

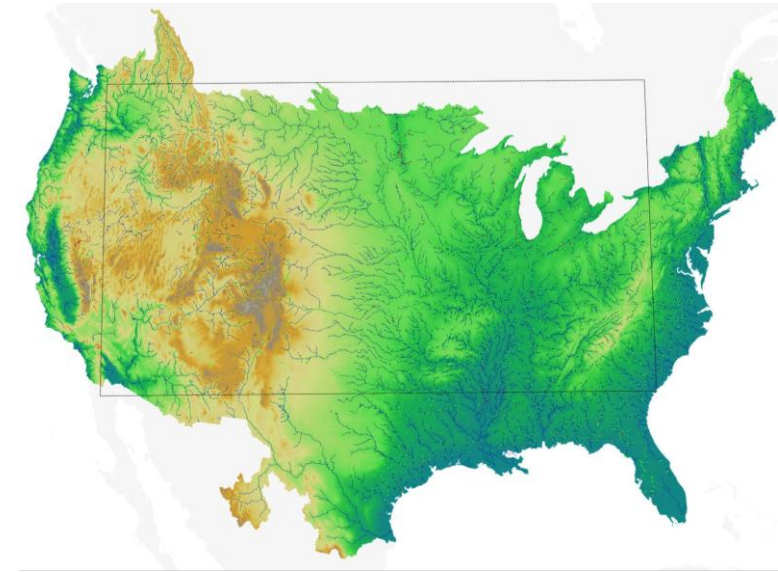
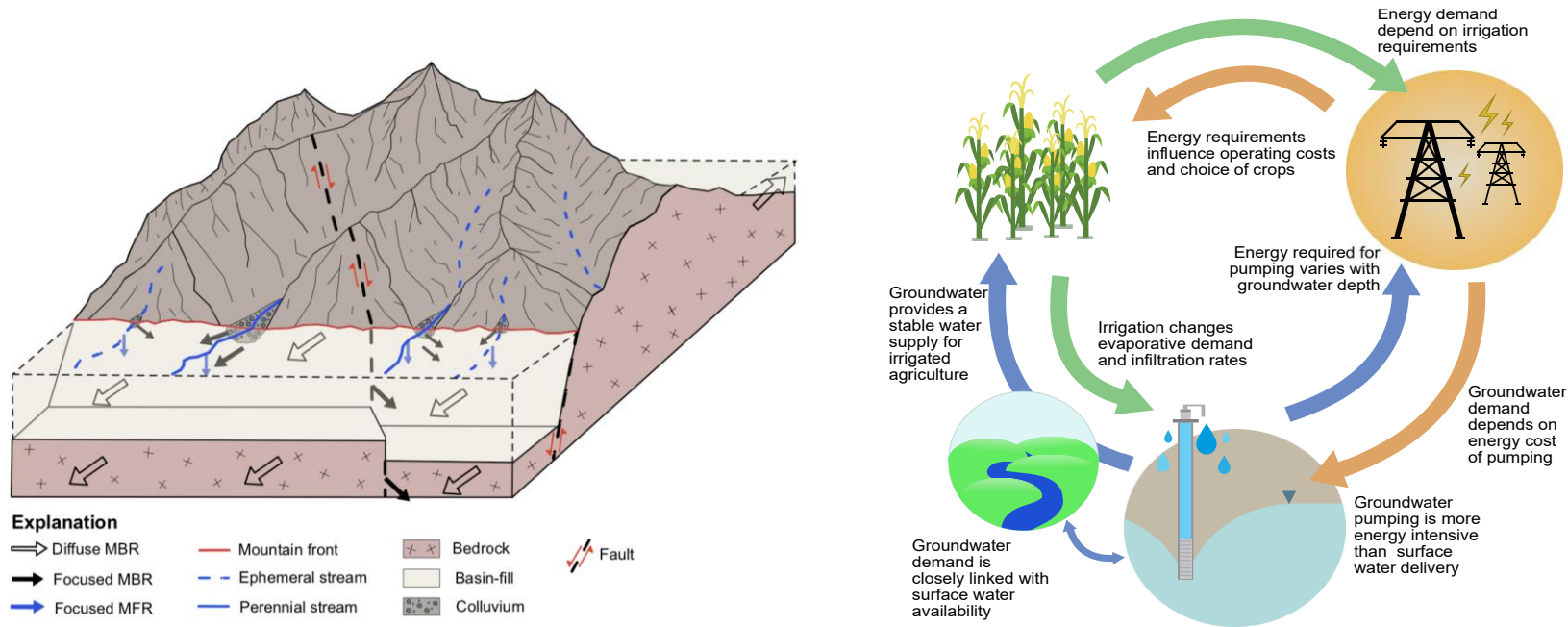
An aerial photograph showing a dark, winding river or stream cutting through a vast, dense green forest. The river forms several loops and meanders, creating a complex pattern against the textured green canopy. The lighting suggests a low sun, casting long shadows and highlighting the edges of the trees.

A national platform for groundwater surface water modeling and exploration

Laura Condon
University of Arizona

Research Insights in Semiarid
Ecosystems (RISE) Symposium
University of Arizona
Sept 26, 2026

I primarily research the role of groundwater in the terrestrial hydrologic cycle



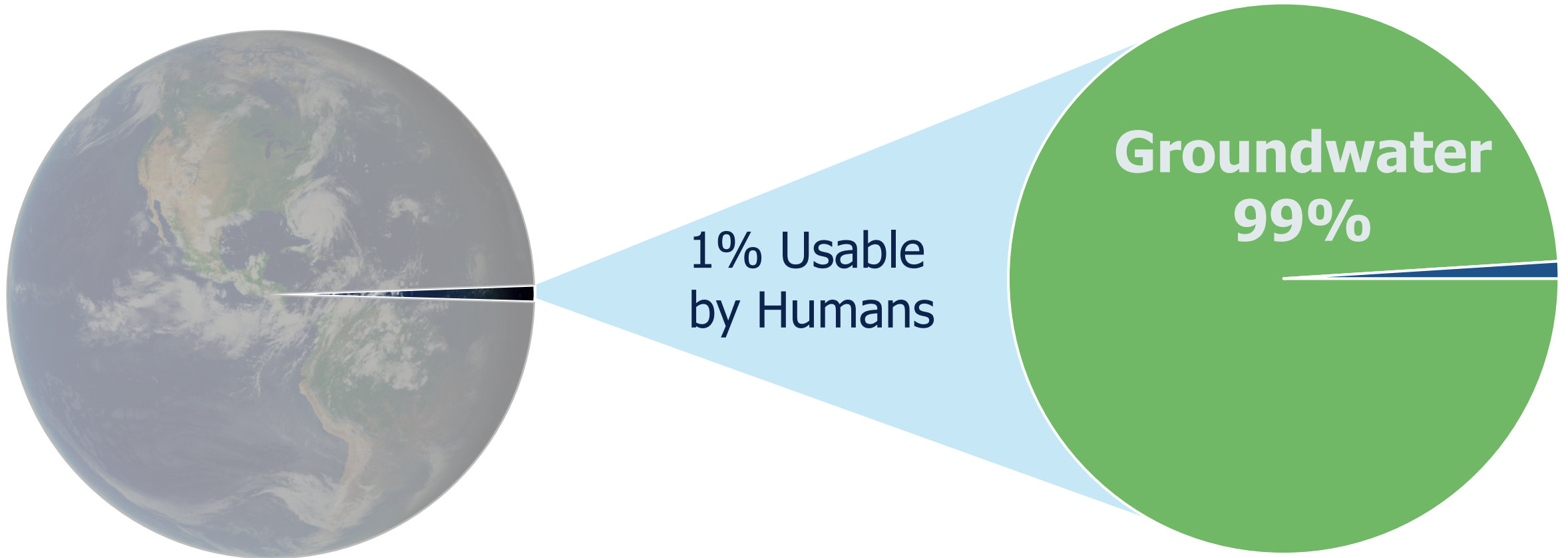
Groundwater surface
water interactions and
watershed dynamics

The role of human
management and
groundwater in the Food-
Energy-Water Nexus

Past and future national
hydrology from the
bedrock to the
treetops

Groundwater is by far our largest groundwater resource, **it is literally everywhere all the time**

All Water on Earth



But it's also
old and slow.

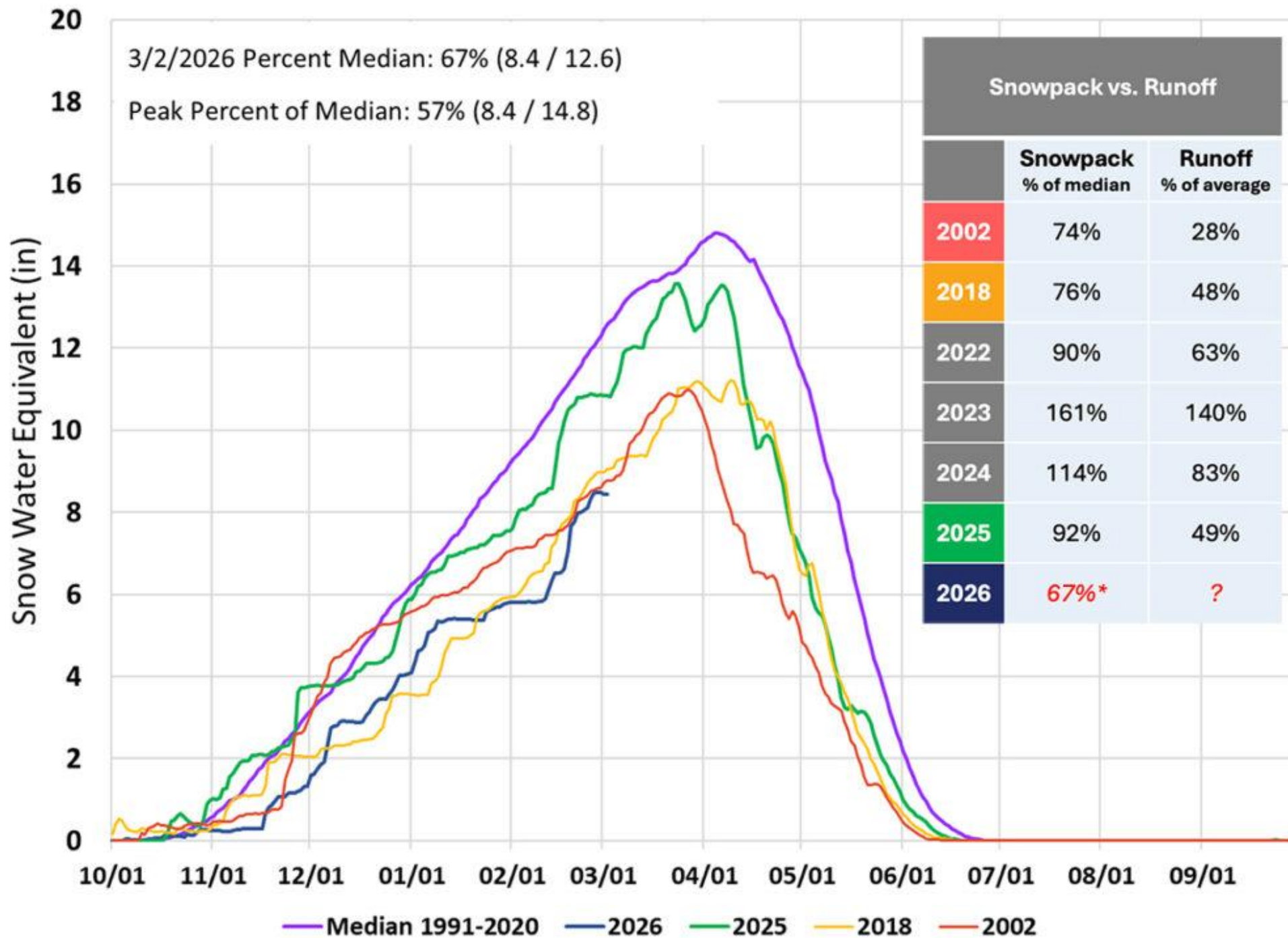
**Do we really need
to worry about
groundwater
dynamics?**



Yes! We really do.



Groundwater and the Colorado River



What does Groundwater have to do with this?

The importance of base flow in sustaining surface water flow in the Upper Colorado River Basin

Matthew P. Miller¹, Susan G. Buto², David D. Susong¹, and Christine A. Rumsey¹

¹US Geological Survey, Utah Water Science Center, Salt Lake City, Utah, USA, ²US Geological Survey, Nevada Water Science Center, Carson City, Nevada, USA

“...56% of the streamflow in the UCRB originated as baseflow...”

Geophysical Research Letters*

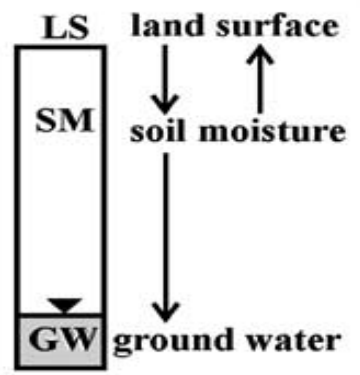
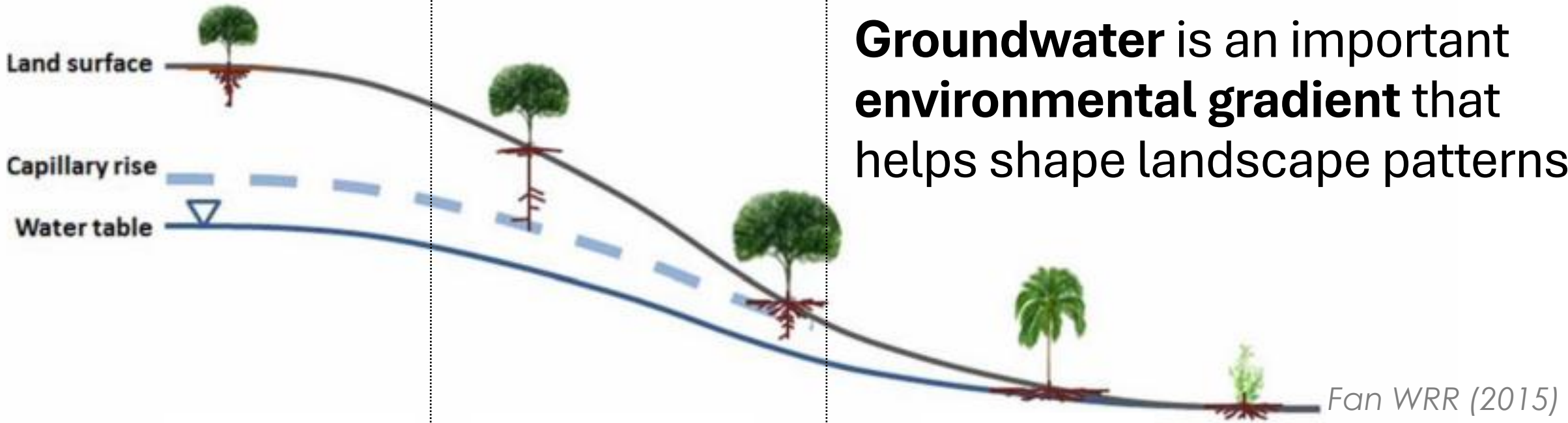
Research Letter |  Open Access |  

How Will Baseflow Respond to Climate Change in the Upper Colorado River Basin?

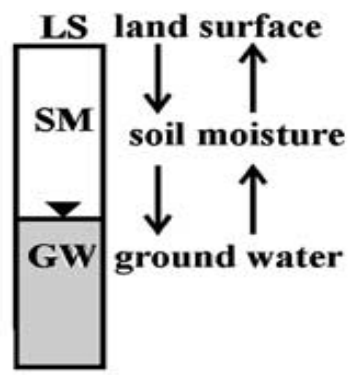
Olivia L. Miller✉, Matthew P. Miller, Patrick C. Longley, Jay R. Alder, Lindsay A. Bearup, Tom Pruitt, Daniel K. Jones, Annie L. Putman, Christine A. Rumsey, Tim McKinney

Baseflow could decline by up to 33% in the future

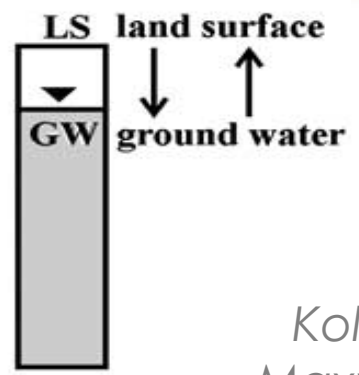
Groundwater is an important **environmental gradient** that helps shape landscape patterns



Water
Limited



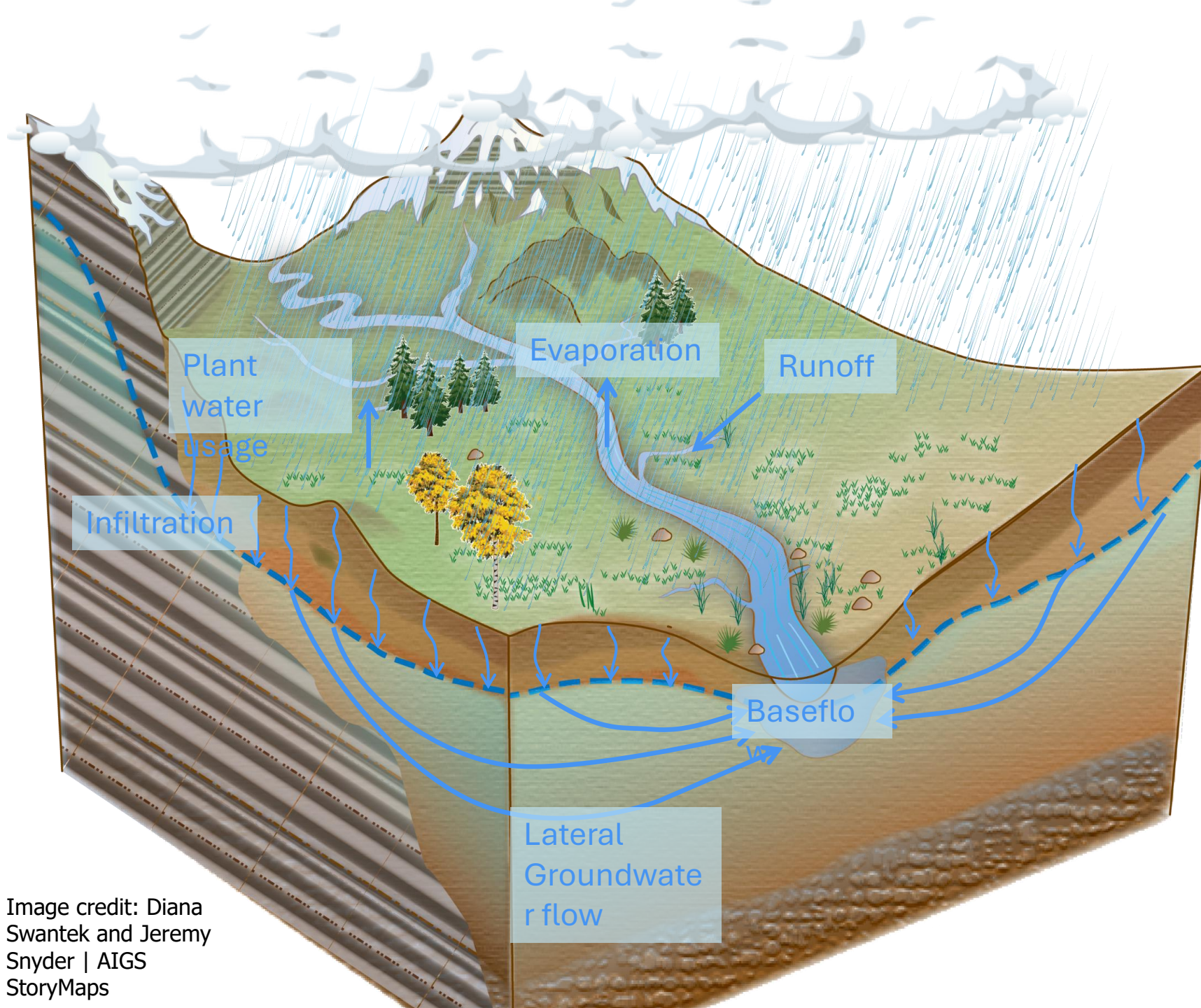
Groundwater
Controlled



Energy
Limited

Kollet and Maxwell WRR (2008)
Maxwell and Kollet NGeo (2008)

Groundwater Flow



Lateral groundwater flow redistributes water across the landscape closing the terrestrial water balance

Groundwater is slow moving and buffering changes surface water dynamics

- Hydrologic sensitivity to climate variability can vary with water table depth and groundwater dynamics
- Groundwater storage response to climate perturbations and streamflow response to groundwater storage changes are both asymmetric and can lead to persistent trends (*Eltahir and Yeh, 1999; Istanbulluoglu et al., 2012*)
- Baseflow decreases short-term variability and increases long-term autocorrelation (*Kustu et al, 2010*)



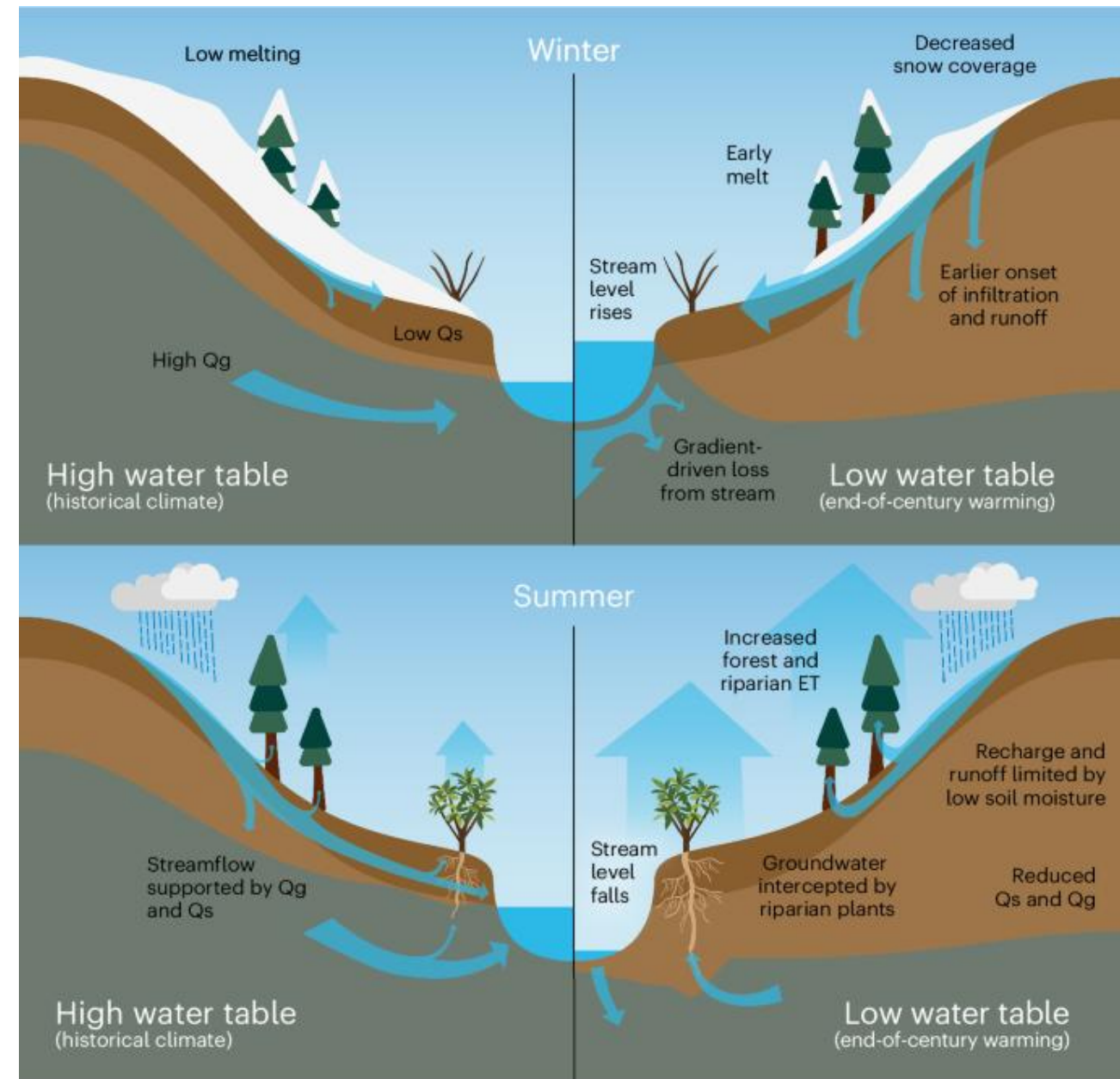
As the basin warms:

1. Increase forest water use reduces GW recharge
2. Results in GW storage loss
3. Severe losses in dry years will not be made up for in wet periods
4. Groundwater depletion reduces streamflow

Declining groundwater storage expected to amplify mountain streamflow reductions in a warmer world

[Rosemary W. H. Carroll](#) , [Richard G. Niswonger](#), [Craig Ulrich](#), [Charuleka Varadharajan](#), [Erica R. Siirila-Woodburn](#) & [Kenneth H. Williams](#)

[Nature Water](#) 2, 419–433 (2024) | [Cite this article](#)

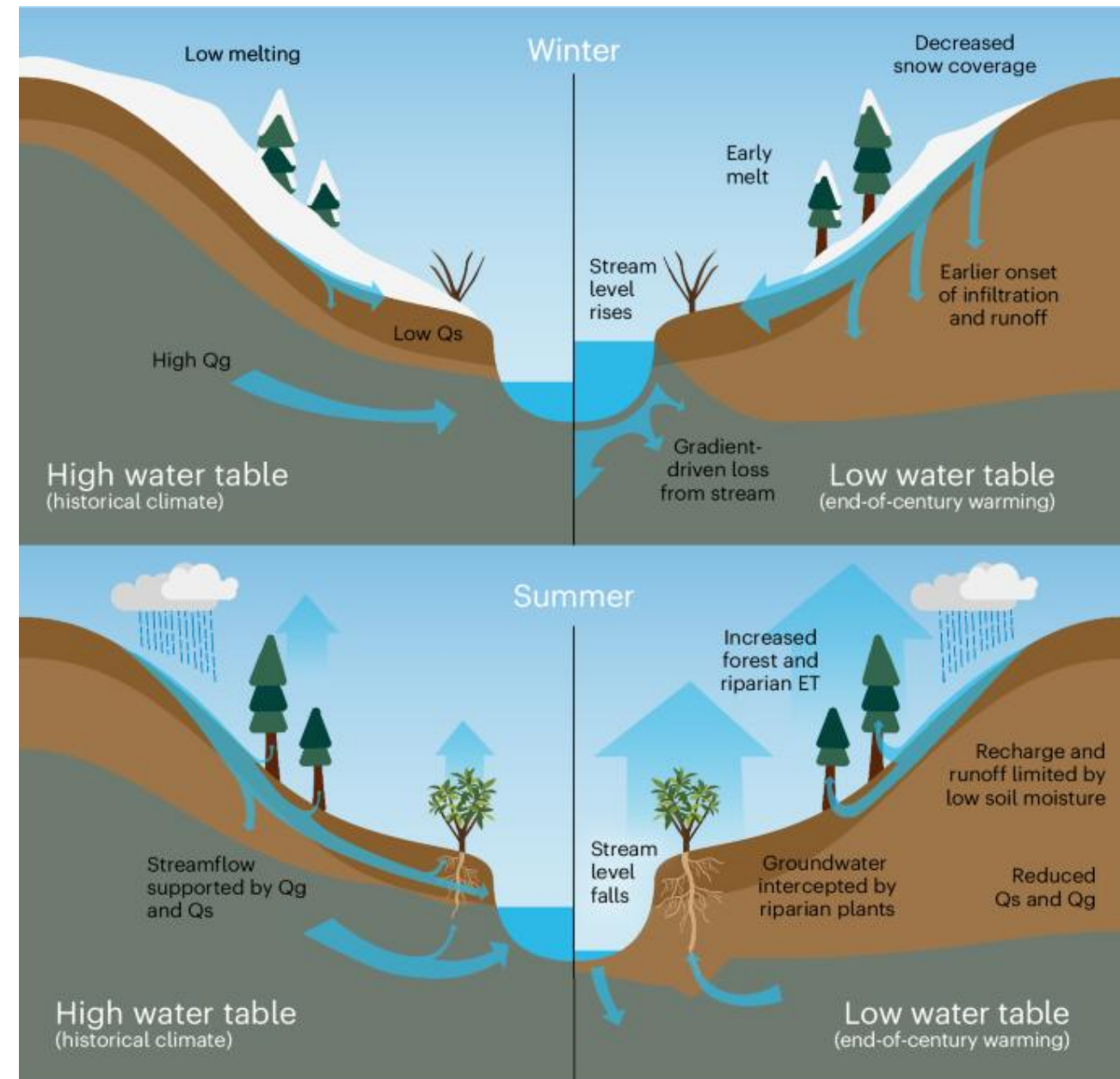


“Groundwater interactions with mountain streams are often simplified in model projections, potentially leading to inaccurate estimates of streamflow response to climate change.”

Declining groundwater storage expected to amplify mountain streamflow reductions in a warmer world

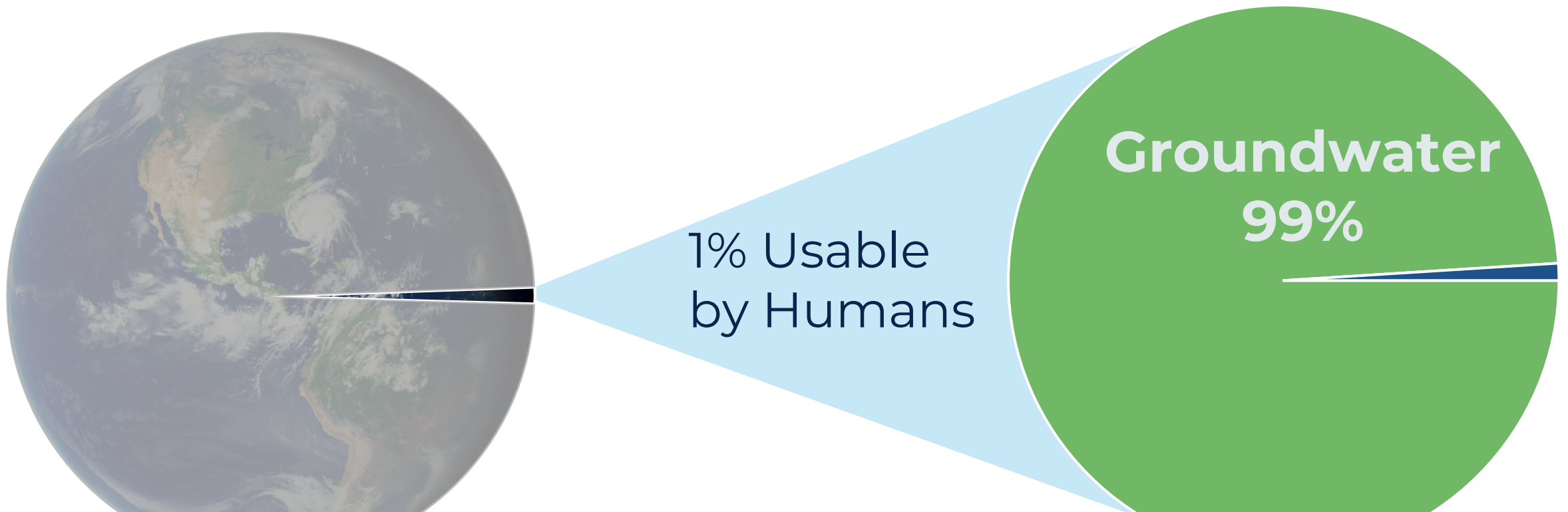
[Rosemary W. H. Carroll](#) , [Richard G. Niswonger](#), [Craig Ulrich](#), [Charuleka Varadharajan](#), [Erica R. Siirila-Woodburn](#) & [Kenneth H. Williams](#)

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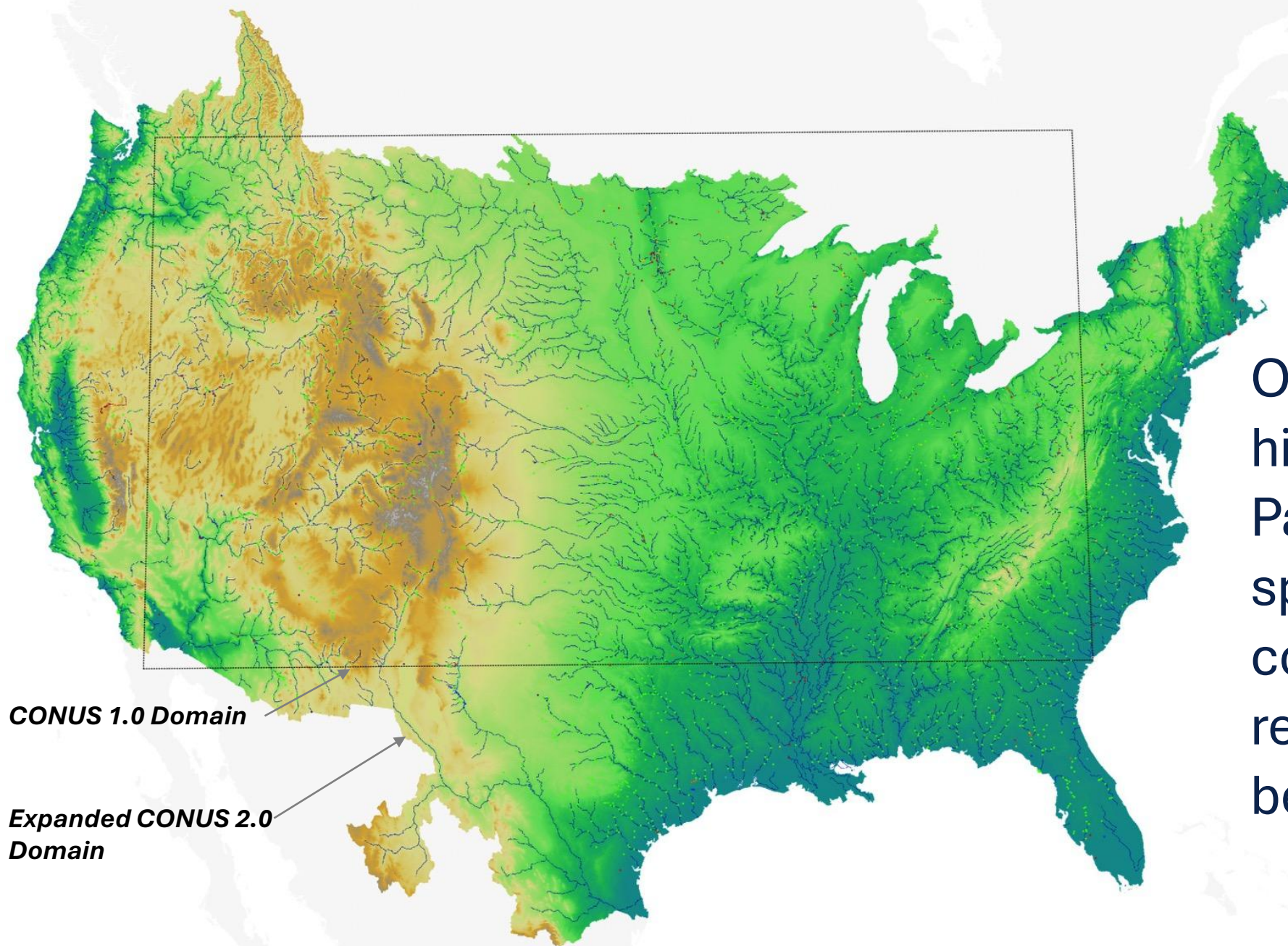
We know that groundwater is by far our largest freshwater resource

All Water on Earth



Yet is is sparsely observed and highly uncertain

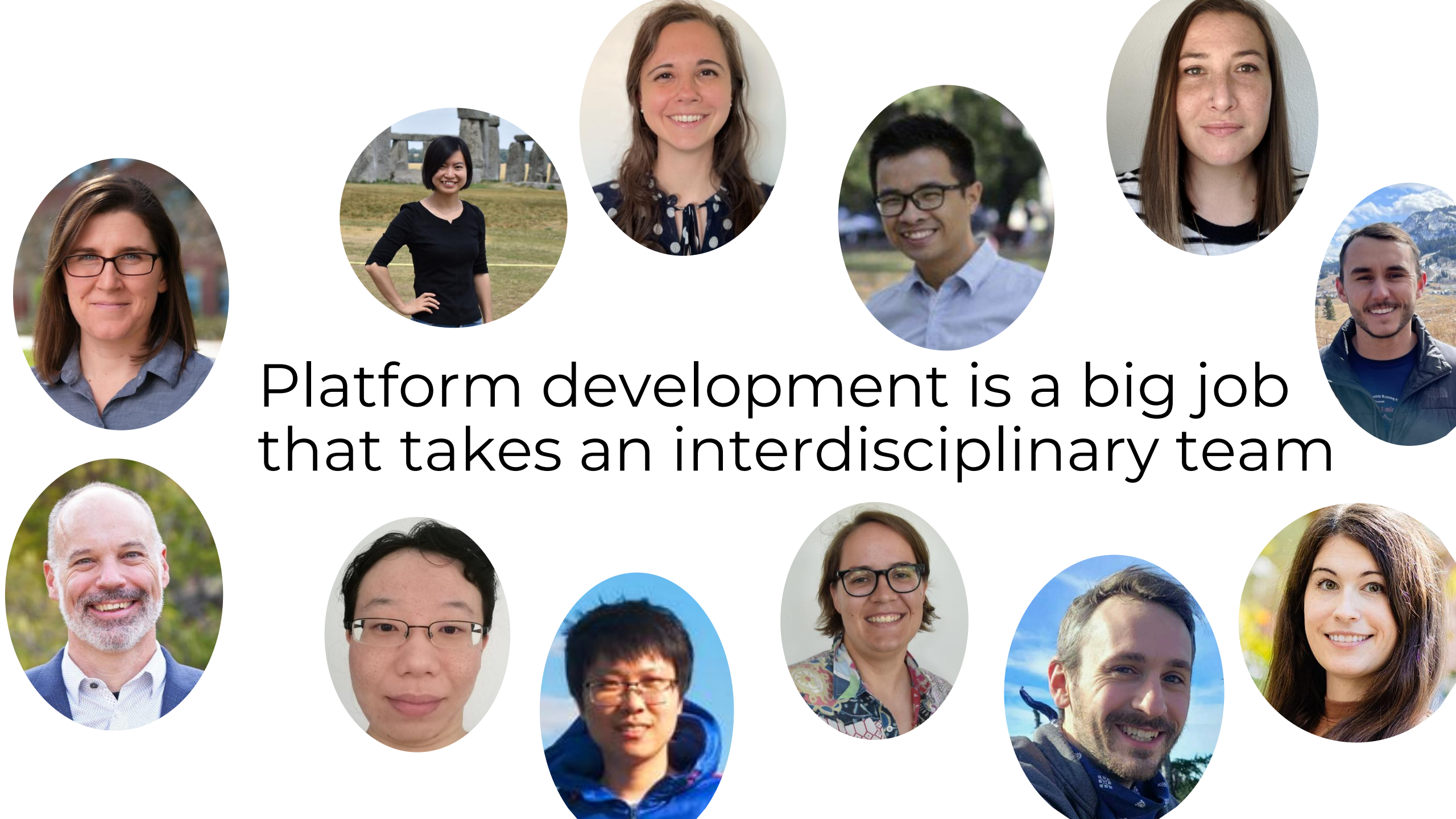
We build models



CONUS 1.0 Domain

Expanded CONUS 2.0 Domain

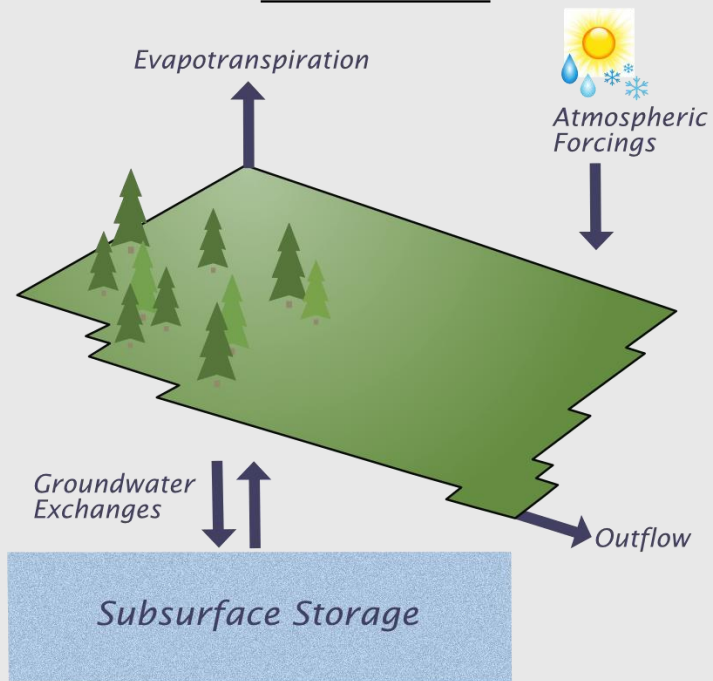
Our team develops a high resolution national ParFlow model spanning the entire contiguous US at 1km resolution from bedrock to treetops



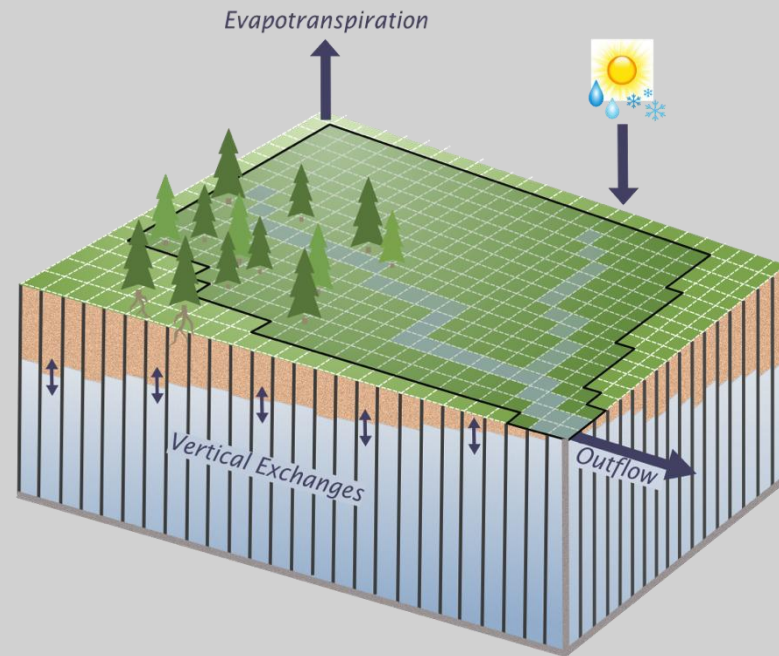
Platform development is a big job
that takes an interdisciplinary team

We build models

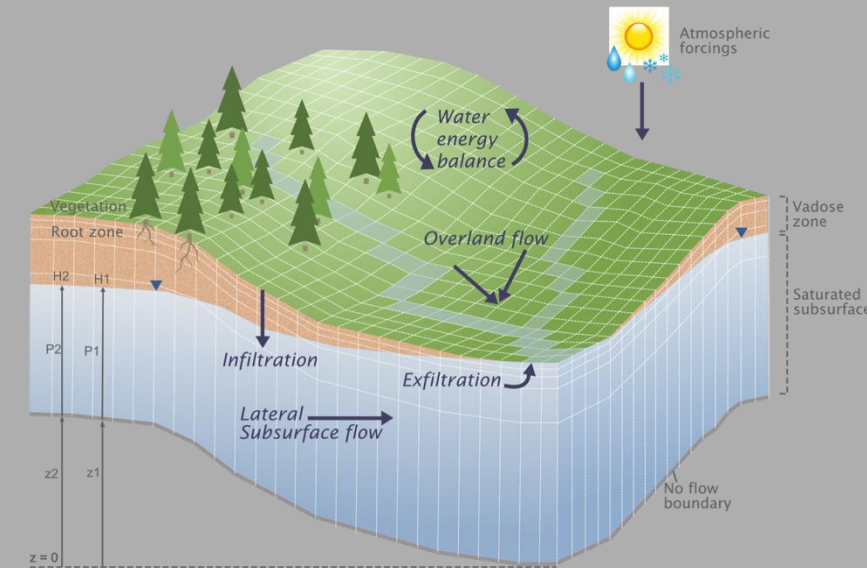
Lumped Parameter Model



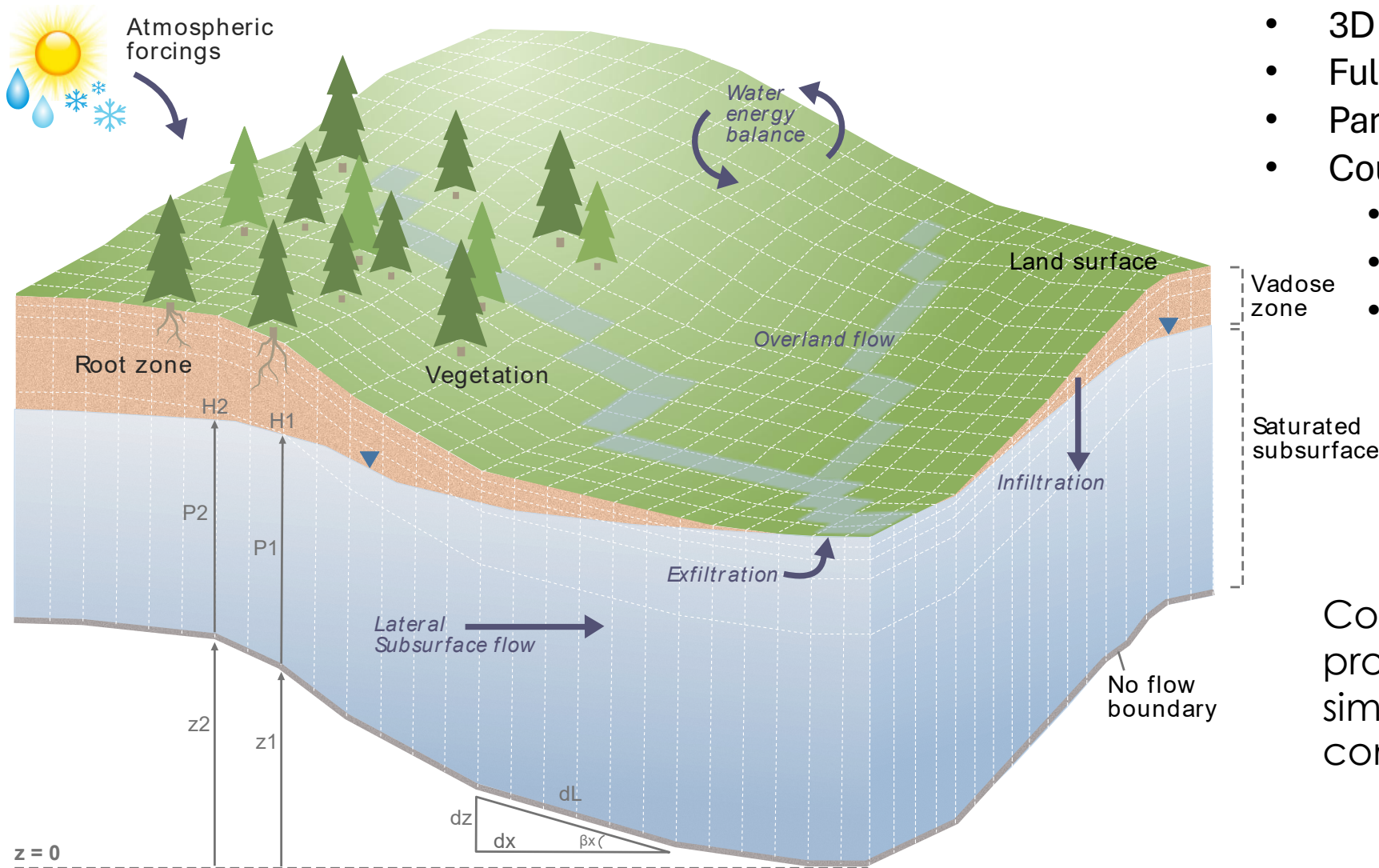
Land Surface Model



Integrated Model



Our national platform uses the integrated hydrologic model ParFlow

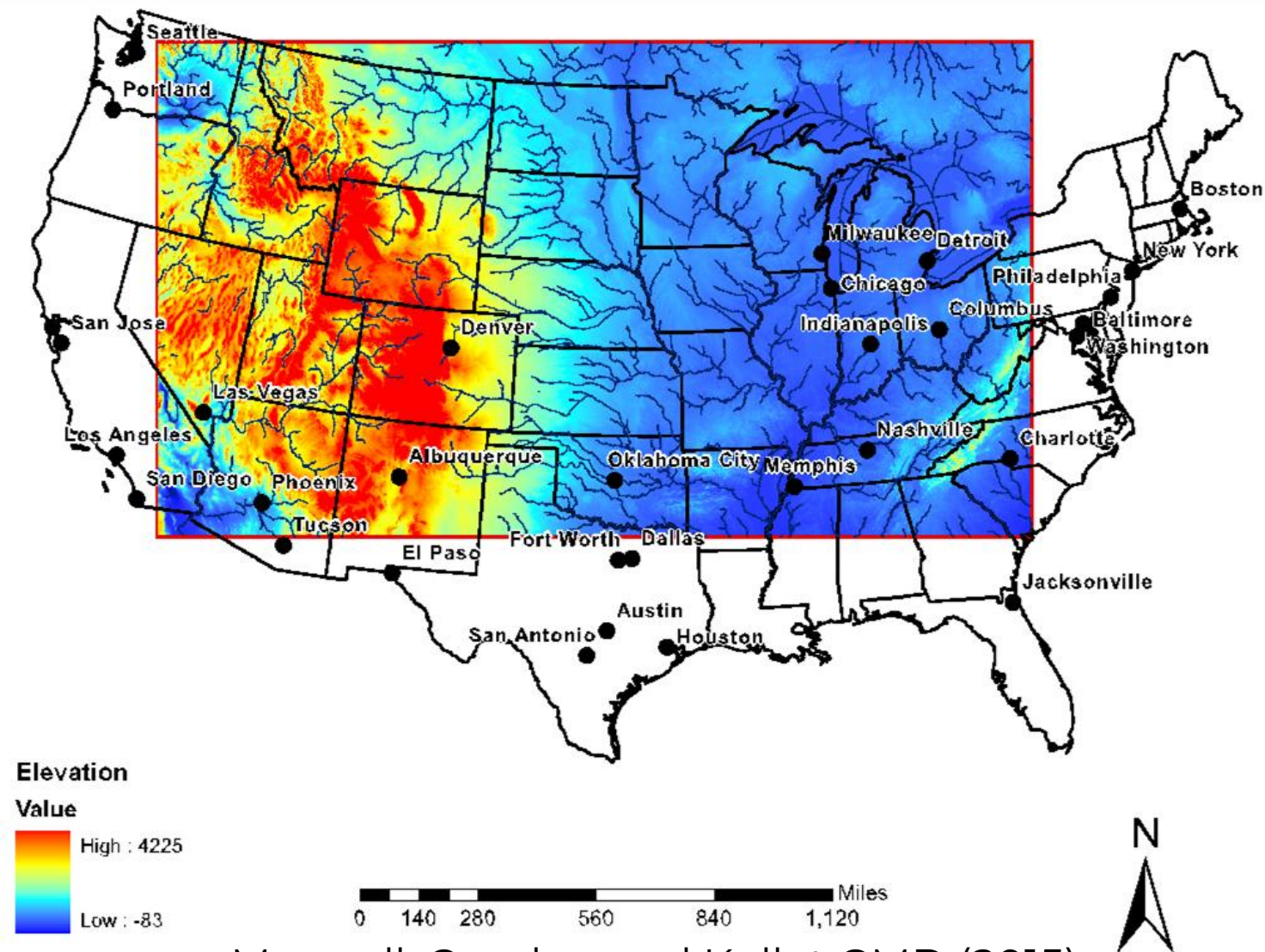


- 3D variably saturated groundwater flow
- Fully integrated surface water
- Parallel implementation
- Coupled land surface processes
 - Land-energy balance
 - Snow dynamics
 - Driven by meteorology

Maxwell (2013); Kollet and Maxwell (2008); Kollet and Maxwell (2006); Maxwell and Miller (2005); Dai et al. (2003); Jones and Woodward (2001); Ashby and Falgout (1996)

Coupling with land surface processes (CLM) allows for simulation of interactions and connections

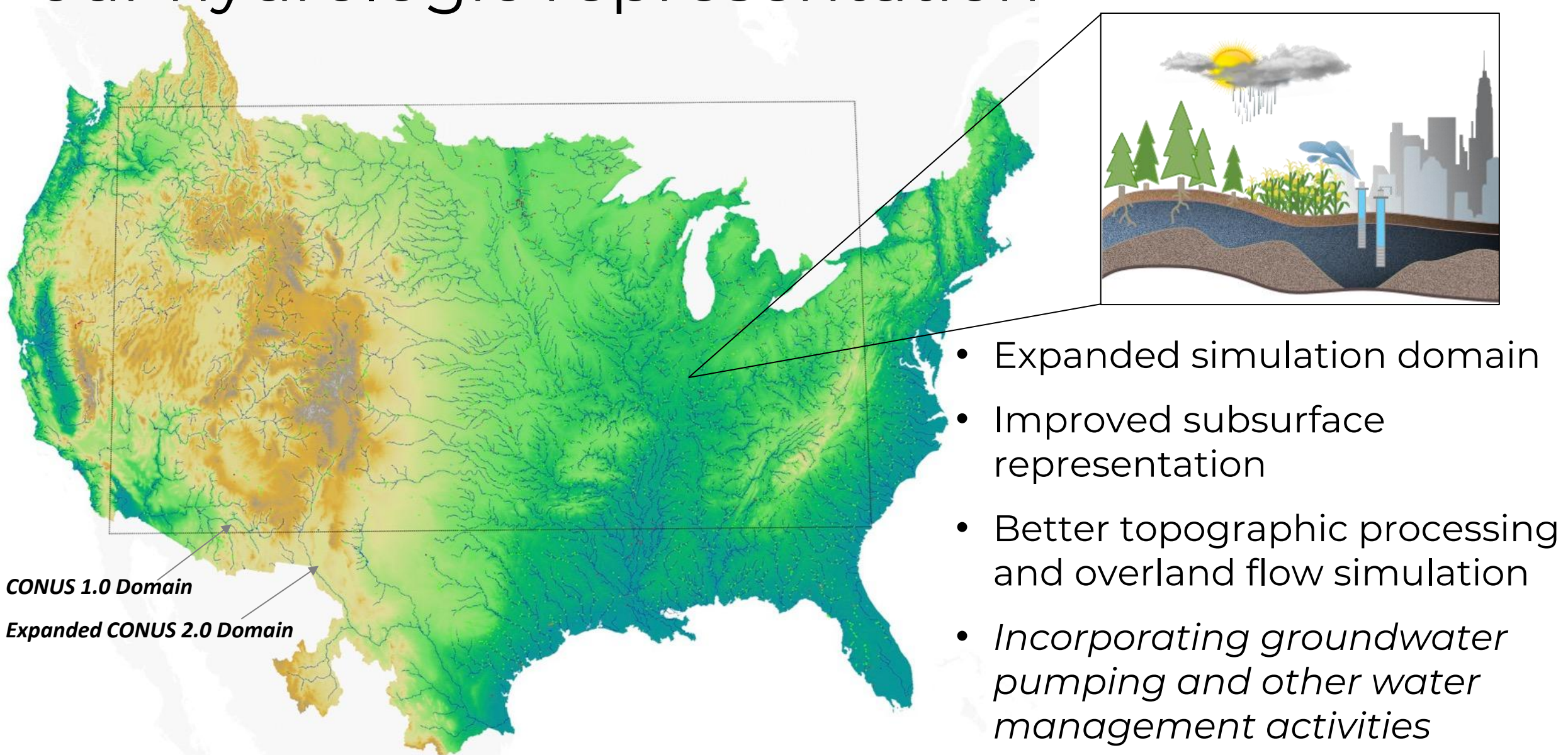
In the early teens we built a proof-of-concept, 6.3M km² domain covering much of the CONUS



Maxwell, Condon and Kollet GMD (2015)

- 1 km lateral resolution
- .1 – 100m vertical resolution over 102m depth
- ~32M unknowns
- The Miss and CO watersheds
- Fully integrated, 3D Richards' EQ, Shallow Water Equations, Land Surface Processes

CONUS 2.0 Model development advances our hydrologic representation



This model has been useful for building our understanding of groundwater land surface connections

WATER RESOURCES

Connections between groundwater flow and transpiration partitioning

Reed M. Maxwell^{1*} and Laura E. Condon²

Understanding freshwater fluxes at continental scales will help us better predict hydrologic response and manage our terrestrial water resources. The partitioning of evapotranspiration into bare soil evaporation and plant transpiration remains a key uncertainty in the terrestrial water balance. We used integrated hydrologic simulations that couple vegetation and land-energy processes with surface and subsurface hydrology to study transpiration partitioning at the continental scale. Both latent heat flux and partitioning are connected to water table depth, and including lateral groundwater flow in the model increases transpiration partitioning from 47 ± 13 to $62 \pm 12\%$. This suggests that lateral groundwater flow, which is generally simplified or excluded in Earth system models,

OPEN ACCESS

IOP Publishing

Environ. Res. Lett. 9 (2014) 034009 (9pp)

Environmental Research Letters

doi:10.1088/1748-9326/9/3/034009

Groundwater-fed irrigation impacts spatially distributed temporal scaling behavior of the natural system: a spatio-temporal framework for understanding water management impacts

Laura E Condon^{1,2} and Reed M Maxwell^{1,2}

¹ Hydrologic Science and Engineering Program and Department of Geology and Geological

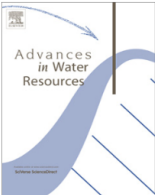


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journal homepage: www.elsevier.com/locate/advwatres



Quantitative assessment of groundwater controls across major US river basins using a multi-model regression algorithm



Laura E. Condon^{a,b,d,*}, Amanda S. Hering^c, Reed M. Maxwell^{a,b,d}

^a Department of Geology and Geological Engineering, Colorado School of Mines, United States

^b Integrated GroundWater Modeling Center, United States

^c Mathematics and Statistics, Colorado School of Mines, United States

^d Center for Water and Society (CCWAS), Integrative Graduate Education and Research Traineeship (IGERT), United States

Hydrol. Earth Syst. Sci., 21, 1117–1135, 2017
www.hydrol-earth-syst-sci.net/21/1117/2017/
doi:10.5194/hess-21-1117-2017

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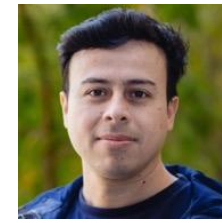


Hydrology and
Earth System
Sciences
Open Access
EGU

Systematic shifts in Budyko relationships caused by groundwater storage changes

Laura E. Condon¹ and Reed M. Maxwell²

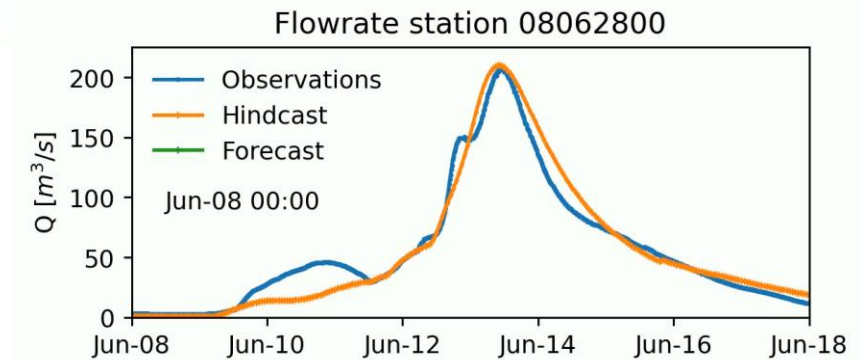
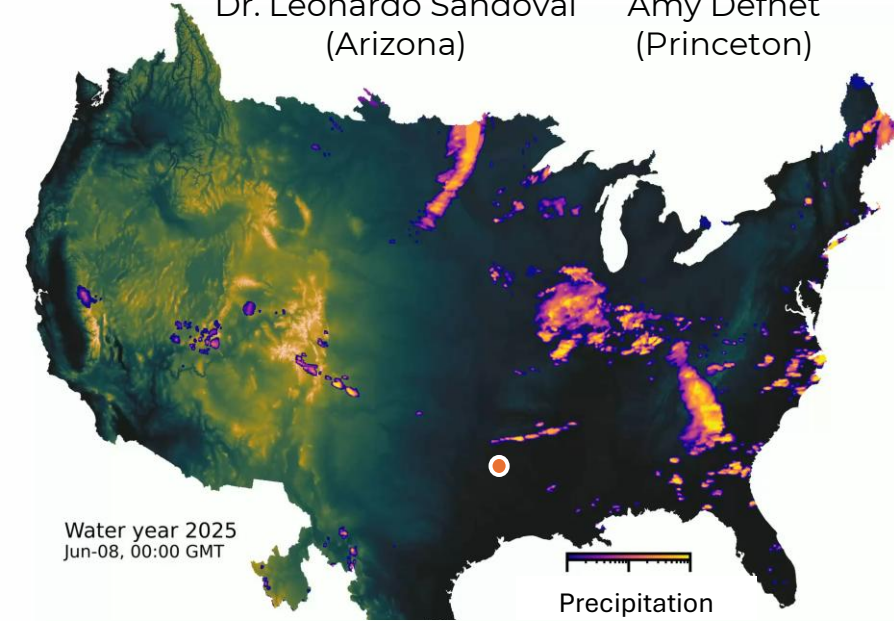
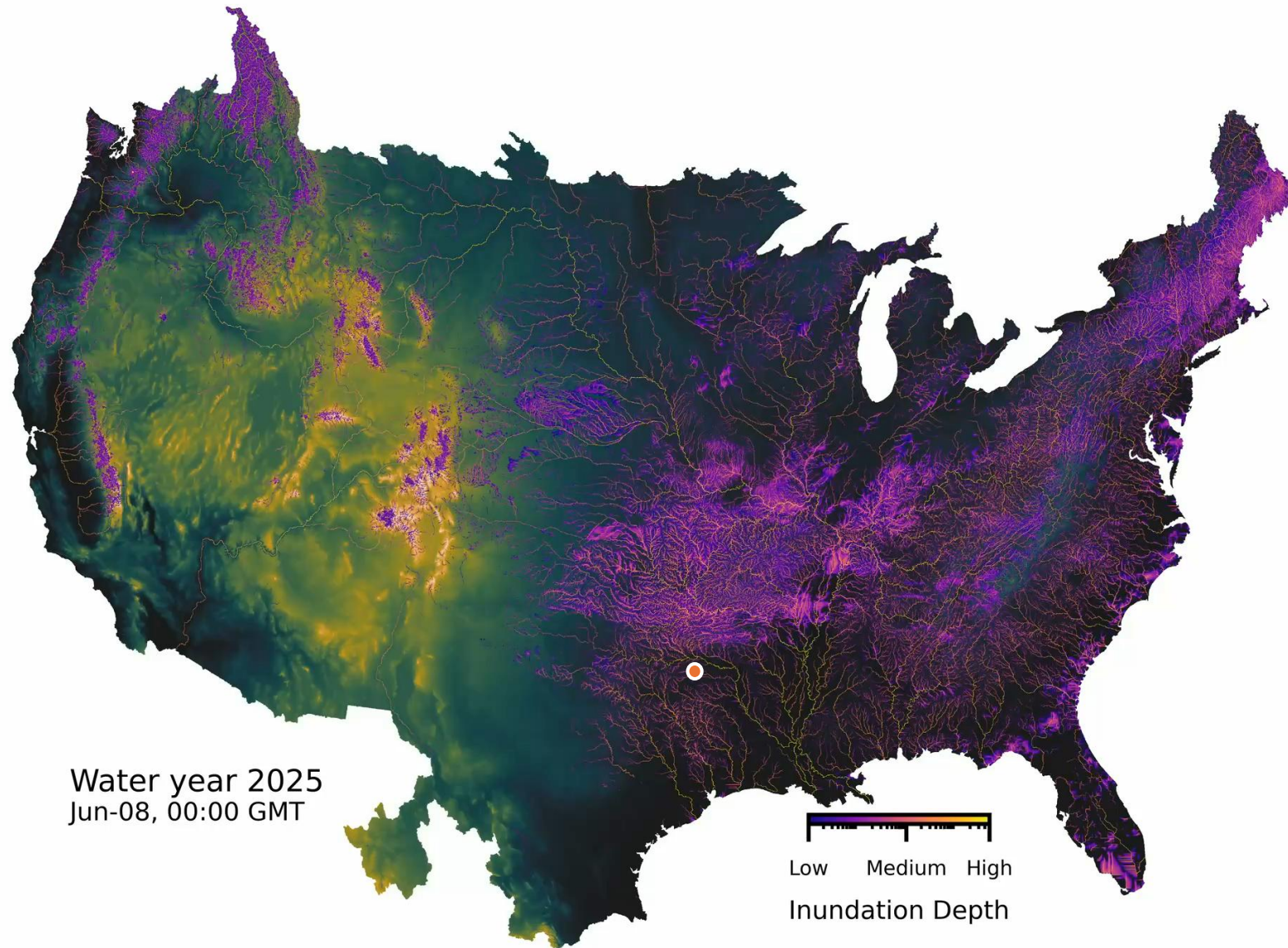
We are now running our model operationally too



Dr. Leonardo Sandoval
(Arizona)



Amy Defnet
(Princeton)



Building and running this model is a huge investment so we built a platform to share it too!



The HydroFrame platform makes our national modeling datasets and tools accessible



HydroGEN

APPLICATIONS

Explore current and future watershed conditions across the US with HydroGEN



HydroData

DATA AND SIMULATIONS

Access Hydrologic Datasets and Model Results



ParFlow CONUS1.0

DATA AND SIMULATIONS

Learn more about the first generation national ParFlow model



ParFlow CONUS2.0

DATA AND SIMULATIONS

Learn more about the second



ParFlow Resources

MODELING TOOLS

Find training resources and

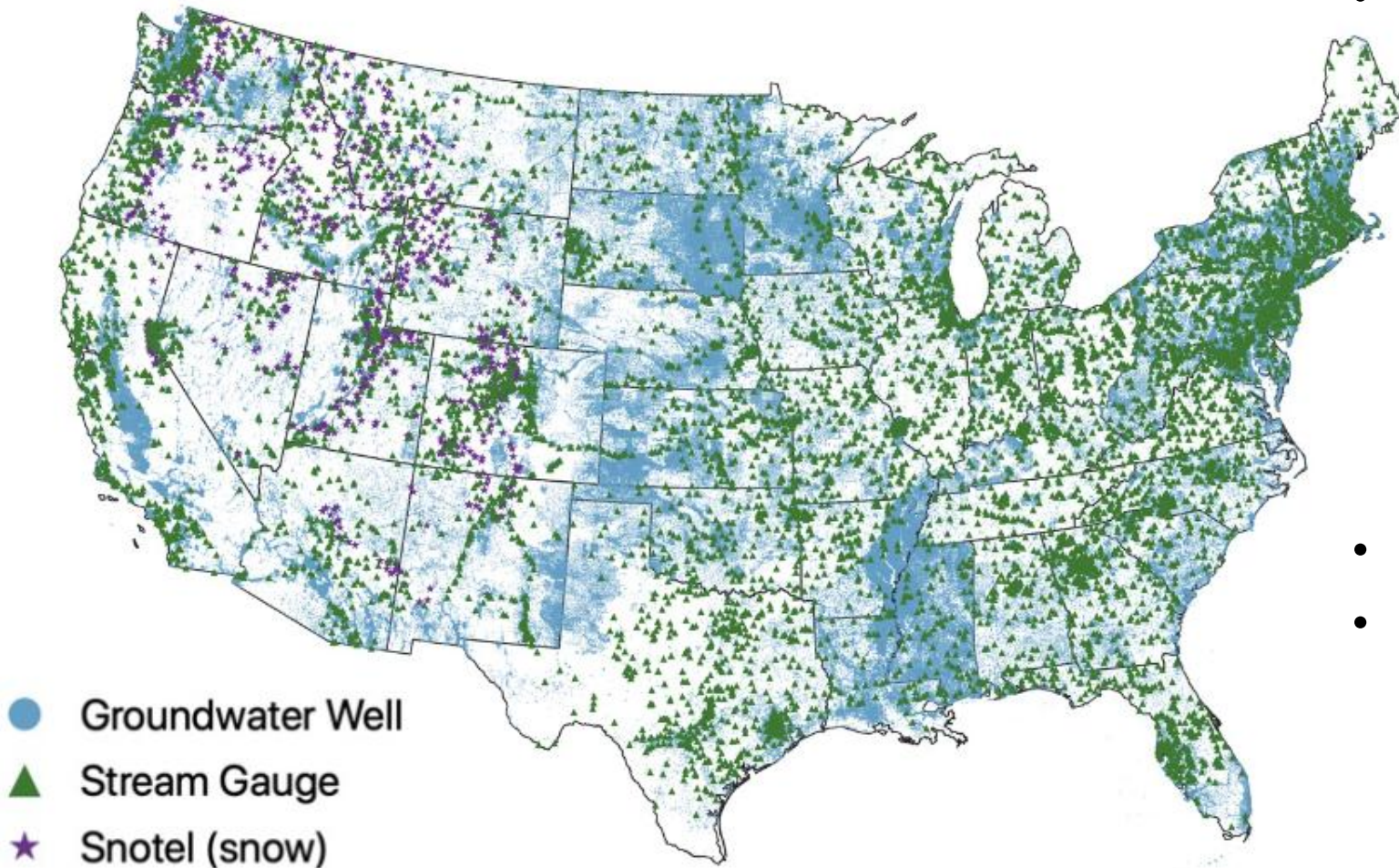


SubsetTools

MODELING TOOLS

Build your own watershed model

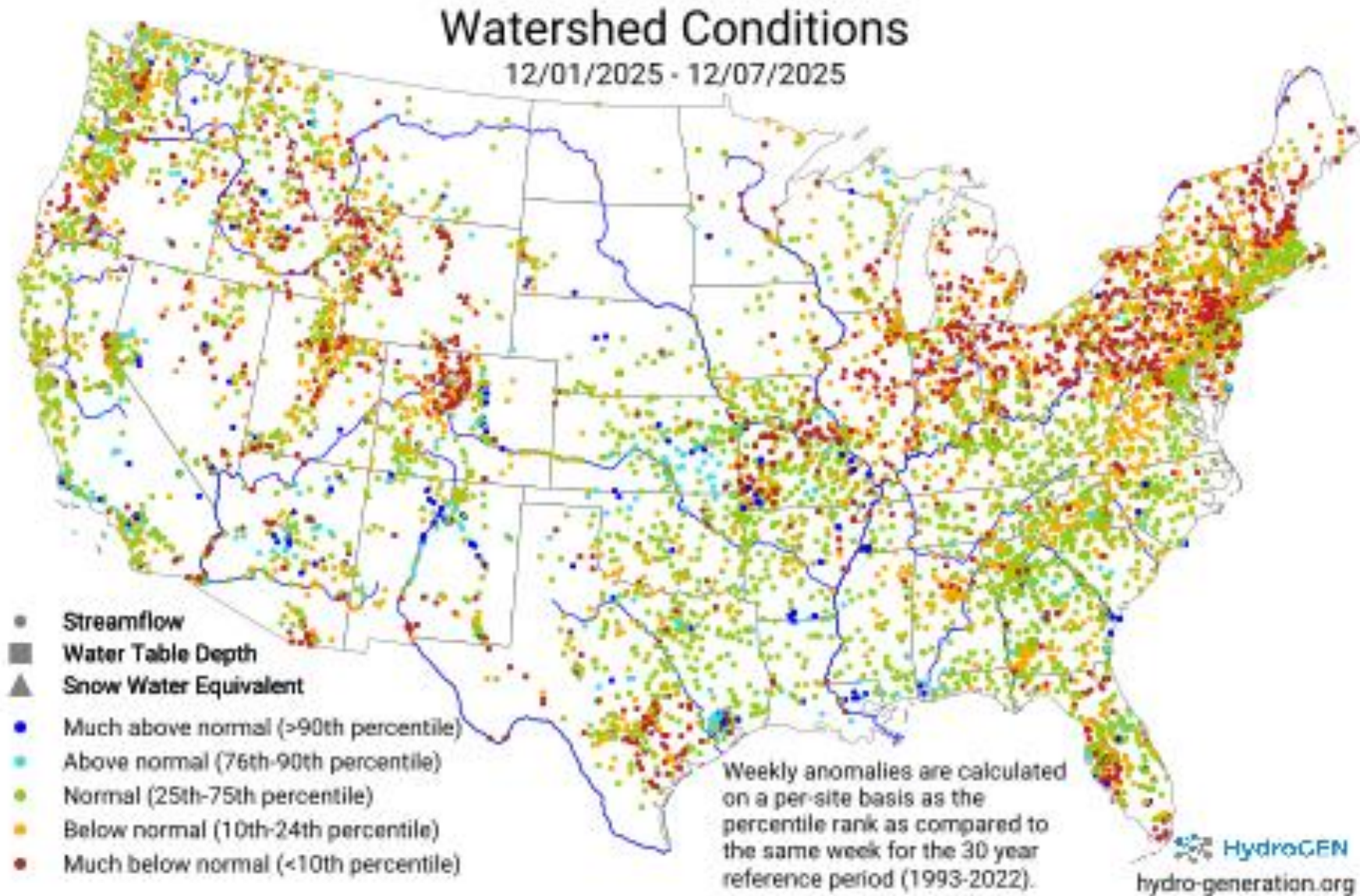
We constructed the **largest** extensive and continuously updated **database of hydrologic observations**



- Continuously updated observations datasets currently on HydroData:
 - Streamflow (USGS)
 - Groundwater Levels (USGS)
 - Soil moisture (SMAP)
 - Snow (SNOTEL)
 - Precipitation & Temperature (NOAA/NWS)
- All data processed for QA/QC
- Public API this fall to allow external users to query and interact with all datasets.

Nearly 900,000 wells with 24M individual water table depth observations

We also
assemble and
continuously
update
watershed
conditions
across the US
for multiple
variables
simultaneously





HydroData

A national collection of ParFlow CONUS simulations as point observations from national observations

- networks that are continuously updated and processed for easy integration across datasets
- API for public data access

hf_hydrodata
latest

Search docs

TABLE OF CONTENTS

- Getting Started
- Available datasets and data products
- Working with Gridded Data
- Working with Point Observations**
- Python API Reference
- Data Use Policy

Home / HydroData

[Edit on GitHub](#)

HydroData

The HydroData data catalog, associated python functions `hf_hydrodata` and API are products of the `HydroFlow` framework. The `HydroFlow` framework generated a variety of outputs (e.g., gridded data, point observations, etc.).

Point Observation Notebooks

Access and cite point observations data

Walk through some example functionality for accessing and citing point observations.



Explore point data availability

Walk through how to explore what data is available.



Plotting returned point data

Walk through some examples for how to plot data returned from `get_point_data`.





SubsetTools

A python package to subset inputs and outputs from the national ParFlow simulations and build watershed models.

 subsettools
latest

Search docs

[Getting started](#)
[How To](#)
[Example notebooks](#)
[API Reference](#)
[Changelog](#)
[Contributing](#)
[Code of Conduct](#)
[Data Use Policy](#)

 / SubsetTools [Edit on GitHub](#)

SubsetTools

Introduction

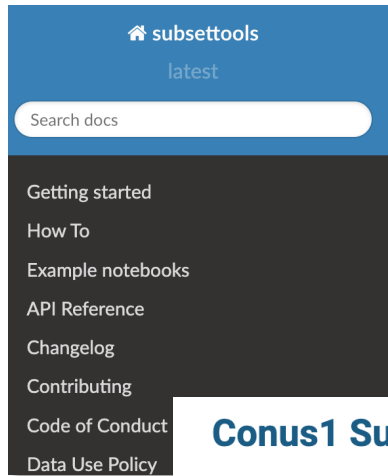
The [SubsetTools](#) package is developed and maintained by the [HydroFrame](#) project. It is designed to subset model inputs and outputs from the national ParFlow modeling framework. We provide tools to subset all required hydrogeologic and climate forcing datasets for a ParFlow simulation as well as obtaining pre-configured run scripts for your desired domain based on the most common use cases.

Example workflows are provided for working with both the first ([PFCONUS1](#)) and second



SubsetTools

You can use SubsetTools to clip any inputs from the national framework and to configure ParFlow run for any watershed in the contiguous US



🏠 / SubsetTools

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SubsetTools 🔗

Introduction

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Conus1 SubsetTools

Define a subset domain area

Illustrates three different ways to define a subset domain.



Subset Gridded Static Inputs

Two different approaches for subsetting static input variables and working with the data



Subset Gridded Forcing Data

Two different approaches for subsetting meteorological forcing variables and working with the data



3.2 Visualize data that was subset using `hf.get_numpy`

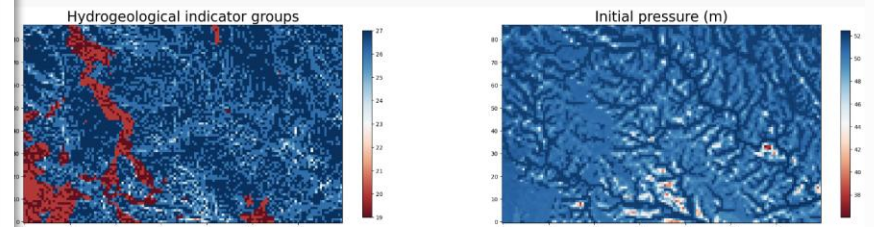
Here we just visualize the same data directly from the numpy arrays returned by the function in sections 2.3 and 2.4.

```
fig, axs = plt.subplots(1, 2, figsize=(28, 10))

ax0 = axs[0]
data = static_data["pf_indicator"][0]
im0 = ax0.imshow(data, cmap="RdBu", origin='lower')
colorbar1 = fig.colorbar(im0, ax=ax0, shrink=0.6)
ax0.set_title(f'Hydrogeological indicator groups', fontsize = 25)

ax1 = axs[1]
data = initial_press[0] # pick the bottom layer of the pressure data
im1 = ax1.imshow(data, cmap = "RdBu", origin='lower')
colorbar1 = fig.colorbar(im1, ax=ax1, shrink=0.6)
ax1.set_title(f'Initial pressure (m)', fontsize = 25)
```

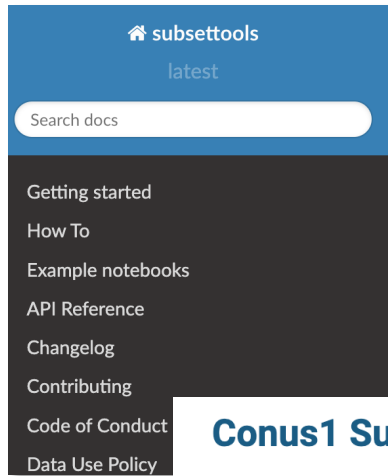
Text(0.5, 1.0, 'Initial pressure (m)')





SubsetTools

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🏠 / SubsetTools

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SubsetTools 🔗

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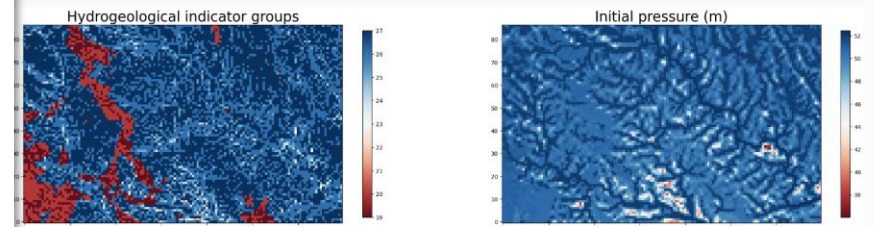
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Text(0.5, 1.0, 'Initial pressure (m)')





All our
resources are
freely
available data
download just
requires a
user sign-up



HydroGEN

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ParFlow CONUS1.0

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DATA AND SIMULATIONS

Learn more about the second



ParFlow Resources

MODELING TOOLS

Find training resources and



SubsetTools

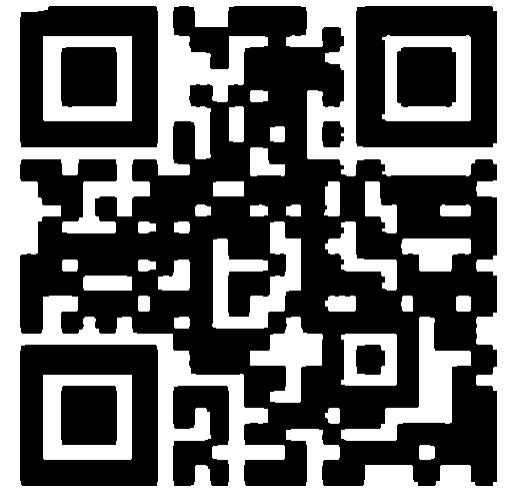
MODELING TOOLS

Build your own watershed model

Thank you for listening!



U.S. DEPARTMENT OF
ENERGY



hydroframe.org