Agricultural sustainability through integrated surface water - groundwater management

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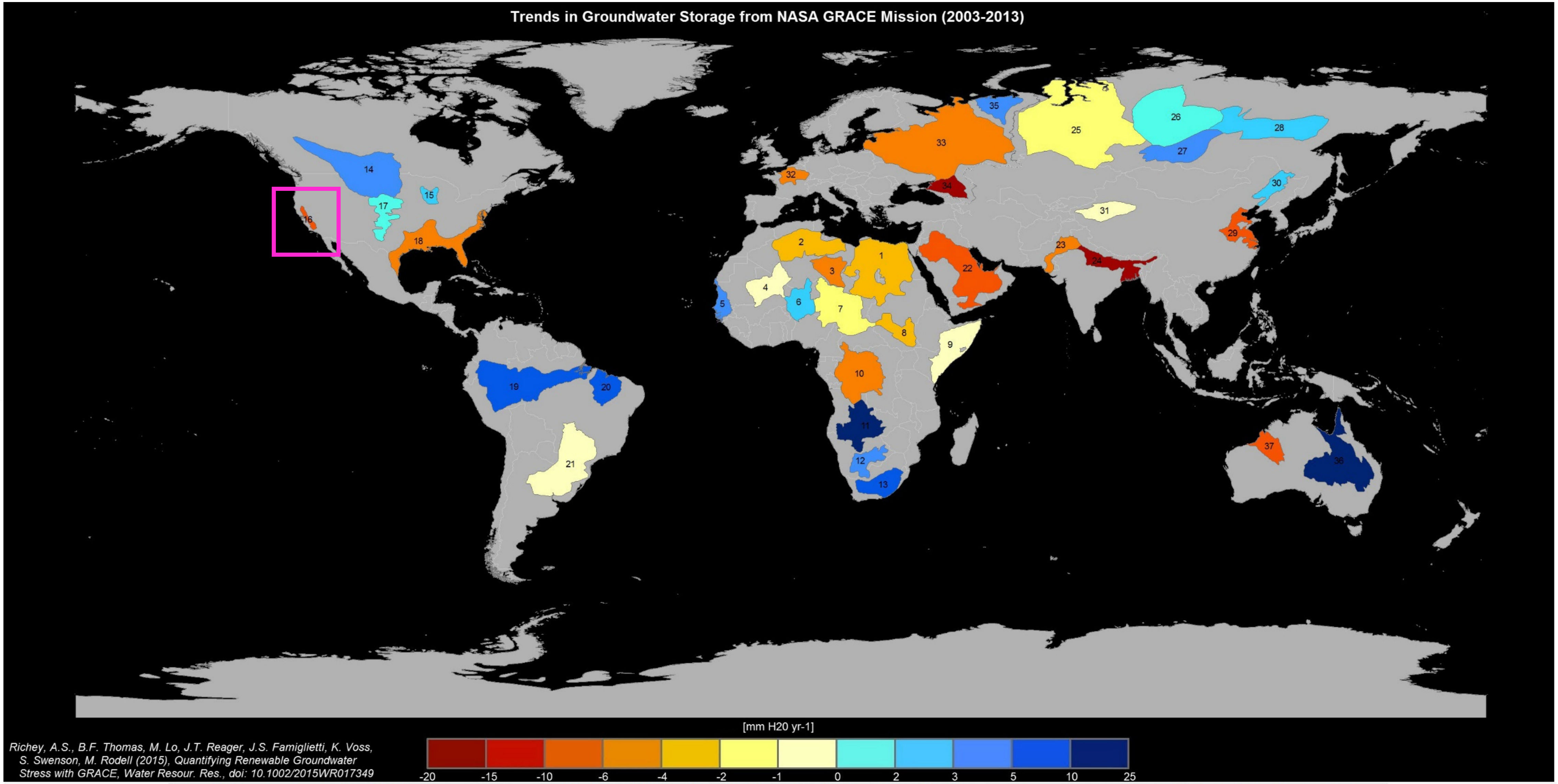
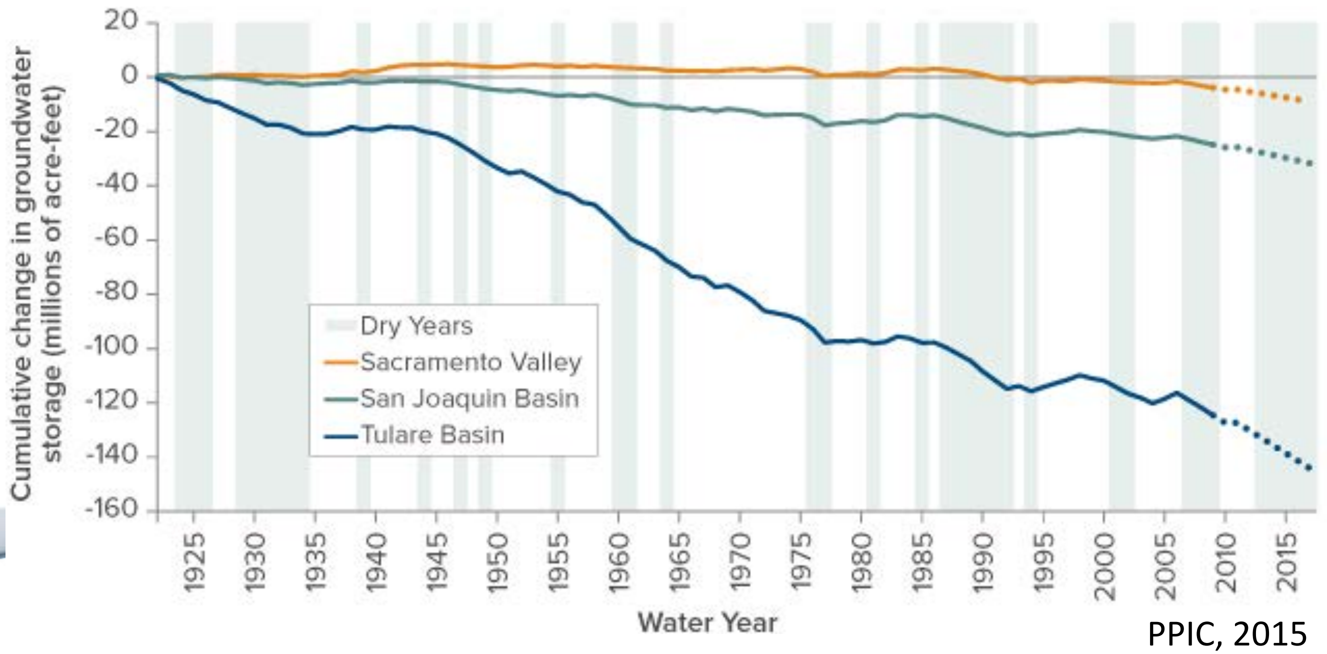


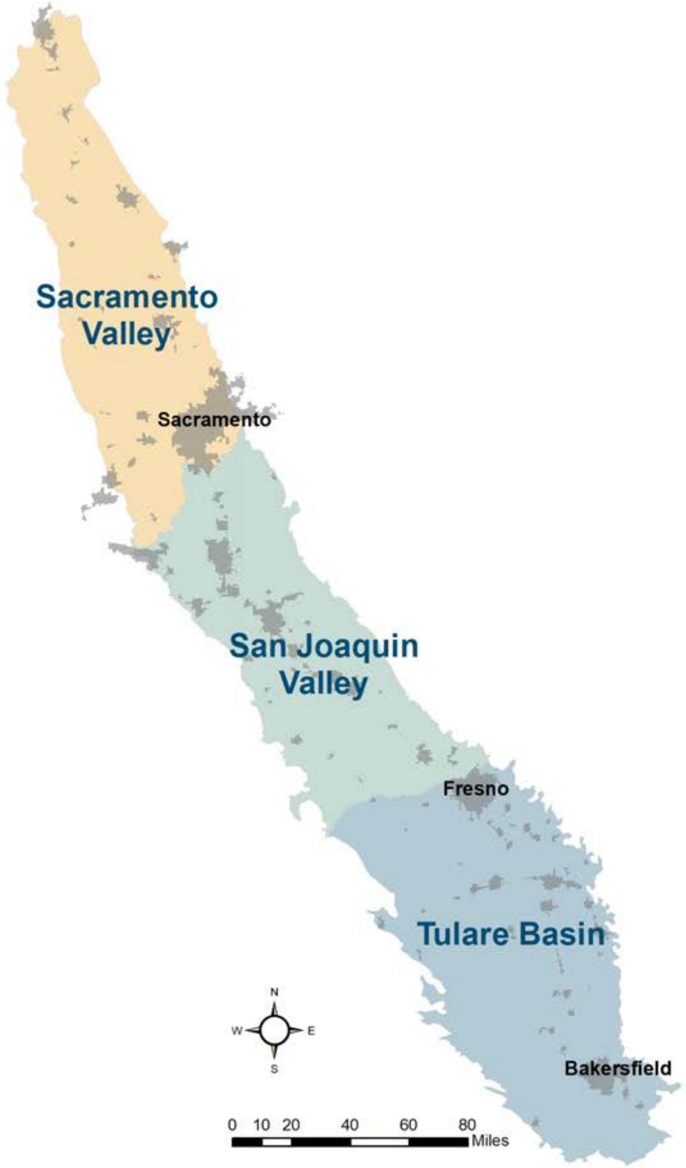
1 Nubian Aquifer System (NAS)
2 Northwestern Sahara Aquifer System (NWSAS)
3 Murzuk-Djado Basin
4 Taoudeni-Tanezrouft Basin
5 Senegalo-Mauritanian Basin
6 Iullemeden-Irhazer Aquifer System
7 Lake Chad Basin
8 Sudd Basin (Umm Ruwaba Aquifer)
9 Ogaden-Juba Basin
10 Congo Basin
11 Upper Kalahari-Cuvelai-Upper Zambezi Basin
12 Lower Kalahari-Stampriet Basin
13 Karoo Basin
14 Northern Great Plains Aquifer
15 Cambro-Ordovician Aquifer System
16 Californian Central Valley Aquifer System
17 Ogallala Aquifer (High Plains)
18 Atlantic and Gulf Coastal Plains Aquifer
19 Amazon Basin
20 Maranhao Basin
21 Guarani Aquifer System
22 Arabian Aquifer System
23 Indus Basin
24 Ganges-Brahmaputra Basin
25 West Siberian Basin
26 Tunguss Basin
27 Angara-Lena Basin
28 Yakut Basin
29 North China Aquifer System
30 Song-Liao Basin
31 Tarim Basin
32 Paris Basin
33 Russian Platform Basins
34 North Caucasus Basin
35 Pechora Basin
36 Great Artesian Basin
37 Canning Basin

Groundwater Depletion in California's Central Valley

- Since 1920s groundwater depletion has reached more than 160 million acre-feet of groundwater
- Sustainable Groundwater Management Act (SGMA) requires overdrafted groundwater basins to achieve balance by 2040



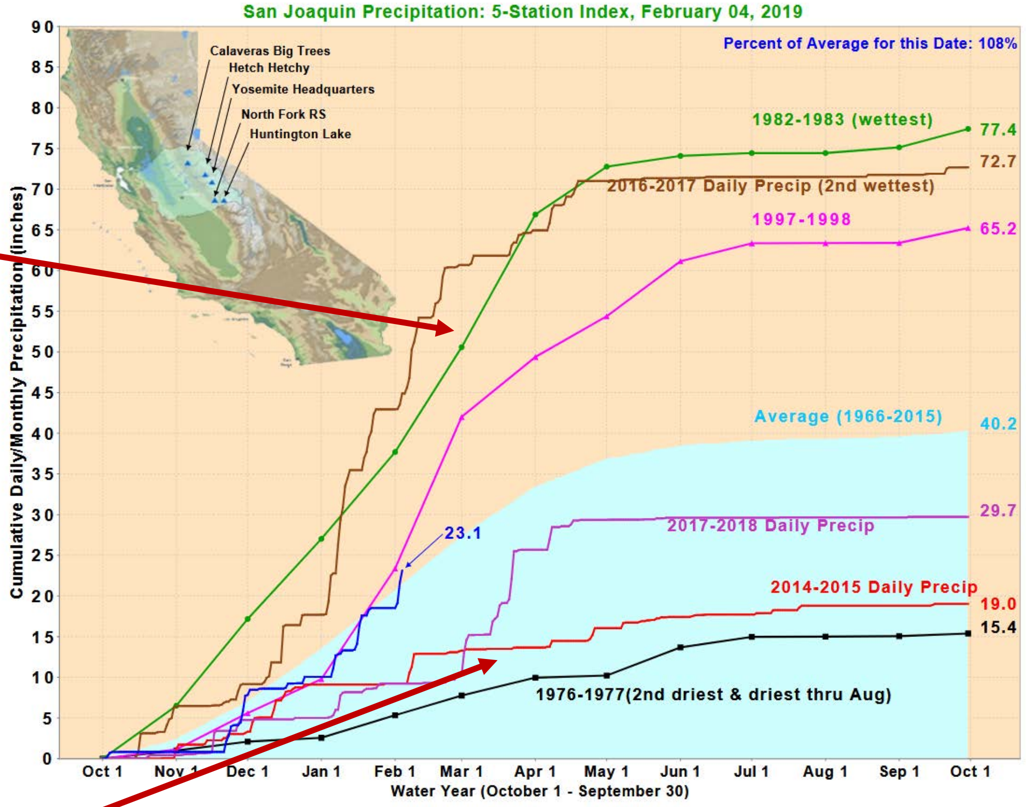
PPIC, 2015



Managing extremes in surface water supply

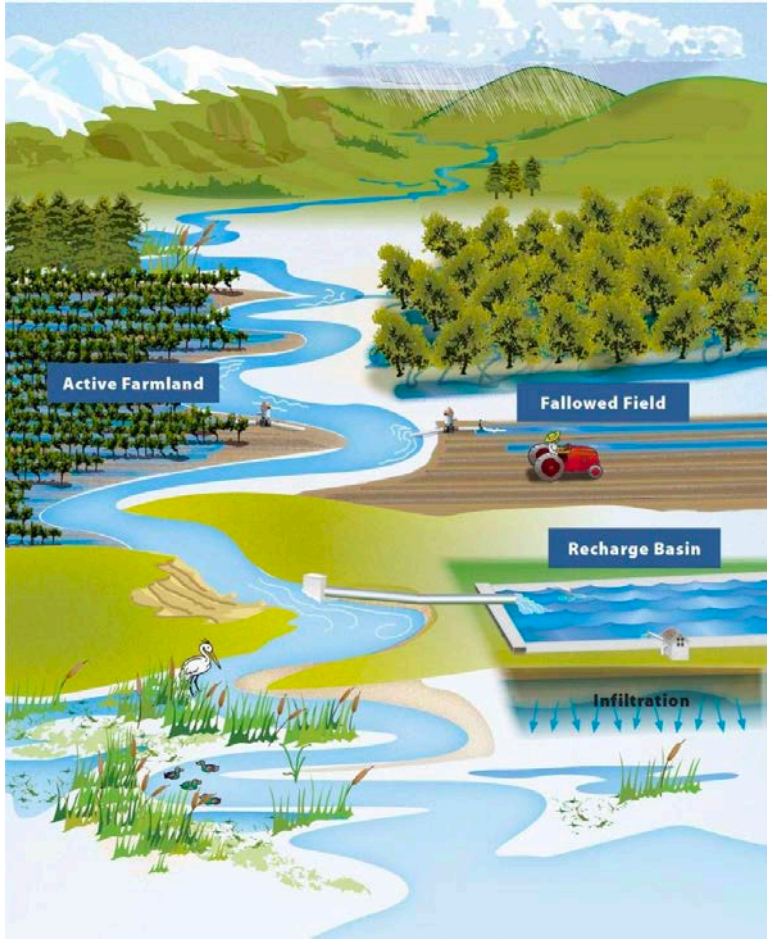
Floods, spring 2017

Drought, 2015



http://cdec.water.ca.gov/

Flood-MAR program



DWR, 2019

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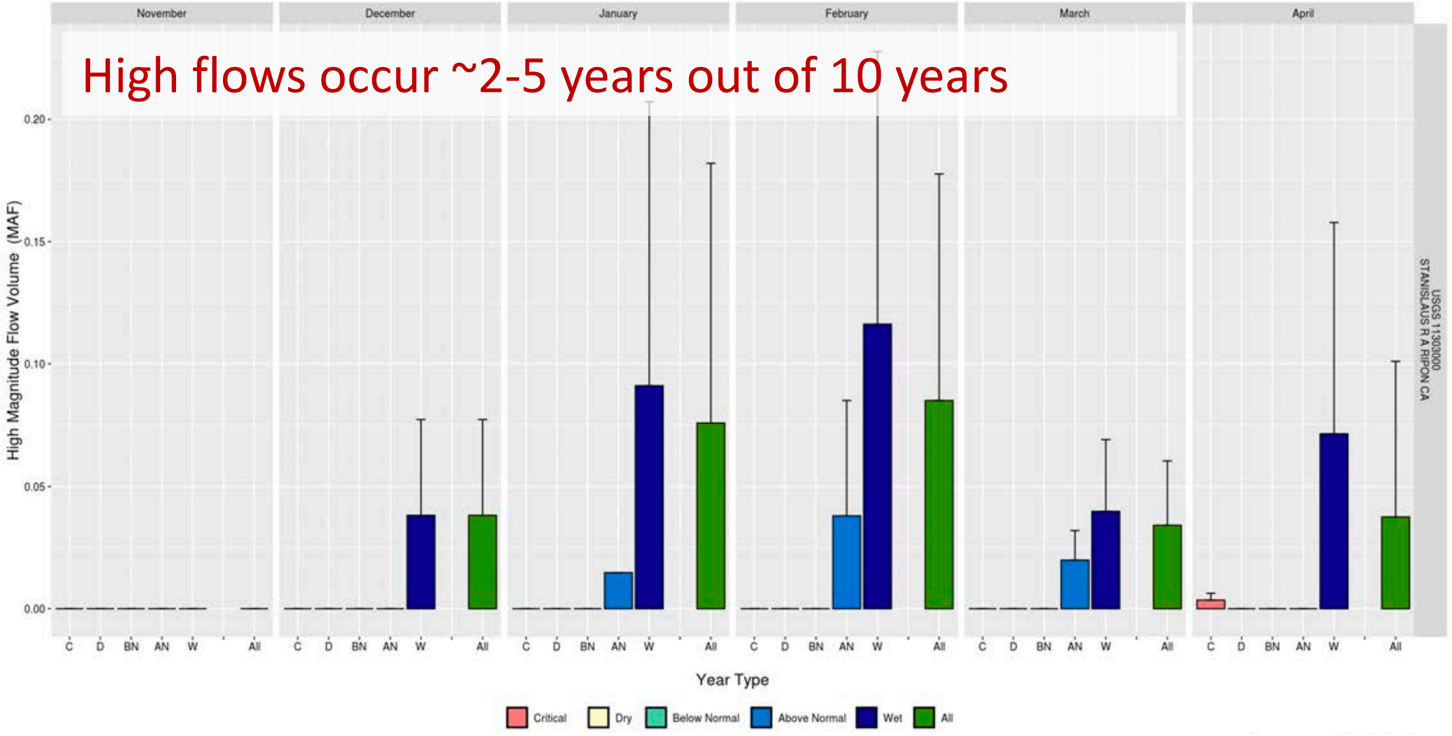
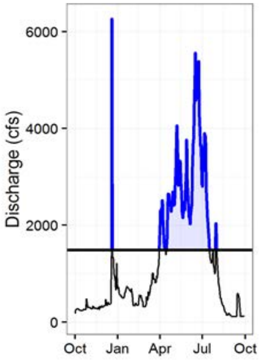
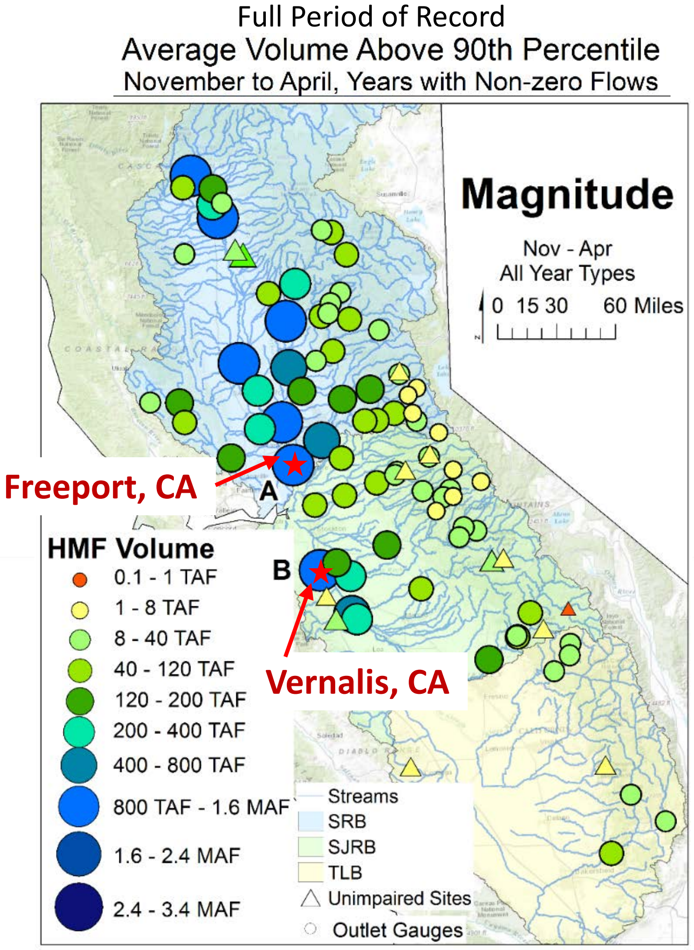
Why agricultural MAR?

- Viable option for regions where large amounts of excess water is less frequently available

High flow availability - Stanislaus River at Ripon, CA







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

Kocis & Dahlke, 2017; Dahlke et al. 2018

Factors influencing Ag-MAR adoption

Cost & incentives

Laws and permits

Hydrogeology

Crop suitability

Location

Water quality

Water availability

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Crop suitability

Terranova, wine grapes, fine sandy loam

- Flooded from April – July, 2011
- Infiltration rates: ~2.5 in/day
- 1,274 AF on wine grapes

Bachand et al. 2014

TABLE 1. Survey results of tree crop vulnerability to saturated conditions

Crop	Rootstock	Tolerance to saturation before budbreak	Tolerance to saturation after budbreak	Recommended N fertilizer rate
				lbs N/ac/yr
Almonds	Peach; peach x almond hybrid	1	1	250
Almonds	Plum; peach x plum hybrid	2–3	1	250
Avocados	—	0	0	150
Cherries	—	1	0	60
Citrus	—	0	0	100
Wine grapes	—	4	2	15–30
Olives	—	?	?	<100
Pears	*P. betulaefolia*	4	4	100–150
Pears	*P. communis*	4	3	100–150
Pears	*Cydonia oblonga*	3–4	2–3	100–150
Pistachios	—	?	?	200
Plums/prunes	Peach	1	1	150
Plums/prunes	Plum; peach x plum hybrid	2–3	1	150
Pomegranate	—	?	?	100
Walnuts	—	2–3	1	200

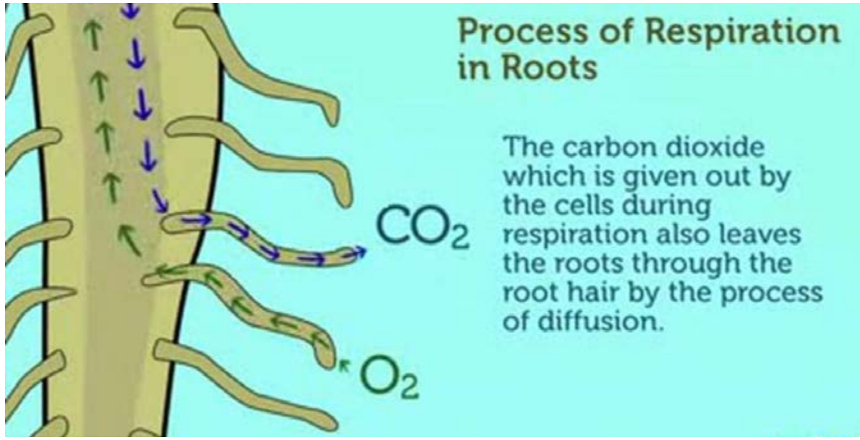
Tolerance rating in the table:

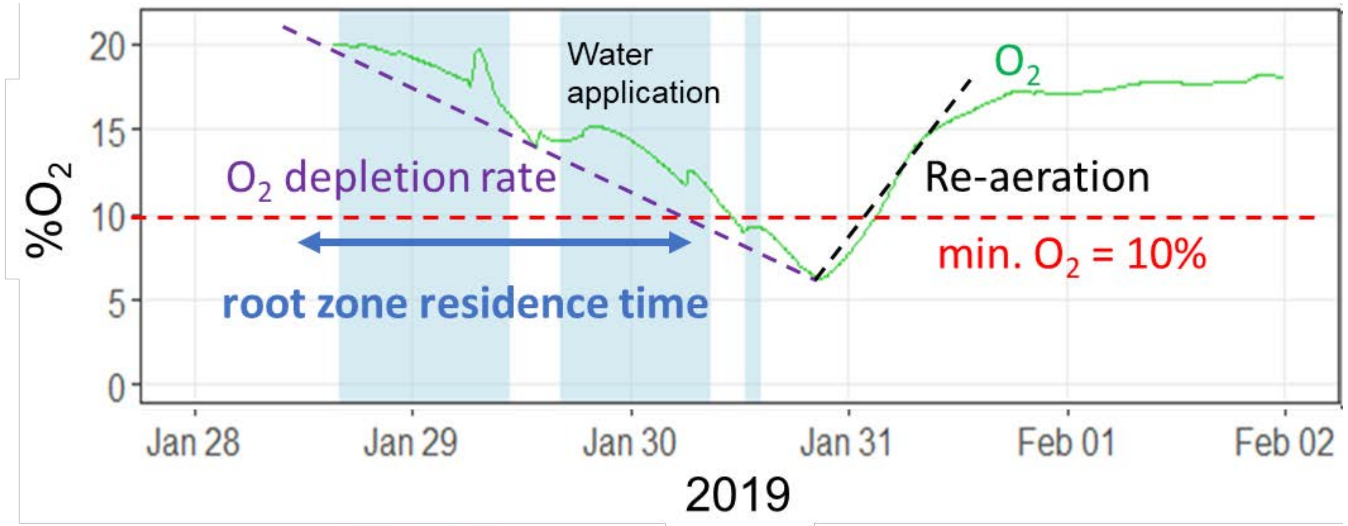
- 0 - no tolerance for standing water
- 1 - tolerant of standing water up to 48 hours
- 2 - tolerant of standing water up to 1 week
- 3 - tolerant of standing water up to 2 weeks
- 4 - tolerant of standing water > 2 weeks
- ? - tolerance unknown

O'Geen et al. 2015, CalAg

Risks of Ag-MAR in perennial cropping systems

- Anaerobic conditions and/or an excessively high water table could:
  - Impact root length, root production (yield),
  - Increase risk of root diseases and plant pests,
  - Increase nutrient and herbicide leaching,
  - Affect field operations due to wet conditions.
- Continued flooding has negative effects on soil respiration (root & microbial)
- Root zone residence time:
  - ➢ Time until critical O_2 level is exceeded = safe flooding duration to avoid root damage





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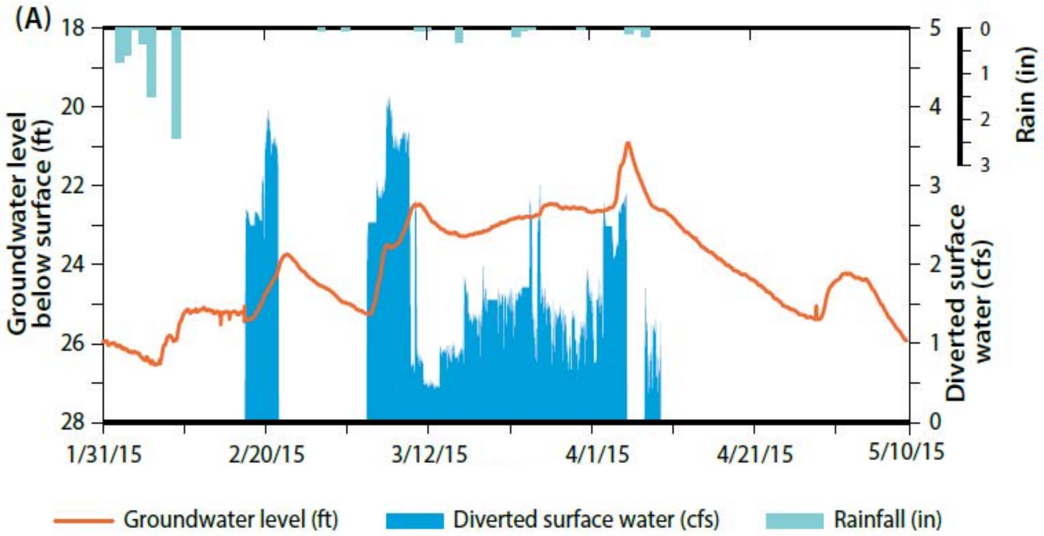
Ganot & Dahlke 2021 in prep

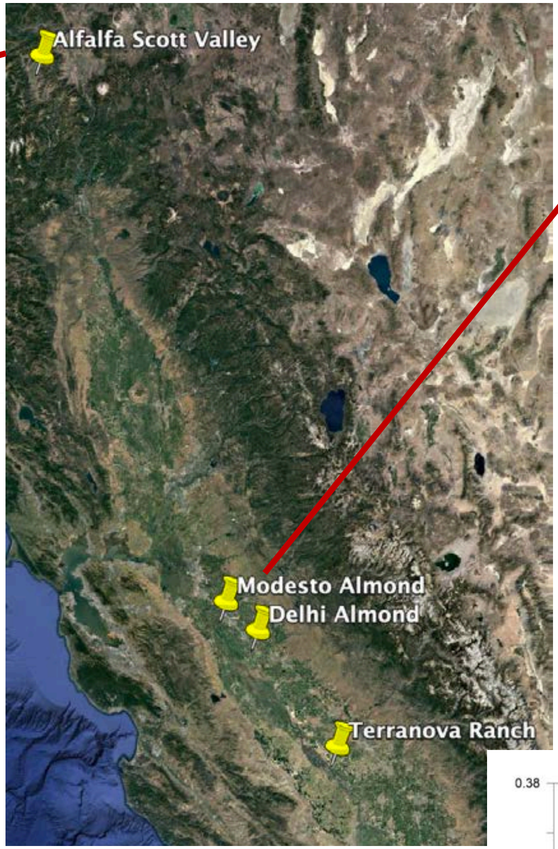
On-farm recharge experiments

Scott Valley, alfalfa, gravelly loam

- Flooded from Jan-Apr, 2015
- Direct recharge of up to 26 AF/acre
- Infiltration rates: ~8.4 in/day



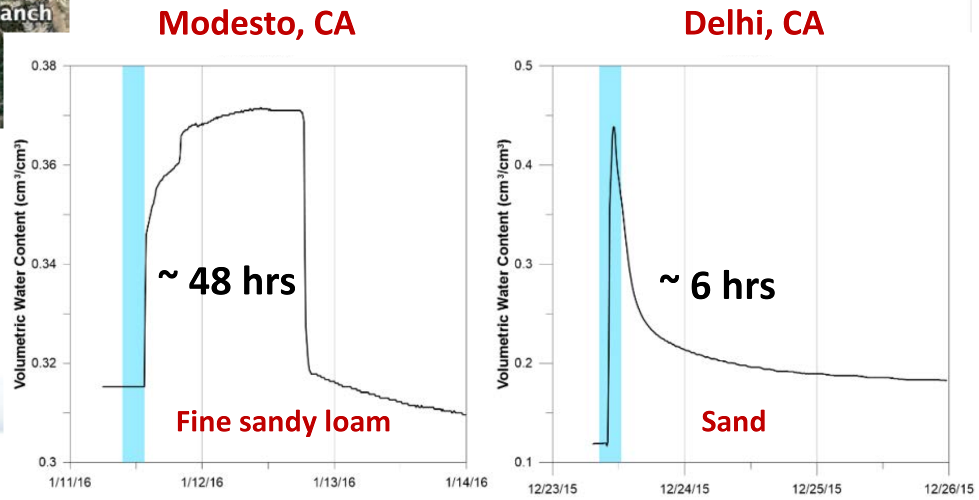
Dahlke et al. 2018



Nonpareil almonds

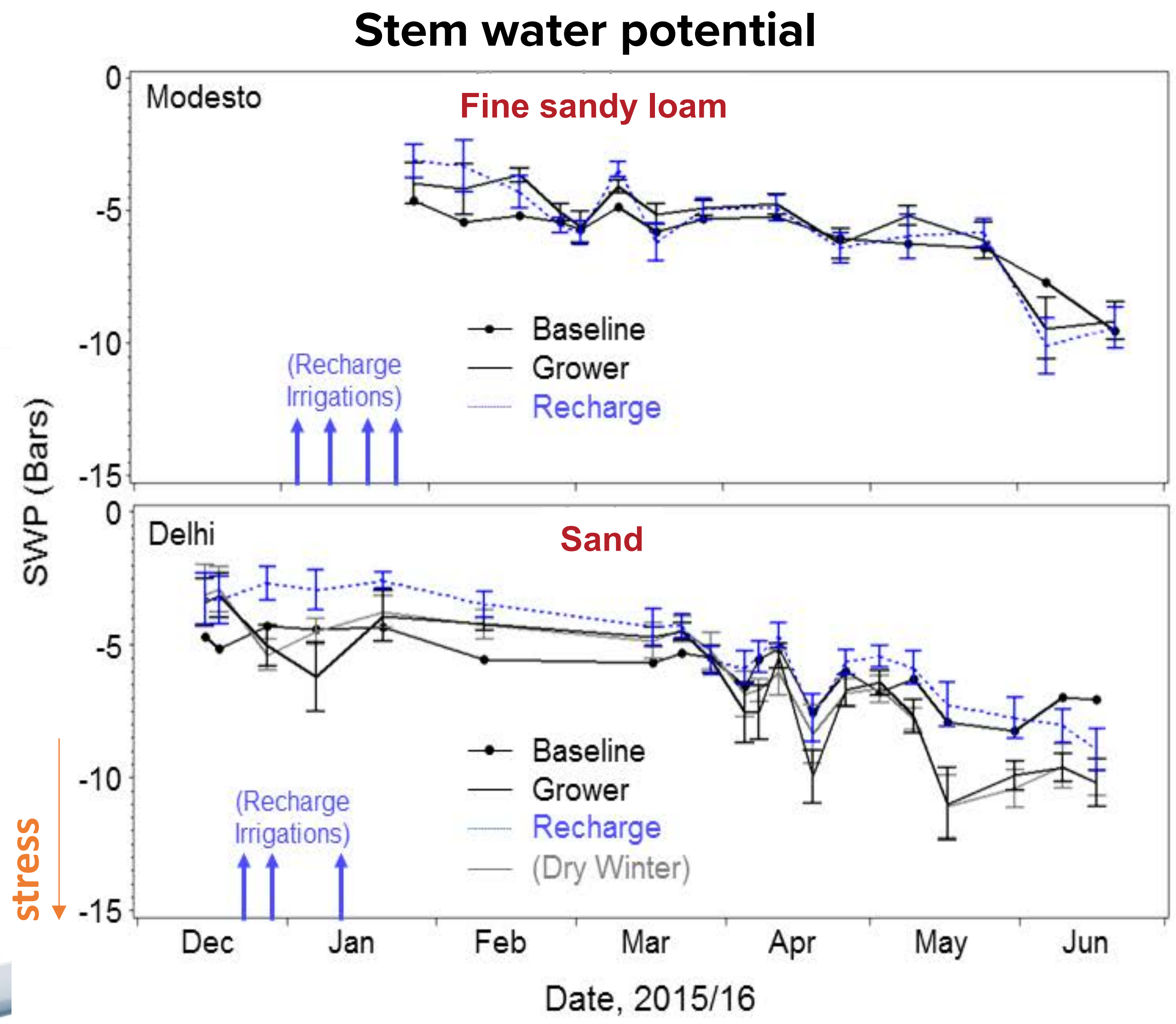
- Flooded Jan. 2016, 2017, 2018
- Recharge of 2 AF/acre
- Infiltration rates: 4-14 in/day

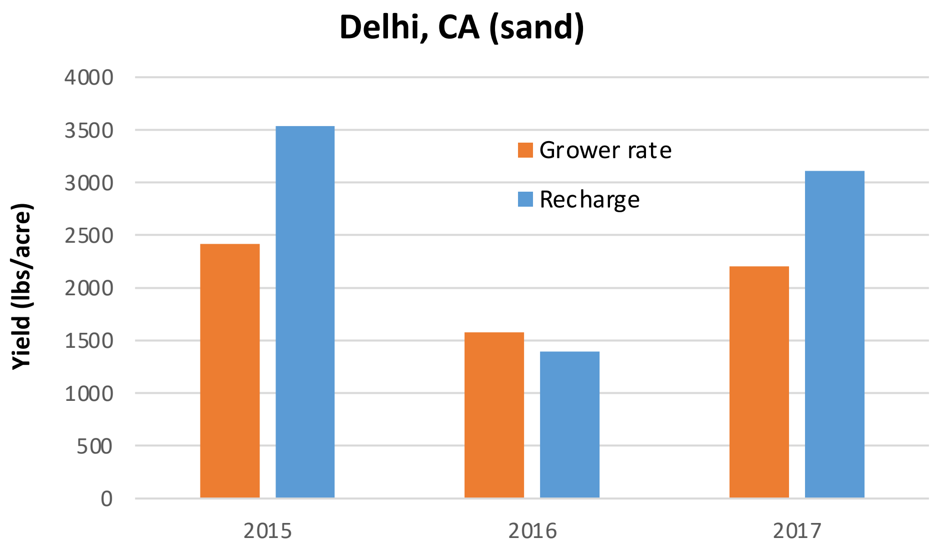
Soil drainage properties

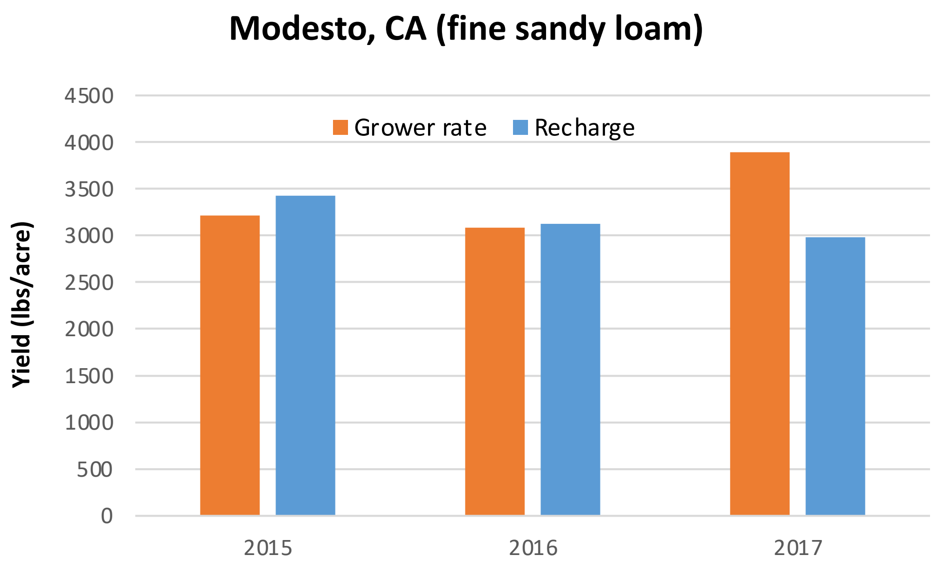


Ma et al. 2020 submitted to CalAg

Crop Suitability - almonds





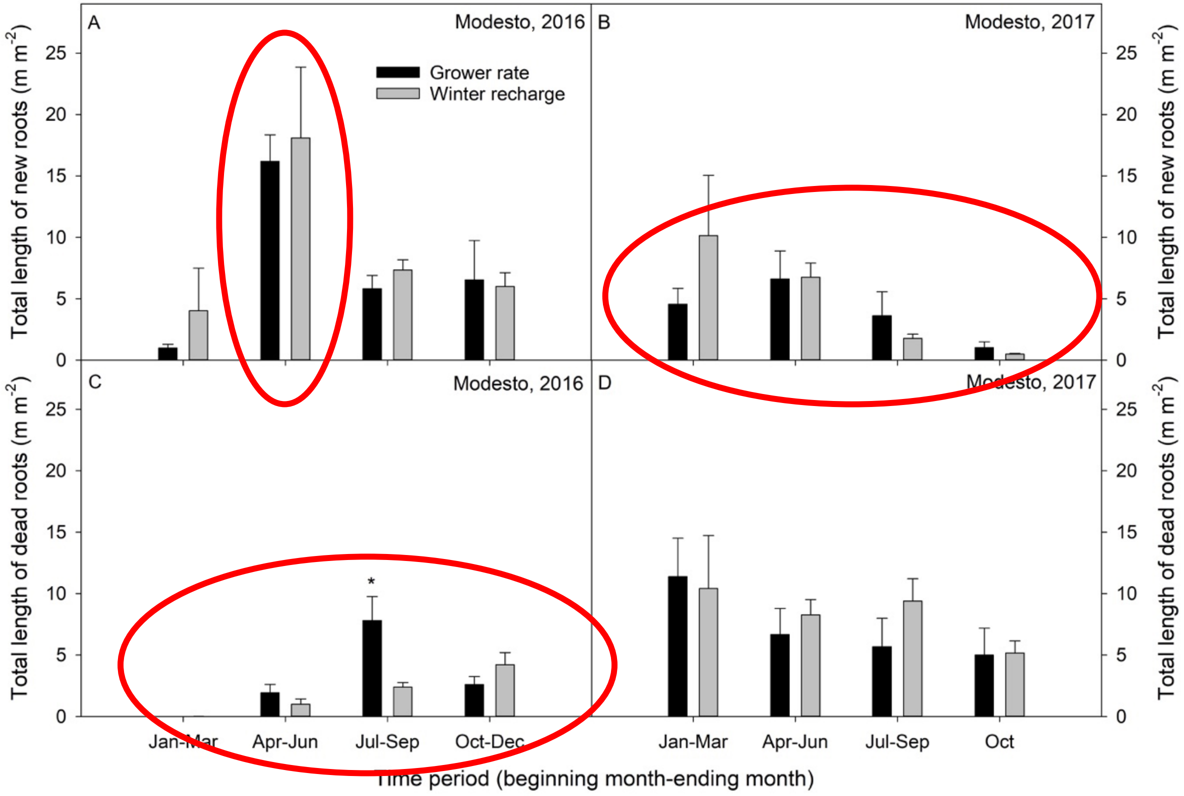


Ma et al. 2020 submitted to CalAg

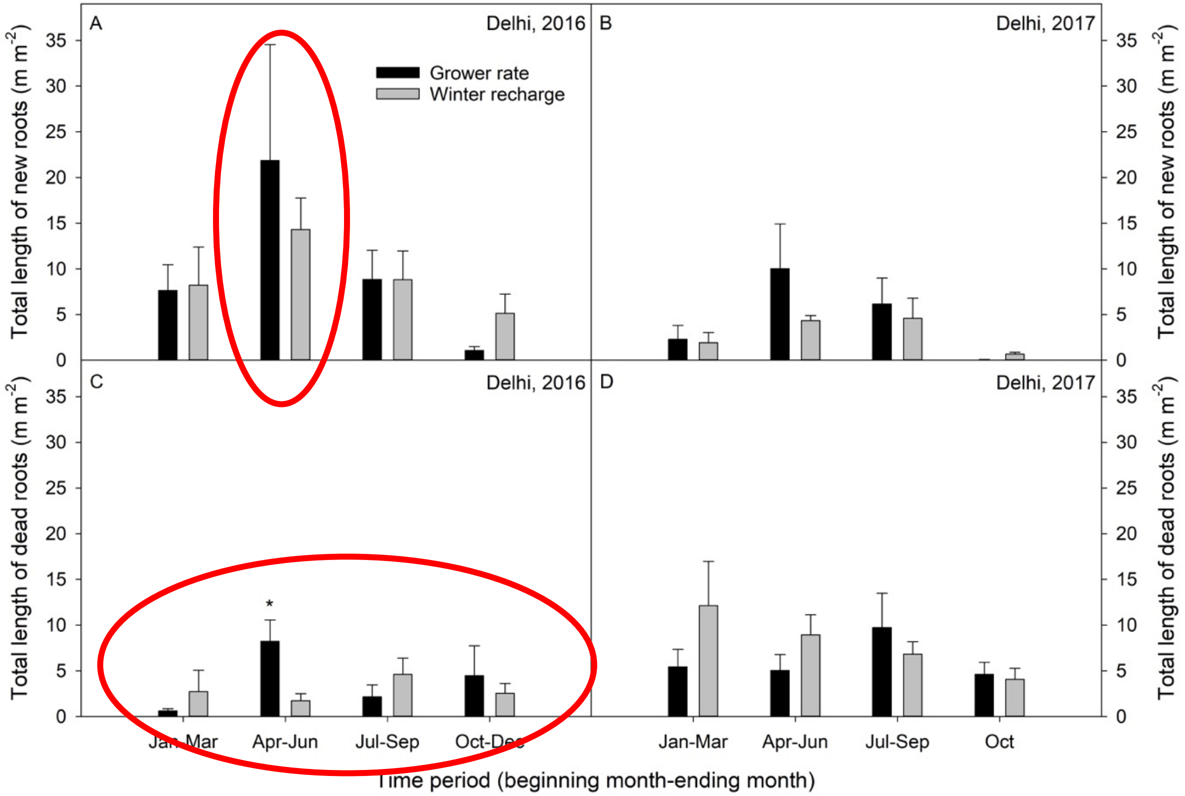
Crop Suitability - almonds

- Recharge in winter showed no significant effects on new root production
- Significant reduction in total length of dead roots (increased root lifespan)

Modesto (fine sandy loam)



Delhi (sand)



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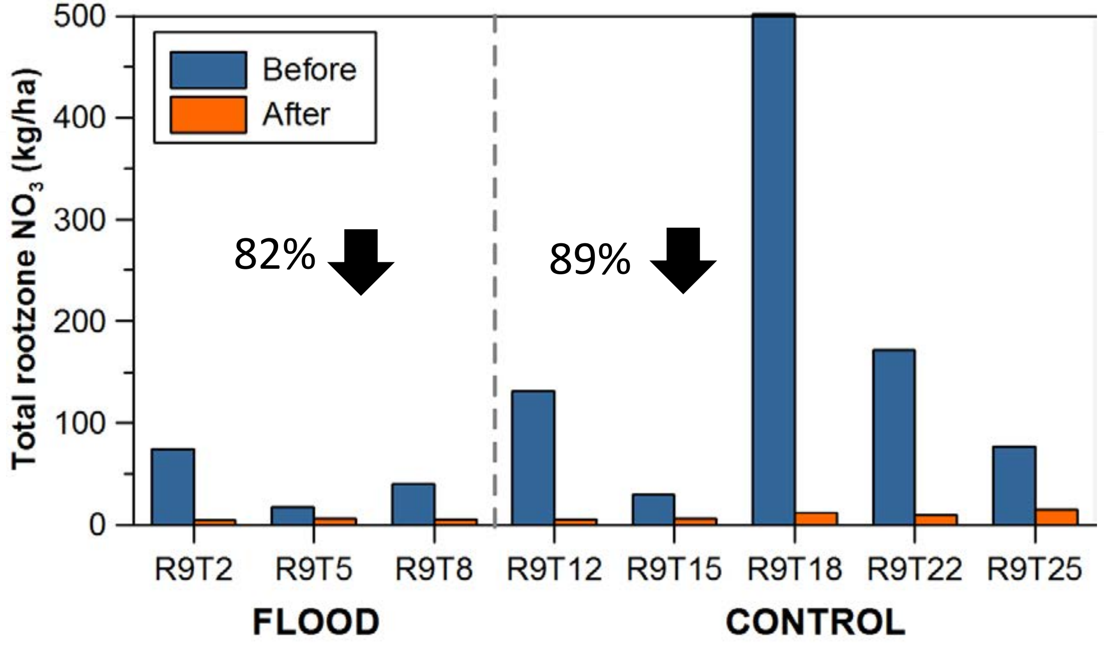
Ma et al. 2020 submitted to CalAg, Volder et al. 2021 in prep

Soil Nitrate Leaching – Almonds (2015/16)

- Orchards were flooded with 24 inches of water, 3-4 irrigation events in Dec/Jan of 2015/16

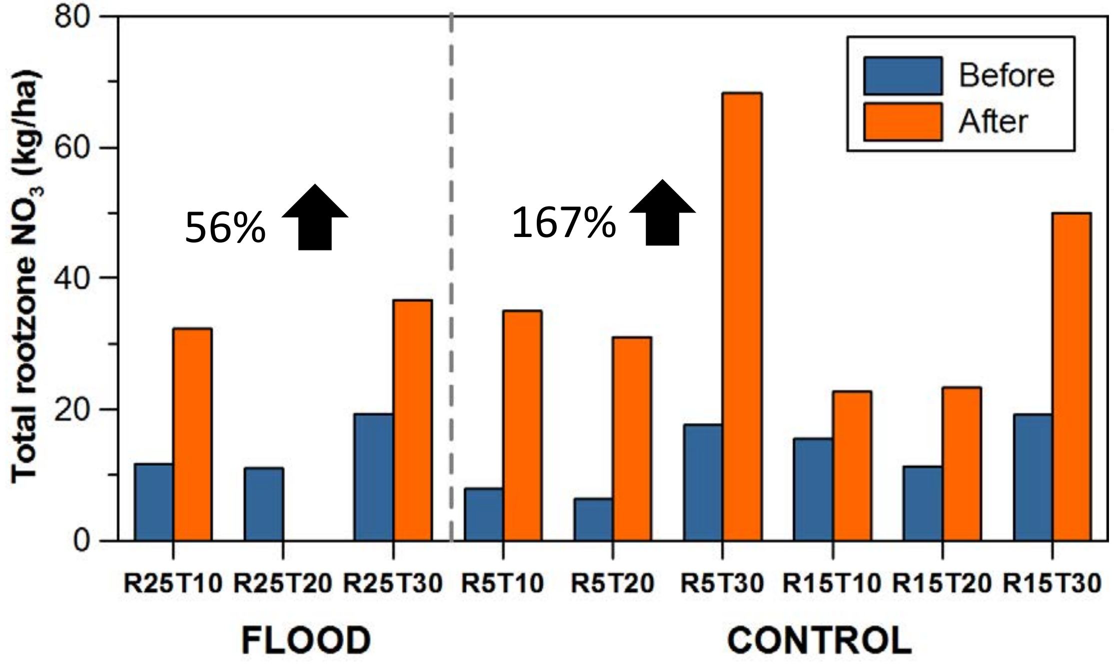
ROOT ZONE (3 FT)

Delhi (sand)



➢ Leaching! (denitrification, mineralization?)

Modesto (fine sandy loam)



➢ Mineralization of organic nitrogen?

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Murphy et al. 2020 submitted

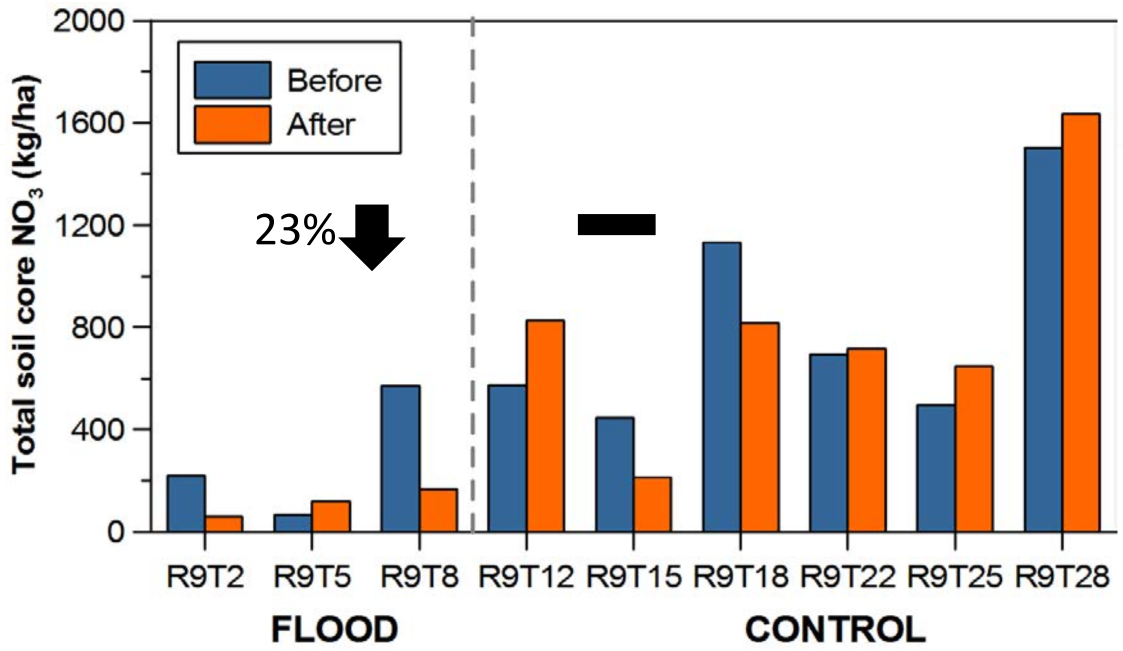
Soil Nitrate: 1 kg/ha = 0.89 lbs/acre

Soil Nitrate Leaching – Almonds (2015/16)

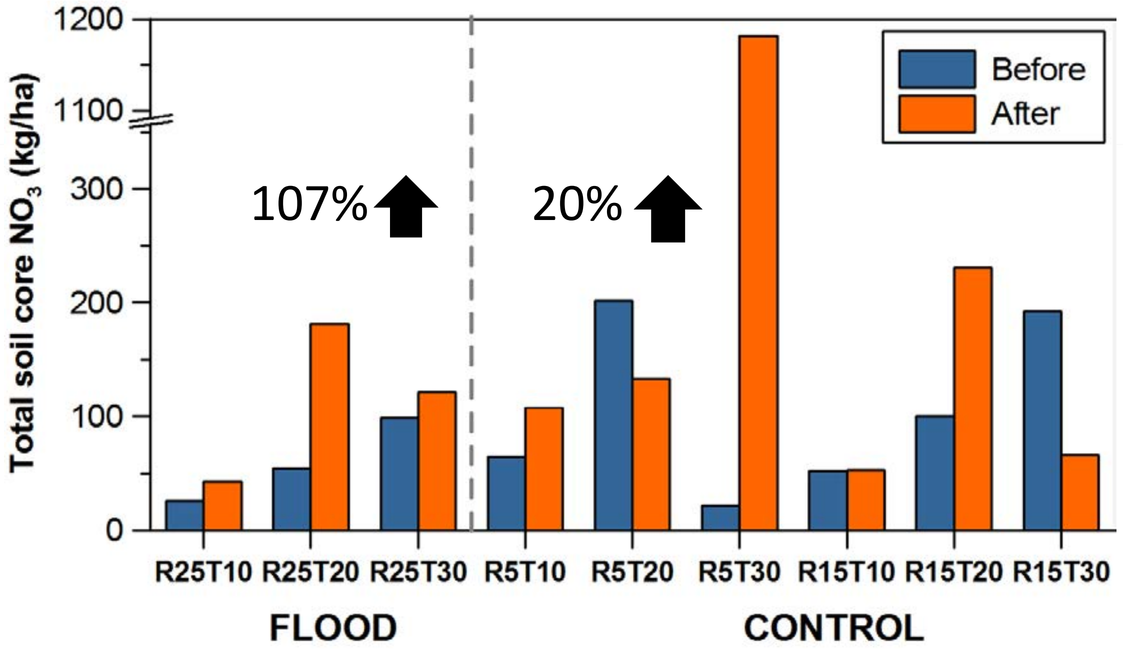
- Orchards were flooded with 24 inches of water, 3-4 irrigation events in Dec/Jan of 2015/16

ENTIRE PROFILE (16ft)

Delhi, CA – fine sand



Modesto, CA – fine sandy loam



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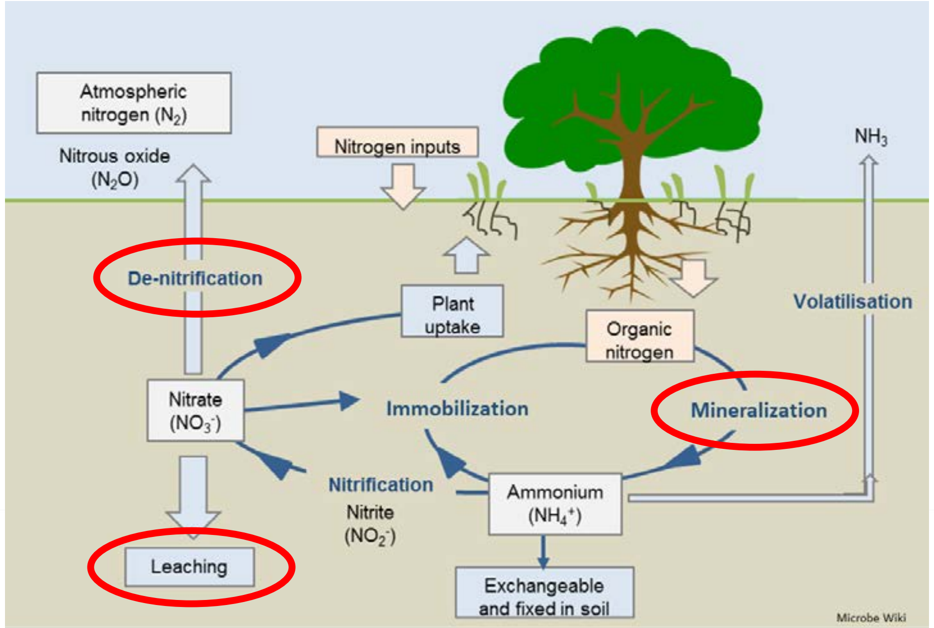
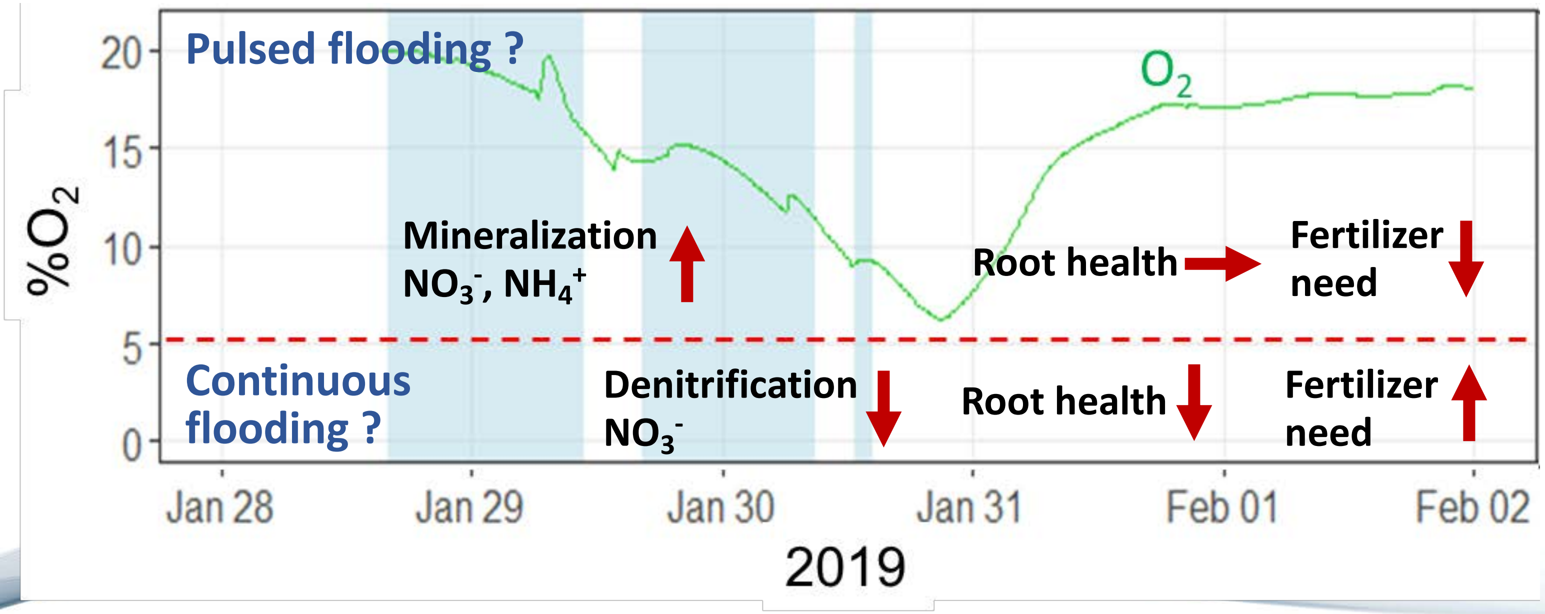
Murphy et al. 2020 submitted

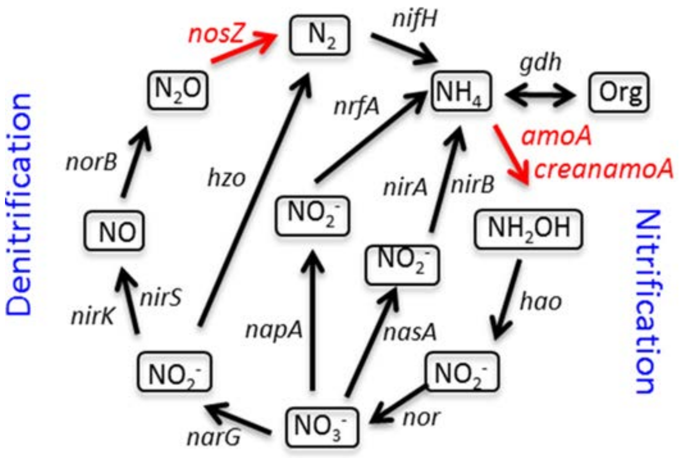
Soil Nitrate: 1 kg/ha = 0.89 lbs/acre

Managing trade-offs in Ag-MAR

- Impact of AgMAR on nitrogen cycling, hydrology, and microbiology as controlled by soil type, crop type, and management practices
- Reactive transport modeling (HYDRUS HP1)

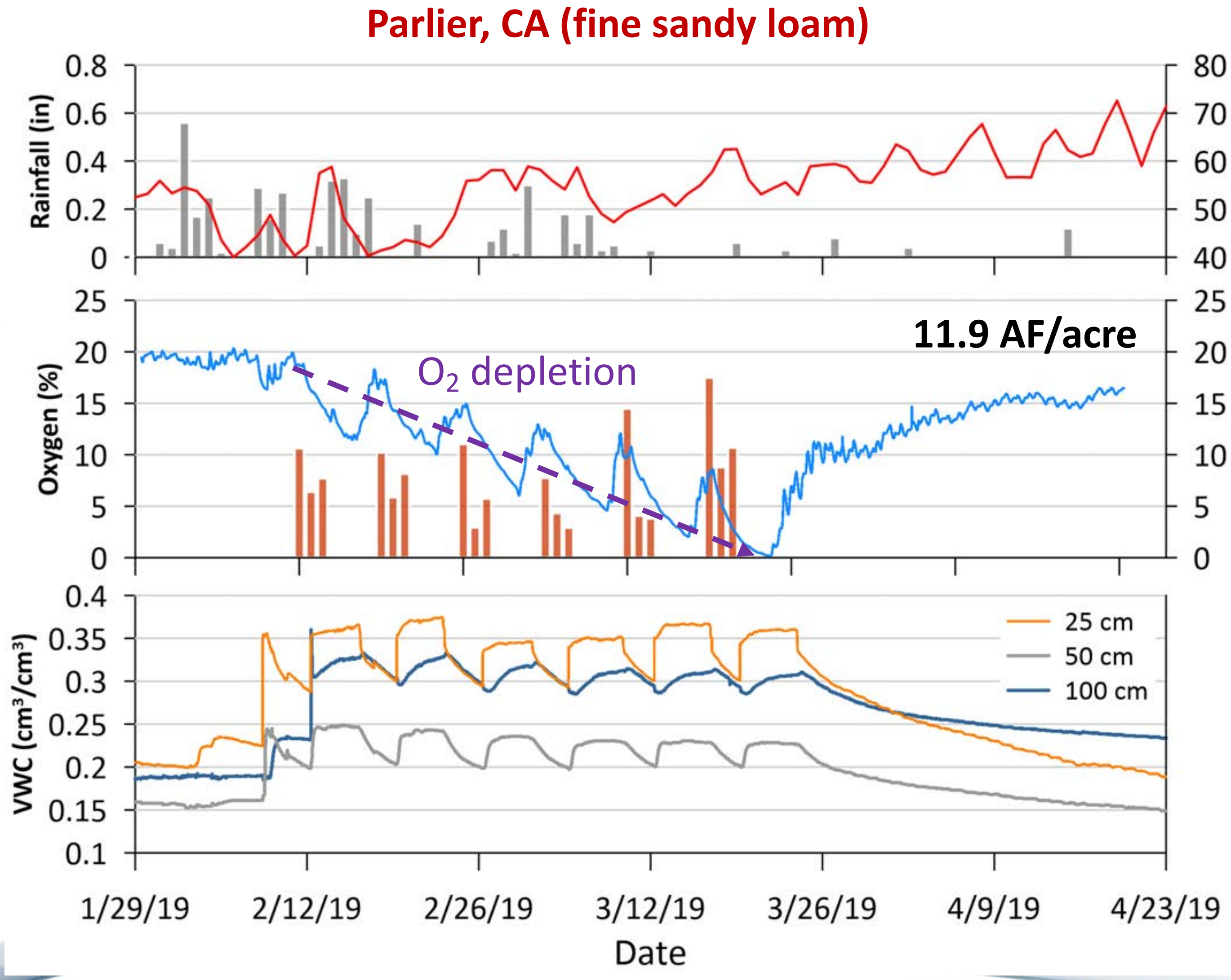


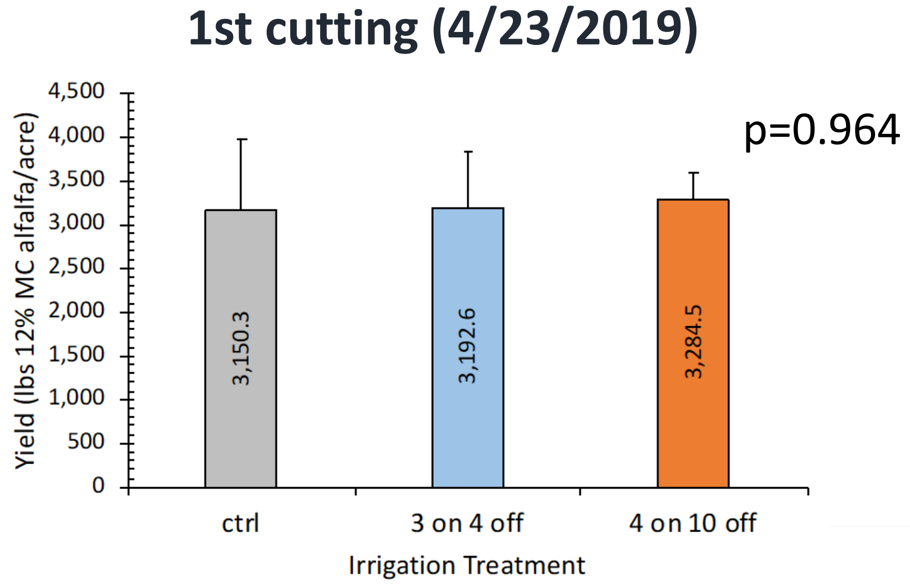


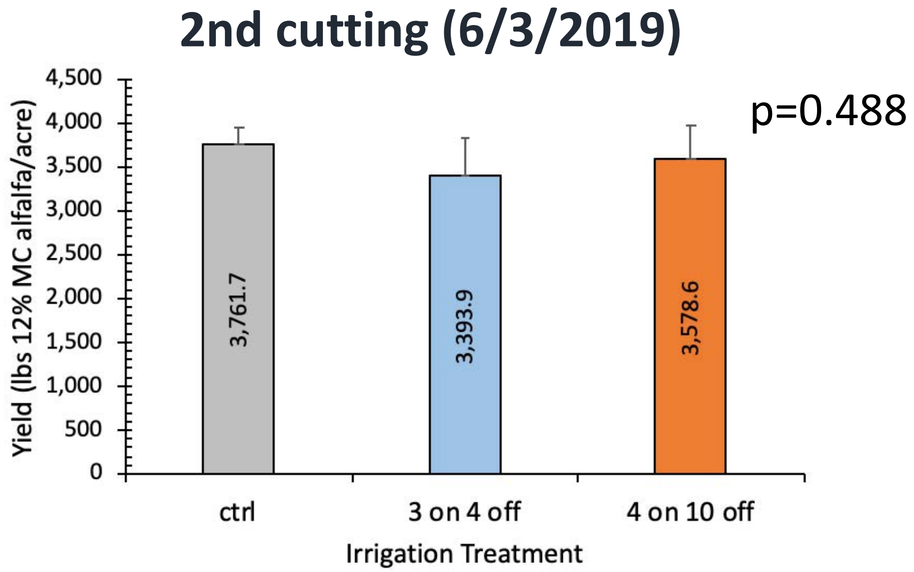


N species and known genes associated with their cycling

Crop Suitability - Alfalfa







(Ameristand 835NT RR, fall dormancy rating of 8)

Dahlke et al. 2021 in prep

Alfalfa Feed Quality Analysis

- Flooding could impact digestible fiber content

	Treatment	Amylase-treated neutral detergent fiber (aNDF)			Acid Detergent Fiber (ADF)			Ash			Crude Protein (CP)		
Control	1	39.75	Good	b	31.54	Good	a	12.07		a	21.56	Premium	a
4 on 10 off	2	42.23	Fair	a	33.31	Fair	a	11.79	High	a	20.17	Premium	b
3 on 4 off	3	40.72	Fair	ab	32.02	Fair	a	11.96		a	20.76	Premium	ab
p-value		*0.047*			*0.078*			*0.69*			*0.036*		

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

	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%.

Dahlke et al. 2021 in prep

Hay report: https://www.ams.usda.gov/mnreports/ml_gr311.txt

Take-Away Points – Crop Suitability

- Flooding of semi-non-dormant alfalfa or almonds showed no significant effect on yield
- On suitable (well drained) soils large amounts of water can be recharged
- Viable option for regions where large amounts of excess water is less frequently available
- Flooding can create short-lived anoxic conditions in the root zone – flooding duration < root zone residence time
- Winter flooding might affect feed quality (digestible fiber content) – more research needed.
- Potentially greater need for herbicide applications to reduce weed pressure

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Factors influencing Ag-MAR adoption

Cost & incentives

Laws and permits

Hydrogeology

Crop suitability

Location

Water quality

Water availability

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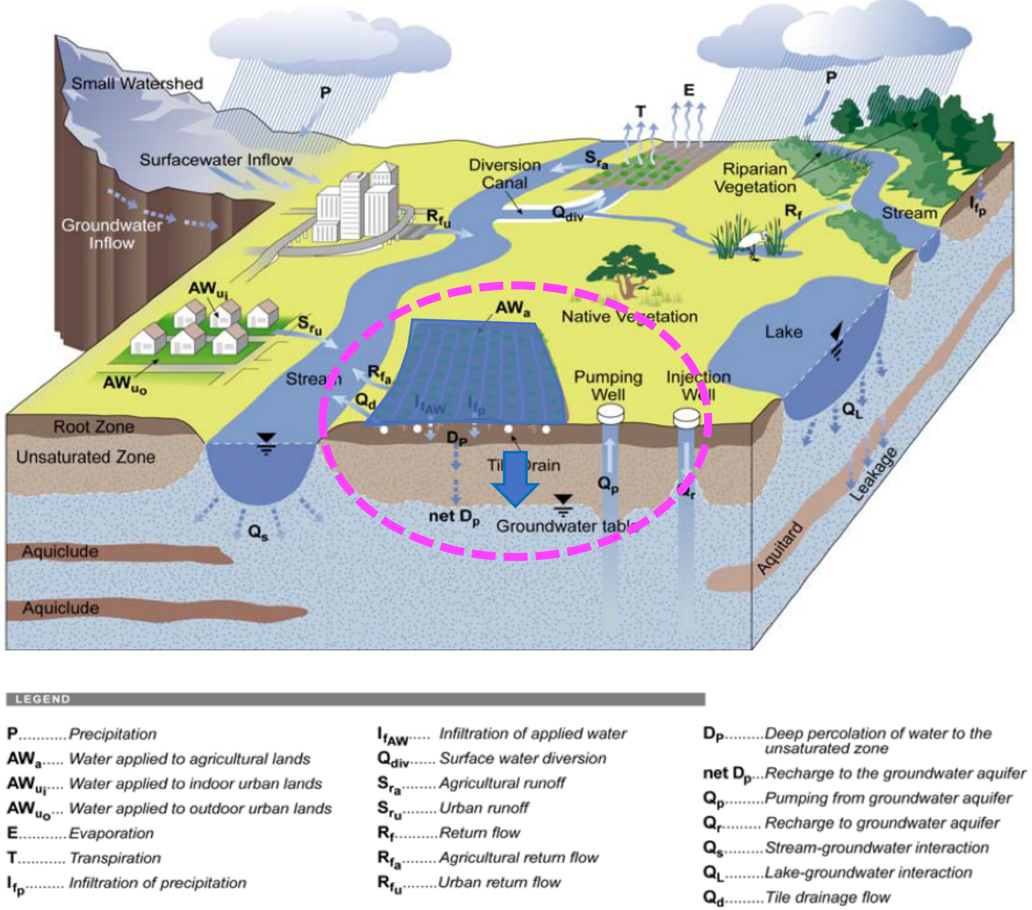
What is the effect of large-scale Ag-MAR on groundwater storage and streamflow?

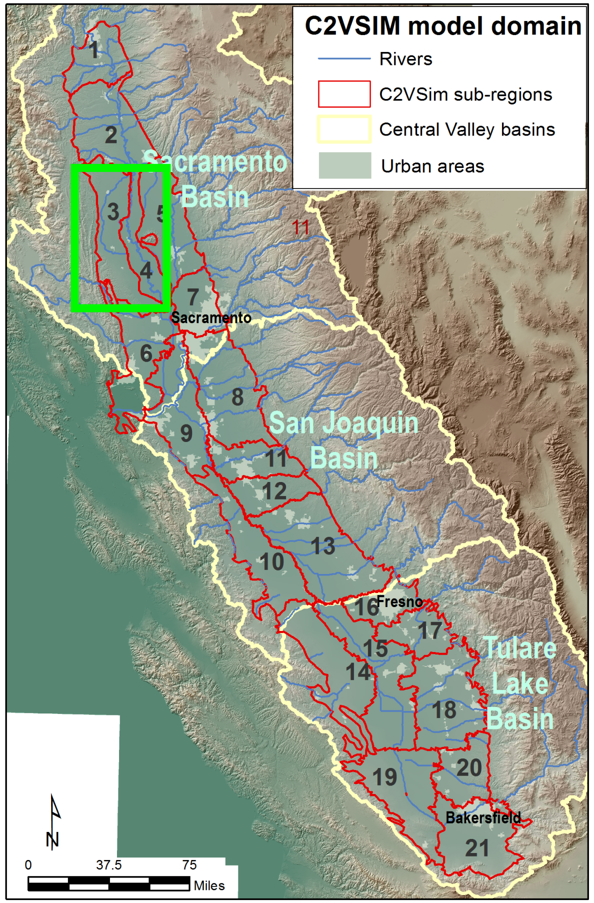
Large-scale integrated groundwater-surface water modeling

C2VSim: Central Valley integrated groundwater-surface water simulation model



- Model domain covers the Central Valley alluvial aquifer (53,645 km^2)
- 32,537 finite elements
- 4 vertical groundwater layers
- Model solves continuity equation for stream nodes and 3D gw flow equation
- Flow through root zone and unsaturated zone represented by 1D vertical flow component
- Unsaturated zone flow is bypassed for MAR simulations
- Simulation period: 1921-2009

Orland-Artois Water District



Kourakos et al., 2019 WRR

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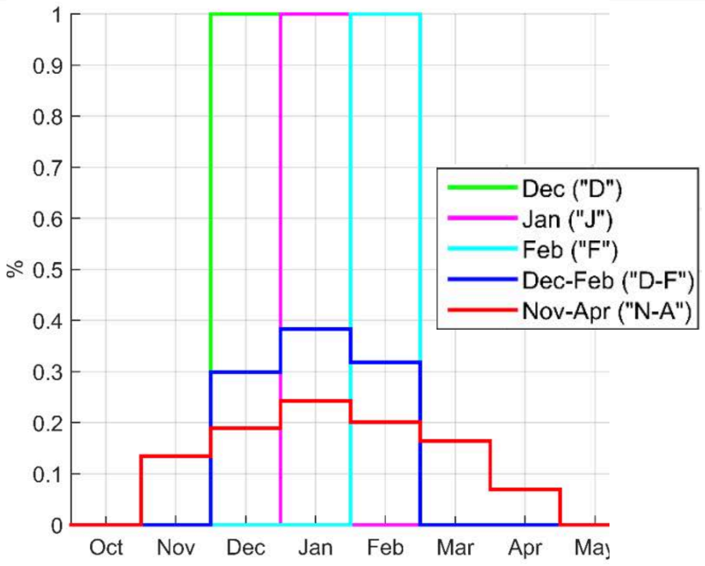
Brush et al., 2013, Dogrul et al. 2016

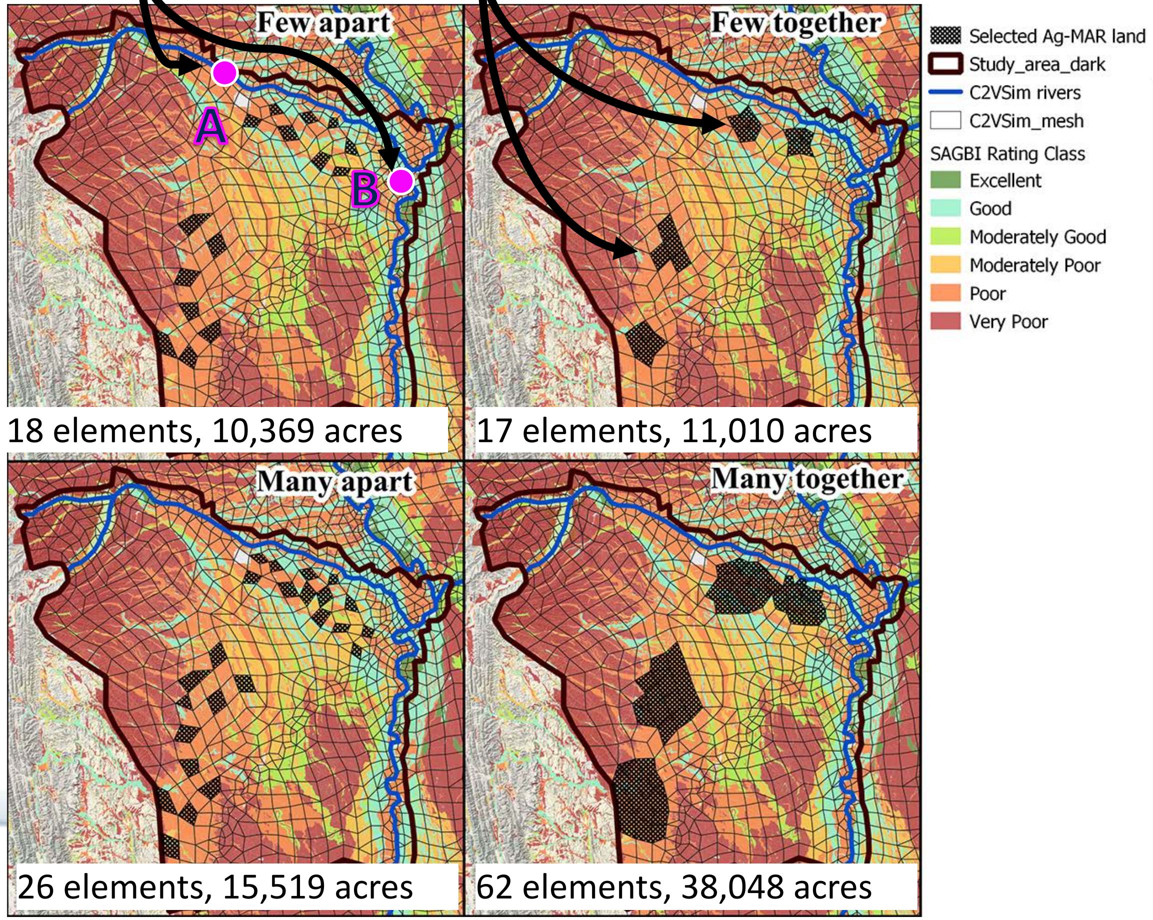
Large-scale integrated groundwater-surface water modeling

MAR Scenarios

- Recharge Amount
- Recharge Timing
- Diversion points
- Recharge Locations

Fixed target depth [ft/year]	Fixed target volume [TAF/year]
2	10
4	30
6	60
10	100

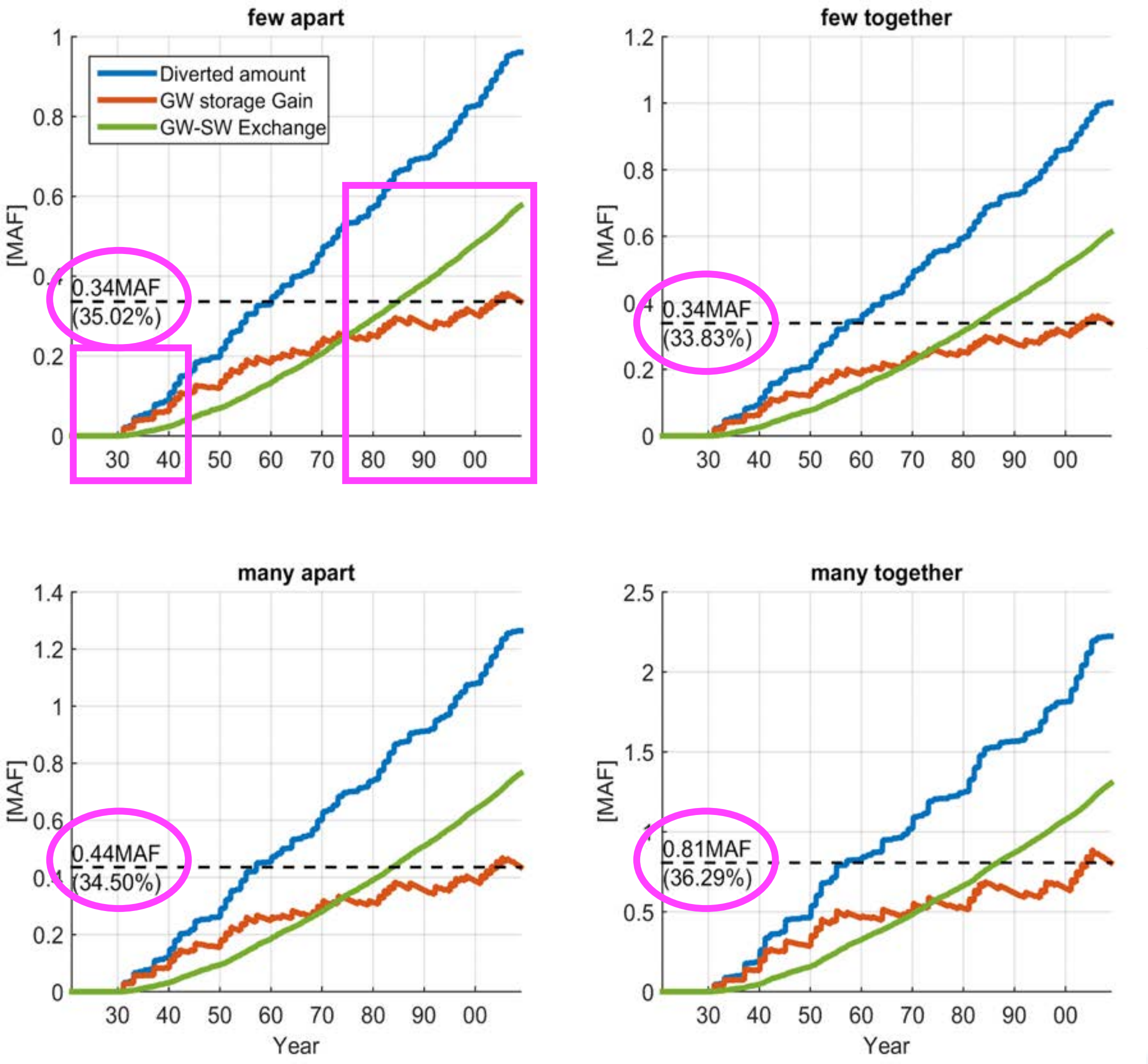




Kourakos et al., 2019 WRR

Surface Water Supply and Groundwater Storage Change

Groundwater Budget Components For Stony Creek RTD2 (2 ft/yr), December only



Groundwater storage gain is high in the first two decades.

Levels off over time as groundwater system finds a new dynamic equilibrium.

The plateau is a function of the average long-term annual recharge.

Distribution of recharge locations does not affect the amount of cumulative baseflow gains and groundwater storage

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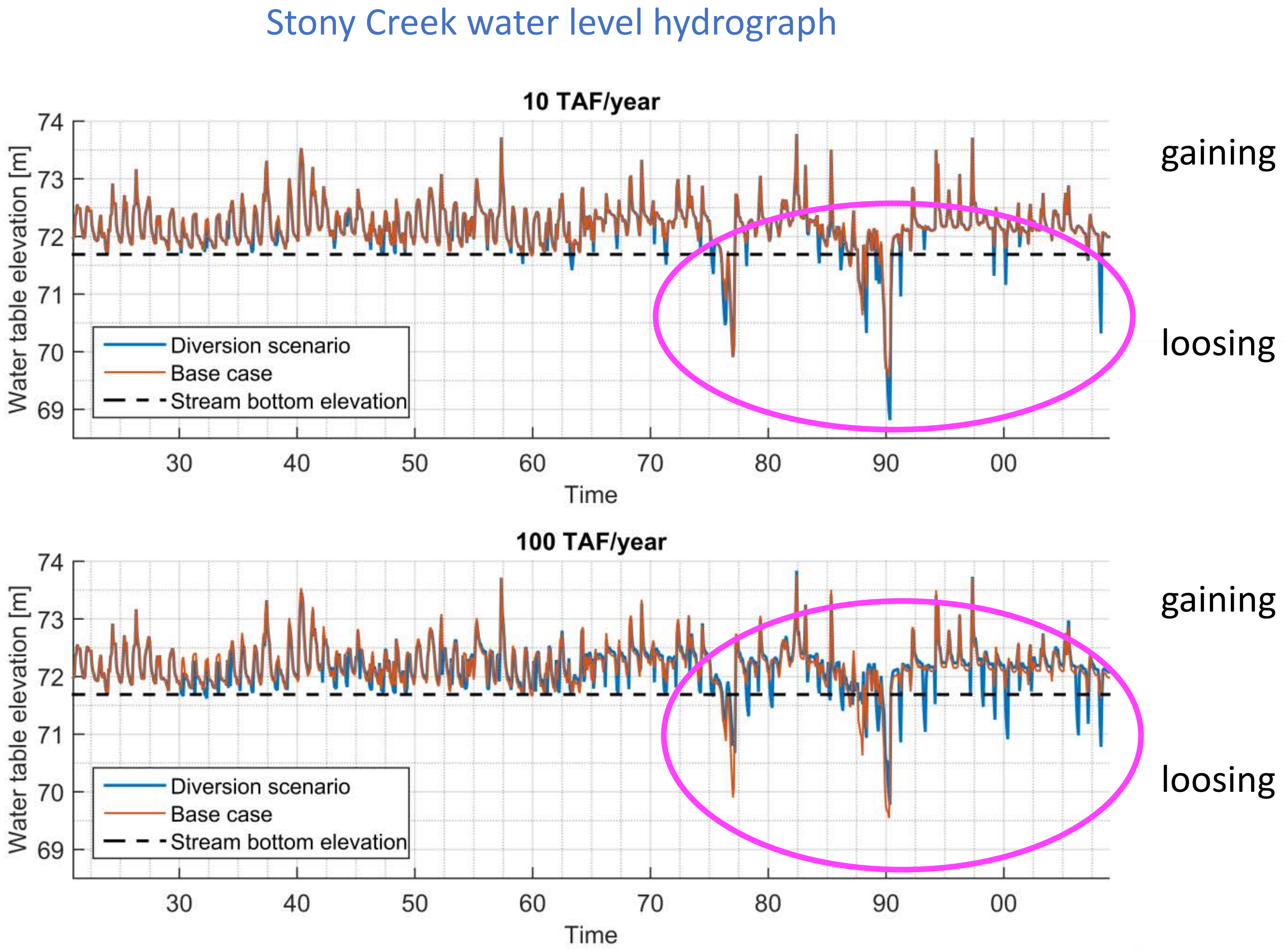
Kourakos et al., 2019 WRR

Streamflow Response to Diversion

Groundwater recharge improves resilience of aquifer and streams to droughts by providing baseflow during extreme drought periods



Kourakos et al., 2019 WRR

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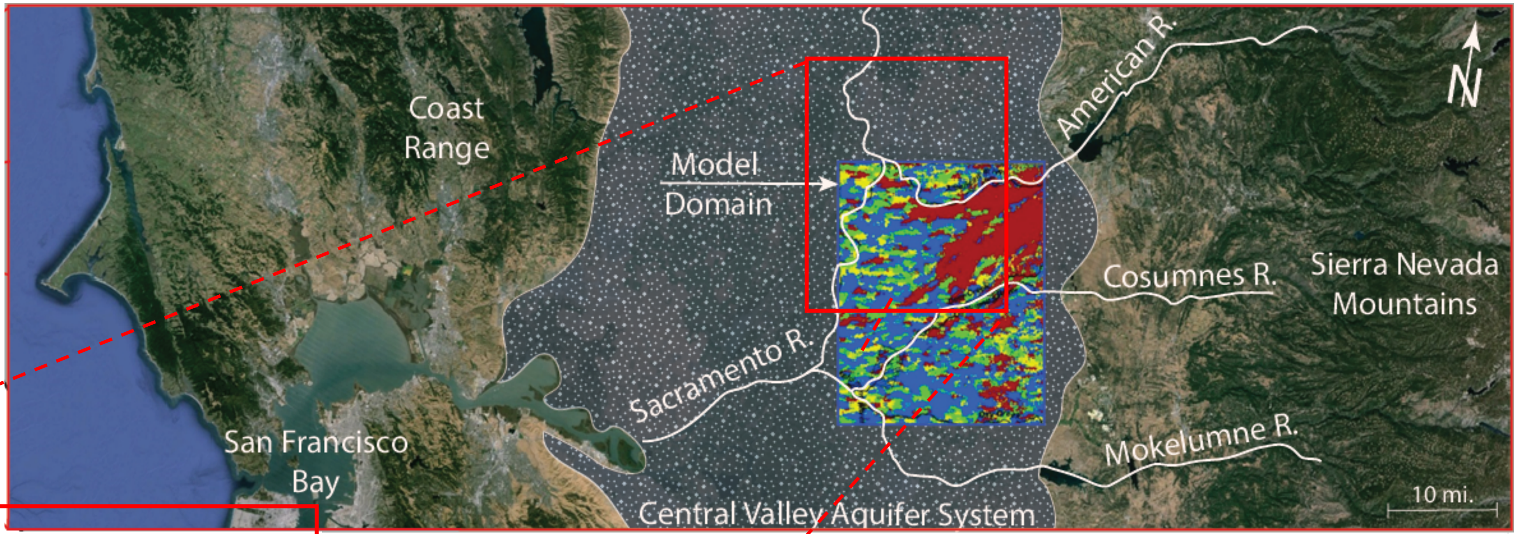
ParFlow Model American-Cosumnes Basin

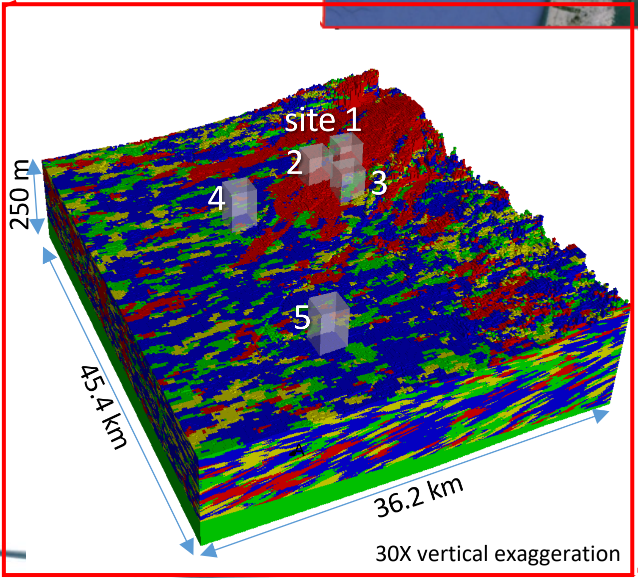
Highly-Detailed Representation of Geologic Heterogeneity (Meirovitz, 2010)

- Stochastic geostatistical model (TPROGS) w/ ~1200 well logs
- 4 hydrofacies Gravel, Sand, Muddy Sand, Mud



Managed Aquifer Recharge Simulations

- 3D, variably-saturated flow model, Parflow (Kollet & Maxwell, 2006)
- 5 recharge sites of 1420 acres each; 10-cm ponded water
- Sites 1-3 have sand & gravel near surface
- Sites 4&5 have muddy sand and mud near surface
- 180-day simulations



Hydrofacies	K_{sat} (m/d)	S_s (m^{-1})	Fraction of Total Vol.
Gravel	67.5	4.0×10^{-5}	0.23
Sand	41.2	8.0×10^{-5}	0.14
Muddy Sand	0.20	1.0×10^{-4}	0.18
Mud	0.0017	1.0×10^{-3}	0.45

Maples et al. 2019

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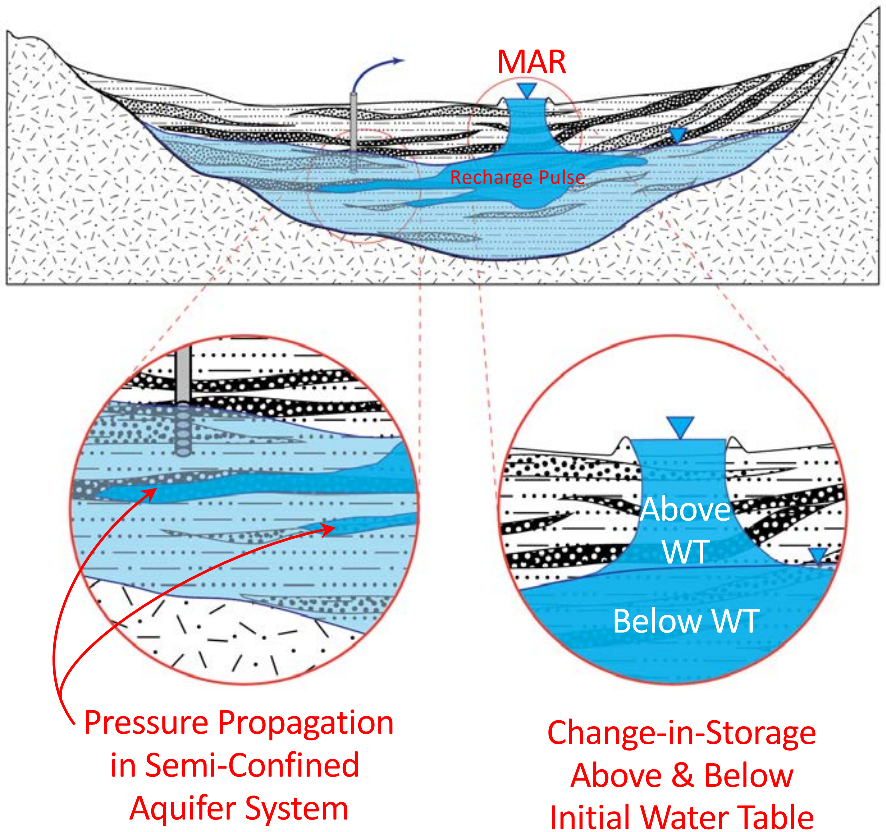
Subsurface recharge processes

Main Benefits of Recharge:

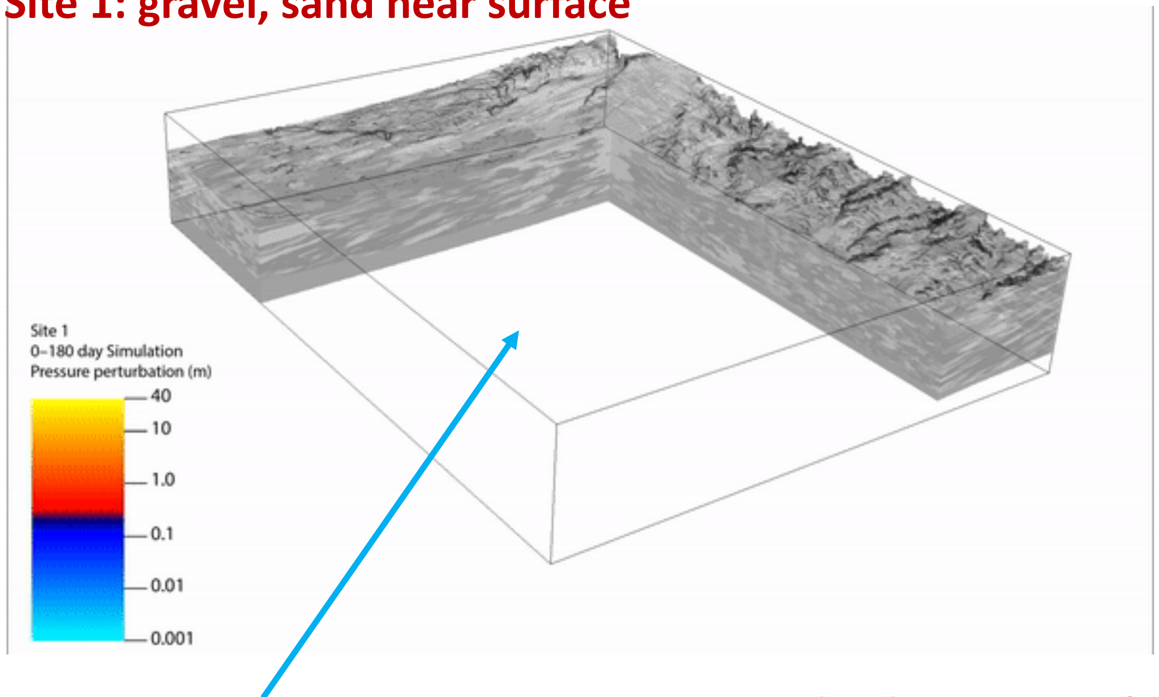
1. Increase in Pressure (i.e., Piezometric Head) in semi-confined aquifers
2. Increase in Groundwater Storage



Maples et al. 2019, Hydrogeology Journal

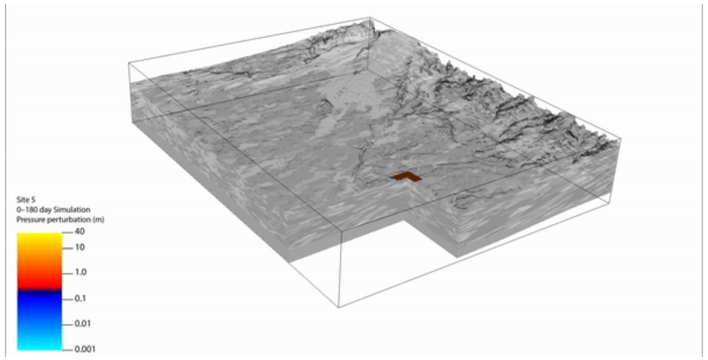
Pressure Perturbation Simulations (0-180 days)

Site 1: gravel, sand near surface



> 200m vertical pressure propagation
> 5km lateral pressure propagation
> Change in groundwater storage 65 times greater than site 5

Site 5: silt, clay near surface



Factors influencing Ag-MAR adoption

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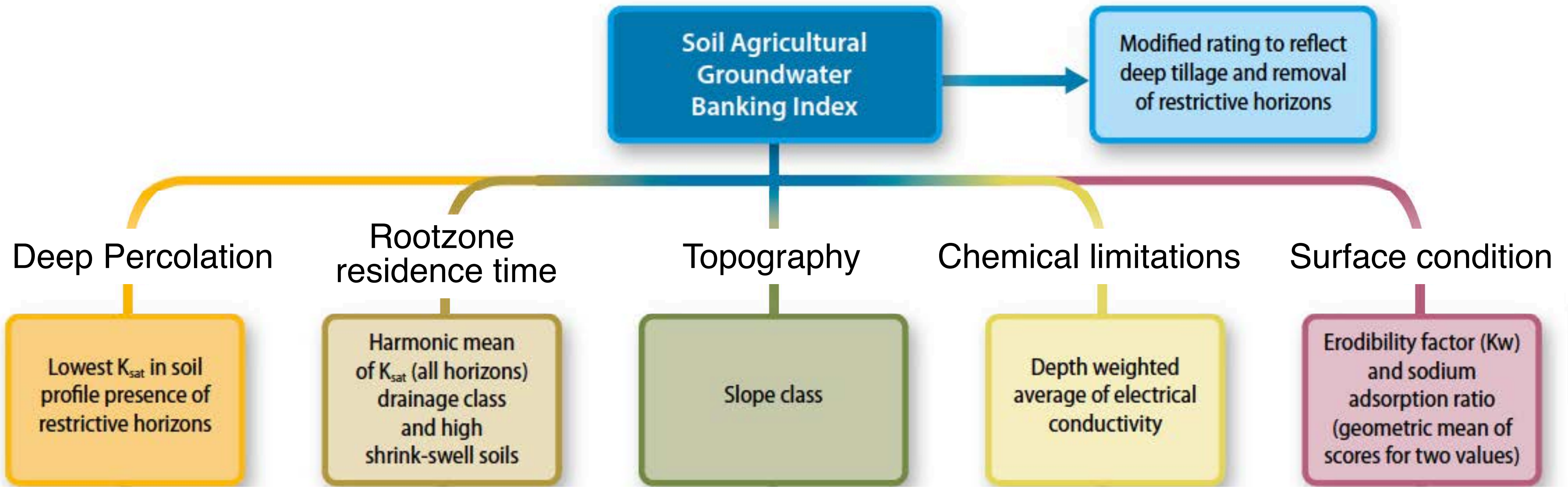
Suitable Ag-MAR Locations

Soil agricultural groundwater banking index (SAGBI)

- considers five major factors critical to sustaining crop health and rapid deep percolation of applied water



O'Geen et al. 2015, CalAg

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

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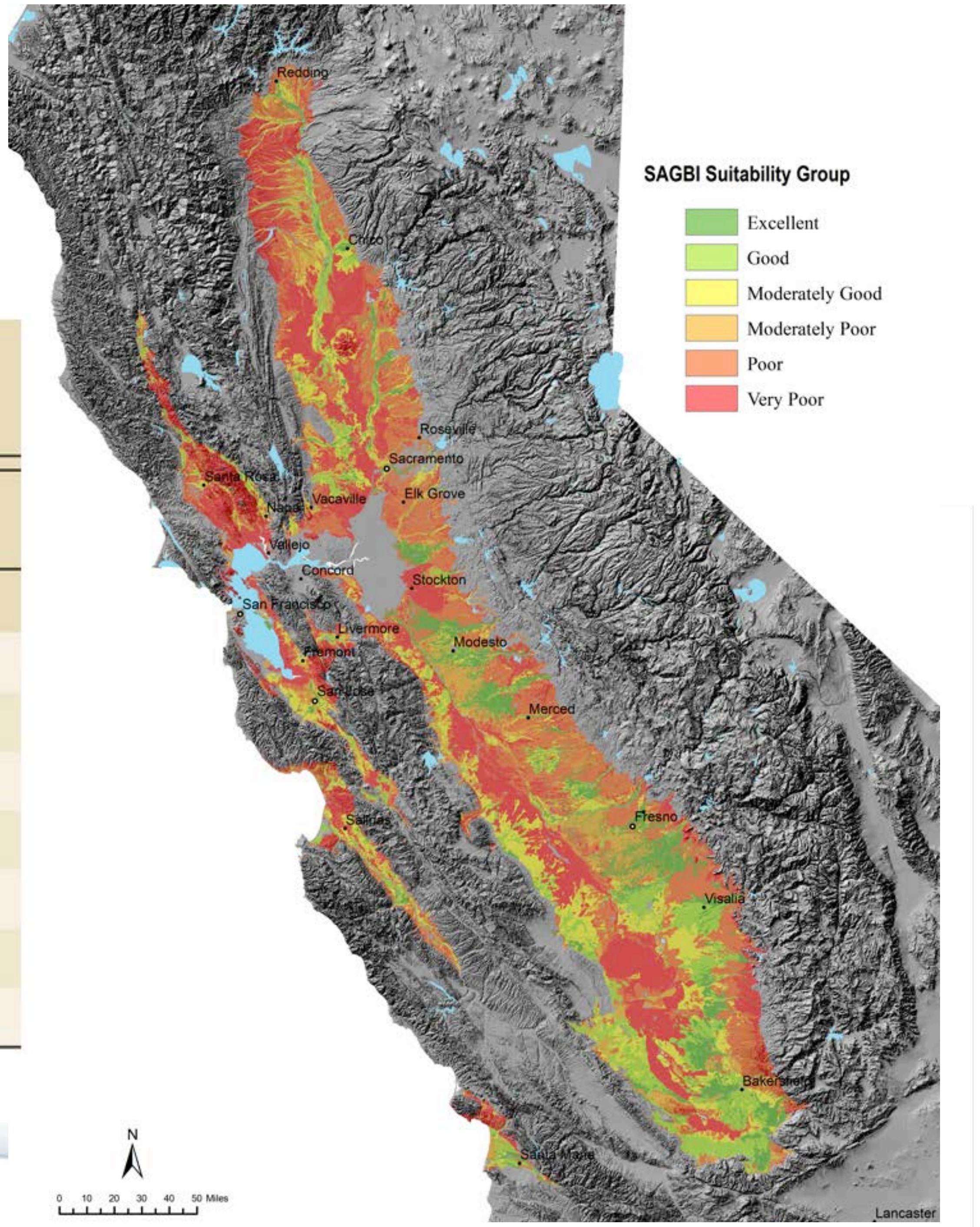
Soil Agricultural Groundwater Banking Index

- About 5.5-6.5 million acres of farmland suitable for recharge

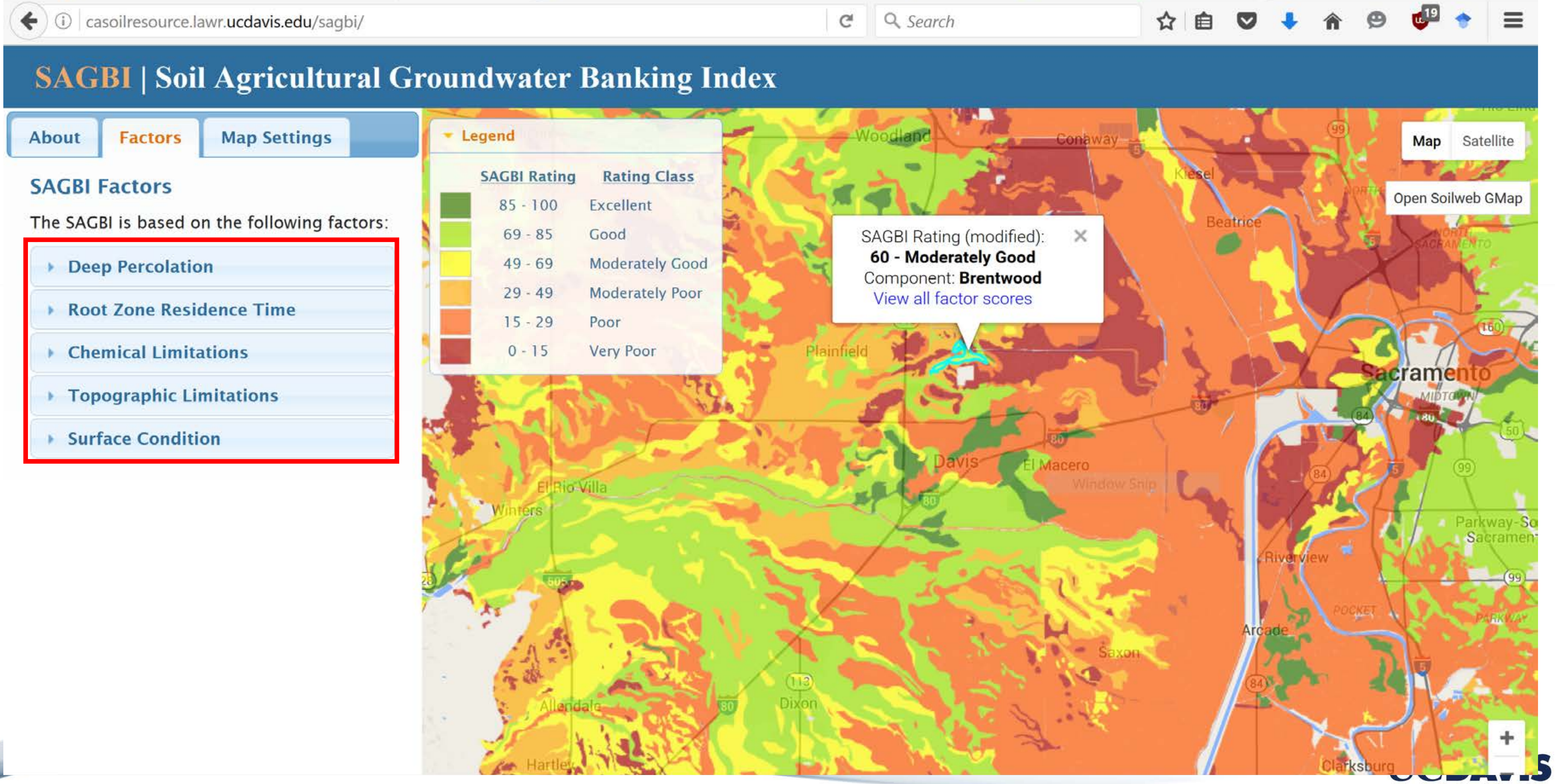
TABLE 2. Summary of the areal extent of Soil Agricultural Groundwater Banking Index groups generated from soil survey data

SAGBI group	Original SSURGO data		SSURGO modified by deep tillage	
	acres	*%**	*acres*	*%**
Excellent	1,477,191	8	1,557,035	9
Good	1,747,712	10	2,020,921	11
Moderately Good	1,786,972	10	1,984,414	11
Moderately Poor	1,343,250	8	1,364,066	8
Poor	4,866,942	28	4,586,645	26
Very Poor	6,375,277	36	6,084,142	35
Total†	17,597,345		17,597,222	



O'Geen et al. 2015, CalAg

Soil Agricultural Groundwater Banking Index



Targeted recharge near rural communities to improve water security

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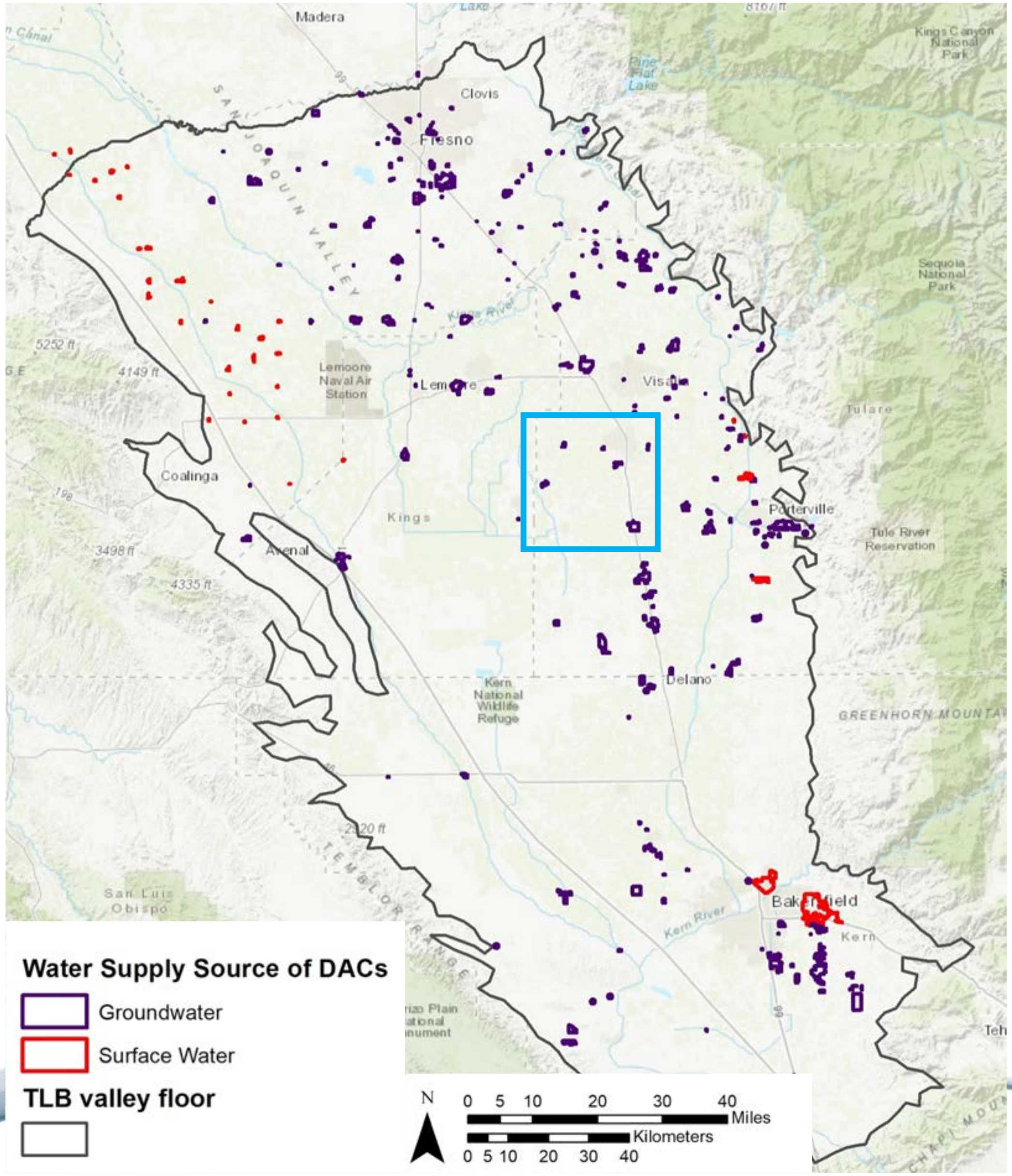
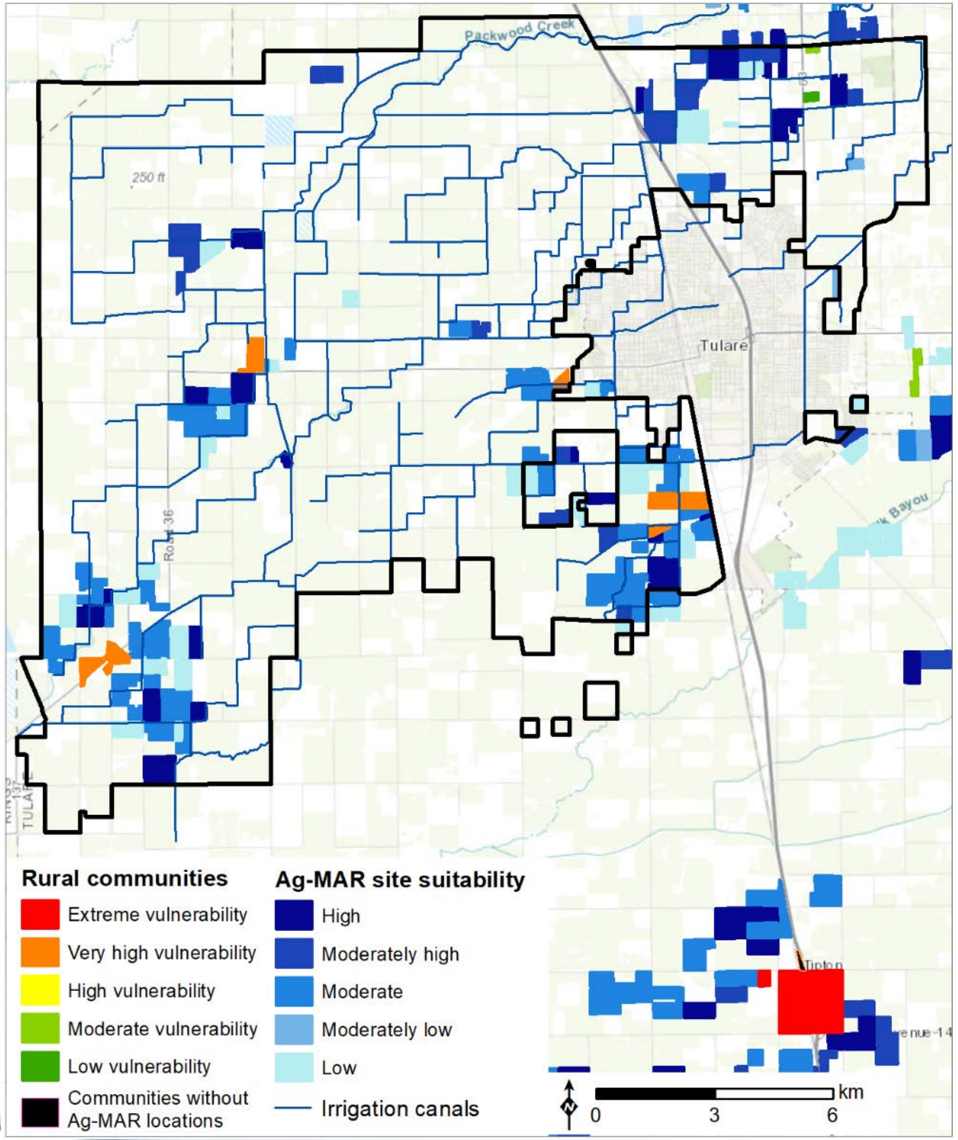
Targeted recharge near vulnerable communities





Marwaha et al. 2020, WRR, submitted

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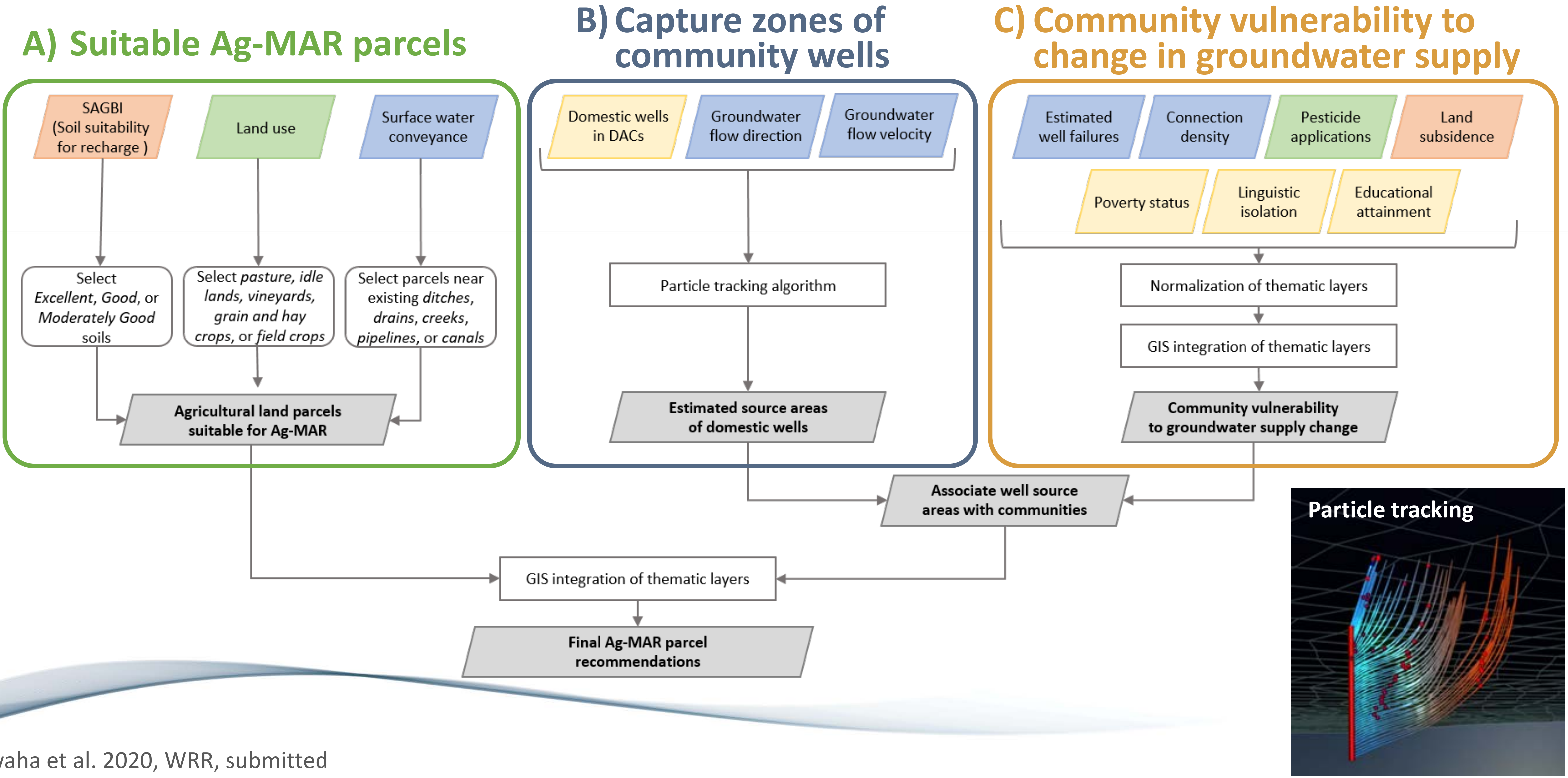
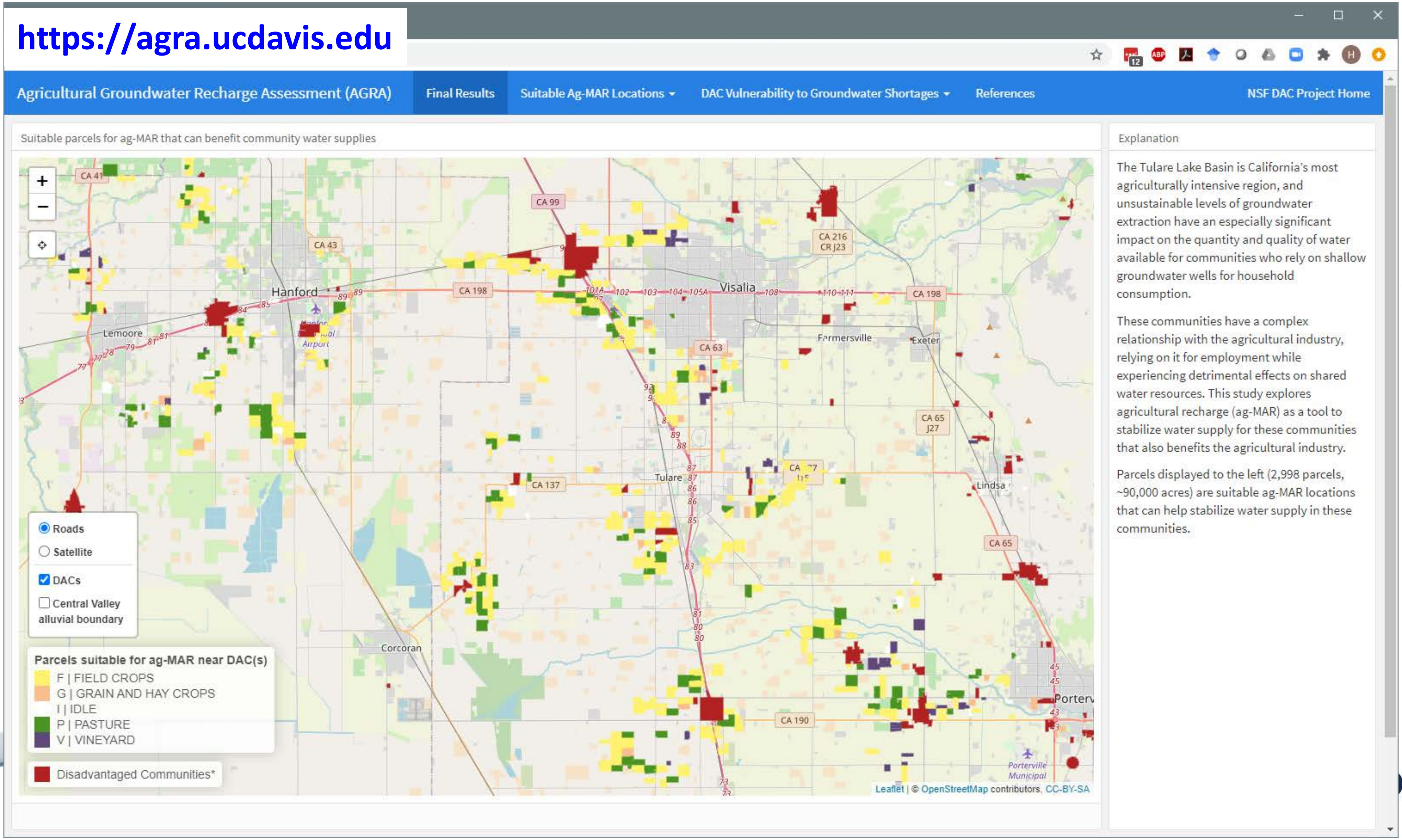
Targeted recharge for increased community resilience



Marwaha et al. 2020, WRR, submitted

Targeted recharge near vulnerable communities



Evolutionary multi-objective optimization of MAR locations

Hydro-economic determination of best MAR sites

- Implement evolutionary multi-objective optimization algorithm with C2VSim-CG model to determine best MAR locations

- Two main objective functions:

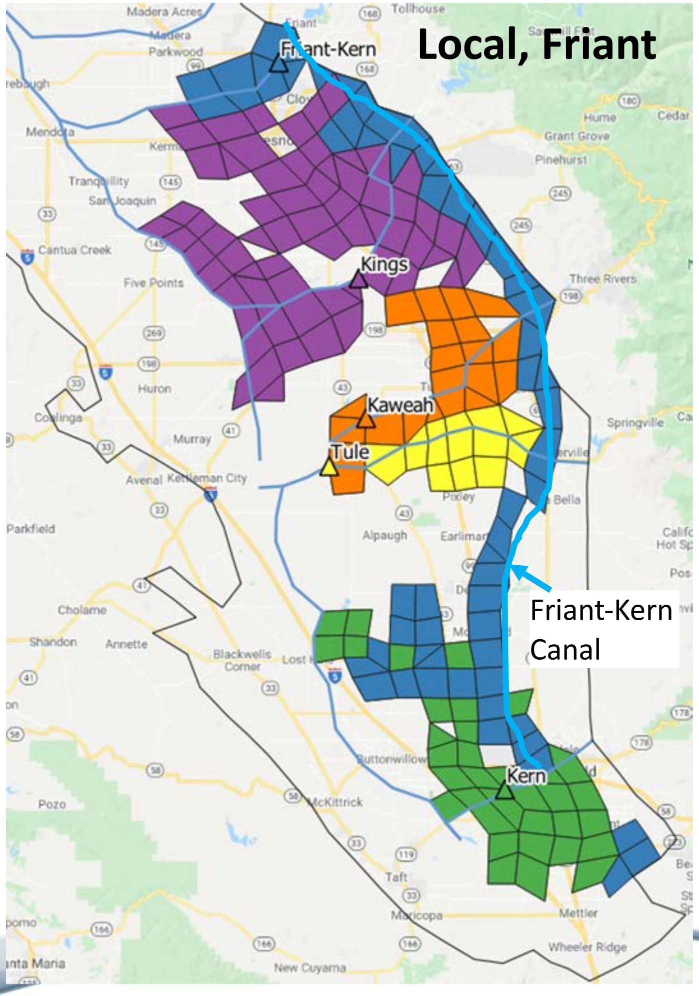
  - Maximize groundwater storage or basin-wide groundwater level

  - Minimize MAR costs = (1) land cost + (2) capital cost + (3) pumping lift cost + (4) water acquisition cost + (5) conveyance cost

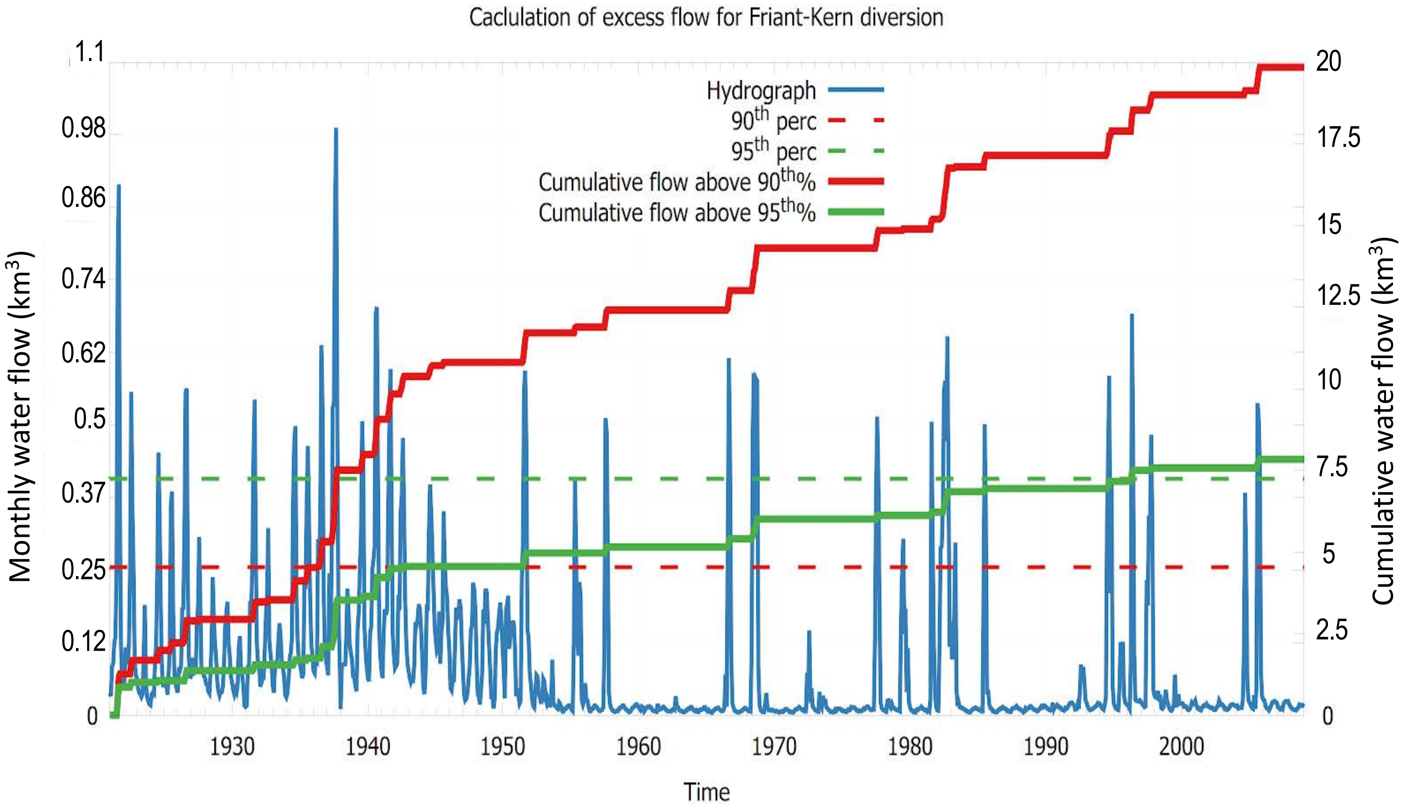
- Recharge is started in 1965 of 1921-2015 modeling period

Scenarios – diversion amounts for recharge

Recharge locations scenarios



Excess flow for the Friant-Kern canal diversion



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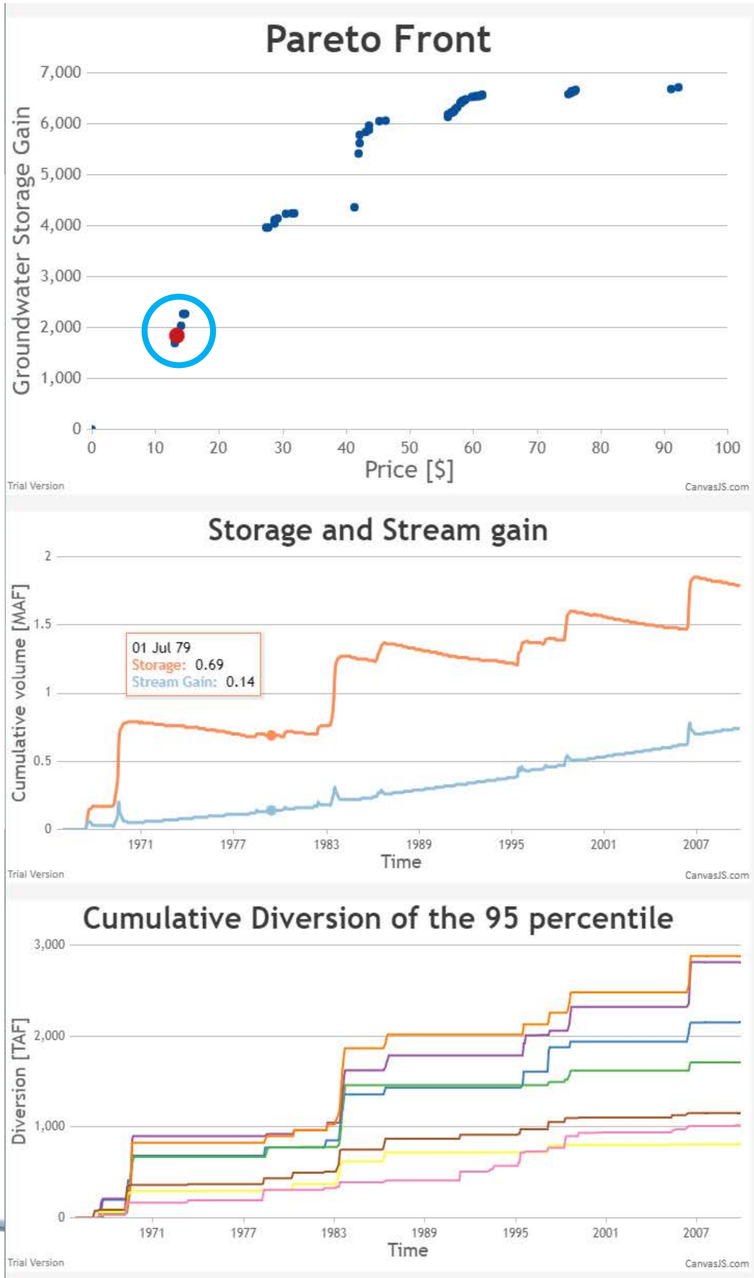
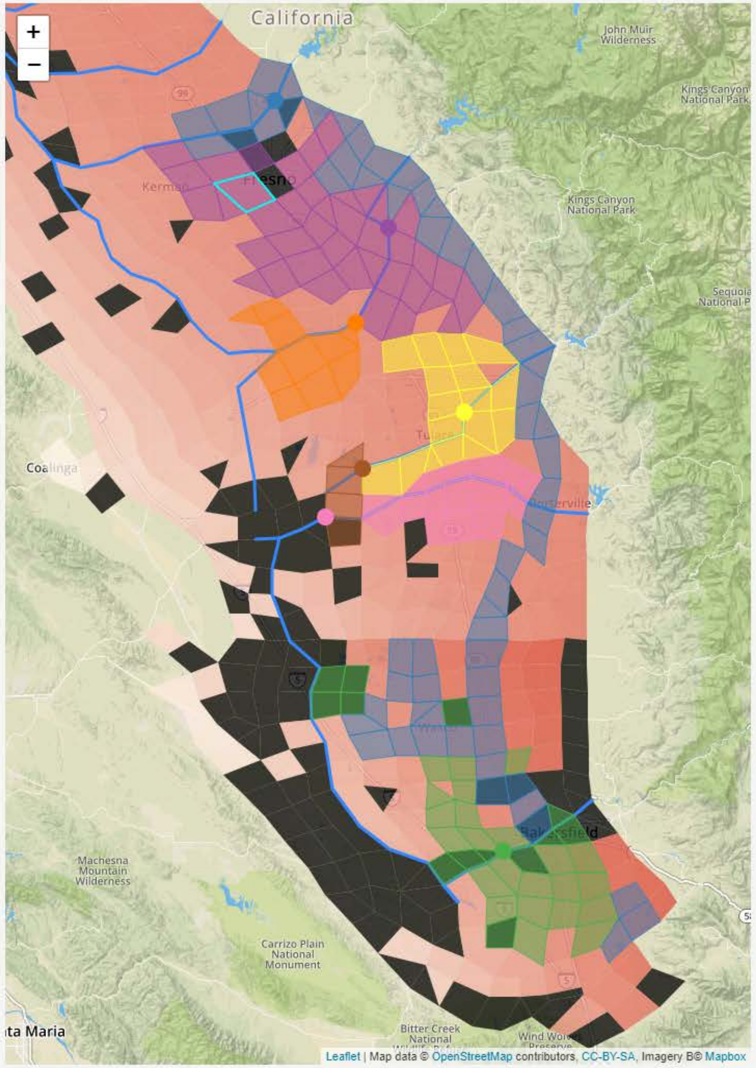
Results

- **Scenario:** Minimize cost & maximize groundwater storage gain
- Minimization function is highly nonlinear
- Gaps are associated with increase in number of optimal elements selected





http://subsurface.gr/joomla/MAR/ParetoAnalysisMAY20_95_temp.html

Conclusions

- On-farm recharge is a viable MAR option for regions where large amounts of excess water is less frequently available
- Recharge can increase groundwater storage and return flow to streams
- Targeted recharge near communities vulnerable to groundwater shortage can provide multiple benefits (water supply, water quality, climate resilience etc.)
- On-farm recharge sites should be carefully selected based on soil type and land use and nutrient use history (e.g. nitrate leaching potential)
- Field-level studies before implementation (i.e. soil analyses, stakeholder interest, surface water availability)

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Questions?

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