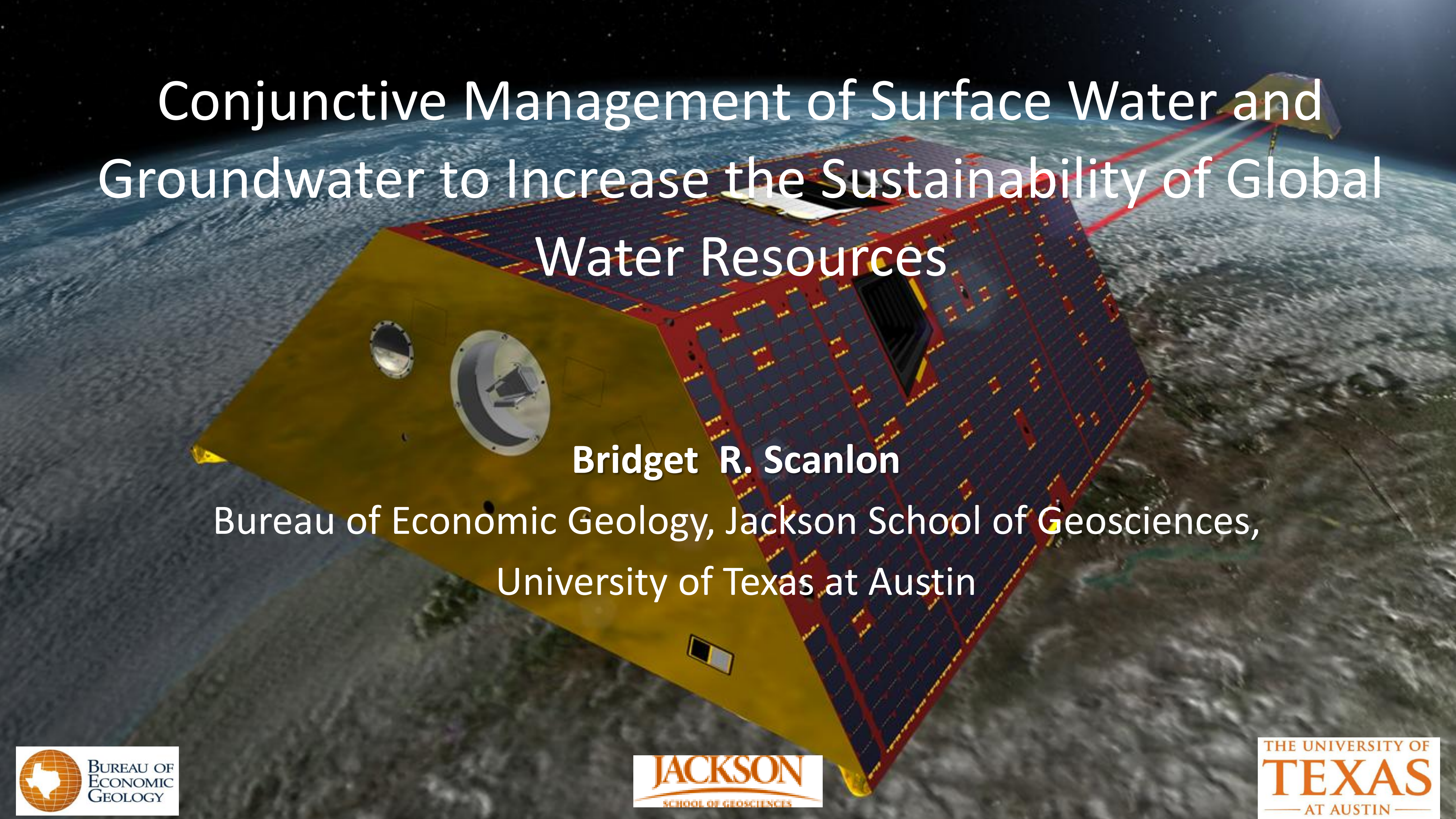


Conjunctive Management of Surface Water and Groundwater to Increase the Sustainability of Global Water Resources

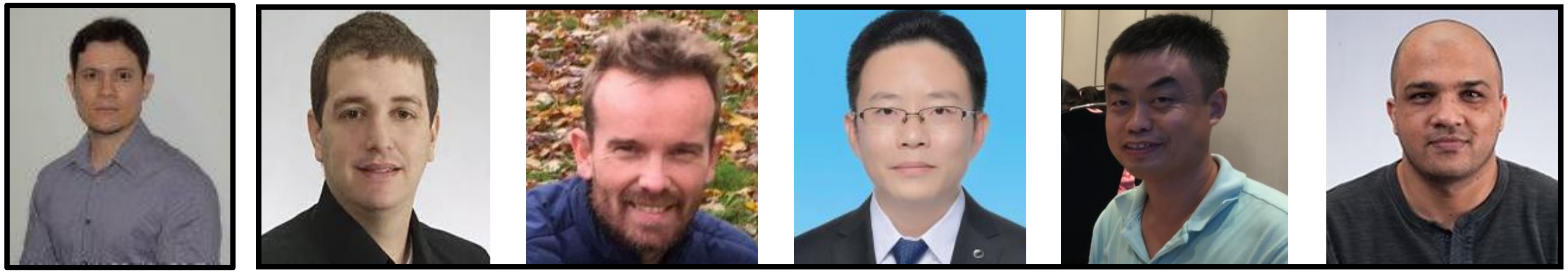
Bridget R. Scanlon

Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin

Bureau of Economic Geology

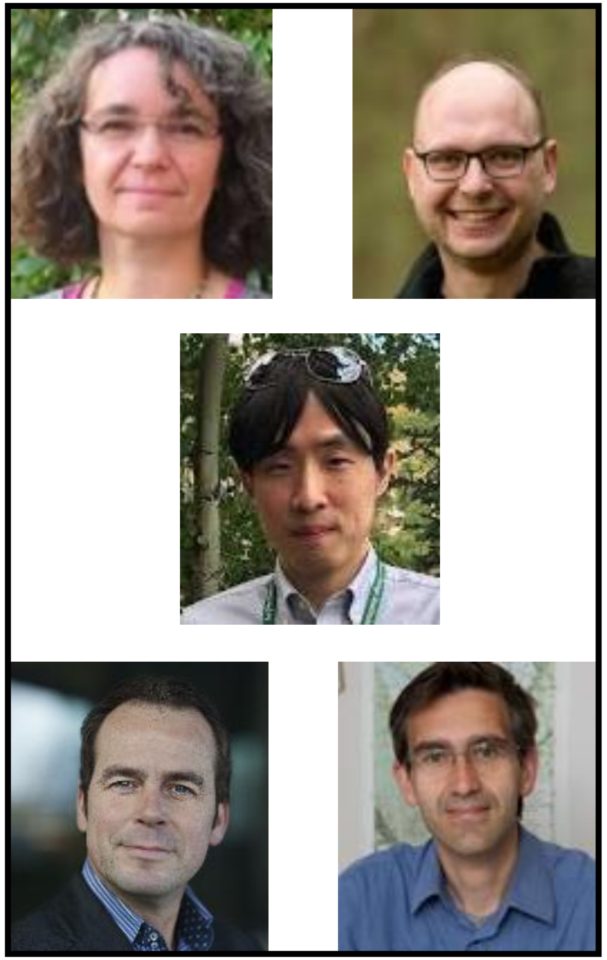
Jackson School of Geosciences

The University of Texas at Austin

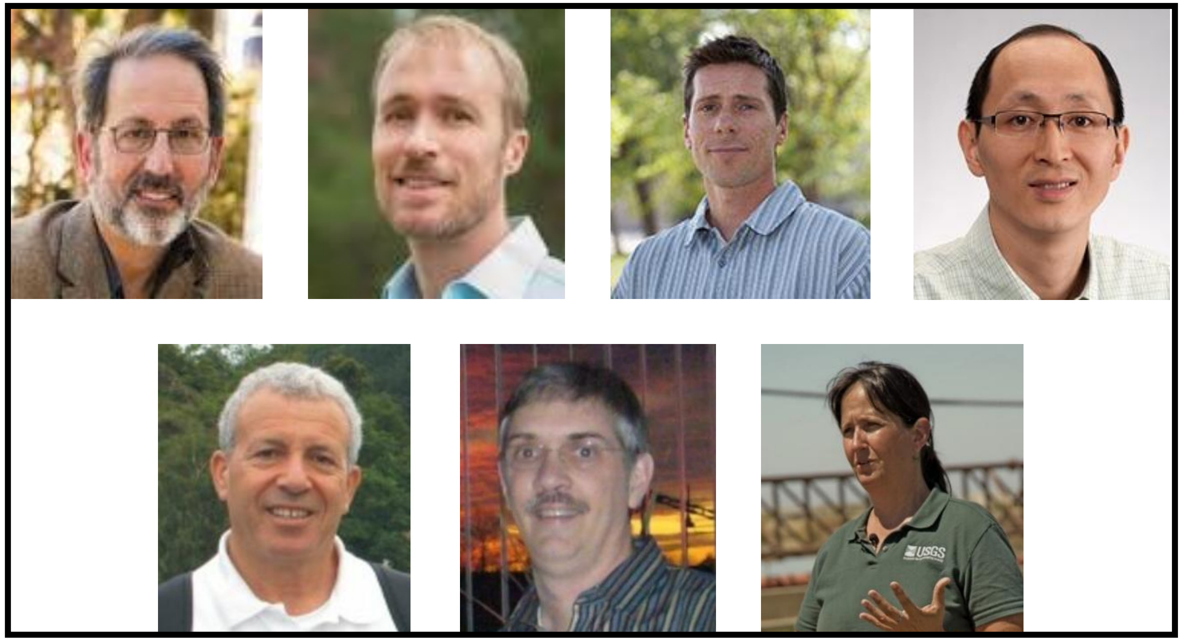


Post-docs and visitors

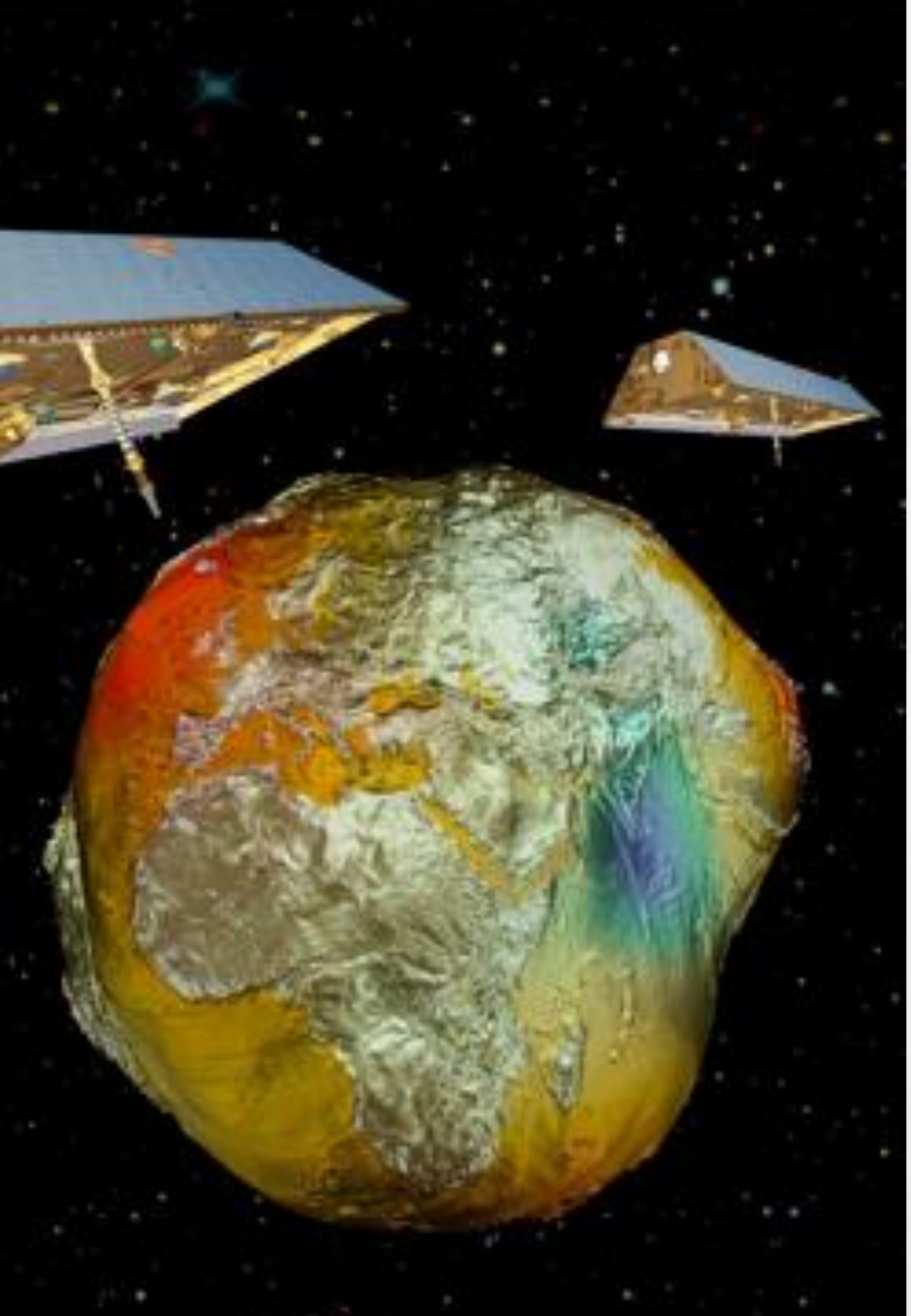
Global modelers



Geodesists



Hydrologists



Outline

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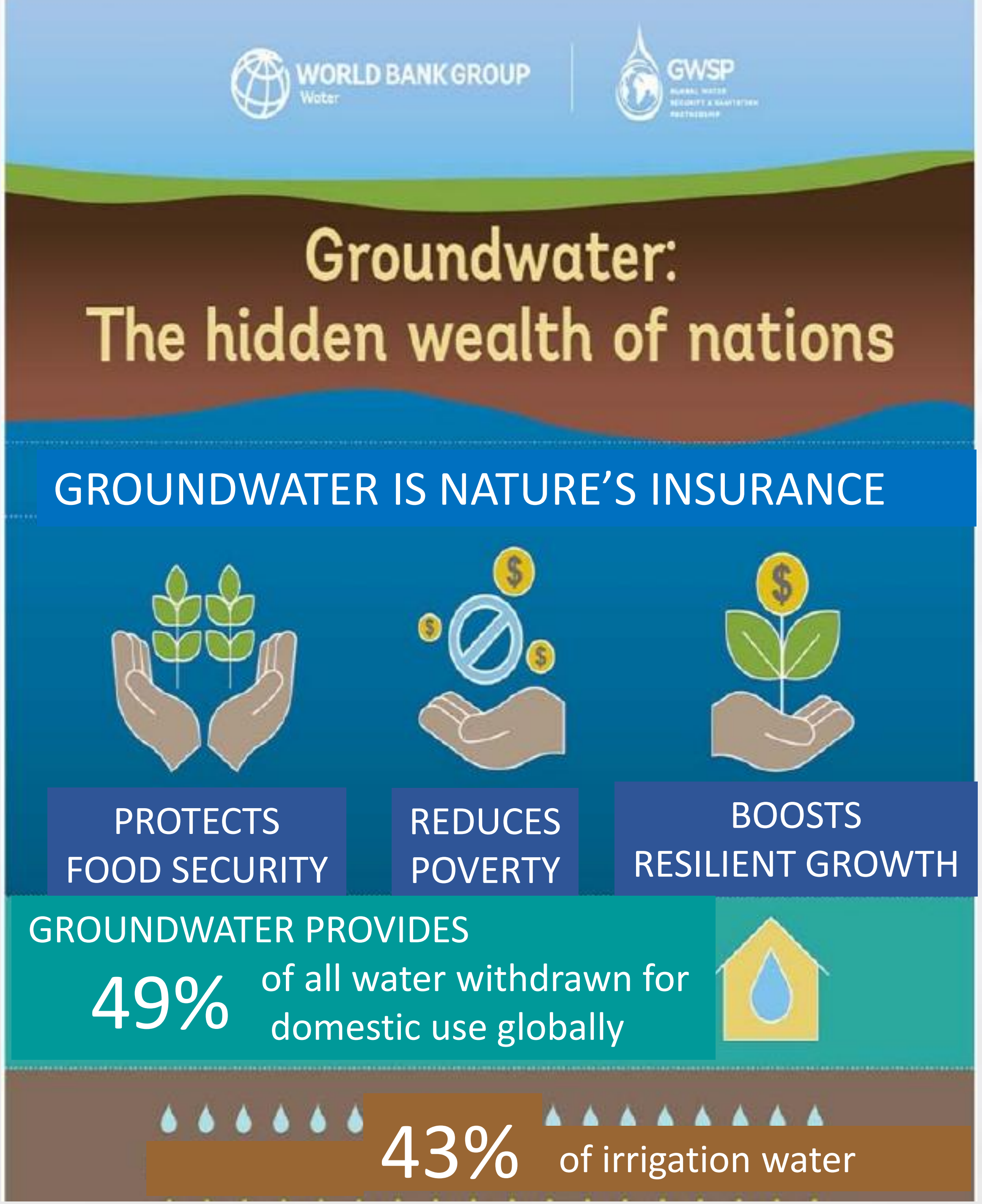
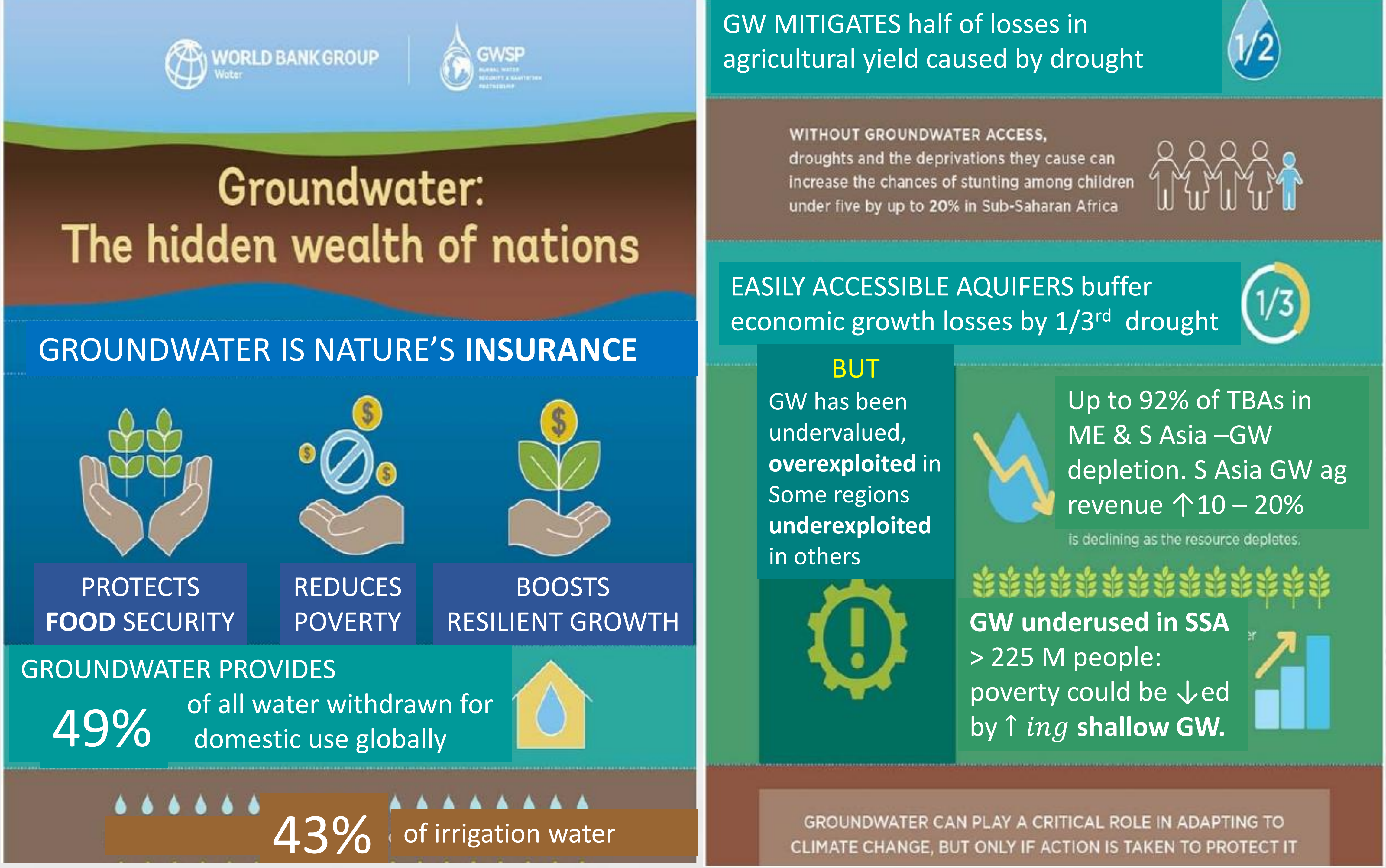
3. Irrigation
   a. Increase irrigation in Sub-Saharan Africa
   b. Switching from SW to GW irrigation (NW India, Pakistan, NW US)
   c. Conjunctive use of SW and GW (CA Central Valley)
   d. Managed Aquifer Recharge: AZ + CA
4. Urban water shortages (Cape Town, Sao Paulo)


WORLD BANK GROUP
Water
GWSP
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49% of all water withdrawn for domestic use globally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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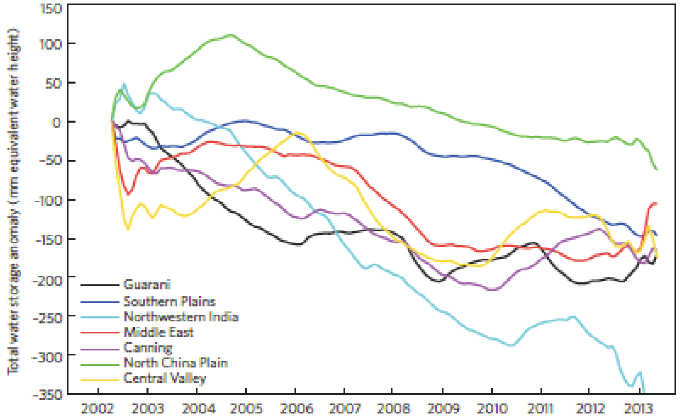
GROUNDWATER PROVIDES
49%
of all water withdrawn for domestic use globally
43%
of irrigation water
GW MITIGATES half of losses in agricultural yield caused by drought
1/2
WITHOUT GROUNDWATER ACCESS,
droughts and the deprivations they cause can increase the chances of stunting among children under five 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.



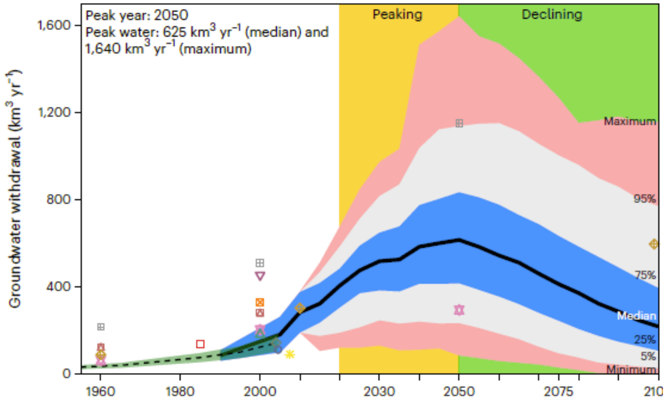
nature sustainability

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 Niazi[1], Thomas B. Wild[1], Sean W. D. Turner[2], Neal T. Graham[1], Mohamad Hejazi[3], Siwa Msangi[4], Son Kim[1], Jonathan R. Lamontagne[5] & Mengqi Zhao[6]



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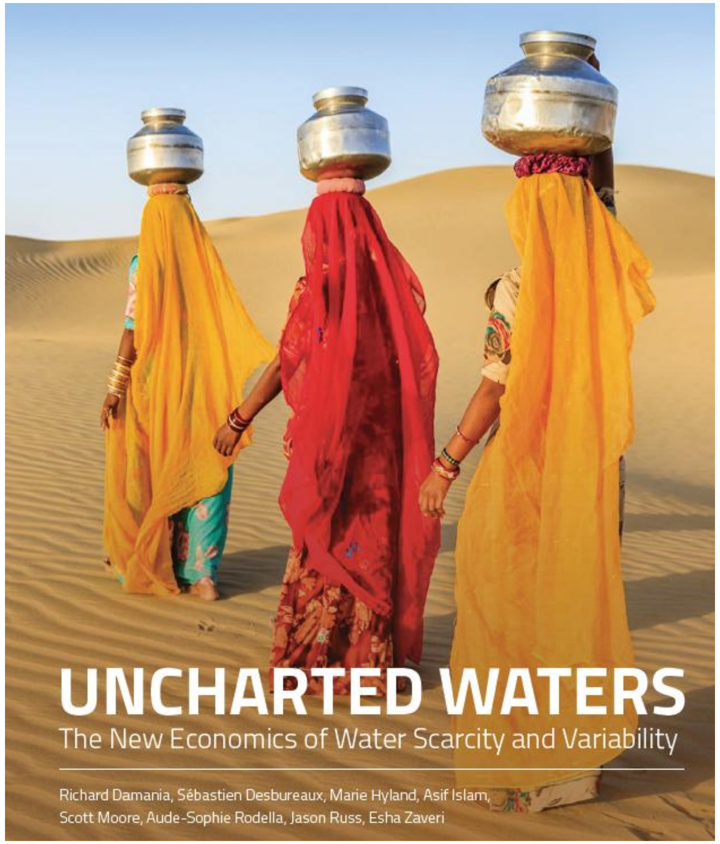
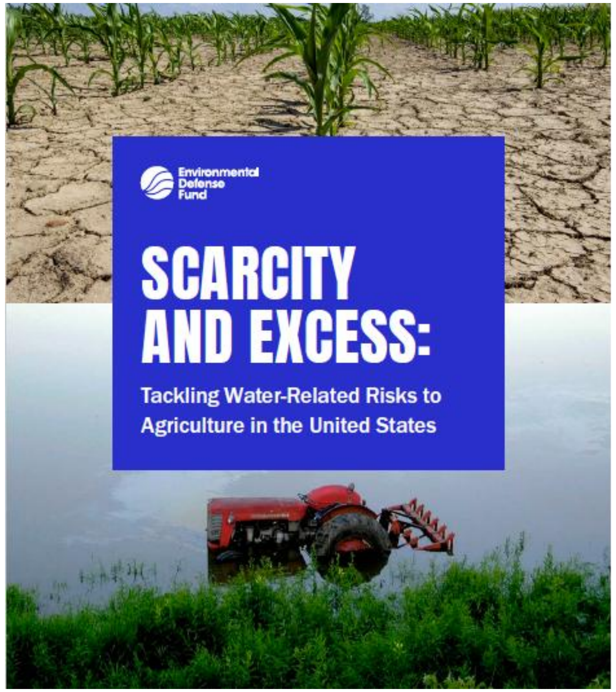


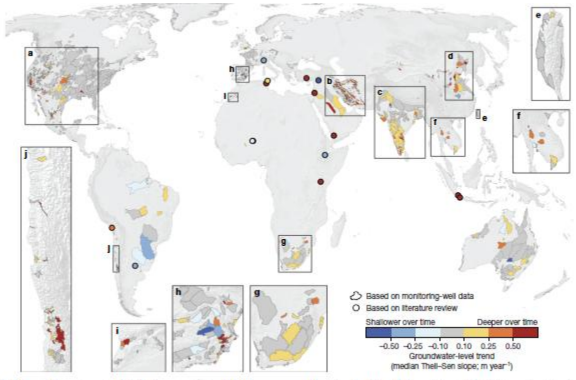
Too much vs too little?



Rapid groundwater decline and some cases of recovery in aquifers globally

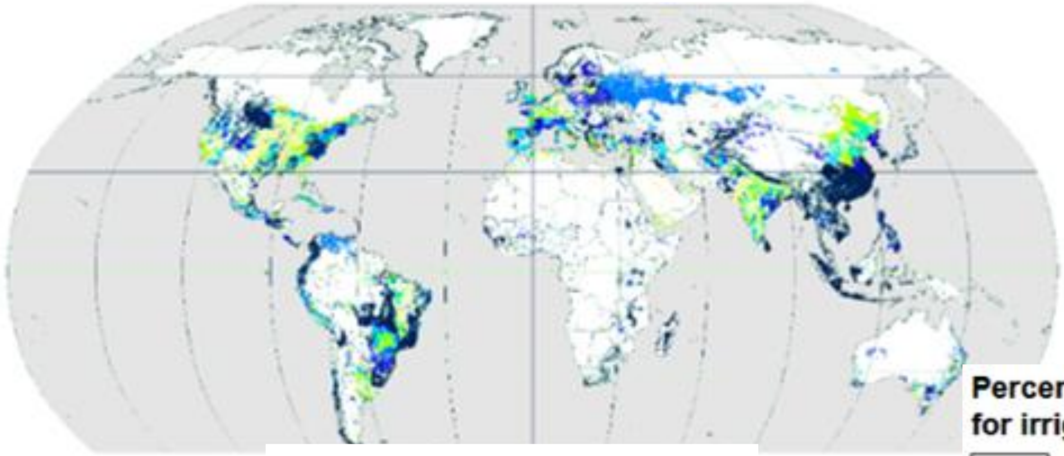
https://doi.org/10.1038/s41586-023-06879-8
Received: 8 April 2023

Scott Jasechko[1,11], Hansjörg Seybold[2,11], Debra Perrone[3,11], Ying Fan[4], Mohammad Shamsudduha[5], Richard G. Taylor[6], Othman Fallatah[7,8] & James W. Kirchner[2,9,10]

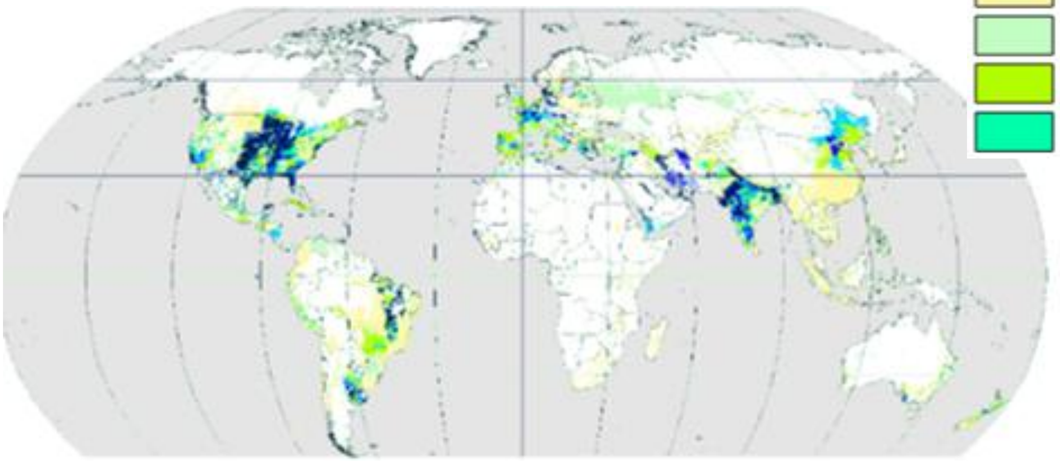


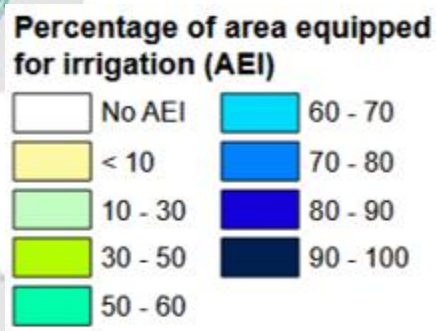
1. Irrigation, Food Production, and Urban Water

Surface Water Irrigation



Groundwater Irrigation

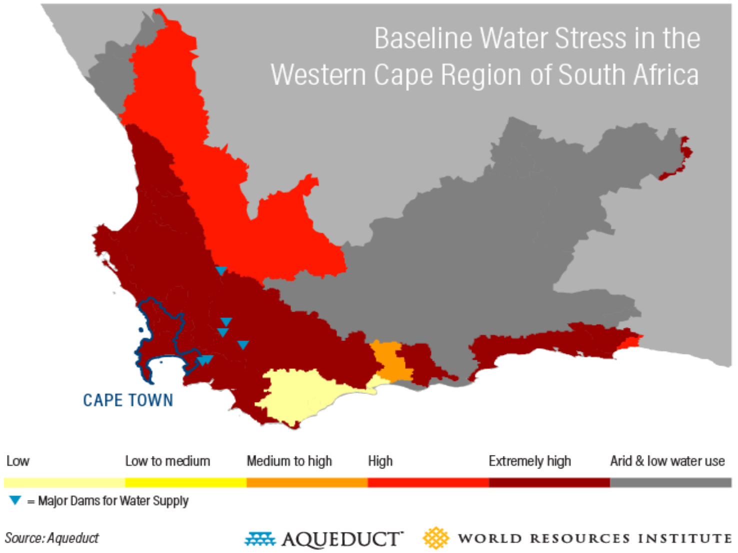




Irrigation: 70% of global water withdrawal
90% of global water consumption

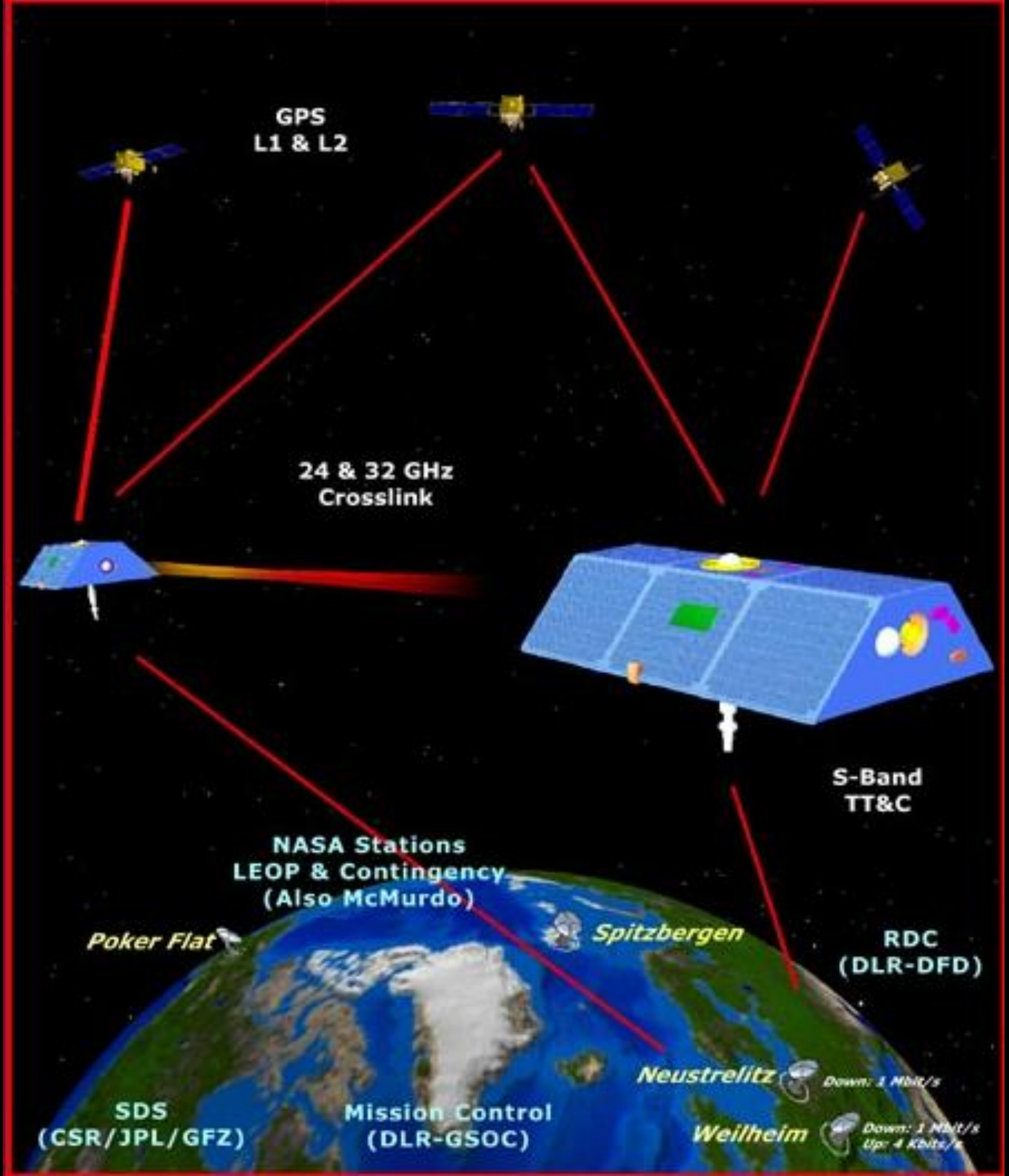
http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm

Cape Town Day Zero



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 km^2

Satellites 220 km apart

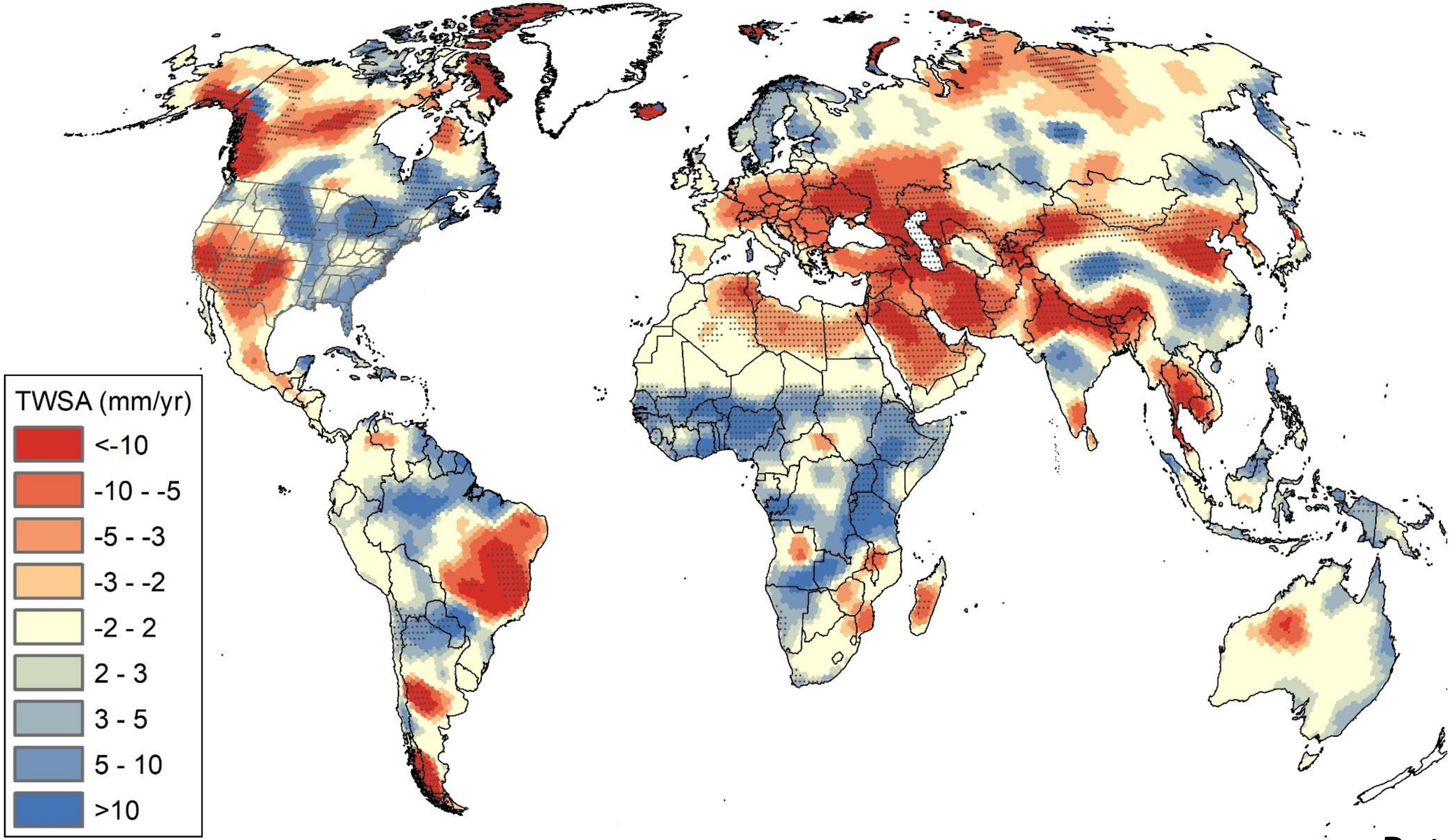
Monthly data
1 gigaton mass change = 1 km^3 of water

Terrestrial water storage (TWS) change

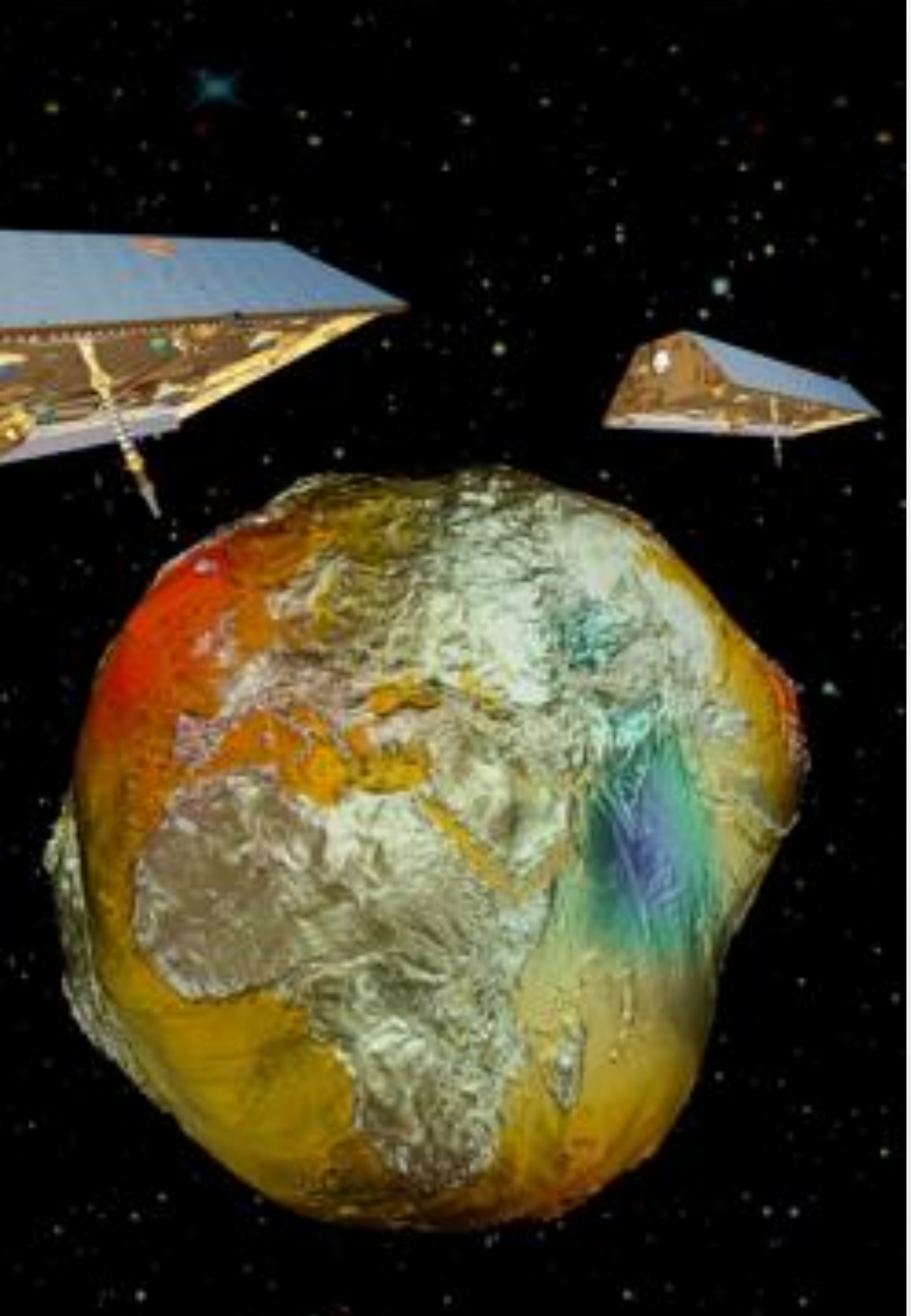
Essential climate variable in
Global Climate Observing System

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

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



Rateb et al., 2022



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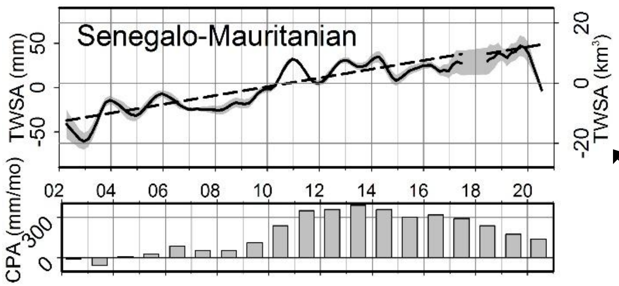
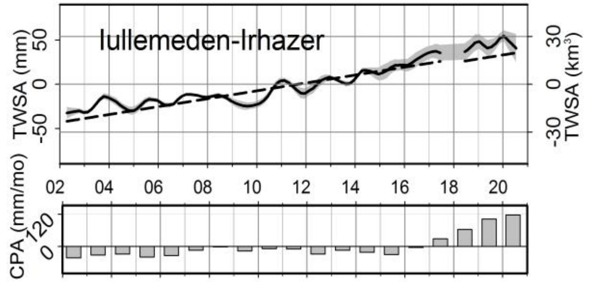
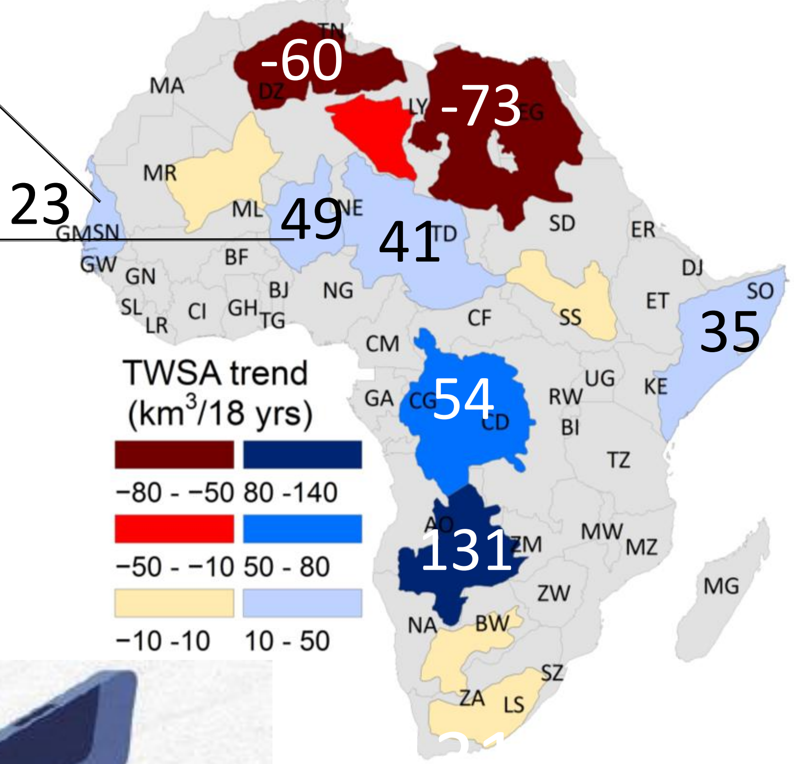
   d. Managed Aquifer Recharge: Arizona
4. Urban water shortages (Cape Town, Sao Paulo)

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

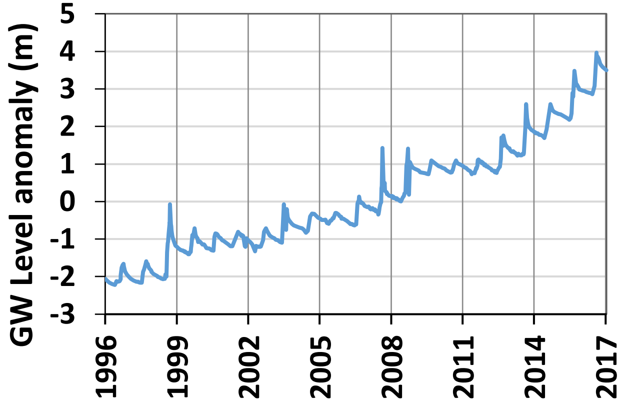




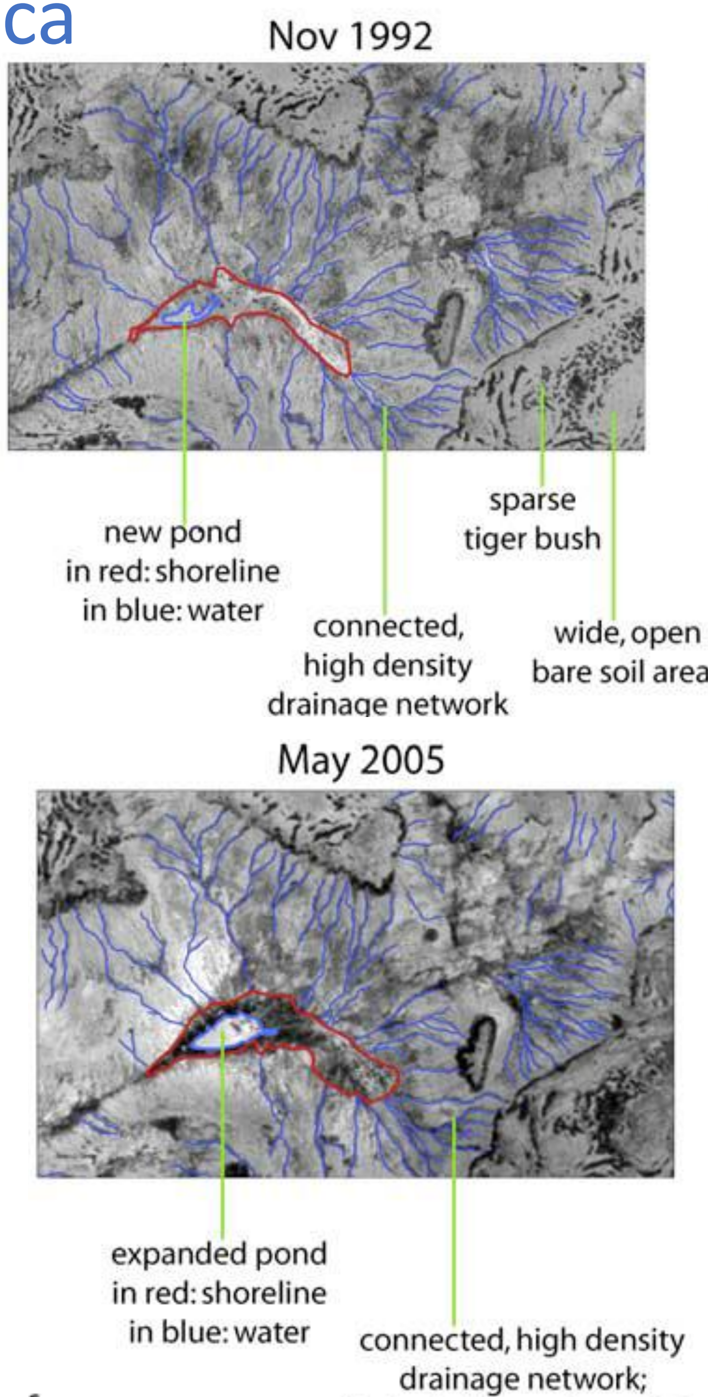
GRACE Total Water Storage Anomaly (2002 – 2020)



GW level hydrograph Niger

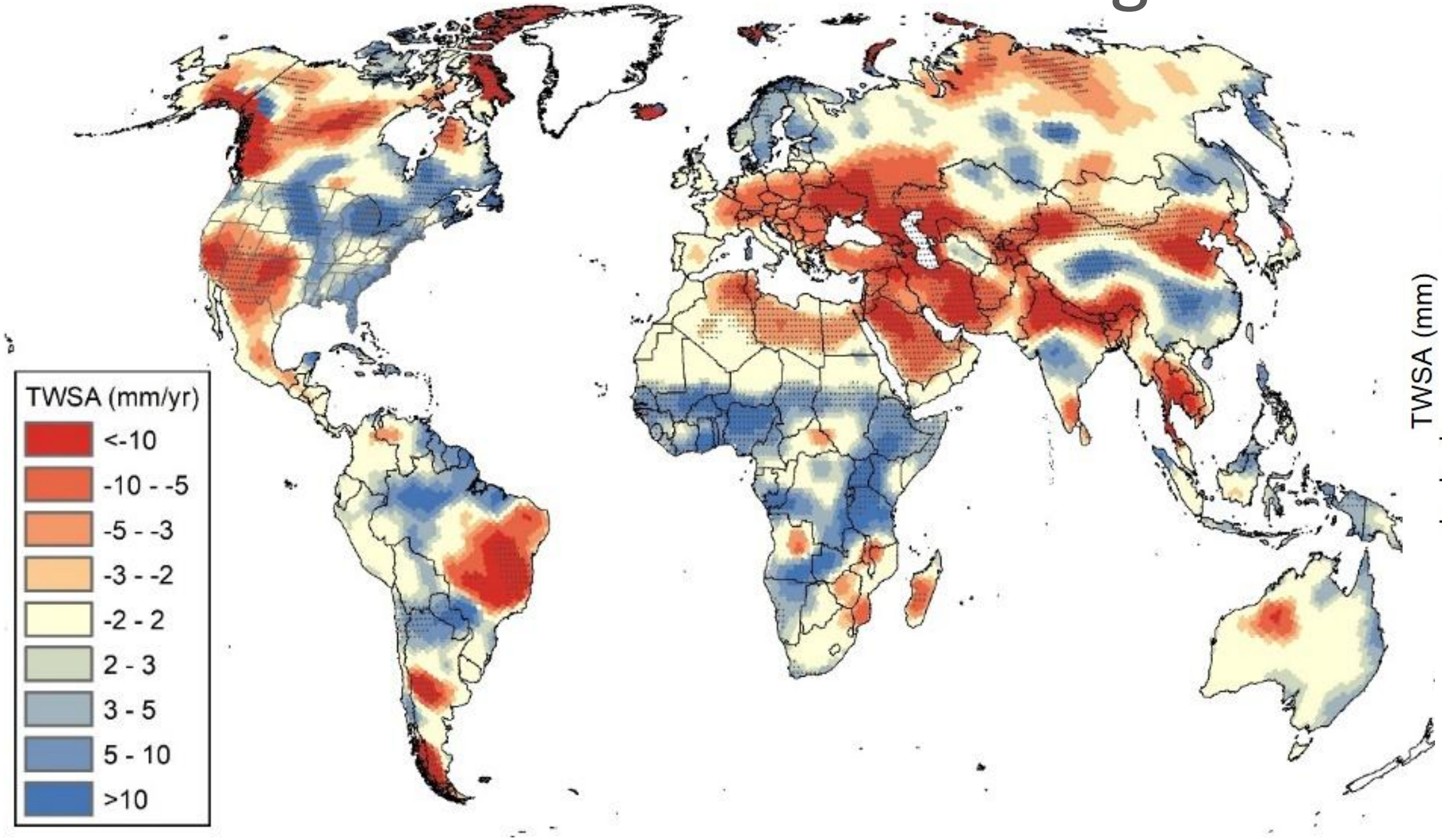


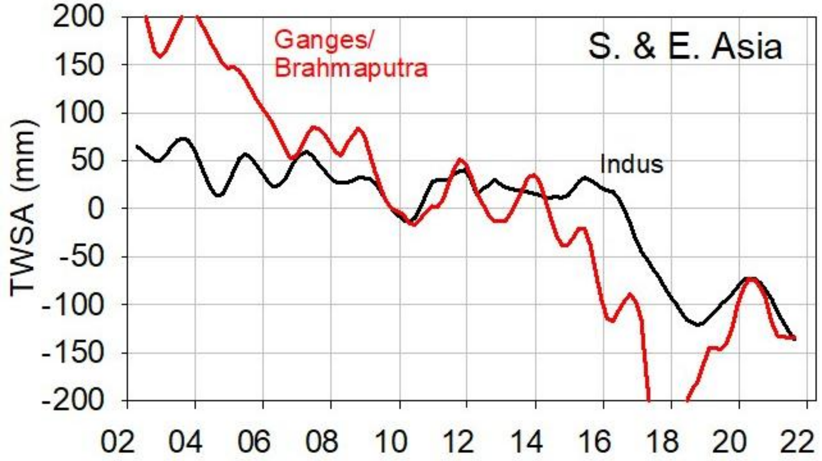
40% basement aquifers
Self-regulating



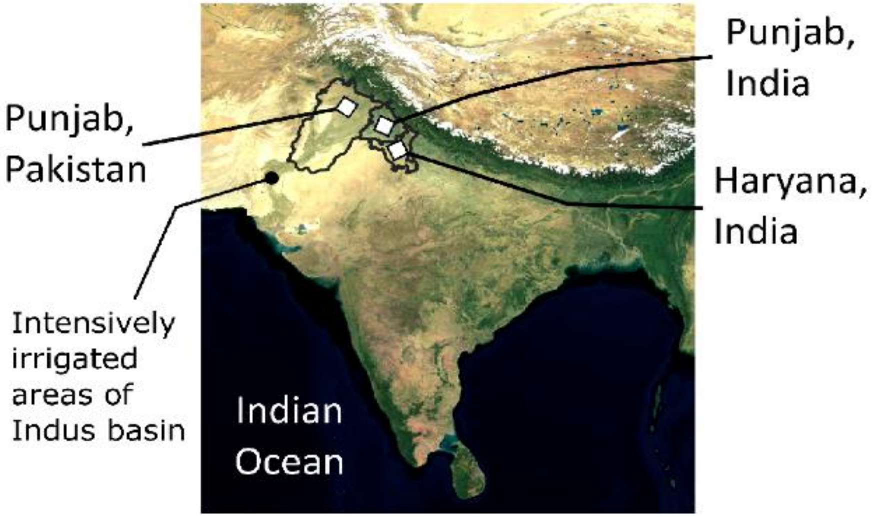
Favreau et al., WRR, 2009
Scanlon et al., ERL, 2022

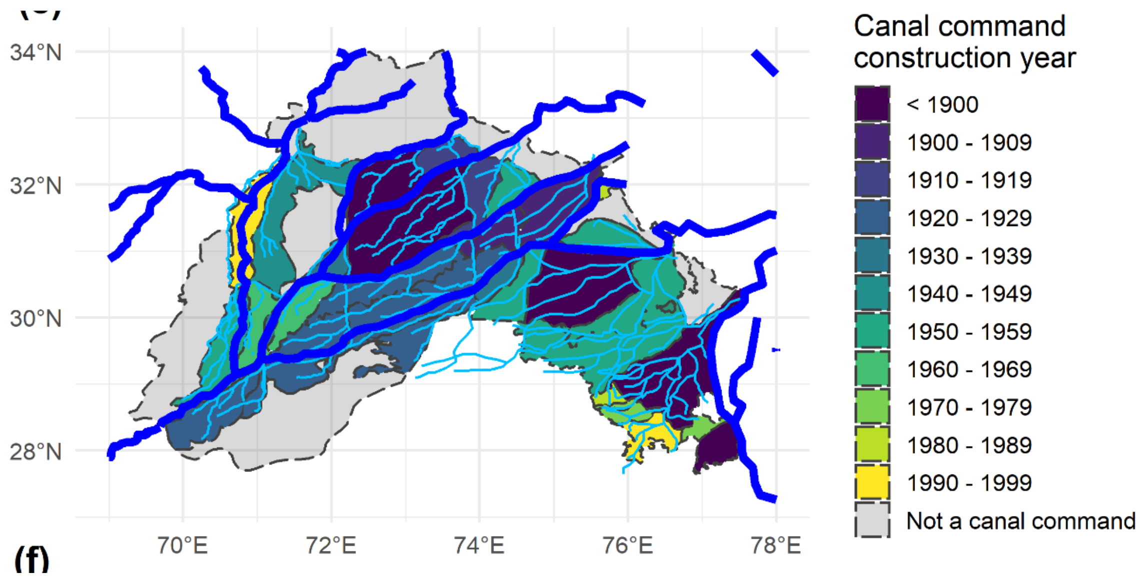
3b. Switching from Surface Water to Groundwater Irrigation
Total Water Storage Time Series

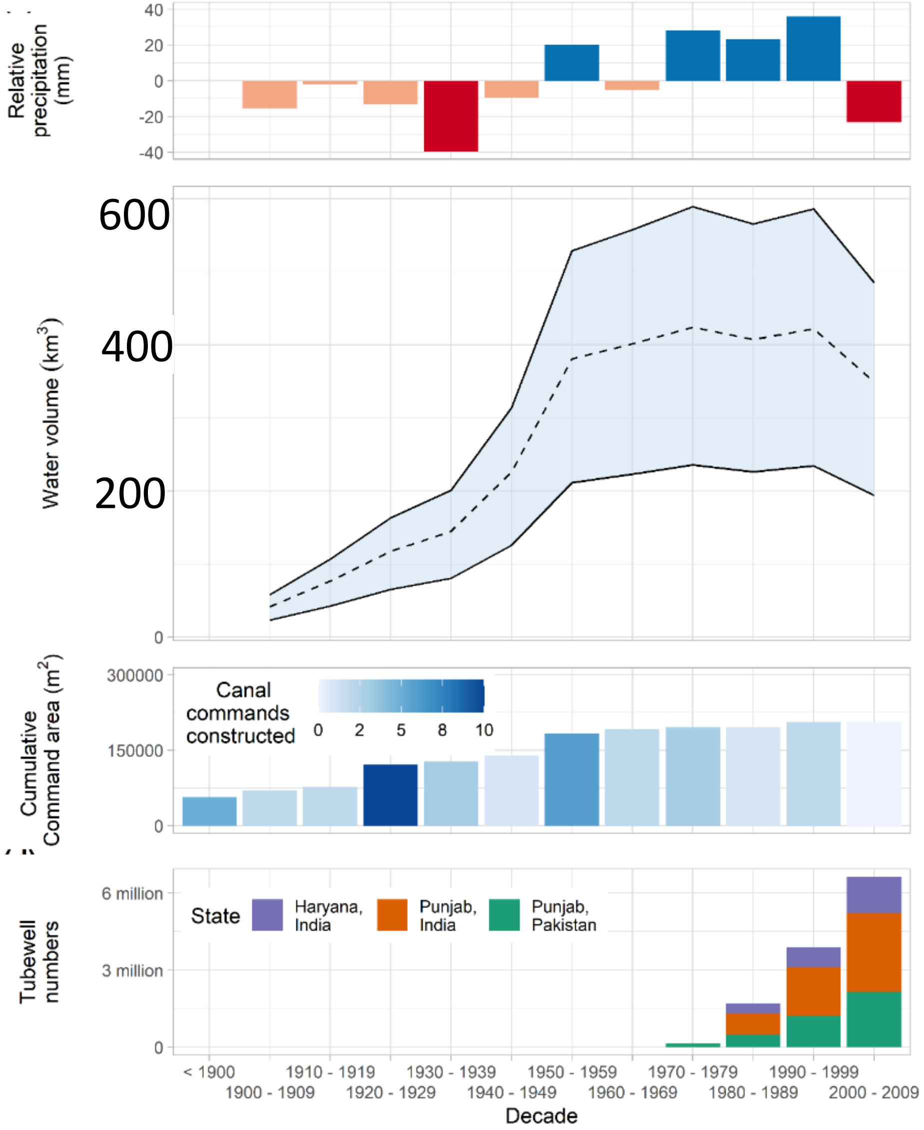




3b. A century of groundwater accumulation in Pakistan and Northwest India (GW level monitoring)







Precip. Anomaly

Water Storage km^3

Canals

Tubewells

MacAllister et al., NGC, 2022

3b. Indo-Gangetic Basin


Monday, 28 November 2022

The Tribune

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NATION

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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Significant drop in volume of water in Ganga, flags WMO

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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.

Government response with aid from **World Bank**:

National program: Atal Bhujal Yojana, 7 states switching from GW wells to irrigation canals

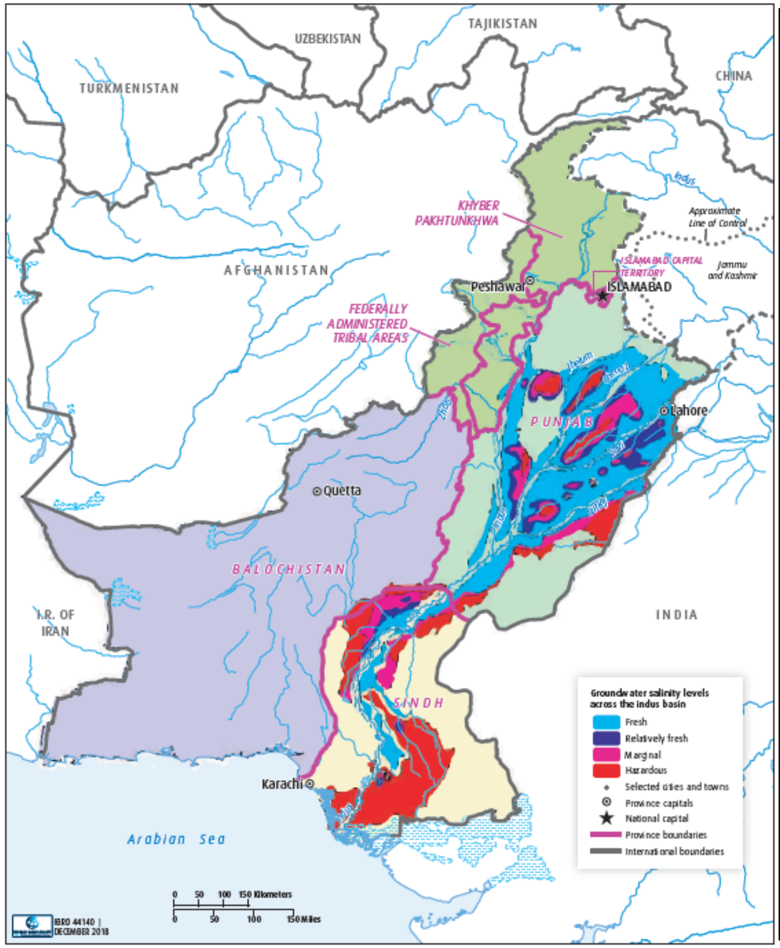
Punjab: Save Water, Earn Money scheme

Incentivizes farmers to reduce groundwater use

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

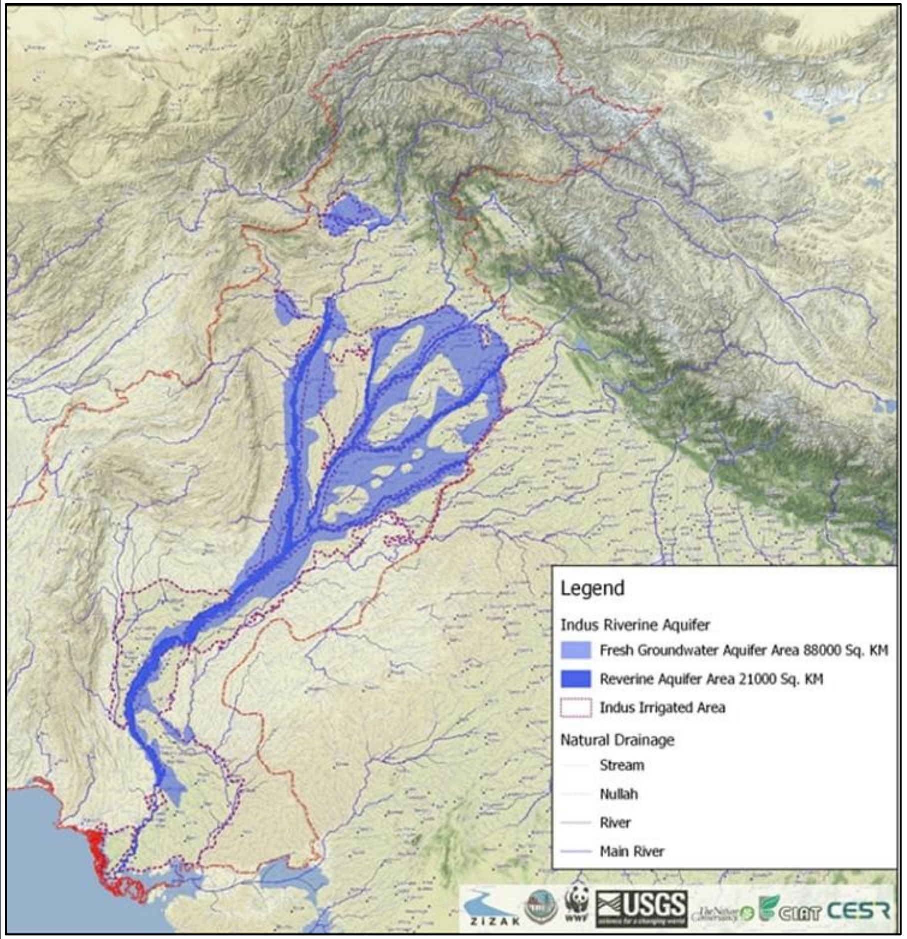
https://www.worldbank.org

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



SW irrigation, 1900s
Water logging and
GW salinization

Qureshi et al., 2004

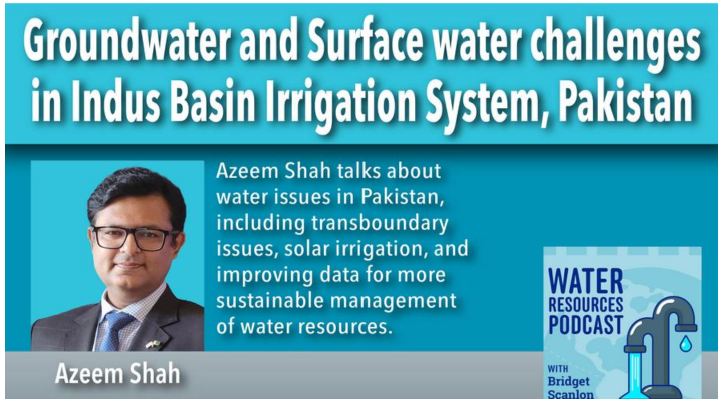


Freshwater aquifers, Indus Plains and riverine corridors, ~ 500 km^3

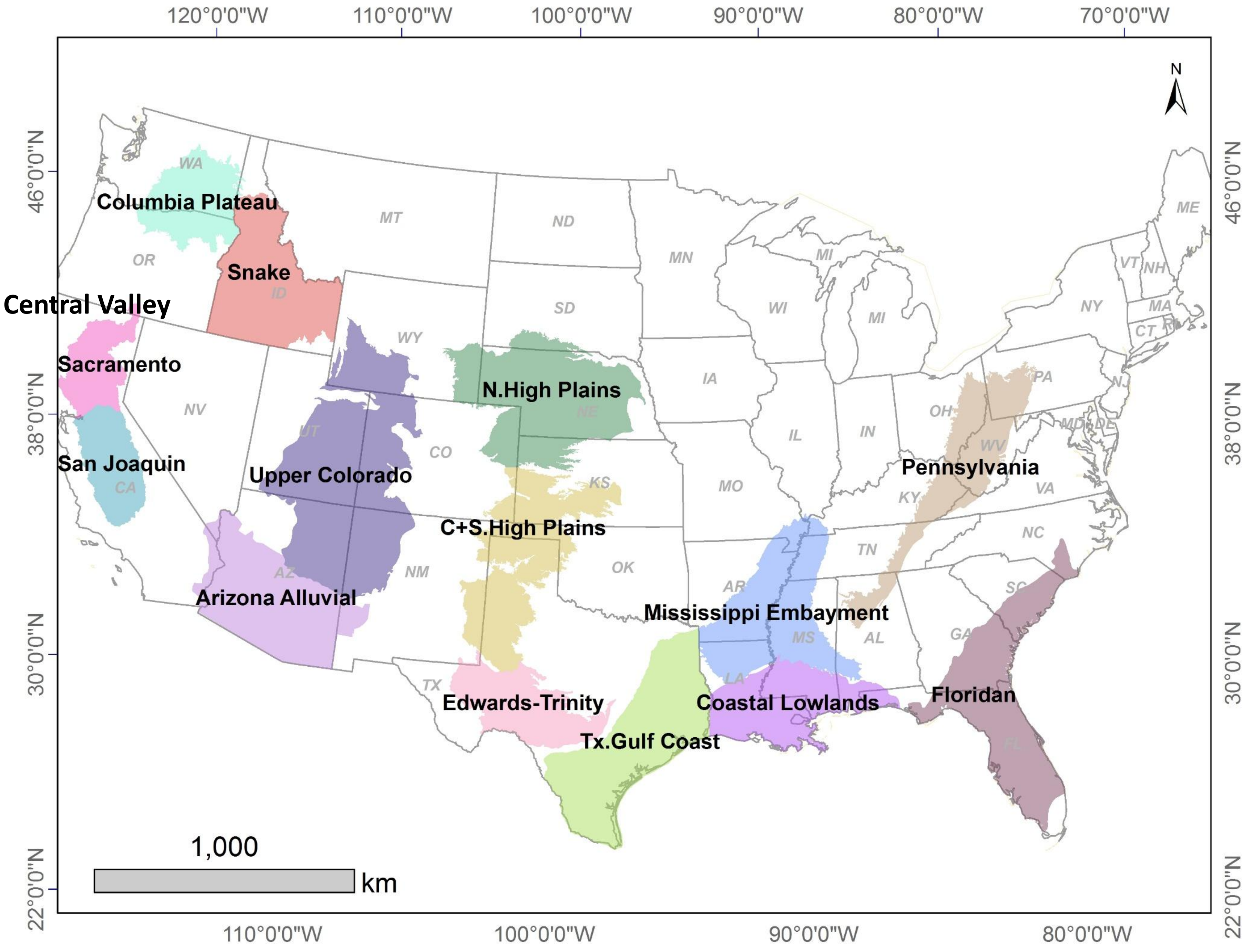
Hussain and Abbas, DE, 2019

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 ≤ 1 m/yr in some areas.
Recharge Pakistan project: GW recharge wells, nature based solutions to recharge aquifer, wetland restoration



Azeem Shah, WRP, 2025



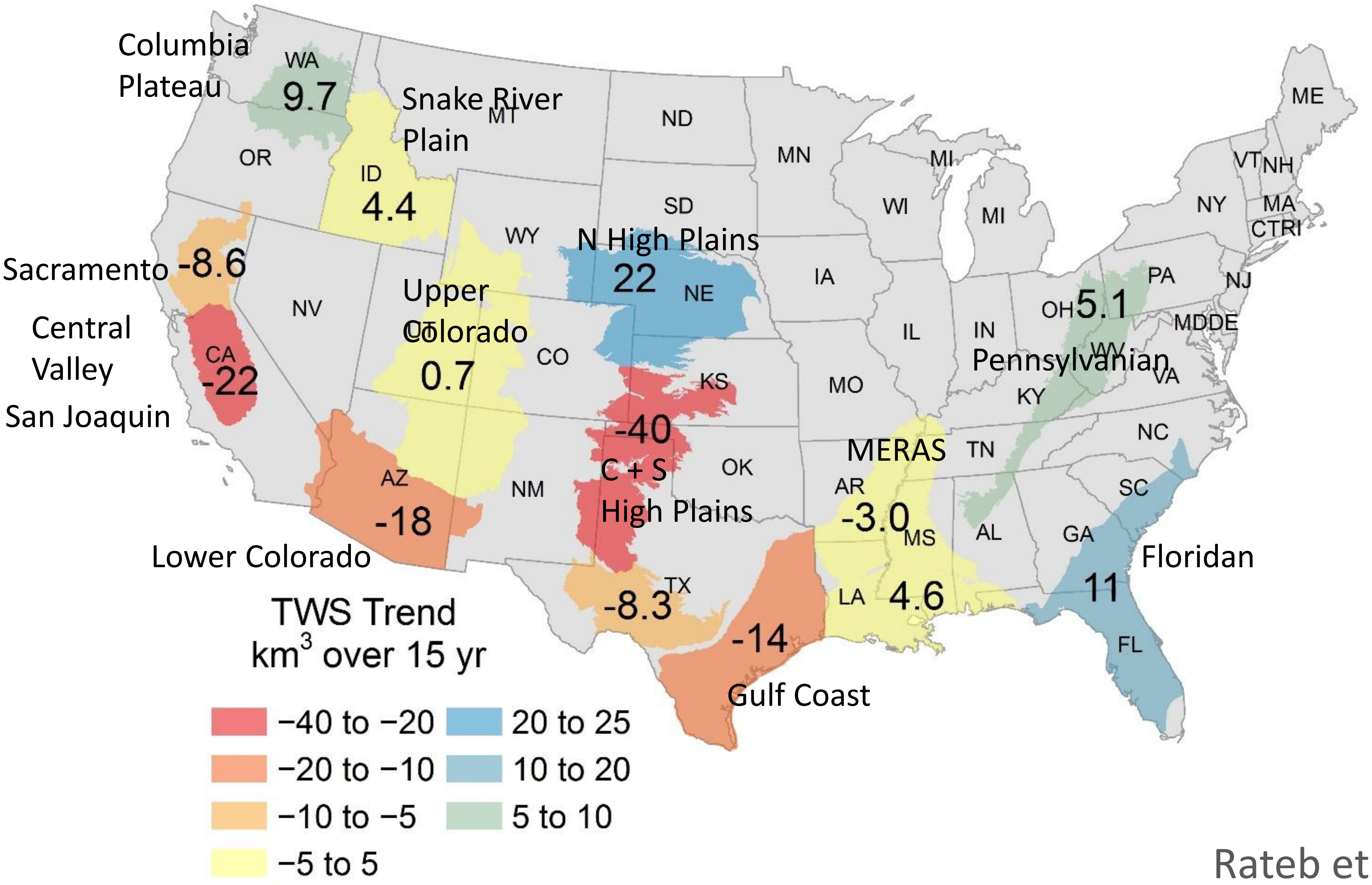
3b. Major Aquifers (14)

Unconfined aquifers
High Plains, AZ Alluvial, Upper Colorado, Snake

Semi-confined aquifers
Columbia & Central Valley:

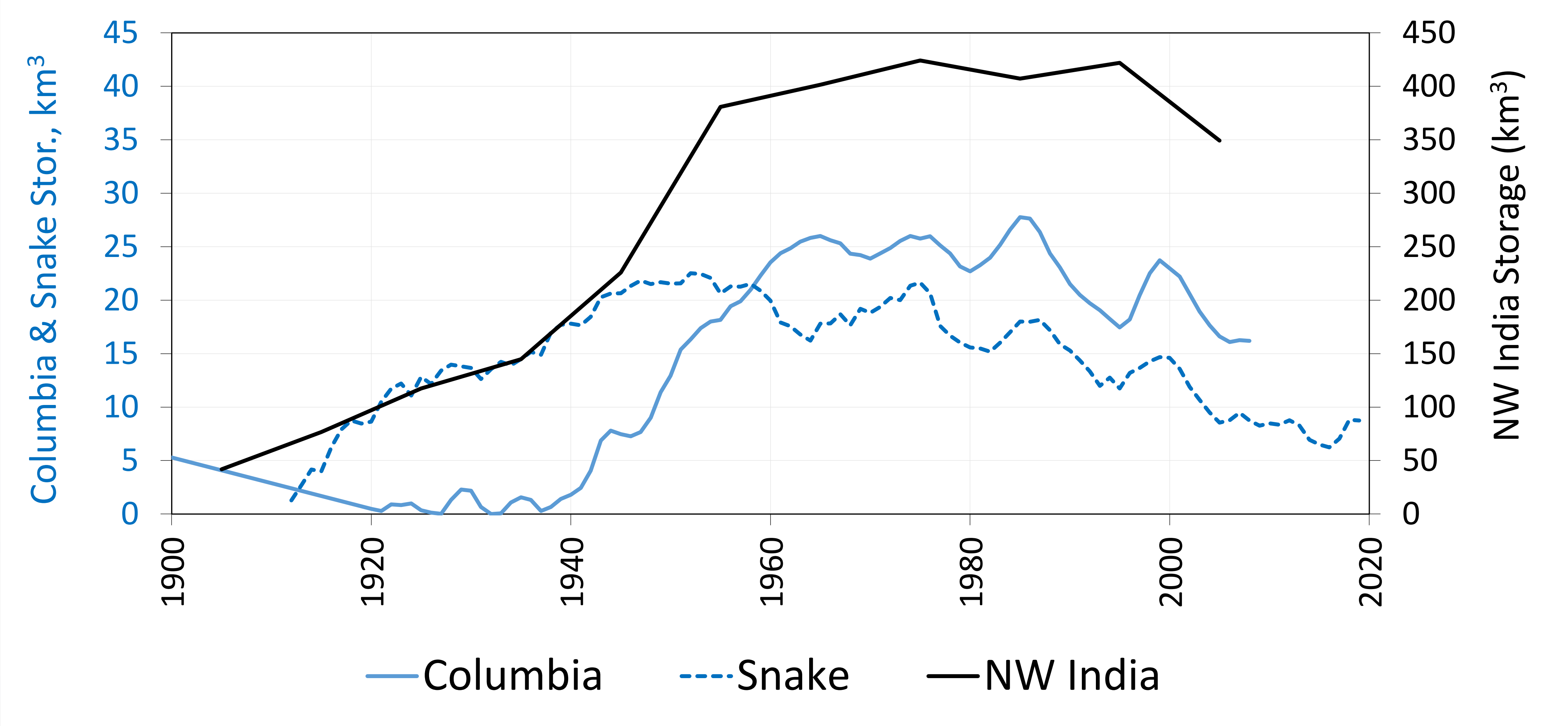
Confined
All other aquifers

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



Rateb et al., WRR, 2021

3b. Long-term Trends in Groundwater Storage



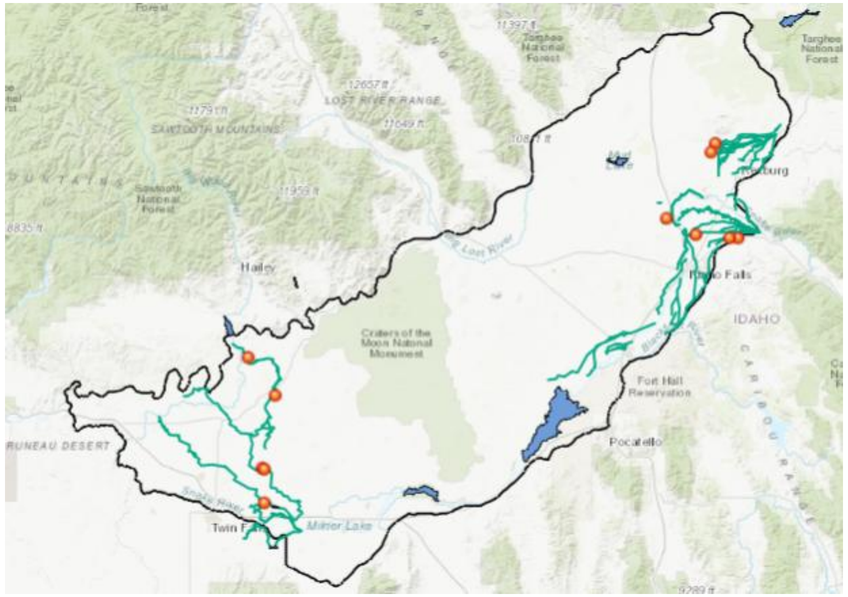
Increases in GW storage attributed to surface water irrigation

Columbia and Snake River Basins, NW US

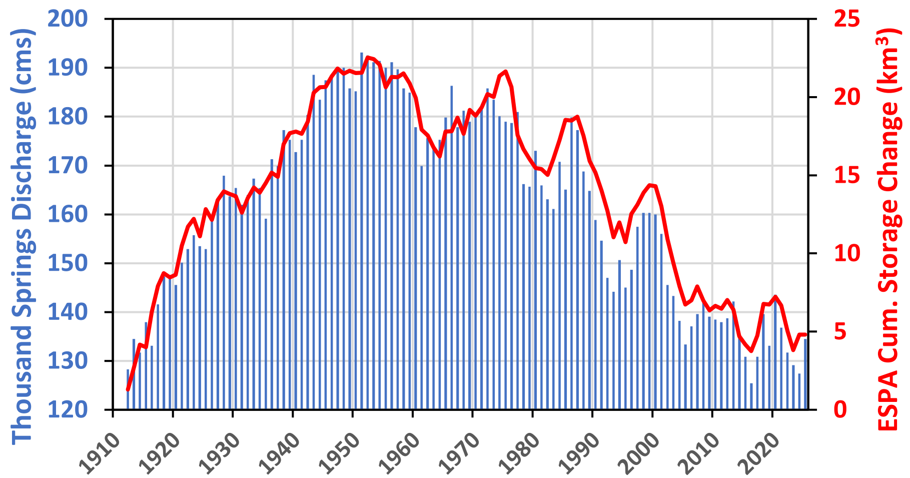
Scanlon et al., 2022

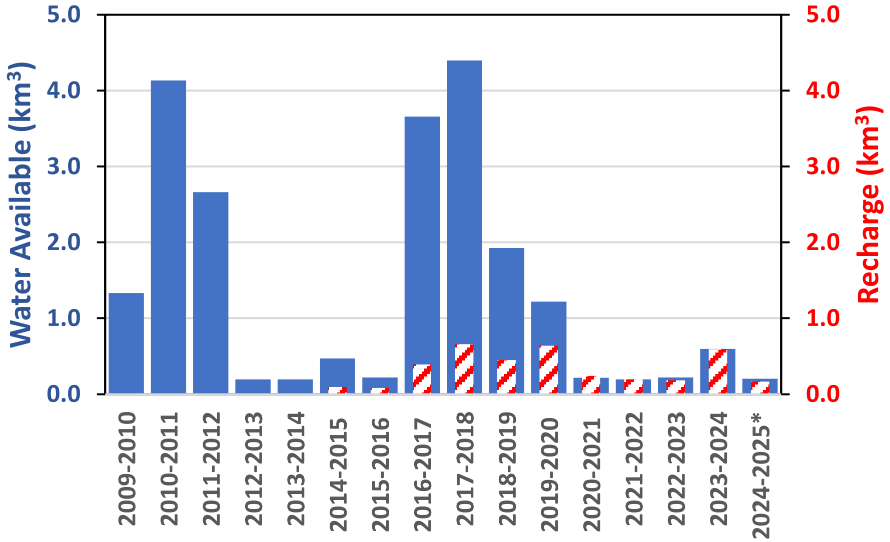
3b. Eastern Snake Plain Aquifer Recharge

Managed Aquifer Recharge Projects



Egin Lakes Recharge project



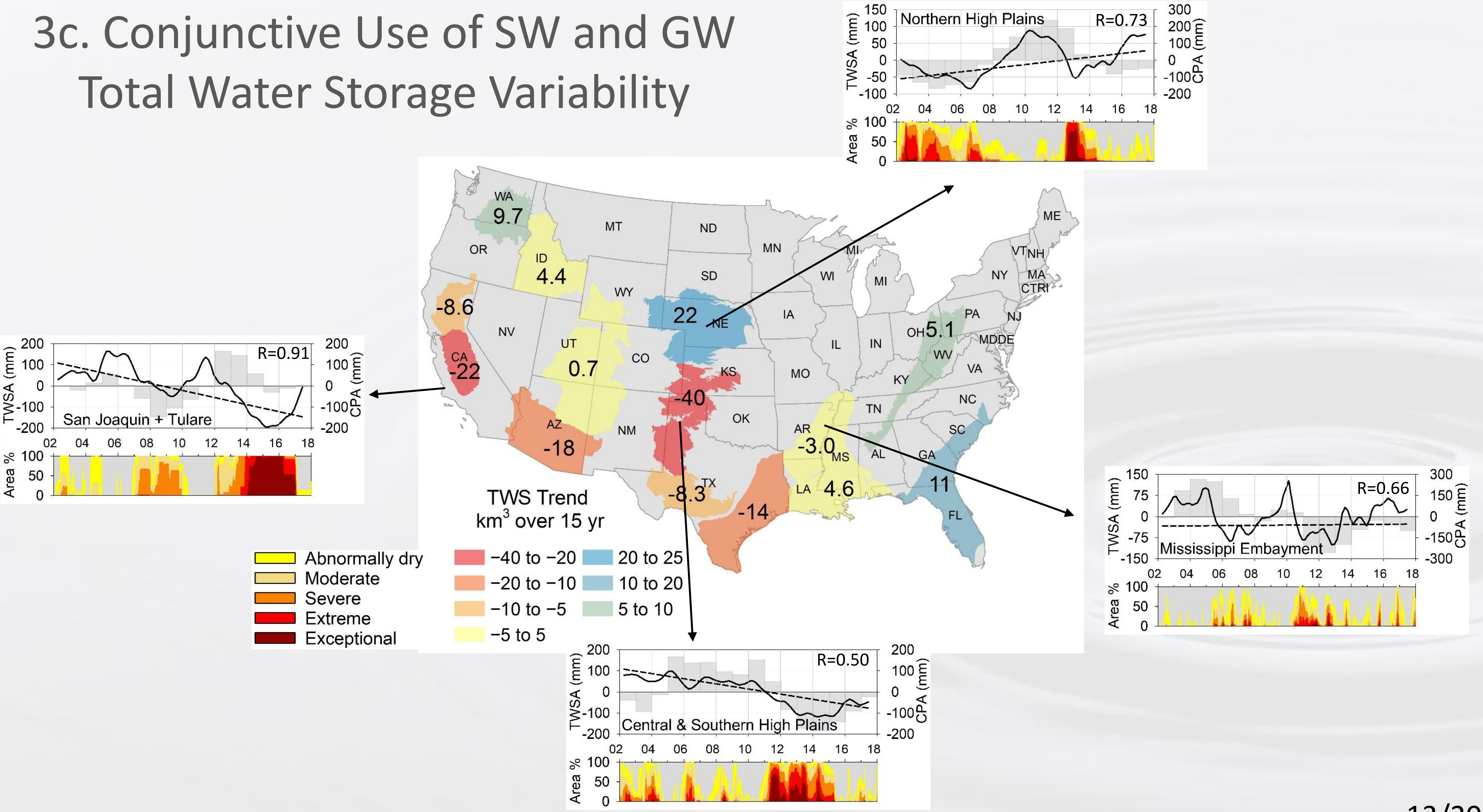


Irrigation infrastructure

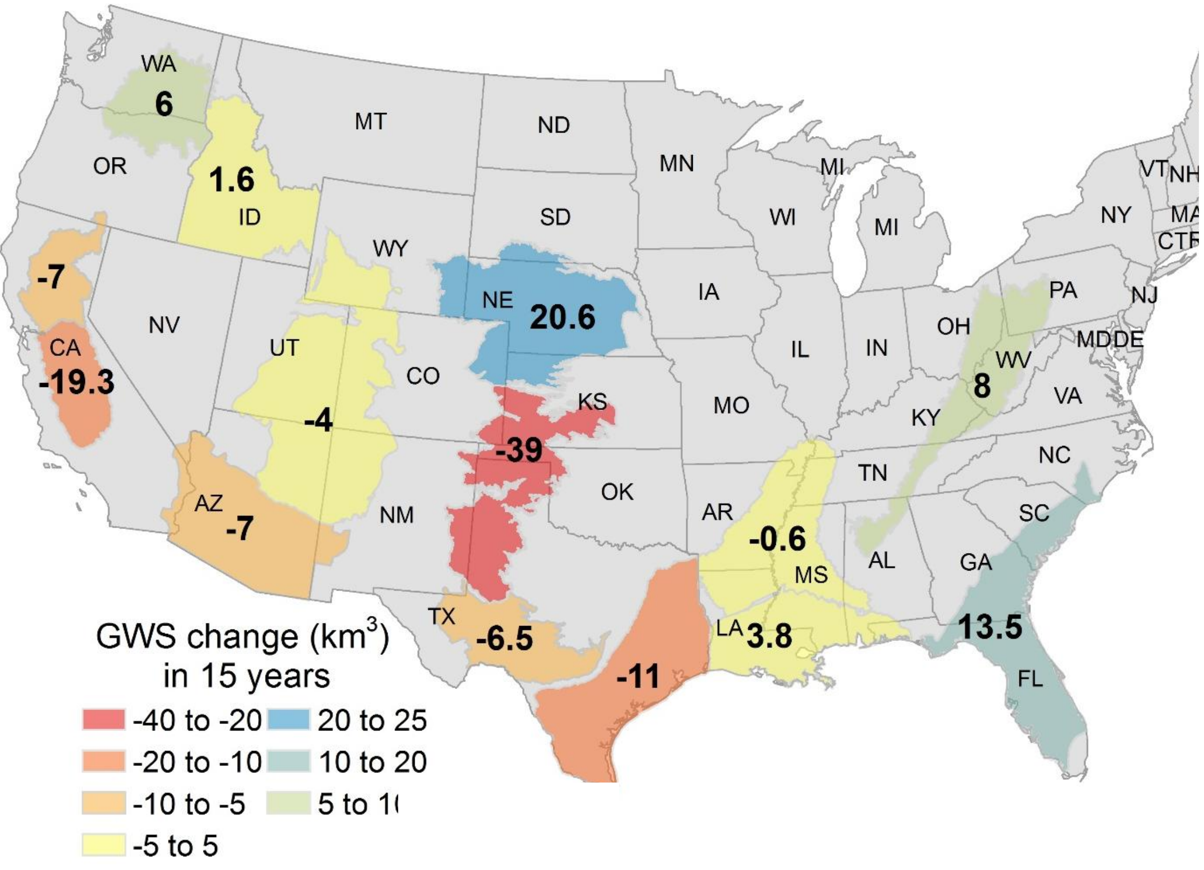
Hikpe et al., GW, 2022

http://idwr.idaho.gov/water-data/projects/espam/

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

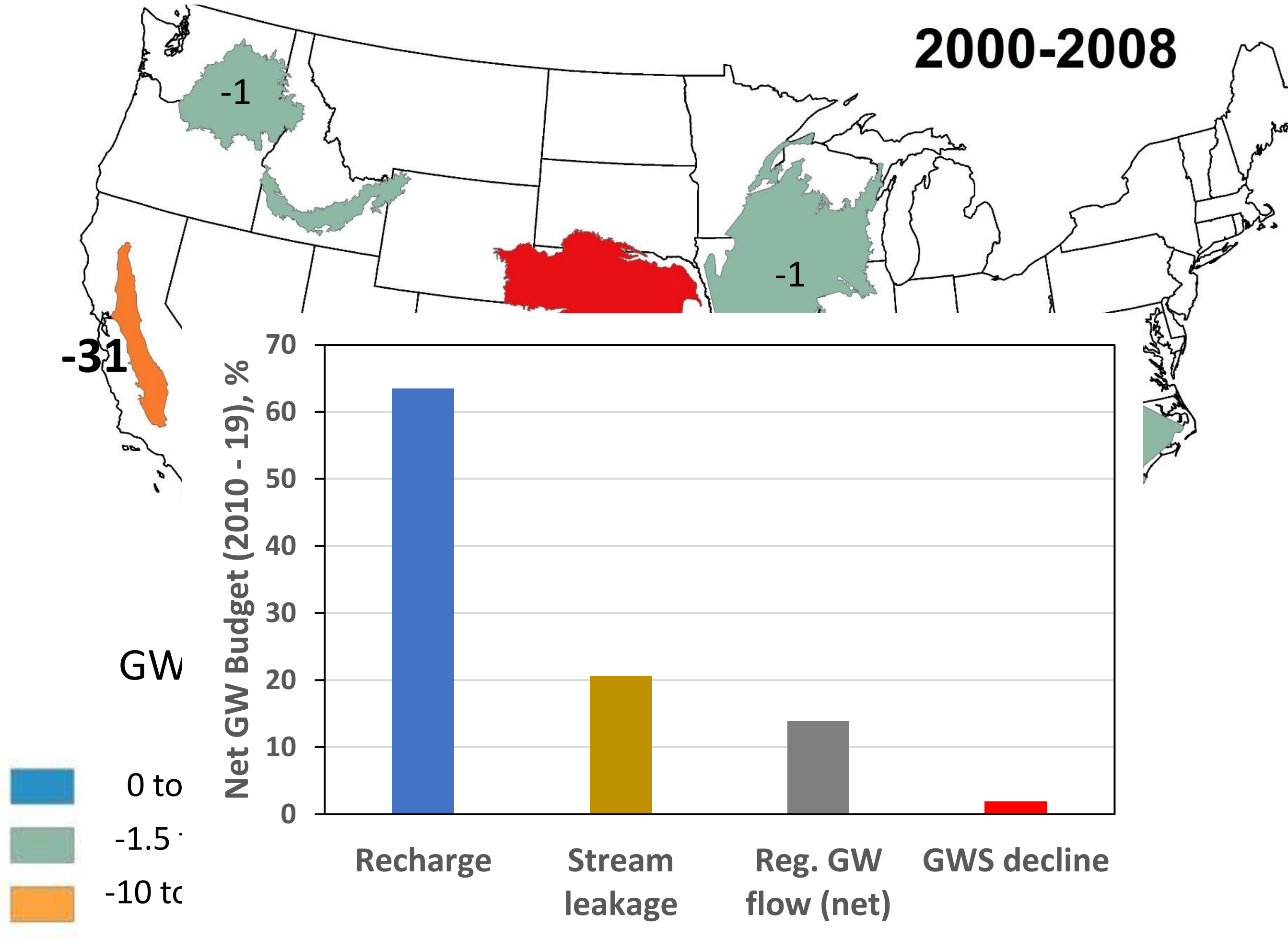


GW Storage Change GRACE (2002 – 2017)



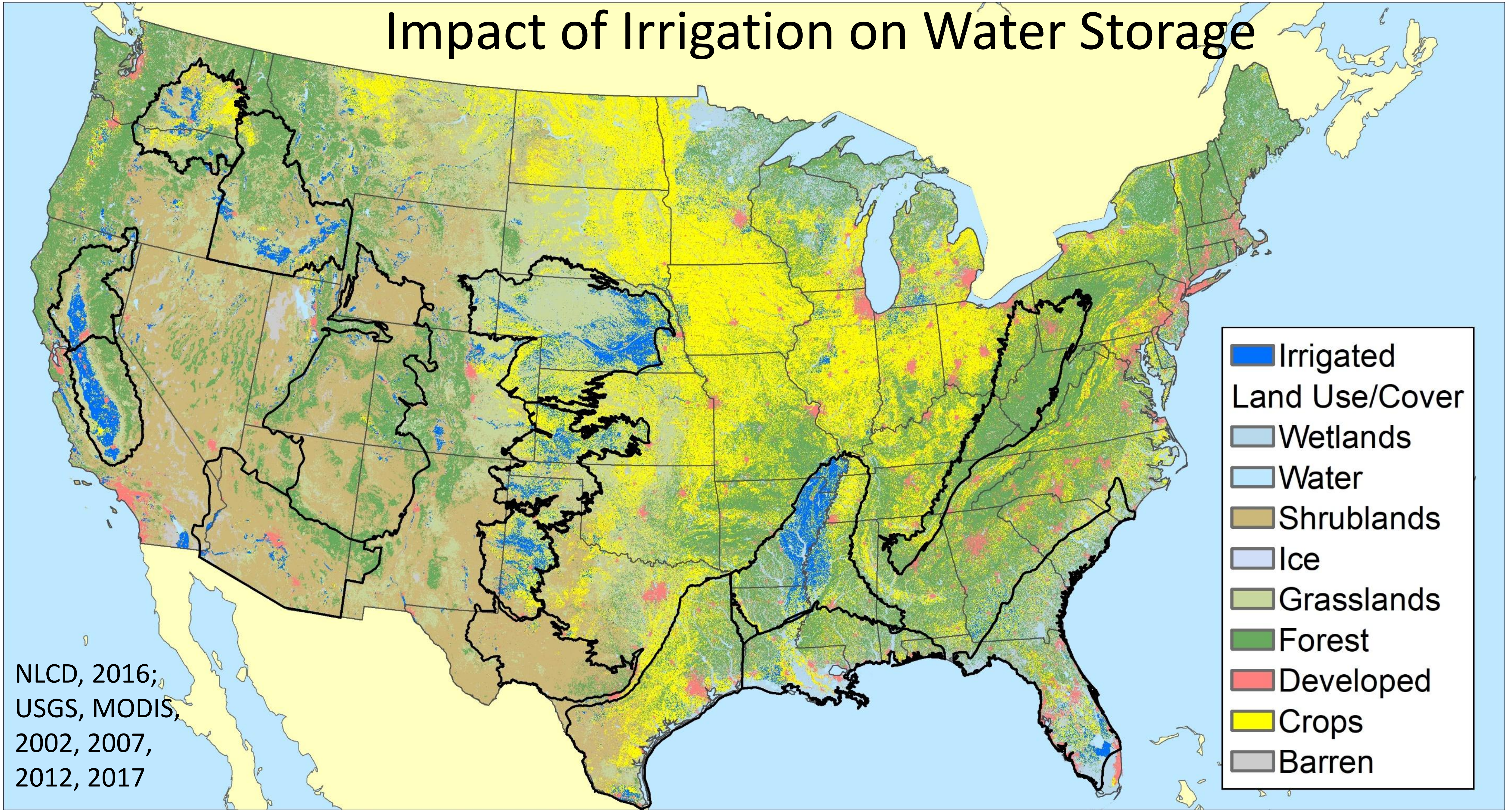
Rateb et al., 2020

GW Storage Change Regional Models and Monitoring

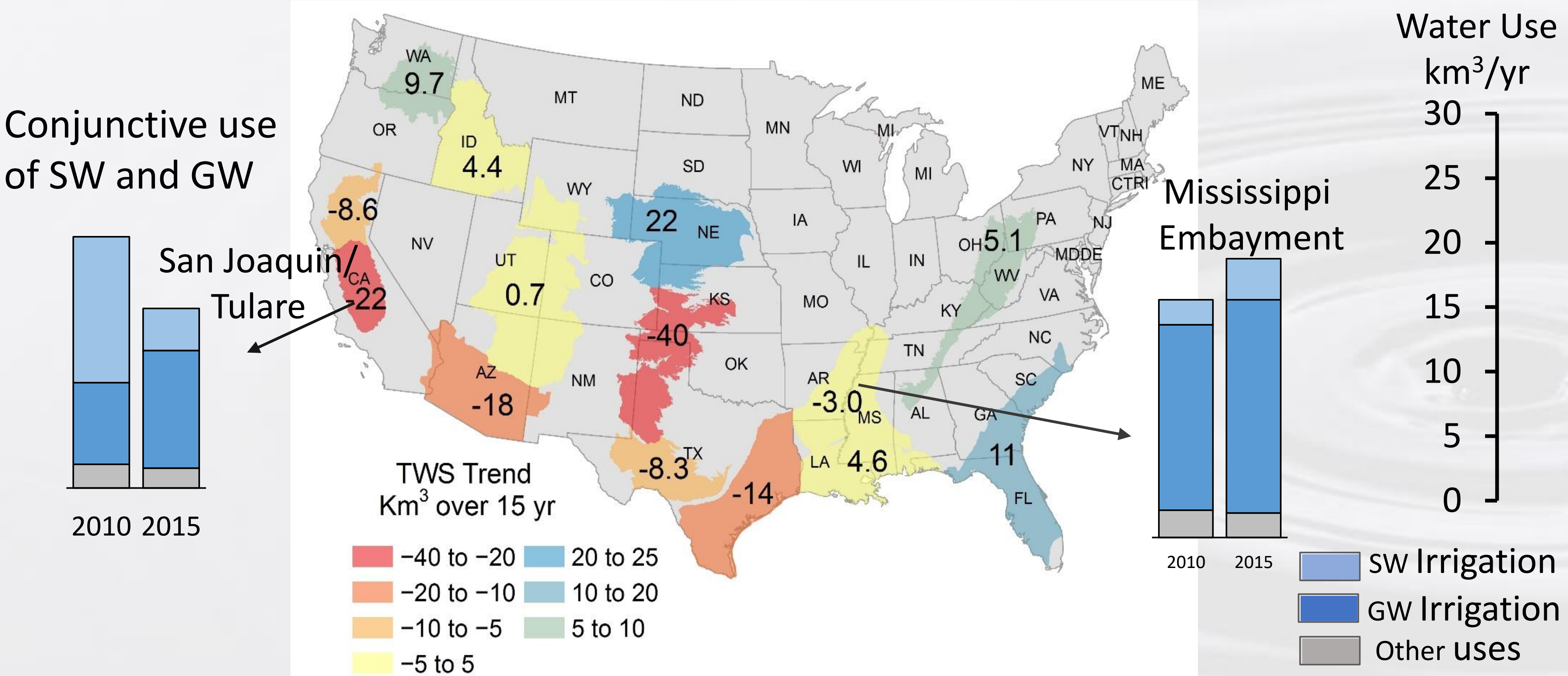


Konikow et al., 2011

Impact of Irrigation on Water Storage



3c. Irrigation Water Use



2010: wet year: 70% SW

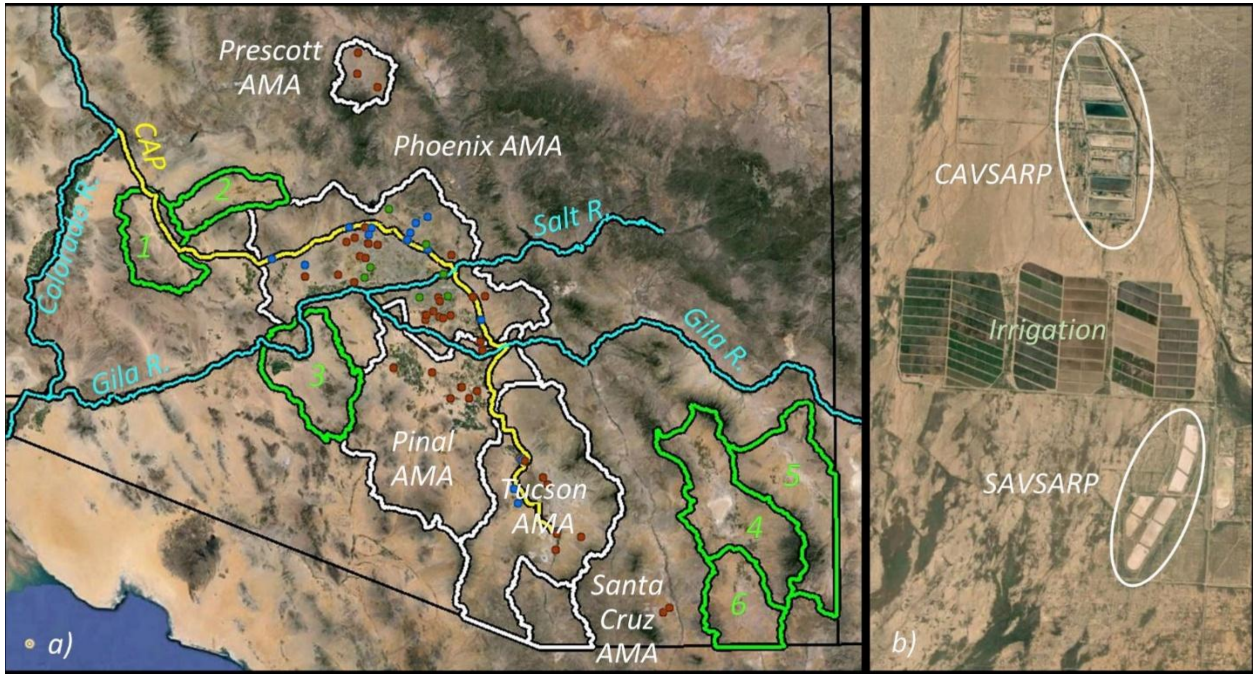
2015: drought: 70% GW

Scanlon et al., ERL, 2021

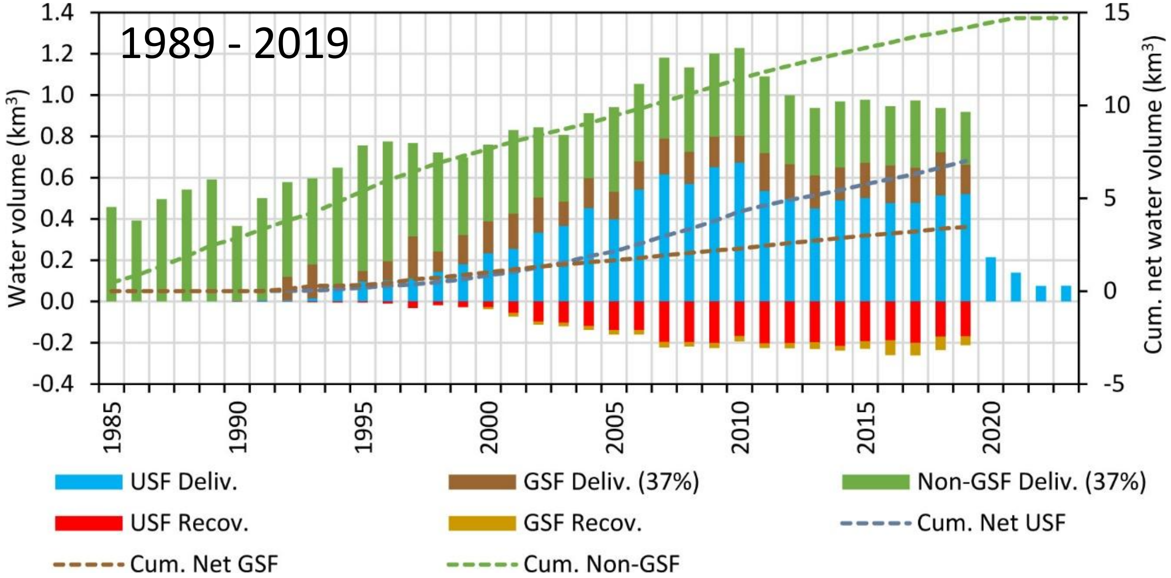
3d. Managed Aquifer Recharge: Arizona Alluvial Valley

Central AZ Project (CAP)
Active Manag. Areas (AMAs)

USF:
Spreading basins



Recharge in Active Management Areas

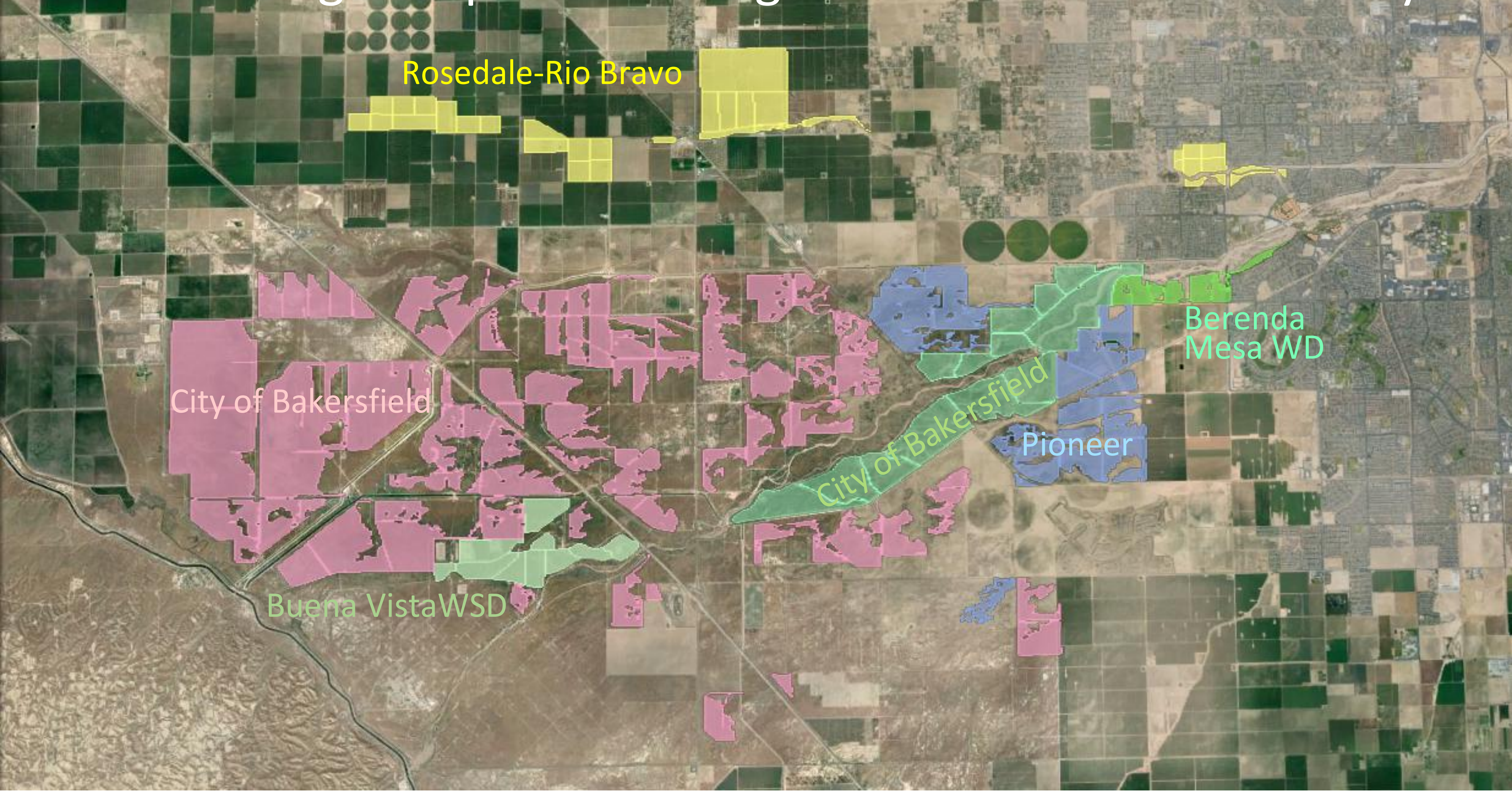


Arizona: **Pump and Replenish**
Pumping GW and replenishing it with MAR is 1000 × less expensive that developing SW treatment plant

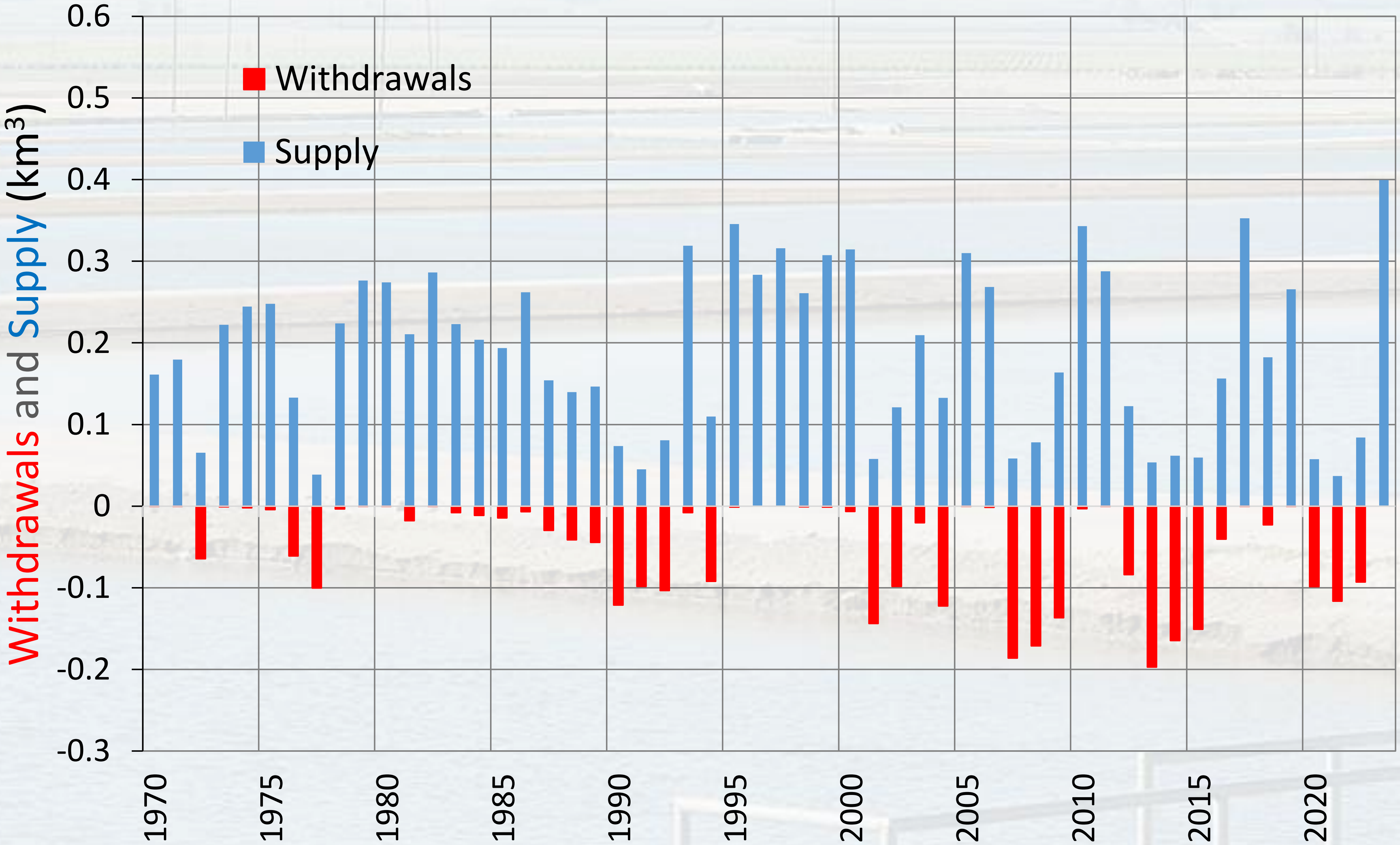
USF: Underground Storage Facilities: 7.0 km^3
GW Savings Facilities: 3.5 km^3 (Switch GW → SW)
Incidental Recharge: 14.2 km^3 (SW irrigation)

Scanlon et al., NCEE, 2025

3d. Managed Aquifer Recharge in California Central Valley

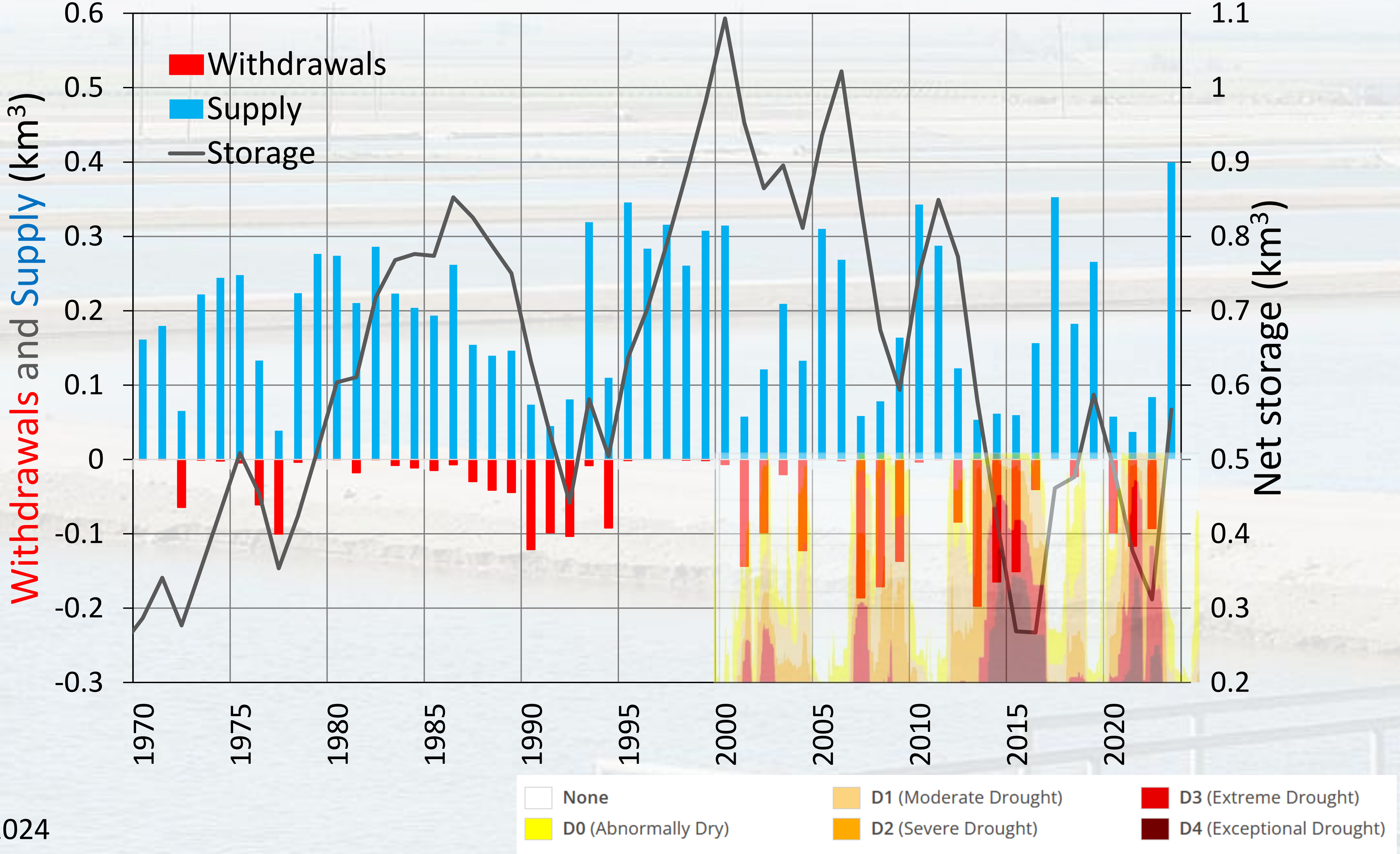


3d. Water Budget in **Arvin Edison** Irrigation District, Central Valley, California



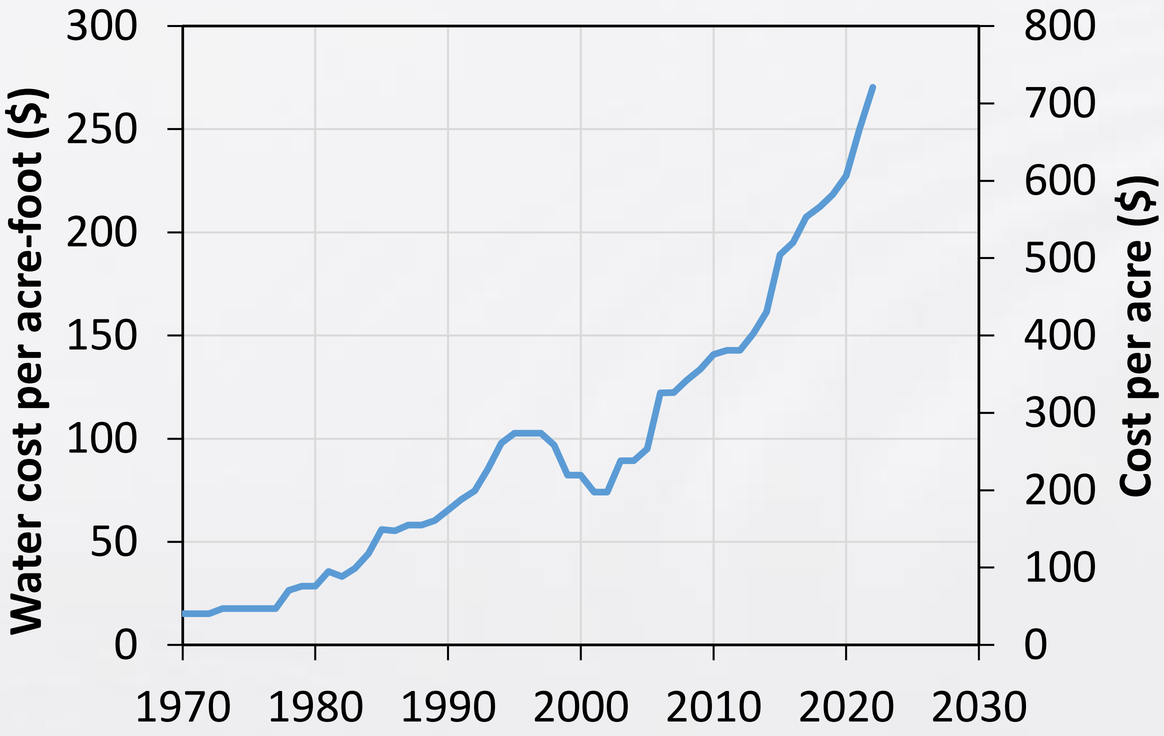
AEWSD Rept. 2024

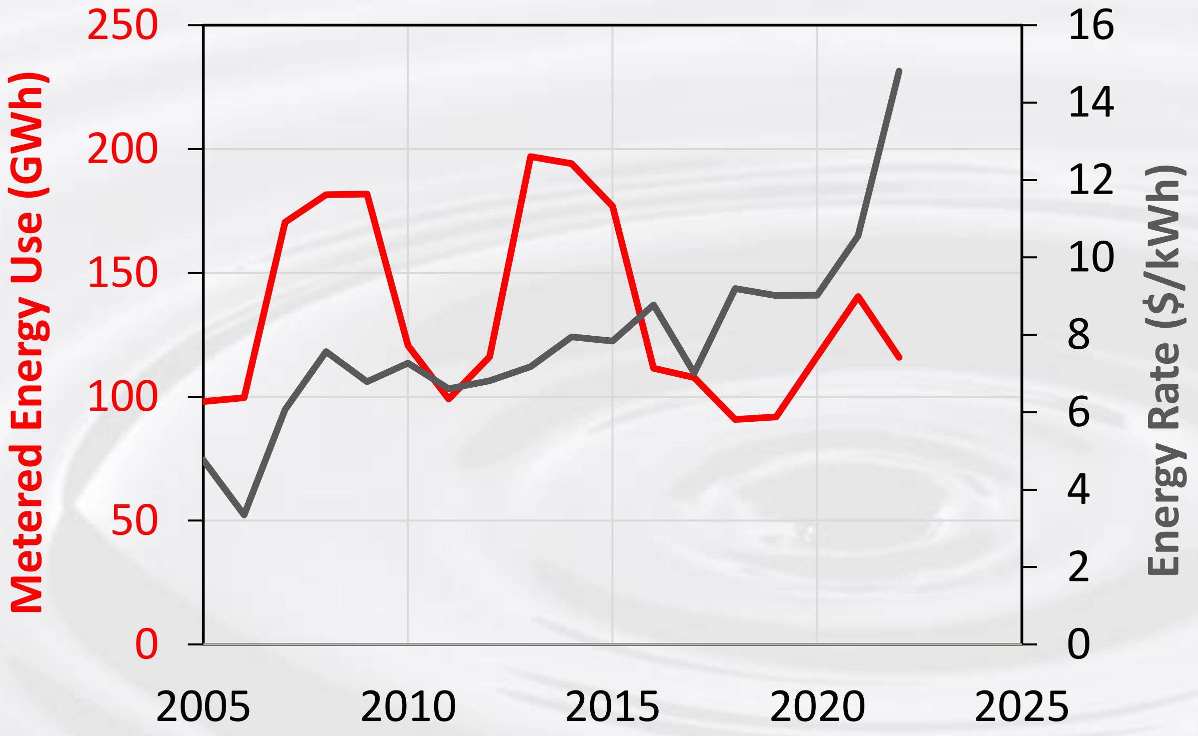
3d. Water Budget in **Arvin Edison** Irrigation District, Central Valley, California



AEWSD Rept. 2024

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

AEWSD Rept. 2024

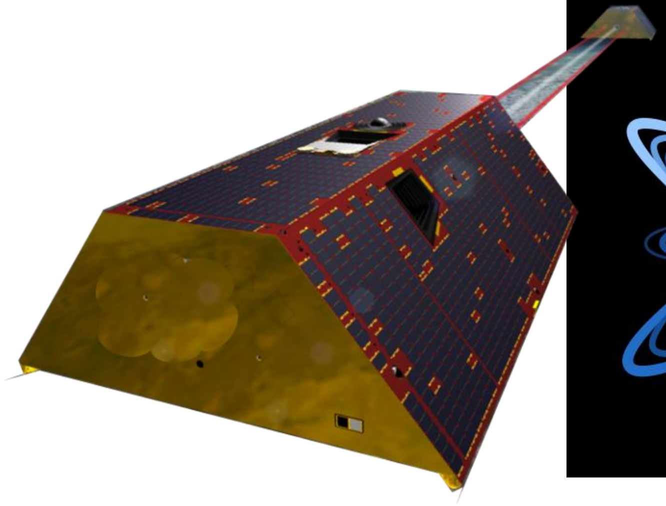
GRACE Continuity (GRACE-C)

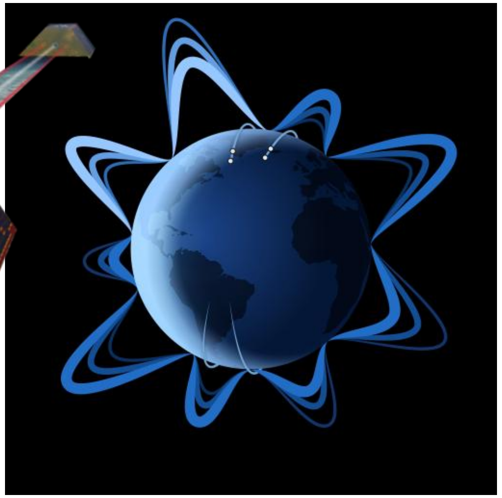
Jet Propulsion Laboratory
California Institute of Technology

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, 89º 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

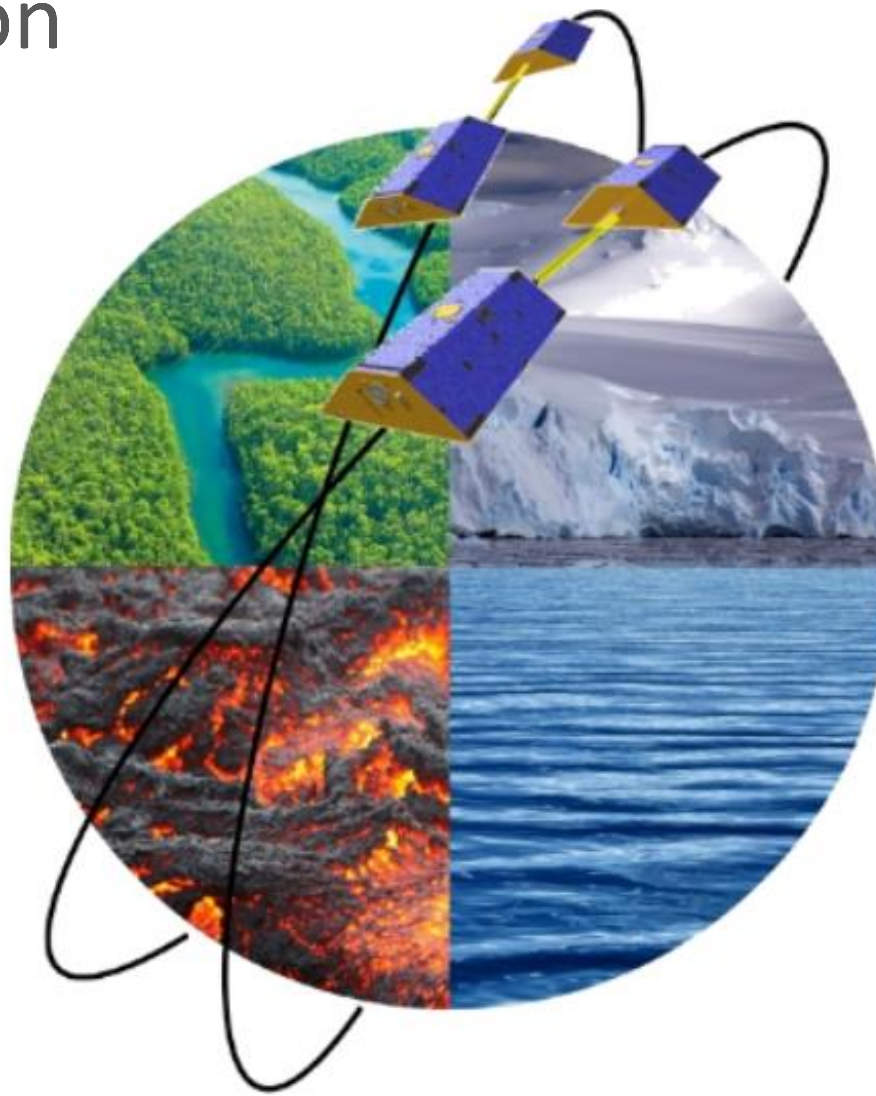
Resolution:

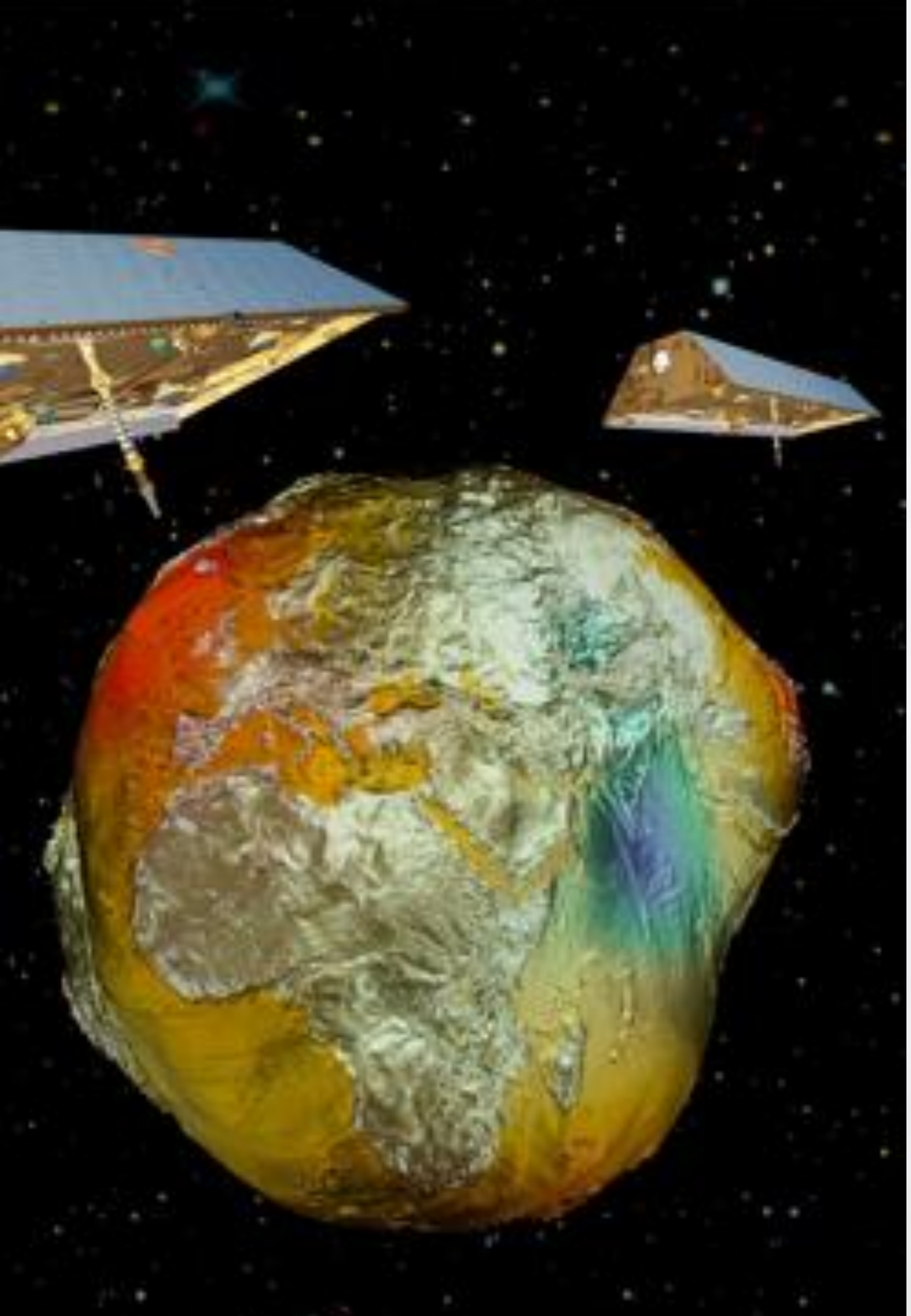
400 km elevation, 70° inclination

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 km^2 to 40,000 km^2)

GOCE satellite: 250 km elevation (2009 – 2013)



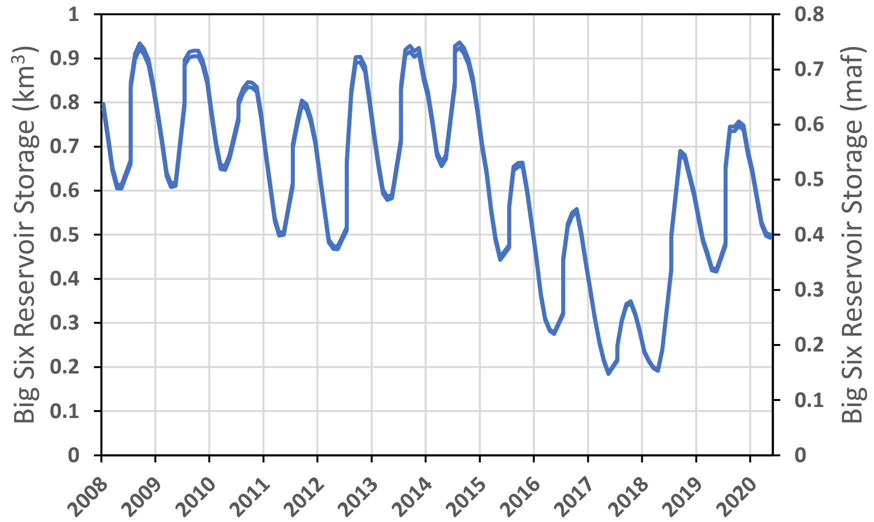


Outline

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

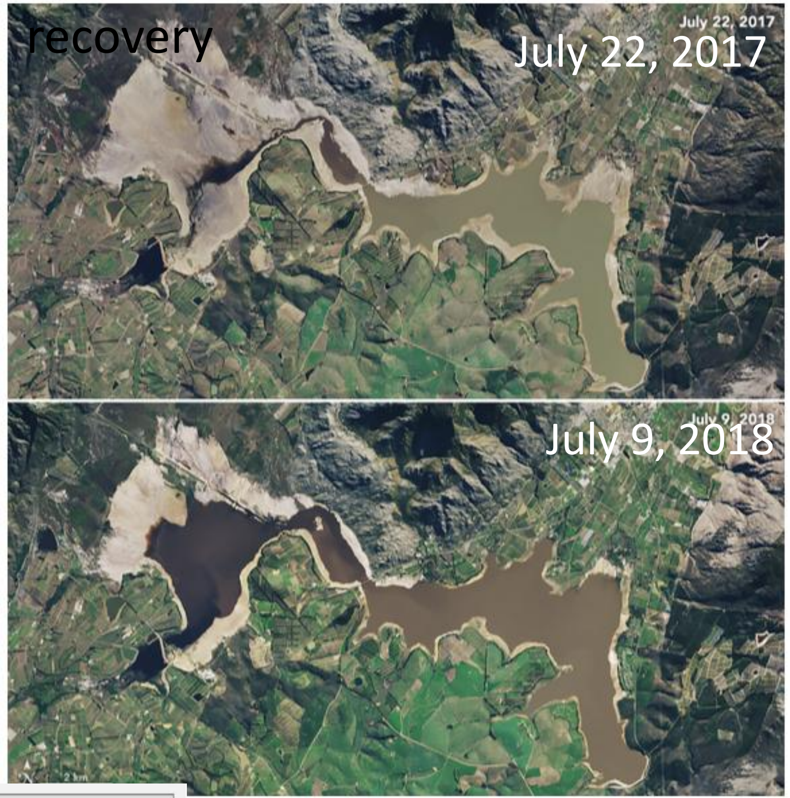


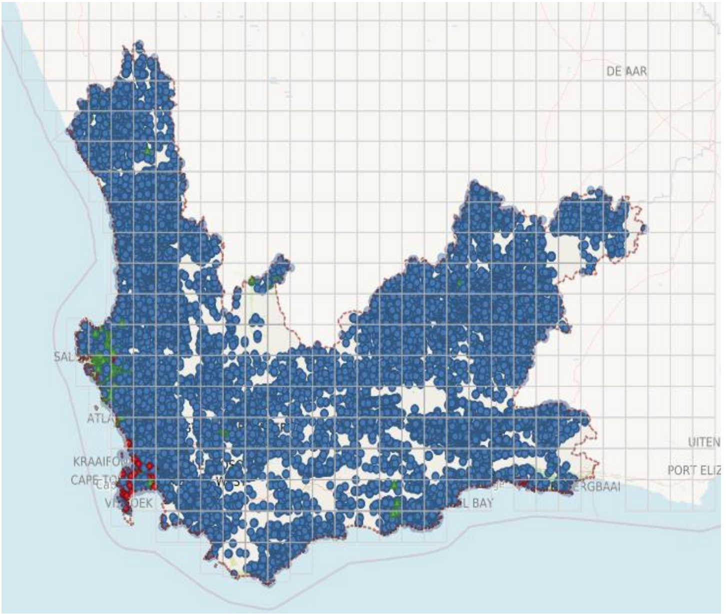
Heavily reliant on SW

Reservoir storage ↓

90% (2014), 50% (2015), 20% (2017)

Theewaterskloof Reservoir: recovery

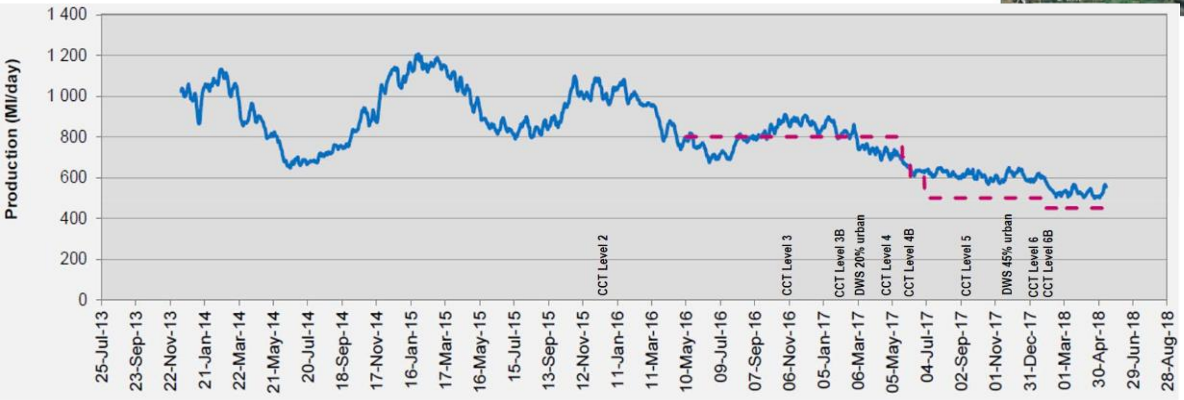




Expansion of GW:

Hundreds of boreholes drilled

Dept. Water and Sanitation: encouraged households to drill GW wells, Non-revenue water



↓ demand

1200 MLD (2015) to

500 MLD (Jan 2018)

Agriculture highly impacted:

3000 jobs lost, 44% ↓ in yield.

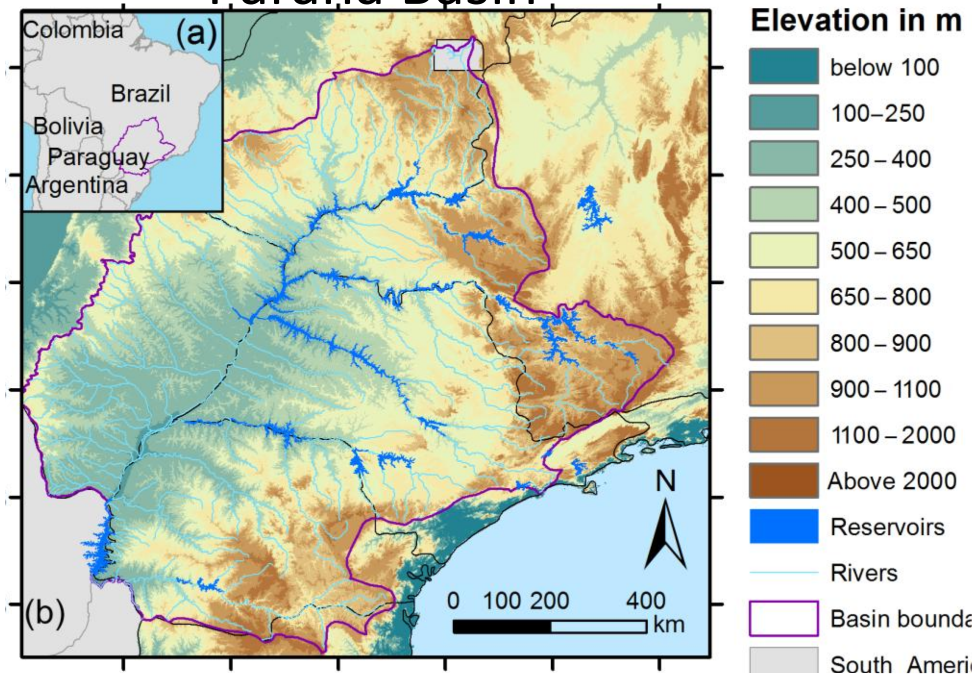
No compensation for farmers.

Livable Urban Waterways:

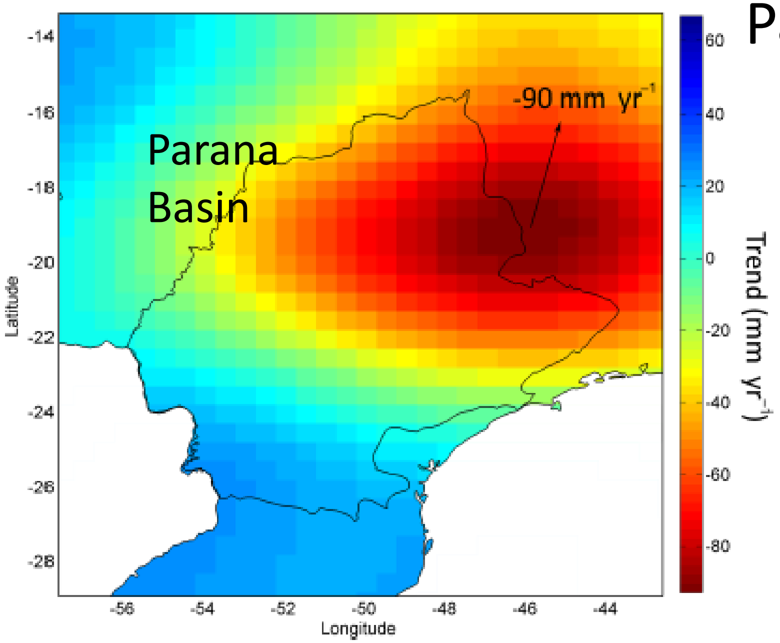
GEOSS project

4.0 Sao Paulo Drought

Parana Basin

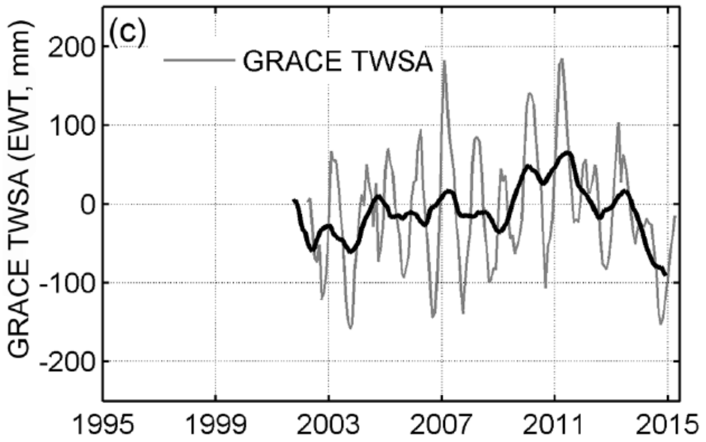


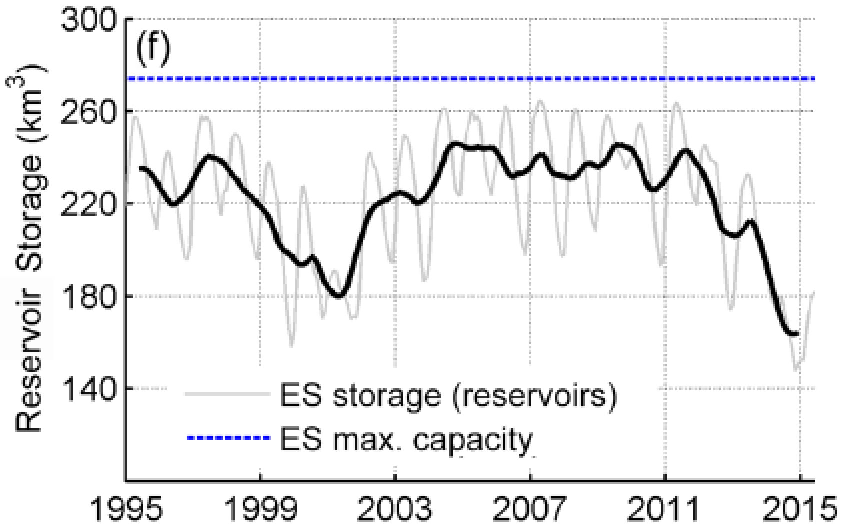
GRACE TWS Anomaly (Apr. 11 – Apr. 2015)



TWS depletion: 148 km^3 total

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





2014 – 2017 drought linked to El Nino
Sao Paulo: SW dominant water source for ~ 20 million people
GW ↑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

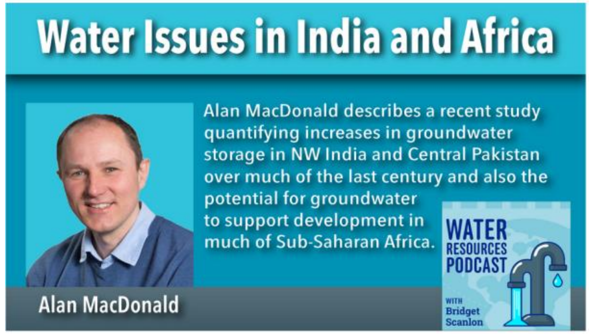
Key Takeaways

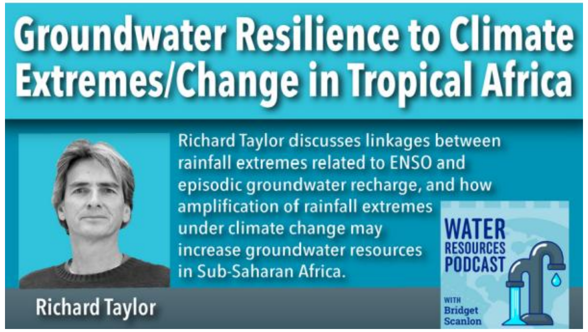
1. **GRACE** data provide global picture of Total Water Storage anomalies but only for 2002 – 2025
2. **Irrigation:**
   a) **↑ GW-fed irrigation in SSA**, switching from native vegetation to cropland ↑ed recharge
   b) **Unmanaged aquifer recharge** is important, inefficient SW irrigation recharges 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

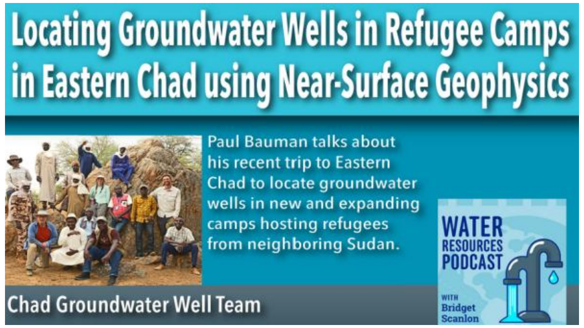
Water Resources Podcast

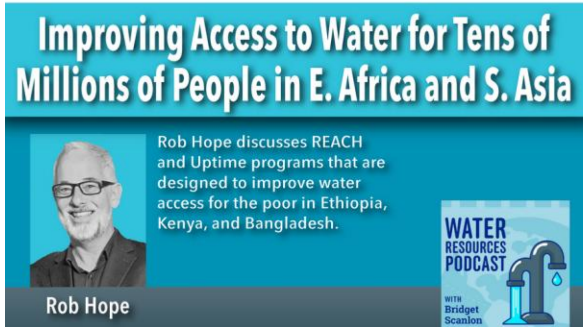
http://wrp.beg.utexas.edu

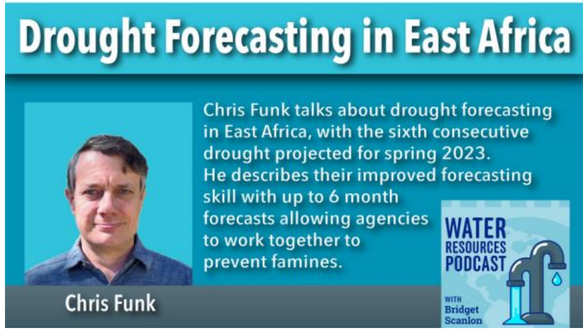
Apple, Spotify etc

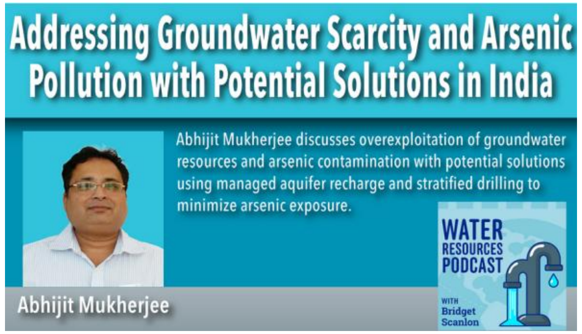


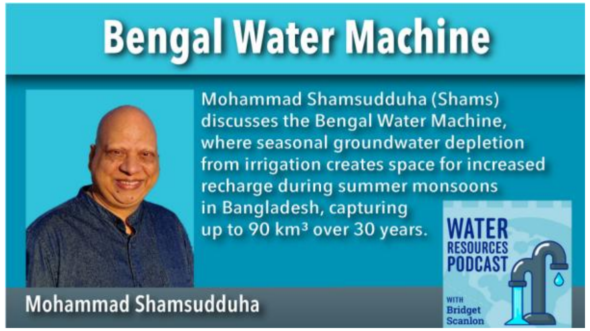


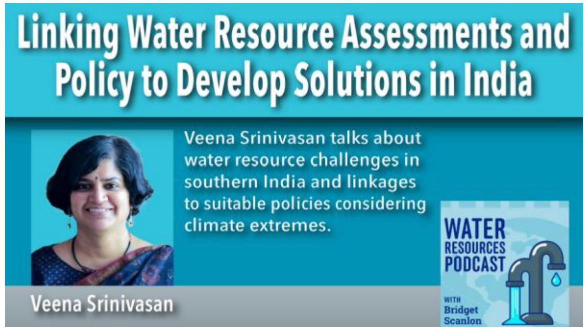


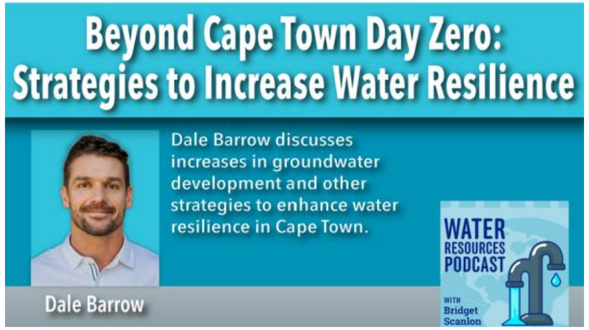


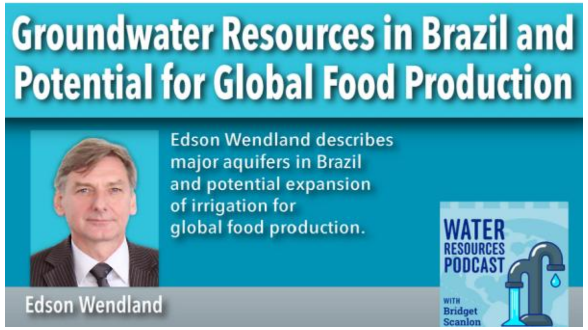


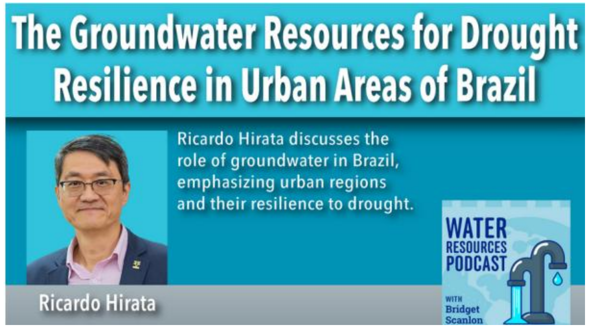












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