Raising or razing the reservoirs:
Optimizing the US reservoir system under 500 years of streamflow variability (preliminary results)

James Rising

Columbia Water Center, AWASH modeling team:
Laureline Josset, Tara Troy, Michelle Ho, Joohye Lim, Luc Bonnafuos, Maura Allaire, Upmanu Lall

Grantham Research Institute, London School of Economics

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Topics

- **The need for integrated perspectives on water and the AWASH model**
- Paleo-variability of streamflows and archetypes
- Reservoir planning and preliminary results
- What we’ve learned

Understanding the future of water in the United States

- **Uncertain policies, unquantified value**
- **Increasingly interconnected water supplies**
  - Trans-basin diversions
  - Interstate treaties and conflicts
  - National economy and policy drivers
  - Broad-scale climate
- **Limited national and local capacity**
  - Our goal: **systems-level analysis** to account for intersectoral connections at **regional scales**

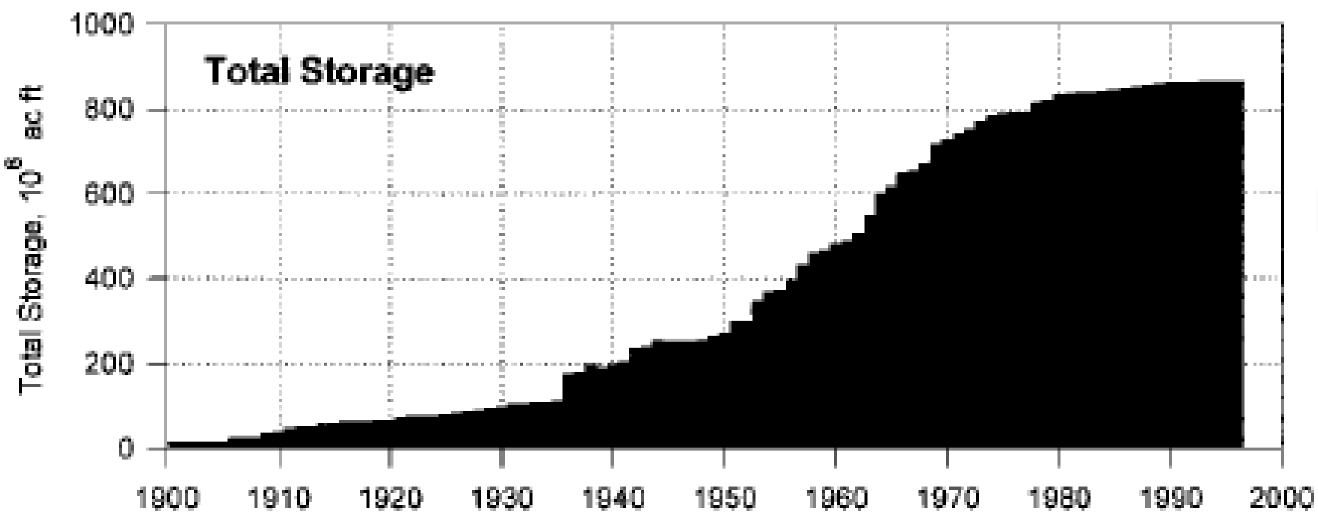
A broad initiative on America’s Water

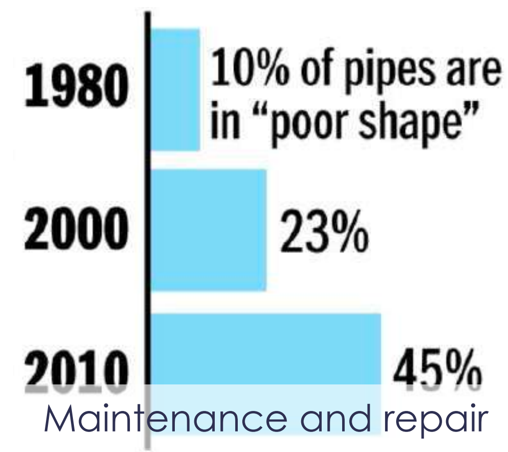
The Changing Landscape of Risk, Competing Demands and Climate

WSC-Category 3
Collaborative:
NSF # 1360446

Should we have reservoirs?

Overdue debate about the future of reservoirs:



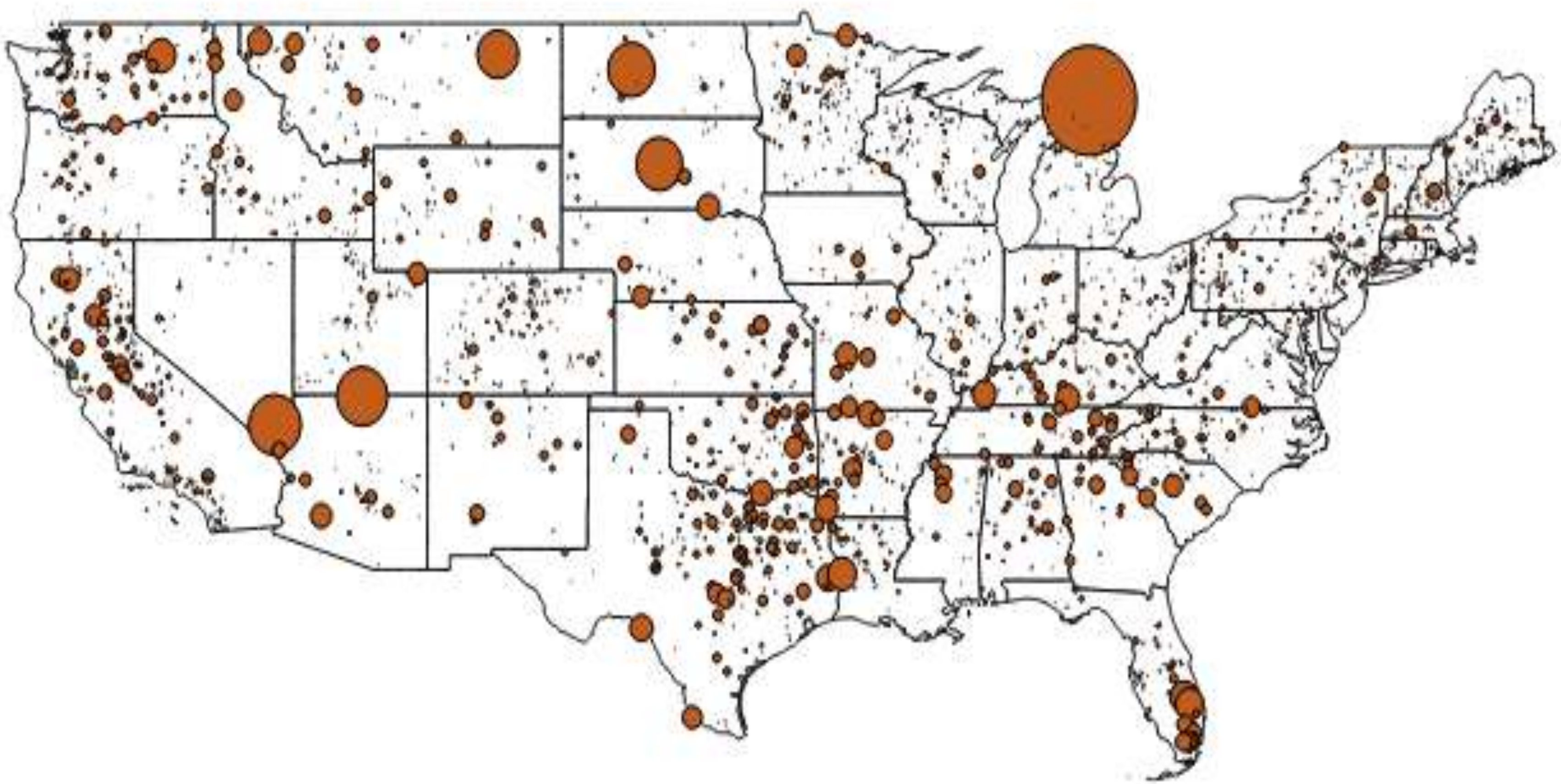


Maintenance and repair


Dam failure disasters

Dam removal

Reservoirs across the United States



Circles reflect total storage capacity.

Keep reservoirs or remove them?

Plenty of competing reasons for reservoirs:

- Navigation (6%)
- Recreation (14%)
- Flood protection (16%)
- Hydropower (17%)
- Irrigation (18%) and water supply (19%)

(% of reservoirs in the US, by primary purpose, from National Inventory of Dams.)

Keep reservoirs or remove them?

Plenty of competing reasons for reservoirs beyond the scope of this analysis:

- Navigation (6%)
- Recreation (14%)
- Flood protection (16%)
- Hydropower (17%)
- **Irrigation (18%) and water supply (19%)**

(% of reservoirs in the US, by primary purpose, from National Inventory of Dams.)

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Keep reservoirs or remove them?

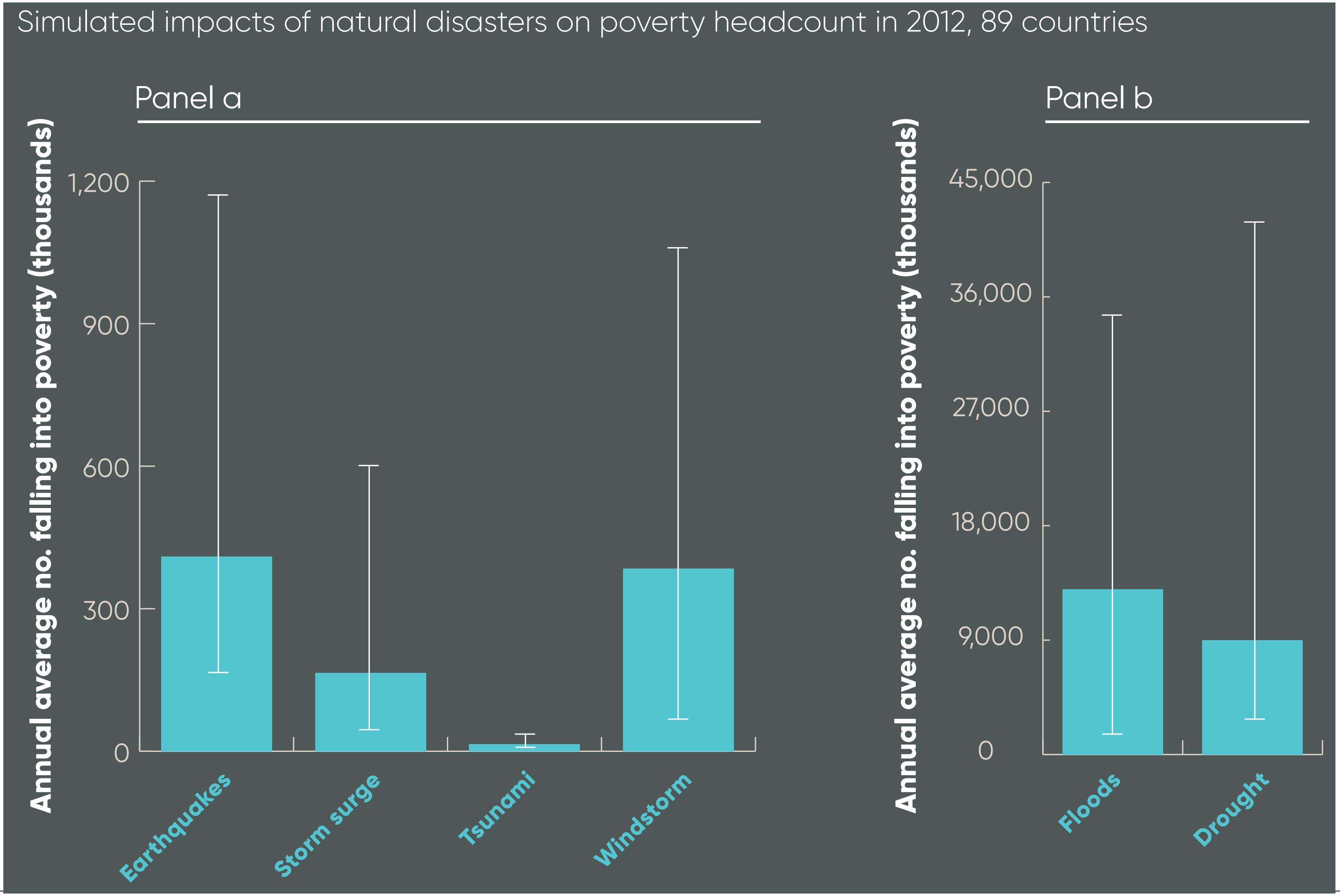
Benefits

- Navigation
- Recreation
- Flood protection
- Hydropower
- **Irrigation and water supply**

Costs

- Public safety
- Impact on the environment
  - Land loss
  - Degrading habitats
- **Repair and maintenance costs**
  - 3x removal costs (Born et al. 1998)

Keep reservoirs or remove them?



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A new model of water, energy, and food resources

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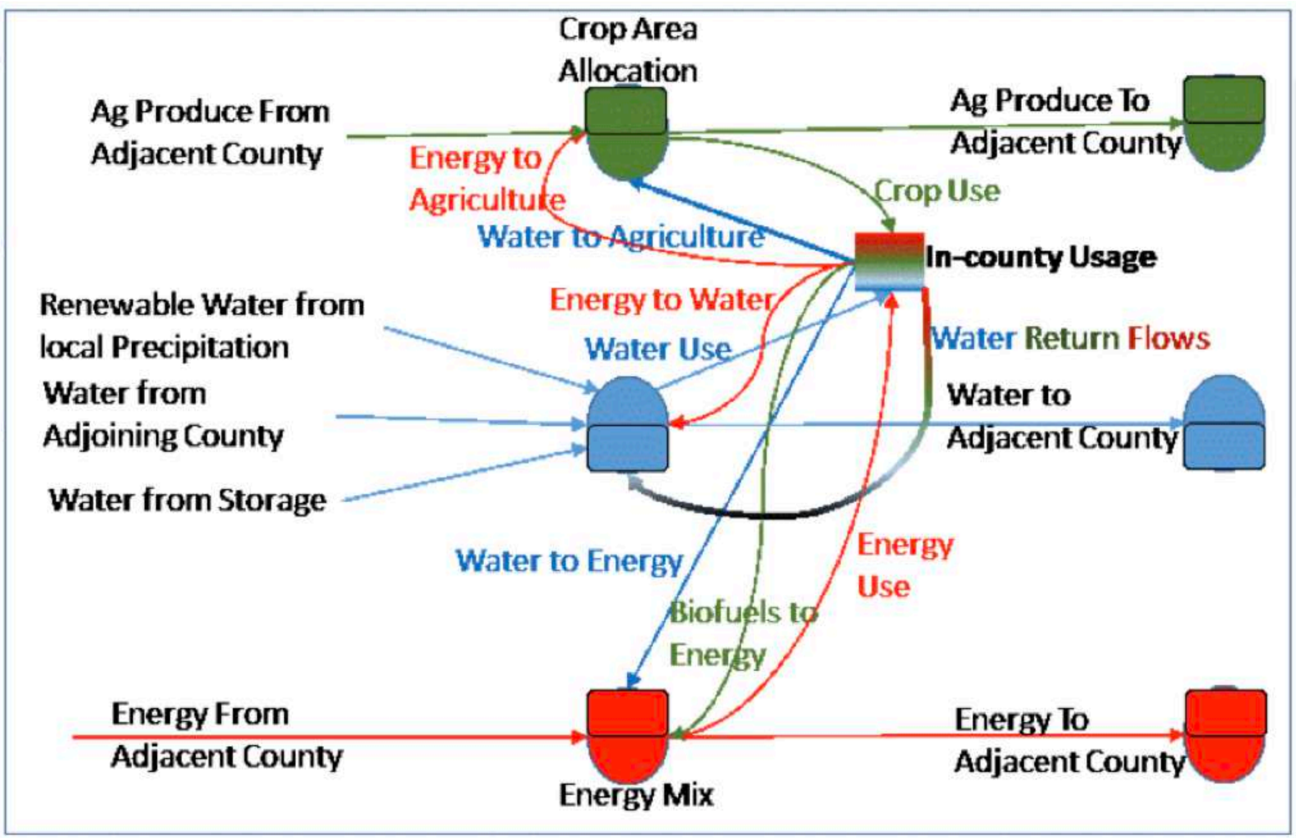
Model objectives

Explore interactions between water, food and energy systems from a national perspective

- **In response to specific types of climate changes**
- **In response to economic factors**
  - GDP growth rate , Global Energy prices, Global Food demand
  - Investment climate – financing, rates, private vs public action
- **In response to demographic factors**
  - Migration, Age distribution, income ….
- **In response to property rights models – water rights /others**
- **In response to conservation technologies**
- **In response to energy policy – renewables, carbon tax, biofuels**
- **In response to agricultural policy or diet preferences – crop insurance etc**

Design decisions

- **Treat arbitrary “resources”: water, energy, products**
  - Models of production, imports and exports, storage



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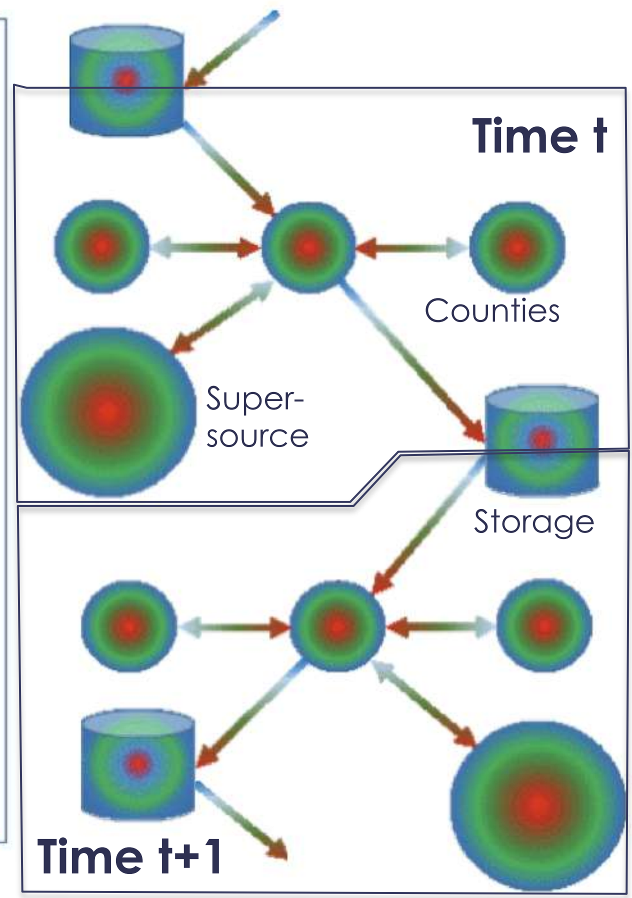

Design decisions

- **Treat arbitrary “resources”: water, energy, products**
  - Models of production, imports and exports, storage
- **Multiple networks of resource movement**

County Neighbors Network

- Default trade network for manufactured goods and agricultural products.

Water Network

- Network of gauges, canals, reservoirs, and junctions.

Electricity Grid

- Transporting electricity from plants to county sinks.

Design decisions

- **Treat arbitrary "resources": water, energy, products**
  - Models of production, imports and exports, storage
- **Multiple networks of resource movement**
  - Counties to neighboring counties
  - Other transport networks (water, electricity)
- **Modeled at a county-month scale for whole US**
- **Interested in spatiotemporal optimization**
  - Short-term optimization of production distribution
  - Long-term optimization of capacity expansion
  - Multiple objective functions to consider

Design decisions

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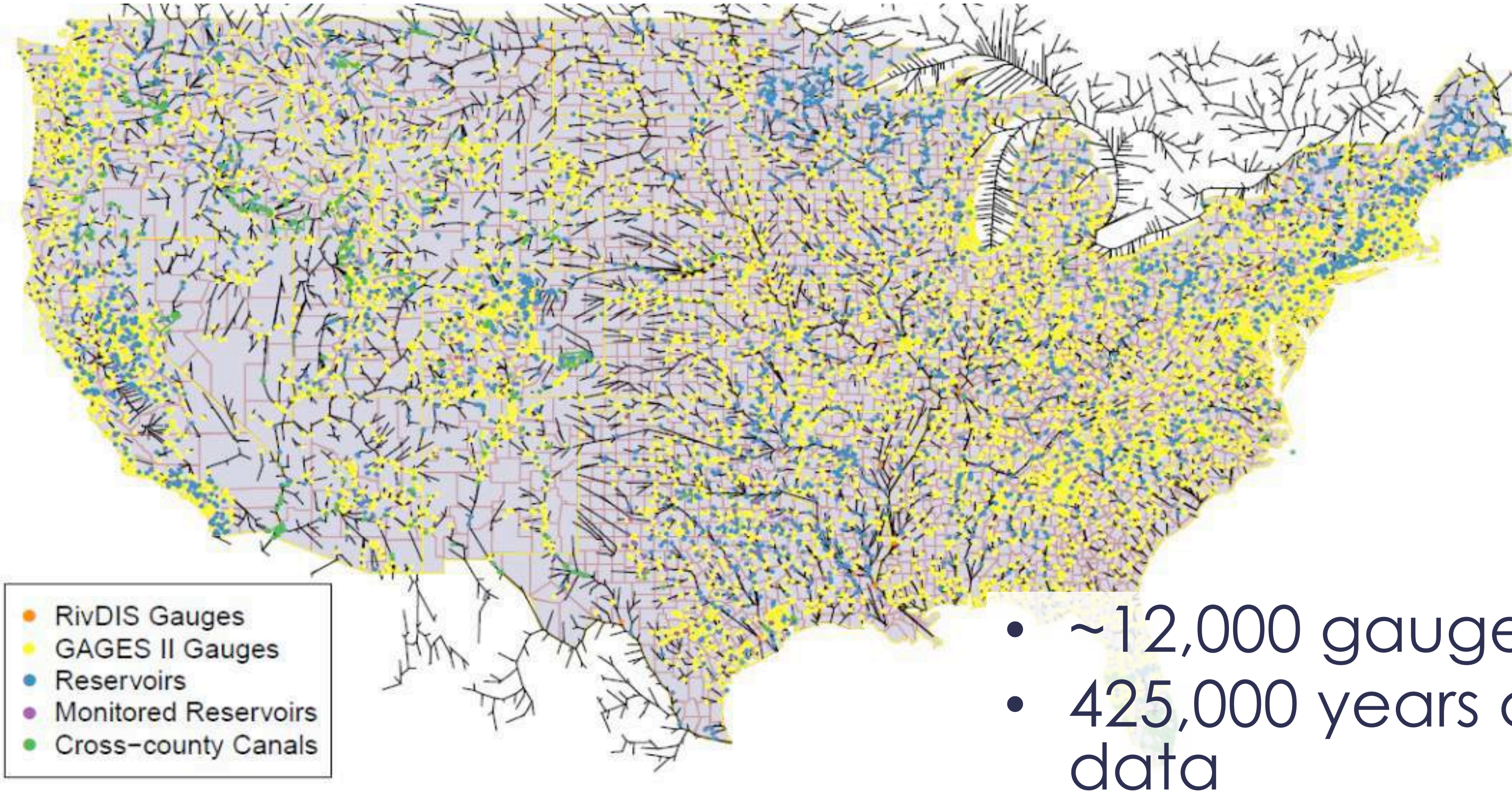
  - Multiple objective functions to consider

Why a new model?

- **Very few models with resolution < states, scope > states**
  - Hydrological-only: VIC, MODFLOW, IGSM (not MIT's)
  - Agriculture and climate: GEPIC (IIASA)
- **Interested in optimization over multiple sectors**
  - InVEST (Polasky et al. 2008):
    - Ecosystem service flows, no spatial connectivity
  - CALVIN (Lund et al. 2009) and WRIMS (Cal. Dep. of Water Res.)
    - Hydrology and management
  - MAgPIE (Lotze-Campen et al. 2008):
    - Agriculture and forestry, large grid and 10-year timestep

- **Need a sector-detailed WEF model, optimization model at high resolution and over uncertainty!**

Flow Gauges, Reservoirs, Cross-border canals



- ~12,000 gauges
- 425,000 years of data

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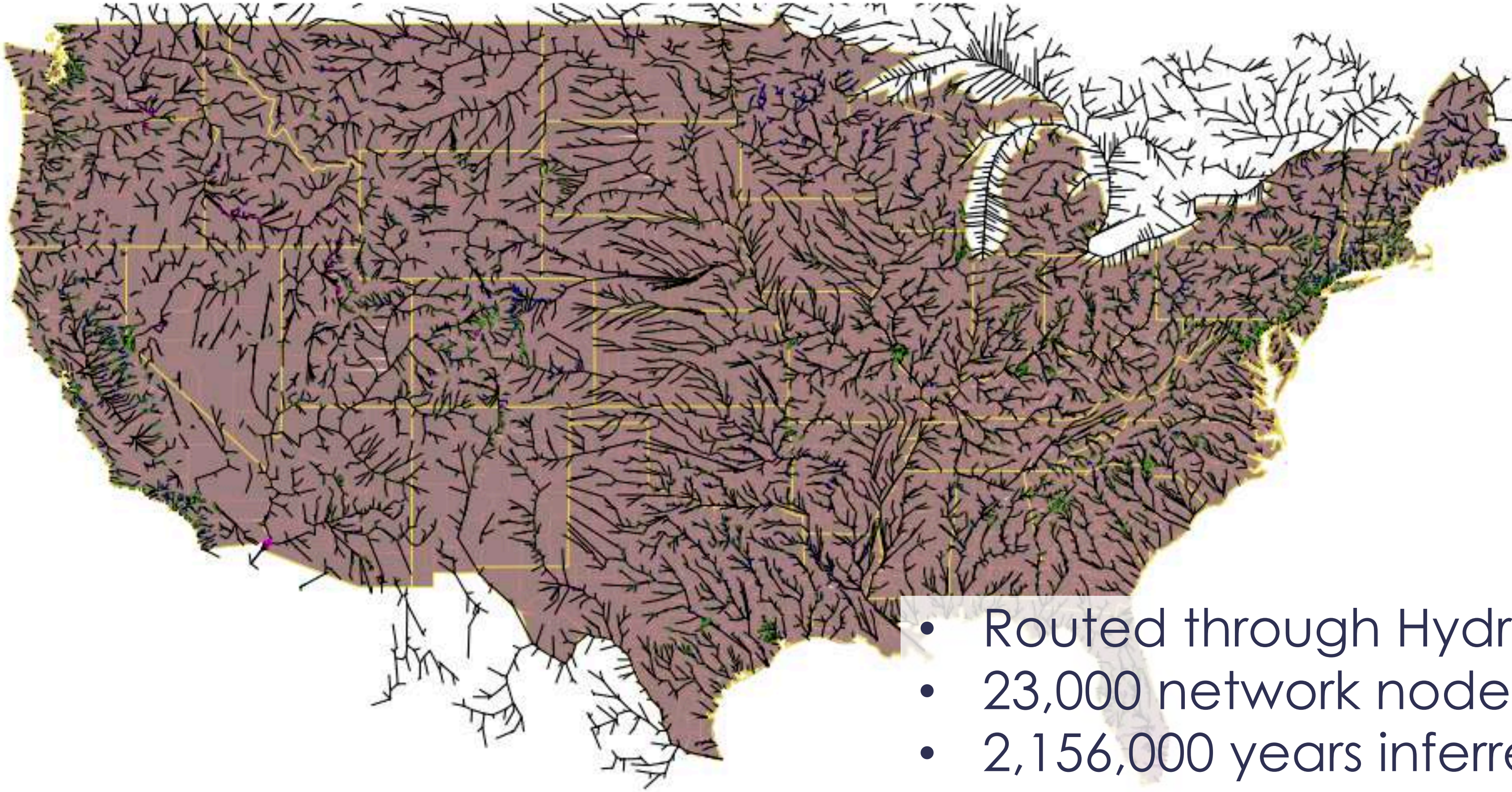
River network



- Routed through HydroSHI
- 23,000 network nodes
- 2,156,000 years inferred

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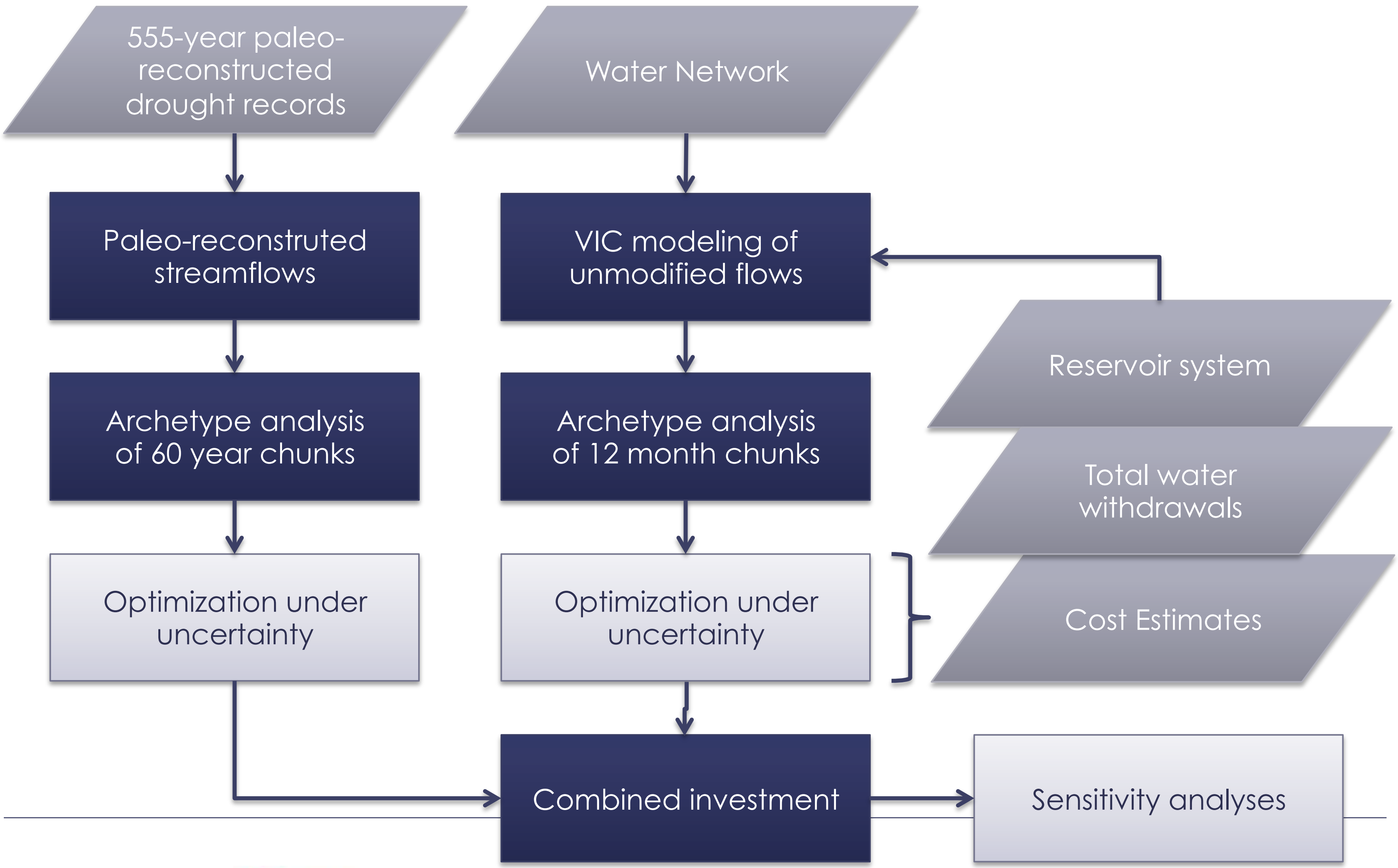
An integrated modeling framework

- **Component-based framework (`Mimi` in `Julia`)**
  - Inputs from outside the model:
  - Inputs from other components:
  - Inputs from optimization:

- **Able to validate components individually and swap them out and have multiple variants.**
  - Existing Mimi components for climate, biodiversity, disease, conflict, natural disasters, FUND, DICE, and PAGE.
- **Linear programming optimization (`Gurobi`)**
  - Automatic construction of LP matrices

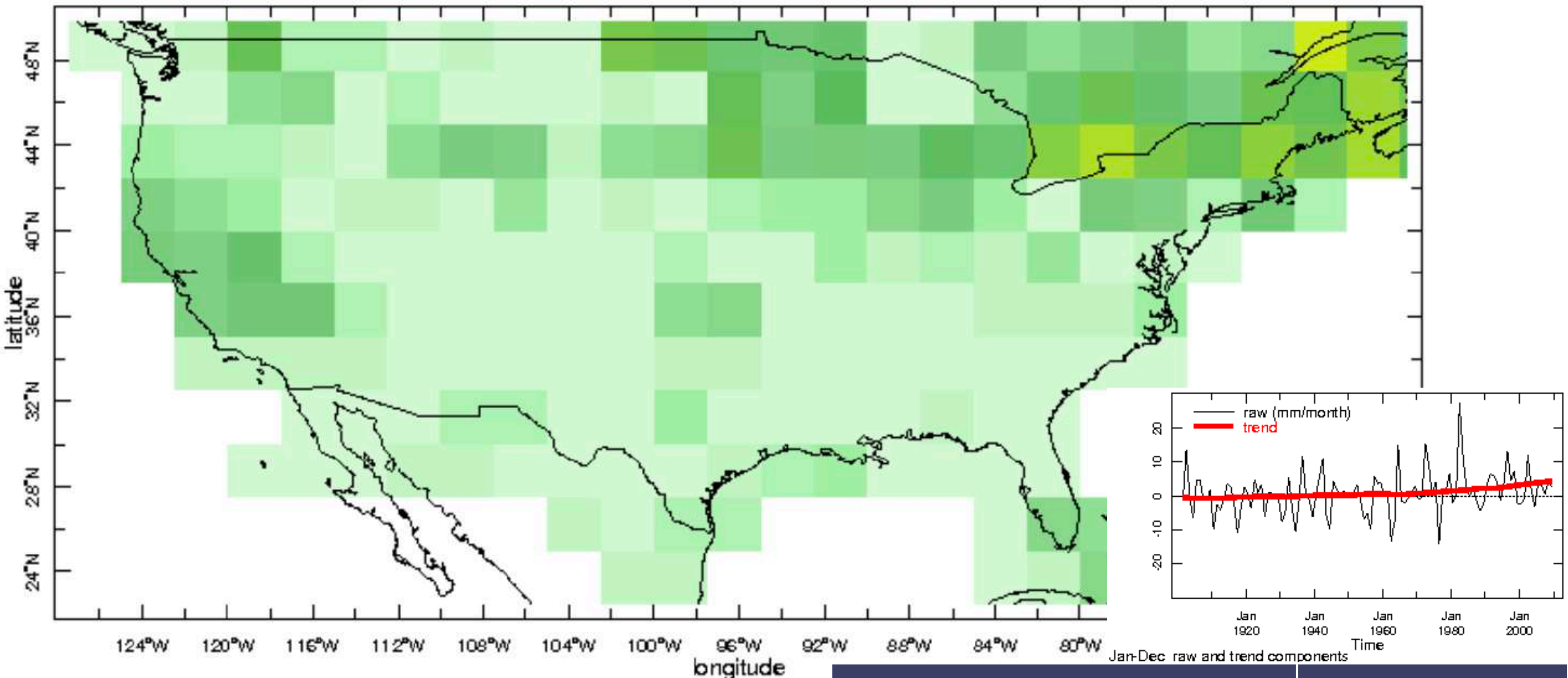
Modeling for this analysis

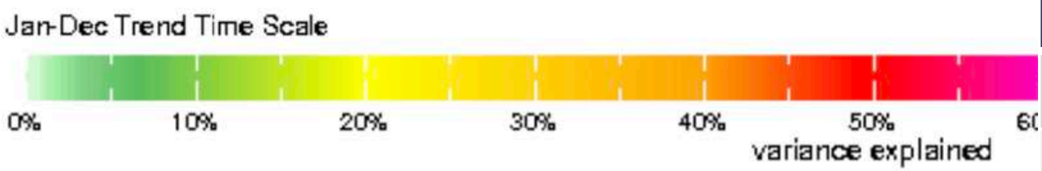


Topics

- The need for integrated perspectives on water and the AWASH model
- **Paleo-variability of streamflows and archetypes**
- Reservoir planning and preliminary results
- What we've learned

Climate change and precipitation





Component	Var. expl.
Smooth trend	5%
Decadal cycles	12%
Interannual residual	78%
Decadal/annual cov.	6%

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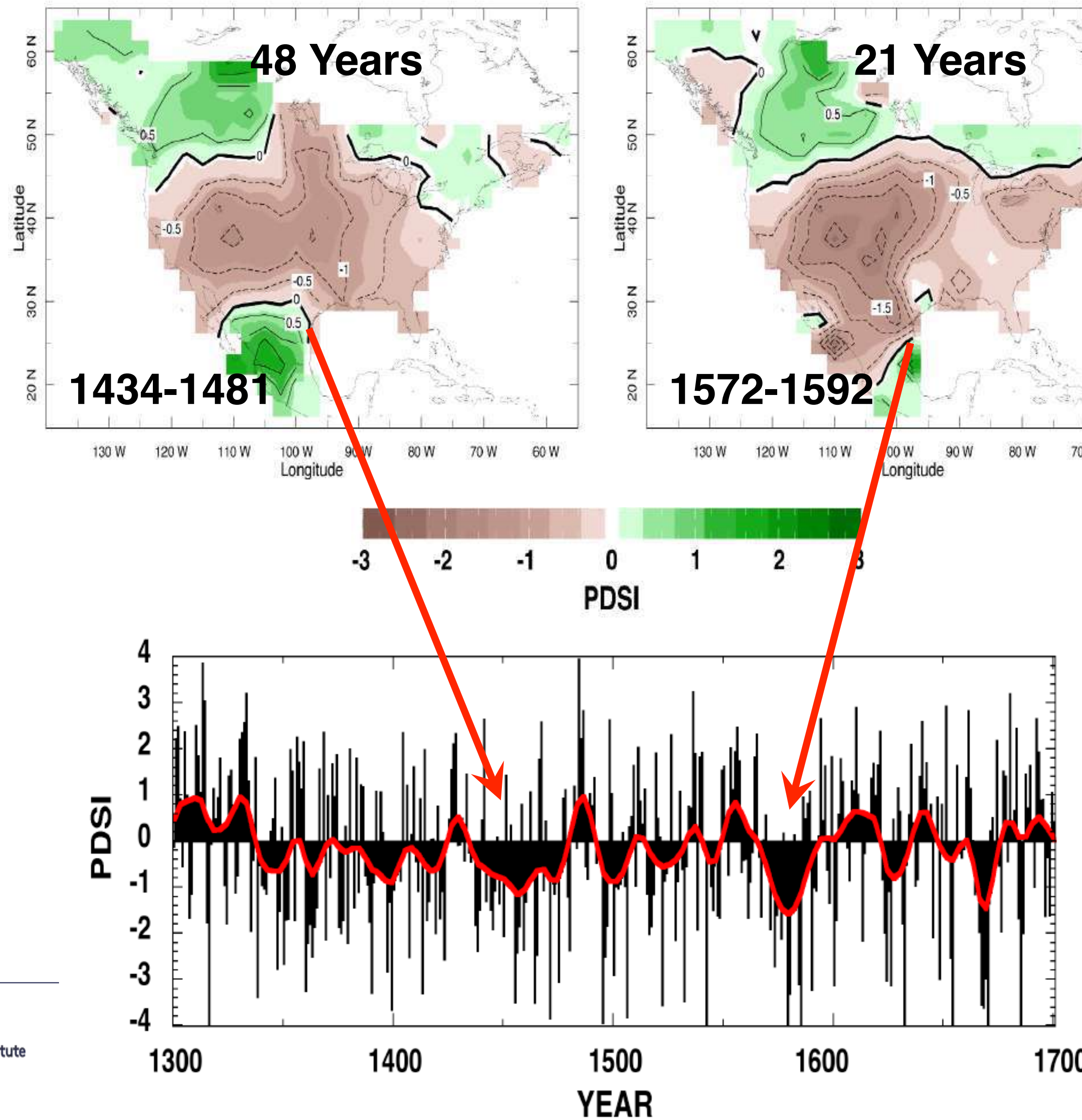
Notable Post-Medieval Megadroughts



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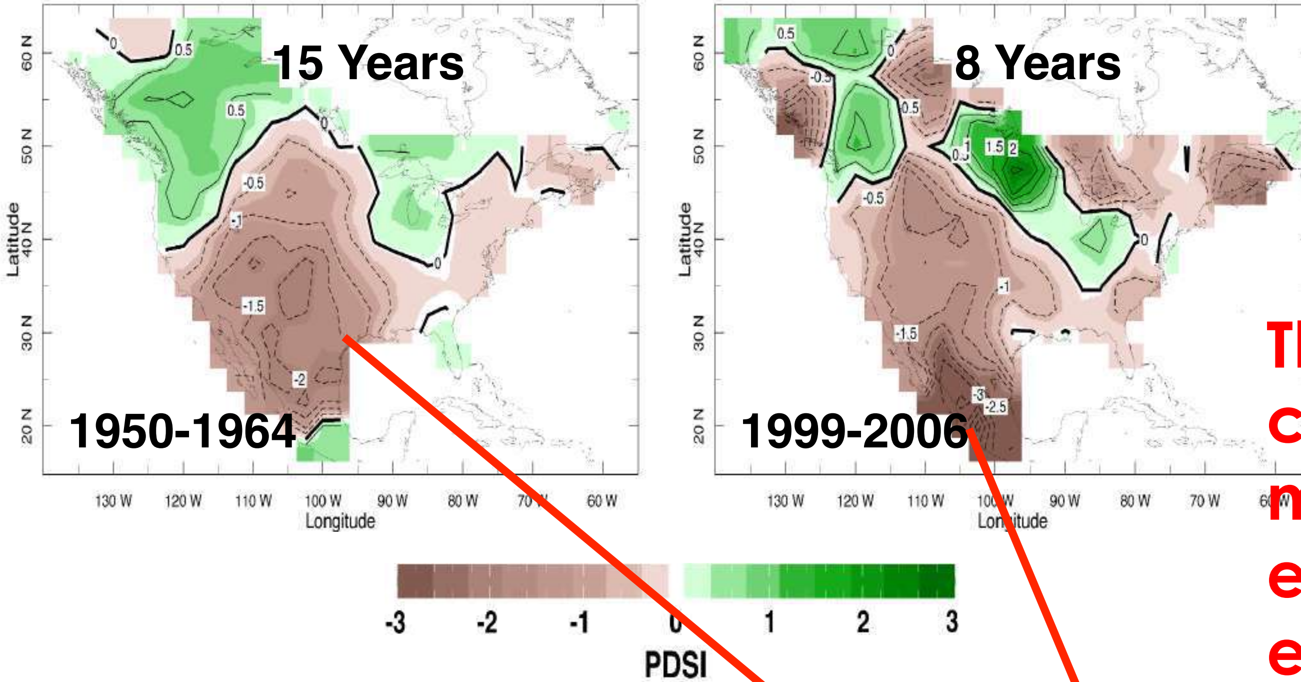
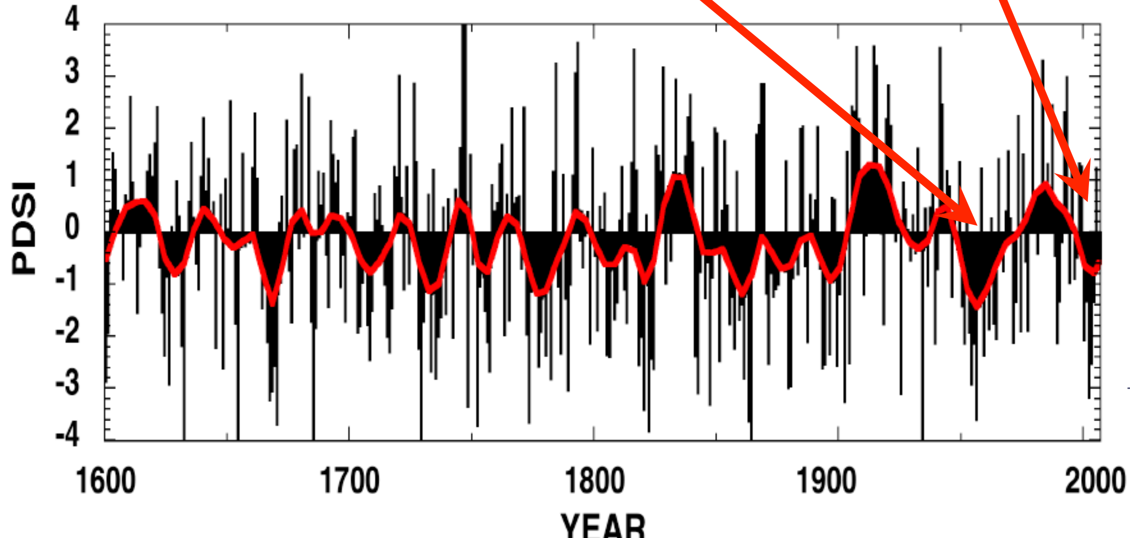
Ed Cook
Lamont-Doherty Earth Observatory, Palisades, NY

Notable 20th Century Droughts





The 20th century may have experienced more modest droughts than the prior record!

Ed Cook
Lamont-Doherty Earth Observatory, Palisades, NY

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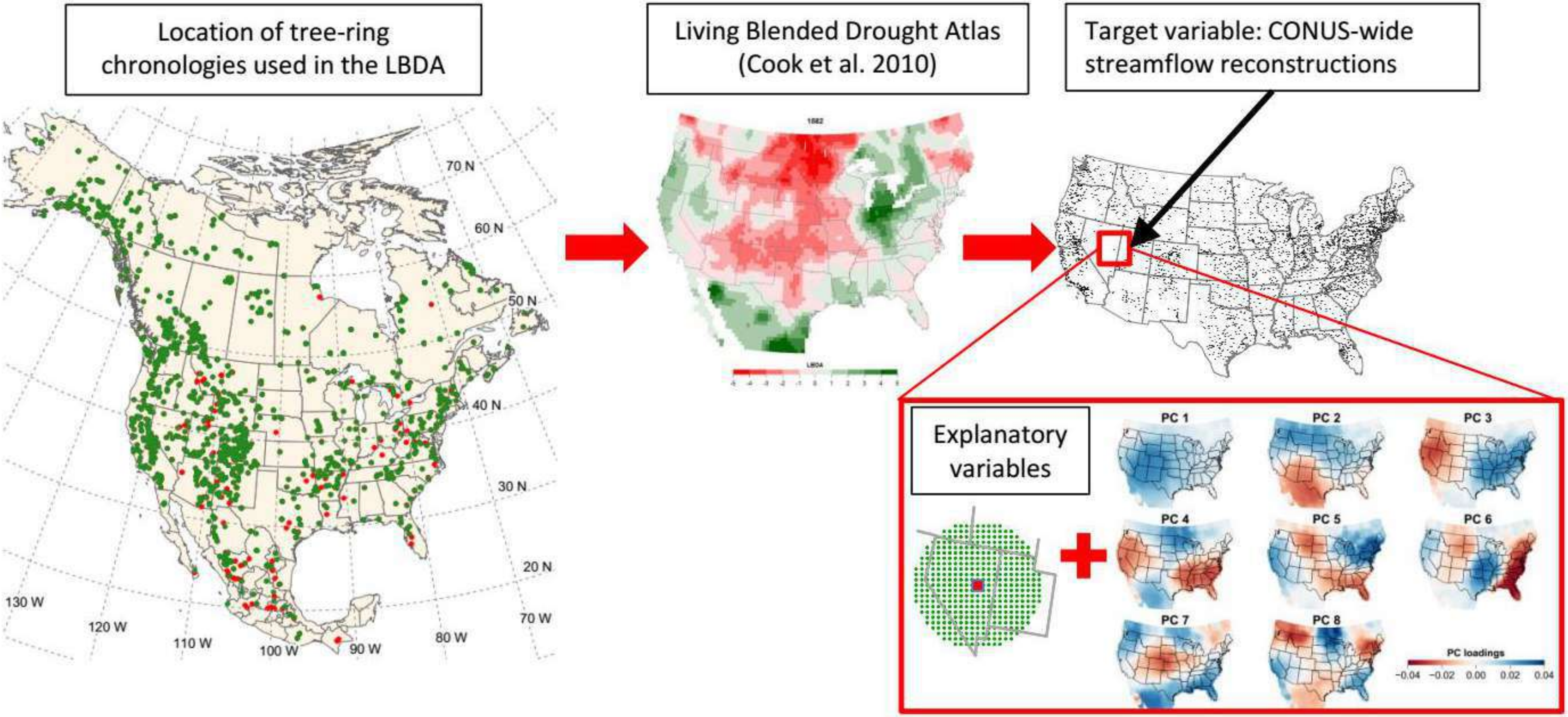
Paleo-reconstruction of streamflows

Translate Living Blended Drought Atlas to gauge streamflows:



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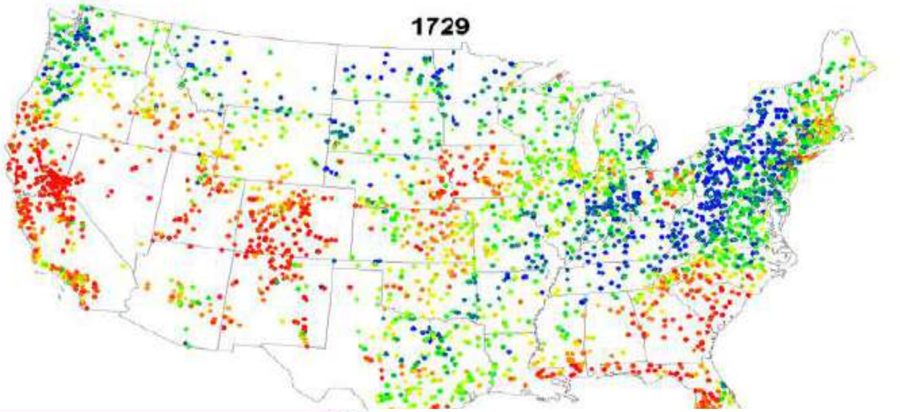
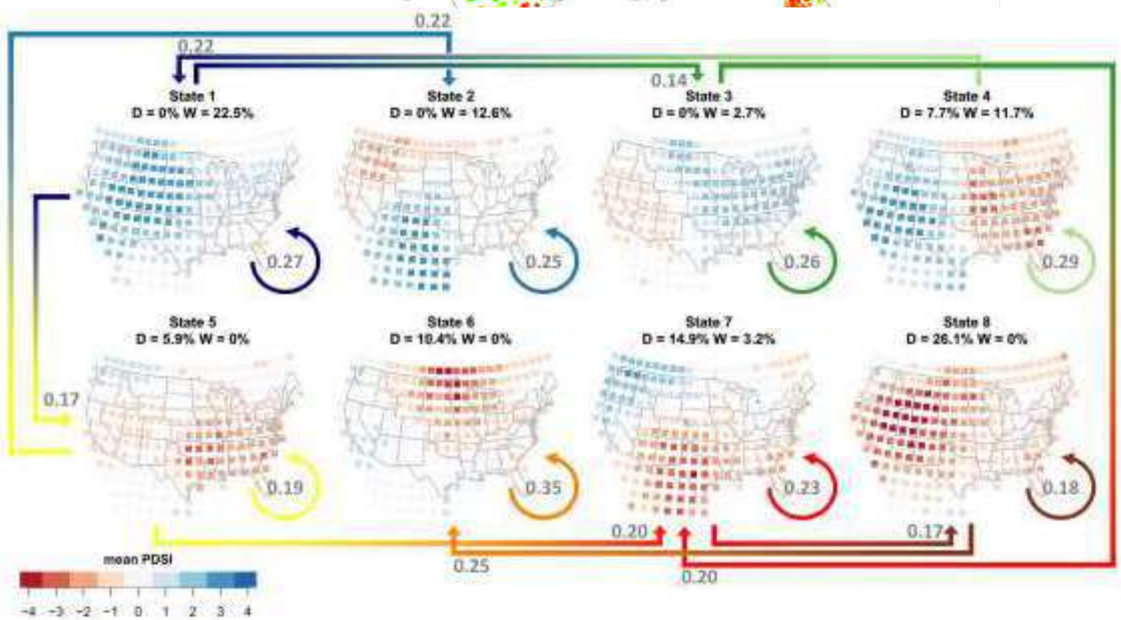
Ho, M., et al. (2017), Water Resources Research

Reconstructing 500 years of streamflow

Annual Flows → Monthly Flows





- Develop Hidden Markov Model of yearly transitions (8 states).
- Adjust climatological gauge flows to match paleo average.
- Add in residuals from historical years matching same HMM state.

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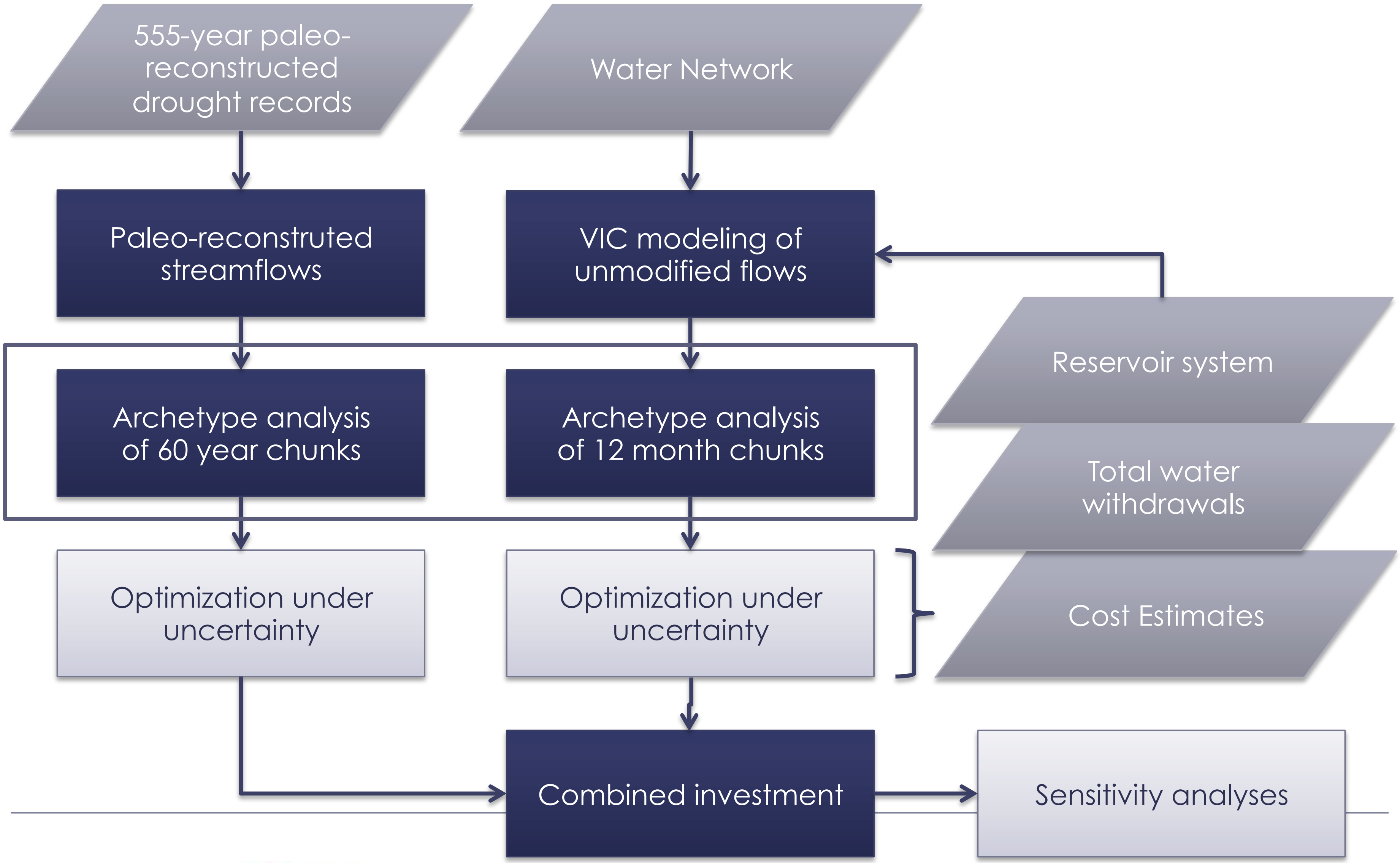
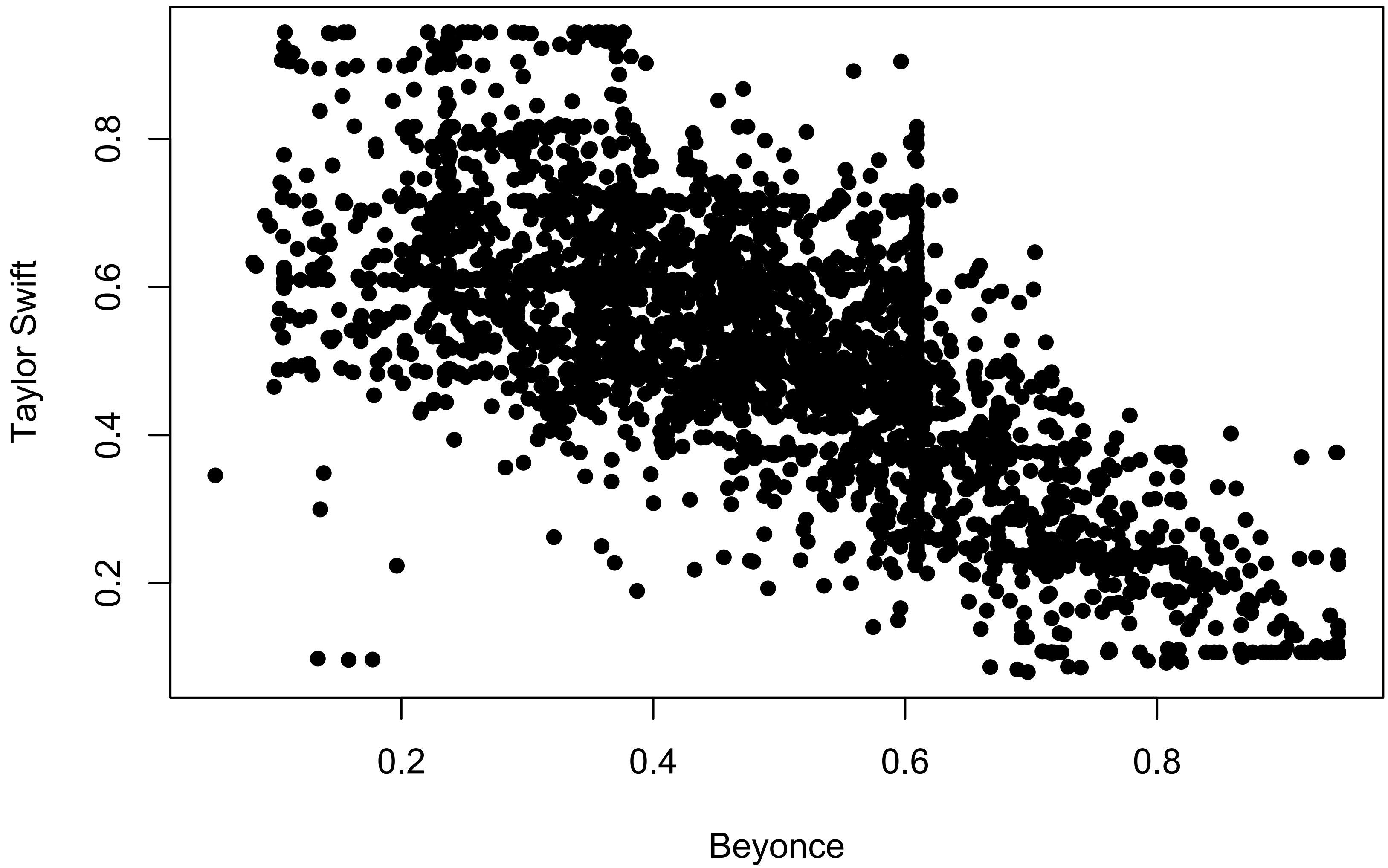
Process and modeling



Example: Interest in Taylor Swift and Beyoncé across US counties



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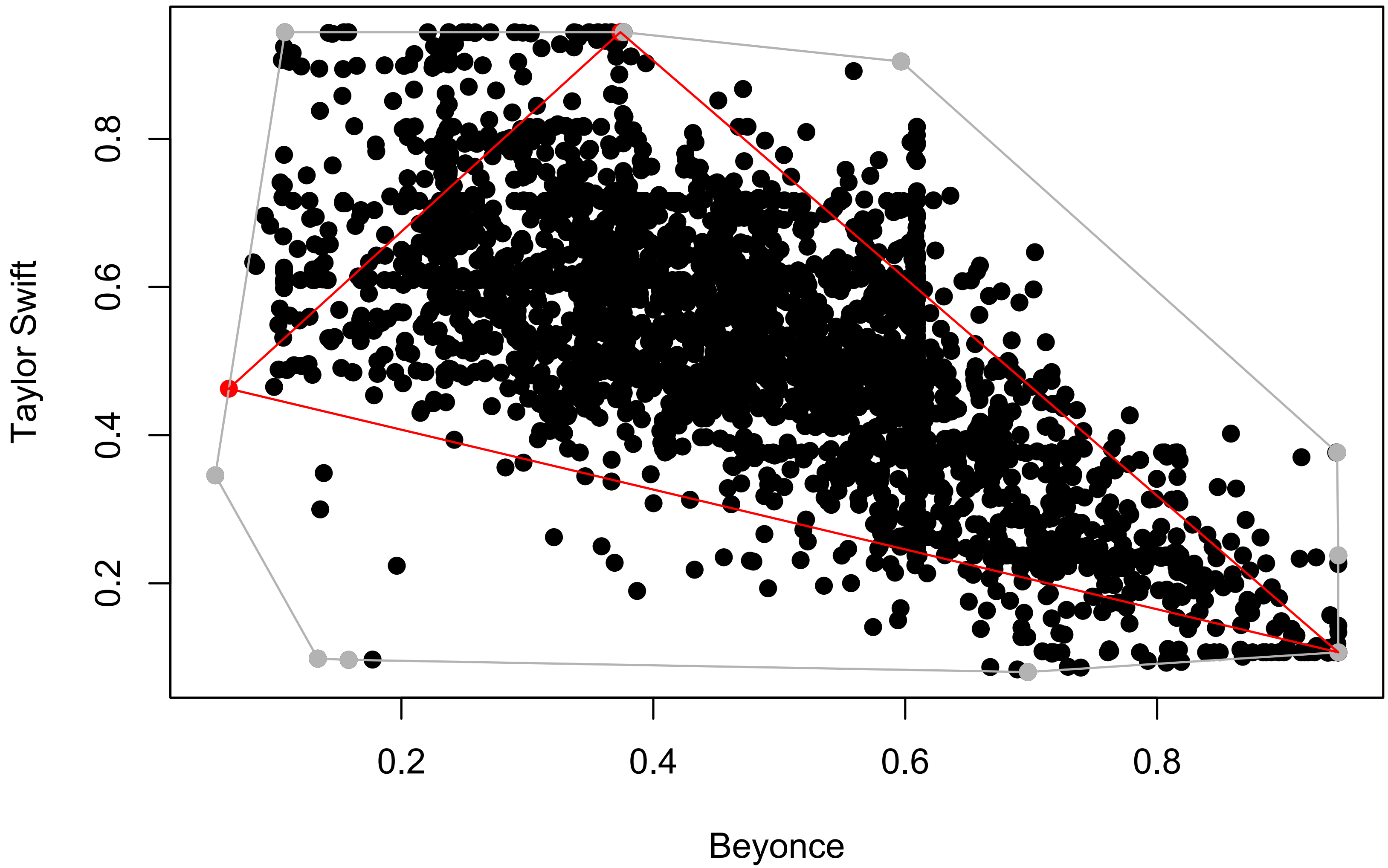

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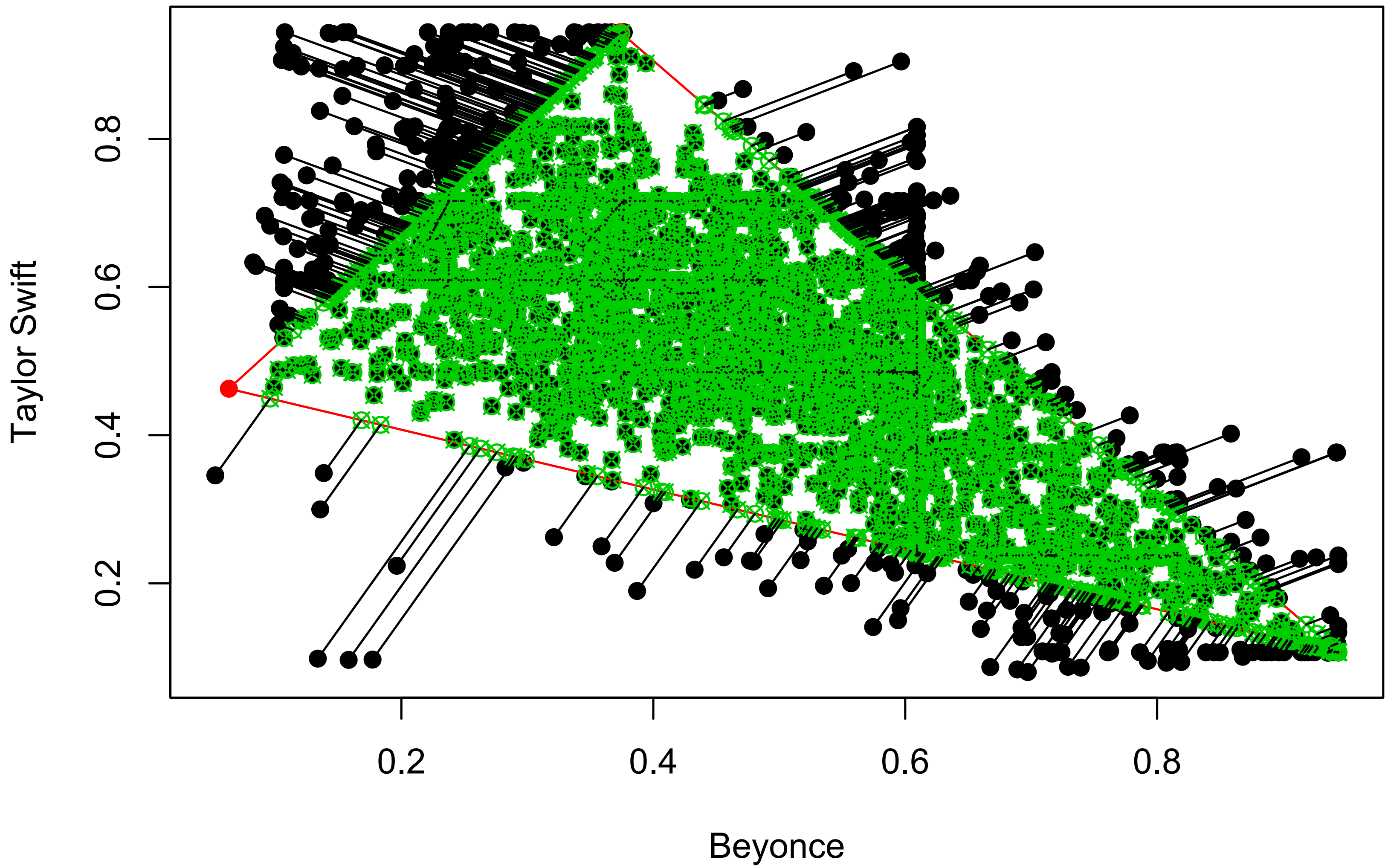
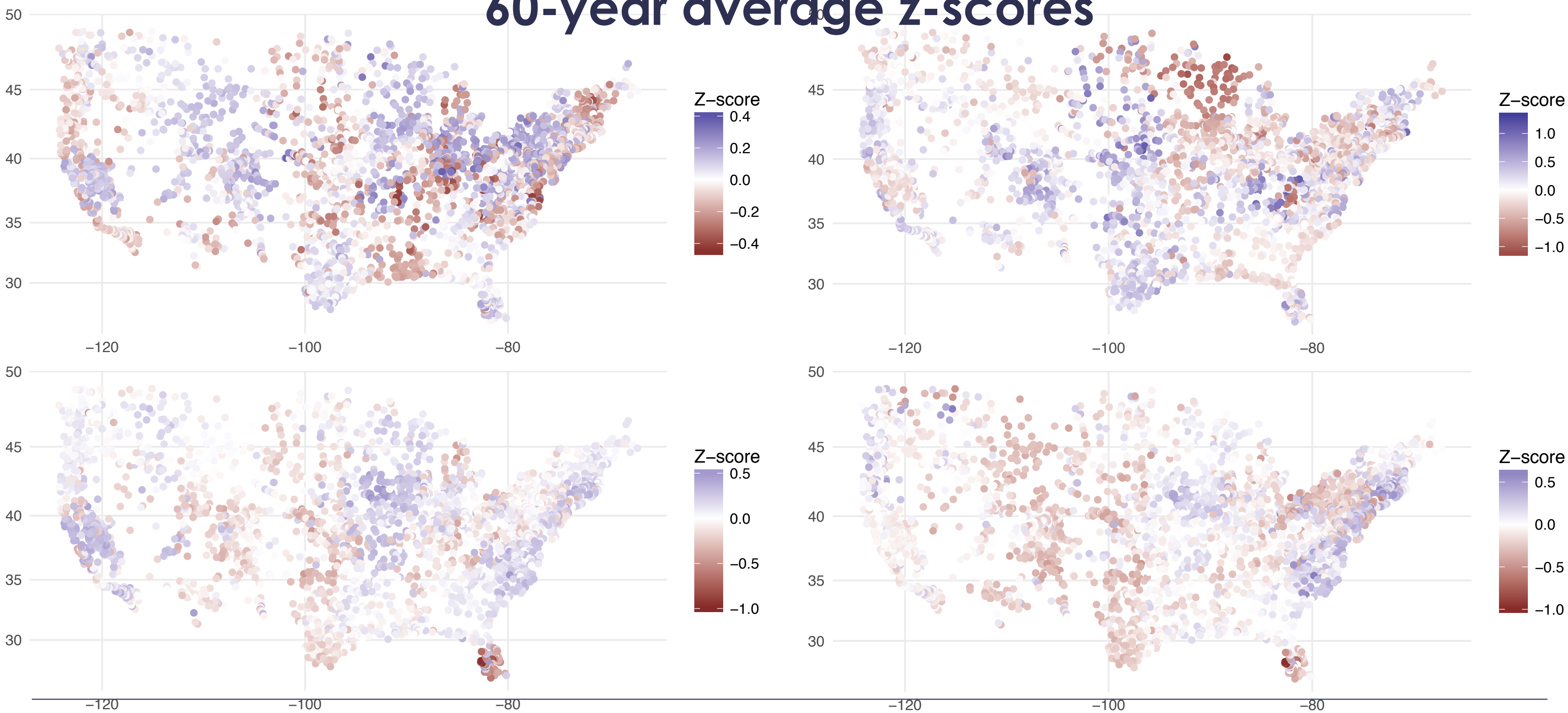


Archetypes of 60-year chunks

Find archetypes of 60-year patterns: (60x#gauges)-dimensional space.

60-year average z-scores



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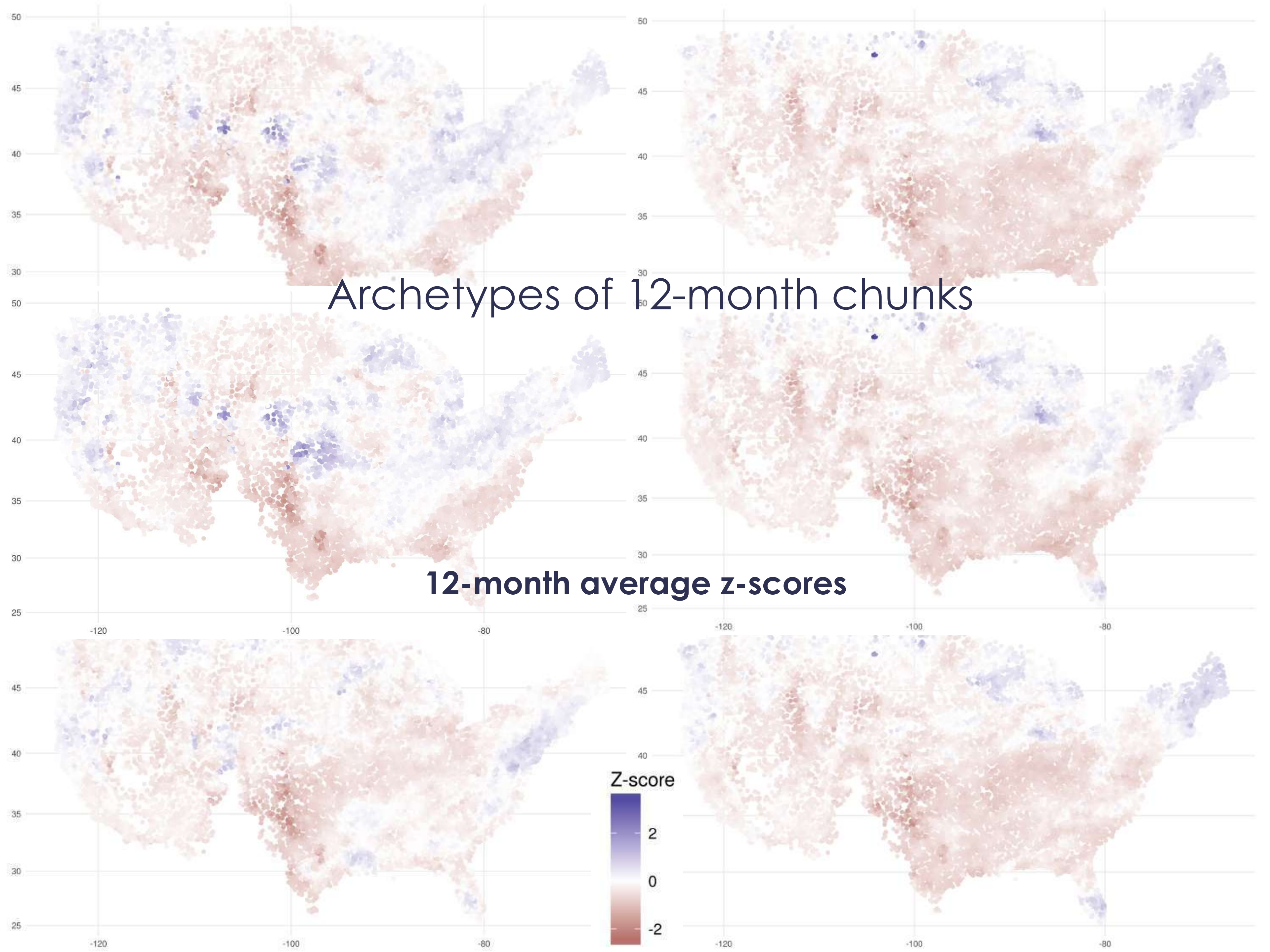
Archetypes of 12-month chunks

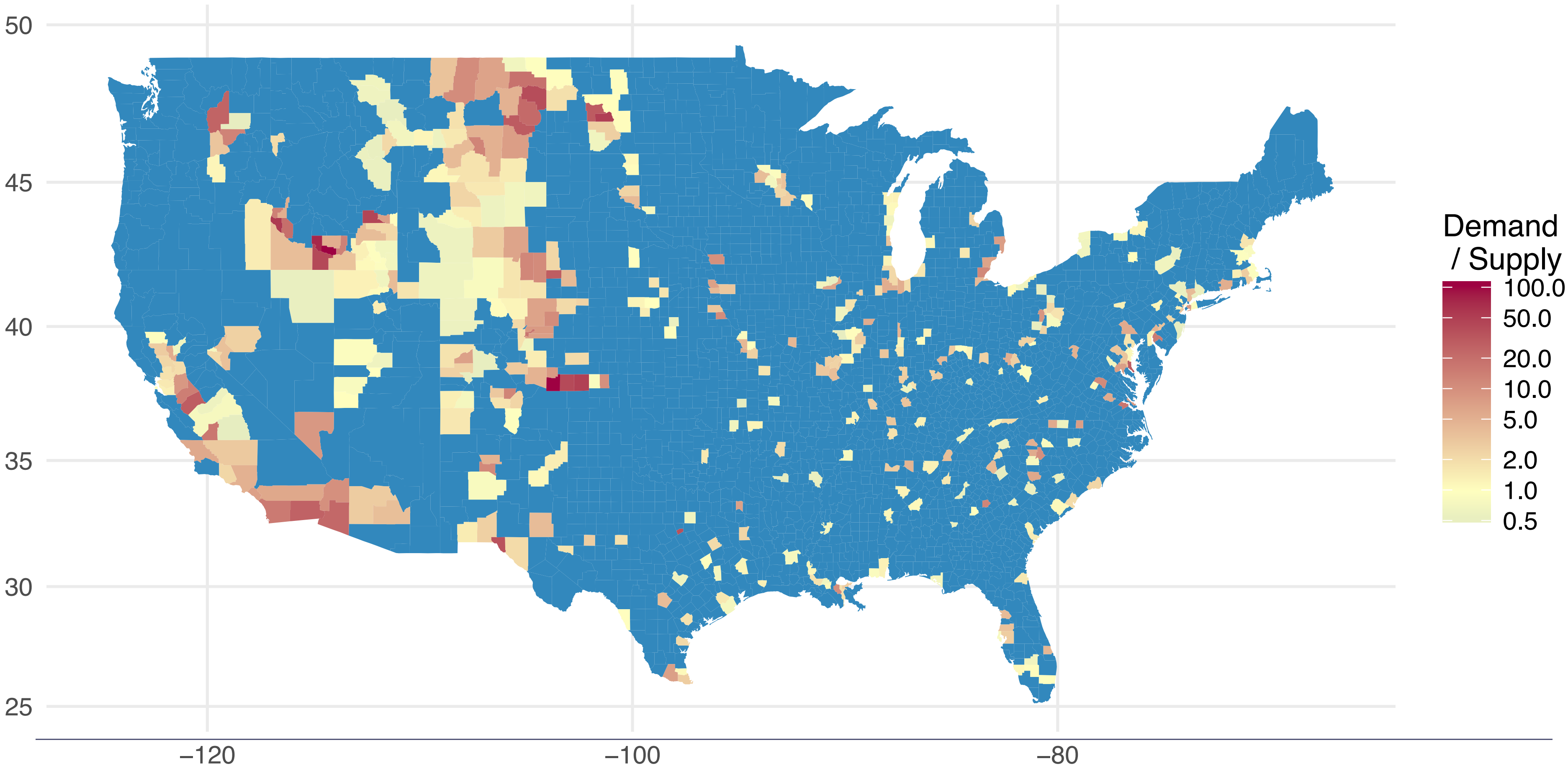
12-month average z-scores



Topics

- The need for integrated perspectives on water and the AWASH model
- Paleo-variability of streamflows and archetypes
- **Reservoir planning and preliminary results**
- What we've learned

Ratio of SW demand (USGS) to average SW supply (local runoff)



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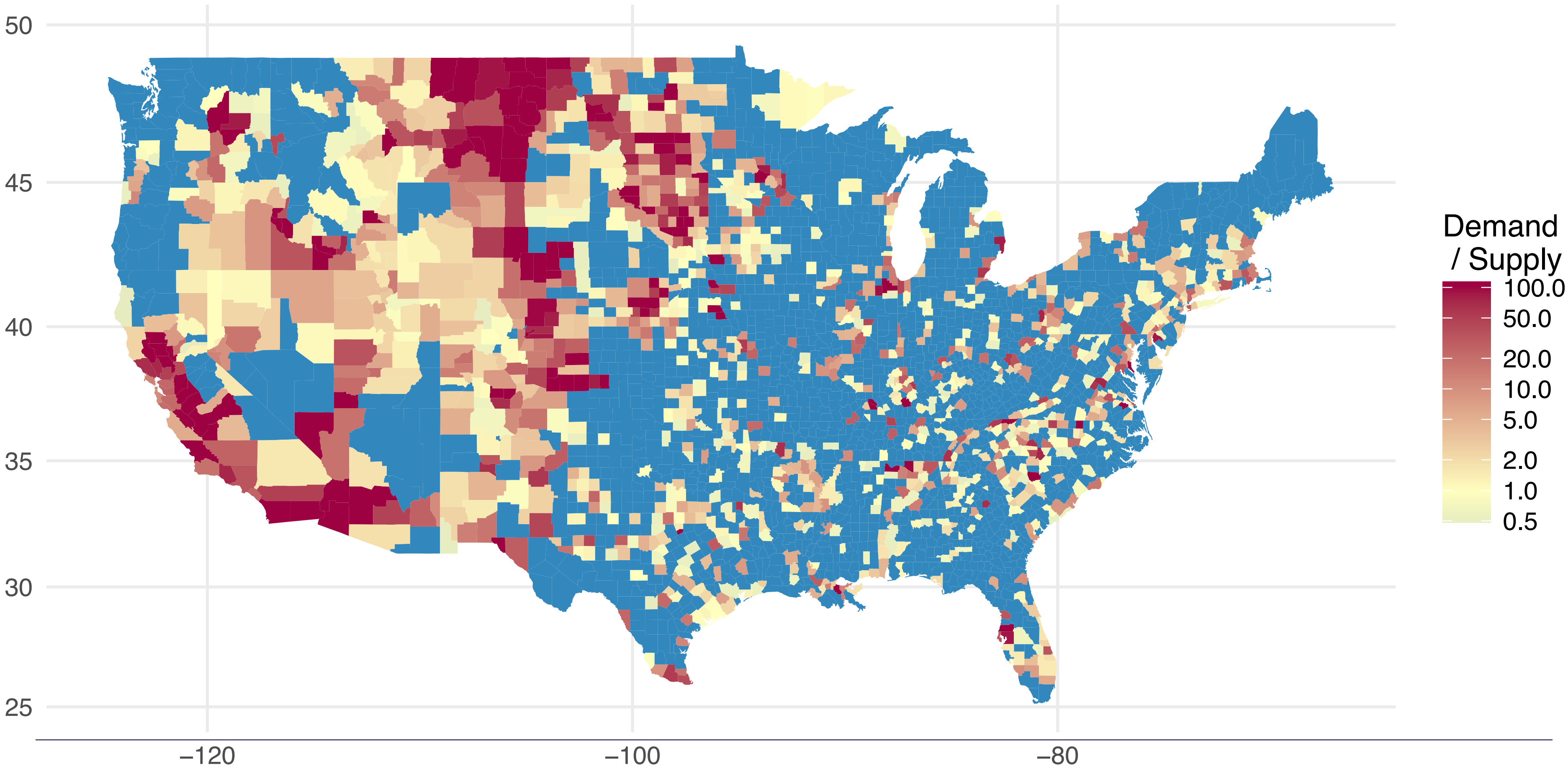
Ratio of SW demand to monthly minimum SW supply



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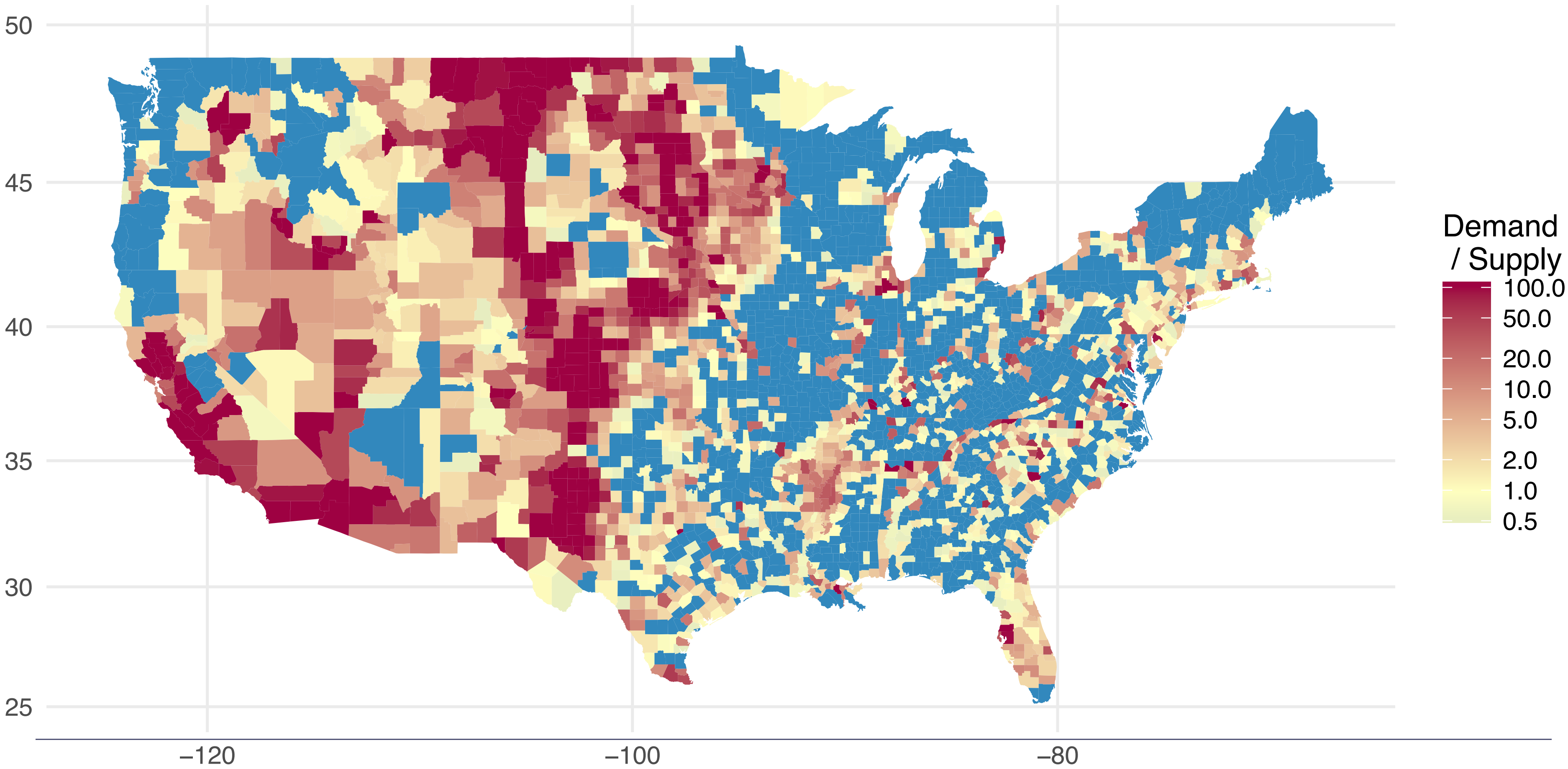
Ratio of total demand to monthly minimum SW supply



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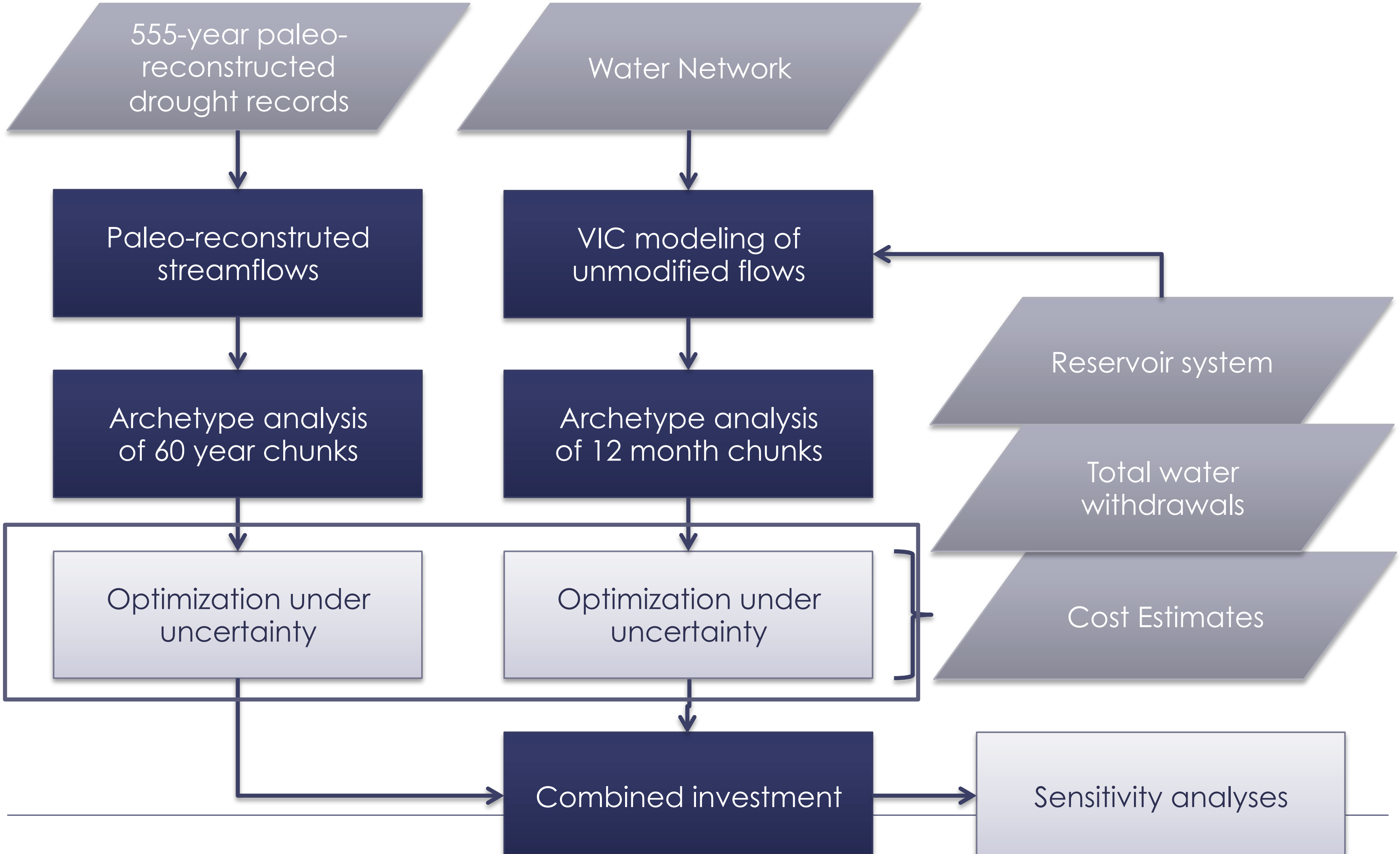
Process and modeling



Simplified optimization (1 location)

- **Inputs:**
  - q_t: precipitation or inflow (volume / year)
  - d_t: water demand (volume / year)
- **Static parameters:**
  - e: Evaporation or other losses (portion / year)
  - T: timestep (years)
- **Choice variables:**
  - w_t: withdrawals (volume / year)
  - x_t: supersource water (volume / year)
  - k_t: investment in increasing capacity (volume / year)
- **State variables:**
  - v_t: reservoir level (volume)
  - c_t: reservoir capacity (volume)

Simplified optimization (1 location)

- **Reservoir dynamics:**

$$v_{t+1} = (1-e)^T v_t + q_t - w_t$$

$$c_{t+1} = c_t + k_t \qquad\qquad v_0 = c_0 = 0$$

- **Constraints:**
  - $w_t + x_t \geq d_t$: Must satisfy demand
  - $v_t \leq c_t$: Cannot over-fill reservoir
  - $w_t \leq v_{t-1} + q_t$: Cannot over-withdrawal reservoir

- **Minimize costs:**

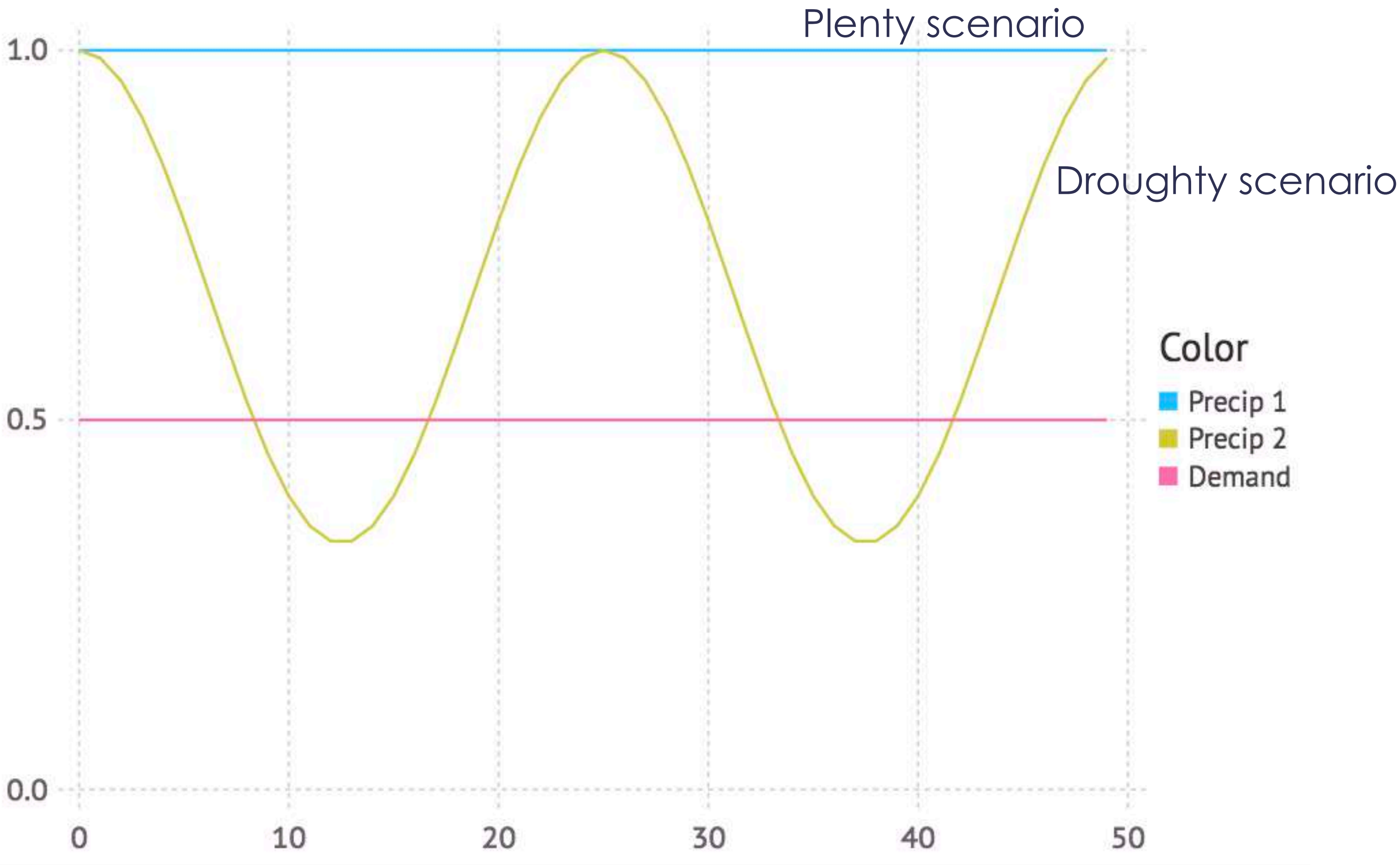
Under certainty:

$$\sum_t (Ax_t + k_t)e^{-\delta t}$$

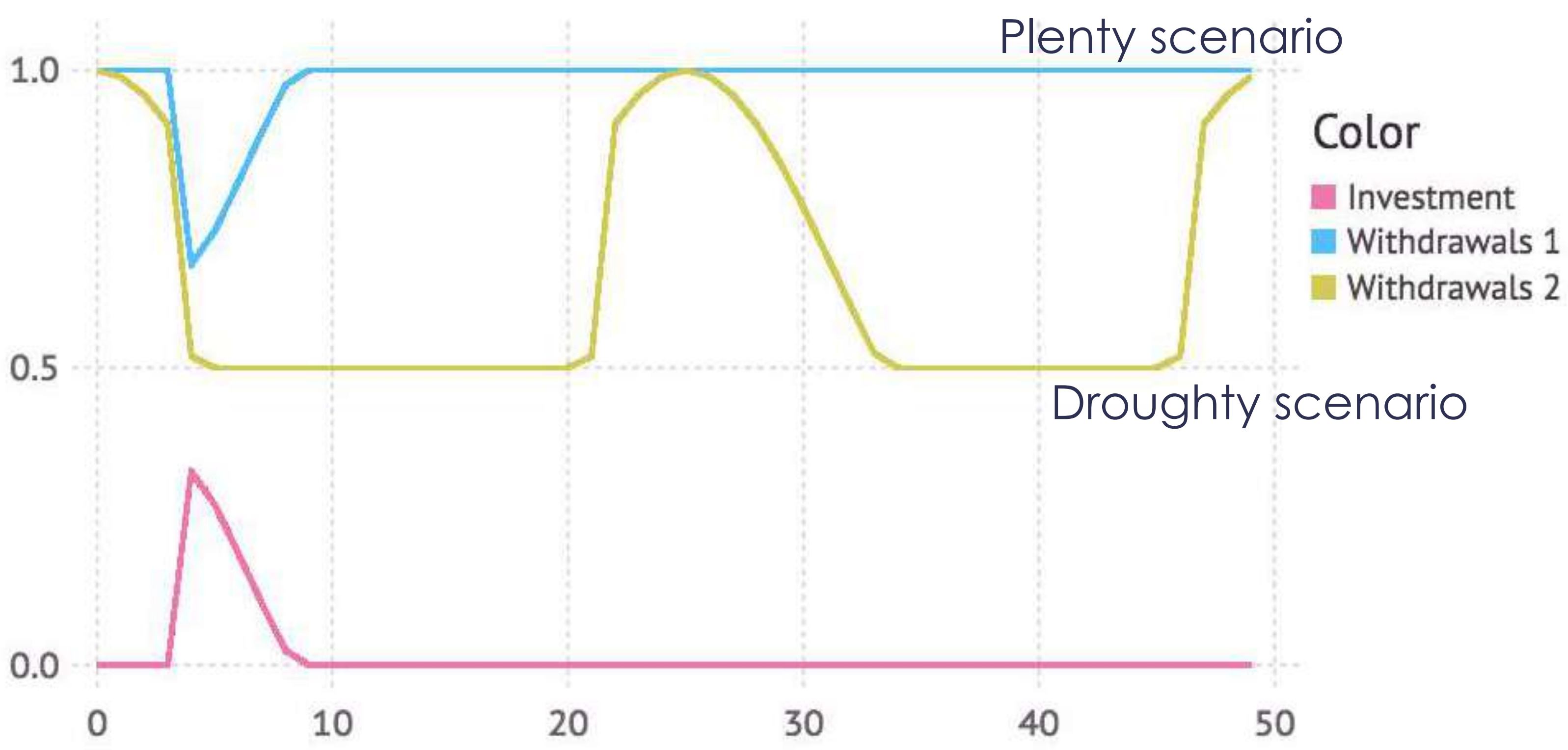
Under uncertainty:

$$\sum_t \left(A\left(\sum_i p_i x_{it}\right) + k_t\right)e^{-\delta t}$$

1 location, 2 scenario Problem



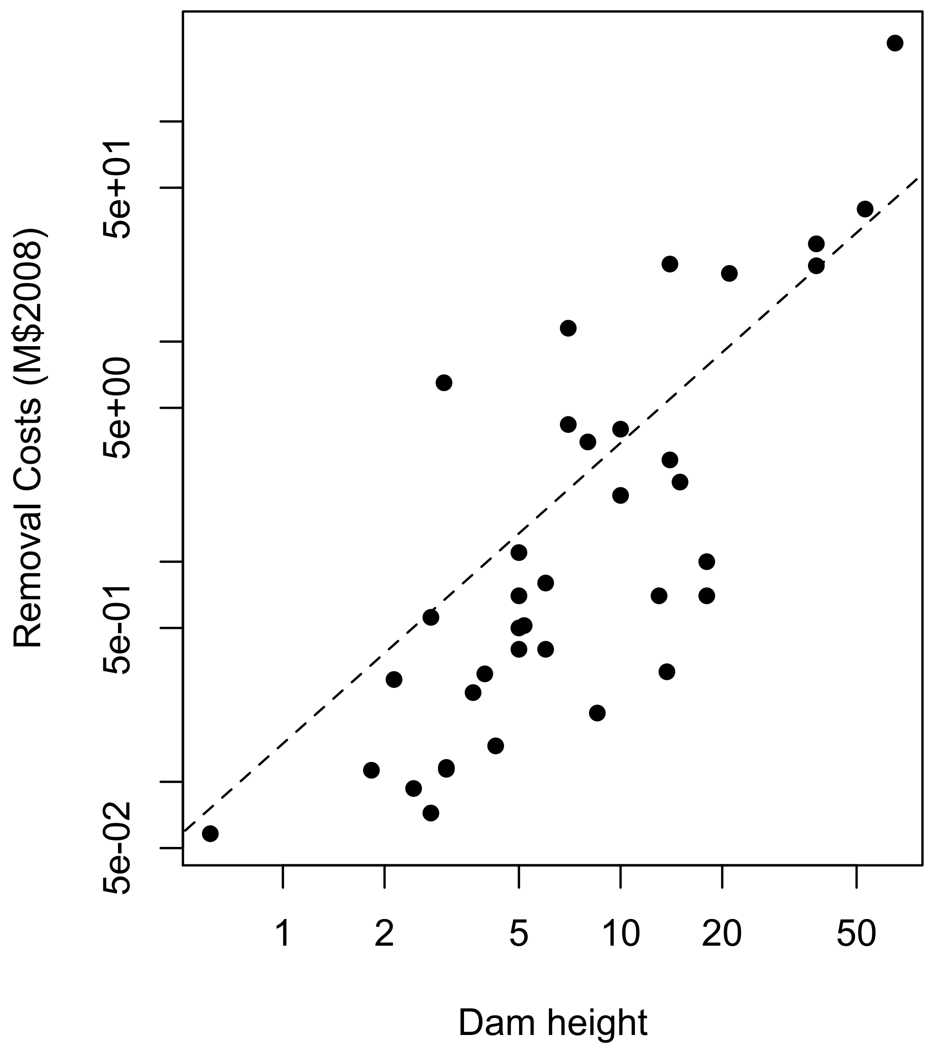
1 location, 2 scenario Solution



Changes for the full optimization

- **Includes groundwater** (costly withdrawals).
- **Small price on surface water withdrawals and reservoir "captures".**
- **Maintenance cost based on reservoir capacity.**
- **Water network dynamics**: flow downstream.
- **Return flows by usage**: 39% (Ag.) to 98% (Energy)
- **Gauge-to-county mapping**: "canals" to counties
- Reservoirs start at current capacity but 0 volume (in monthly opts, 12 months to of initialization).

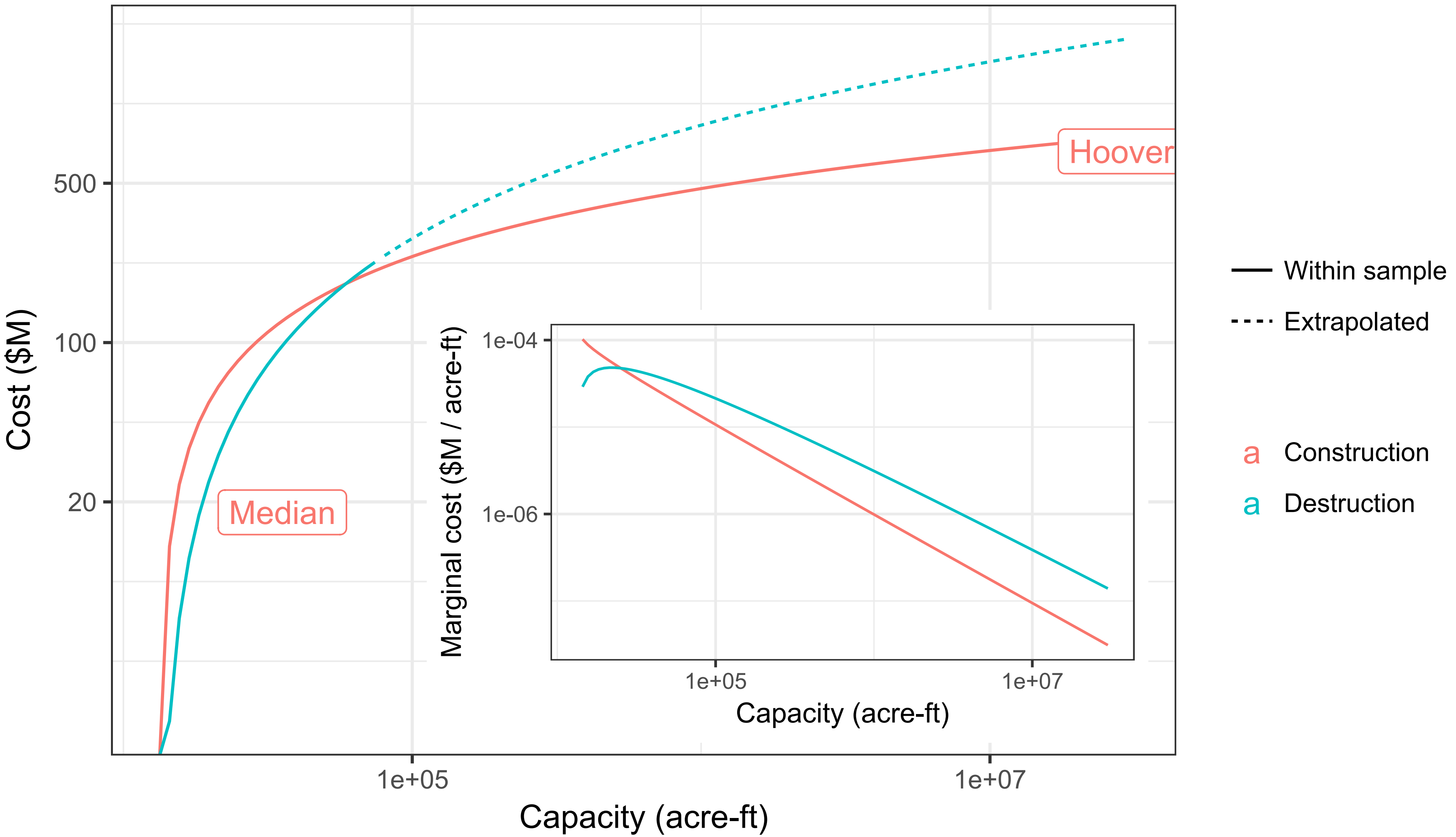
Estimating removal costs



	Dependent variable:	
	Log Cost ($2008M)	
	(1)	(2)
Log height	1.625***	1.366***
	(0.207)	(0.225)
Removal year		0.049***
		(0.016)
Constant	−3.076***	−100.937***
	(0.456)	(32.442)
Observations	37	33
R^2	0.638	0.655
Adjusted R^2	0.628	0.632
Residual Std. Error	1.243 (df = 35)	1.149 (df = 30)
F Statistic	61.786*** (df = 1; 35)	28.514*** (df = 2; 30)
Note:		*p<0.1; **p<0.05; ***p<0.01

Born et al. 1998, Water Power Magazine 2009

Removal and construction vs. capacity



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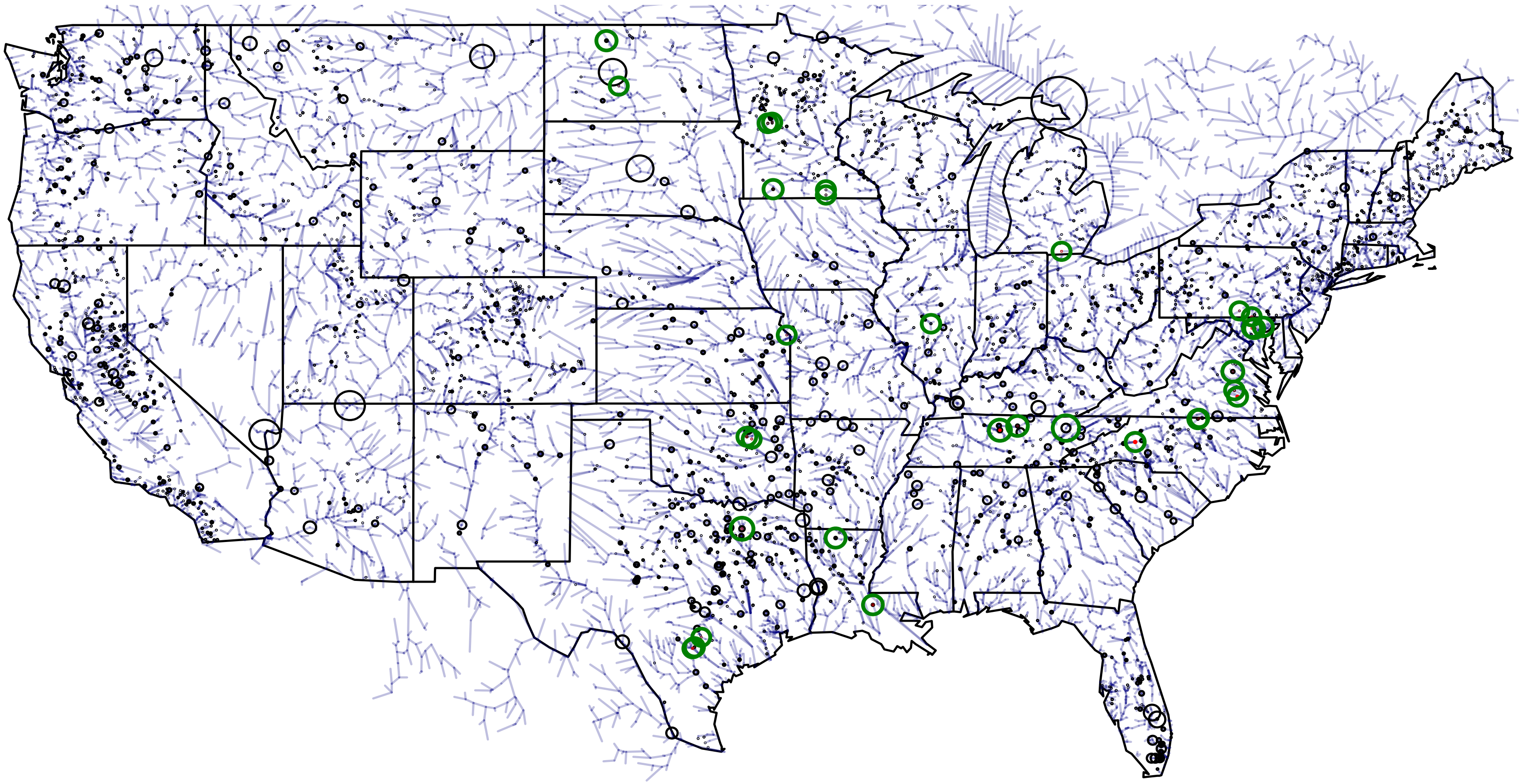
Results due to monthly variability



Black circles: Existing capacity of reservoirs;
Red filled circles (highlighted in green): maximum usage of capacity across scenarios.

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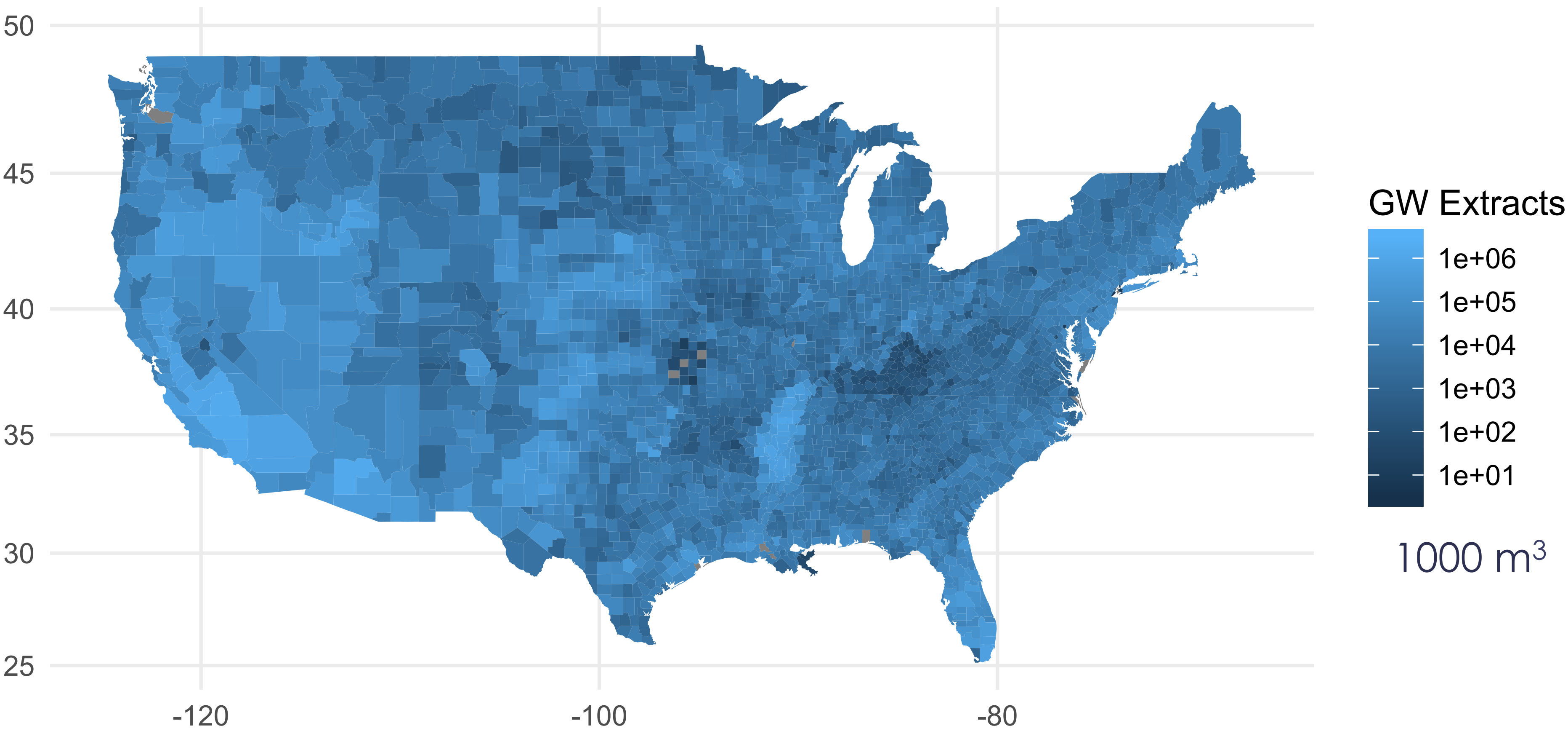
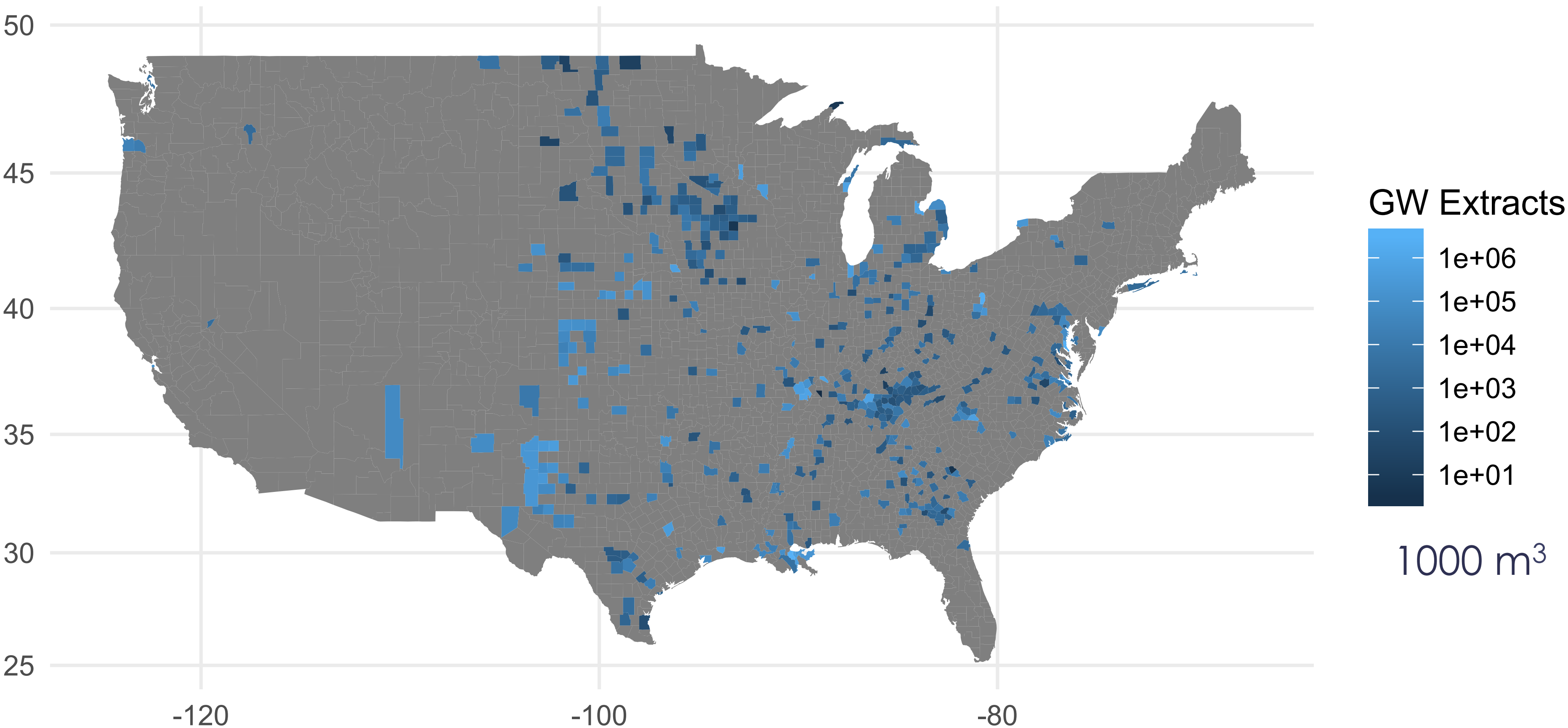
Observed GW withdrawals



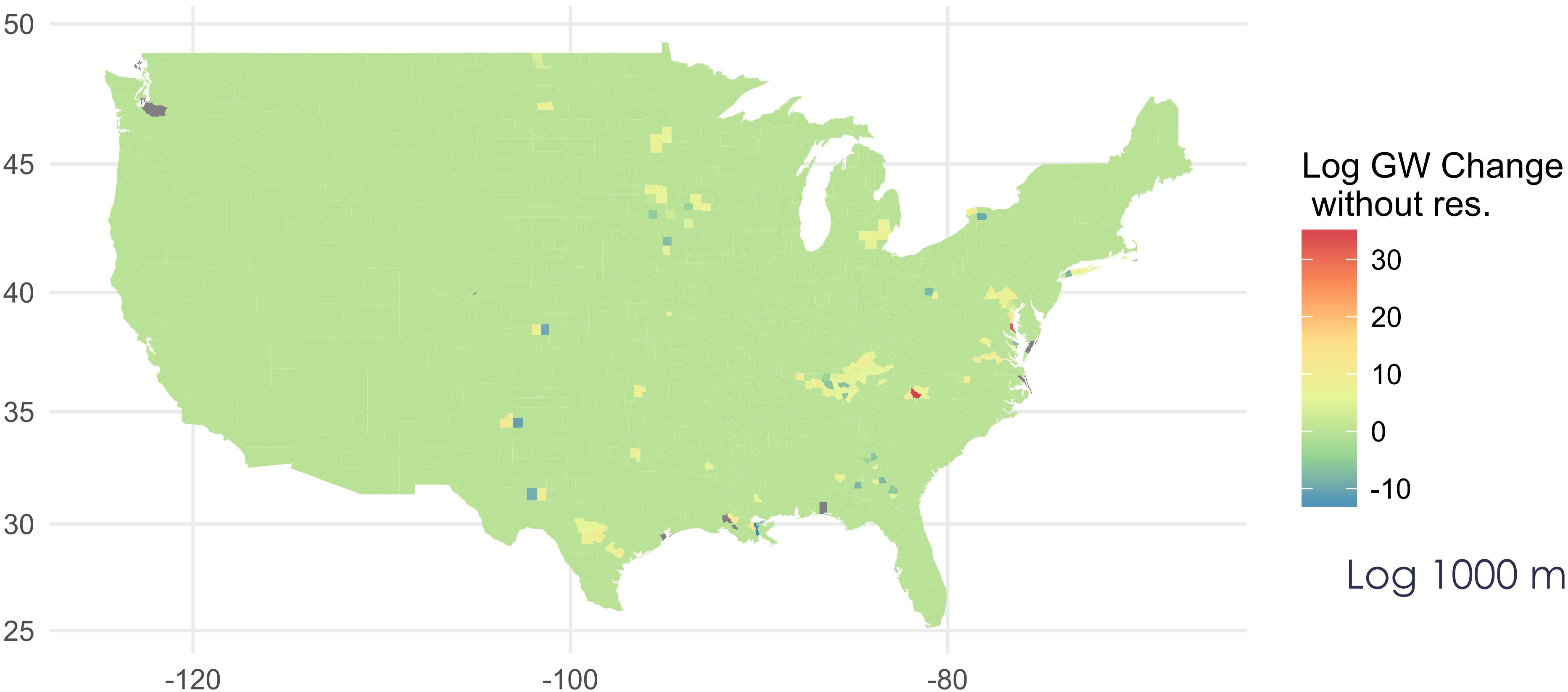
Observed 12-month GW extraction by USGS.

Optimal groundwater without reservoirs



Maximum 12-month GW extraction across scenarios.

Changes in GW from Reservoirs



Log 1000 m^3

Maximum and minimum (negative) 12-month GW difference across scenarios.

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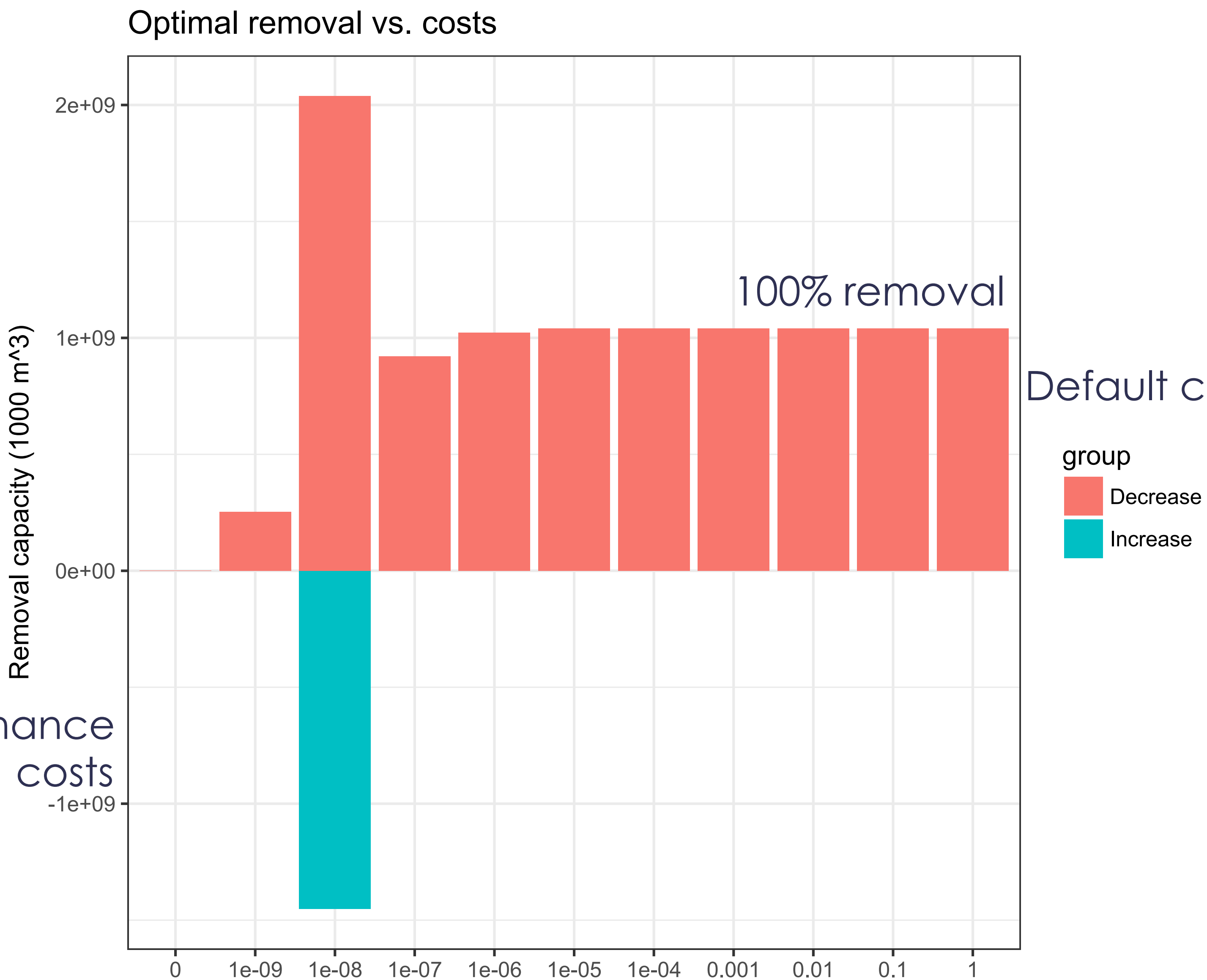
Results for 60-year chunks



100% removal

Default costs

0 maintenance costs

Scaling of maintenance costs

Topics

- The need for integrated perspectives on water and the AWASH model
- Paleo-variability of streamflows and archetypes
- Reservoir planning and preliminary results
- **What we've learned**

Overview of results

- Some small river reservoirs help buffer monthly demands, but most don't.
- Costs of maintenance cannot justify reservoirs for long-term droughts, so long as groundwater is available.

What haven't we learned?

- **Lots of reasons for reservoirs ignored here.**
- **Totally ignore water rights.**
- **Should optimal differ so far from observed?**
  - Do we even know true WEF flows?
- **Groundwater costs unavailable most areas.**

Broad lessons from AWASH

- **Opportunities for better supply decisions**
  - Conjunctive use, over borders, over years
  - Wide variation, based on margin of decision
- **Resolution matters**
  - Optimizing county to state >> state to country
  - Buffering water over years saves a little ($17 mil), but over seasons essential
- **Opportunities for better demand decisions**
  - Huge difference between observed and optimized
- **Opportunities to make a better model**
  - AWASH is a work-in-progress
  - Strong design for continued improvements

Analyses to come

ANALYSES TO PUBLISH

- **Benefits of conjunctive use (SW + GW) policies**
- **Potential for better use by coordinating water rights across different borders**
- **Redistribution of agriculture in Colorado to be more sustainable**

CLIMATE

- **Explore current water demand susceptibility to climate variability using paleo-reconstructed streamflow for 500 years of data**

WATER POLICIES AND FINANCING

- **Shadow price of water**
- **Impacts of water compacts and policies on water stresses (e.g. farm bill)**
- **Water rights market: highlight where water rights trading possibilities may potentially lead to reduce vulnerabilities**

THE FUTURE OF WATER-ENERGY-FOOD

- **Investigate scenarios capturing potential future of US:**
    - Population projections, energy prices, GDP, imports and exports
    - Impact of diet changes and food demand? E.g. “Low-carb diets”, meat consumption, high cash crops (almonds)
    - Penetration of renewable energies, wind and solar droughts impact on hydropower

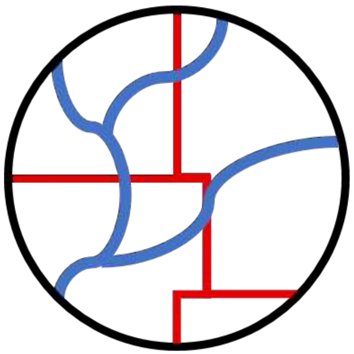
Beyond research

- **Some broad goals**
  - A tool for policy-makers
    - Infrastructure design and financing
    - Environmental policy (e.g. minimum flows)
    - Demonstrate the potential of national water planning
  - A tool to educate
    - Light online version of the model for education purposes
  - Looking to expand to WEF modeling in EU and Africa

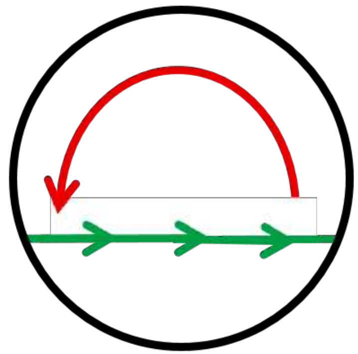
- **Challenges**
  - Plenty of assumptions and approximations
  - Lack of data

Thank you!

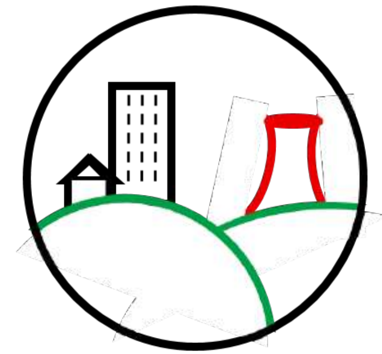
Check out the model: http://awashmodel.org/



SPATIAL

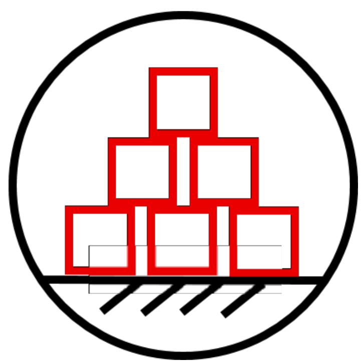


OPTIMIZING

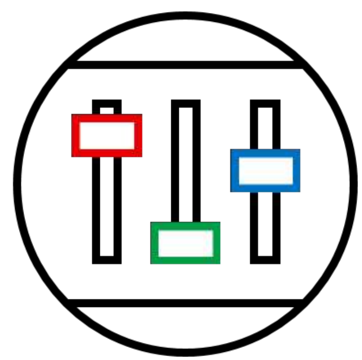


MULTI-DEMAND

MULTI-SUPPLY



EMPIRICAL



CONFIGURABLE

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