasner, Matt Fidelibus, Nick Clark, Astrid Volder, Roger Duncan

NSF
USDA NIFA
Gordon and Betty Moore Foundation
NRCS Natural Resources Conservation Service
ERS Economic Research Service United States Department of Agriculture
U.S. Department of the Interior Bureau of Reclamation — RECLAMATION Managing Water in the West
california almonds Almond Board of California

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UCDAVIS
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