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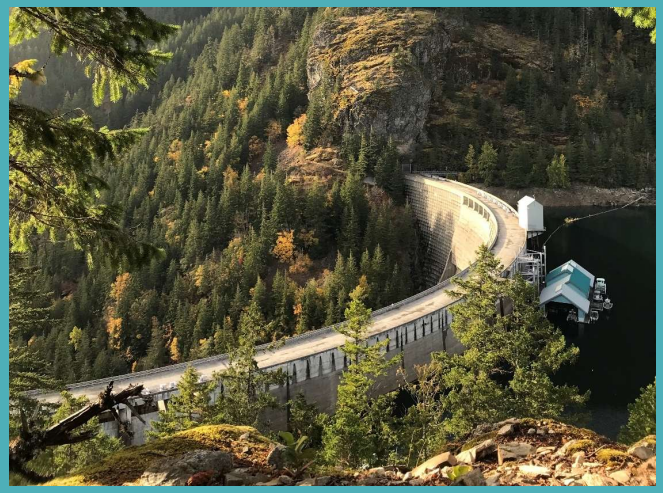

Photo by Ying Zhang

GCIMS/GCAM Modeling of Hydrology and Water for Energy

Thomas B. Wild
Marshall Wise
Mengqi Zhao
Hassan Niazi
Kamal Chowdhury

On behalf of the GCIMS team

GCAM Annual Meeting June 2, 2026

Pacific Northwest NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

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Multisector Modeling of Water and Energy

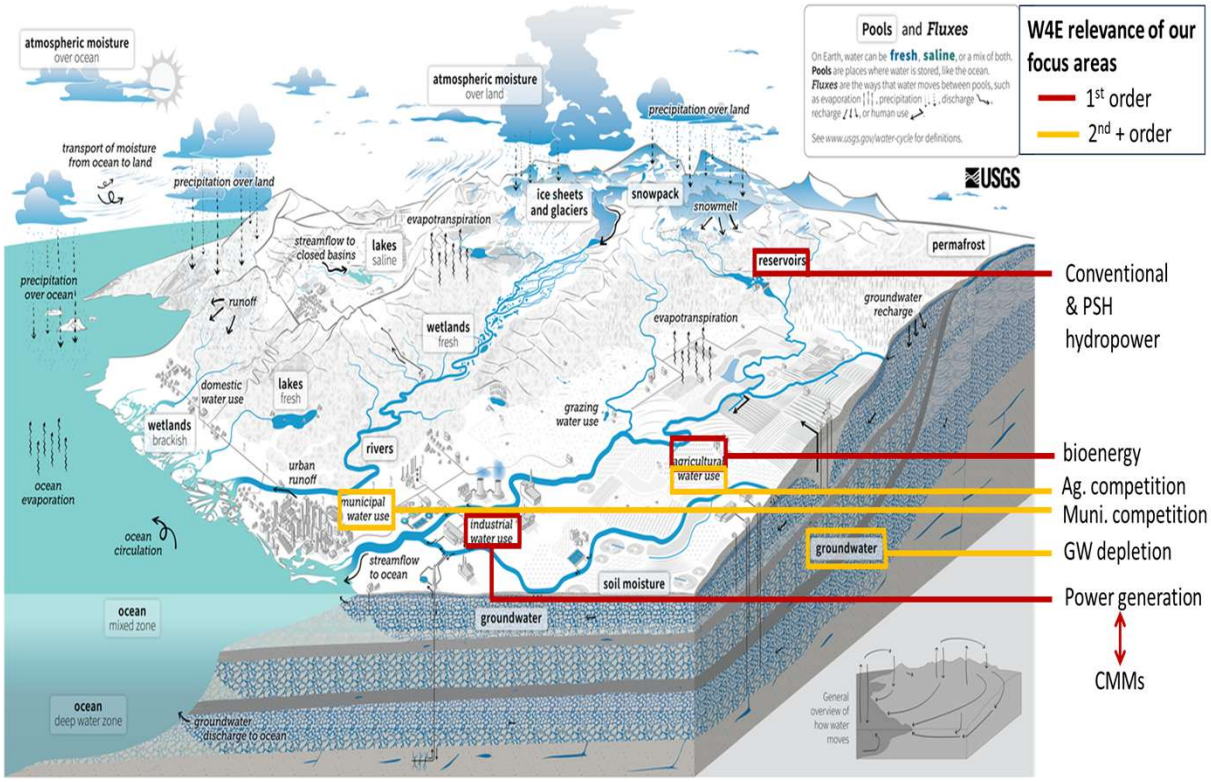

Figure adapted from USGS: : https://www.usgs.gov/water-science-school/science/water-cycle-diagrams

- Water is critical to the reliability of the energy system in many ways.
  - Cooling of thermo-electric power plants.
  - Hydro and geothermal power.
  - Electricity and cooling demands for Datacenters
  - Biological production of fuels and biotechnology products.
- Comprehensive analysis of water for energy requires integration with agriculture, industrial, domestic.
- Water modeling in GCIMS involves several GCIMS models in addition to GCAM.

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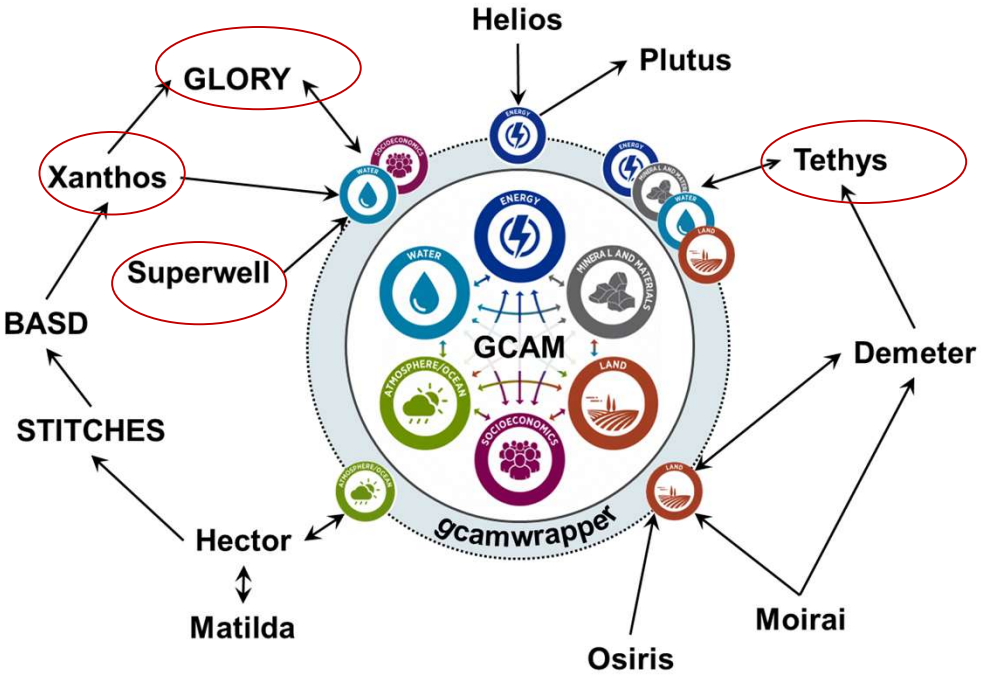
GCIMS Modeling Capabilities: Water Focus



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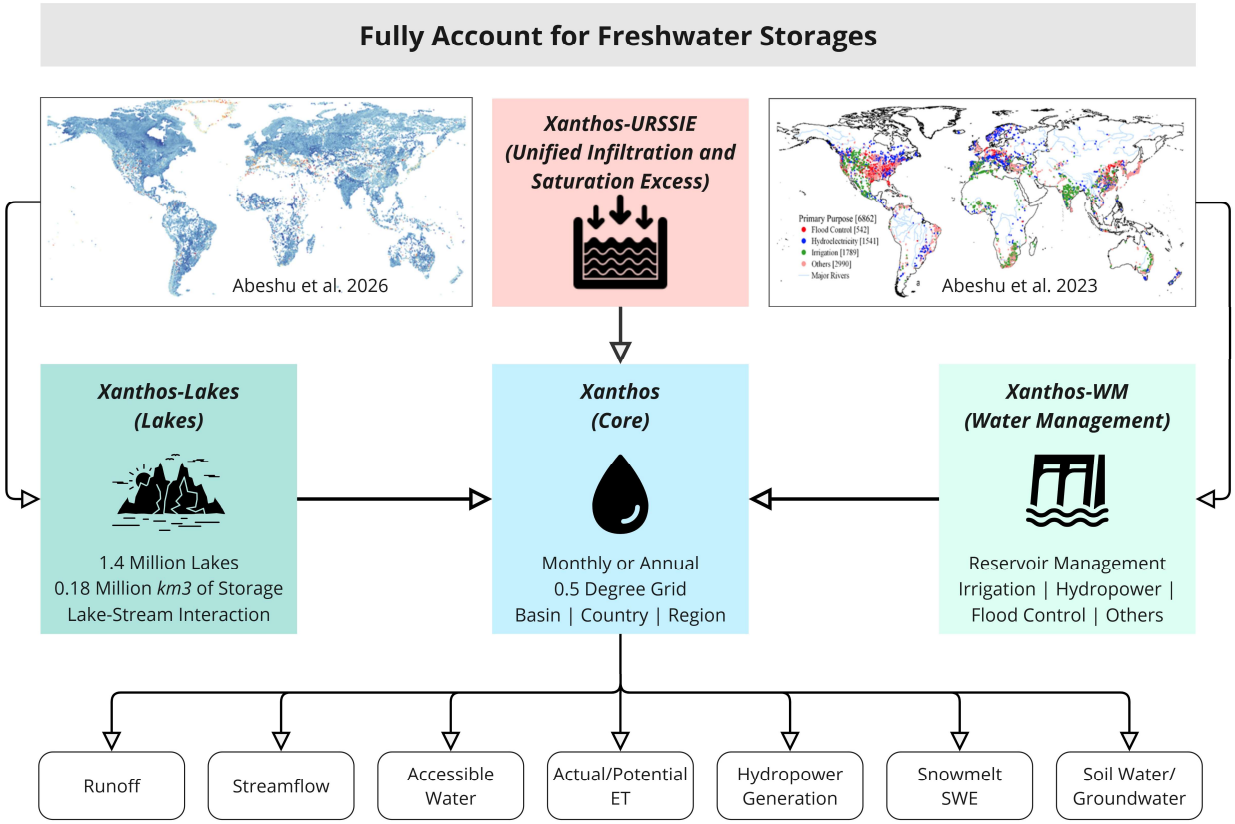
Xanthos: 0.5 Degree Global Hydrology Model

Overview

- Xanthos is a global hydrologic model designed to quantify and analyze global water availability.
- Xanthos-Core simulates historical and future global water availability on a monthly time step at a spatial resolution of 0.5 degree.
- Xanthos includes other modules representing global reservoirs (Xanthos-WM) and lakes (Xanthos-Lakes) to fully capture freshwater storages.
- Xanthos has a finer resolution hydrologic module with unified infiltration and saturation excess runoff (Xanthos-URSSIE).



Aggregated Water Availability from Xanthos to GCAM Water Basins

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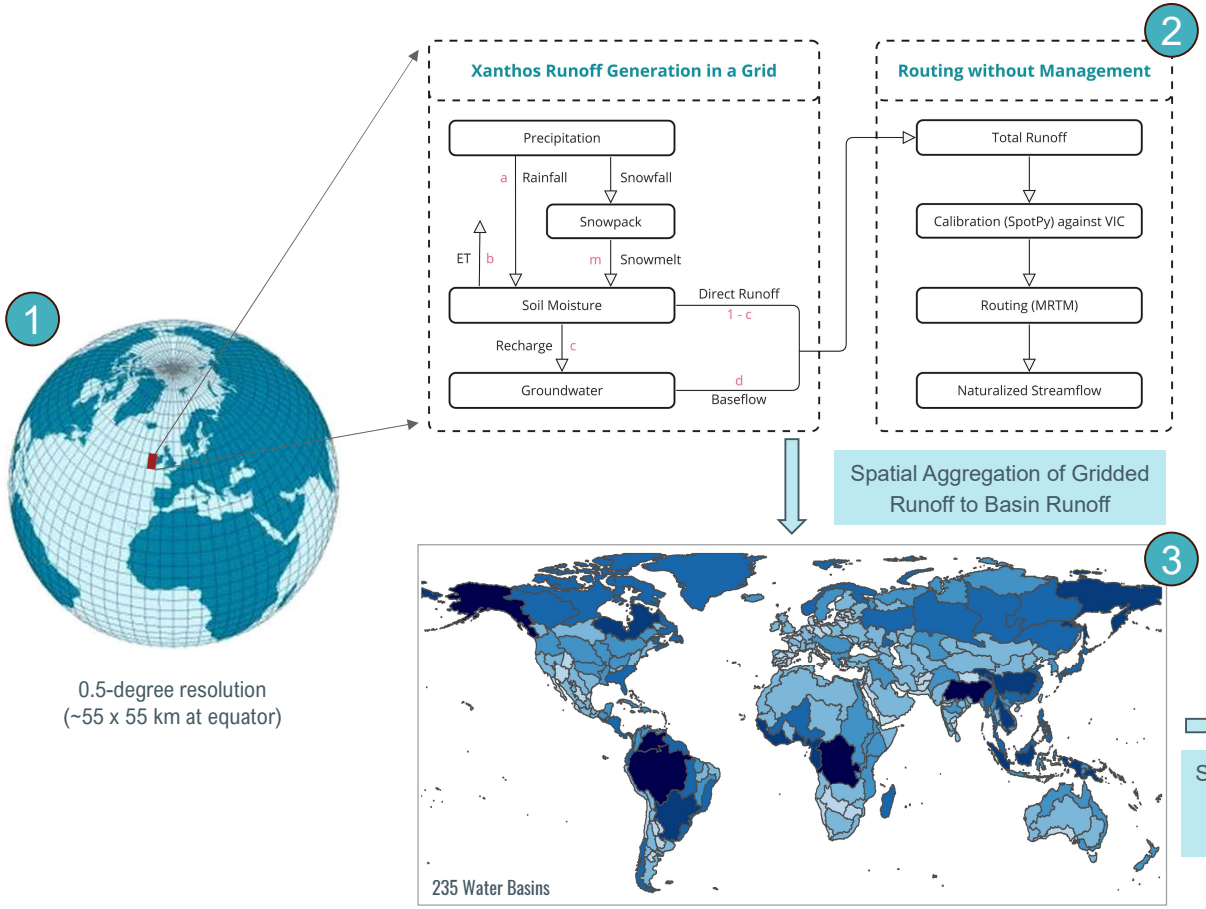
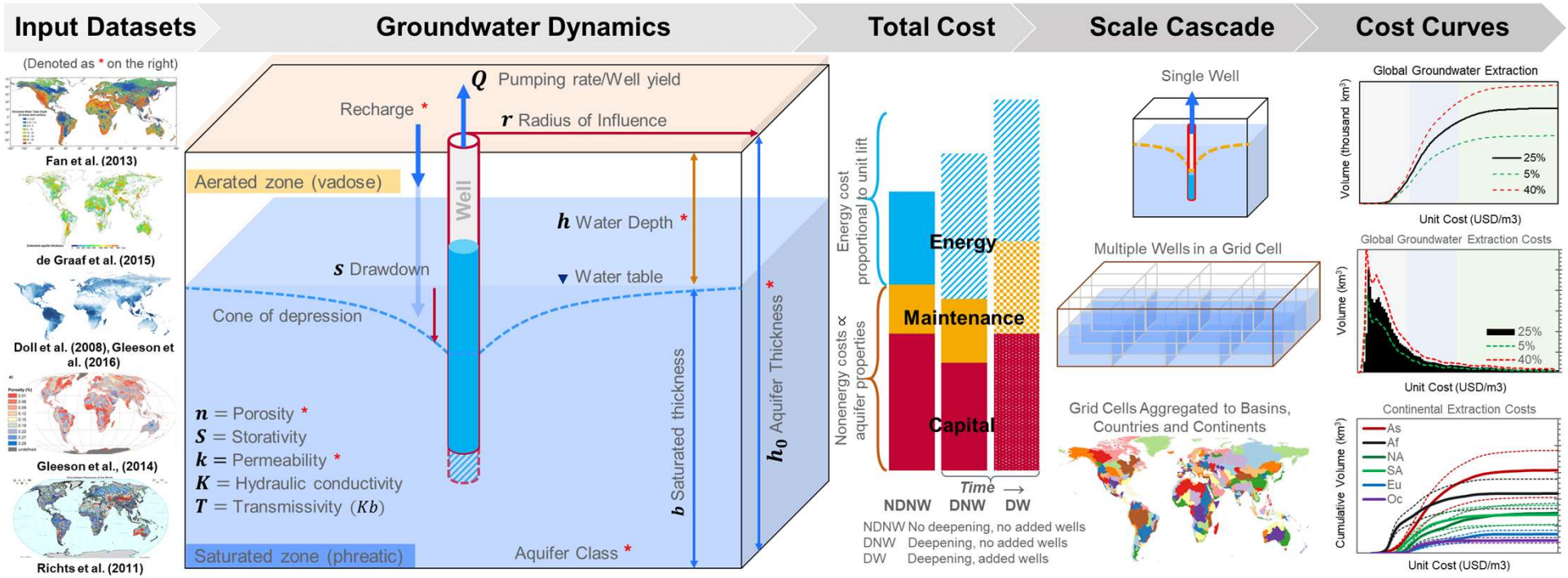


Superwell: Long-term physics-based gridded annual groundwater cost accounting model (Jointly developed with the IM3 project)



INTEGRATED MULTISECTOR MULTISCALE MODELING

Niazi, H., Ferencz, S. B., Graham, N. T., Yoon, J., Wild, T. B., Hejazi, M., Watson, D. J., & Vernon, C. R. (2025). **Long-term hydro-economic analysis tool for evaluating global groundwater cost and supply: Superwell v1.1**. *Geosci. Model Dev.*, *18*(5), 1737-1767. https://doi.org/10.5194/gmd-18-1737-2025

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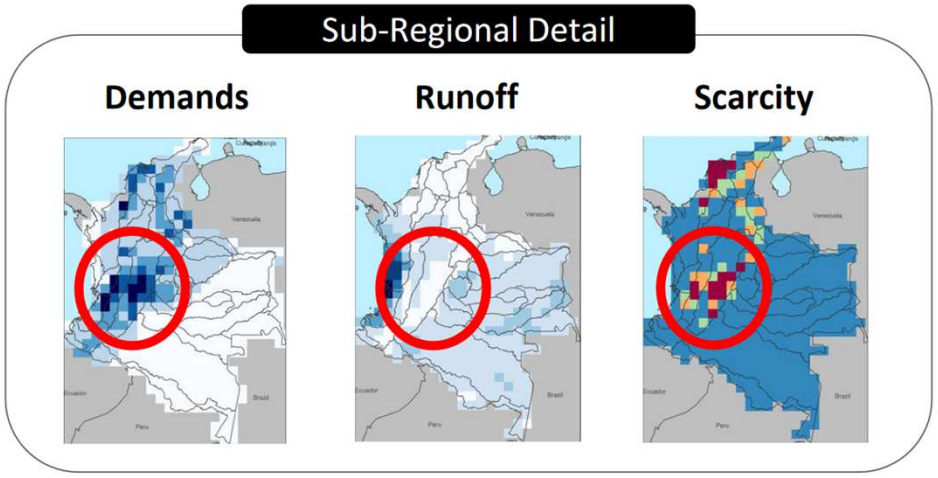
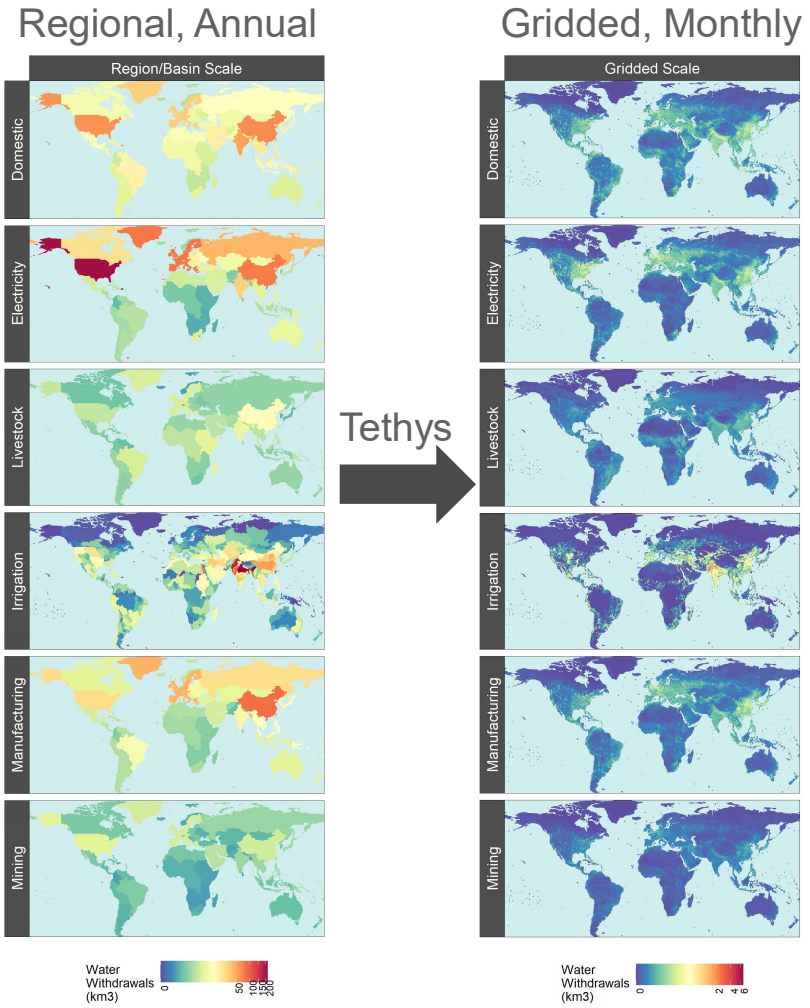
Tethys Model, and Why Downscale?

- Tethys is a spatiotemporal downscaling model for global water demand
- It disaggregates GCAM water withdrawals and consumption across 6 sectors
- Facilitate coupling with gridded hydrology models
- Localized water demand projections are needed to understand water scarcity





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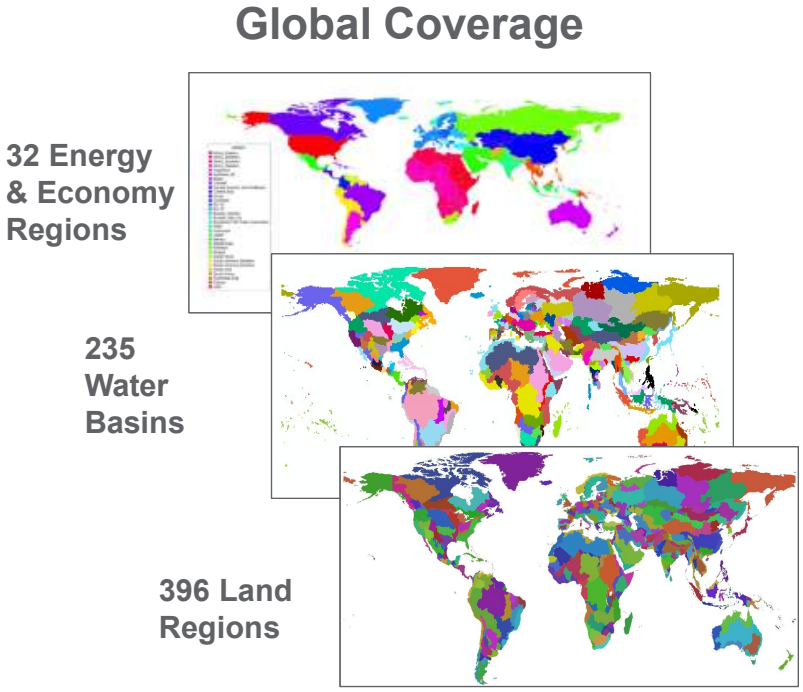
The representation of water in the GCIMS/GCAM

- **Water Resource Parameters:** can be generated at 0.5 degree grids from Xanthos and Superwell.
- **Human-water dynamics**: linking physics and economics to project co-evolution of water supplies (by source), demands (by sector), and cascading MSD impacts
- **Cross-sector competition**: emphasizes how electricity, agriculture, industry, and other users compete for scarce water at basin-to-global scales.
  - Includes energy-for-water and water-for-energy interactions.



- 32 Energy/Economic regions
- 396 Land regions based on water basins

GCAM-USA (50 States + DC)

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The representation of water in the GCIMS/GCAM

- **Water Resource Parameters:** can be generated at 0.5 degree grids from Xanthos and Superwell.
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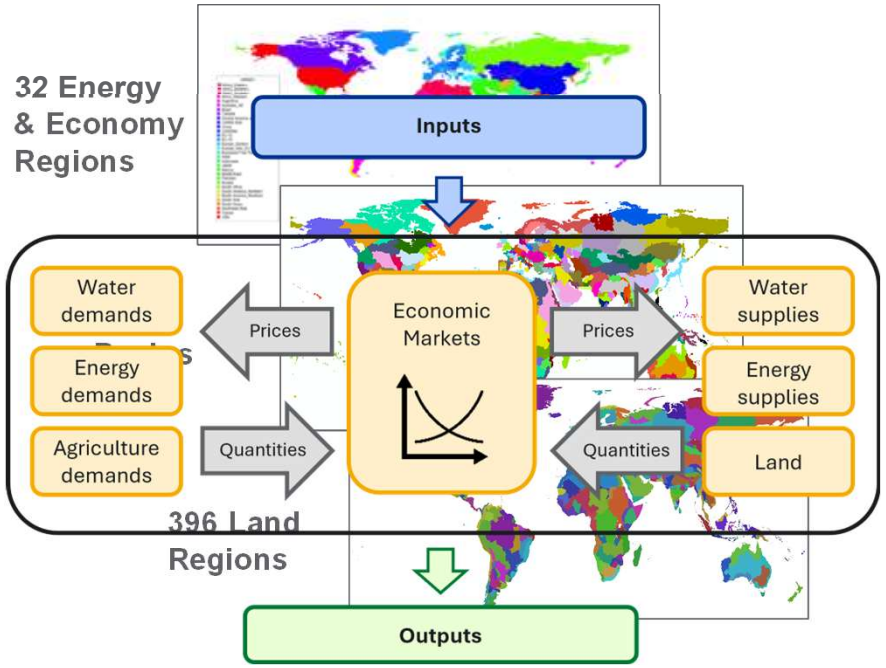
- **Cross-sector competition**: emphasizes how electricity, agriculture, industry, and other users compete for scarce water at basin-to-global scales.
  - Includes energy-for-water and water-for-energy interactions
- **Water allocation:** economic equilibrium and scarcity pricing solved jointly with other markets for 235 basins
  - Approach does not assume perfect markets but lets us calibrate to and capture real-world access to and use of water.
  - Equilibrium represents the competition for scarce resources with water "prices" reflecting the water value at the margin.
- **Timescales**: Approach supports analysis of short-term shocks and variability as well as longer term analyses.

Global Coverage



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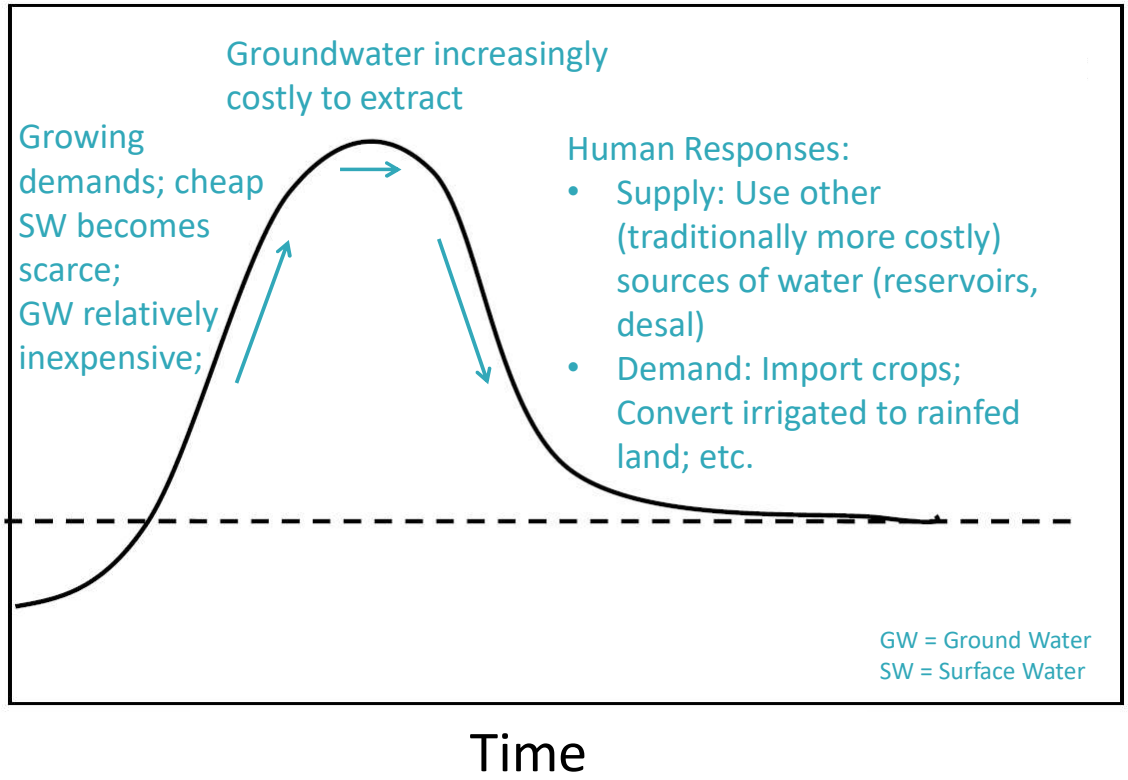
GCAM-USA (50 States + DC)

GCIMS/GCAM Multisectoral Water Analysis: Research Questions from Niazi et al. (2024)

Might future non-renewable (fossil) groundwater extraction peak-and-decline globally?

In which basins might this phenomenon occur, and when?

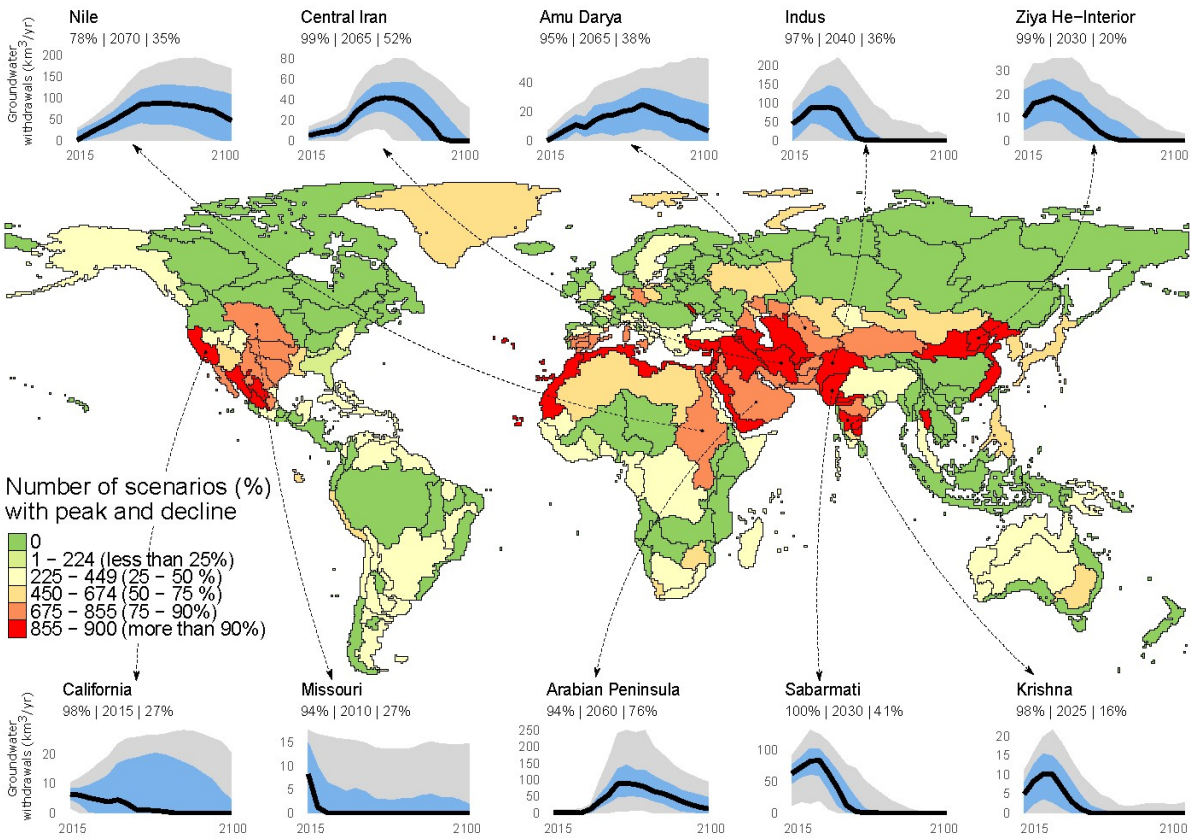
Does this behavior occur robustly across a diverse array of futures?



- Niazi, H., Wild, T.B., Hejazi, M., Graham, N.T., Turner, S.W.D, Lamontagne, J., Zhao, M., Msangi, S., Kim, S. (2024). Global Peak Water Limit of Future Groundwater Withdrawals. Nature Sustainability

Groundwater extraction peaks and declines globally across a large suite of scenarios

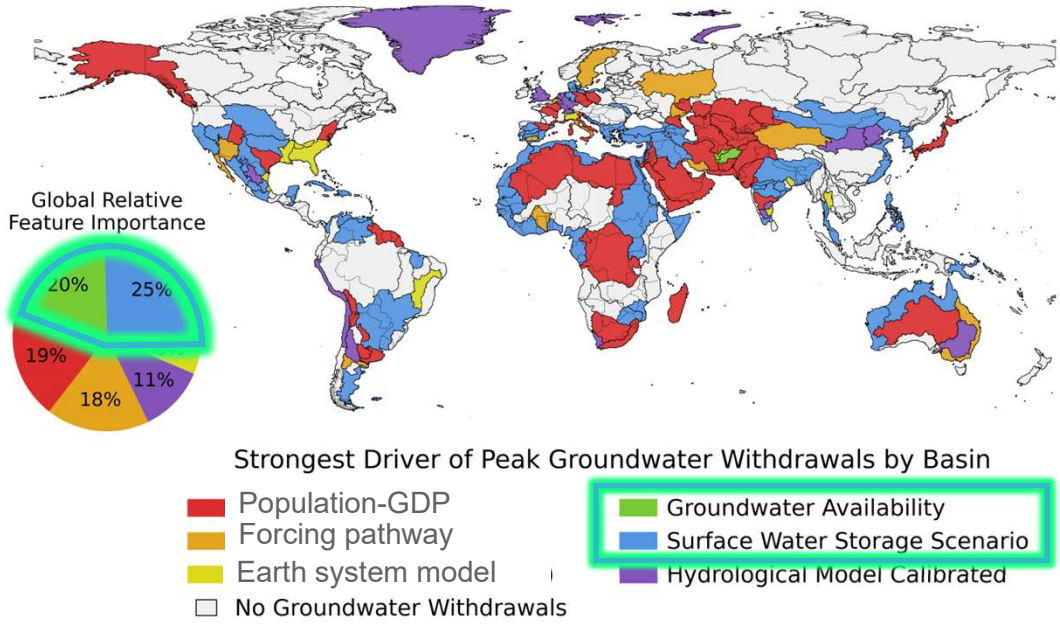
- Groundwater shows a peak and decline pattern, like other depletable natural resources
- Global result is robust across 98% of scenarios
- Peak timing in next 10-30 years in many basins has implications: increasing water prices; shifting crop production and trade patterns
- *This analysis would not be possible without a multisector, global modeling study linking physical resources and economics.*



Niazi et al. (2024), Nat Sust.

Further Exploration of these Scenarios: ML-driven discovery of key drivers of future groundwater Peak-and-Decline

Supply-side drivers (reservoir storage & groundwater restrictions) are not always the dominant drivers for future peaking groundwater use. Population and income growth are the most important in many regions.



Methods: Used **ML-based** Classification and Regression Tree (CART) analysis with a random forest regression to identify the strongest drivers globally and in each basin for peak magnitude and timing.

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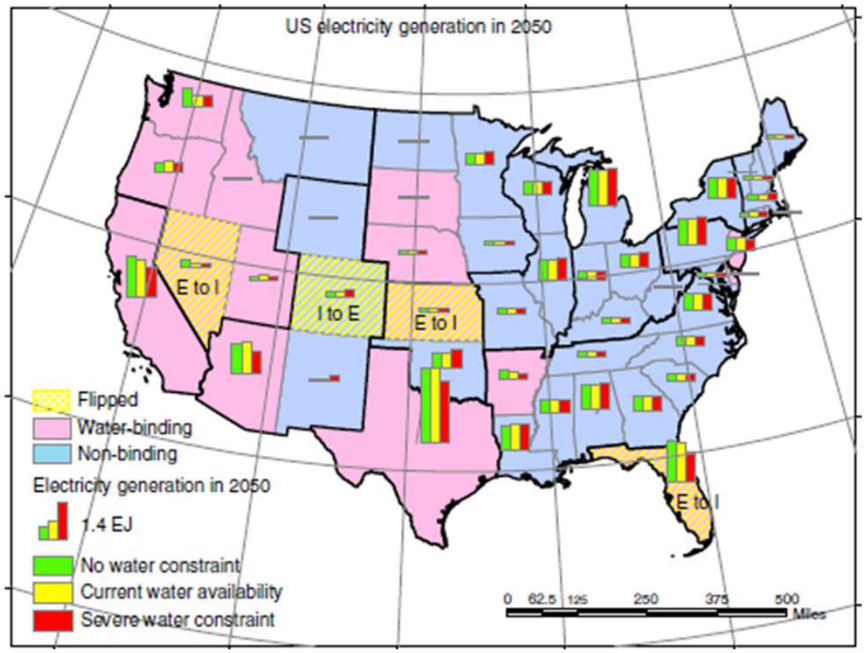
Wild et al. (in prep.)

Current Research: Water availability and consequences for the power grid

Prior GCIMS work shows water impacts on longer-term capacity expansion, relevant for near-term decision making

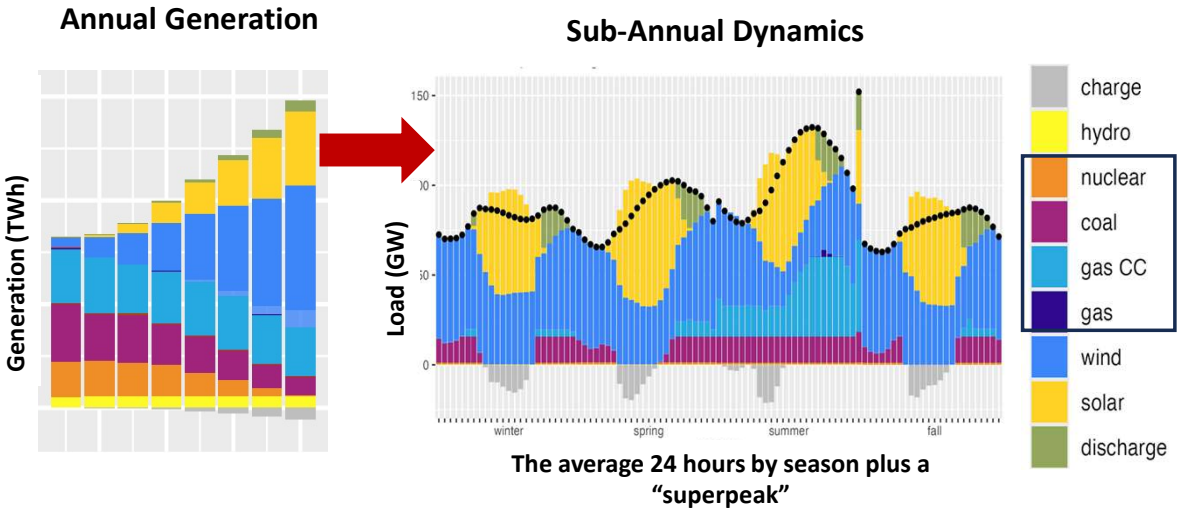


Liu et al, 2019. Implications of water constraints on electricity capacity expansion in the United States. *Nature Sust.*

Latest GCAM-USA (w/ dispatch and storage) can explore impact of hourly→daily→seasonal→annual Δ streamflow & temperature dynamics on both

(1) near-term dispatch,

(2) investments in new capacity (affect the longer-term but are made in the near-term).



The average 24 hours by season plus a "superpeak"

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Current Research: Modeling Geothermal Energy in GCAM-USA

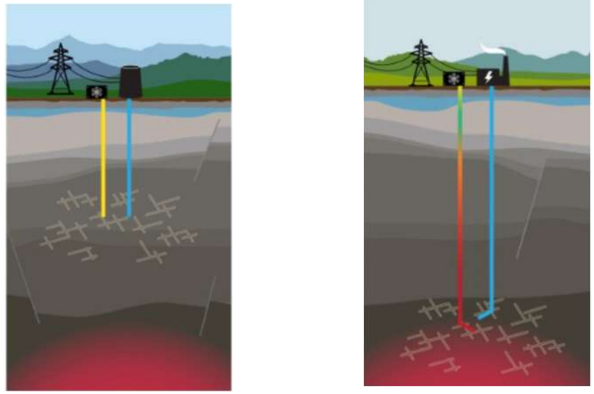
Motivation – respond to new interest for geothermal energy

- Technology developments in Enhanced Geothermal Systems
- Growing needs for reliable electricity
- Potential co-location with data centers

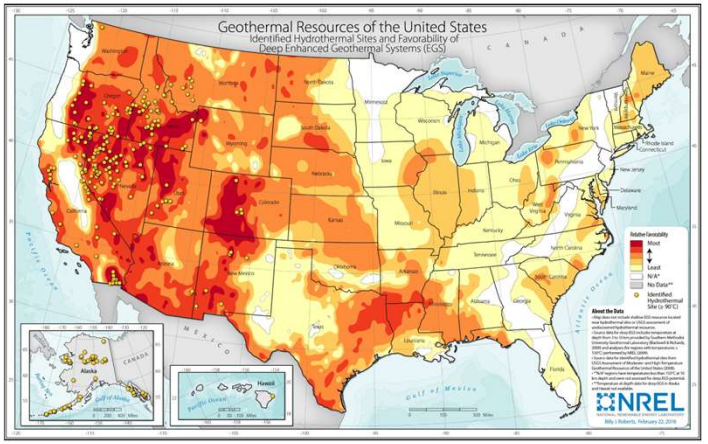
Approach - Explore the potential scale and role of geothermal energy, considering

- Economic competition with other electricity and energy technologies
- Regional heterogeneity in water availability
- Regional heterogeneity in geothermal resources.

Hydrothermal **EGS**



Source: US Department of Energy



Source: **NLOR**, Geothermal Resource Data, Tools, and Maps

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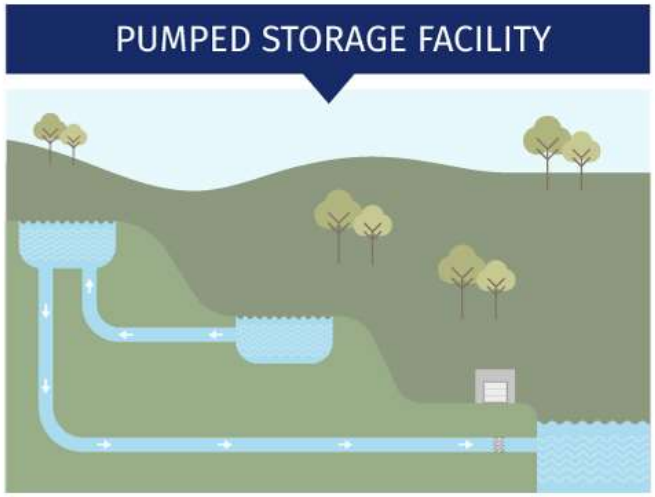
Current Research: Modeling the Hydropower in the integrated context of water availability, water management, demands in the energy system

Conventional Hydro: Energy Generation

- More variable generation due to limited water storage
- Lower cost and impacts (e.g., low water use)

- Storage: Capable of baseload, load following, and peaking
- Higher cost and impacts

Pumped Storage Hydro (PSH): Energy Storage



- Primary role is for Load Following and Peaking
- Potentially longer-duration storage than batteries.

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HydroSMADE: Site-level Monthly Hydropower Availability over 1950-2100

MSD LIVE

Published February 3, 2026 | Version v1

Model Output | File Exploration Enabled | Open

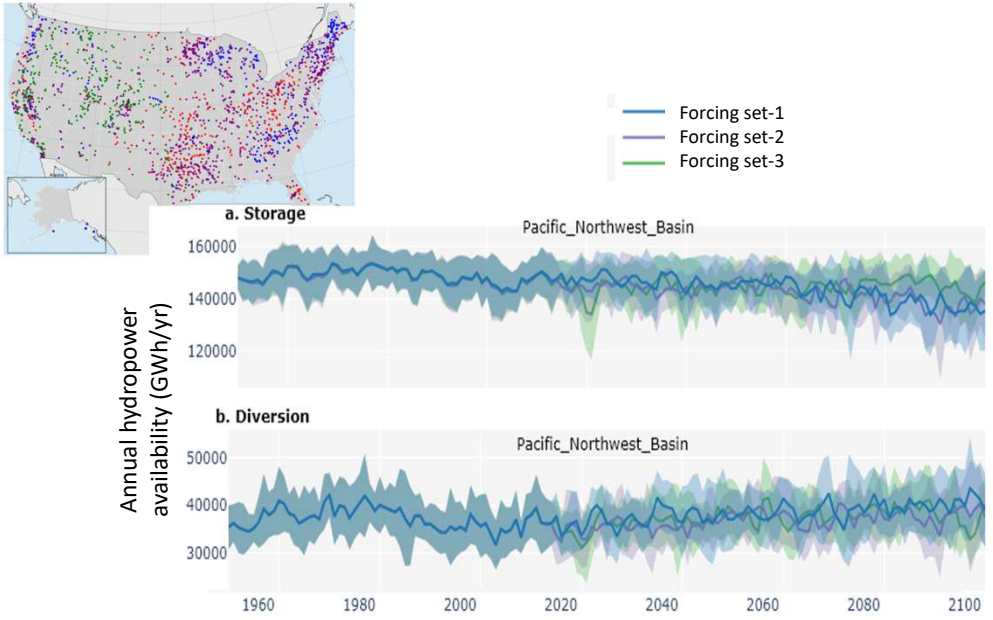
Repository of HydroSMADE: Hydropower Site-level Monthly Availability Data Ensemble for 1950-2100 at Existing and Potential Global Sites

Chowdhury, AFM Kamal; Abeshu, Guta Wakbulcho; Zhao, Mengqi; Wild, Thomas B; Niazi, Hassan; Zhang, Ying; Kim, Gi Joo; Binsted, Matthew; Lamontagne, Jonathan; Li, Hong-Yi

Show details

Description

This repository presents HydroSMADE—Hydropower Site-level Monthly Availability Data Ensemble, a new open dataset that provides monthly hydropower availability for 1,593 existing and 124,333 potential sites worldwide over the period 1950–2100. The dataset is generated by using a global hydrologic model (Xanthos) with explicit representation of hydropower operation. Specifically, HydroSMADE distinguishes between storage and diversion sites, applies optimized operating rules, and incorporates site-specific characteristics such as generation capacity, maximum turbine flow, and reservoir storage.



- HydroSMADE data is freely available on MSD-Live.
- Details on the methods and technical validation are provided in *Chowdhury et al. (in review)*.

- 30 scenarios represent a wind-range of future hydrologic conditions.

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Thank you

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Massachusetts Institute of Technology
Tufts UNIVERSITY
UCDAVIS UNIVERSITY OF CALIFORNIA
WESTERN WASHINGTON UNIVERSITY
UNIVERSITY of HOUSTON
UNIVERSITY OF MARYLAND