

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

Bridget R. Scanlon

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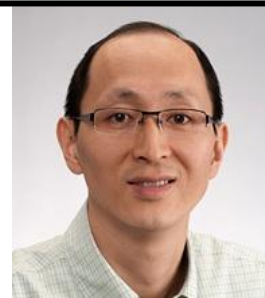


Post-docs
and visitors

Global modelers

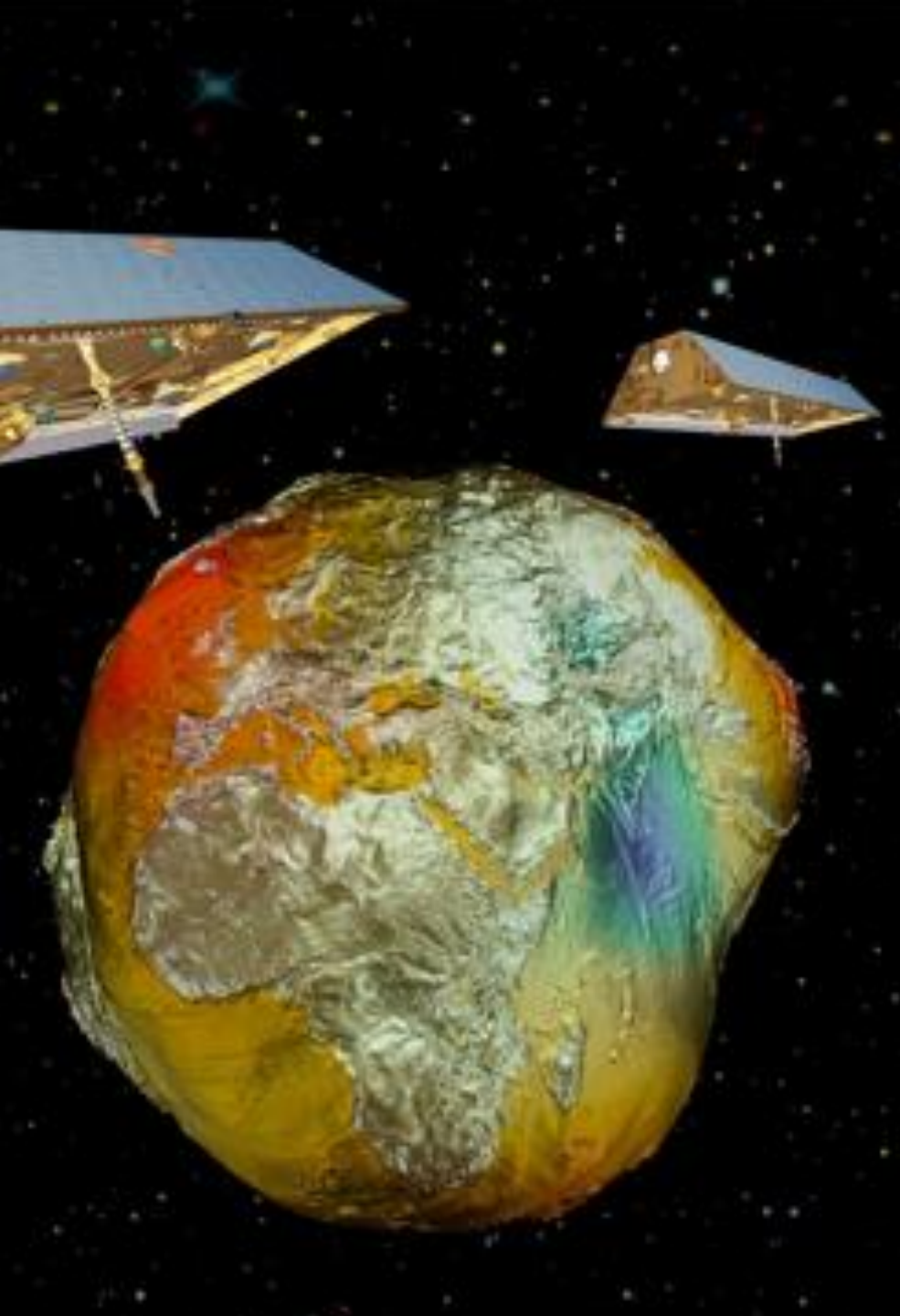


Geodesists



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)

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of all water withdrawn for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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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.**



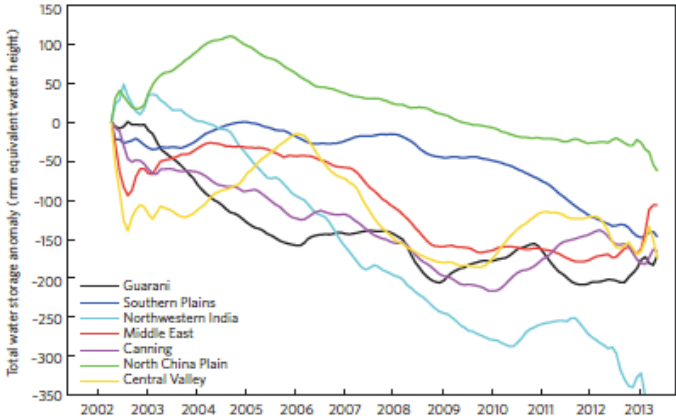
GROUNDWATER CAN PLAY A CRITICAL ROLE IN ADAPTING TO
CLIMATE CHANGE, BUT ONLY IF ACTION IS TAKEN TO PROTECT IT

COMMENTARY:

The global groundwater crisis

J. S. Famiglietti

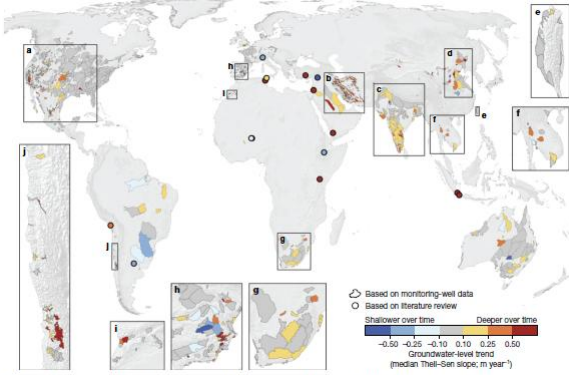
Groundwater depletion the world over poses a far greater threat to global water security than is currently acknowledged.



Rapid groundwater decline and some cases of recovery in aquifers globally

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

Scott Jasechko^{1,2,3,4}, Hansjörg Seybold^{2,3,4}, Debra Perrone^{2,3,4}, Ying Fan⁴,
Mohammad Shamsudduha², Richard G. Taylor², Othman Fallatah^{2,3} & James W. Kirchner^{2,3,4}



nature sustainability

Article

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

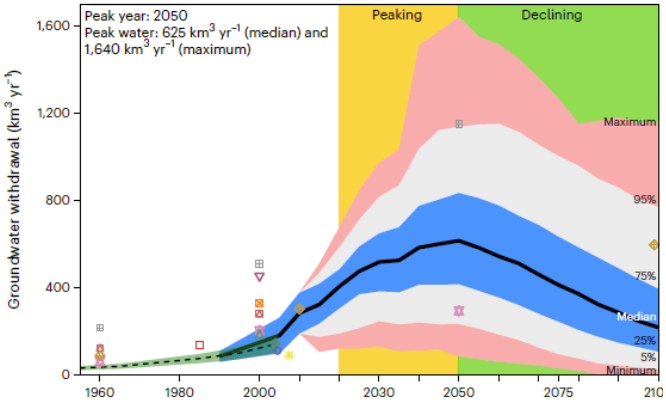
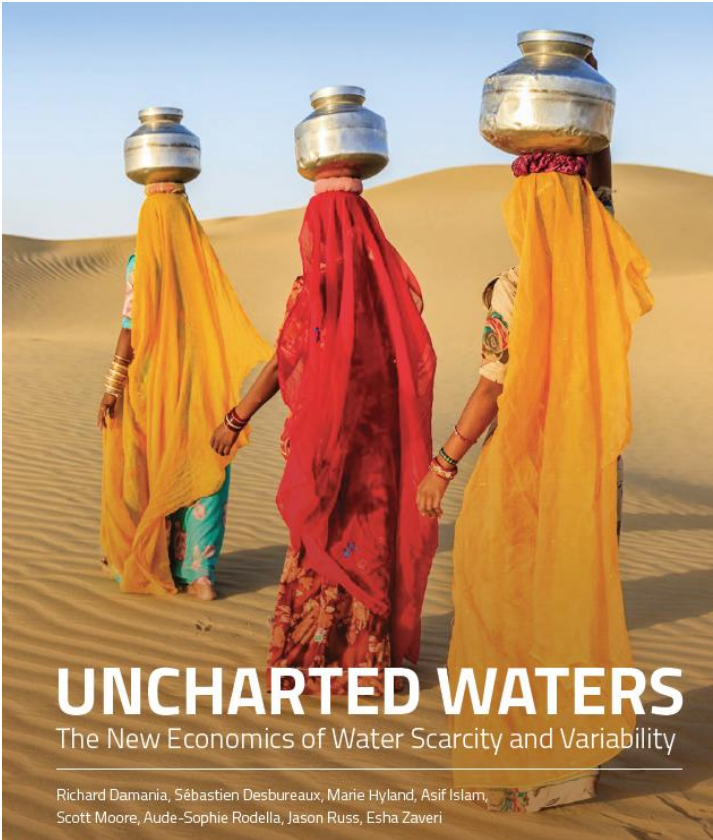
Global peak water limit of future groundwater withdrawals

Received: 24 May 2023

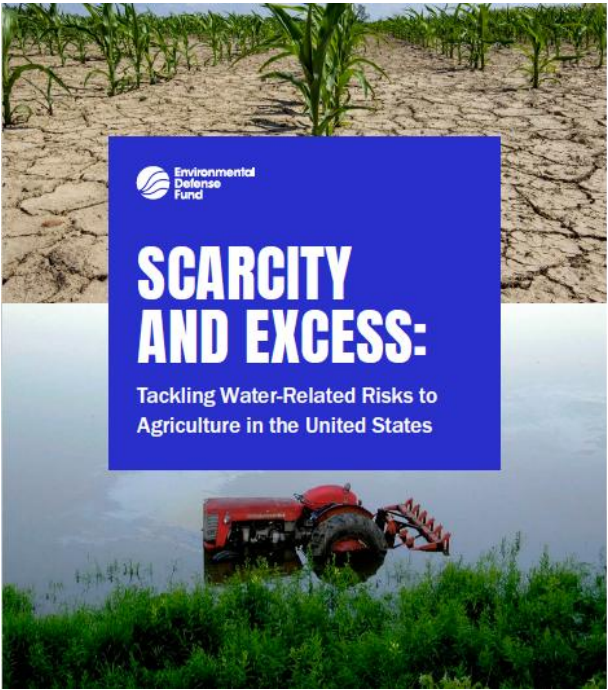
Accepted: 6 February 2024

Published online: 22 April 2024

Hassan Niazi^{1,2,3}, Thomas B. Wild¹, Sean W. D. Turner^{2,3}, Neal T. Graham^{2,3},
Mohamad Hejazi^{2,3}, Siwa Msangi^{2,3}, Son Kim^{2,3}, Jonathan R. Lamontagne^{2,3}
& Mengqi Zhao^{2,3}

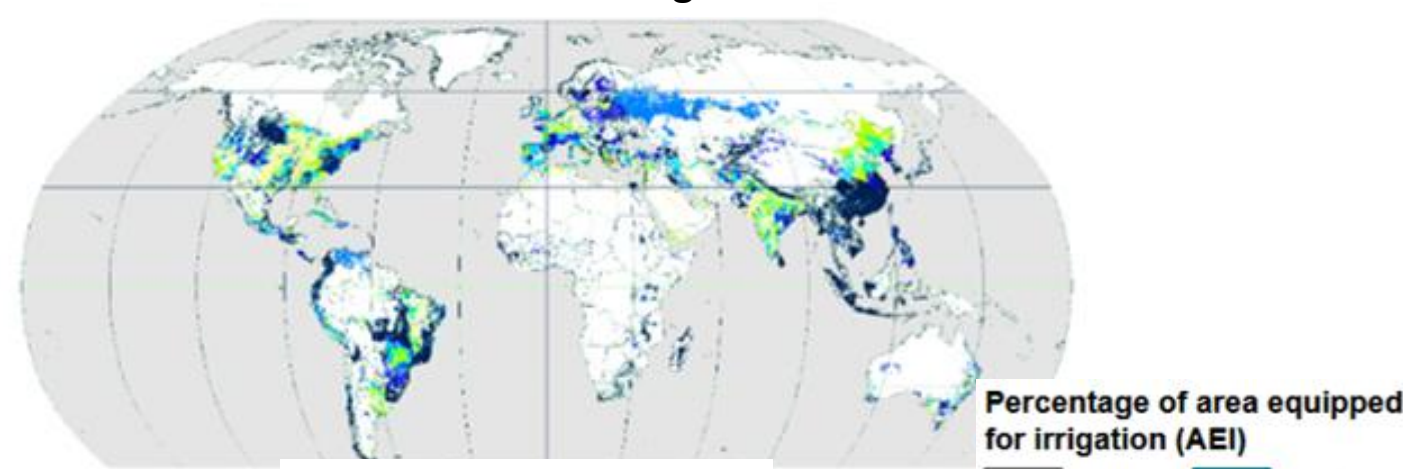


Too much vs too little?

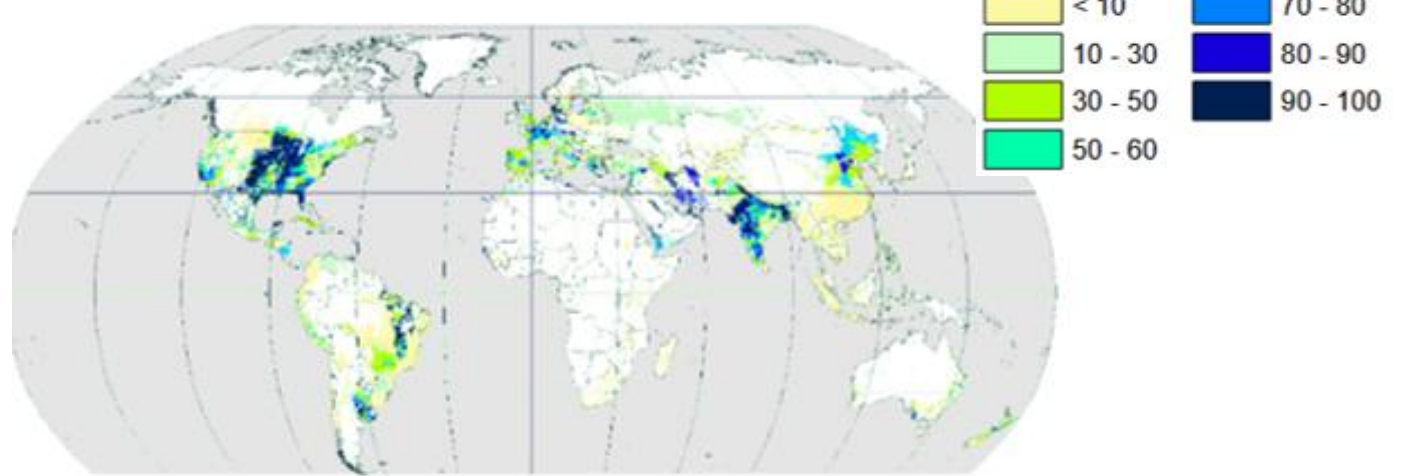


1. Irrigation, Food Production, and Urban Water

Surface Water Irrigation

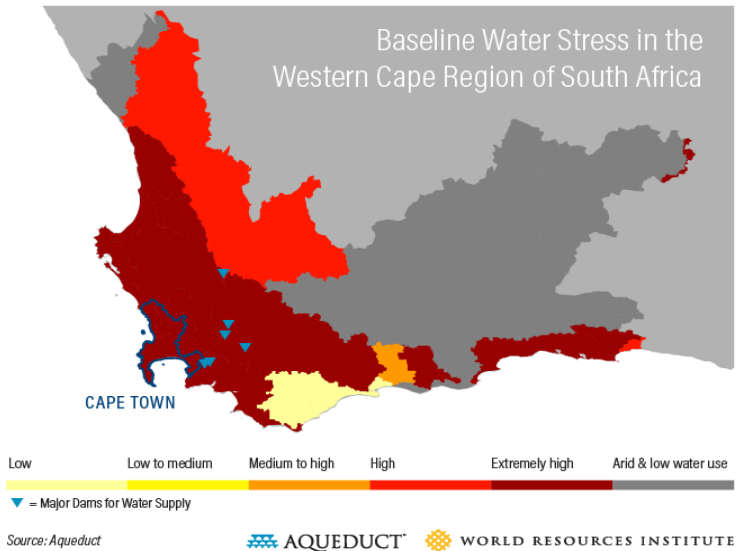


Groundwater Irrigation



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
4/20

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

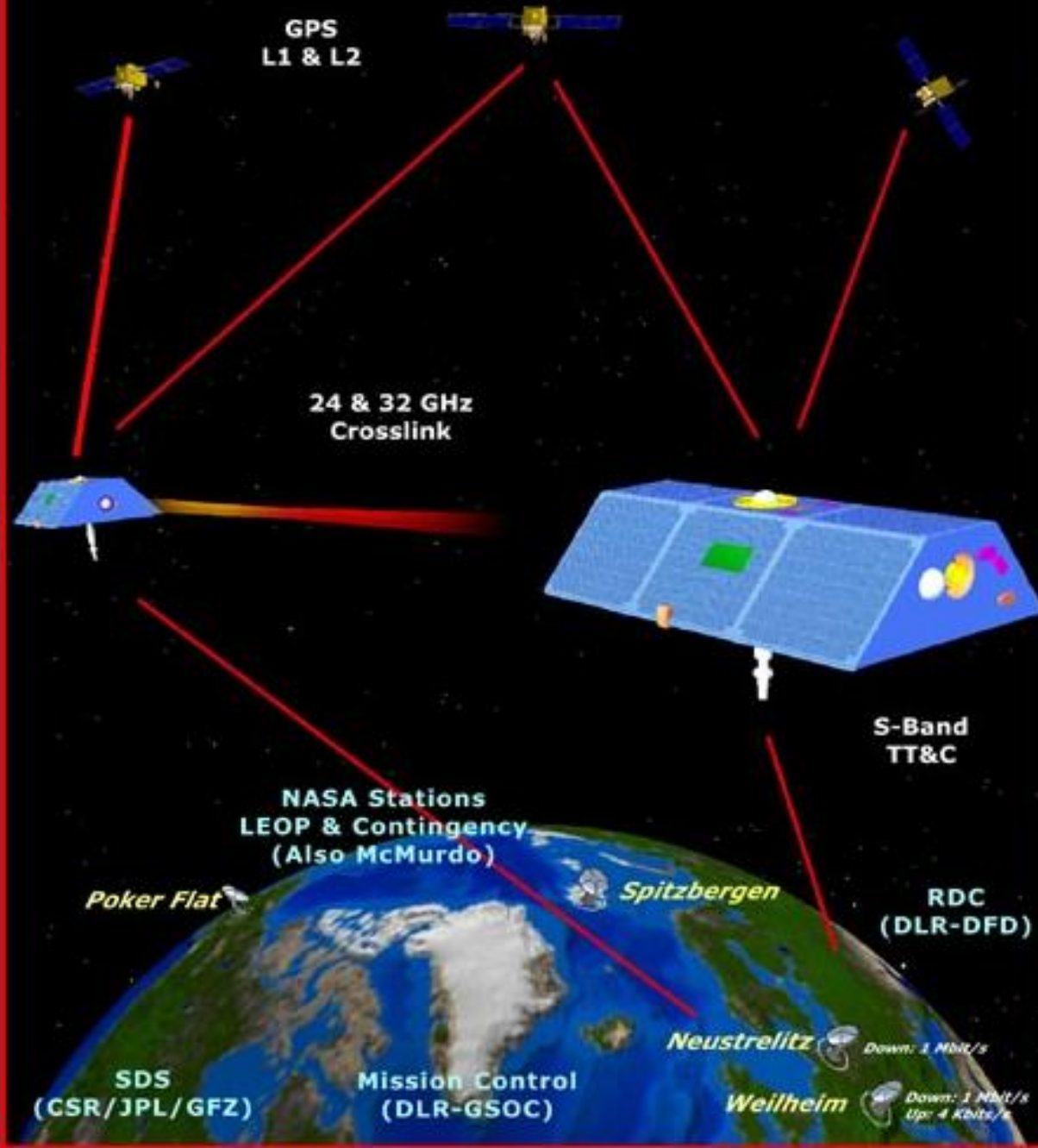
Monthly data

1 gigaton mass change = 1 km³ of water

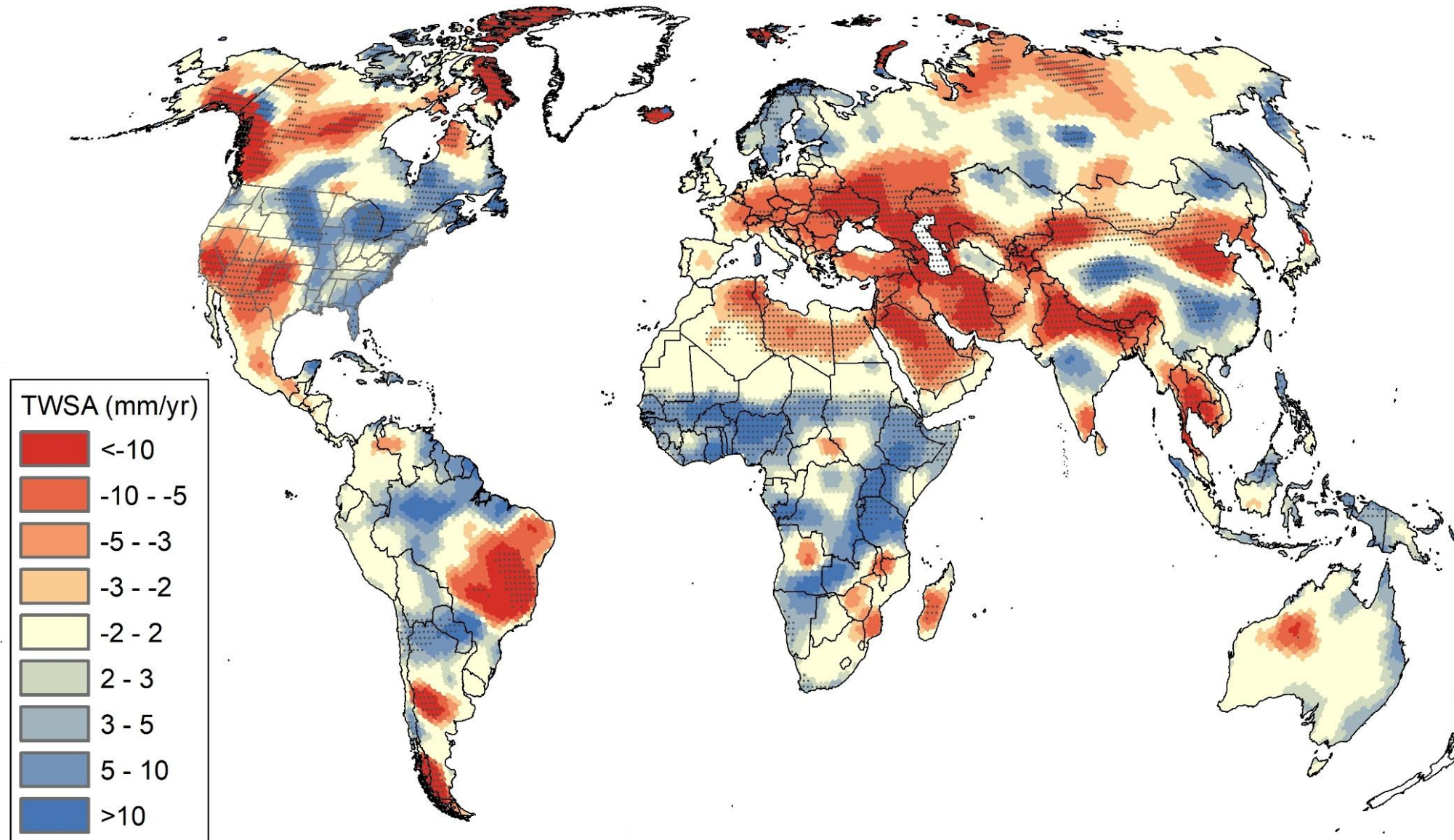
Terrestrial water storage (TWS) change

Essential climate variable in
Global Climate Observing System

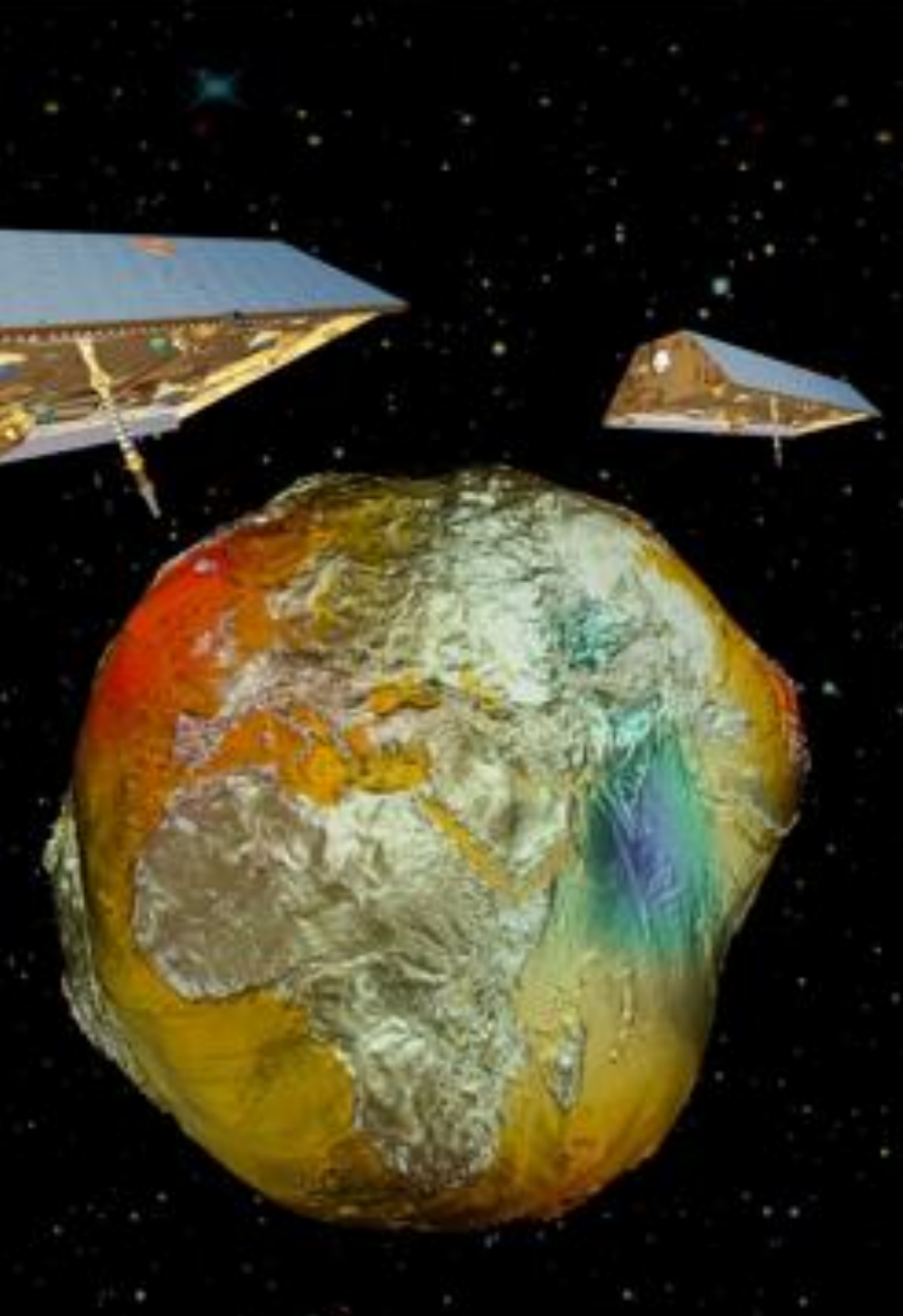
<http://grace.jpl.nasa.gov/mission/gravity-101/>



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



Rateb et al., 2022

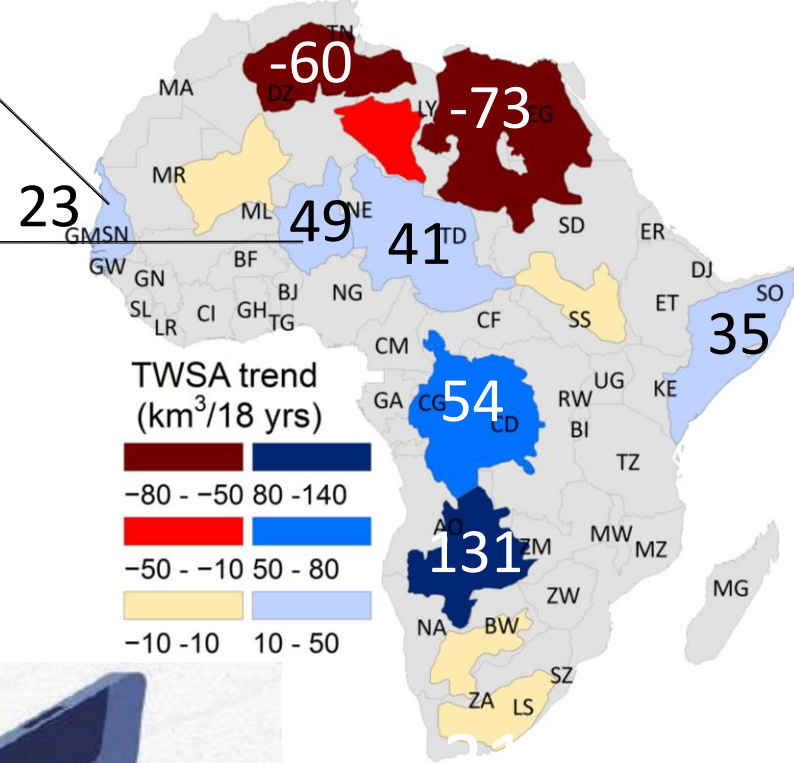
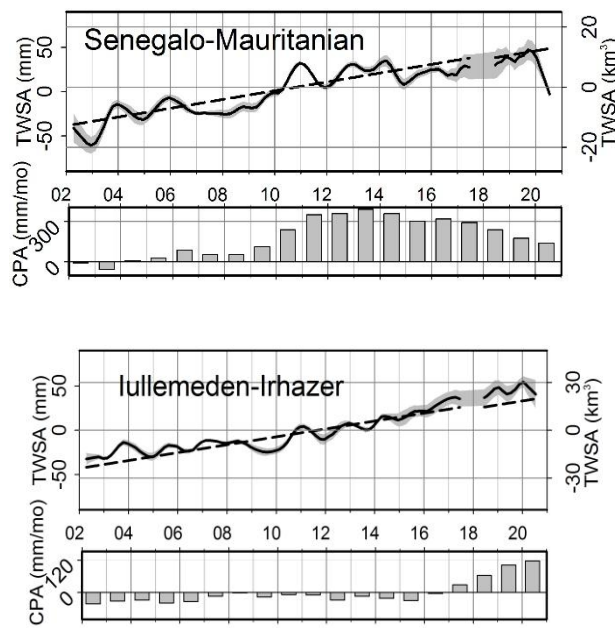


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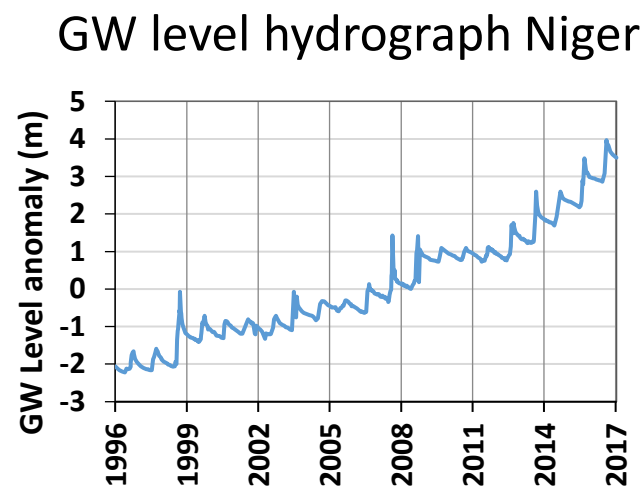
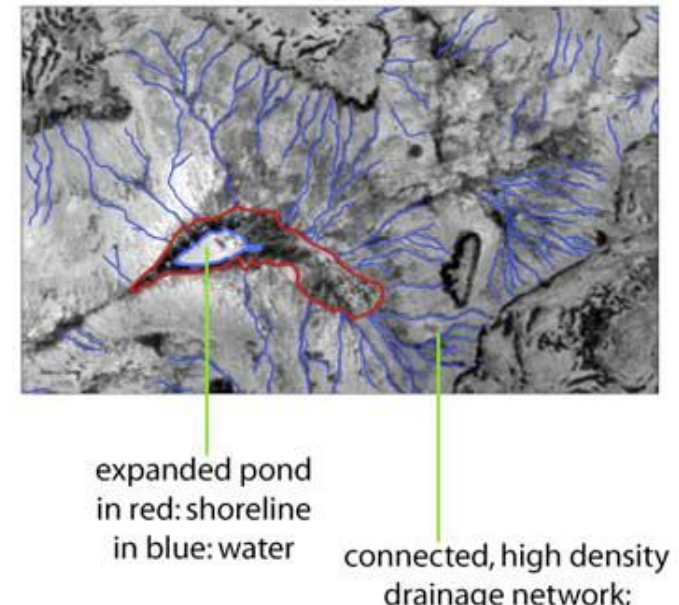
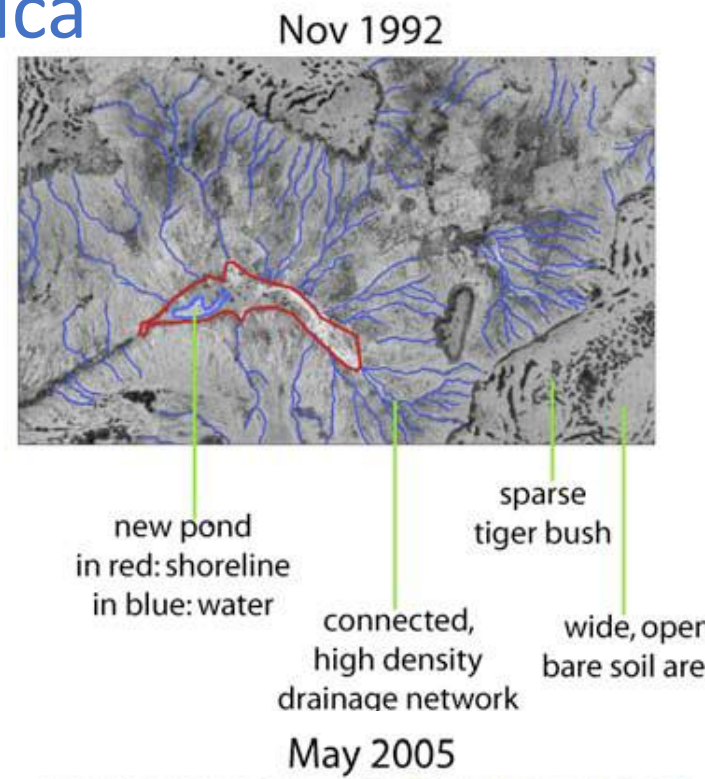
3a. Potential to Expand Irrigation in Sub-Saharan Africa

GRACE Total Water Storage Anomaly (2002 – 2020)



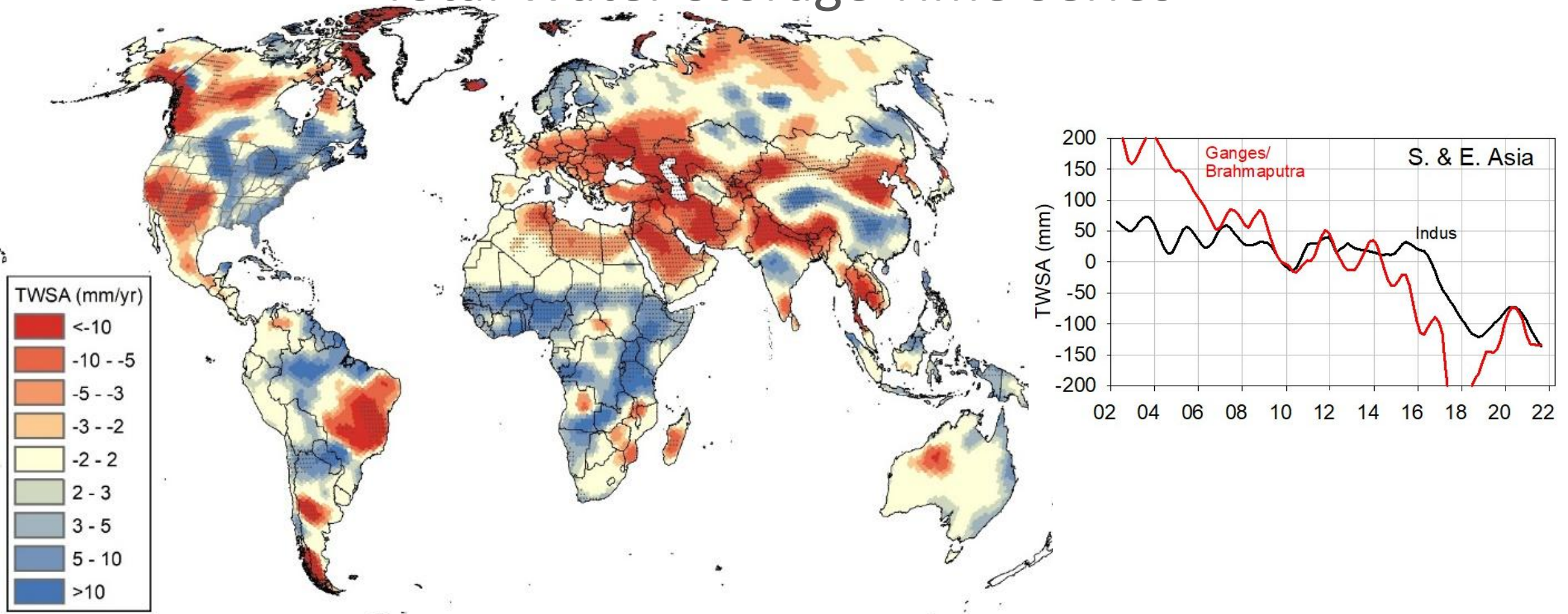
40% basement aquifers
Self-regulating

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

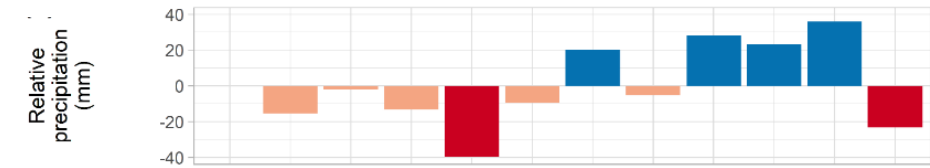
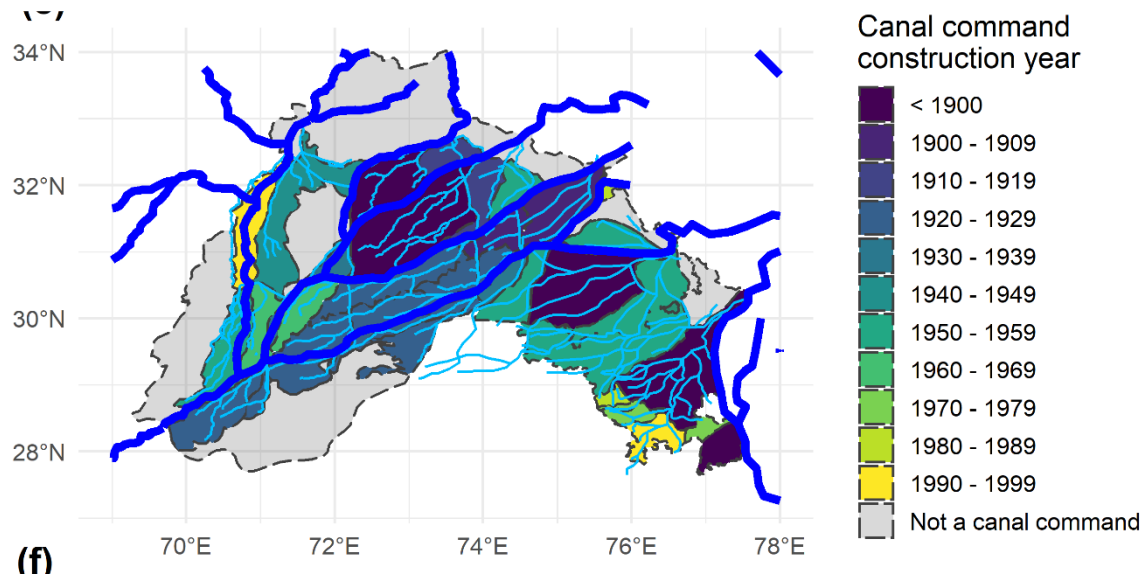
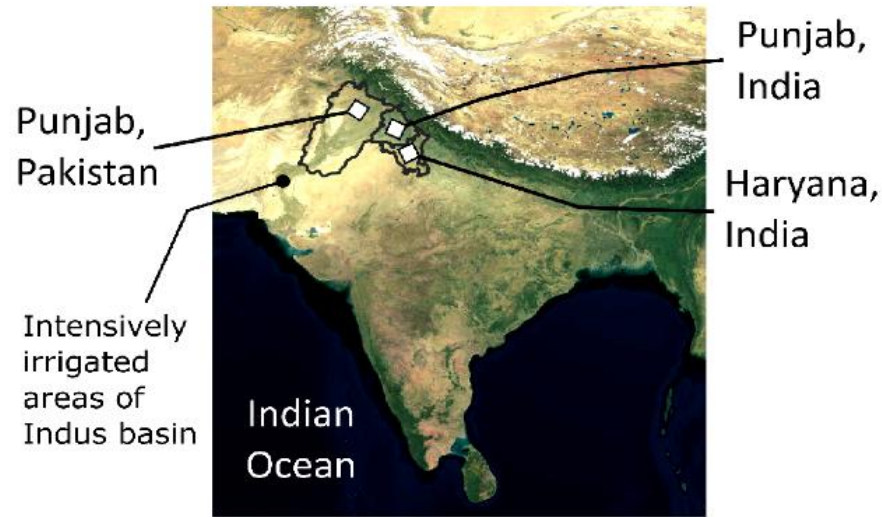


3b. Switching from Surface Water to Groundwater Irrigation

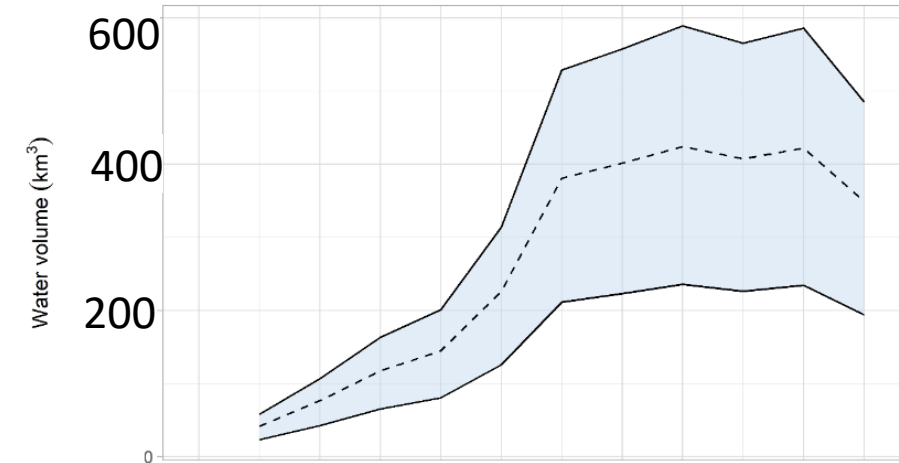
Total Water Storage Time Series



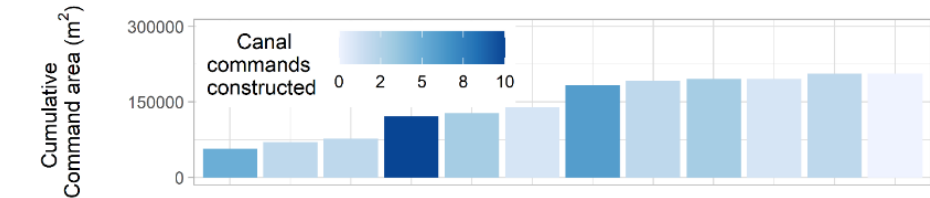
3b. A century of groundwater accumulation in Pakistan and Northwest India (GW level monitoring)



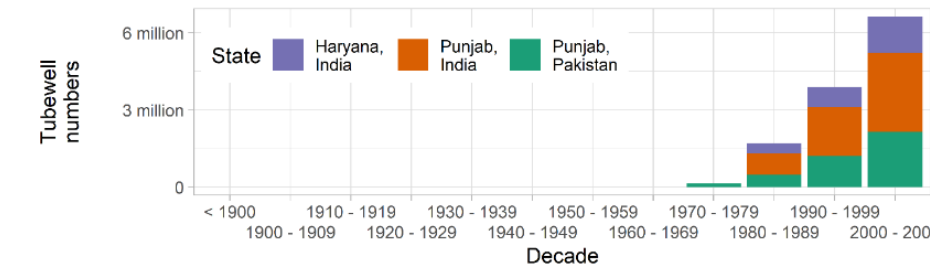
Precip. Anomaly



Water Storage km³



Canals



Tubewells

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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A- A+

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

41°



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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

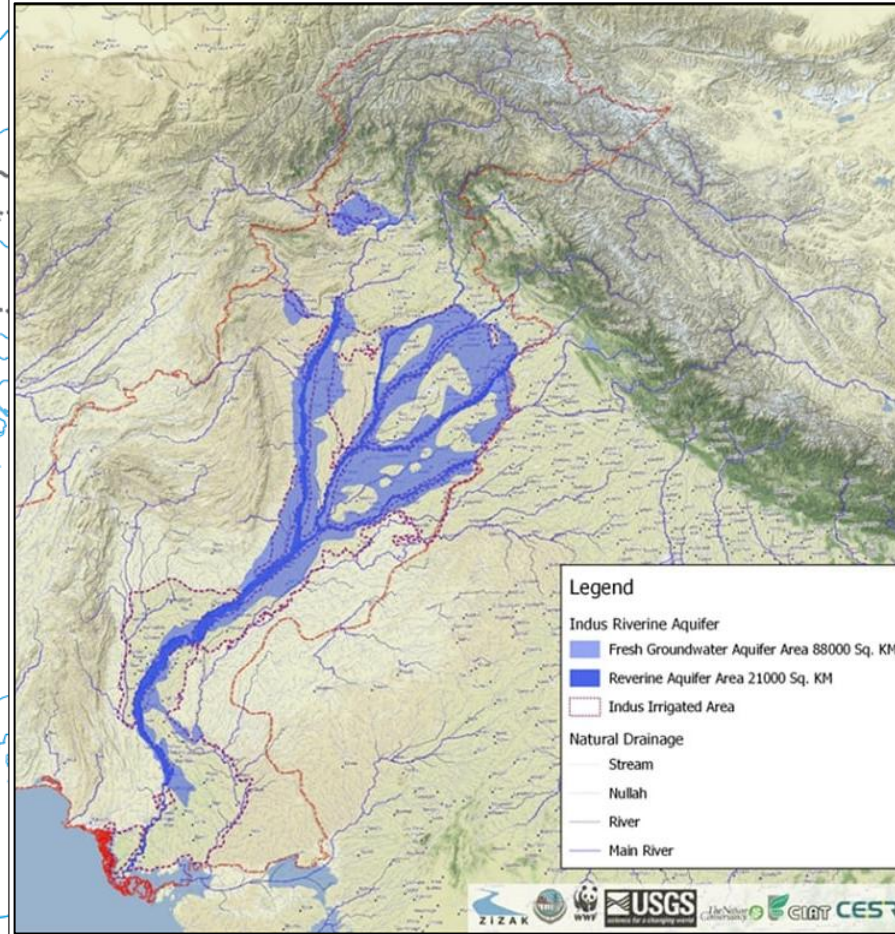
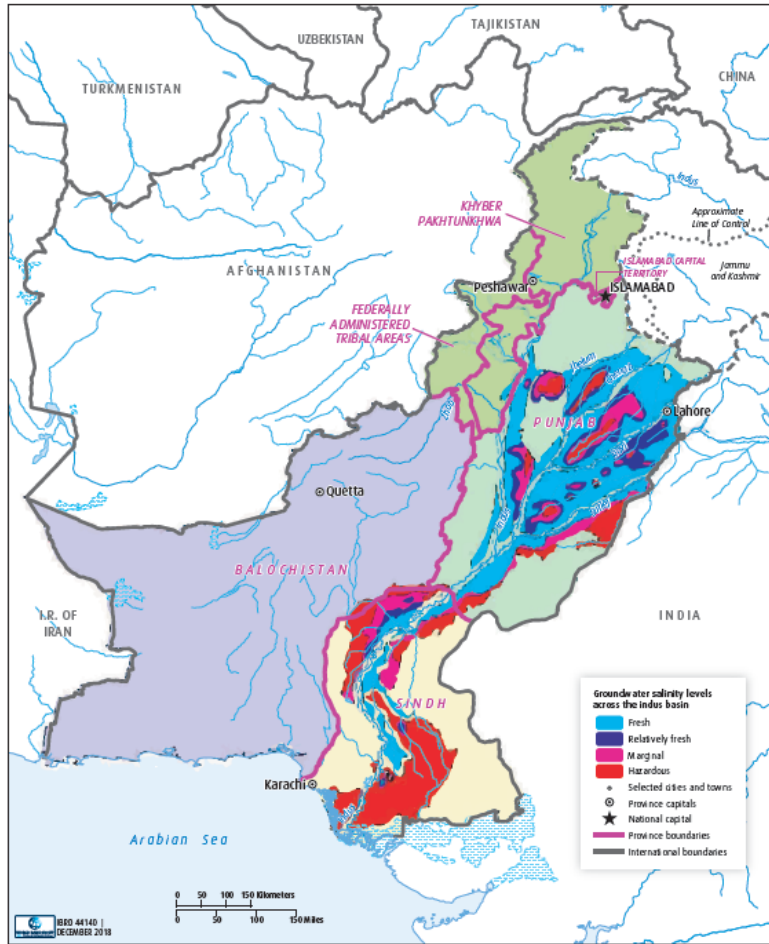
In many rainfall-scarce areas, groundwater has been exploited to plant water-guzzling crops like paddy and sugarcane, especially in Vidarbha and Rayalaseema.

Build a Website by Wix.com

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 km³

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

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

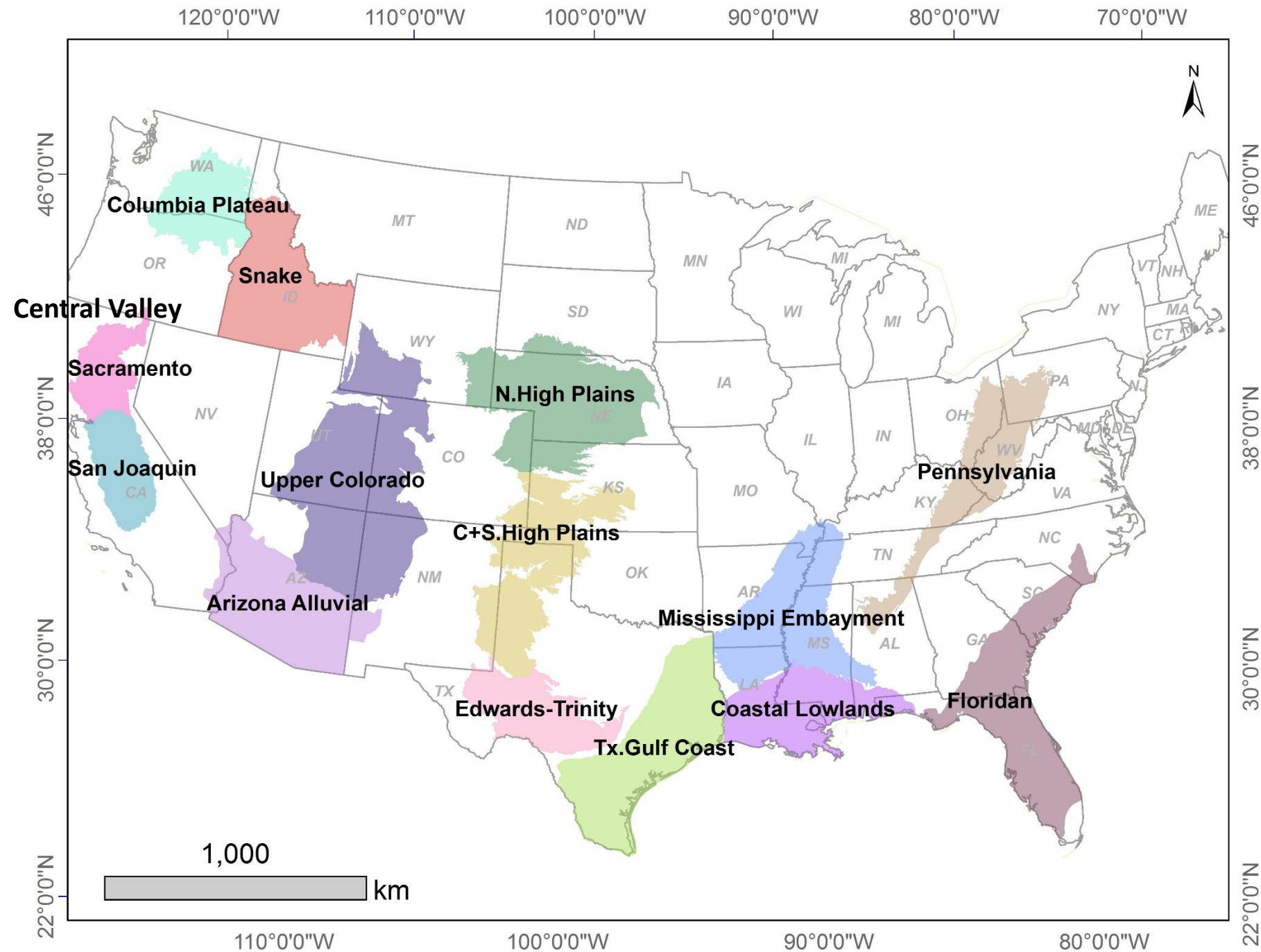


Azeem Shah

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, WRP, 2025



3b. Major Aquifers (14)

Unconfined aquifers

High Plains, AZ Alluvial,
Upper Colorado, Snake

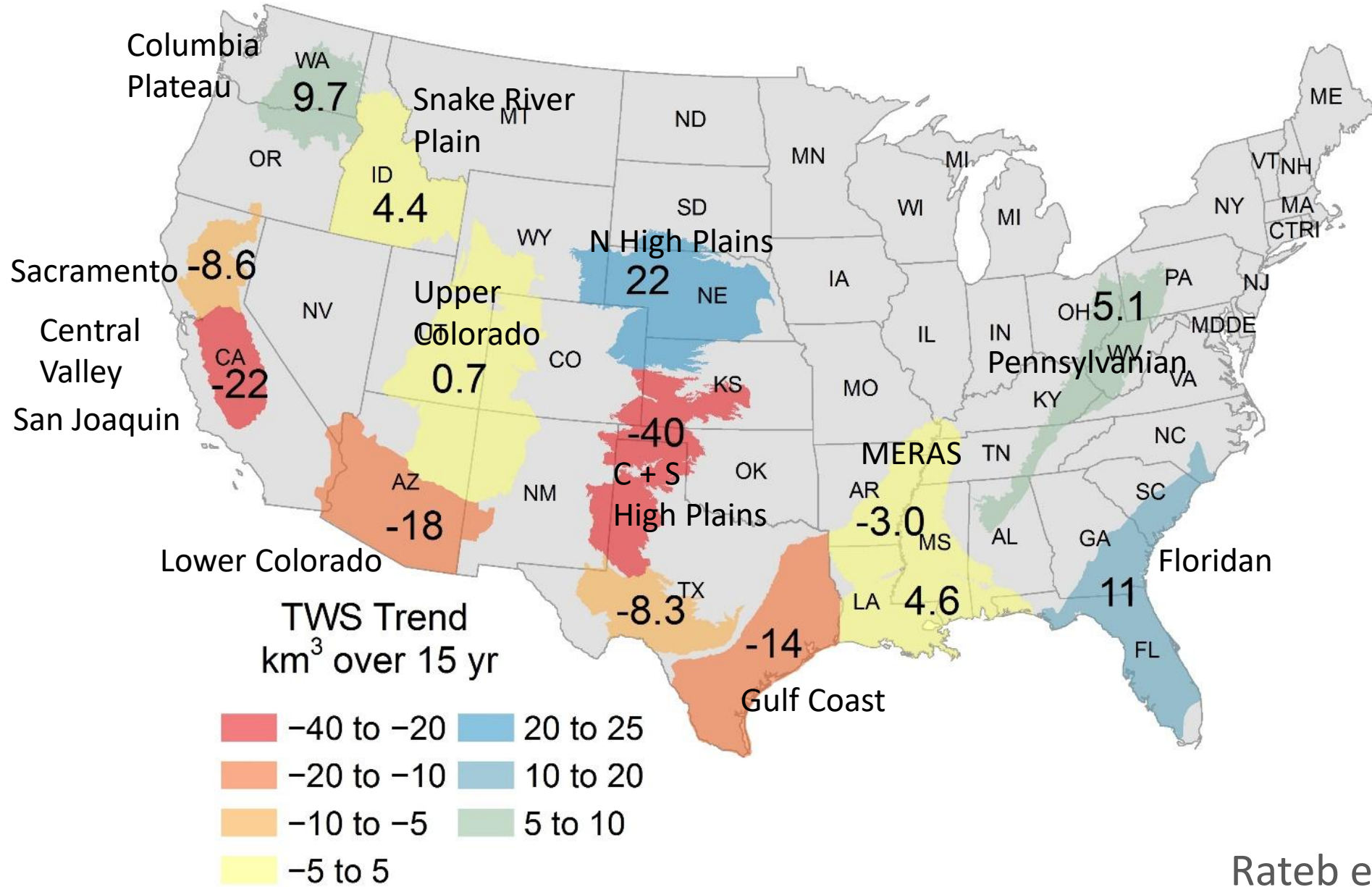
Semi-confined aquifers

Columbia & Central Valley:

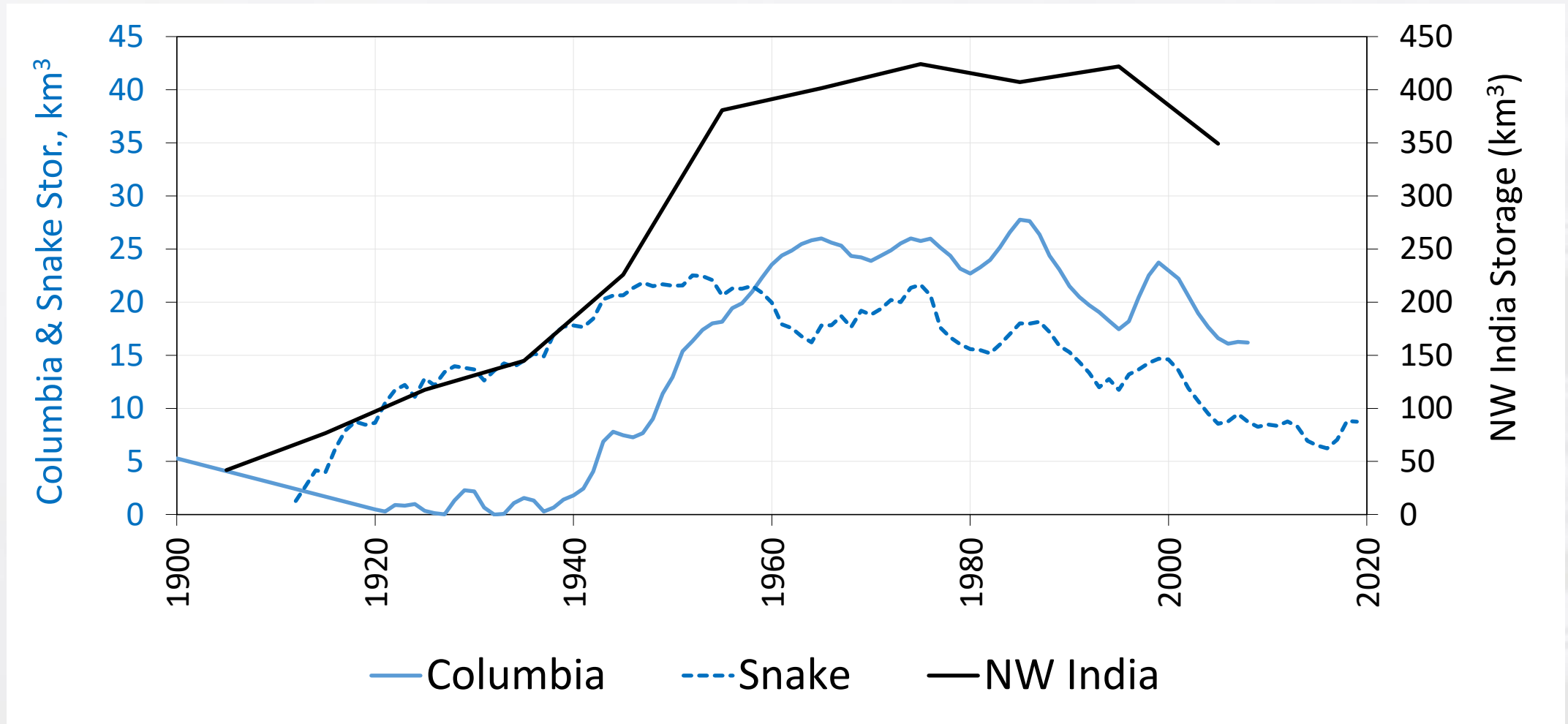
Confined

All other aquifers

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



3b. Long-term Trends in Groundwater Storage

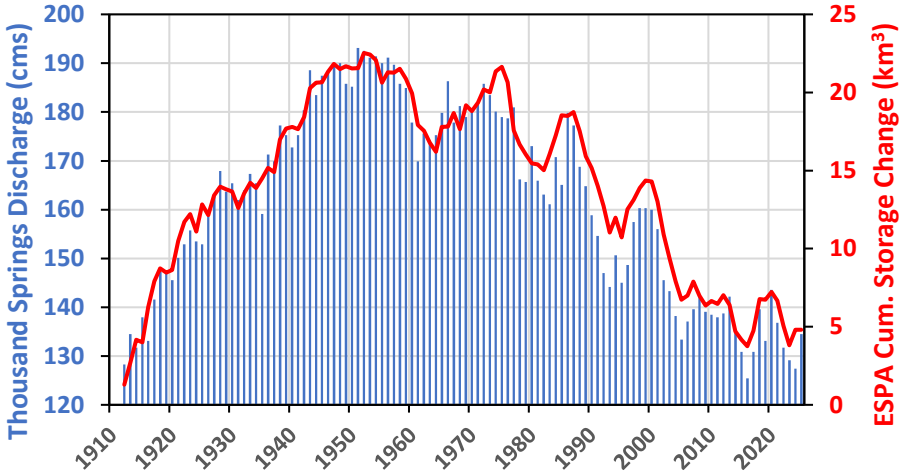


Increases in GW storage attributed to surface water irrigation
Columbia and Snake River Basins, NW US

3b. Eastern Snake Plain Aquifer Recharge

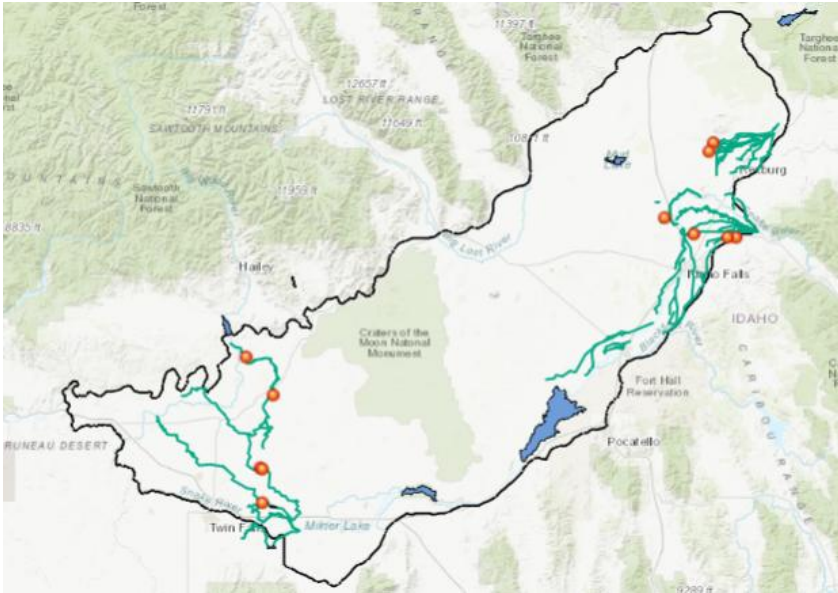


Thousand Springs



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

Managed Aquifer Recharge Projects

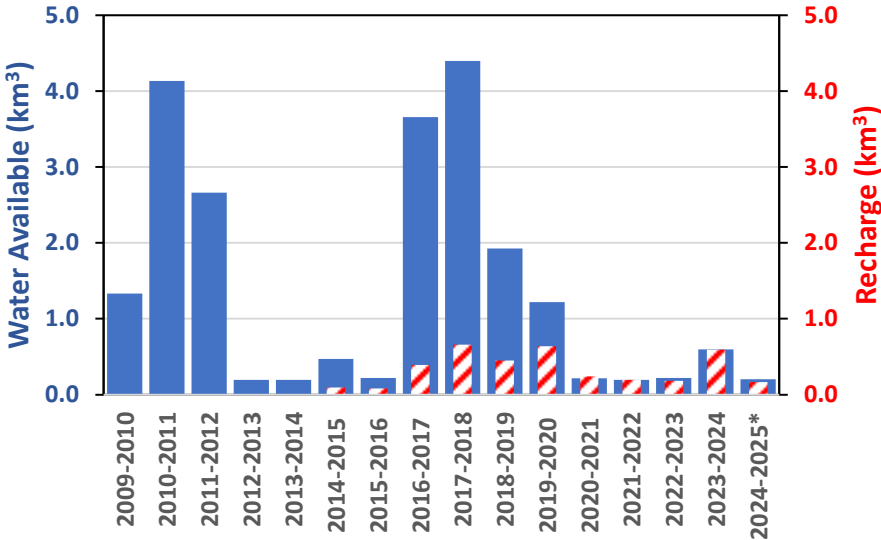


Egin Lakes Recharge project

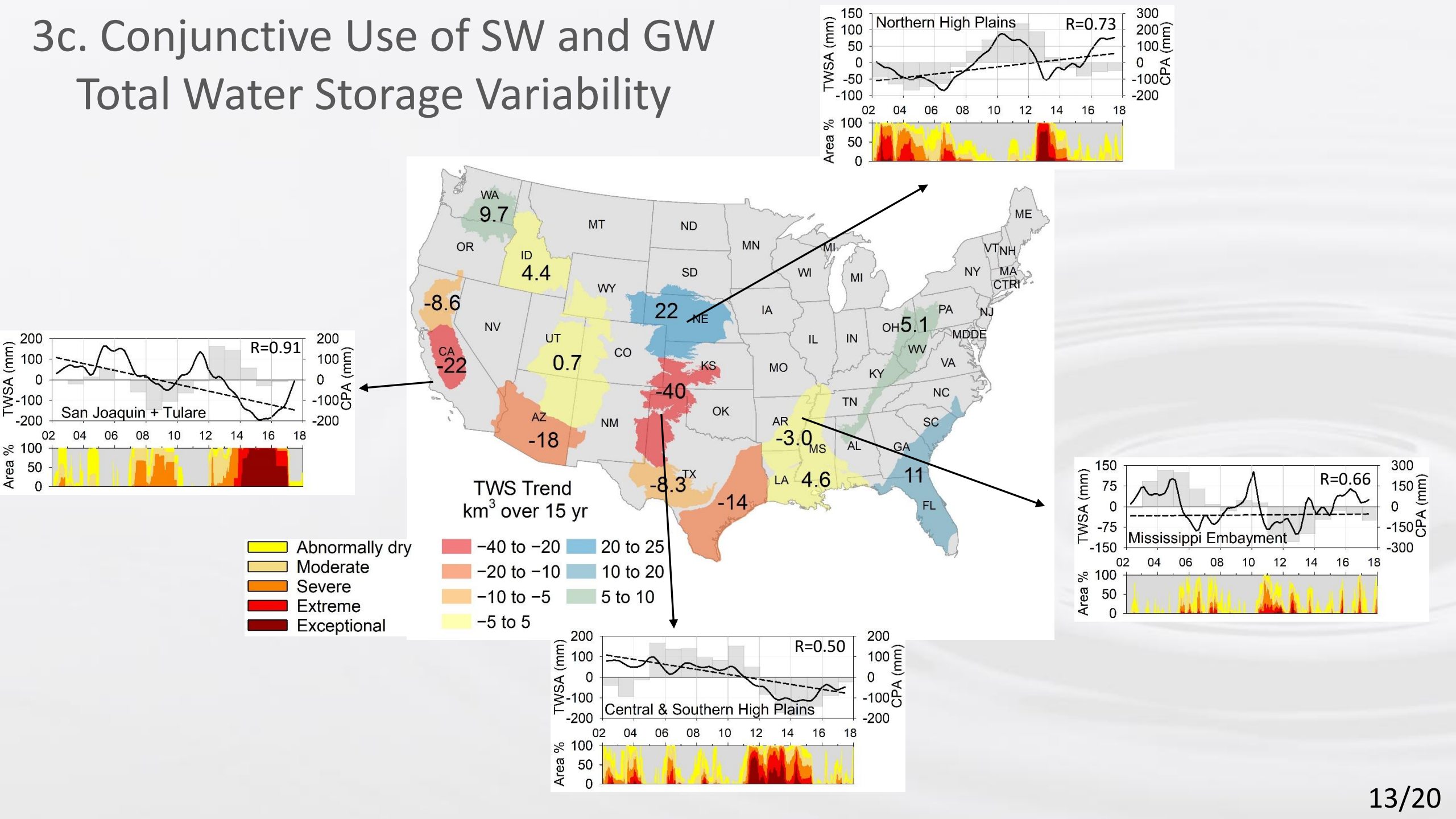


Irrigation infrastructure

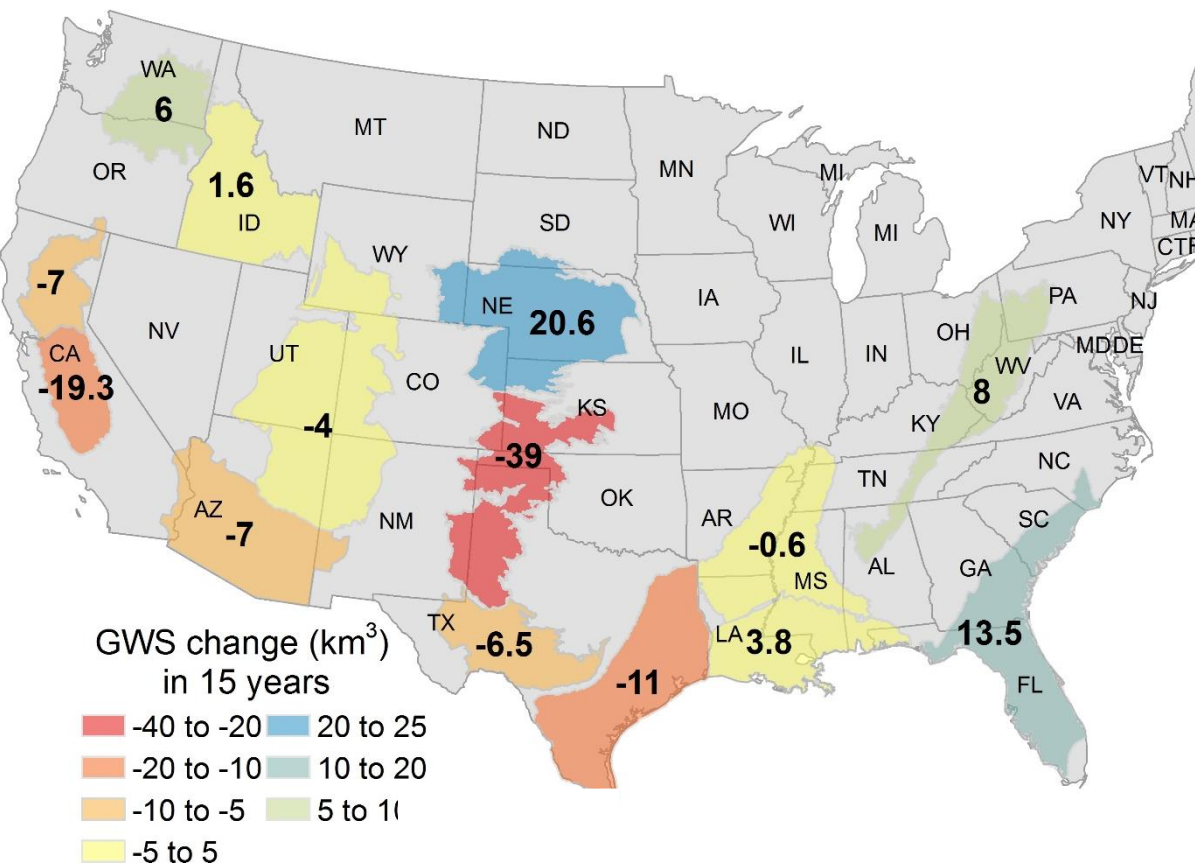
Hikpe et al., GW, 2022



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

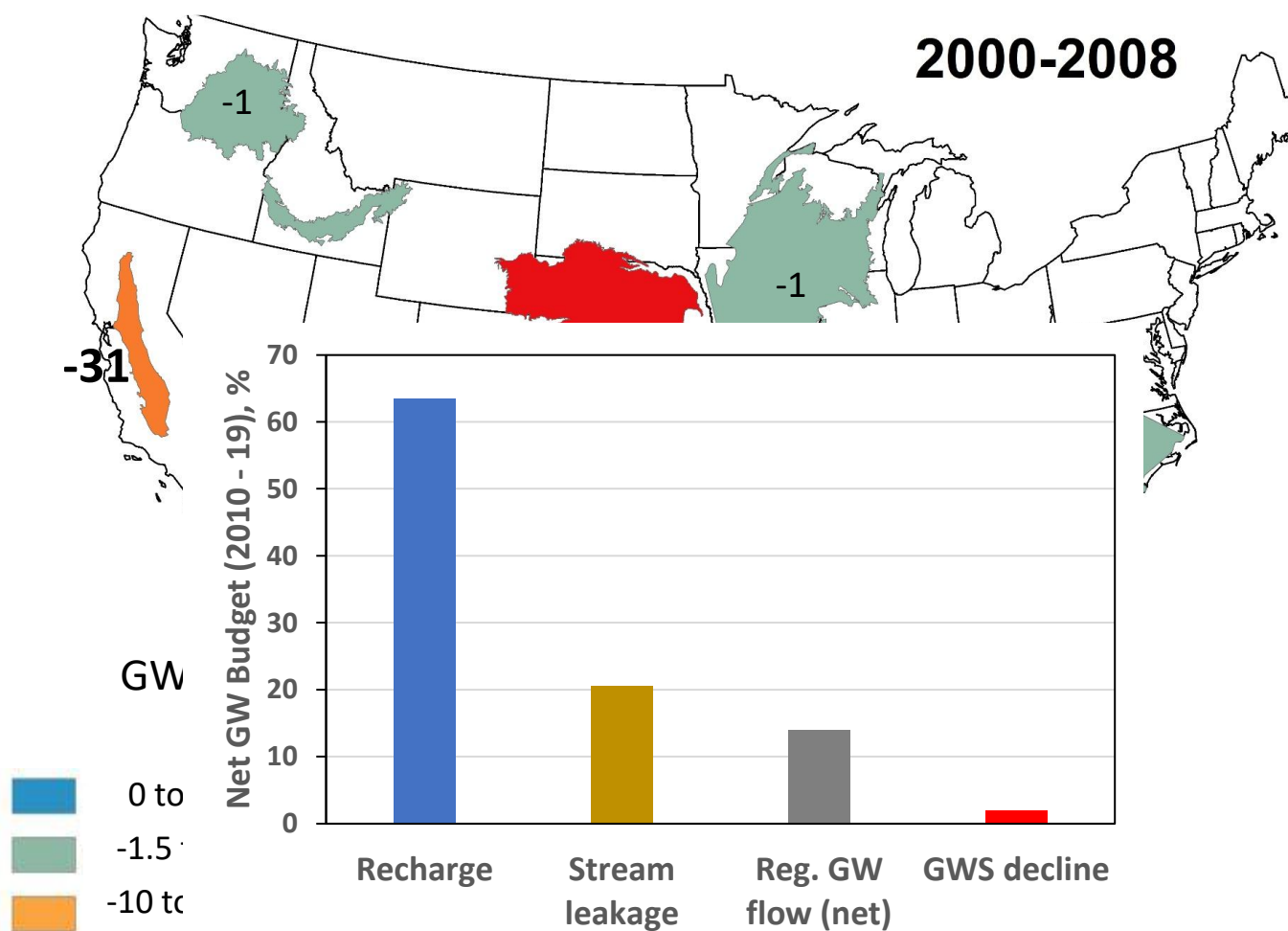


GW Storage Change GRACE (2002 – 2017)



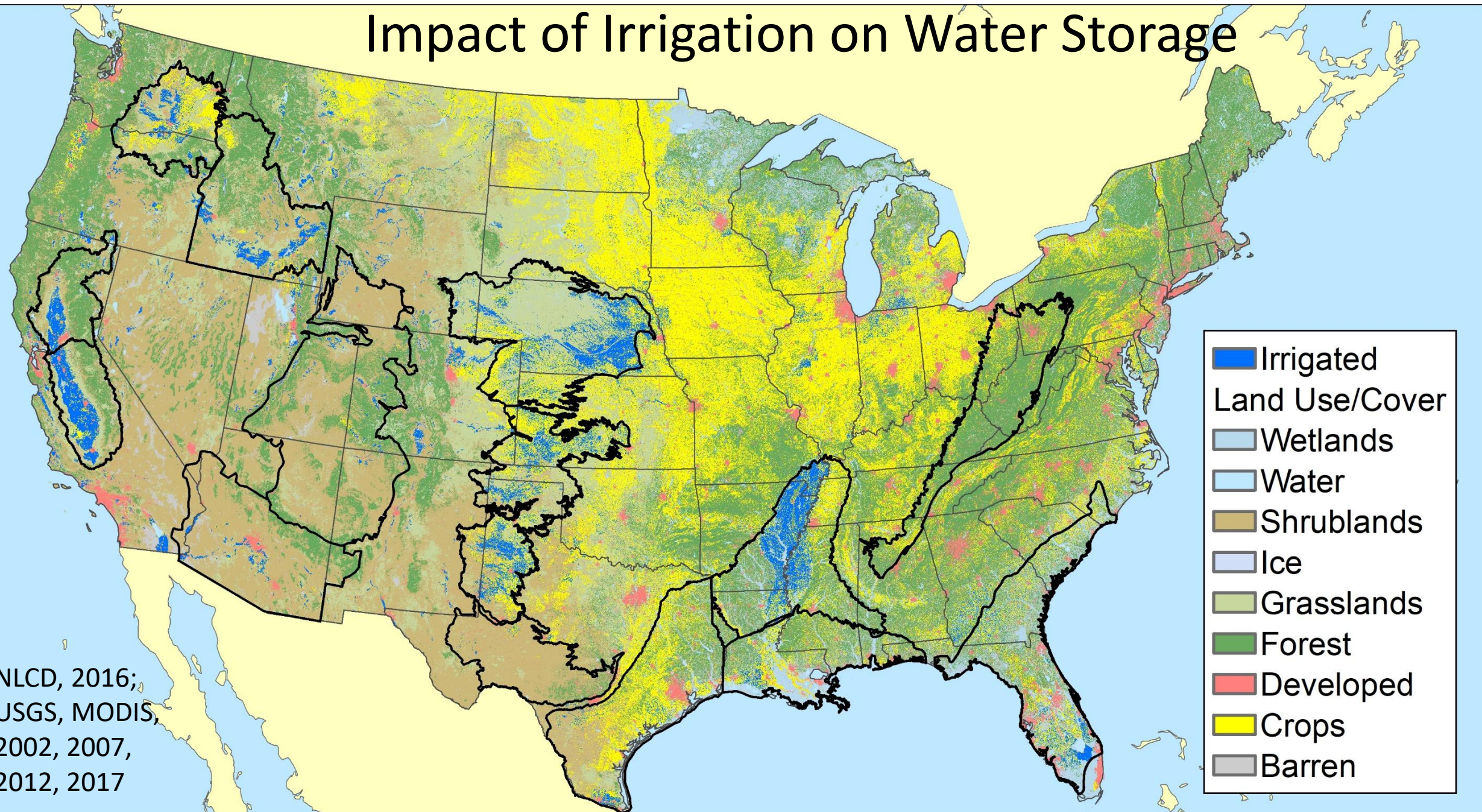
Rateb et al., 2020

GW Storage Change Regional Models and Monitoring



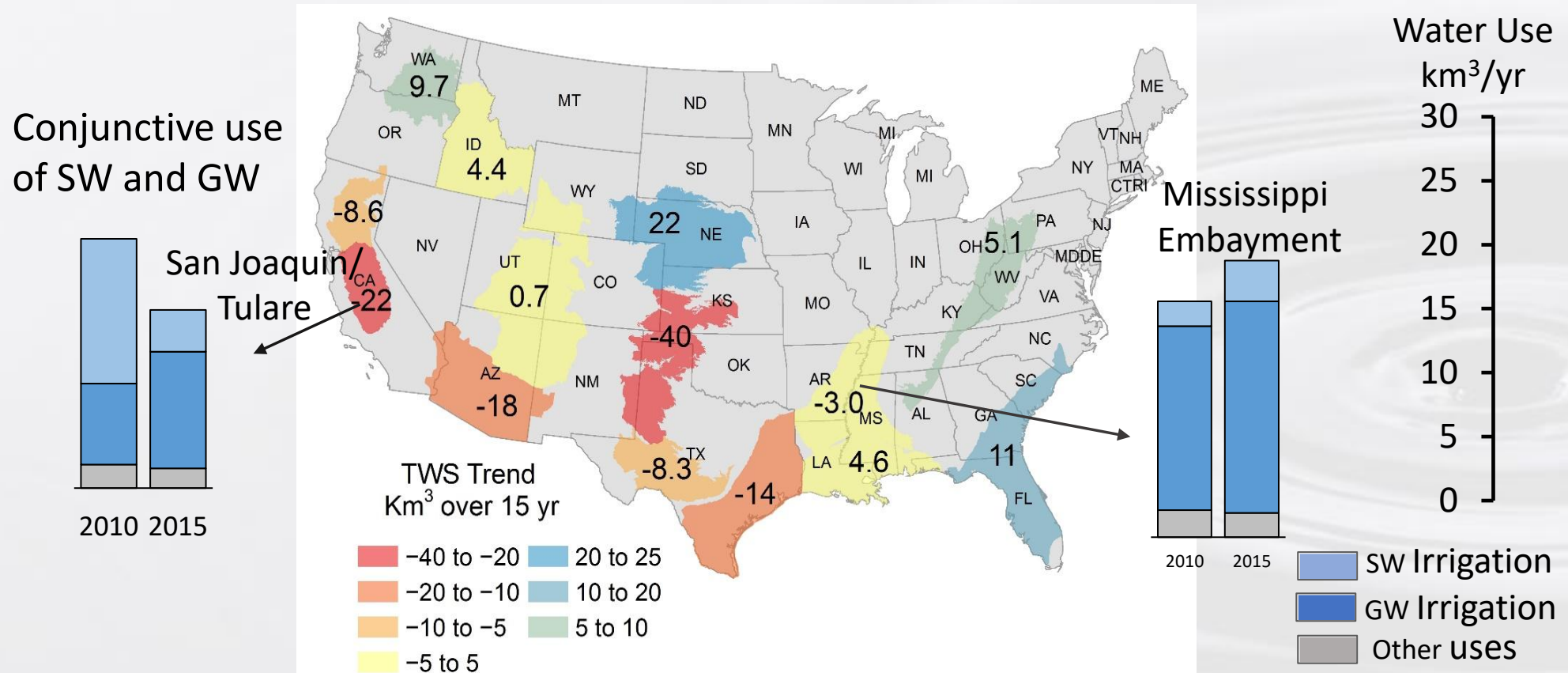
Konikow et al., 2011

Impact of Irrigation on Water Storage



NLCD, 2016;
USGS, MODIS,
2002, 2007,
2012, 2017

3c. Irrigation Water Use



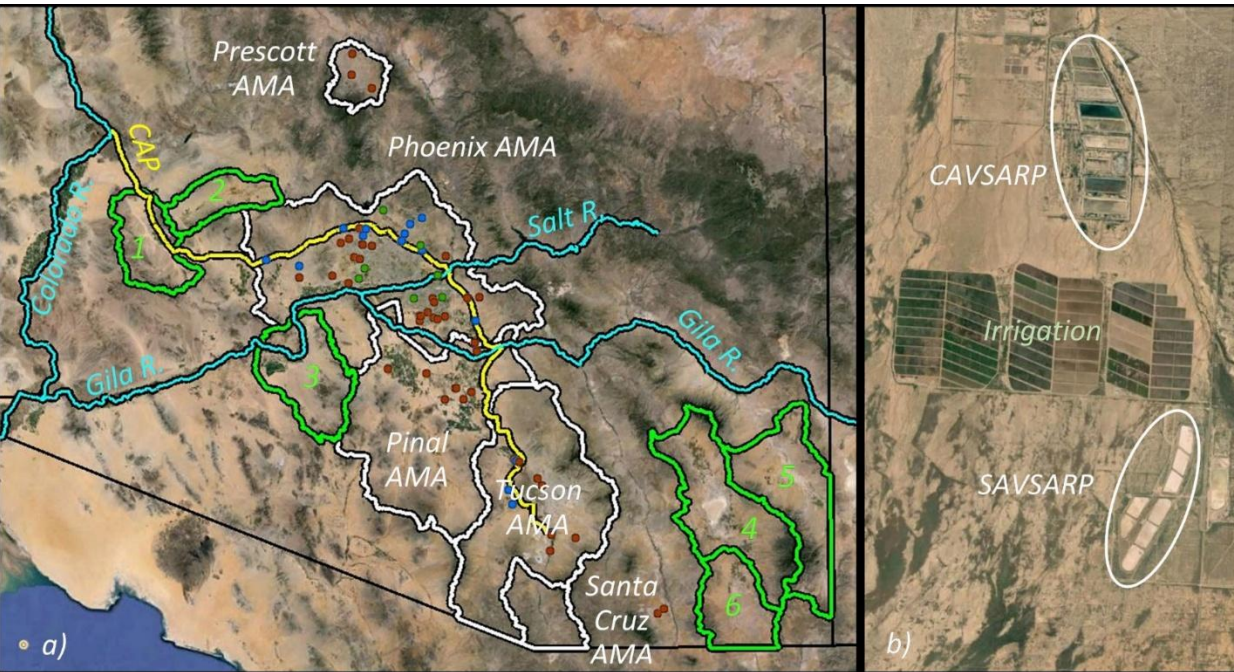
2010: wet year: 70% SW
2015: drought: 70% GW

Scanlon et al., ERL, 2021

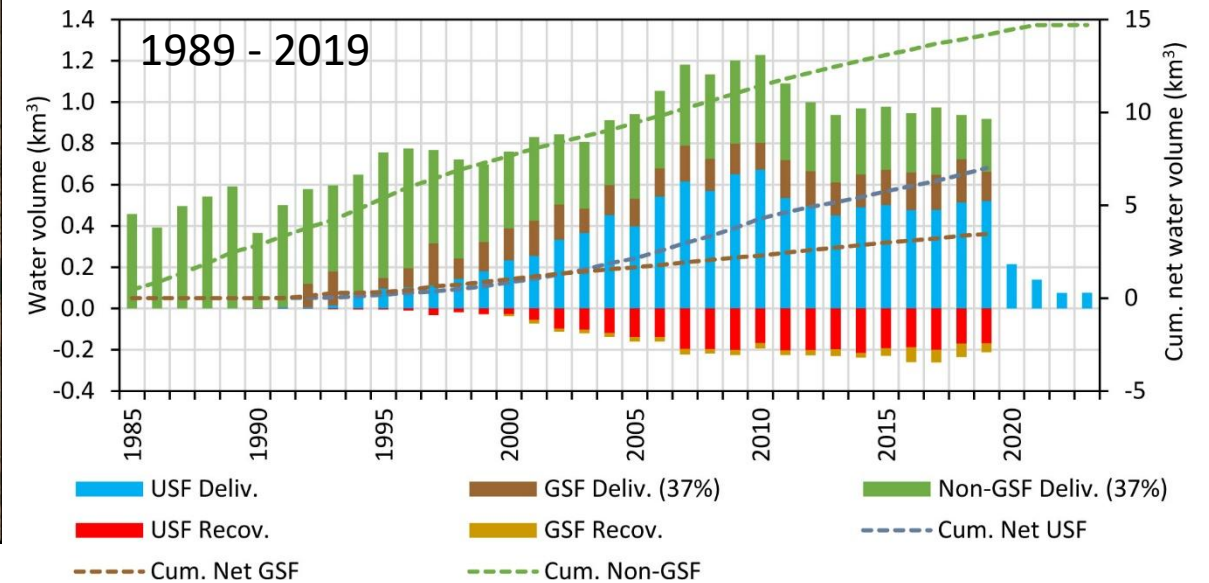
3d. Managed Aquifer Recharge: Arizona Alluvial Valley

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

USF:
Spreading basins



Recharge in Active Management Areas



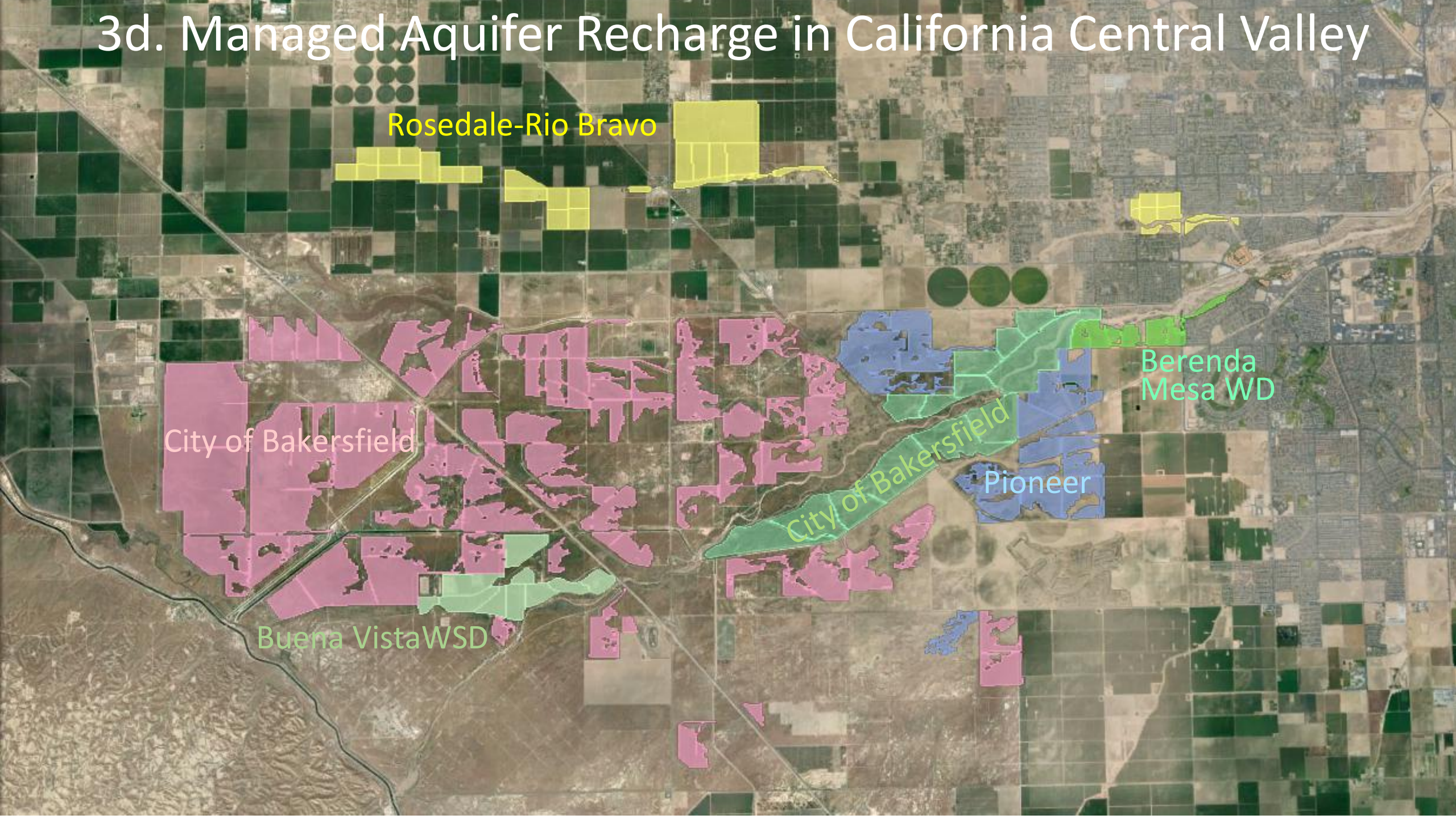
Arizona: Pump and Replenish

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

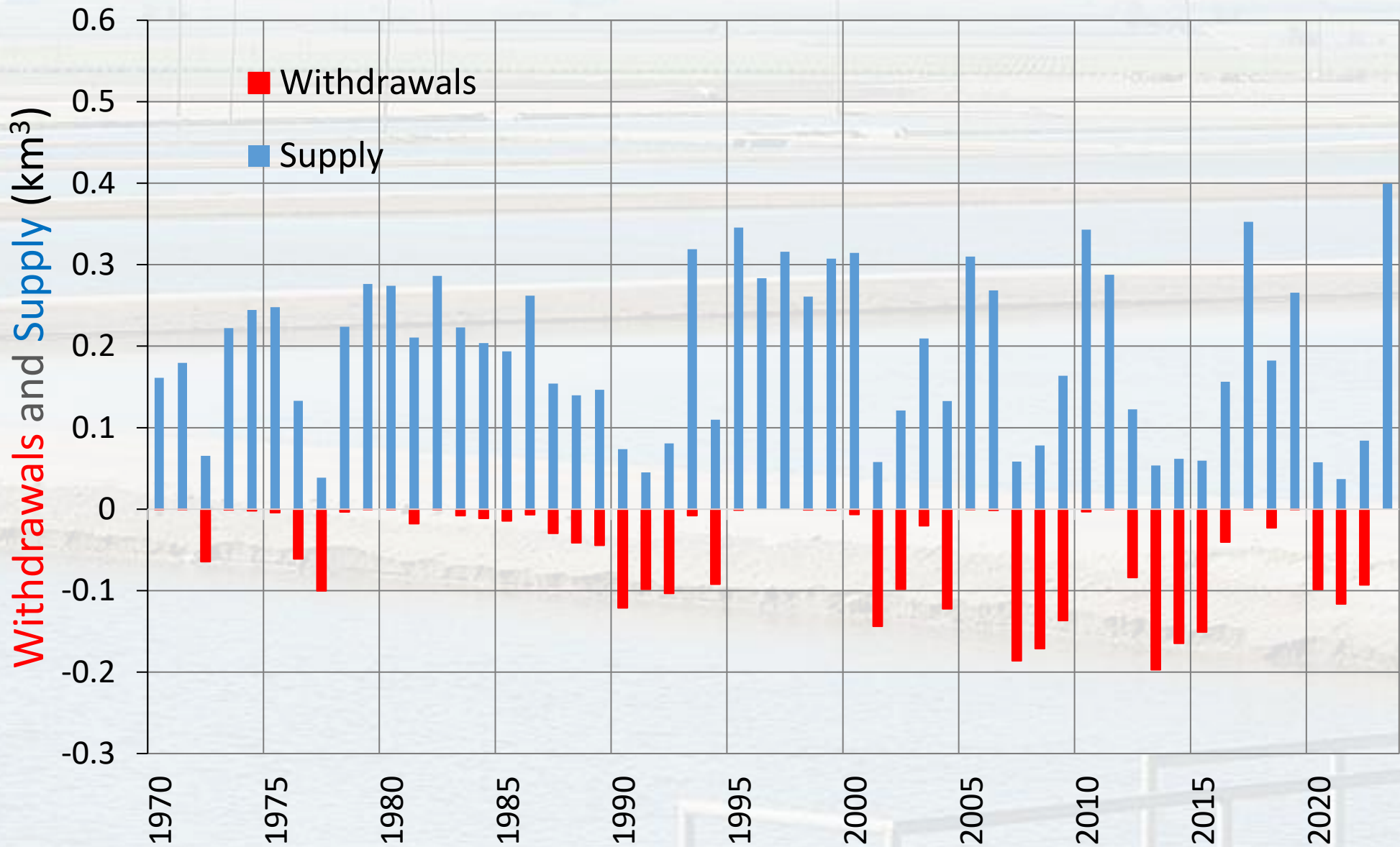
USF: Underground Storage Facilities: 7.0 km³
GW Savings Facilities: 3.5 km³ (Switch GW → SW)
Incidental Recharge: 14.2 km³ (SW irrigation)

Scanlon et al., NCEE, 2025

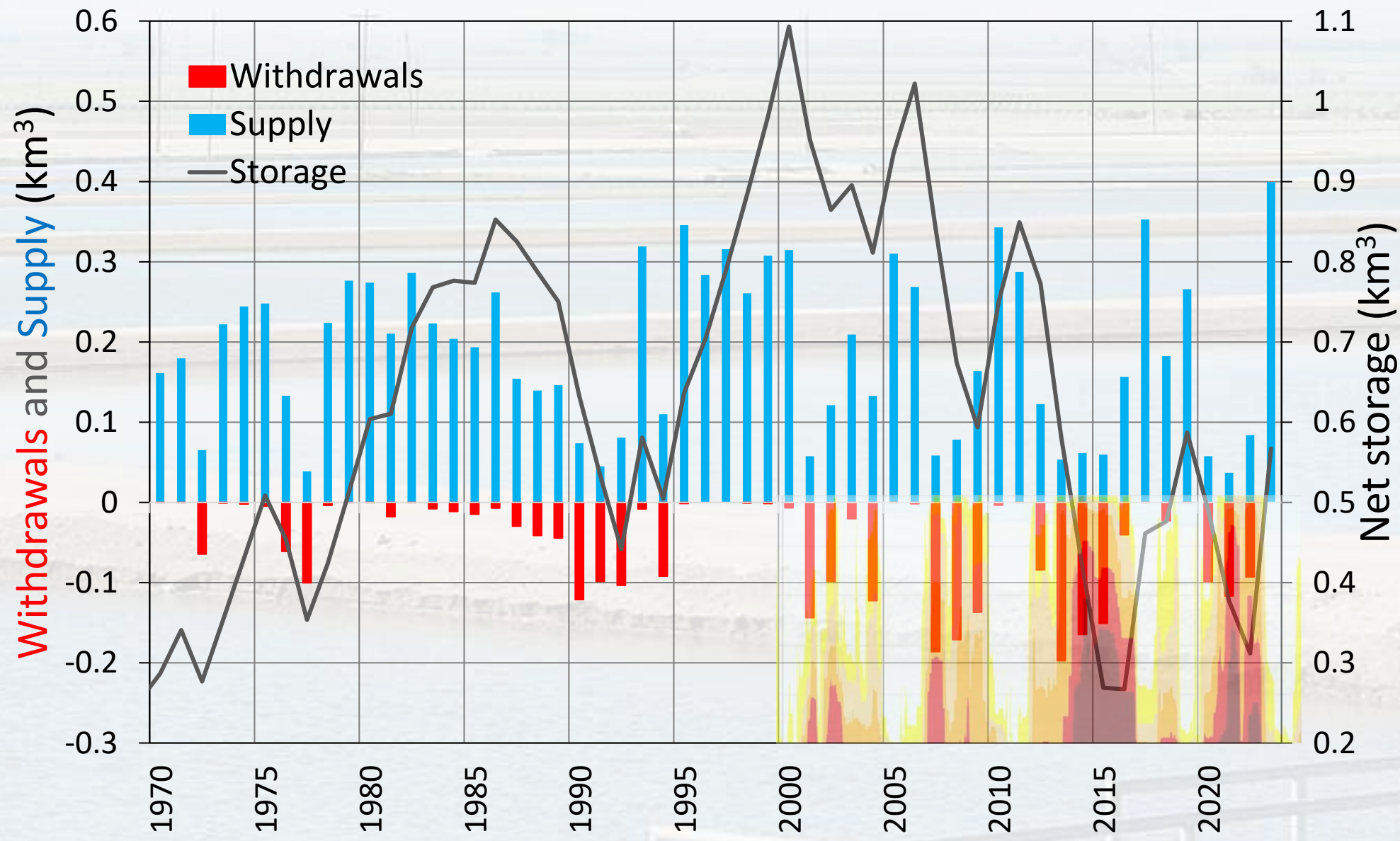
3d. Managed Aquifer Recharge in California Central Valley



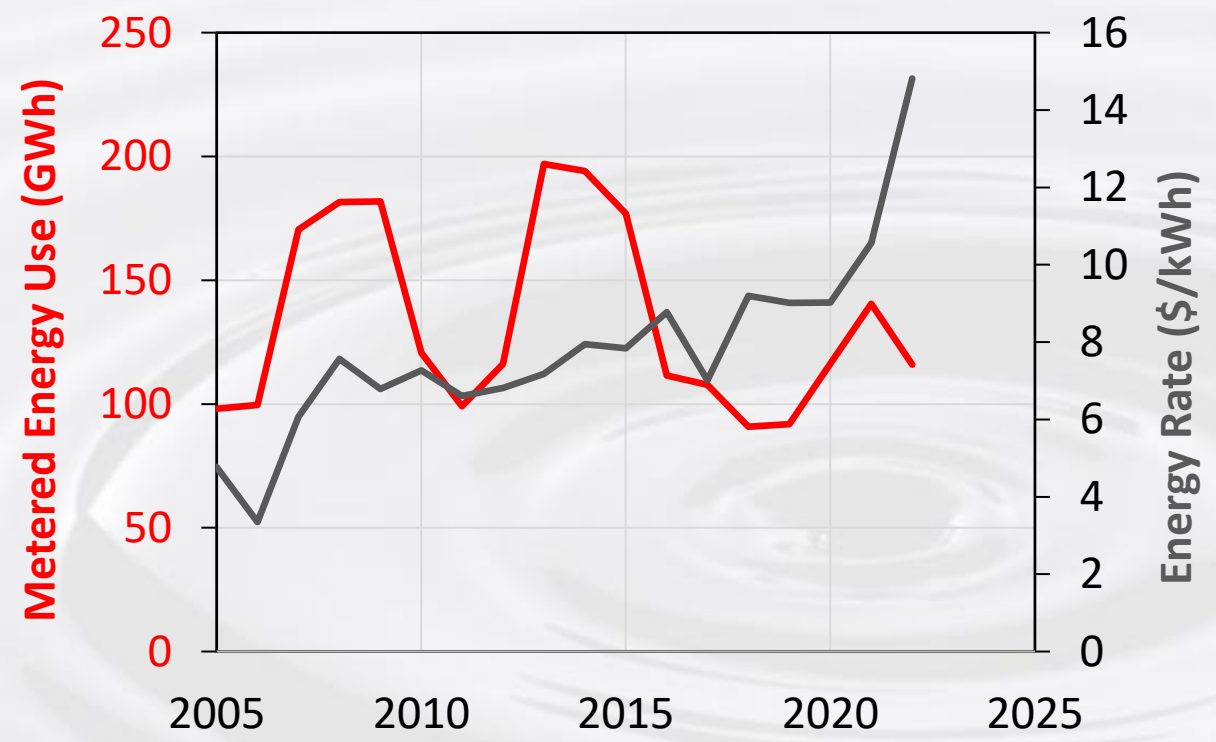
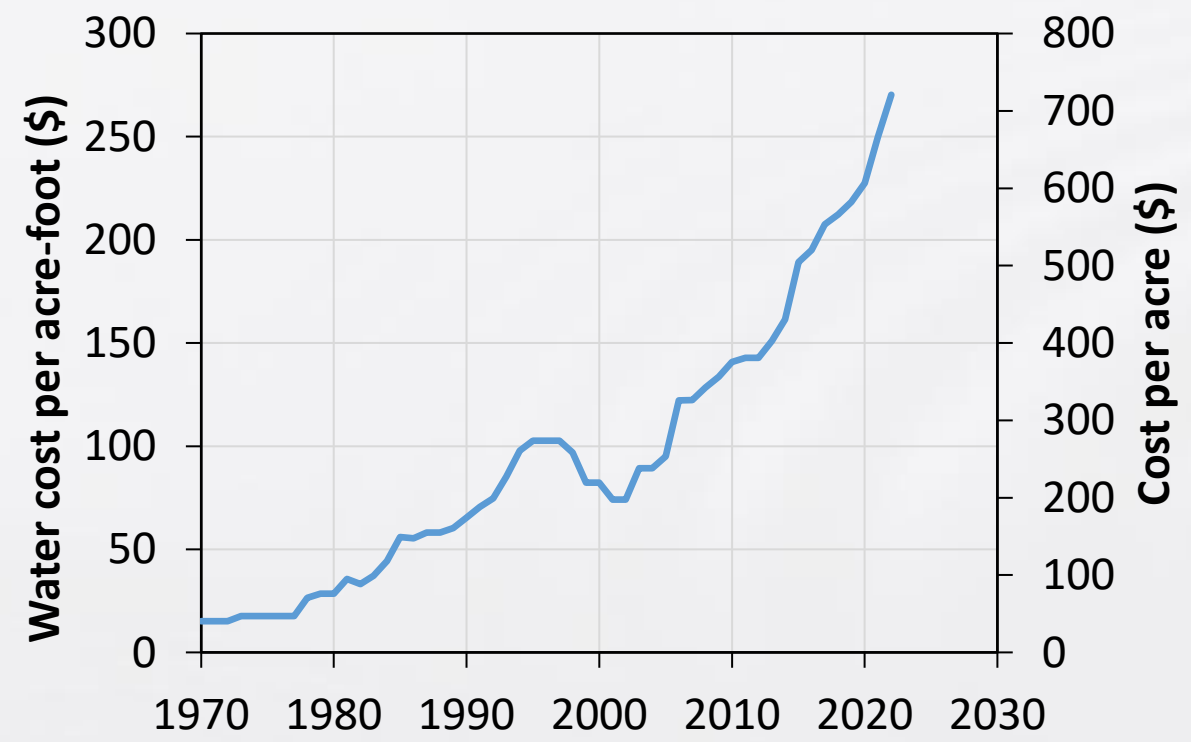
3d. Water Budget in **Arvin Edison** Irrigation District, Central Valley, California



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



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



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

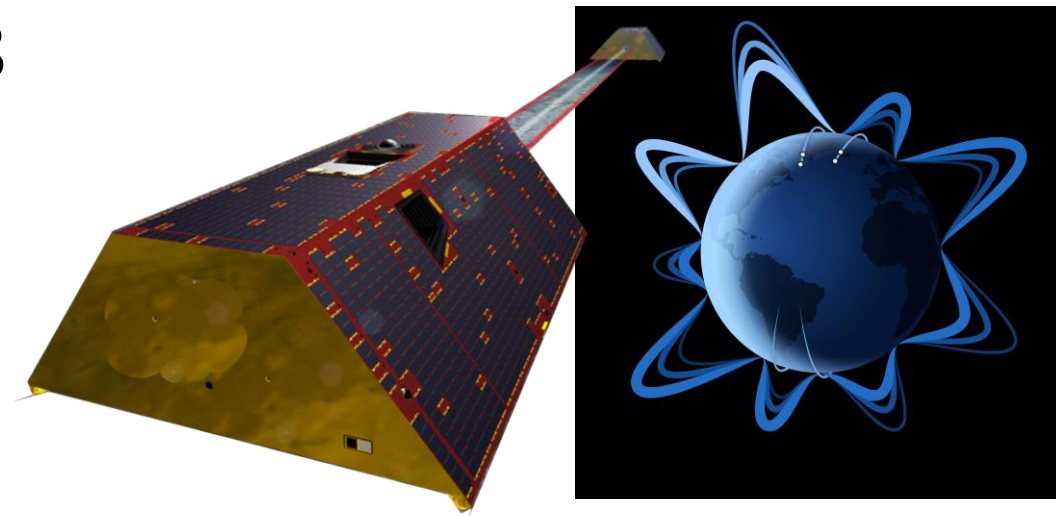


GRACE Continuity (GRACE-C)

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

Measurement System

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

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

MAGIC: Mass change And Geosciences International Constellation

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

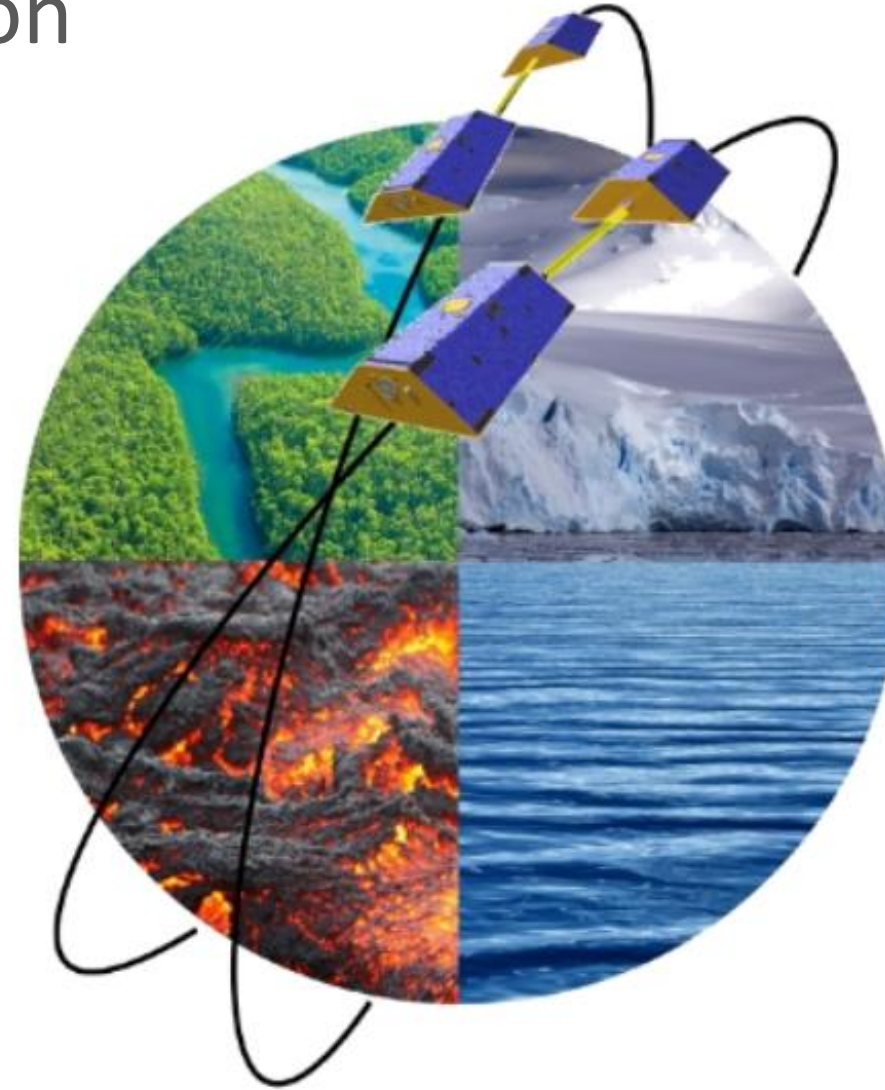
Resolution:

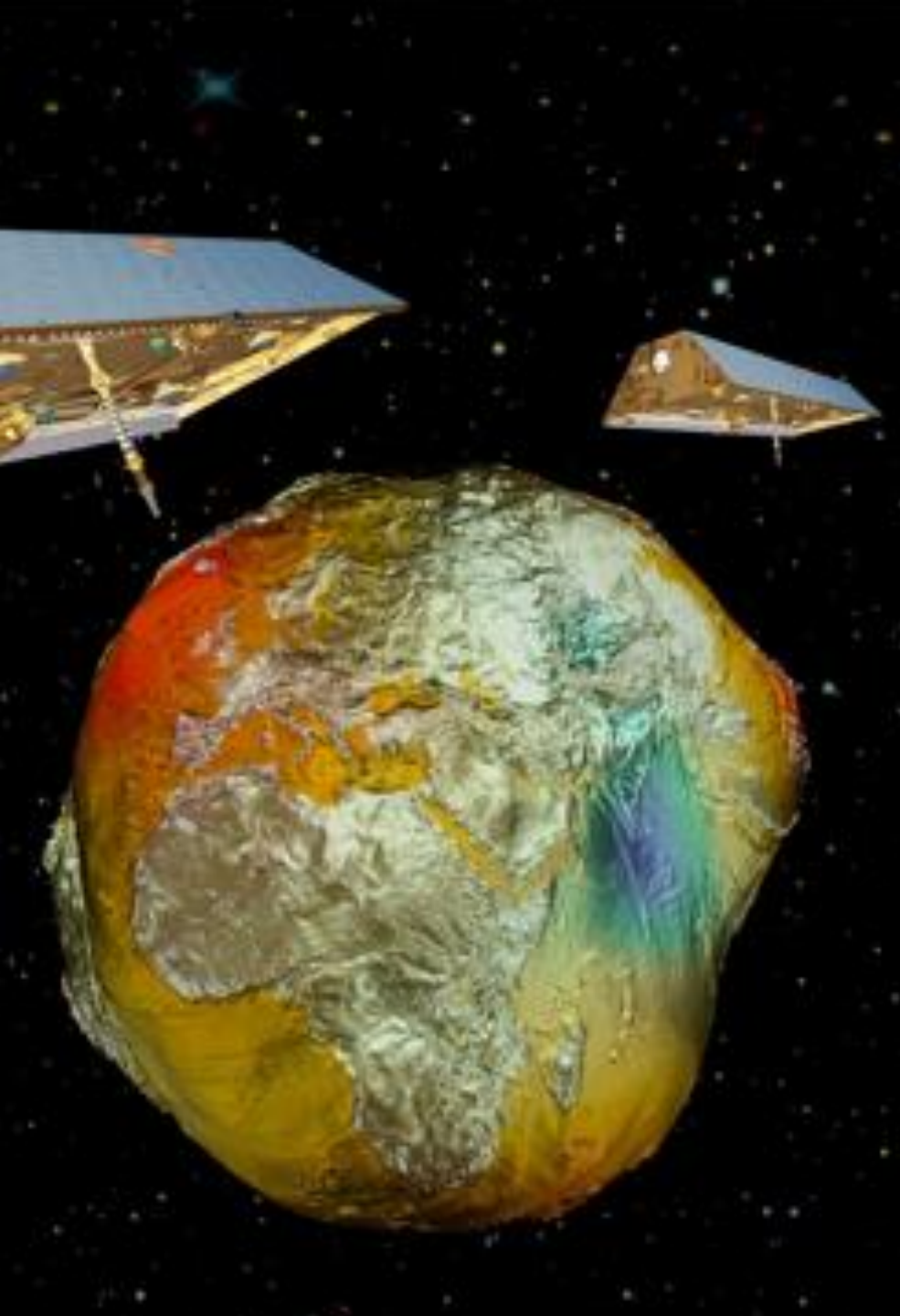
400 km elevation, 70° inclination

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)



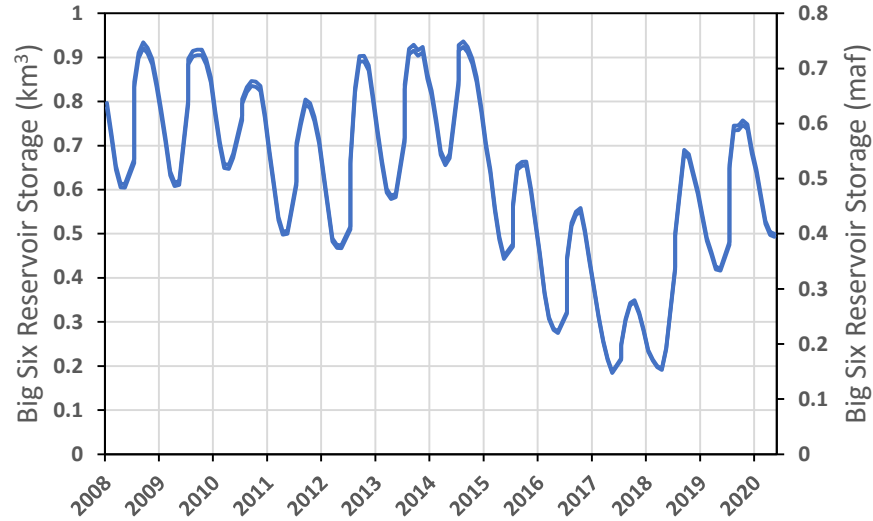


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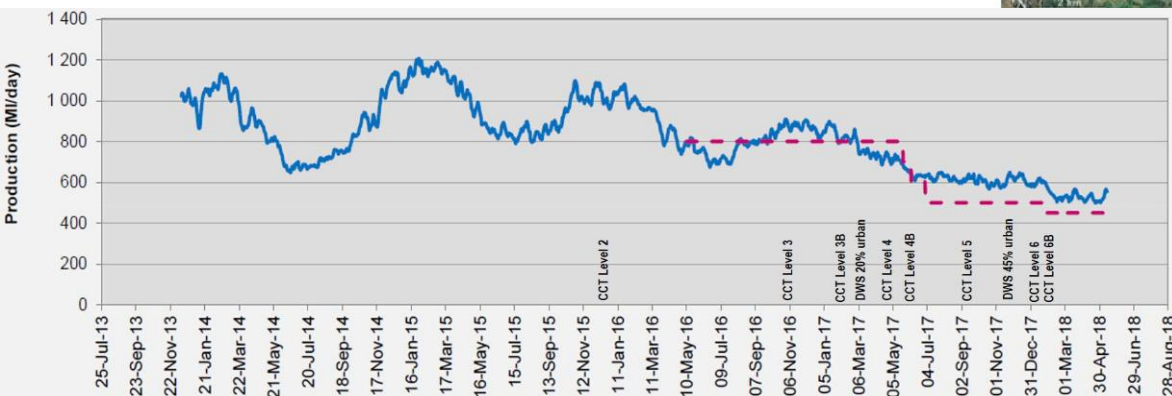
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4. Urban water shortages (Cape Town, Sao Paulo)

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%

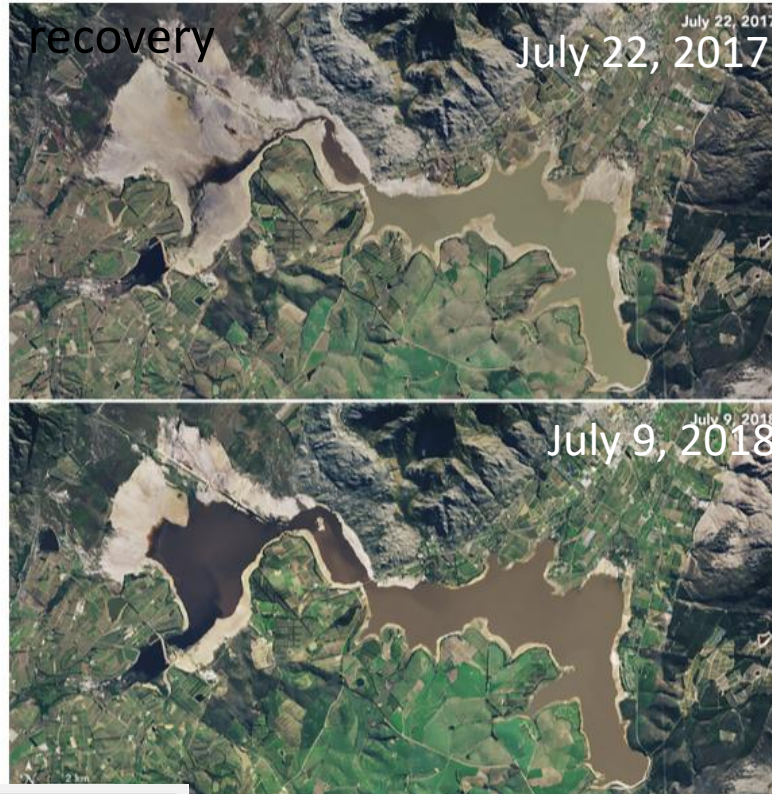
Western Cape Water Supply System



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

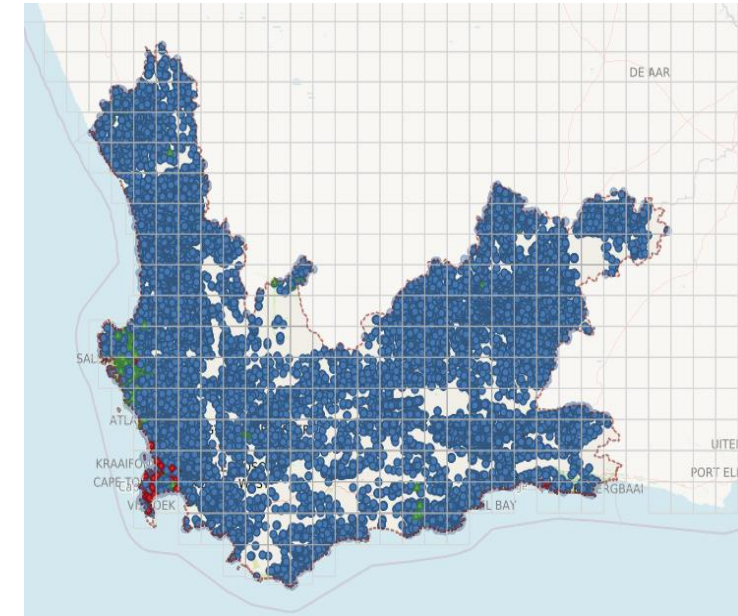


Theewaterskloof Reservoir:



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

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

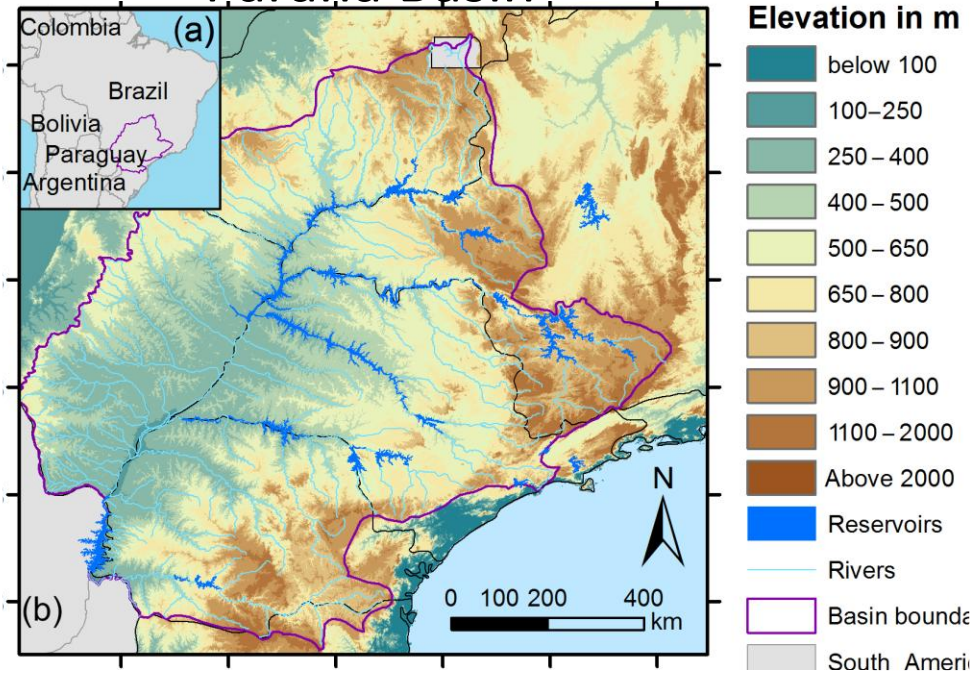


Expansion of GW:
Hundreds of boreholes drilled
Dept. Water and Sanitation:
encouraged households to drill
GW wells, Non-revenue water

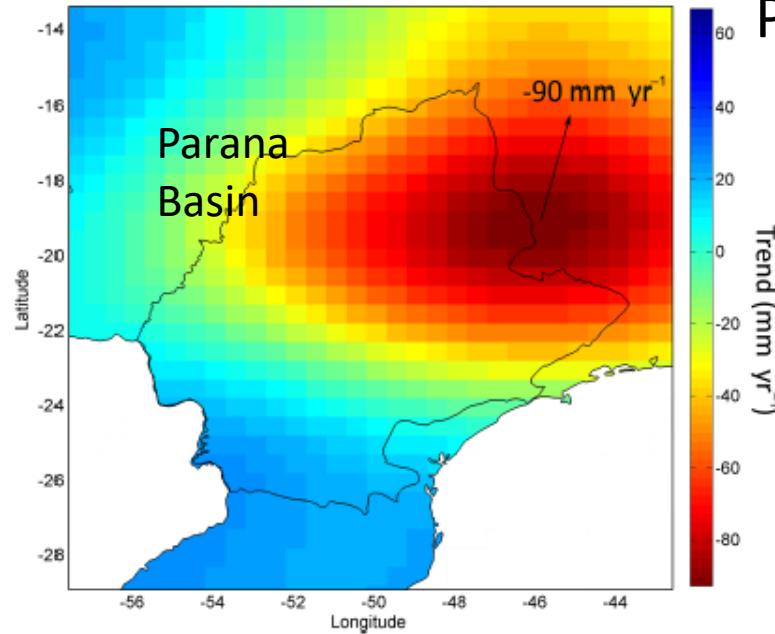
Livable Urban Waterways:
GEOSS project

4.0 Sao Paulo Drought

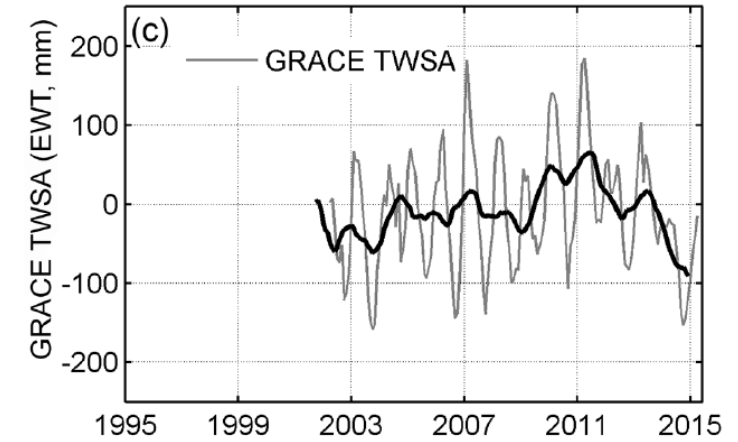
Parana Basin



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



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



TWS depletion: 148 km³ total

2014 – 2017 drought linked to El Nino

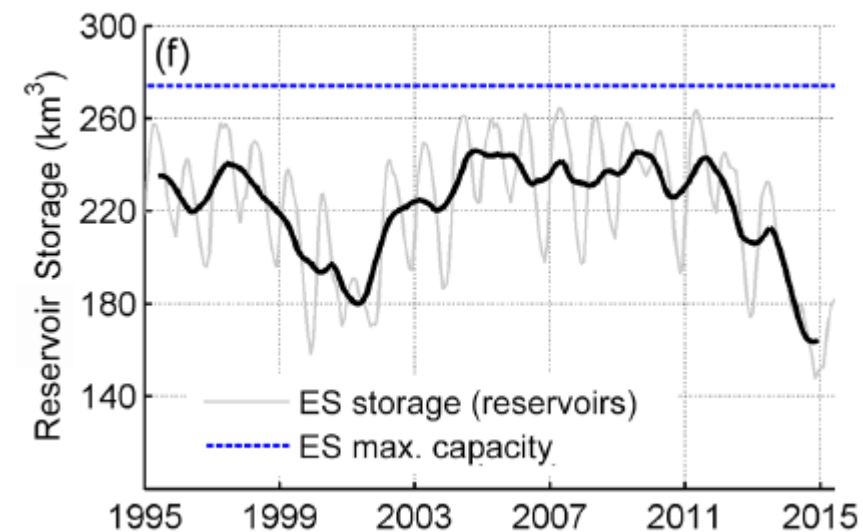
Sao Paulo: SW dominant water source for ~ 20 million people

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

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Water Issues in India and Africa



Alan MacDonald

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.



Groundwater Resilience to Climate Extremes/Change in Tropical Africa



Richard Taylor

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.



Assessing the Barriers to Groundwater Development in Sub-Saharan Africa



Jude Cobbing

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.



Groundwater: Achieving Global Development Goals



Karen Villholth

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.



Role of Groundwater in Developing Countries in the World Bank



Francois Bertone



Lucy Lytton

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



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



Chad Groundwater Well Team

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



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



Rob Hope

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



Drought Forecasting in East Africa



Chris Funk

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.



Addressing Groundwater Scarcity and Arsenic Pollution with Potential Solutions in India



Abhijit Mukherjee

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



Bengal Water Machine



Mohammad Shamsudduha

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.



Linking Water Resource Assessments and Policy to Develop Solutions in India



Veena Srinivasan

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



Beyond Cape Town Day Zero: Strategies to Increase Water Resilience



Dale Barrow

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



South African Lighthouse of Hope from Nature-Based Wastewater Treatment



Kevin Winter

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



Groundwater Resources in Brazil and Potential for Global Food Production



Edson Wendland

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



The Groundwater Resources for Drought Resilience in Urban Areas of Brazil

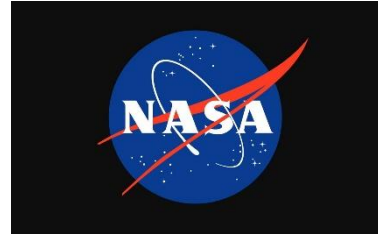


Ricardo Hirata

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



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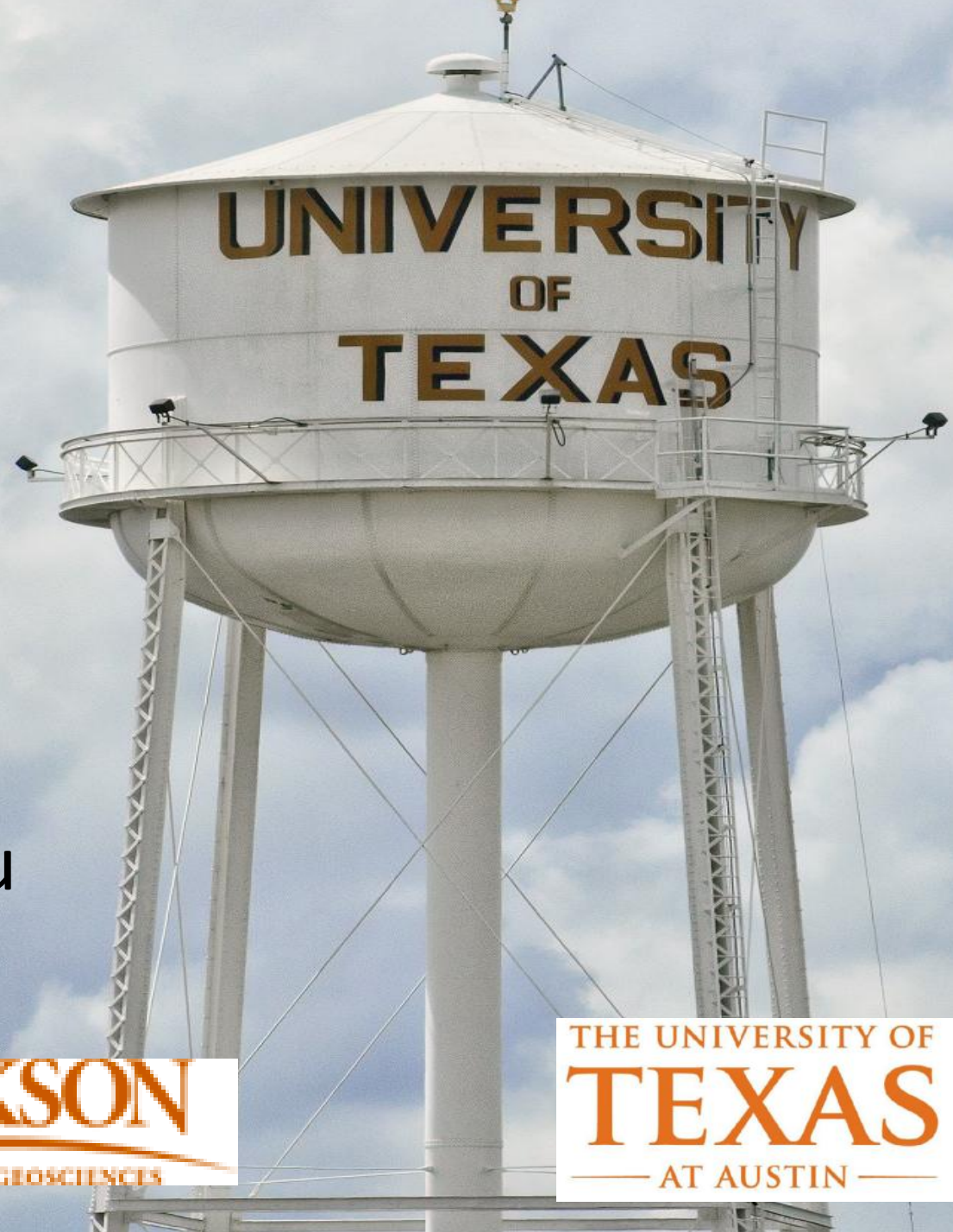
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