

Conjunctive Management of Surface Water and Groundwater to Increase the Sustainability of Global Water Resources

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University of Texas at Austin

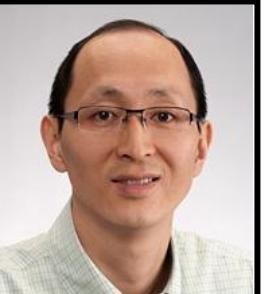
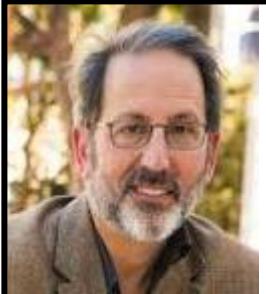


Post-docs
and visitors

Global modelers

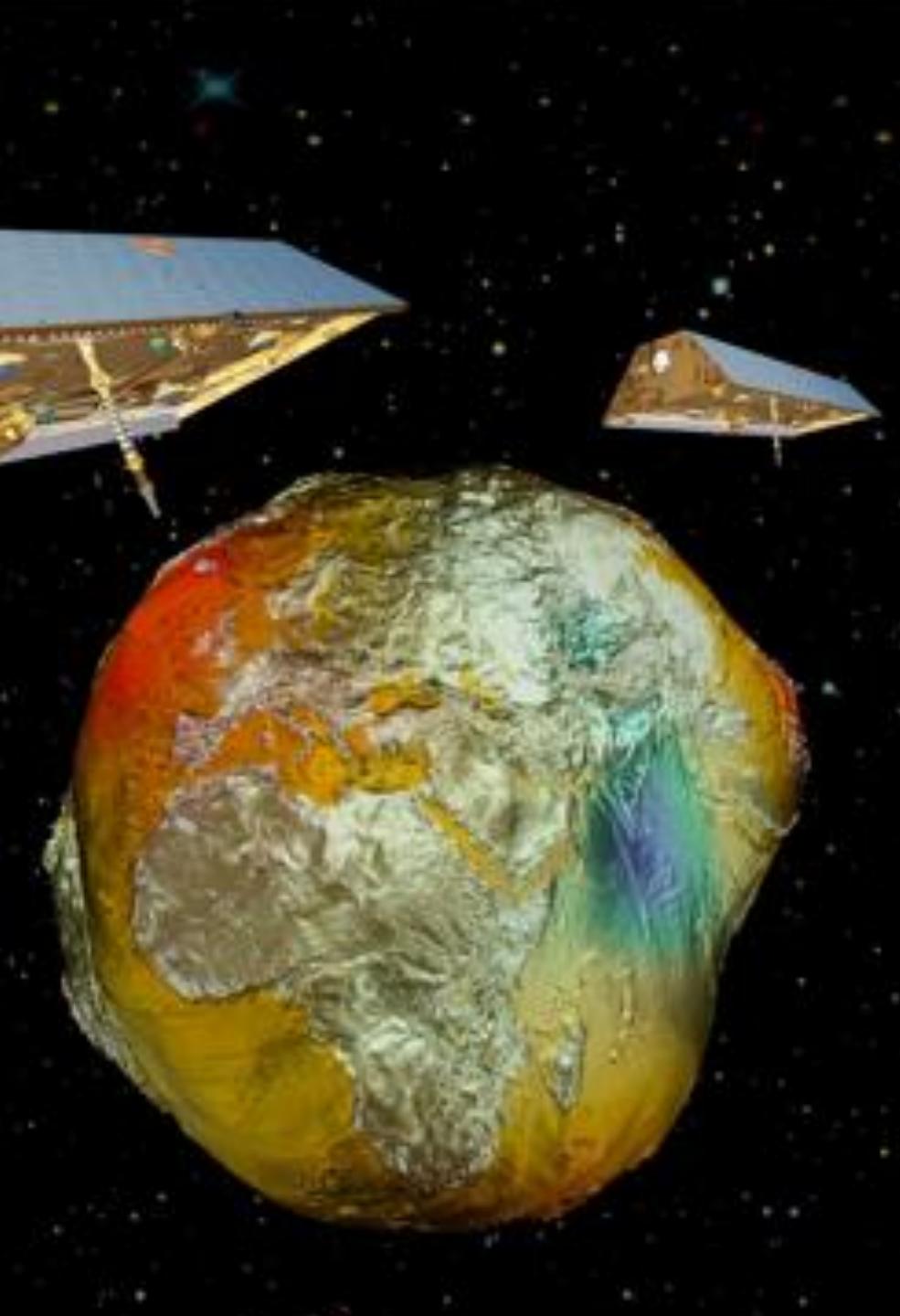


Geodesists



Hydrologists





Outline

1. Background
2. Global water resources using GRACE
3. Irrigation
 - a. Increase irrigation in Sub-Saharan Africa
 - b. Switching from SW to GW irrigation (NW India, Pakistan, NW US)
 - c. Conjunctive use of SW and GW (CA Central Valley)
 - d. Managed Aquifer Recharge: AZ + CA
4. Urban water shortages (Cape Town, Sao Paulo)



WORLD BANK GROUP
Water



GWSP
GLOBAL WATER
SECURITY & PARTNERSHIP
PARTNERSHIP

Groundwater: The hidden wealth of nations

GROUNDWATER IS NATURE'S INSURANCE



PROTECTS
FOOD SECURITY



REDUCES
POVERTY



BOOSTS
RESILIENT GROWTH

GROUNDWATER PROVIDES

49% of all water withdrawn for
domestic use globally



43% of irrigation water



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43%

of irrigation water

GW MITIGATES half of losses in
agricultural yield caused by drought

1/2

WITHOUT GROUNDWATER ACCESS,
droughts and the deprivations they cause can
increase the chances of stunting among children
under five by up to 20% in Sub-Saharan Africa



EASILY ACCESSIBLE AQUIFERS buffer
economic growth losses by 1/3rd drought

1/3

BUT

GW has been
undervalued,
overexploited in
Some regions
underexploited
in others



Up to 92% of TBAs in
ME & S Asia –GW
depletion. S Asia GW ag
revenue ↑10 – 20%

is declining as the resource depletes.



GW underused in SSA
> 225 M people:
poverty could be ↓ed
by ↑ *ing* shallow GW.



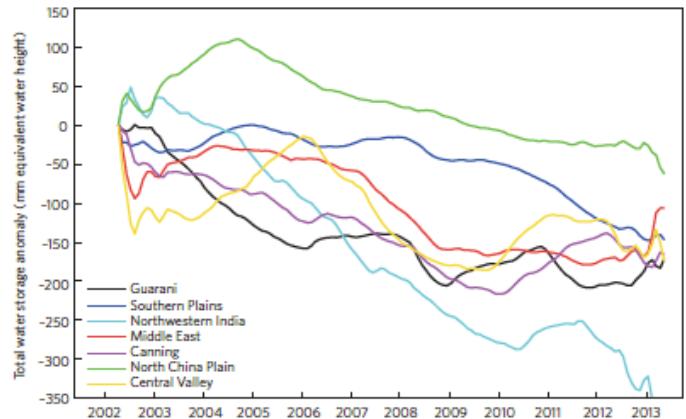
GROUNDWATER CAN PLAY A CRITICAL ROLE IN ADAPTING TO
CLIMATE CHANGE, BUT ONLY IF ACTION IS TAKEN TO PROTECT IT

COMMENTARY:

The global groundwater crisis

J. S. Famiglietti

Groundwater depletion the world over poses a far greater threat to global water security than is currently acknowledged.

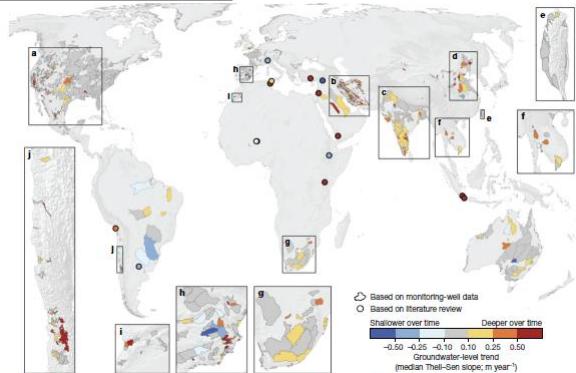


Rapid groundwater decline and some cases of recovery in aquifers globally

<https://doi.org/10.1038/s41586-023-06879-8>

Scott Jasechko^{1,102}, Hansjörg Seybold^{2,11}, Debra Perone^{3,11}, Ying Fan⁴,
Mohammad Shamsuddoha⁵, Richard G. Taylor⁶, Othman Fallatah^{7,8} & James W. Kirchner^{2,9,10}

Received: 8 April 2023



nature sustainability

Article

<https://doi.org/10.1038/s41893-024-01306-w>

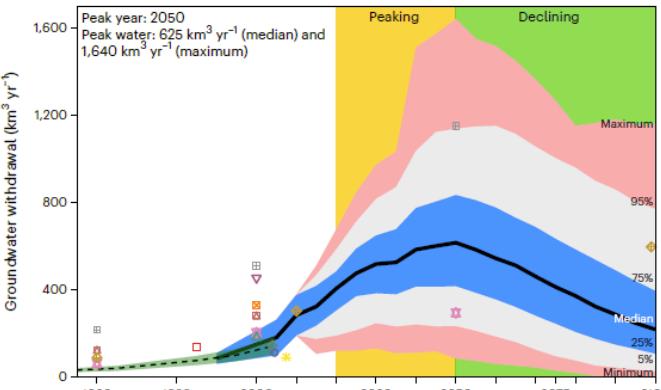
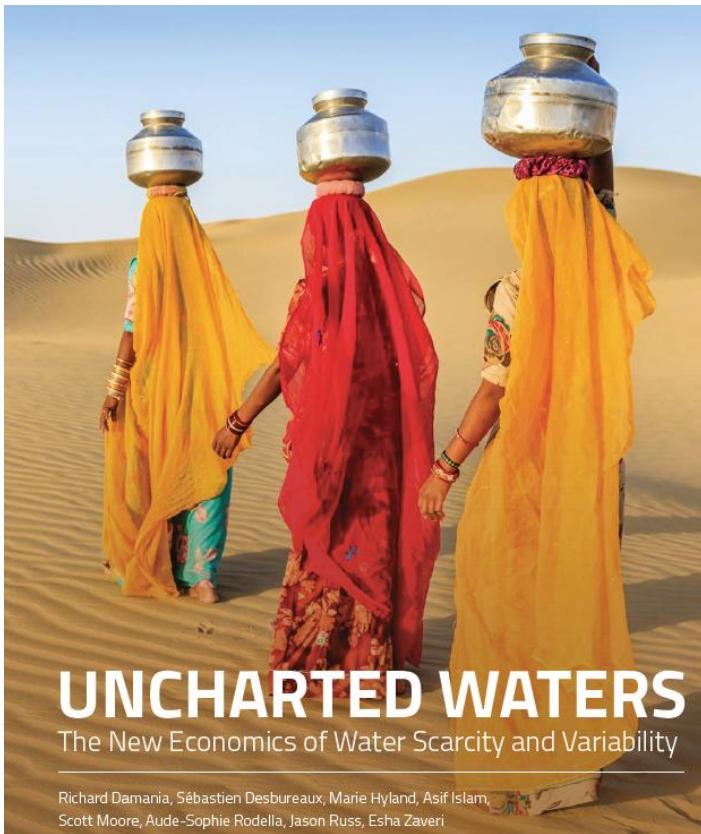
Global peak water limit of future groundwater withdrawals

Received: 24 May 2023

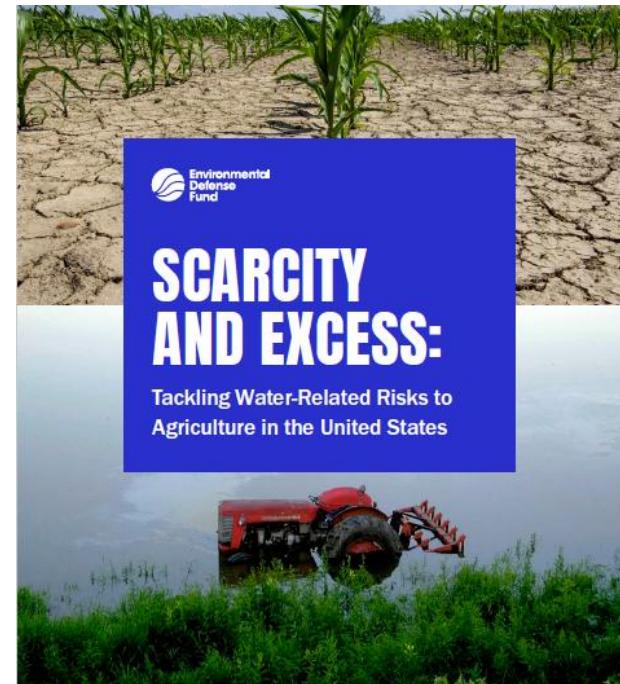
Accepted: 6 February 2024

Published online: 22 April 2024

Hassan Niazi¹ , Thomas B. Wild¹, Sean W. D. Turner², Neal T. Graham³,
Mohamad Hejazi³, Siwa Msangi⁴, Son Kim⁵, Jonathan R. Lamontagne⁵
& Mengqi Zhao⁶



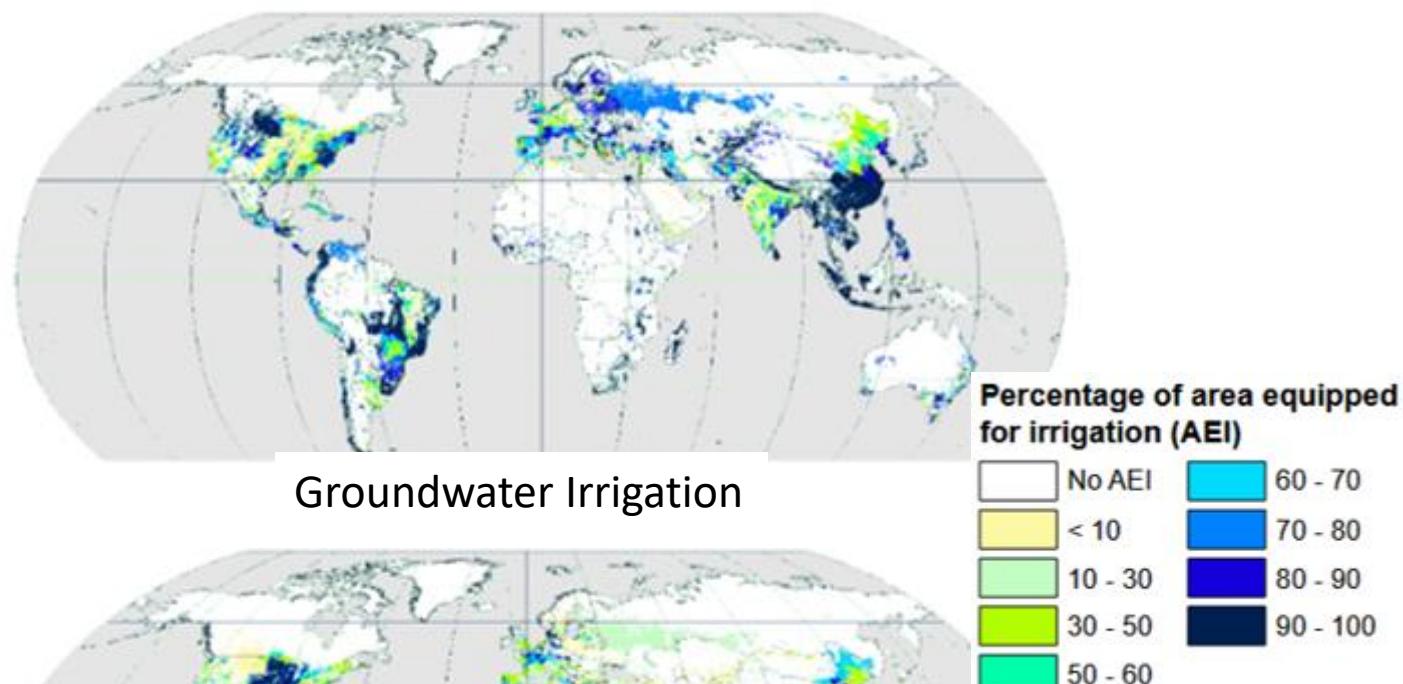
Too much vs too little?



1. Irrigation, Food Production, and Urban Water

Cape Town Day Zero

Surface Water Irrigation



Irrigation: 70% of global water withdrawal

90% of global water consumption

<http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm>

Baseline Water Stress in the Western Cape Region of South Africa

CAPE TOWN

Legend: Low to medium, Medium to high, High, Extremely high, Arid & low water use

Major Dams for Water Supply

AQUEDUCT™ WORLD RESOURCES INSTITUTE

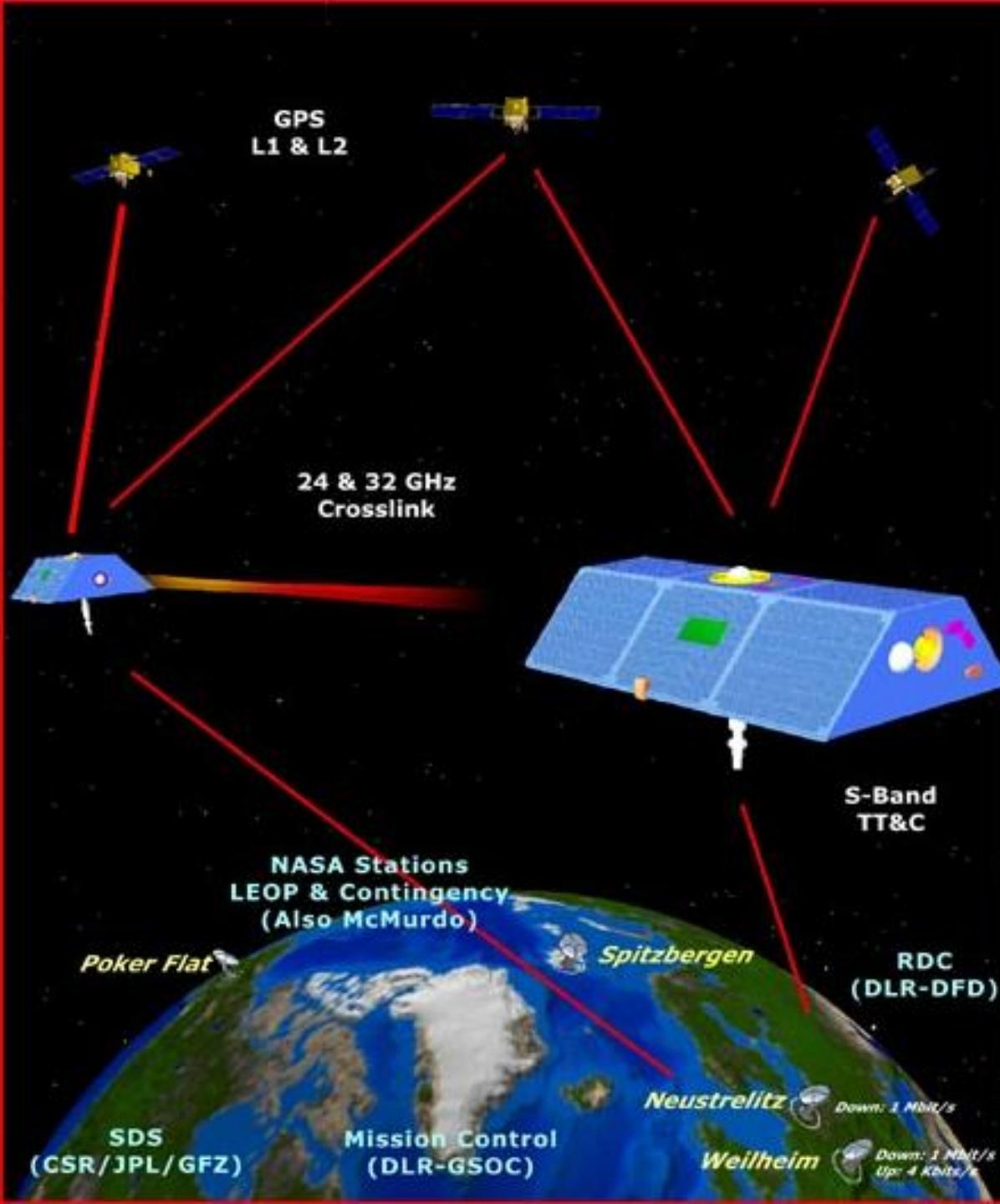
Source: Aqueduct AQUEDUCT WORLD RESOURCES INSTITUTE

See Below

Sao Paulo



Siebert et al., HESS, 2010



2. GRACE

Gravity Recovery and Climate Experiment

GRACE: March 2002 – 2017 (low solar activity)

GRACE Follow-On: 2018 →

500 km above land surface controls resolution of GRACE data

Resolution: ~350 km, ~120,000 km²

Satellites 220 km apart

Monthly data

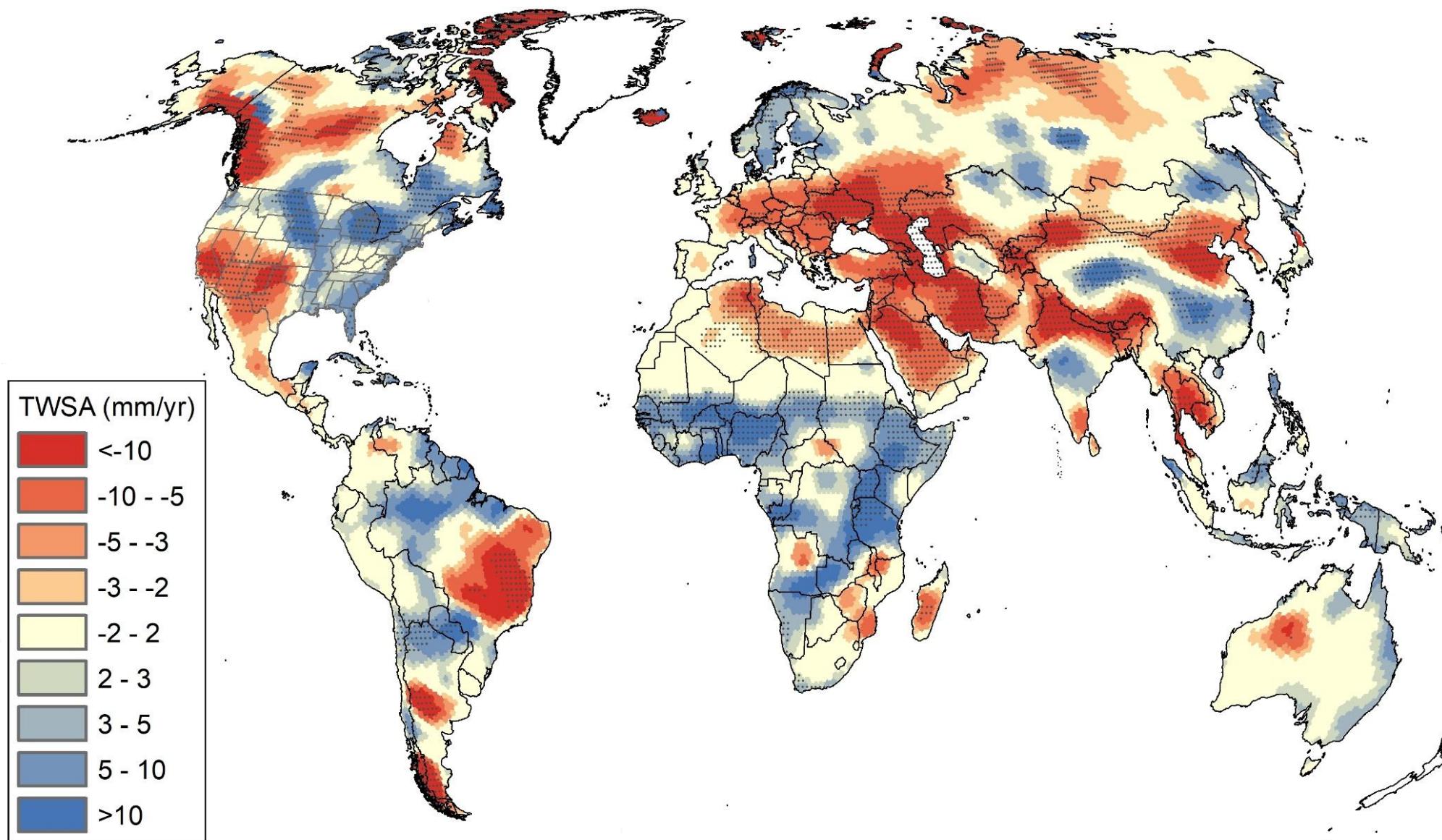
1 gigaton mass change = 1 km³ of water

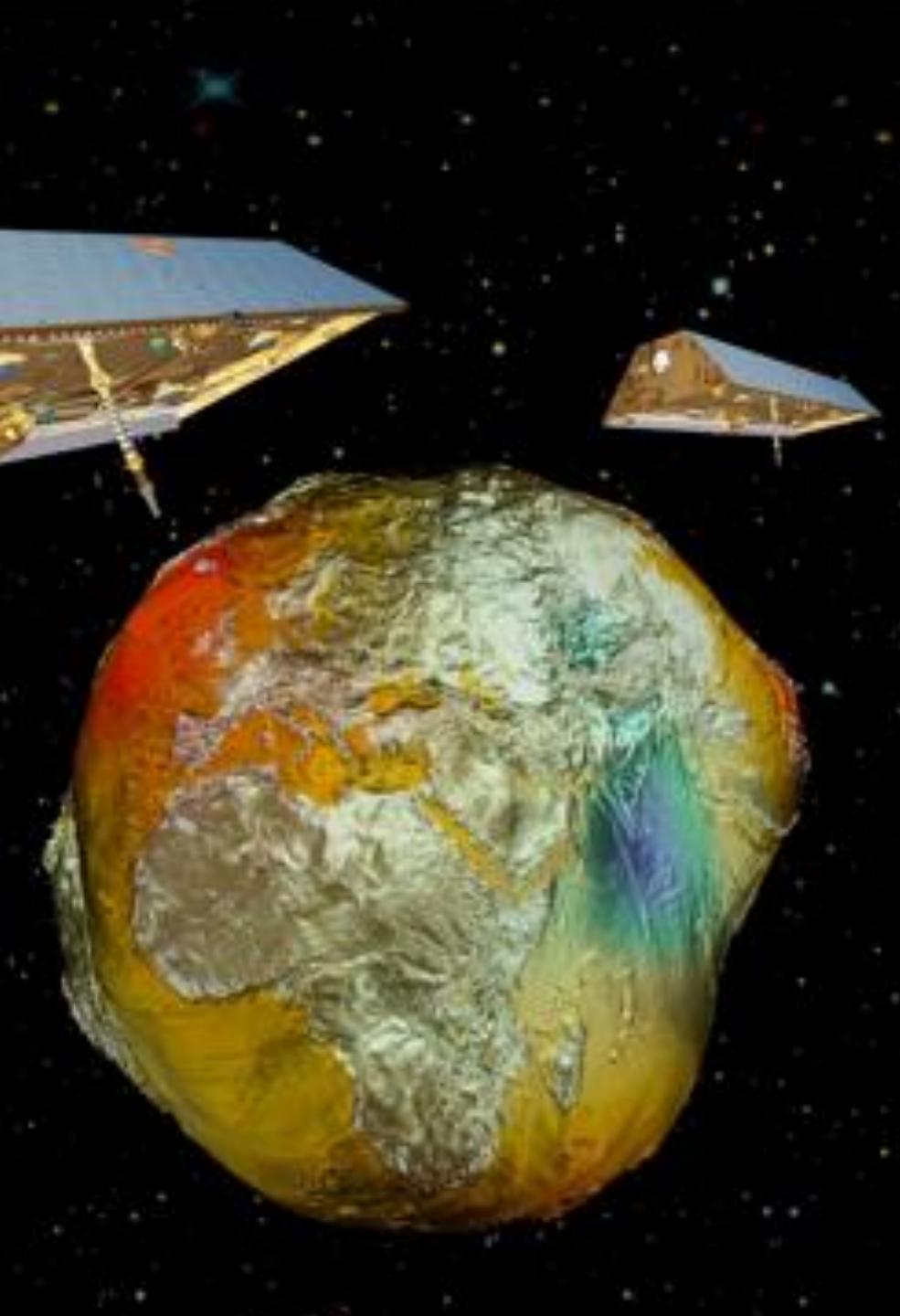
Terrestrial water storage (TWS) change

Essential climate variable in
Global Climate Observing System

<http://grace.jpl.nasa.gov/mission/gravity-101/>

2. GRACE Total Water Storage Anomalies (04/2002 – 09/2021)



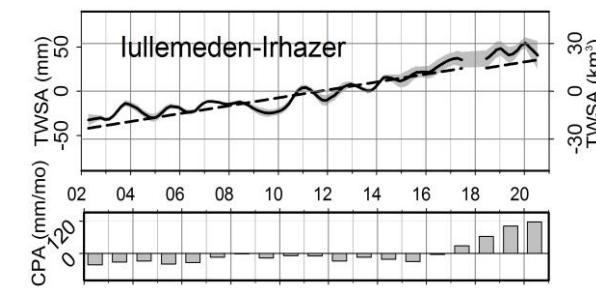
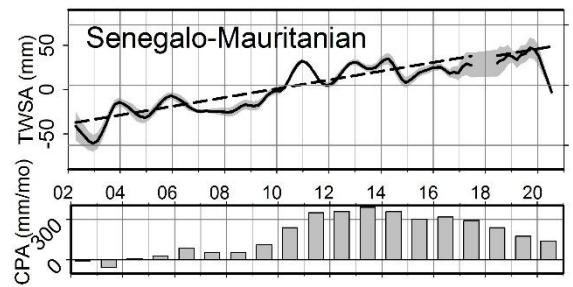


Outline

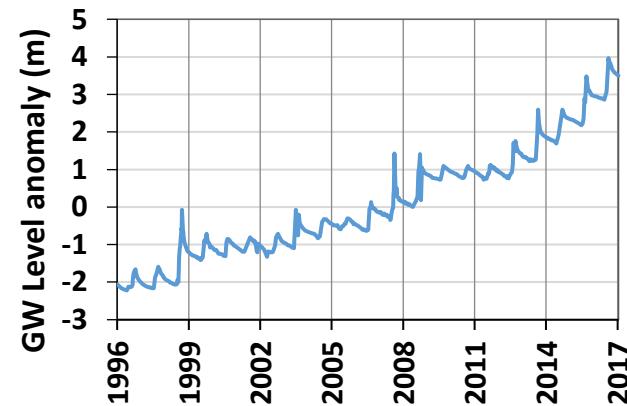
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3a. Potential to Expand Irrigation in Sub-Saharan Africa

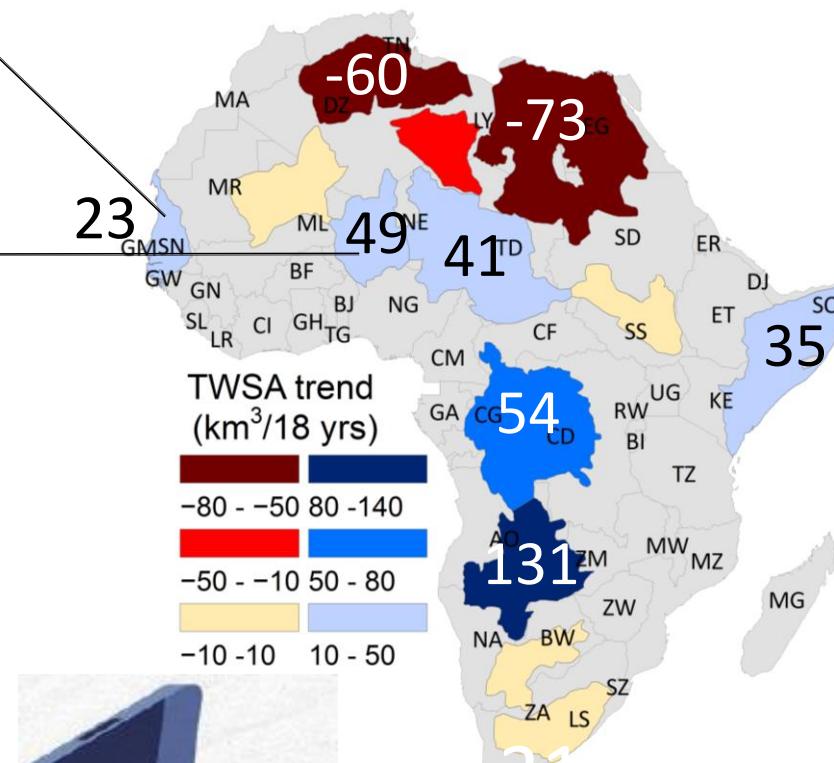
Nov 1992



GW level hydrograph Niger

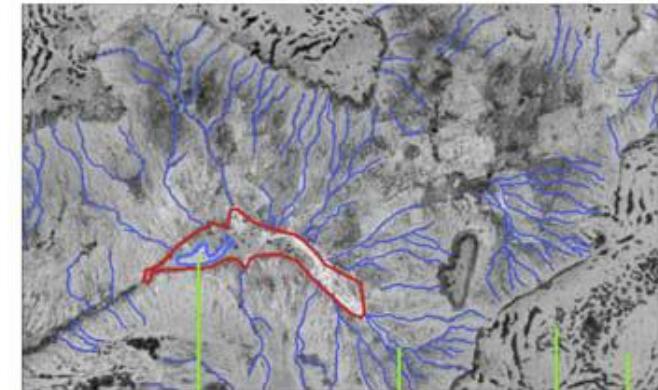


GRACE Total Water Storage Anomaly (2002 – 2020)



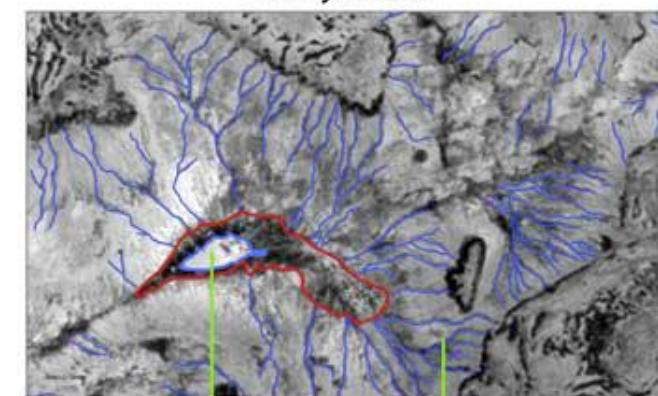
40% basement
aquifers
Self-regulating

Favreau et al., WRR, 2009
Scanlon et al., ERL, 2022



new pond			sparse
in red: shoreline			tiger bush
	in blue: water	connected, high density drainage network	wide, open bare soil area

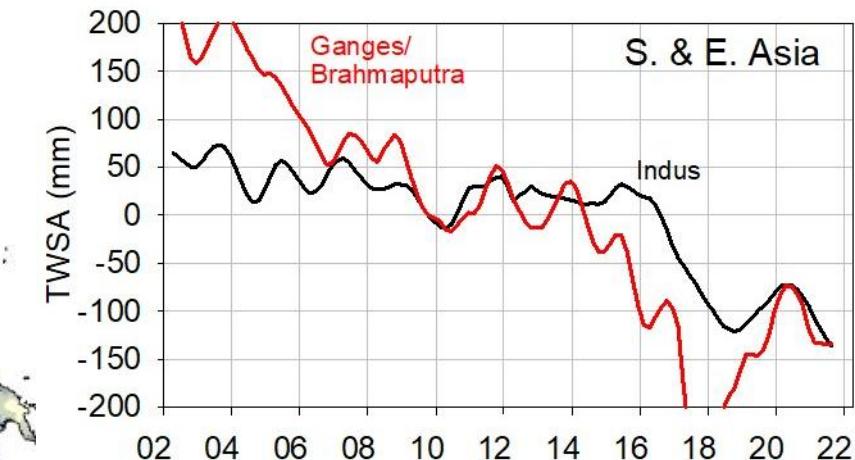
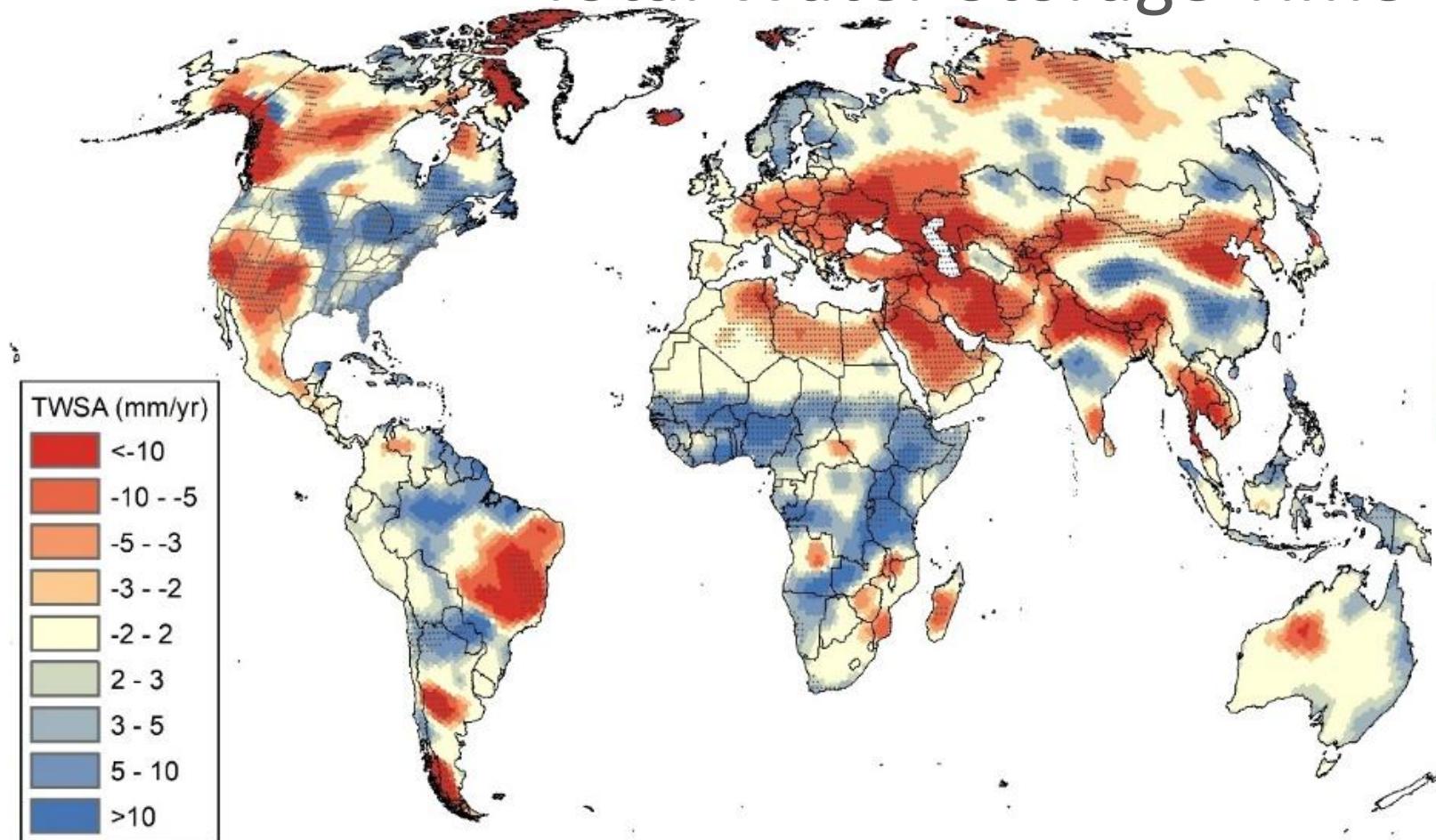
May 2005



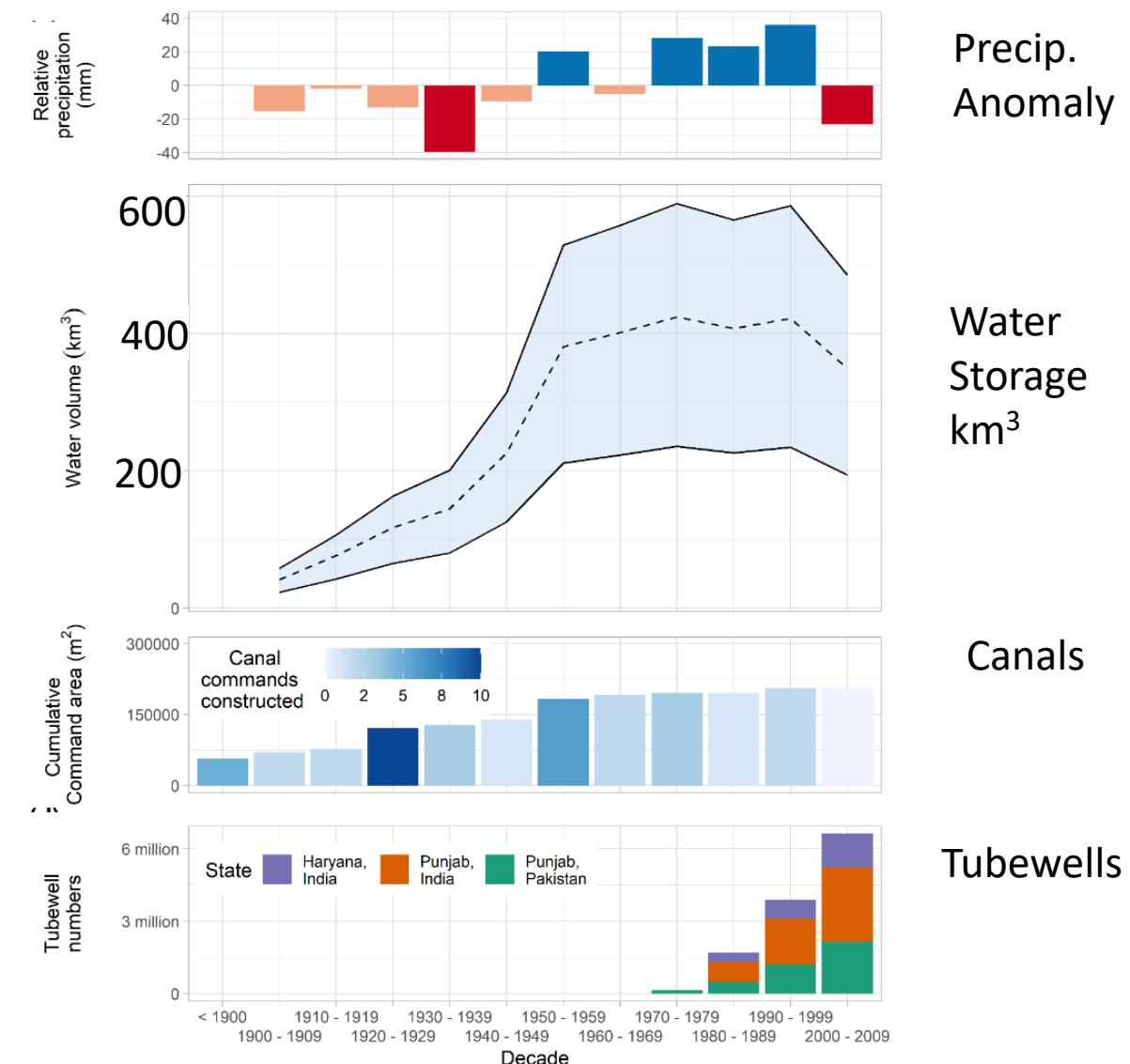
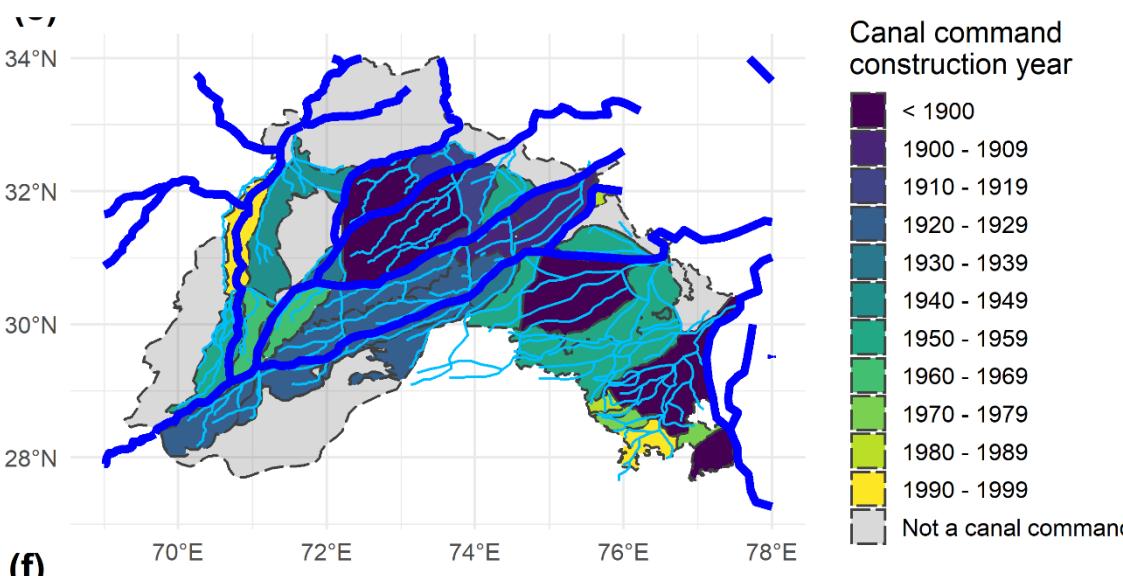
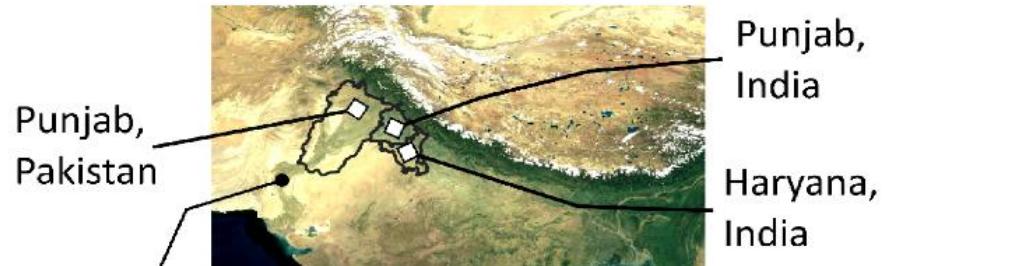
expanded pond
in red: shoreline
in blue: water

connected, high density drainage network;

3b. Switching from Surface Water to Groundwater Irrigation Total Water Storage Time Series



3b. A century of groundwater accumulation in Pakistan and Northwest India (GW level monitoring)



North India running out of water, confirms NASA

CHANDIGARH: The worst fears about the northern region of the country losing its groundwater have been confirmed. The National Aeronautics and Space Administration's (NASA) satellite imagery made available to the Centre warns of fast disappearing of subsoil water in these states.

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Updated At: Aug 16, 2015 02:04 PM (IST)

41°

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POLITICS ECONOMY EXTERNAL AFFAIRS SECURITY LAW SCIENCE SOCIETY CULTURE

ENVIRONMENT

Groundwater Withdrawals Across India Have Increased Tenfold in Six Decades

In many rainfall-scarce areas, groundwater has been exploited to plant water-guzzling crops like paddy and sugarcane, especially in Vidarbha and Rayalaseema.



3b. Indo-Gangetic Basin

[Explore](#) [Search](#)
 **Hindustan Times**

Monday, Dec 05, 2022 | New Delhi 13°C

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Significant drop in volume of water in Ganga, flags WMO

[India News](#)

Government response with aid from World Bank: National program: Atal Bhujal Yojana, 7 states switching from GW wells to irrigation canals

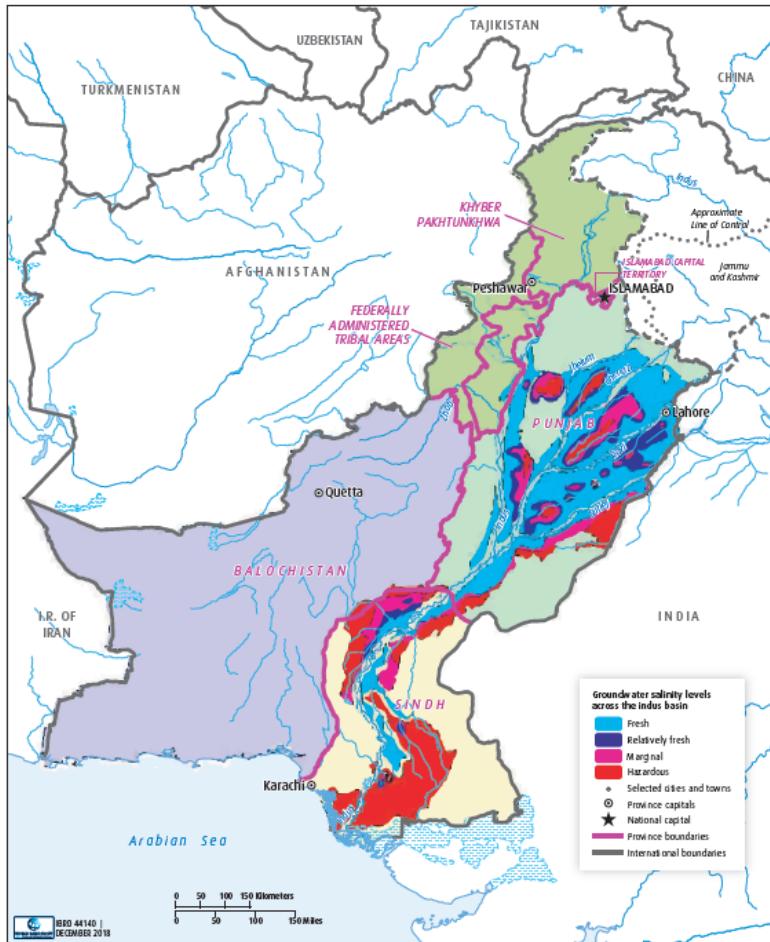
Punjab: Save Water, Earn Money scheme

Incentivizes farmers to reduce groundwater use

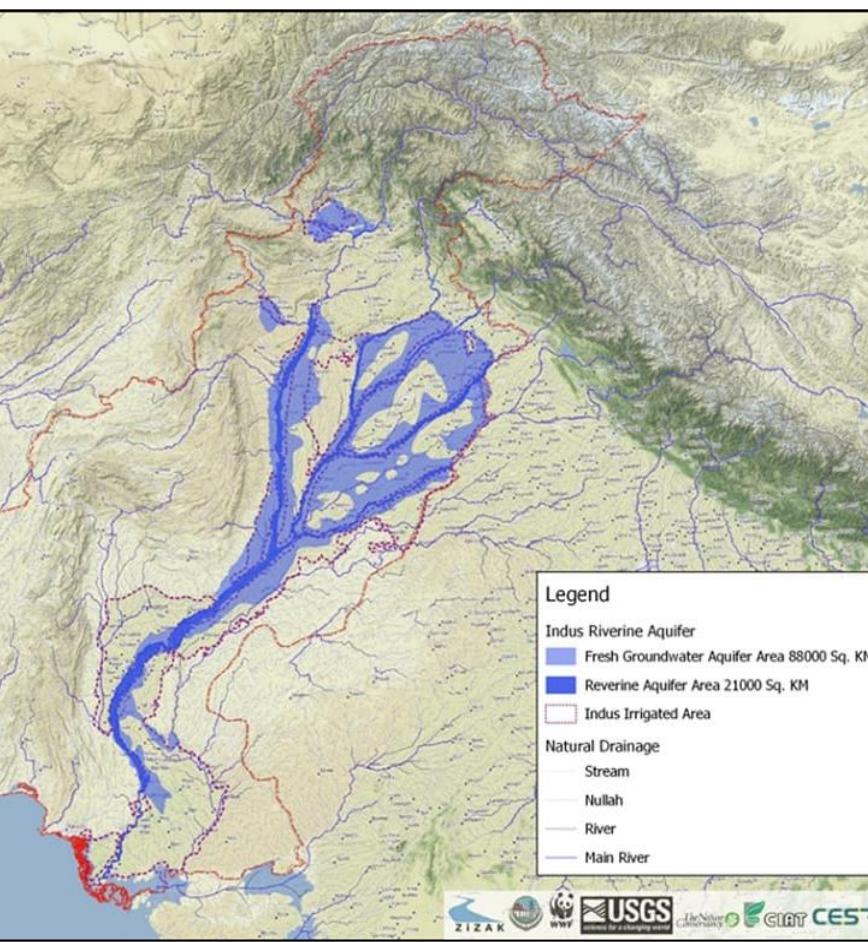
Some **cities** in Punjab moving from GW to canals

<https://www.worldbank.org>

3b. Switching from Surface-Water to Groundwater Irrigation in Indus Basin



SW irrigation, 1900s
Water logging and
GW salinization
Qureshi et al., 2004



Freshwater aquifers, Indus Plains and
riverine corridors, $\sim 500 \text{ km}^3$

Solutions:

Salinity Control and
Reclamation Project (SCARP):
1.5 million tube wells installed
waterlogged areas
Conjunctive use of SW and GW
GW depletion: water level
declines $\leq 1 \text{ m/yr}$ in some
areas.

Recharge Pakistan project: GW
recharge wells, nature based
solutions to recharge aquifer,
wetland restoration

Groundwater and Surface water challenges in Indus Basin Irrigation System, Pakistan



Azeem Shah talks about
water issues in Pakistan,
including transboundary
issues, solar irrigation, and
improving data for more
sustainable management
of water resources.

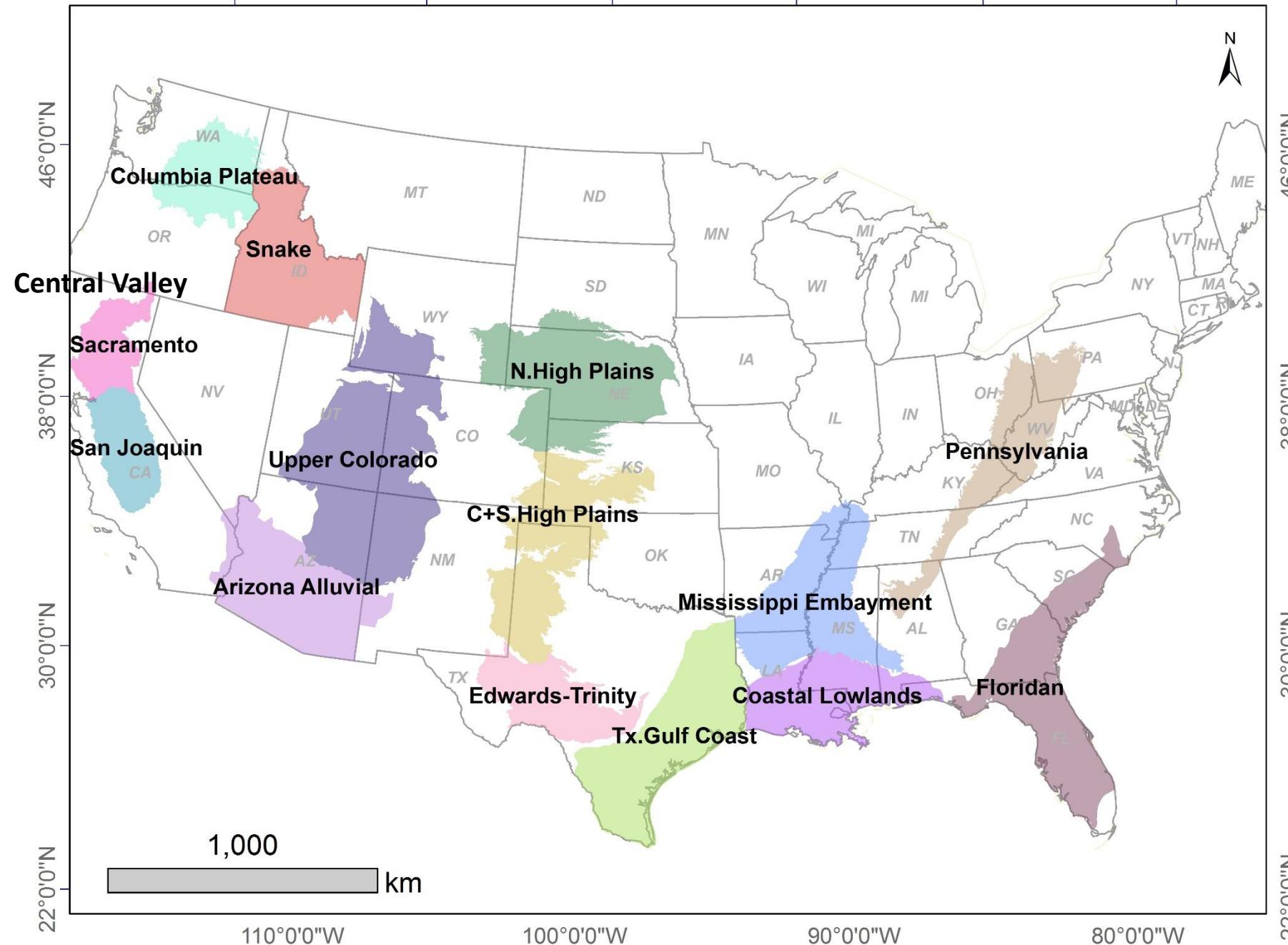
Azeem Shah



WITH
Bridget
Scanlon

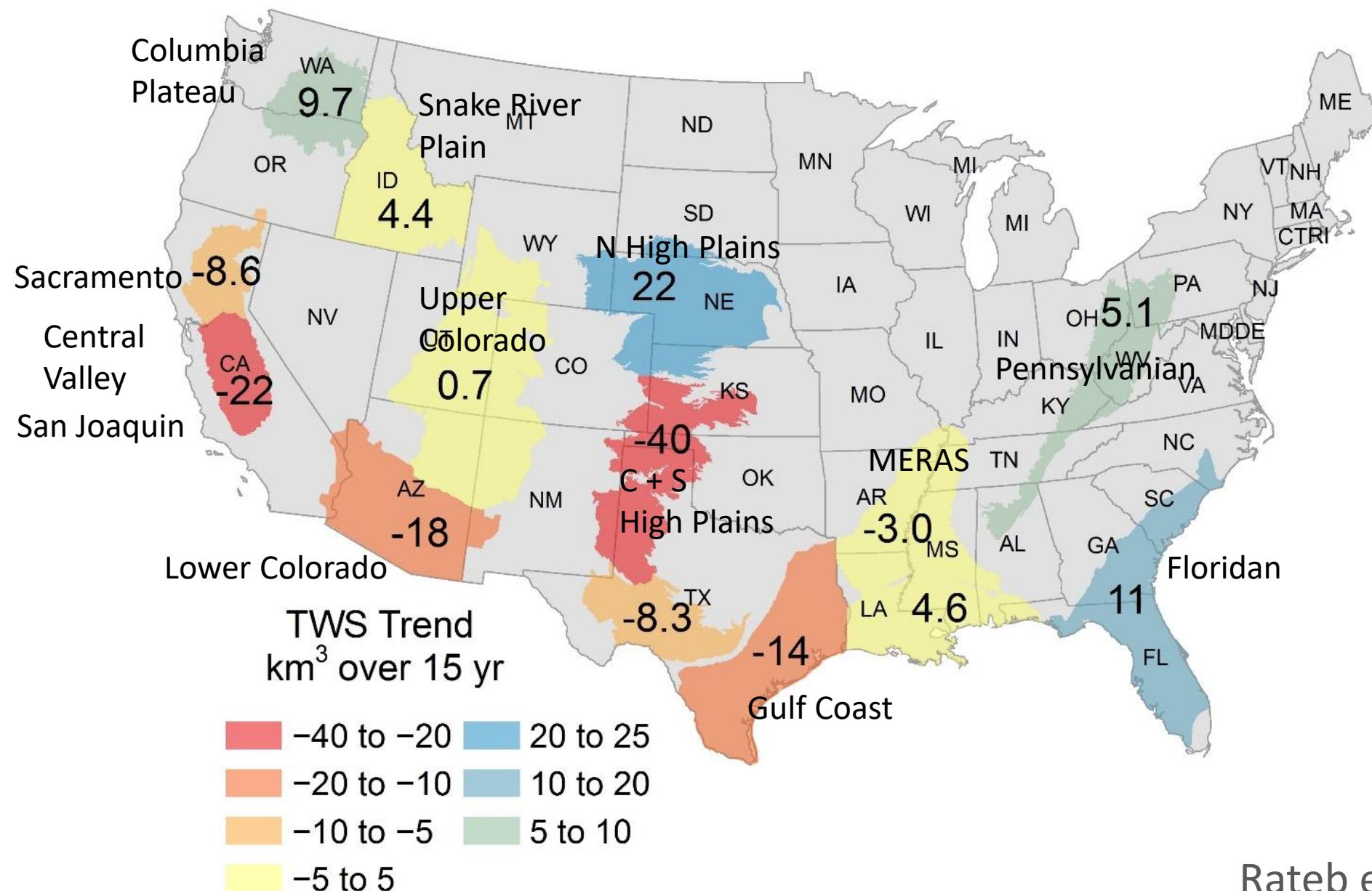
Azeem Shah, WRP, 2025

3b. Major Aquifers (14)

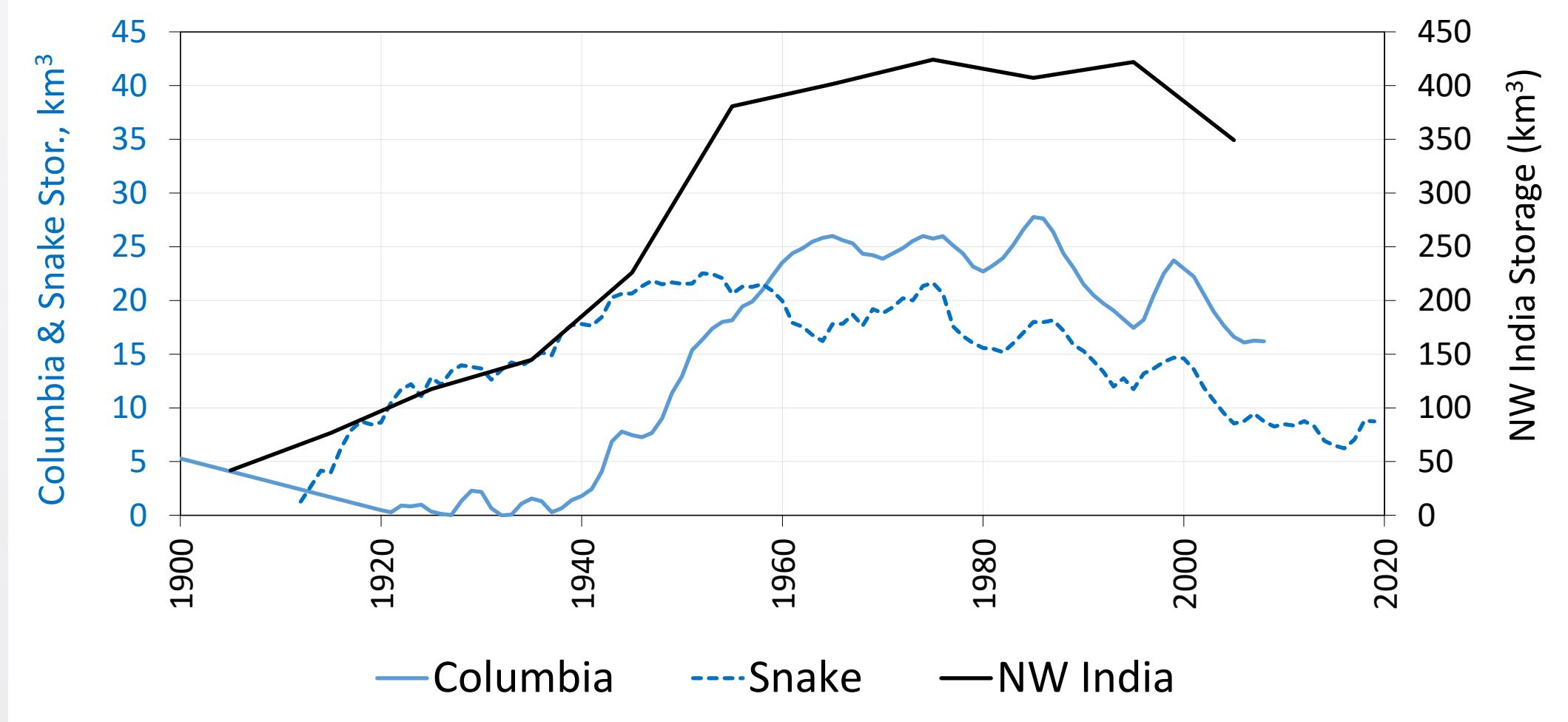


Unconfined aquifers
High Plains, AZ Alluvial,
Upper Colorado, Snake
Semi-confined aquifers
Columbia & Central Valley:
Confined
All other aquifers

3b. Total Water Storage Trends in the U.S. (GRACE: 2002 – 2017)



3b. Long-term Trends in Groundwater Storage

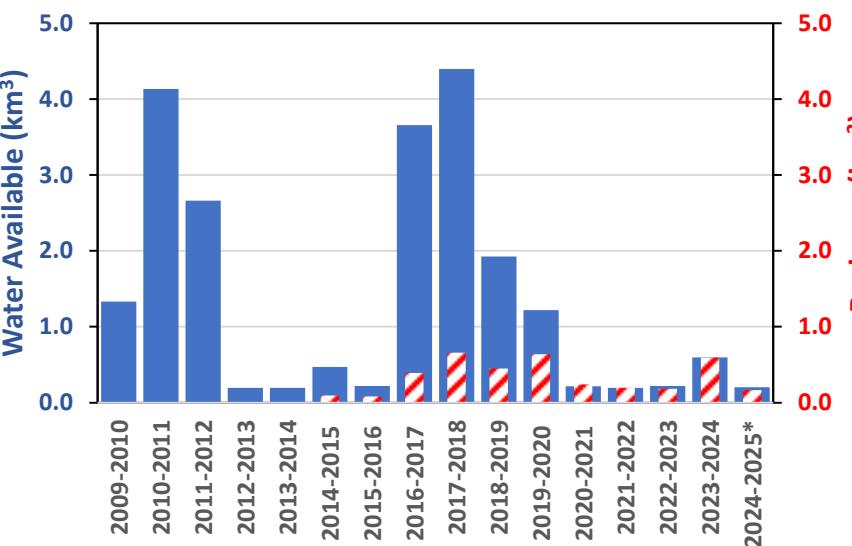
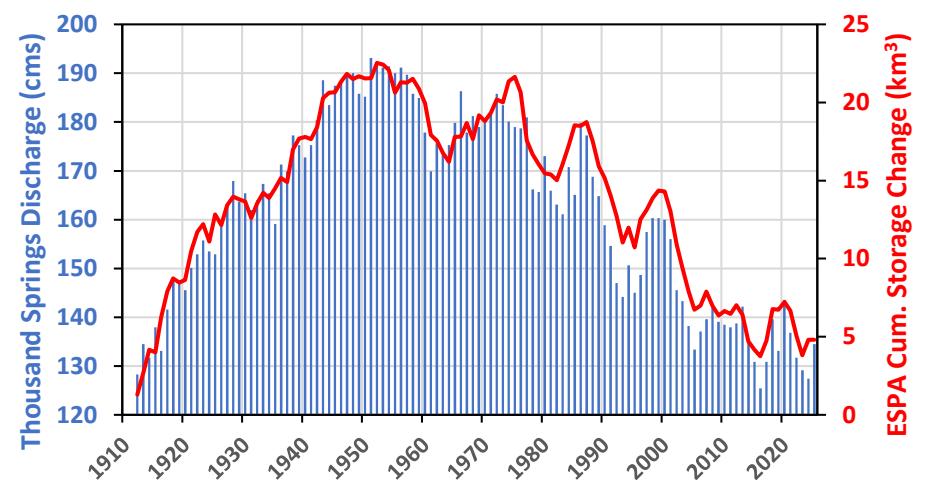
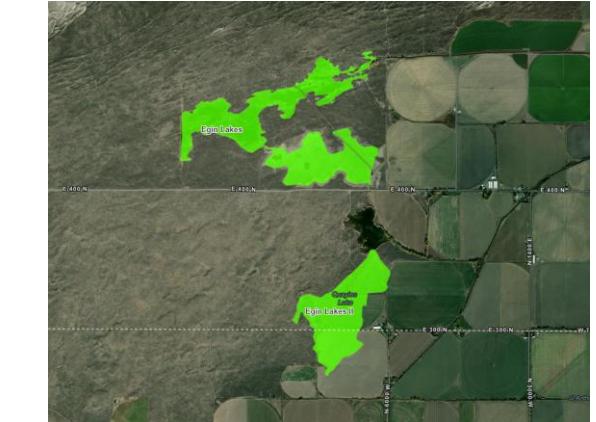
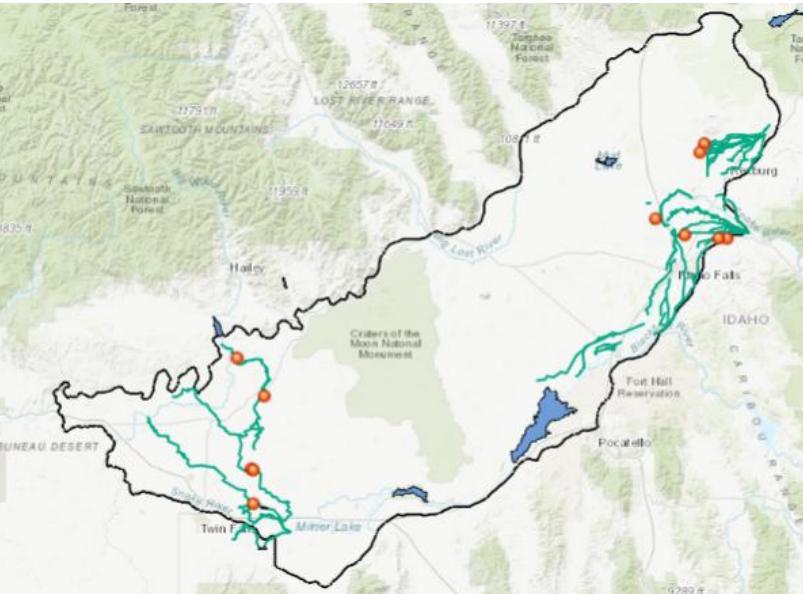


Increases in GW storage attributed to surface water irrigation
Columbia and Snake River Basins, NW US

3b. Eastern Snake Plain Aquifer Recharge

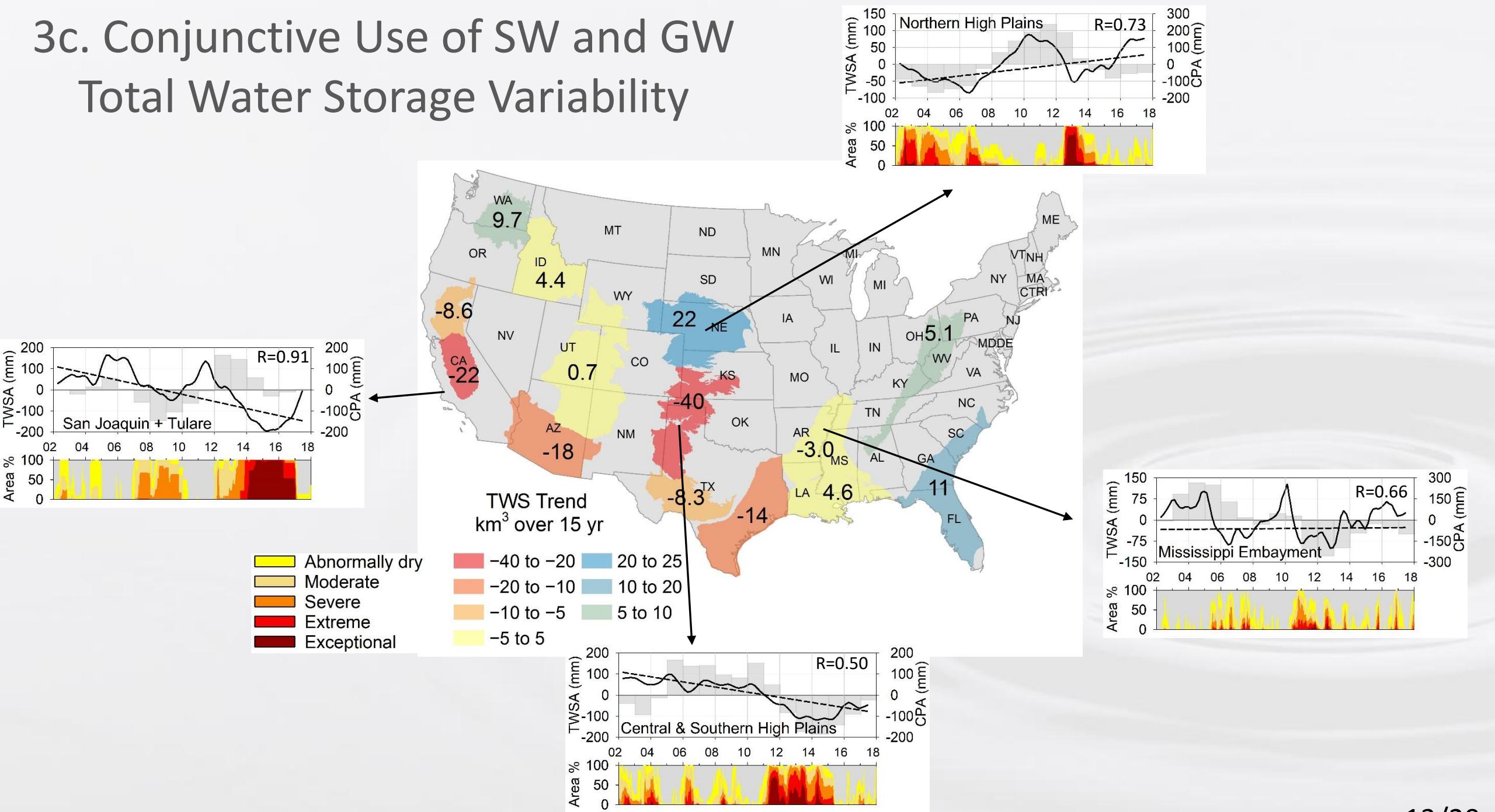


Managed Aquifer Recharge Projects

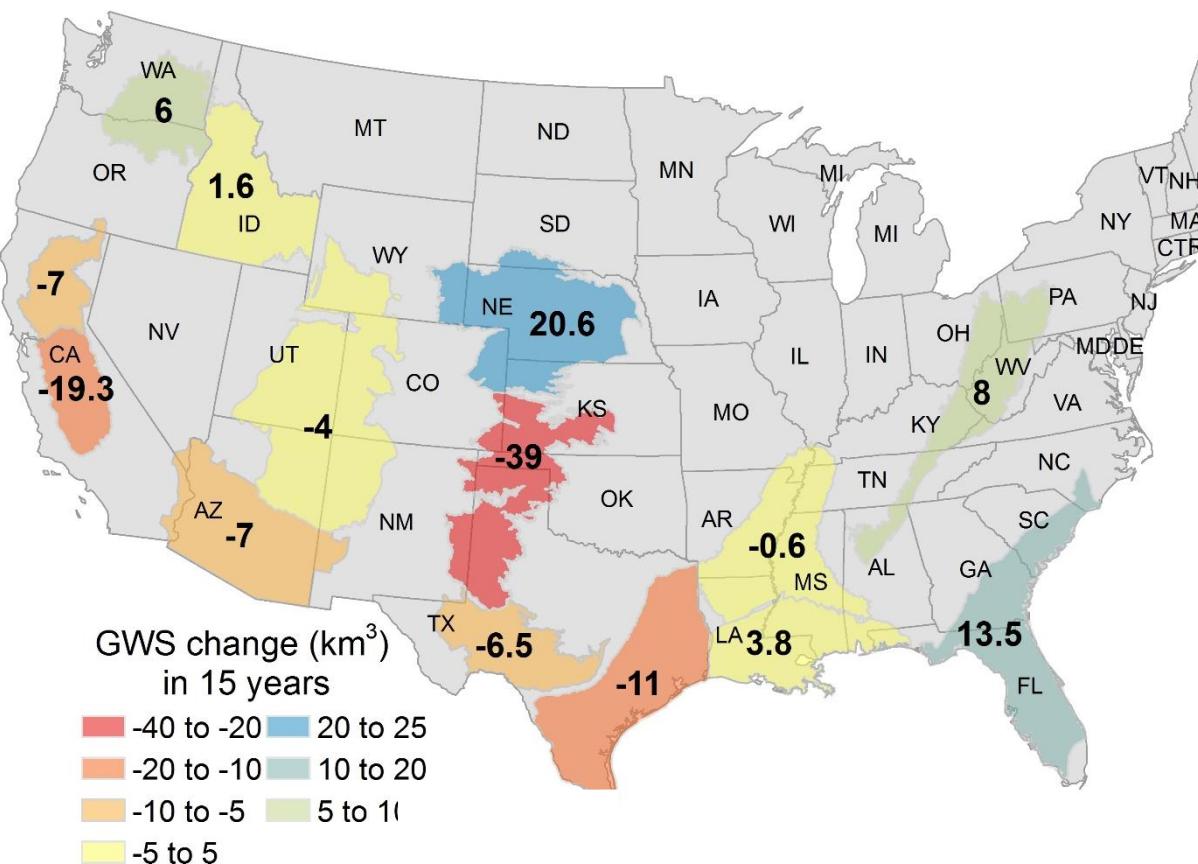


Hikpe et al., GW, 2022

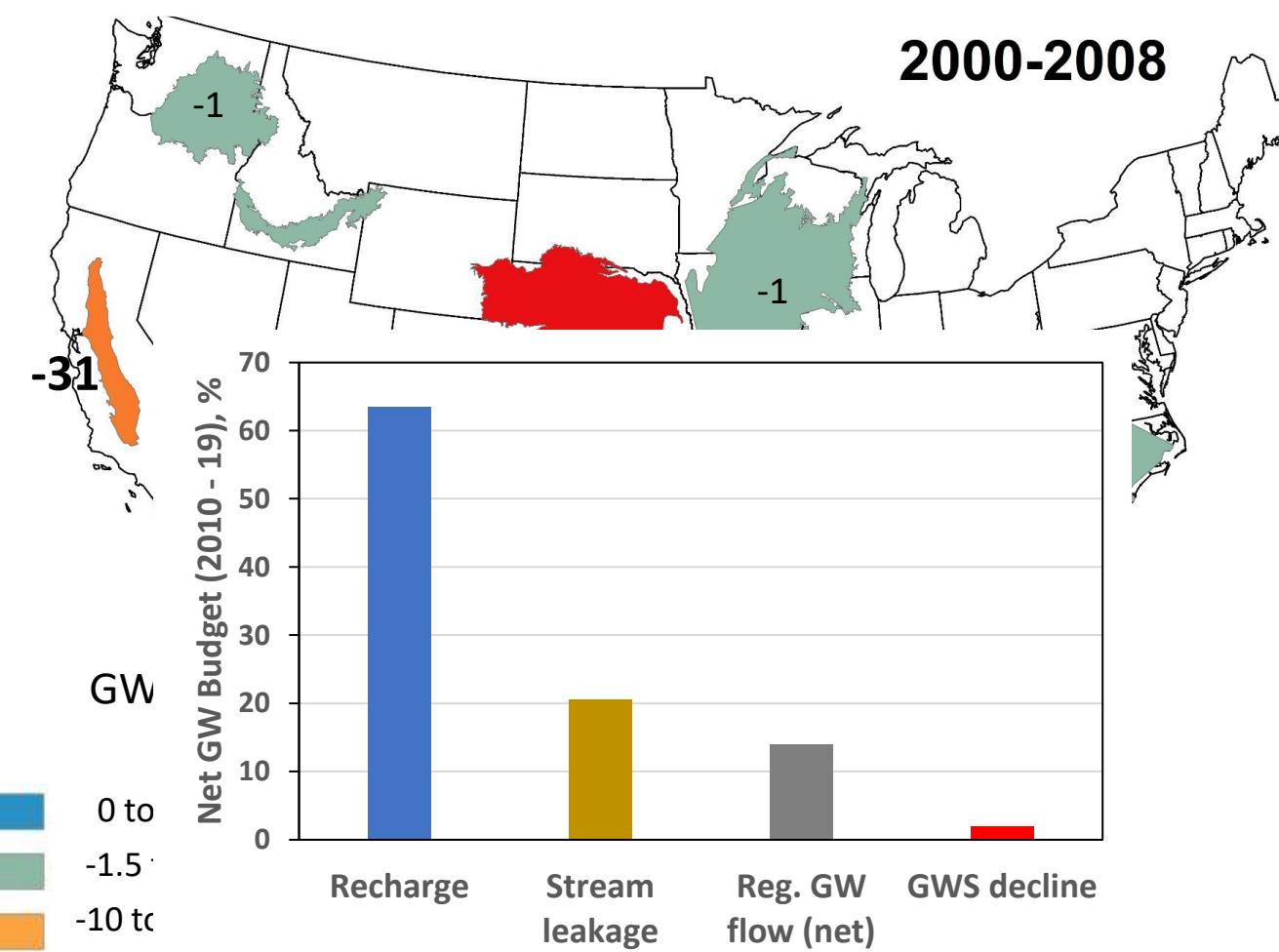
3c. Conjunctive Use of SW and GW Total Water Storage Variability



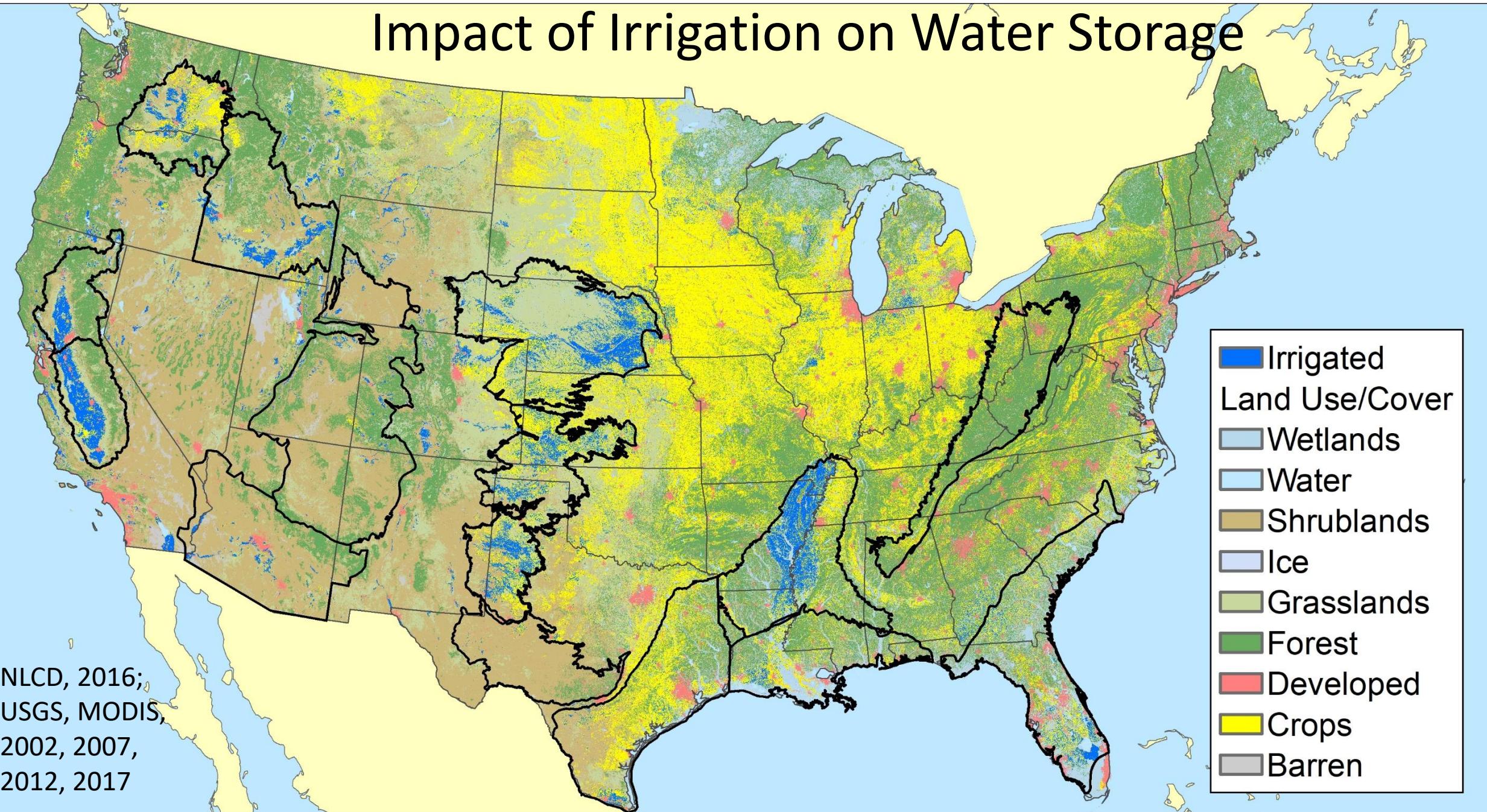
GW Storage Change GRACE (2002 – 2017)



GW Storage Change Regional Models and Monitoring

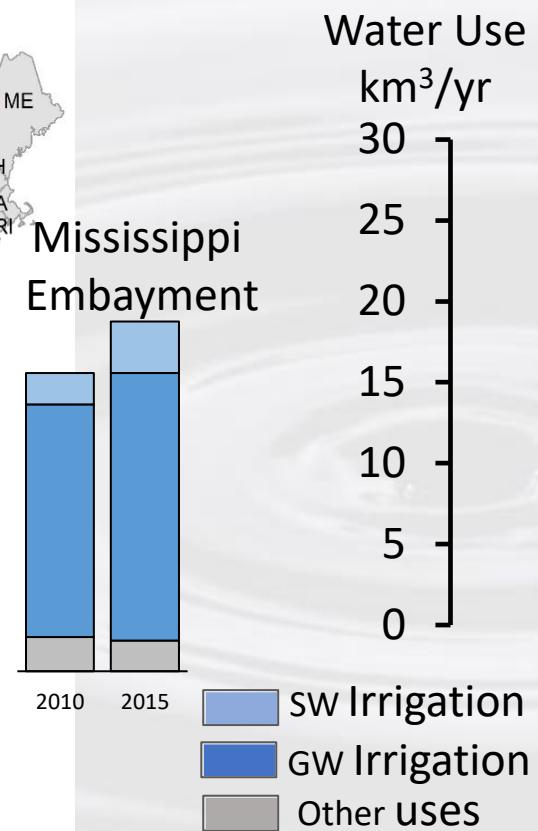
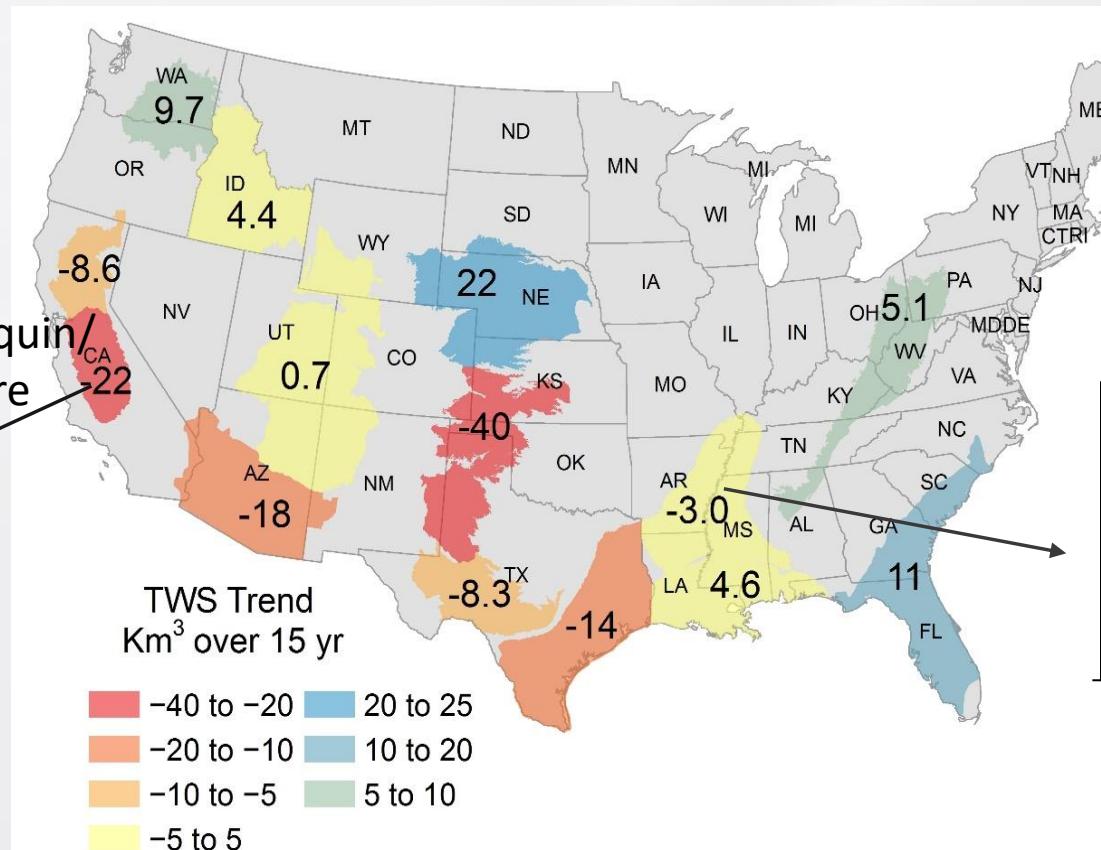
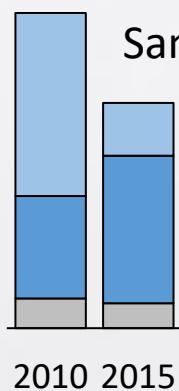


Impact of Irrigation on Water Storage



3c. Irrigation Water Use

Conjunctive use of SW and GW



2010: wet year: 70% SW

2015: drought: 70% GW

Scanlon et al., ERL, 2021

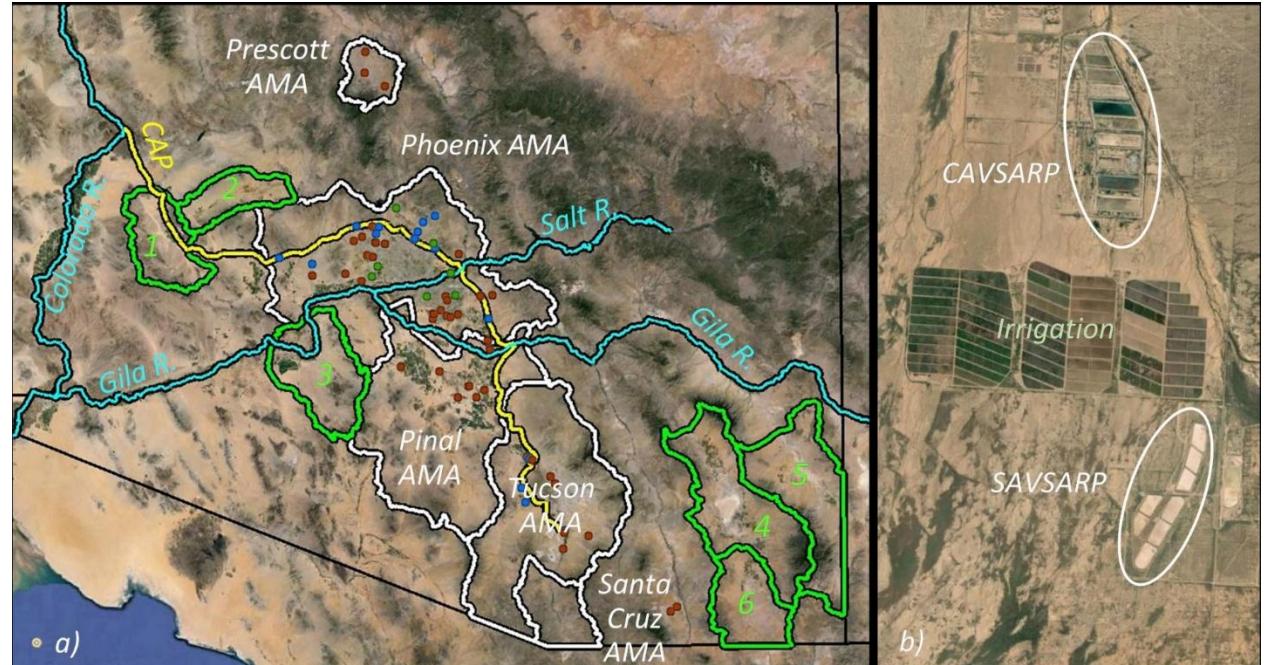
3d. Managed Aquifer Recharge: Arizona Alluvial Valley

Central AZ Project (CAP)

Active Manag. Areas (AMAs)

USF:

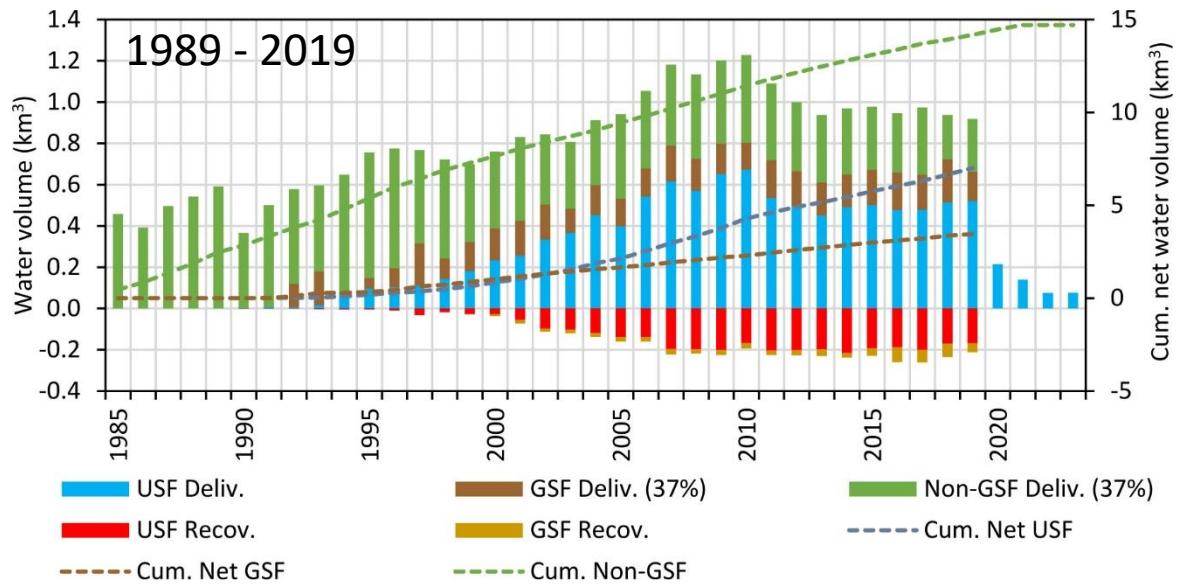
Spreading basins



Arizona: Pump and Replenish

Pumping GW and replenishing it with MAR is 1000 × less expensive than developing SW treatment plant

Recharge in Active Management Areas

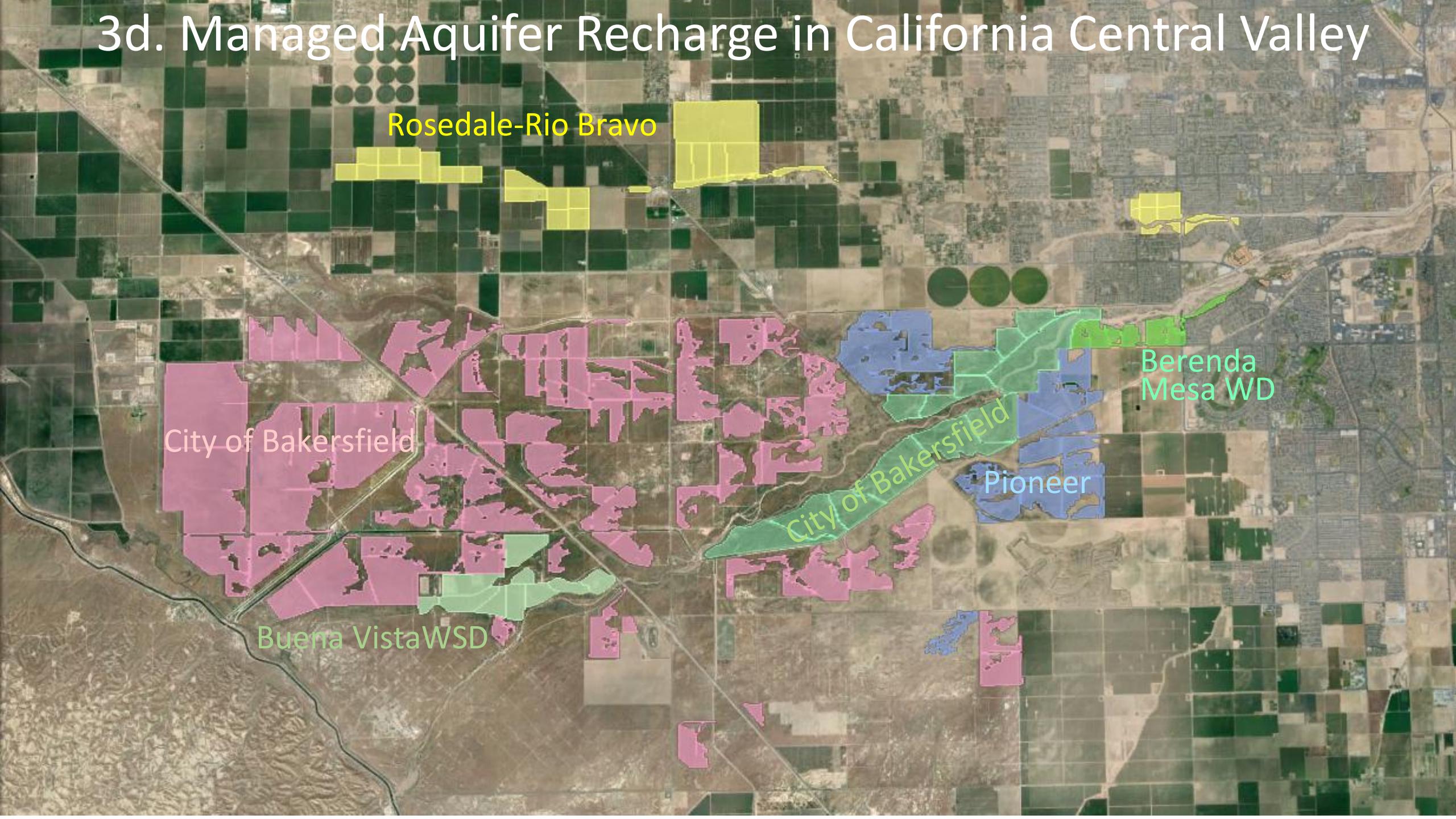


USF: Underground Storage Facilities: 7.0 km^3

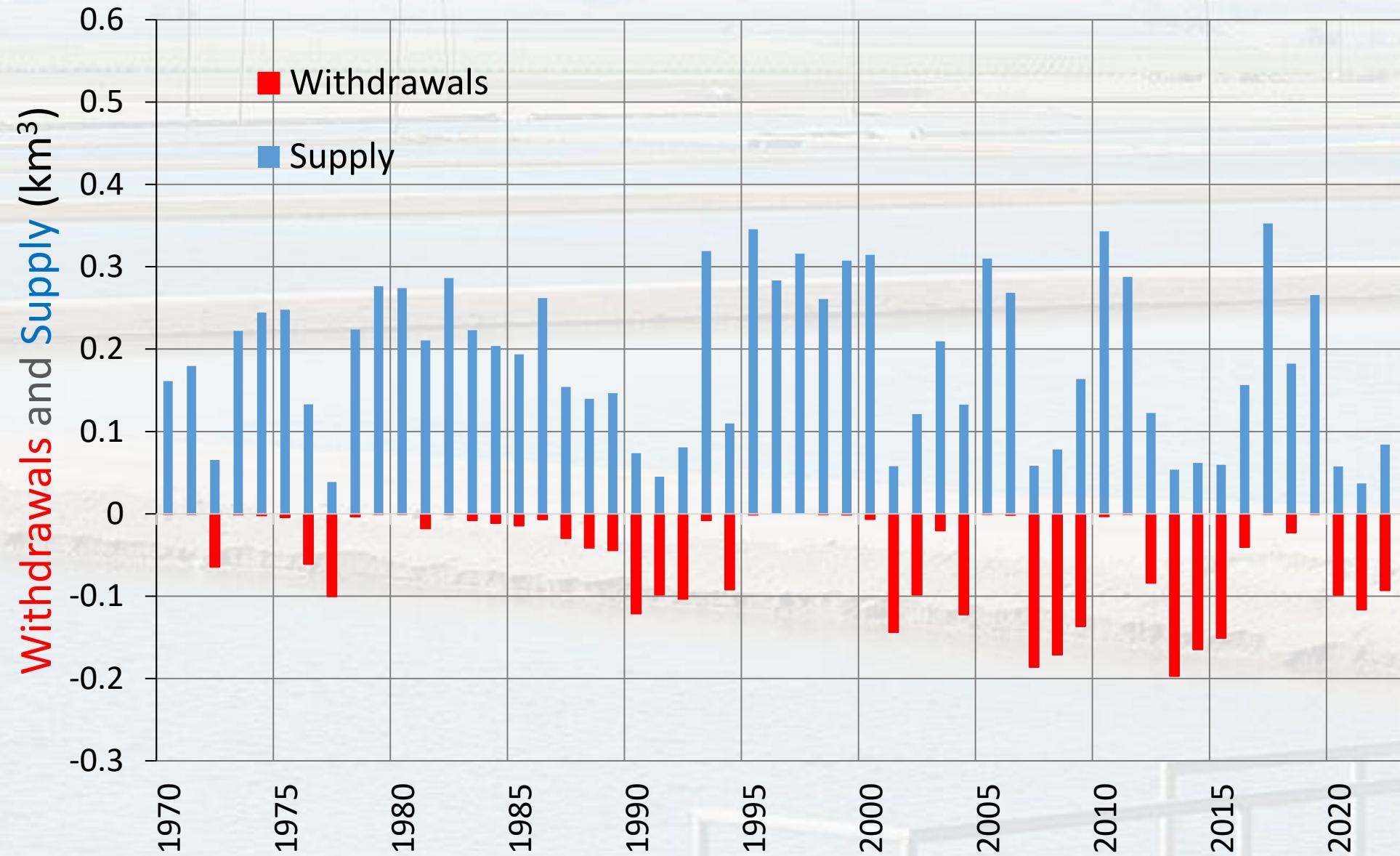
GW Savings Facilities: 3.5 km^3 (Switch GW \rightarrow SW)

Incidental Recharge: 14.2 km^3 (SW irrigation)

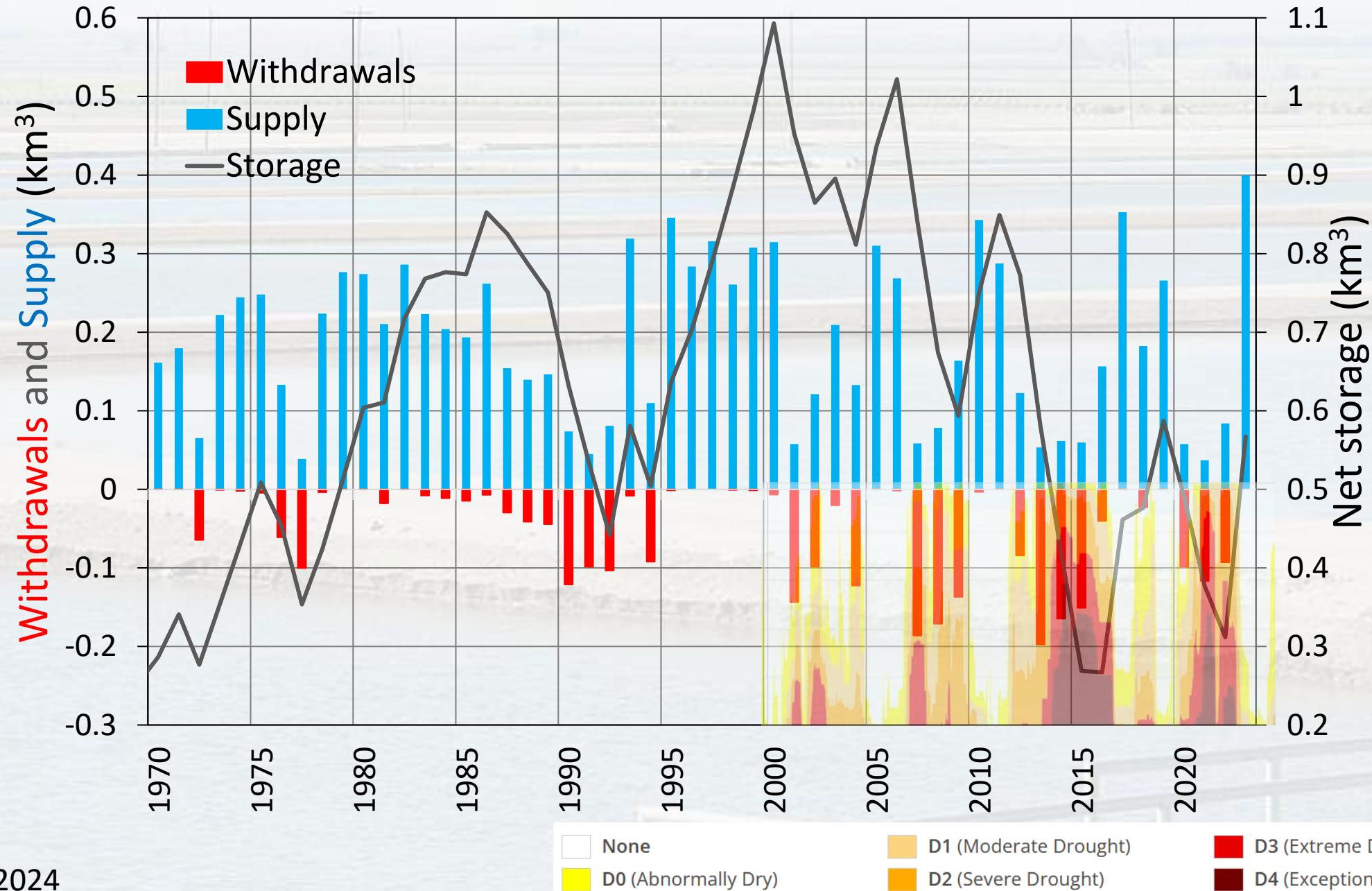
3d. Managed Aquifer Recharge in California Central Valley



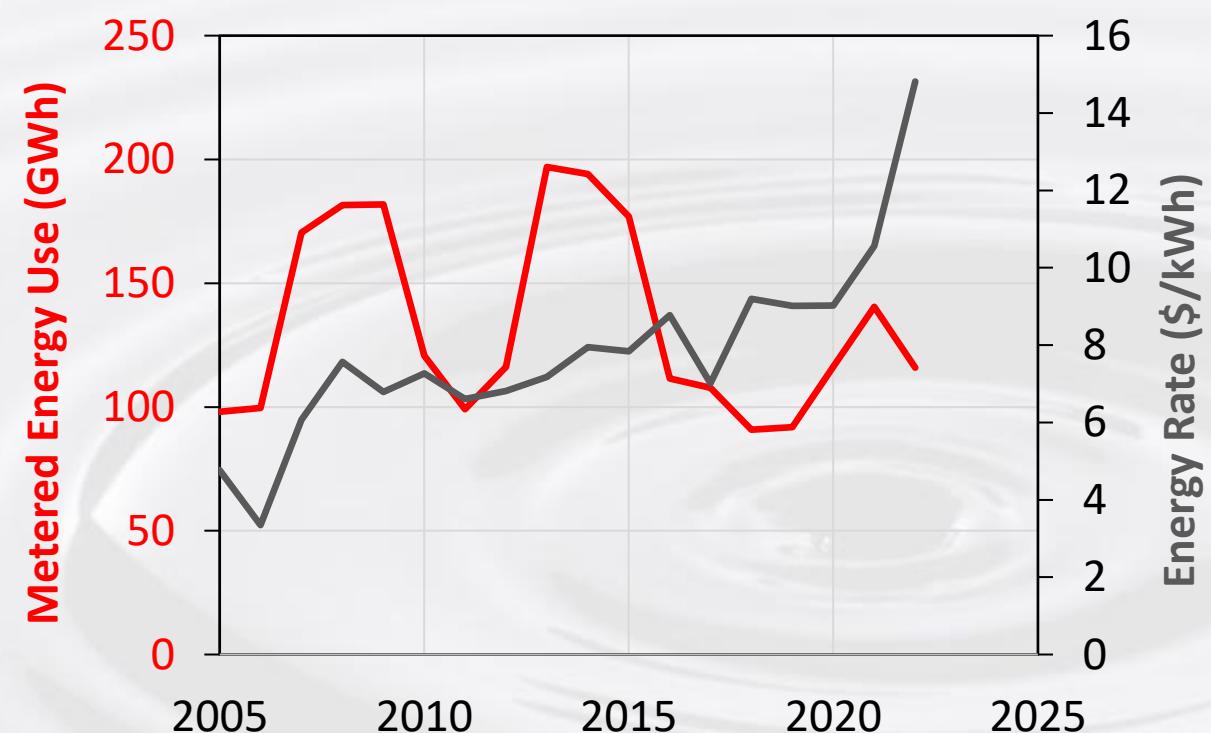
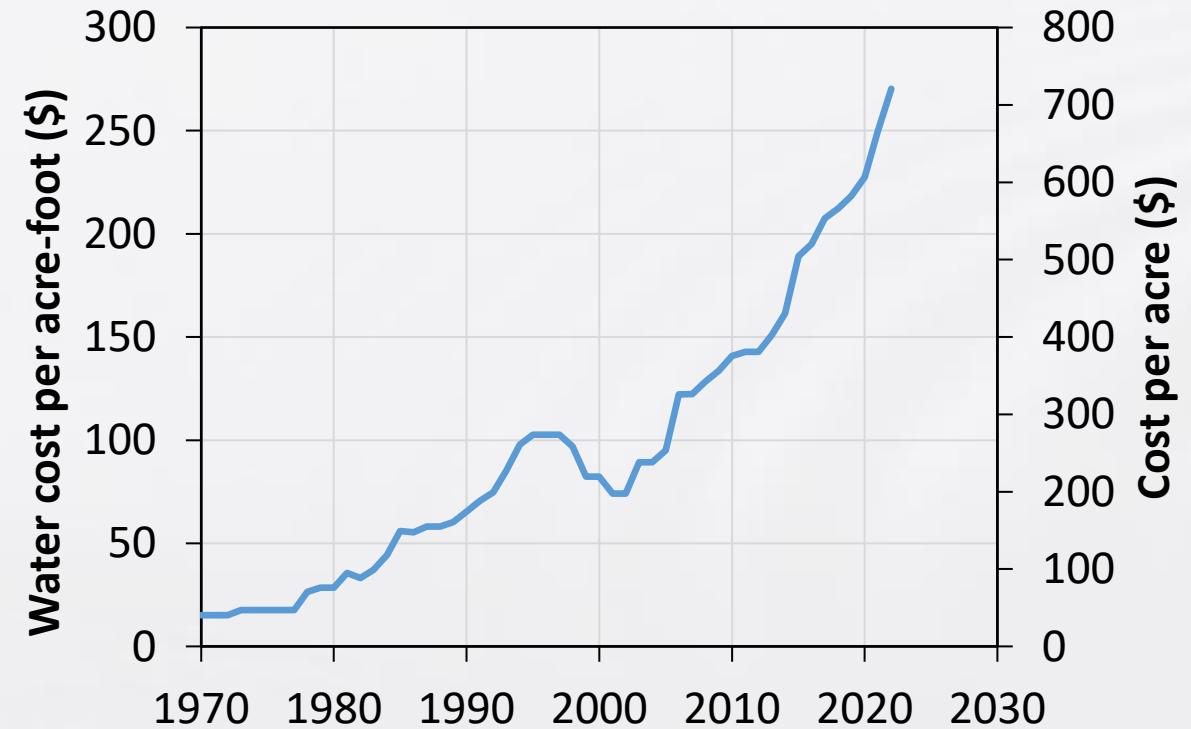
3d. Water Budget in Arvin Edison Irrigation District, Central Valley, California



3d. Water Budget in Arvin Edison Irrigation District, Central Valley, California



3d. Increasing Cost and Energy Intensity of Water at Arvin Edis



Water costs increased from \$5/af in 1990 to \$270/af in 2022

Power costs increased from \$3/af in 1970 to \$81/af in 2022

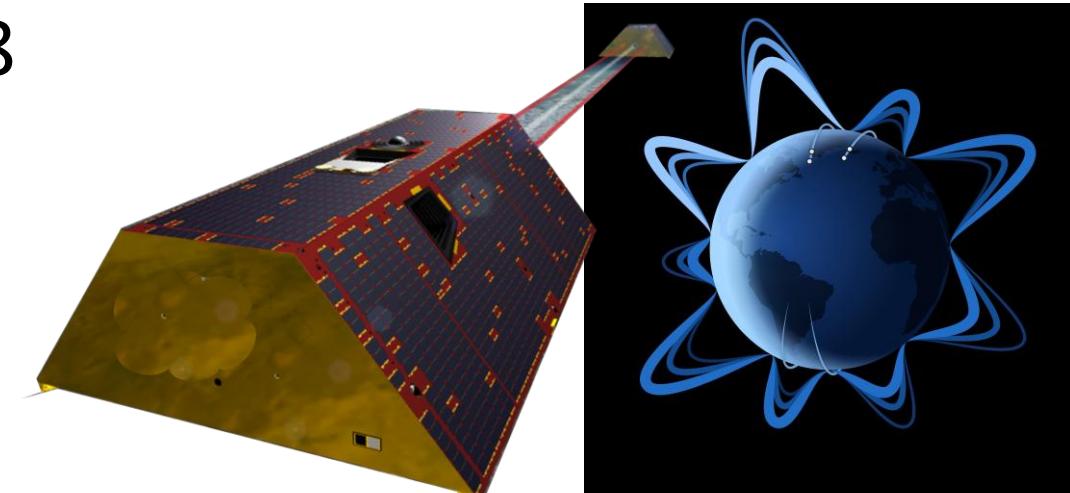
Power = 40% of cost in 2022



Target Launch: 2028

Project/Program Constraints

- Partnership between NASA & DLR
- Similar design to GRACE (F0)
- Baseline design life: 2 years (7 years consumables)
- Orbit: 500 km altitude, 89° Inclination



Mission Science

- Mass Change produces observations consistent with the GRACE(FO), documented in the baseline Mass Change Designated Observable study

Measurement System

- Satellite to Satellite Tracking:
 - Laser Ranging Interferometer
 - Accelerometer
 - GNSS Receiver
 - Star Camera Attitude determination

MAGIC: Mass change And Geosciences International Constellation

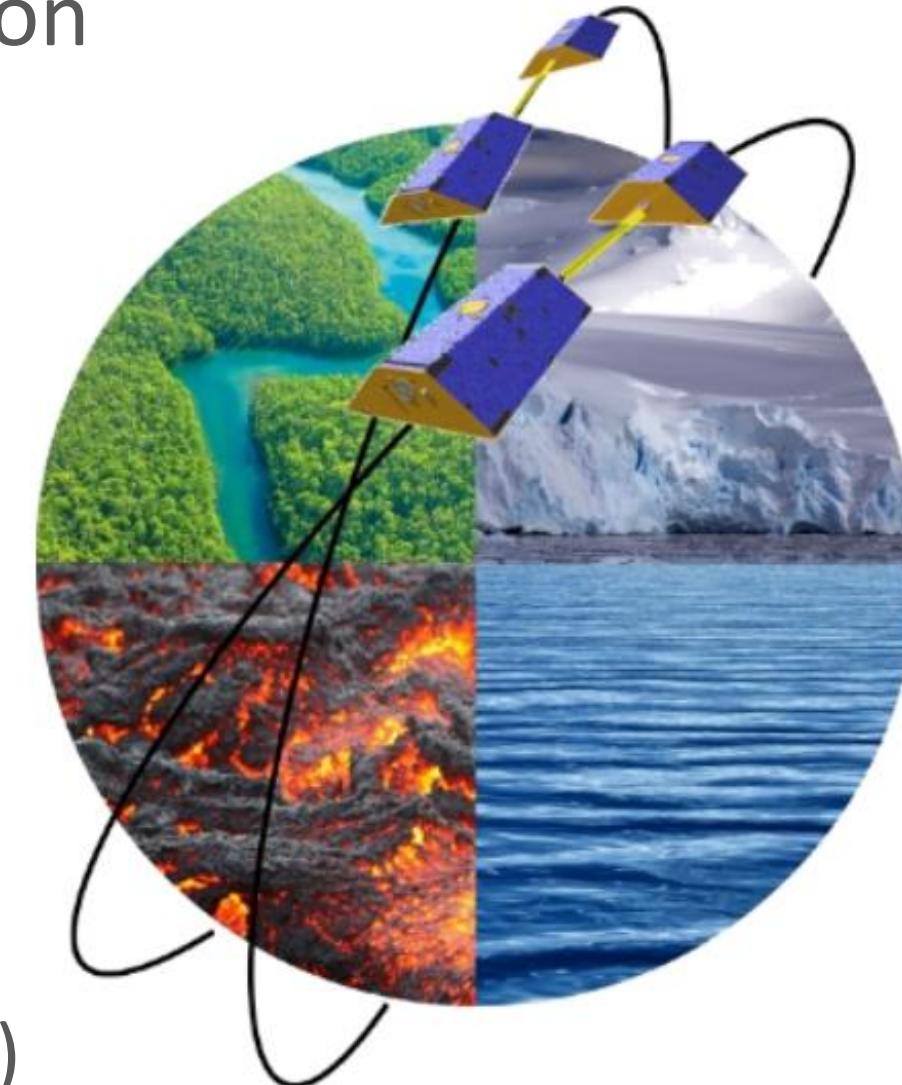
European Next Generation Gravity Mission
(NGGM): Target Launch: 2032

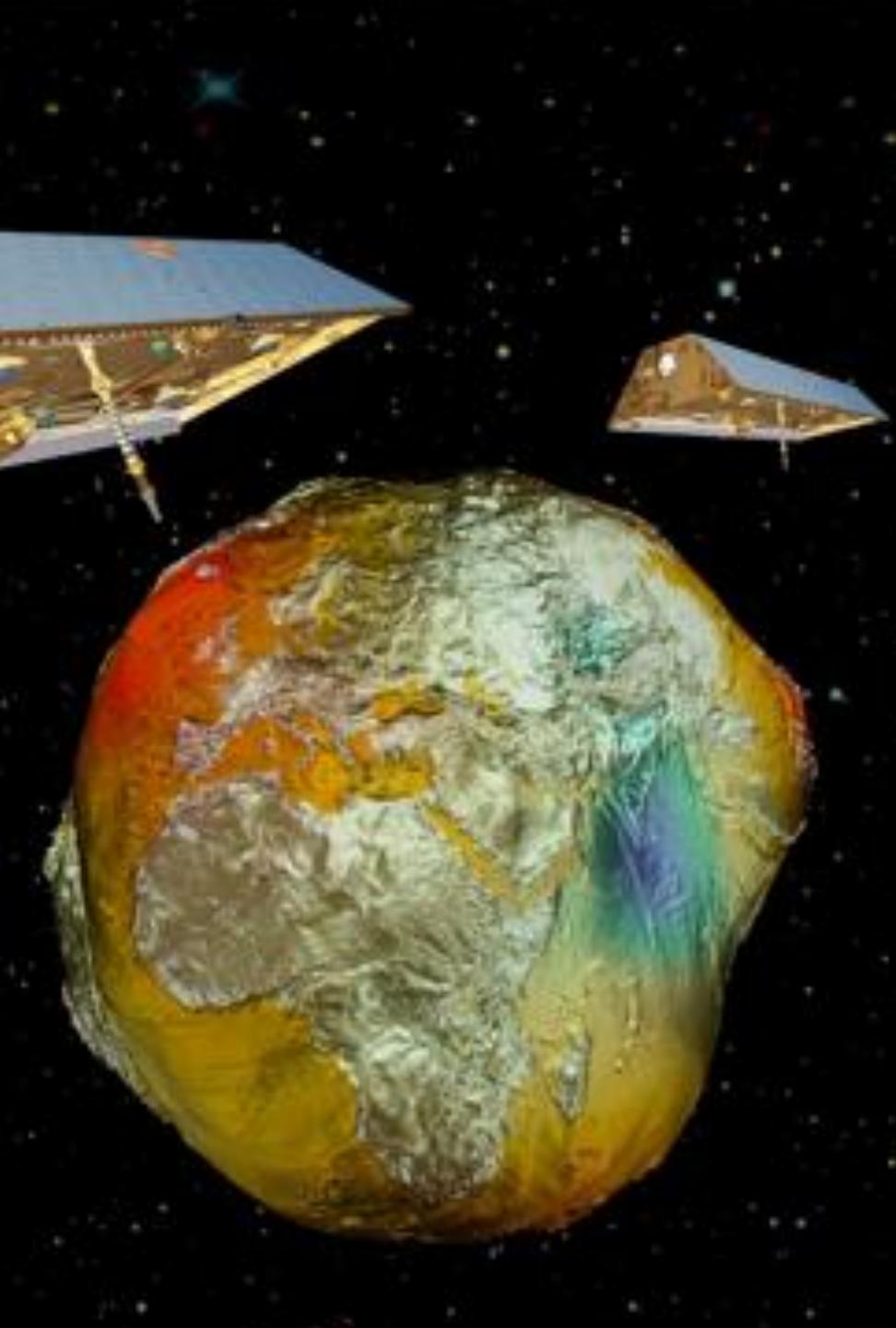
Resolution:

400 km elevation, 70° inclination

Wiese et al., 2022: trade space considering spatiotemporal resolution and uncertainty;
Monthly solution ± 20 mm uncertainty
↑ resolution of TWSA from **350 km to 200 km**
(120,000 km² to 40,000 km²)

GOCE satellite: 250 km elevation (2009 – 2013)



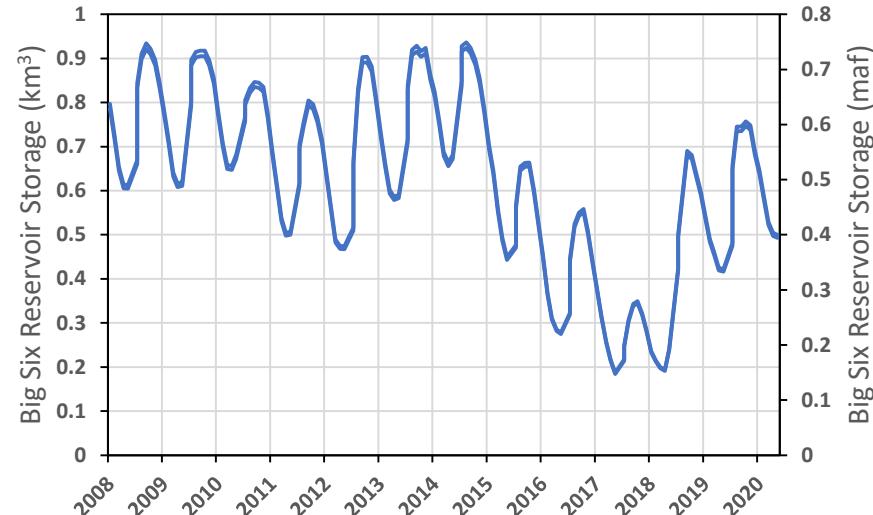


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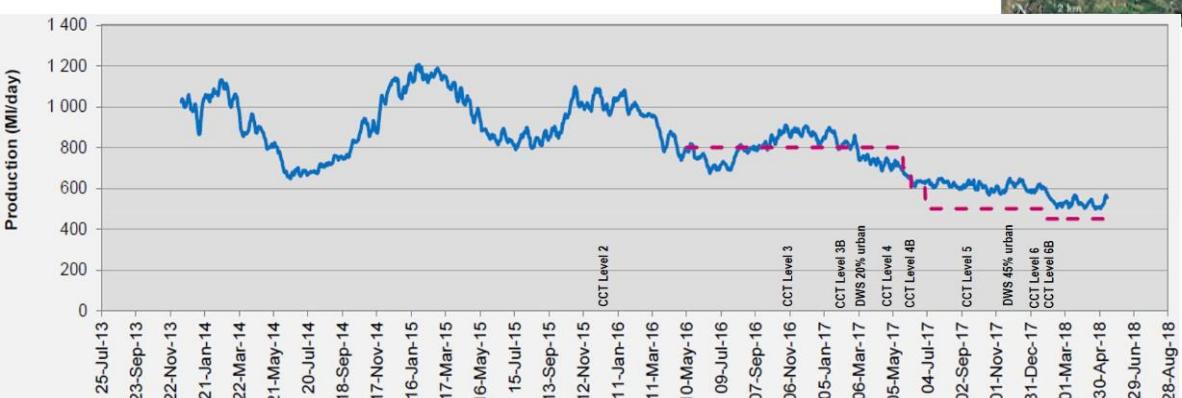
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4. Urban water shortages (Cape Town, Sao Paulo)

4.0 Cape Town Day Zero (13.5 % reservoir capacity), drought linked to El Nino, 70% increase in population (1995: 2.5 M – 2015: 4.1 M), water storage only ↑ed 17%

Western Cape Water Supply System



Heavily reliant on SW
Reservoir storage ↓
90% (2014), 50% (2015), 20% (2017)

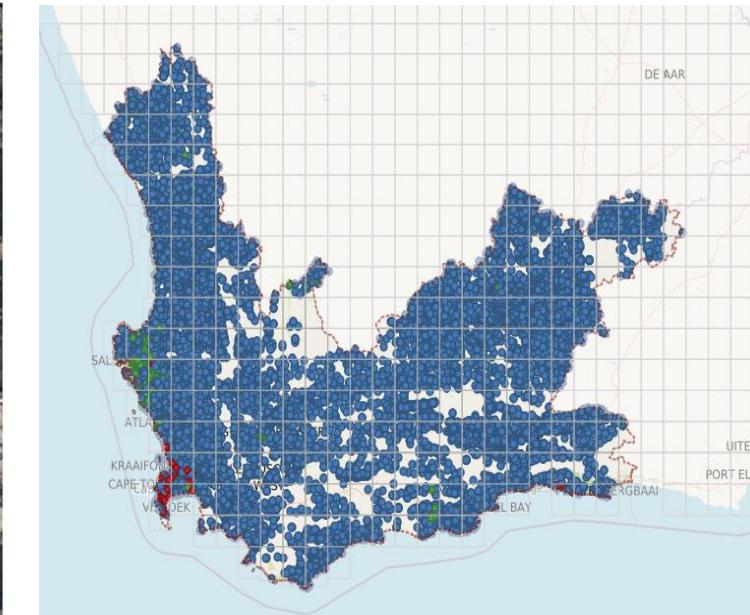


Theewaterskloof Reservoir:



↓ demand
1200 MLD (2015) to
500 MLD (Jan 2018)

Agriculture highly impacted:
3000 jobs lost, 44% ↓ in yield.
No compensation for farmers.

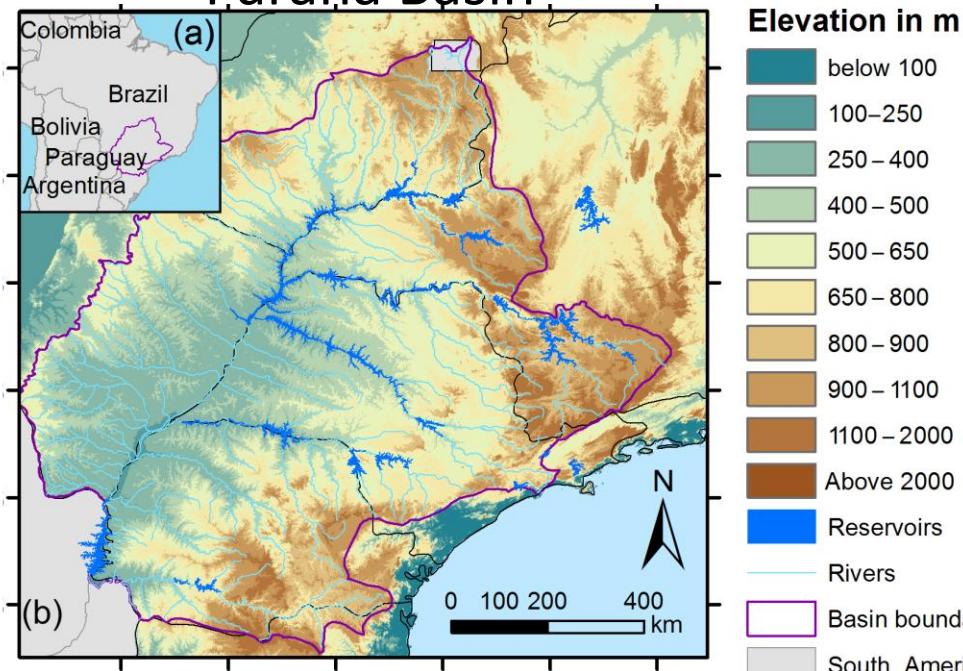


Expansion of GW:
Hundreds of boreholes drilled
Dept. Water and Sanitation:
encouraged households to drill
GW wells, Non-revenue water

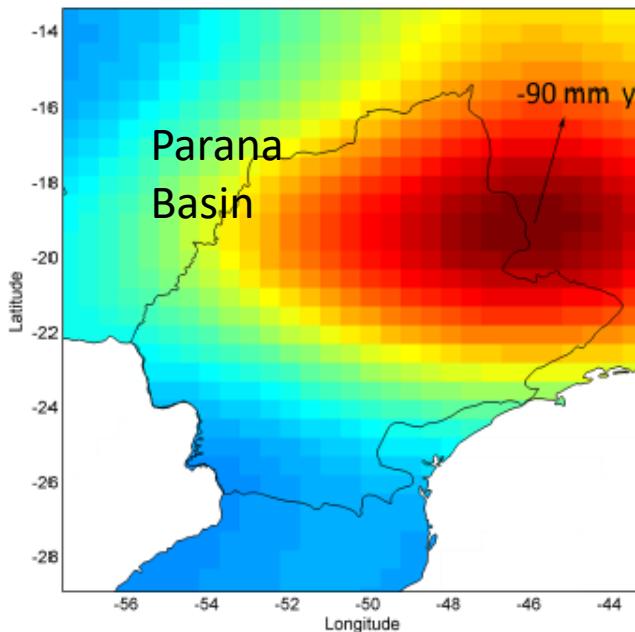
Livable Urban Waterways:
GEOSS project

4.0 Sao Paulo Drought

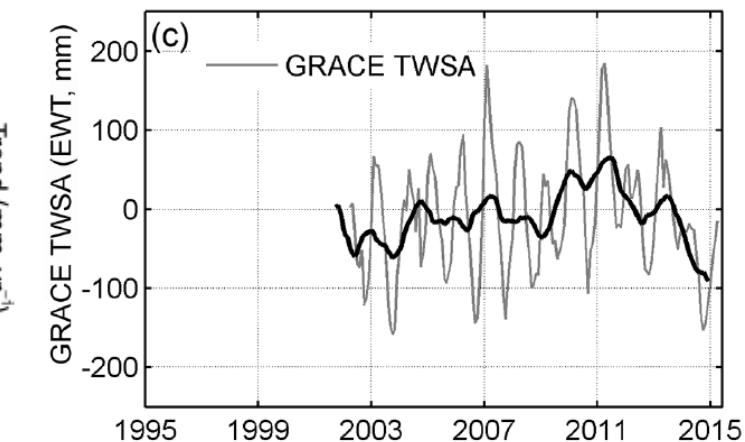
Parana Basin



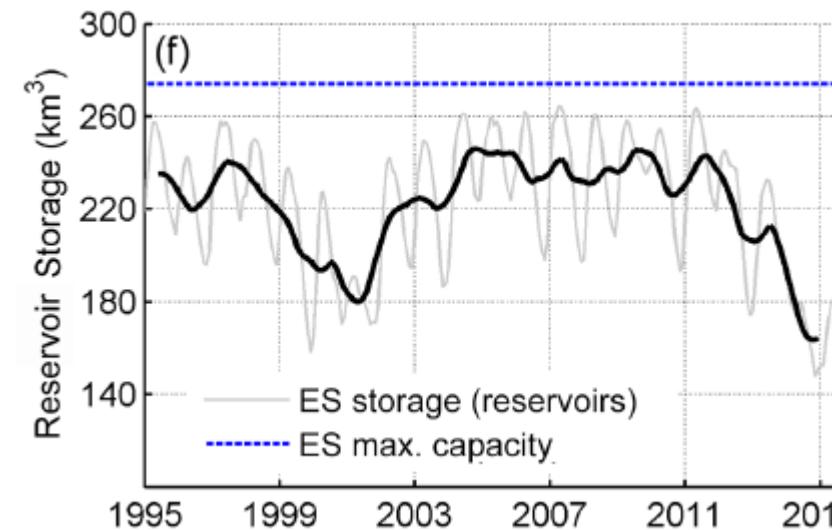
GRACE TWS Anomaly
(Apr. 11 – Apr. 2015)



GRACE Total Water Storage Trends (2011 – 2015) in Parana Basin



TWS depletion: 148 km^3 total



2014 – 2017 drought linked to El Nino

Sao Paulo: SW dominant water source for ~ 20 million people

GW \uparrow ed drought resilience: 10,000 – 12,000 private wells drilled

GW use increased from 1% to 25% of total water supply during drought

60% of wells not regulated. Non revenue water

Melo et al., HESS, 2016

Key Takeaways

1. GRACE data provide global picture of Total Water Storage anomalies but only for 2002 – 2025
2. Irrigation:
 - a) ↑ GW-fed irrigation in SSA, switching from native vegetation to cropland ↑ed recharge
 - b) Unmanaged aquifer recharge is important, inefficient SW irrigation recharges GW (Ag-MAR, Flood-MAR) (Pakistan, NW India, NW US)
SW irrigation, salinization, waterlogging → transition to GW irrigation → conjunctive use
 - c) GW and SW: a single resource, need to be managed together
Conjunctive use of SW and GW in CA, AZ, -→ increase sustainable management
 - d) Managed Aquifer Recharge: highly successful in CA, AZ, ID, drought mitigation, irrigation infrastructure, suitable geology
3. Urban water shortages:
 - Cape Town and Sao Paulo, heavily reliant on surface water reservoirs
 - Expanding GW use, decentralization, non-revenue water

Water Resources Podcast

<http://wrp.beg.utexas.edu>
Apple, Spotify etc

Water Issues in India and Africa



Alan MacDonald describes a recent study quantifying increases in groundwater storage in NW India and Central Pakistan over much of the last century and also the potential for groundwater to support development in much of Sub-Saharan Africa.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Groundwater Resilience to Climate Extremes/Change in Tropical Africa



Richard Taylor discusses linkages between rainfall extremes related to ENSO and episodic groundwater recharge, and how amplification of rainfall extremes under climate change may increase groundwater resources in Sub-Saharan Africa.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Assessing the Barriers to Groundwater Development in Sub-Saharan Africa



Jude Cobbing discusses the water resources in Sub-Saharan Africa, the barriers to development, including financing, drilling and pumping technologies, and energy access, and approaches to addressing these barriers as shown in South Africa.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Groundwater: Achieving Global Development Goals



Karen Villholth discusses importance of groundwater in achieving the United Nations Sustainable Development Goals related to water and food security with particular emphasis in Sub-Saharan Africa.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Role of Groundwater in Developing Countries in the World Bank



Francois Bertone and Lucy Lytton discuss the recent World Bank report on The Hidden Wealth of Nations, The Economics of Groundwater in Times of Climate Change

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Locating Groundwater Wells in Refugee Camps in Eastern Chad using Near-Surface Geophysics



Paul Bauman talks about his recent trip to Eastern Chad to locate groundwater wells in new and expanding camps hosting refugees from neighboring Sudan.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Chad Groundwater Well Team

Improving Access to Water for Tens of Millions of People in E. Africa and S. Asia



Rob Hope discusses REACH and Uptime programs that are designed to improve water access for the poor in Ethiopia, Kenya, and Bangladesh.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Drought Forecasting in East Africa



Chris Funk talks about drought forecasting in East Africa, with the sixth consecutive drought projected for spring 2023. He describes their improved forecasting skill with up to 6 month forecasts allowing agencies to work together to prevent famines.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Addressing Groundwater Scarcity and Arsenic Pollution with Potential Solutions in India



Abhijit Mukherjee discusses overexploitation of groundwater resources and arsenic contamination with potential solutions using managed aquifer recharge and stratified drilling to minimize arsenic exposure.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Bengal Water Machine



Mohammad Shamsudduha (Shams) discusses the Bengal Water Machine, where seasonal groundwater depletion from irrigation creates space for increased recharge during summer monsoons in Bangladesh, capturing up to 90 km³ over 30 years.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Linking Water Resource Assessments and Policy to Develop Solutions in India



Veena Srinivasan talks about water resource challenges in southern India and linkages to suitable policies considering climate extremes.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Beyond Cape Town Day Zero: Strategies to Increase Water Resilience



Dale Barrow discusses increases in groundwater development and other strategies to enhance water resilience in Cape Town.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

South African Lighthouse of Hope from Nature-Based Wastewater Treatment



Kevin Winter discusses nature-based approaches to treating informal settlement discharge for use in agriculture and other sectors.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

Groundwater Resources in Brazil and Potential for Global Food Production



Edson Wendland describes major aquifers in Brazil and potential expansion of irrigation for global food production.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

The Groundwater Resources for Drought Resilience in Urban Areas of Brazil

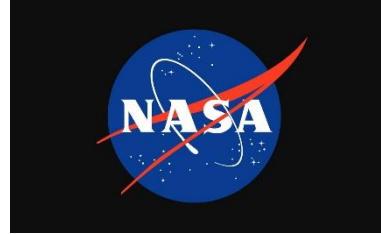


Ricardo Hirata discusses the role of groundwater in Brazil, emphasizing urban regions and their resilience to drought.

WATER RESOURCES PODCAST

WITH Bridget Scanlon

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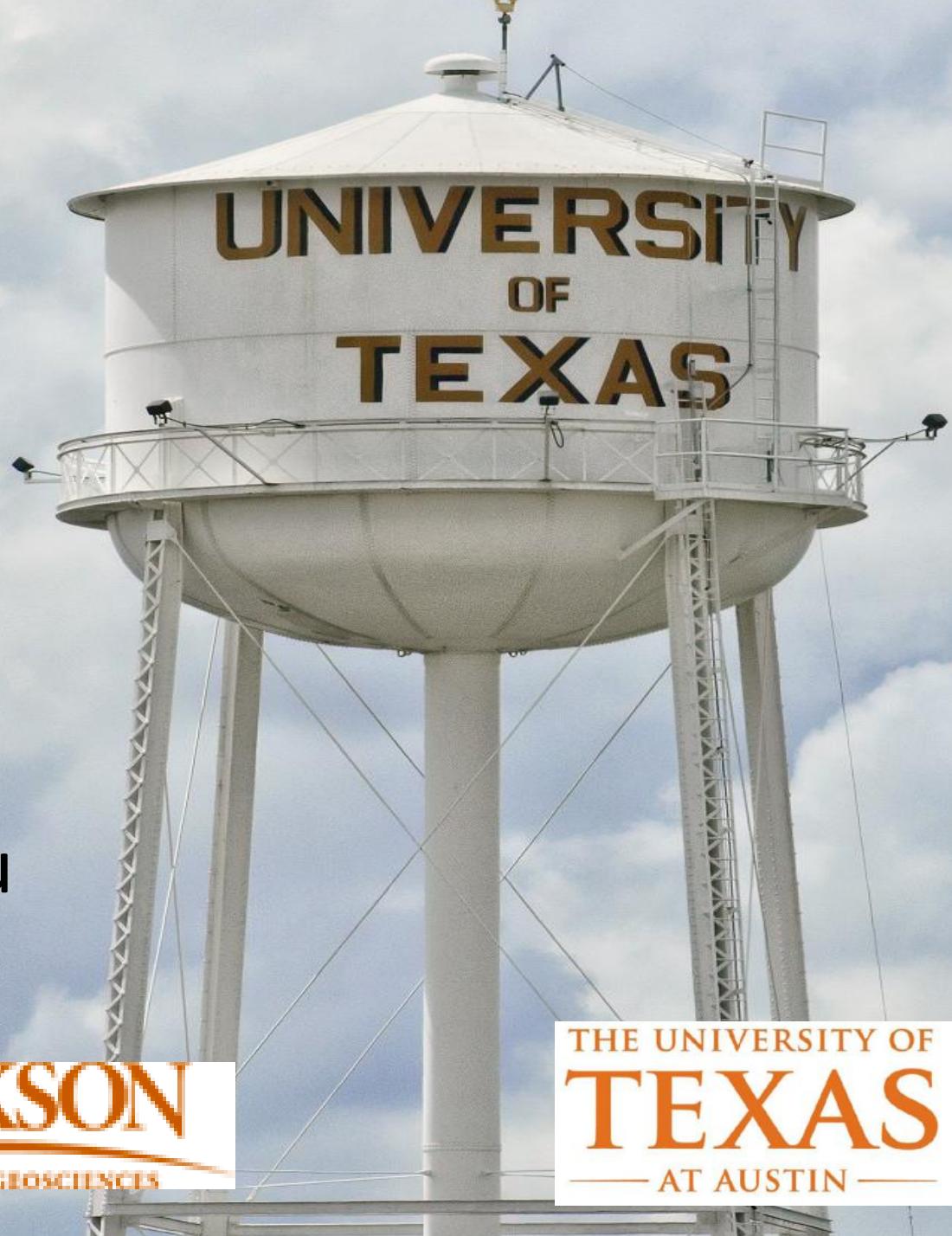
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