

# Advancing the science of complex adaptive human-Earth systems through MultiSector Dynamics

Antonia Hadjimichael  
Penn State University

Escuela de Gobierno y  
Transformación Pública del  
Tecnológico de Monterrey  
June 2022





**Navigating climate risks and transitions  
in an increasingly interconnected and  
rapidly changing world requires deep  
interdisciplinary integration and new  
modes of scientific inquiry**

# A recent example...

The temperature extremes and energy demands during the event were equivalent to past winter storms in Texas<sup>1</sup> but caused \$195 billion and 246 deaths in Texas alone.

Winter Storm Uri  
February 13–17, 2021

AUSTIN, TEXAS · February 16, 2021





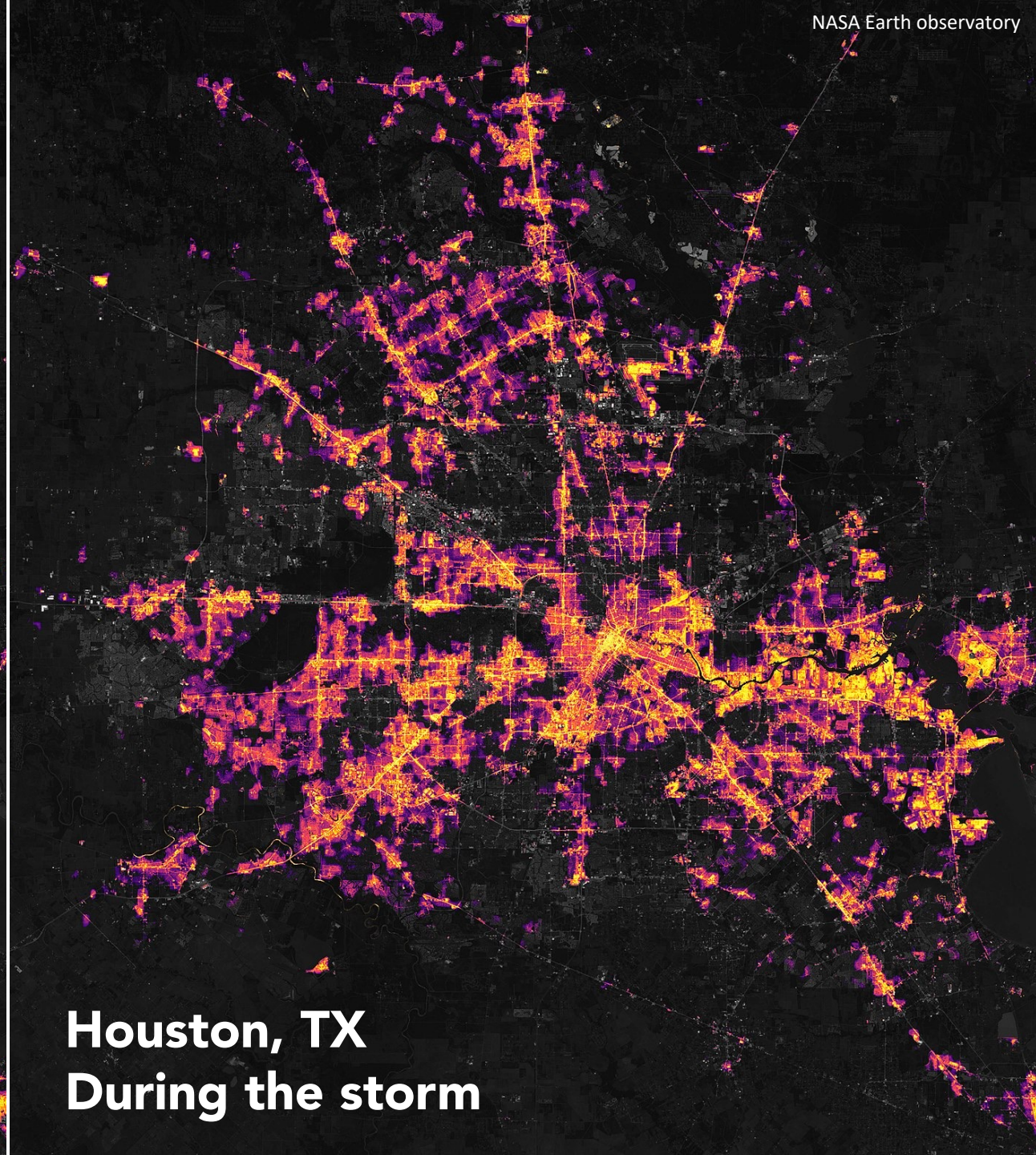
Besides the environmental hazard, these impacts were due to several institutional, infrastructural and socio-economic reasons:

- Texas operates on an isolated power grid
- Power generation systems were not sufficiently weatherized
- Insufficient planning for high demands

**Rolling blackouts across the state left millions without electricity, water or food**



**Houston, TX  
Before the storm**



**Houston, TX  
During the storm**

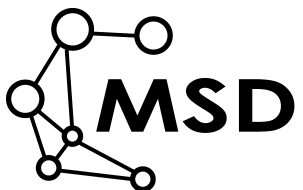
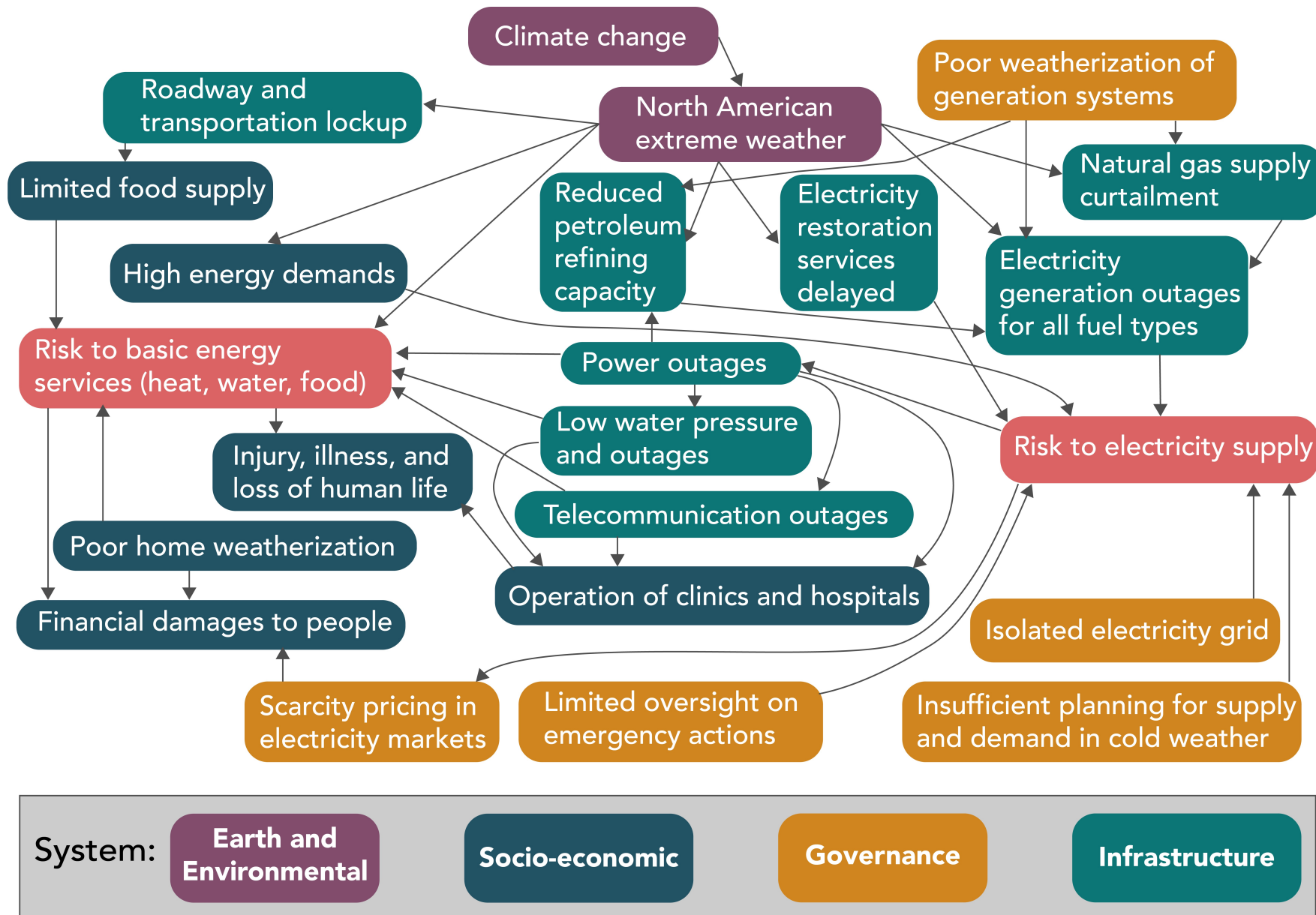
## Human response:

- Increased energy demands
- Buying additional fuel and generators
- Storing food and water
- Electricity scarcity pricing



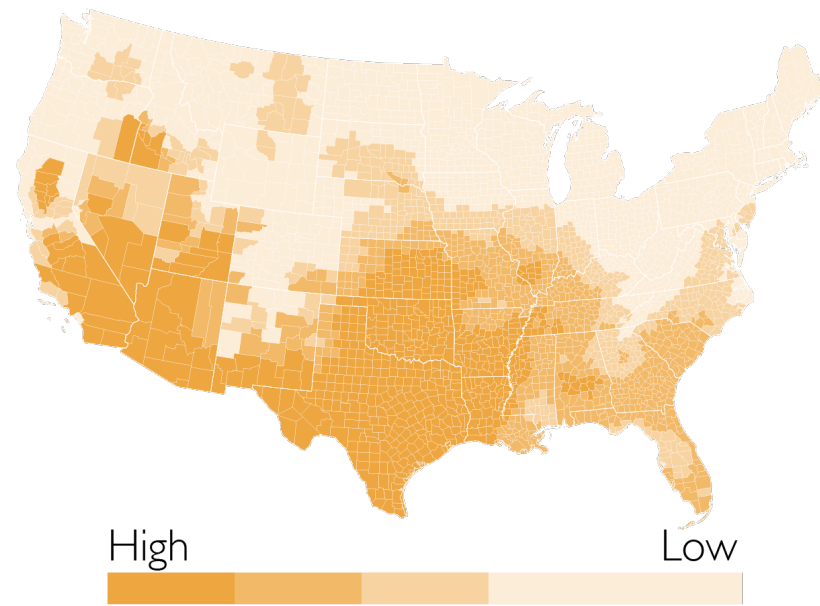
Propane tanks are placed in a line as people wait for the power to turn on to fill their tanks in Houston. (Mark Felix for The Washington Post)

Risk emerged as a result of many **dynamic processes** and actions across many **systems** and across different **scales**

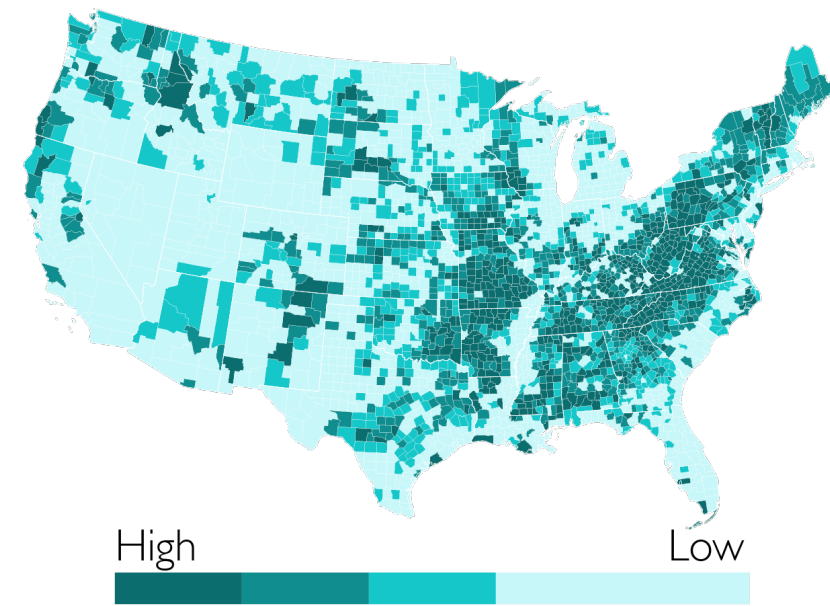


Winter storms are only one type of hazard potentially facing a region

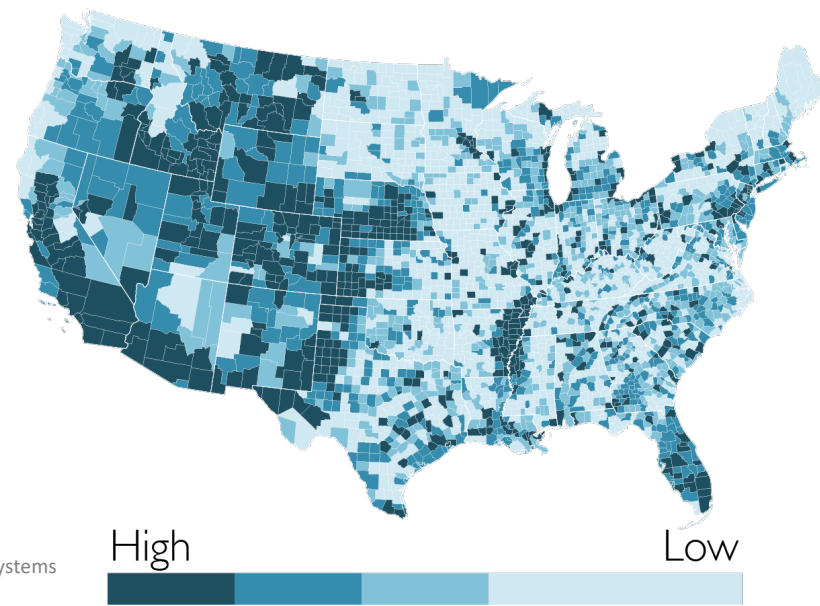
Temperature Stress



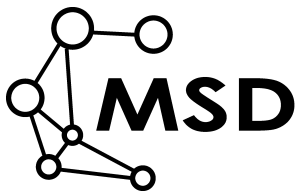
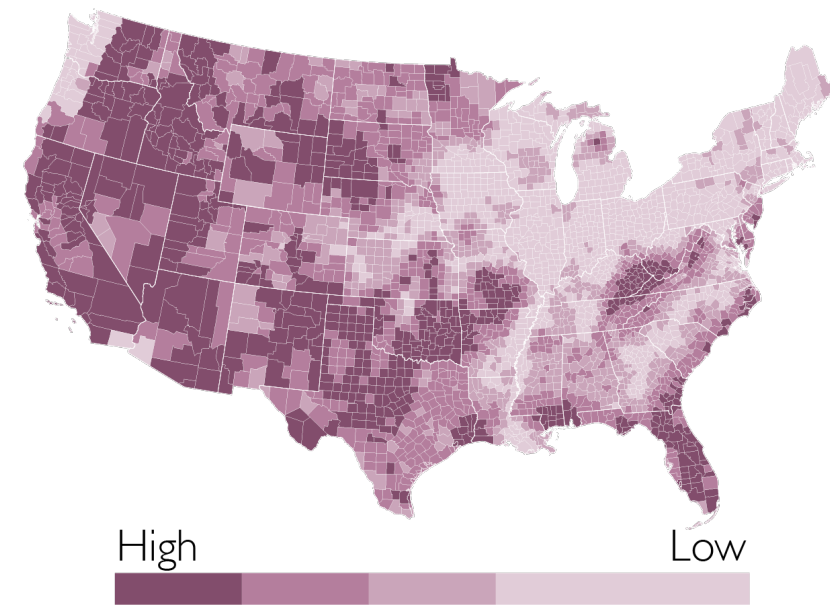
Flood Risk



Water Stress



Wildfire risk





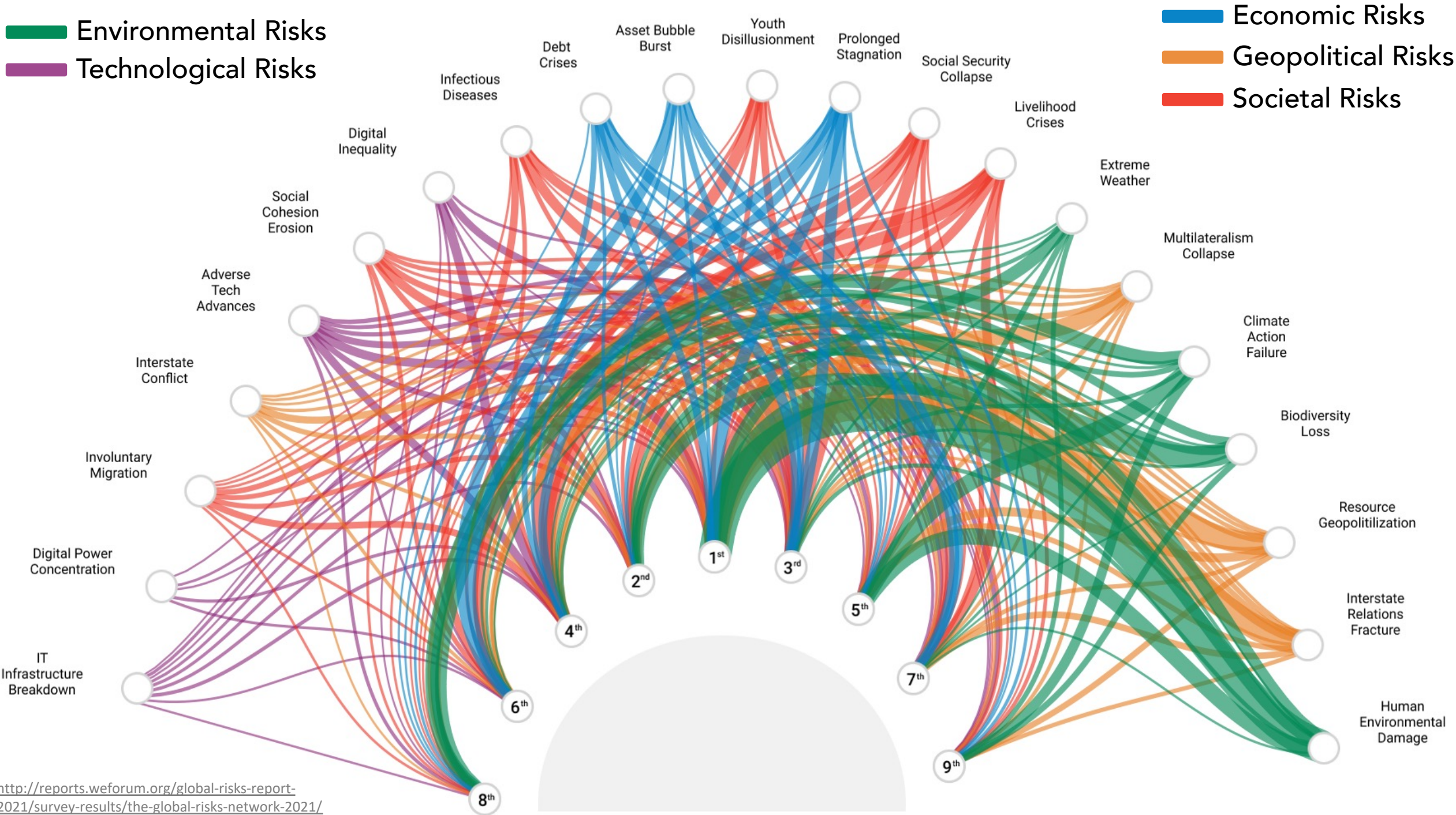
Globally, we are facing interconnected,  
multisectoral risks.



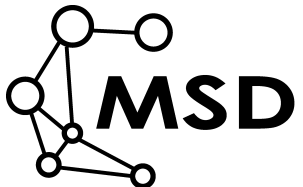
A group of refugees and migrants walk towards the border of Greece and North Macedonia. Credit: UNHCR

█ Environmental Risks  
█ Technological Risks

█ Economic Risks  
█ Geopolitical Risks  
█ Societal Risks



There are several promising frameworks to help us understand these interactions.



# A framework for complex climate change risk assessment

Systemic failures, extreme events and 'hyper-risks' emerge as a result of the **highly complex and highly interconnected** human-Earth systems

**Dynamic relationships** between agents, systems and sectors transmit risk for one to another

Drivers can amplify or buffer existing threats

Need for **fundamental innovations** in risk assessment





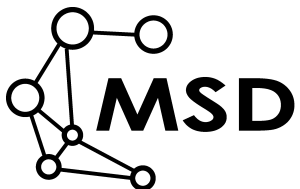
Besides risks we must navigate:

- important transitions in energy and other sectors,
- fundamental transformations to place ourselves in sustainable future pathways

# A scientific grand challenge:

Better understand how interdependent global-to-local challenges are shaping critical pathways of societal change

Deep integration of diverse perspectives and technical capabilities



# These challenges have been articulated by several communities

Contents lists available at [ScienceDirect](#)

**Environmental Innovation and Societal Transitions**

journal homepage: [www.elsevier.com/locate/eist](http://www.elsevier.com/locate/eist)

ELSEVIER

Commentary

**The role of inter-sectoral dynamics in sustainability transitions: A comment on the transitions research agenda**

Allan Dahl Andersen<sup>a,\*</sup>, Markus Steen<sup>b</sup>, Tuukka Mäkitie<sup>a</sup>, Jens Hanson<sup>a</sup>, Taran M. Thune<sup>a</sup>, Birthe Soppe<sup>c,d</sup>

Check for updates

Contents lists available at [ScienceDirect](#)

**Environmental Modelling and Software**

journal homepage: <http://www.elsevier.com/locate/envsoft>

ELSEVIER

Socio-technical scales in socio-environmental modeling: Managing a system-of-systems modeling approach

Check for updates

Takuya Iwanaga<sup>a,\*</sup>, Hsiao-Hsuan Wang<sup>b</sup>, Serena H. Hamilton<sup>a,c</sup>, Volker Grimm<sup>d,e</sup>, Tomasz E. Koralewski<sup>b</sup>, Alejandro Salado<sup>f</sup>, Sondoss Elsawah<sup>a,g</sup>, Saman Razavi<sup>h</sup>, Jing Yang<sup>i</sup>, Pierre Glynn<sup>j</sup>, Jennifer Badham<sup>k</sup>, Alexey Voinov<sup>l,m</sup>, Min Chen<sup>n</sup>, William E. Grant<sup>b</sup>, Tarla Rai Peterson<sup>o</sup>, Karin Frank<sup>d</sup>, Gary Shenk<sup>p</sup>, C. Michael Barton<sup>q</sup>, Anthony J. Jakeman<sup>a</sup>, John C. Little<sup>r</sup>

One Earth

**Perspective**

Gold Standard for the Global Goals  
1 ton of CO<sub>2</sub> offset  
CellPress

**Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step**

Evelina Trutnevyte,<sup>1,\*</sup> Léon F. Hirt,<sup>1</sup> Nico Bauer,<sup>2</sup> Aleh Cherp,<sup>3,4</sup> Adam Hawkes,<sup>5</sup> Oreane Y. Edelenbosch,<sup>6,7</sup> Simona Pedde,<sup>8</sup> and Detlef P. van Vuuren<sup>9,10</sup>

**Understanding Dynamics and Resilience in Complex Interdependent Systems**  
*Prospects for a Multi-Model Framework and Community of Practice*

Report of a workshop held under the auspices of the U.S. Global Change Research Program  
Interpreting Science on Integrative Modeling with support from the U.S. Department of Energy

U.S. Global Change Research Program

**nature**

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nature > [perspectives](#) > article

Published: 01 May 2013

**Globally networked risks and how to respond**

Dirk Helbing

Nature 497, 51–59 (2013) | [Cite this article](#)

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Vincent A. W. J. Marchau  
Warren E. Walker  
Pieter J. T. M. Bloemen  
Steven W. Popper *Editors*

**Decision Making under Deep Uncertainty**  
From Theory to Practice

DMDU

OPEN Springer

*Routledge Studies in Sustainability Transitions*

**MODELLING TRANSITIONS**  
VIRTUES, VICES, VISIONS OF THE FUTURE

Edited by  
Enayat A. Moallemi and Fjalar J. de Haan

Routledge

**Panarchy**

UNDERSTANDING TRANSFORMATIONS IN HUMAN AND NATURAL SYSTEMS

EDITED BY  
Lance H. Gunderson  
C. S. Holling

**Convergence**

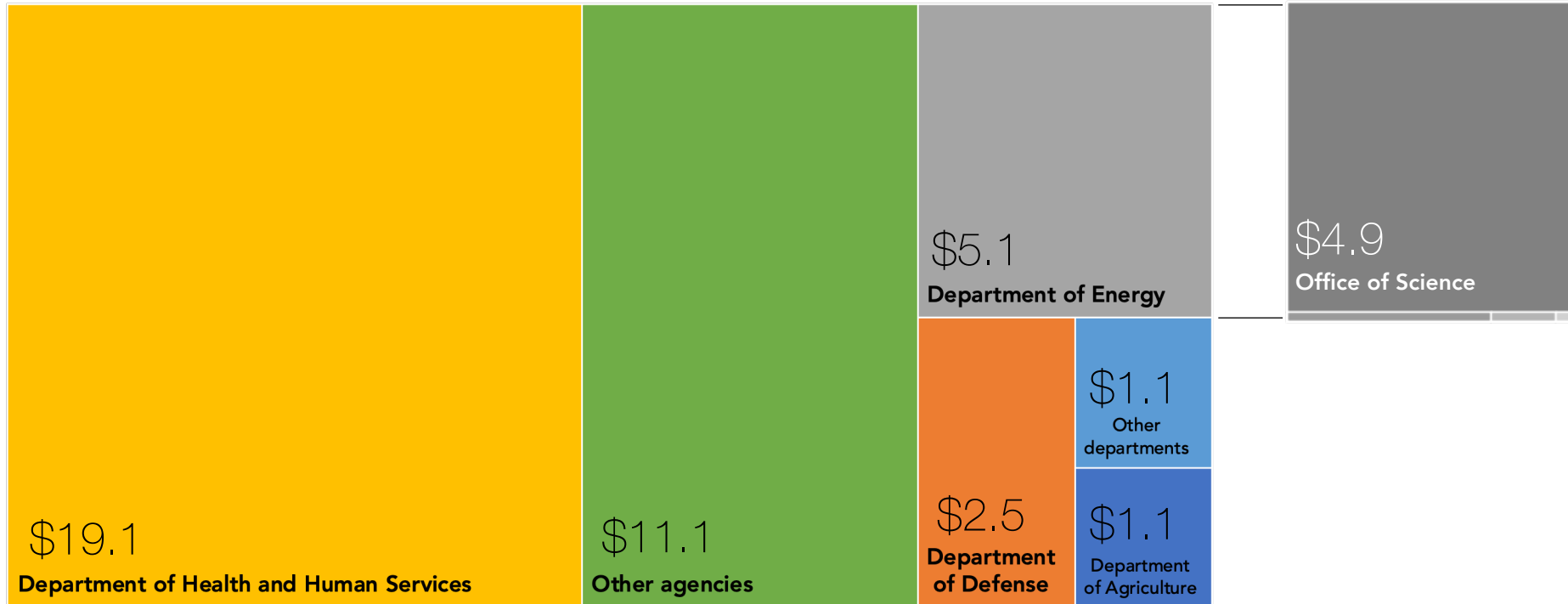
Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond

NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES

# Opportunity for this research to coalesce

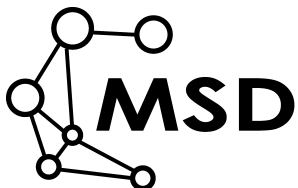
## Federal obligations for basic research, by agency (FY 2019)

US Dollars in Billions



**Department of Energy Office of Science** has created the *Multisector Dynamics* research program to fund research in this area

They have committed initial and sustained funding to create a **Community of Practice** around this challenge



Source: National Center for Science and Engineering Statistics, Survey of Federal Funds for Research and Development, FYs 2019–20.



# CoP goal and activities

## Communication

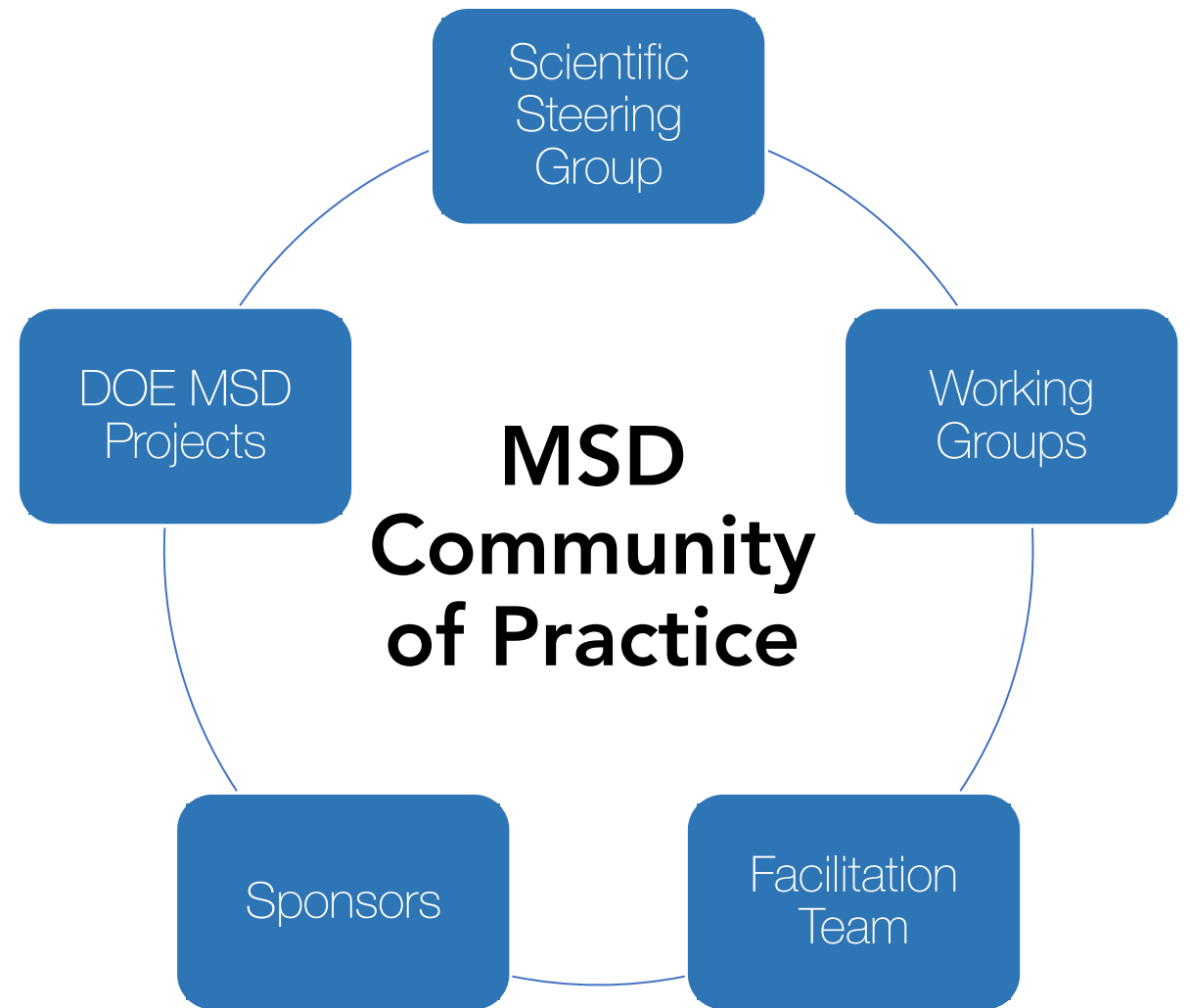
- Website
- Newsletter
- Webinars
- Outreach

## Conceptual Framework

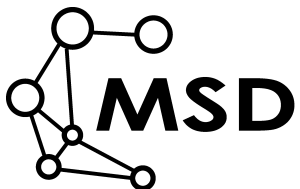
- Vision report and journal article
- Review process

## Technical coordination

- Working groups



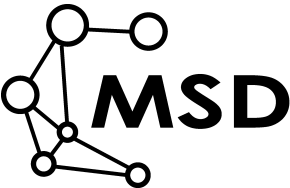
**Goal:** Bring together currently dispersed research teams and communities that are working on related challenges, both nationally and internationally. Establish mechanisms for collaboration and synthesis to accelerate discovery and add value to individuals and projects.



# Facilitation Team



Richard Moss, PNNL  
Patrick Reed, Cornell University  
Erwan Monier, UC Davis  
Antonia Hadjimichael, Penn State University



# Scientific Steering Group



Nathalie Voisin, PNNL



Klaus Keller, Dartmouth



Megan Konar, UIUC



Jen Morris, MIT



Jim Yoon, PNNL



Christa Brelsford, ORNL



Stuart Cohen, NREL



Ana Dyreson, MTU



Casey Burleyson, PNNL

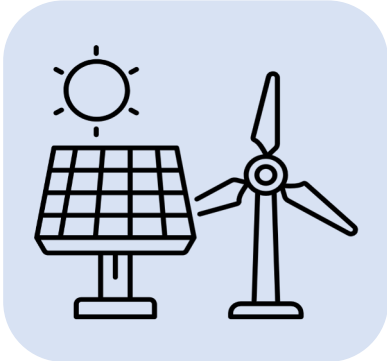


Vivek Srikrishnan, Cornell



Jordan Macknick, NREL

# Current Working Groups



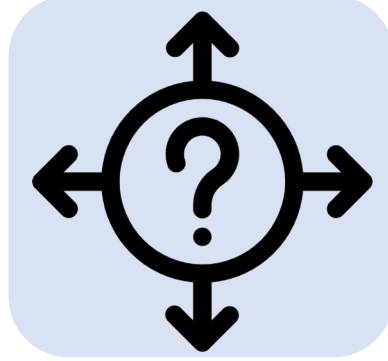
MultiSector  
Impacts of  
Energy  
Transitions



Urban  
Systems



Human  
System  
Modeling



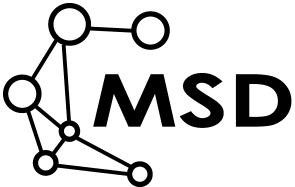
Uncertainty  
Quantification  
and Scenario  
Development



Education and  
Professional  
Development



Facilitating  
FAIR Data

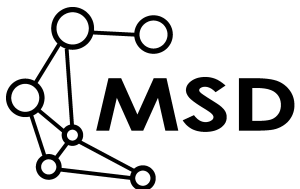


# MSD Vision Report

Outline a vision for MSD as an emerging transdisciplinary field

Clarify core definitions, share research questions, highlight scientific opportunities, and provide steps for improving our community's capacity to support needed scientific progress.

<https://multisectordynamics.org/vision>



## MULTISECTOR DYNAMICS

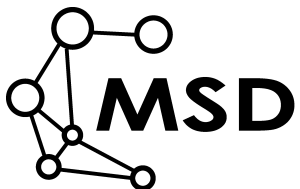
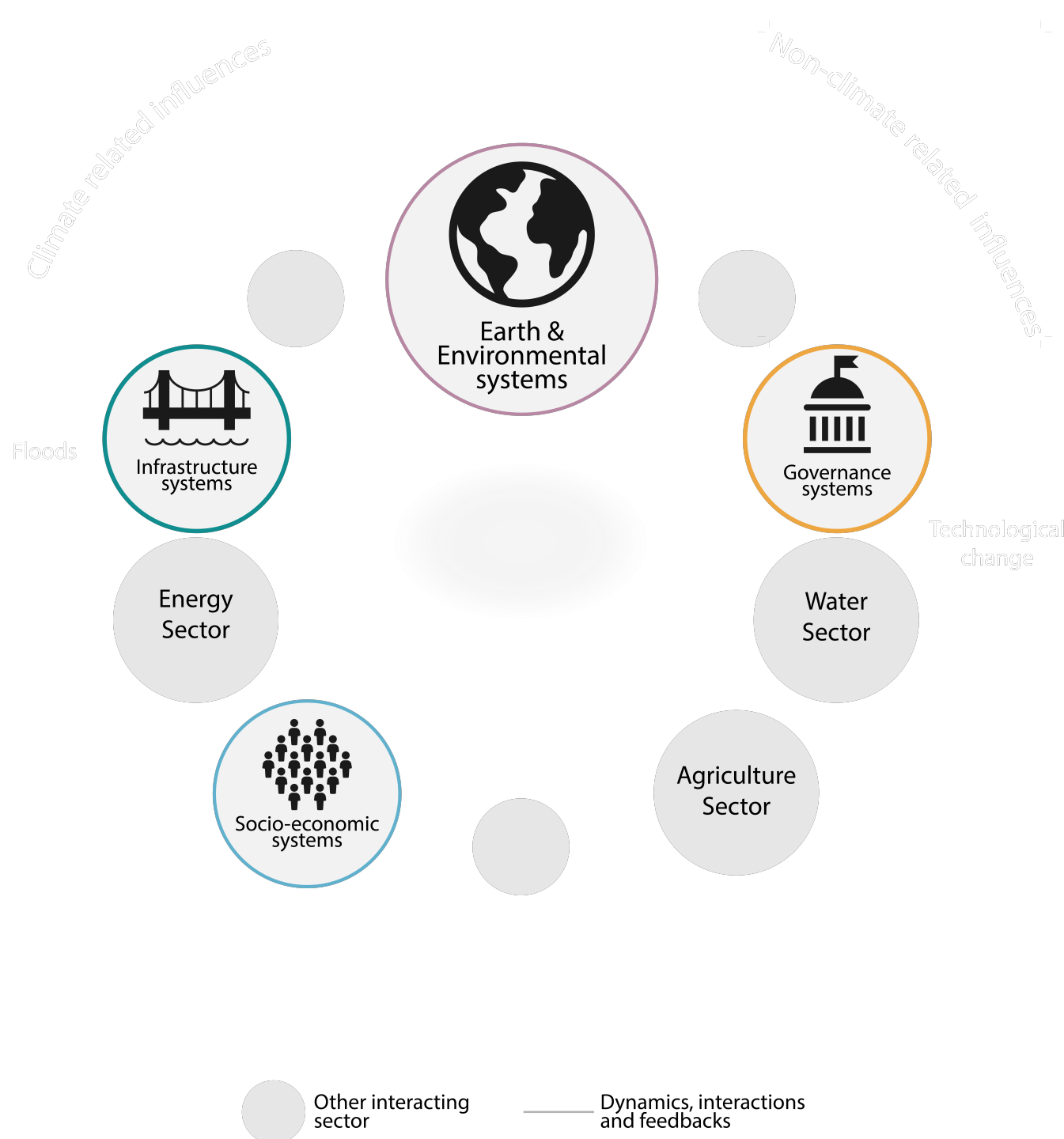
Scientific Challenges  
and a Research  
Vision for 2030



# What is MSD?

## Sector:

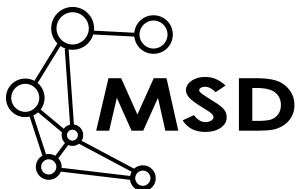
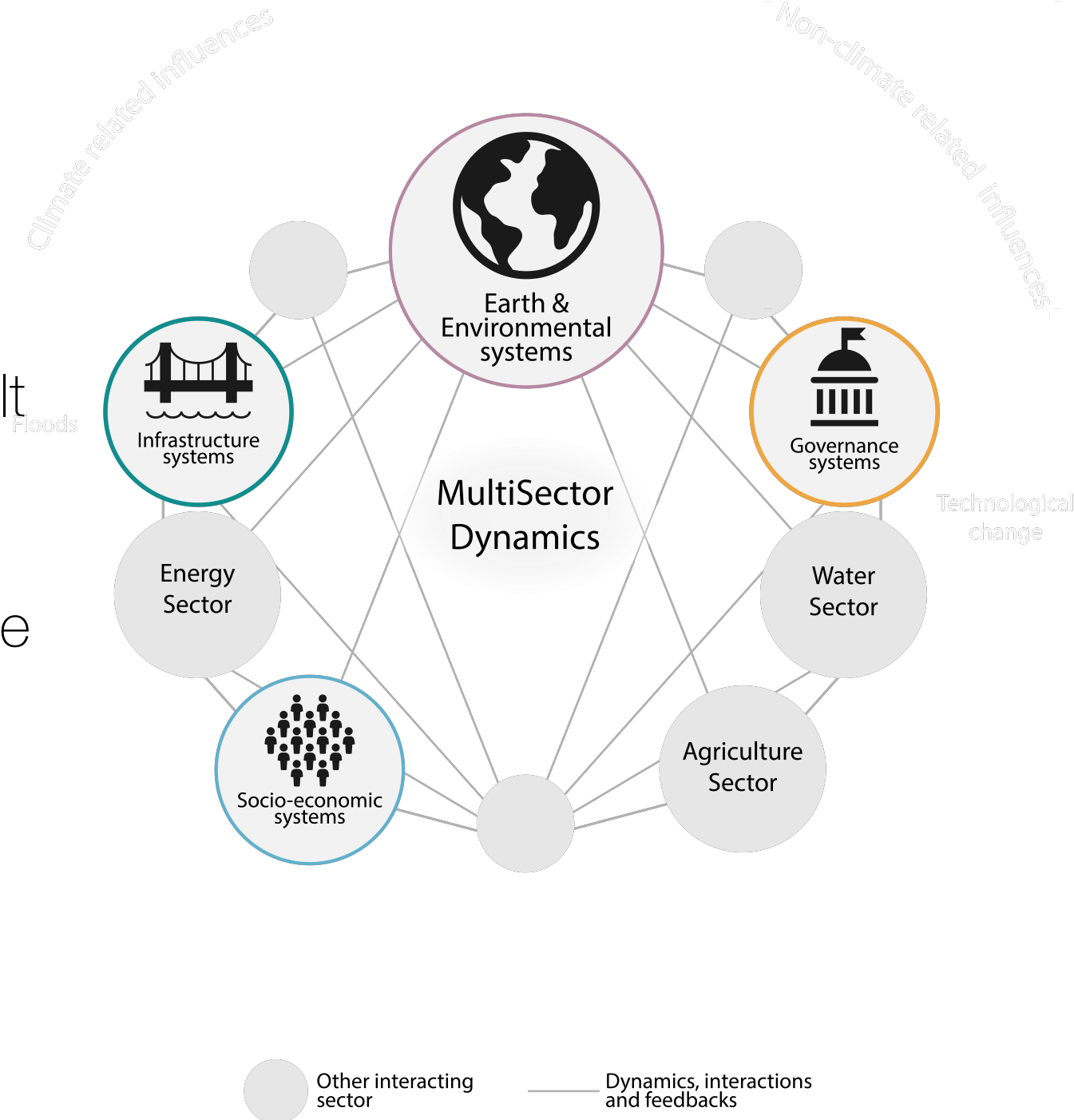
“ Complex **systems of systems** that deliver services, amenities, and products critical to society. ”



# What is MSD?

## Dynamics:

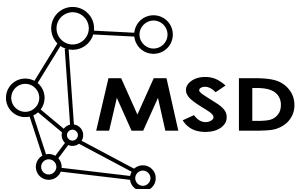
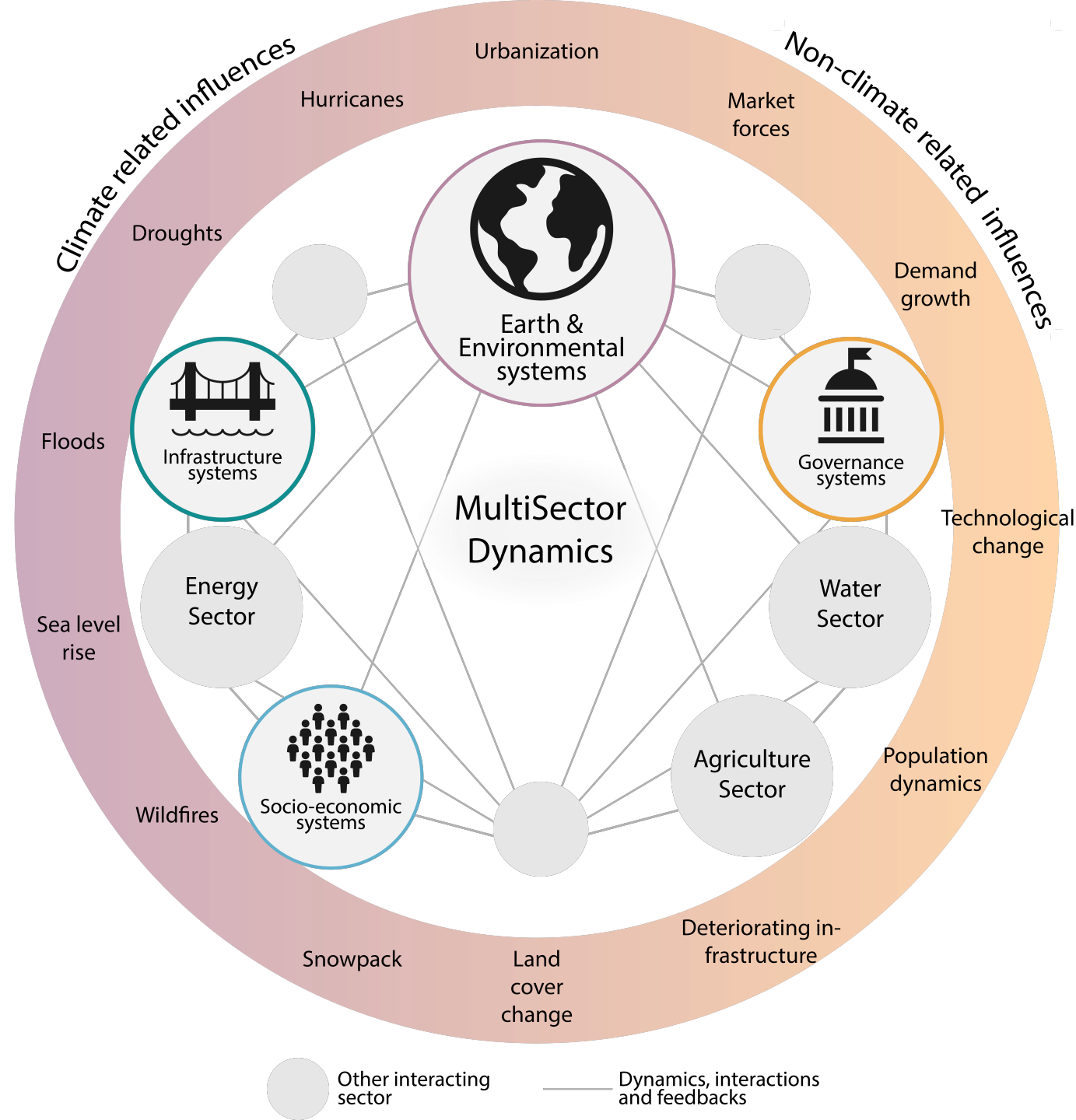
“ Pathways of change that result from transitions and shocks. Shaped by **interconnectedness**, alternative perspectives, cross-scale influences, and deep uncertainties.”



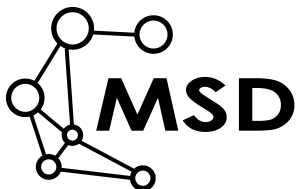
# What is MSD?

The study of how complex built, natural, and socio-economic systems **co-evolve in response to change**.

A transdisciplinary research area that seeks to advance our understanding of how **human-Earth systems and feedbacks shape pathways of change across scales and uncertainties**.



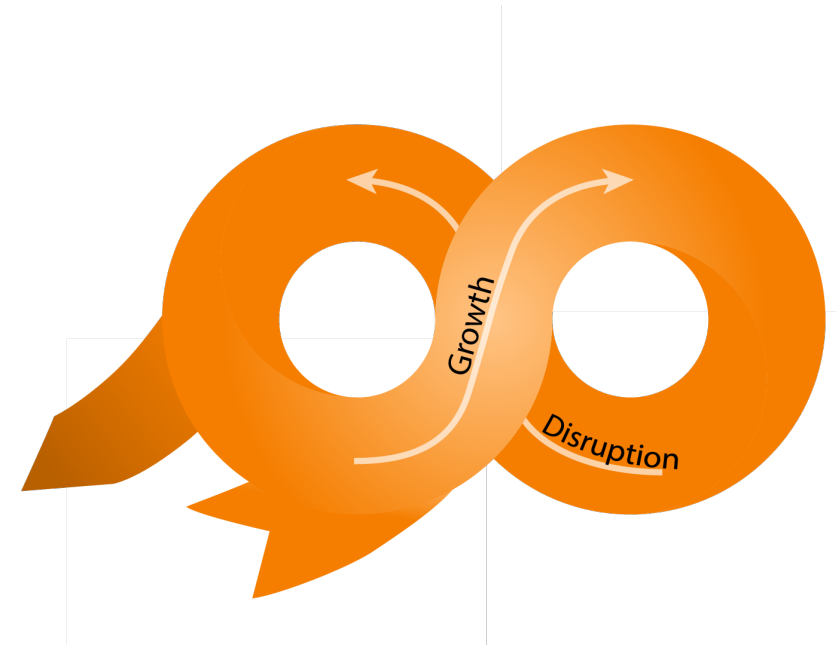
This framing is not entirely new but draws inspiration from several disciplines





# Multisector dynamics emerge from complex adaptive systems of systems

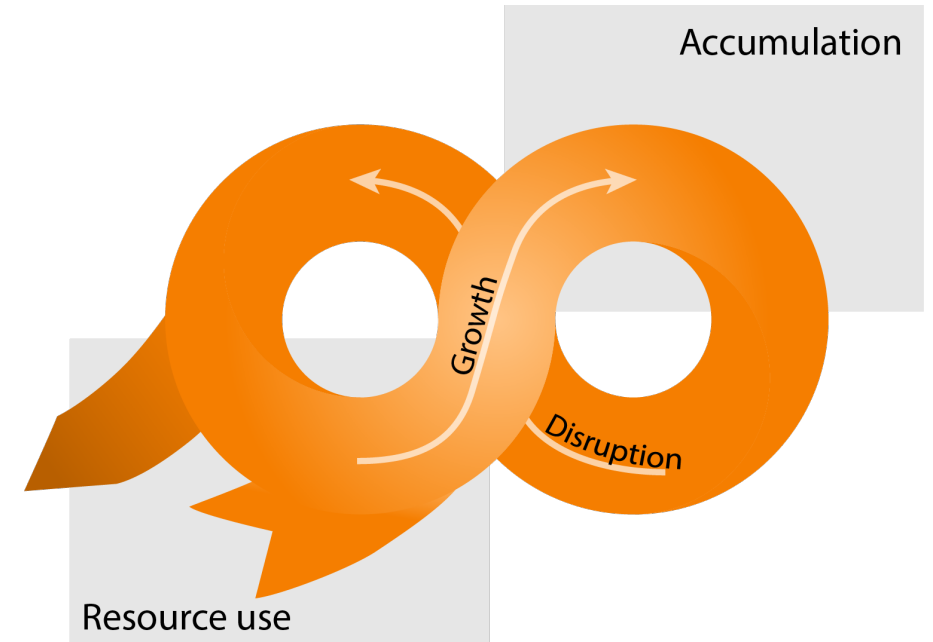
Complex adaptive systems can be conceptualized in terms of **cycles of growth and disruption**



# Multisector dynamics emerge from complex adaptive systems of systems

Complex adaptive systems can be conceptualized in terms of **cycles of growth and disruption**

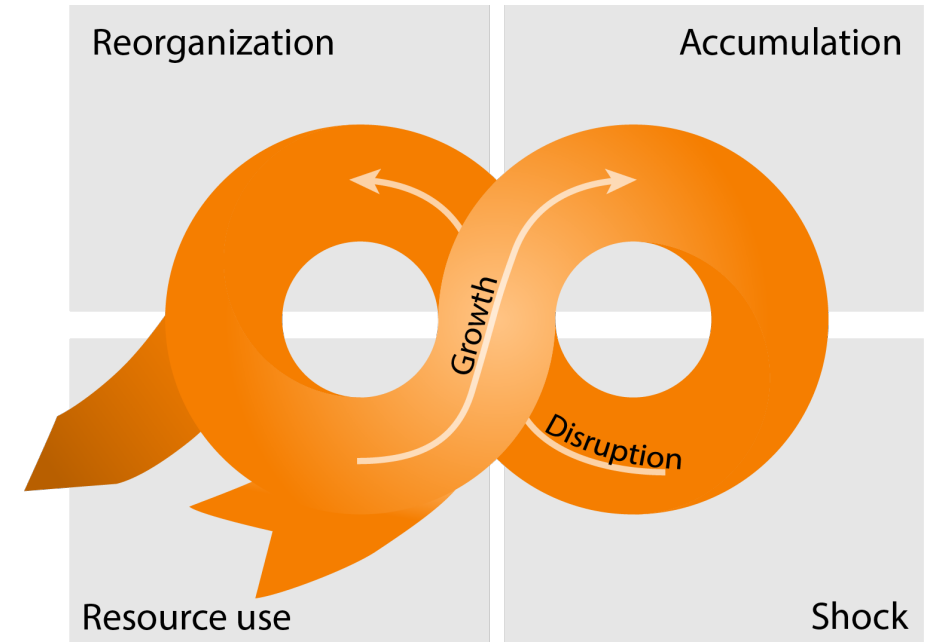
1. **Growth phase** – accumulation of resources and capital



# Multisector dynamics emerge from complex adaptive systems of systems

Complex adaptive systems can be conceptualized in terms of **cycles of growth and disruption**

1. **Growth phase** – accumulation of resources and capital
2. **Disruption phase** – occurrence of system shock, subsequent reorganization

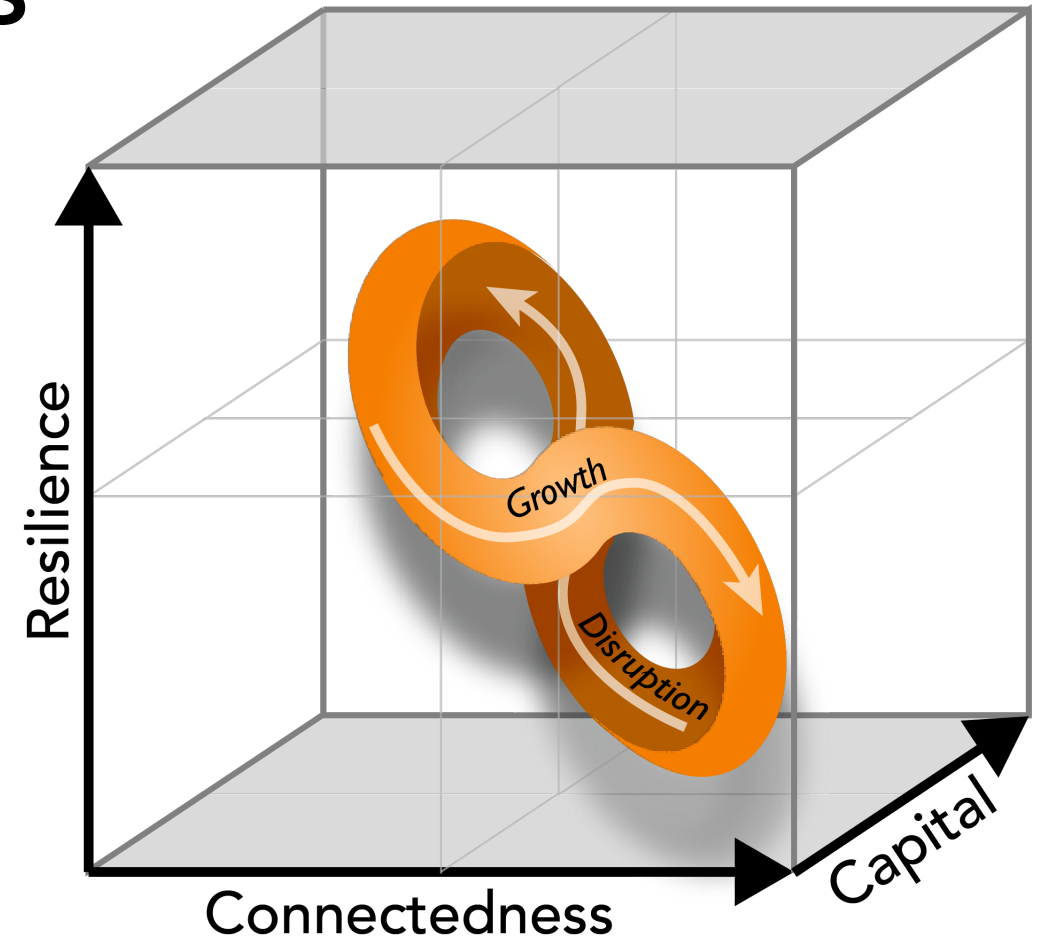


# Key system properties

**Connectedness:** Increases as the system grows, becomes more aggregated and organized

**Capital:** system potential, reflects monetary assets or natural or human capacities that accumulate as the system develops

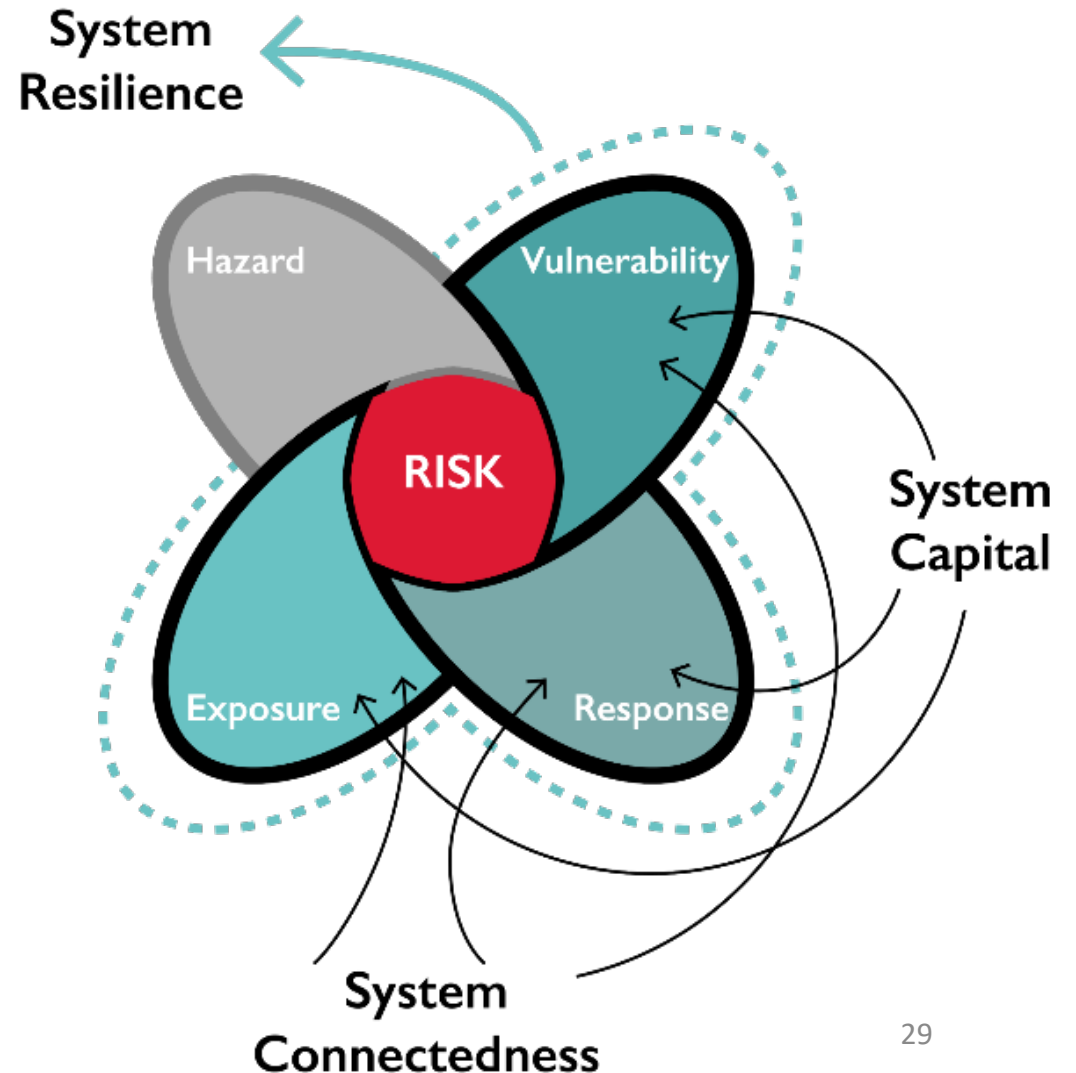
**Resilience:** the capacity of a system to absorb a shock and adapt to maintain essentially the same function and identity



# Bridging Risk and Resilience

**Hazards** can **cascade** between systems and **interact** with drivers of **vulnerability**, **exposure** and **response**.

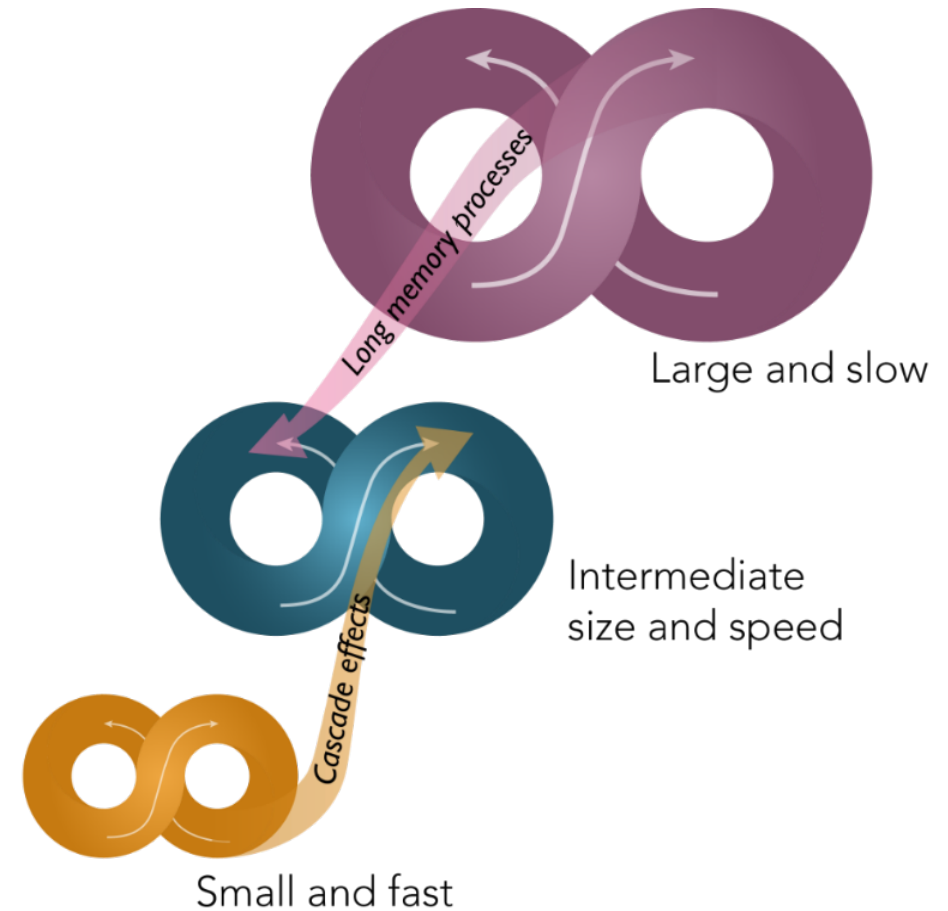
System **organization** and **aggregation** can **shape resilience** to hazards in both positive and negative ways through the presence of **drivers** and their **interactions**



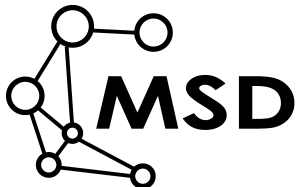
# Adaptive system cycles across scales

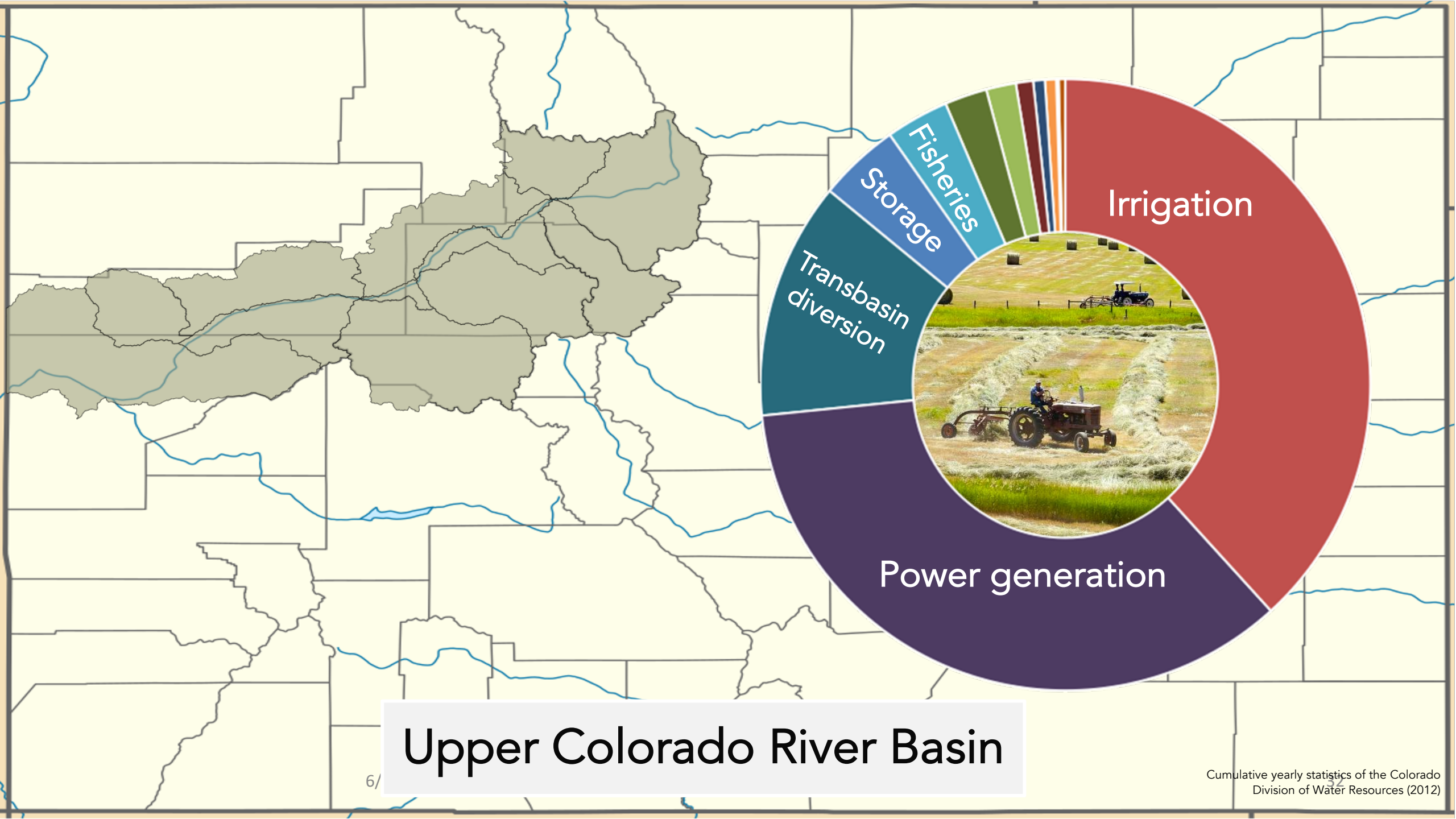
**Multi-scale feedbacks** are critical for understanding how systems co-evolve to:

- Shape path dependencies
- Amplify or dampen dynamics
- Lead to emergent behaviors



A research example...

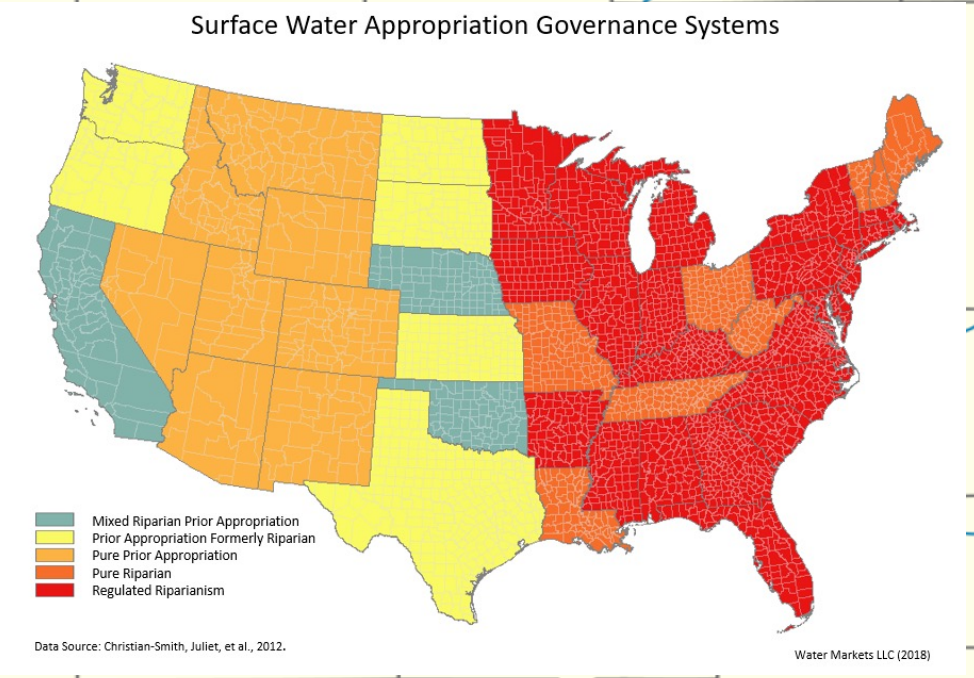
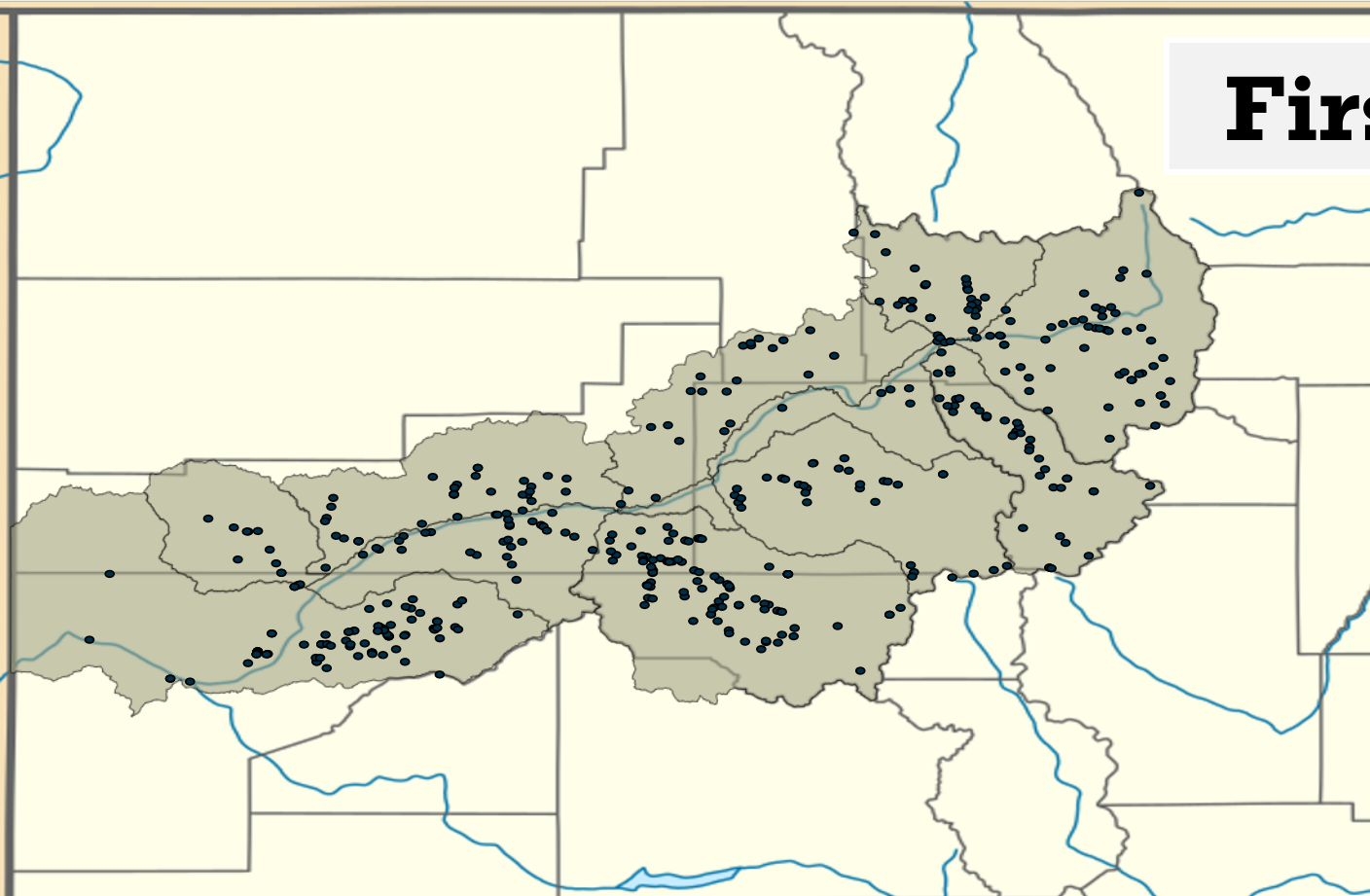




# Upper Colorado River Basin



# First in time, first in right



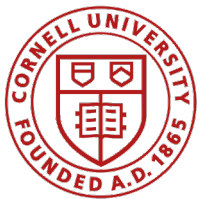
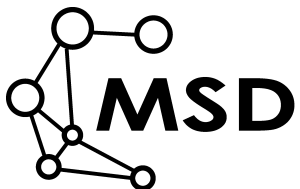
*Gets **all** water demands met before others*



**Prior-appropriation doctrine:**  
Each diversion with level of seniority and decreed flow

Upper Colorado River Basin

- How **vulnerable** are these water users to **future** climatic stress, increasing water demands and other uncertain drivers?
- Can we identify which stressors are most **consequential** for these users and under what conditions?
- Are there **asymmetries** in impacts across users?



6/3/22



NCAR

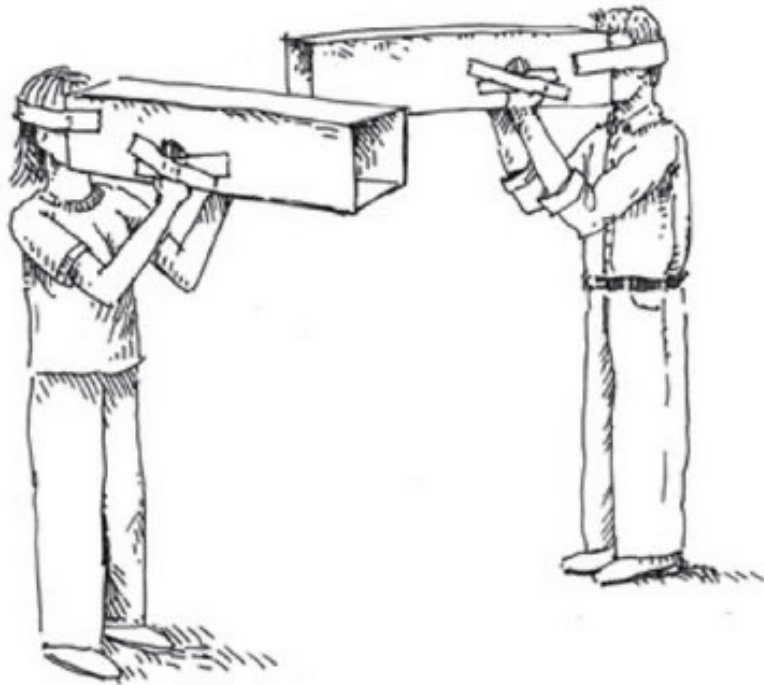


COLORADO

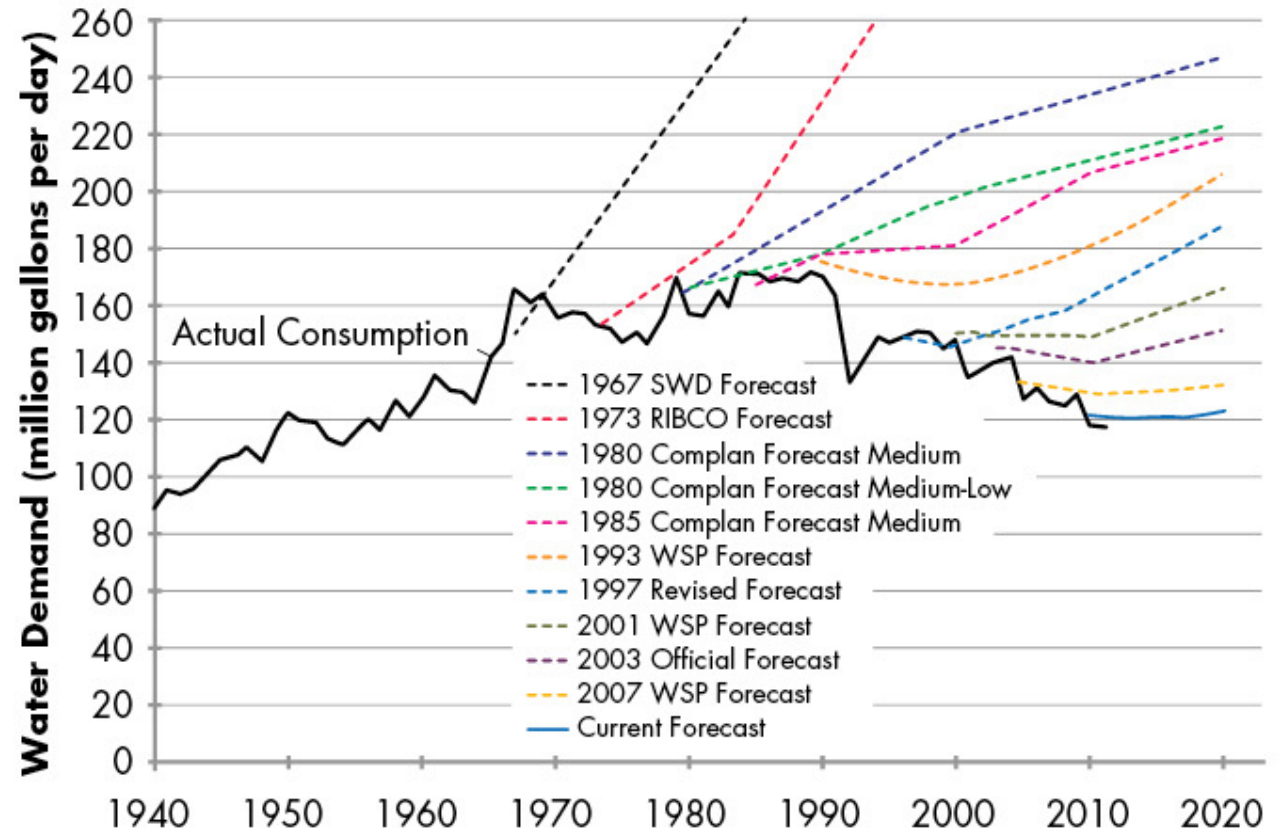
Colorado Water  
Conservation Board

Department of Natural Resources

# Assessing future impacts: are 1 2 5 10 possible futures representative?



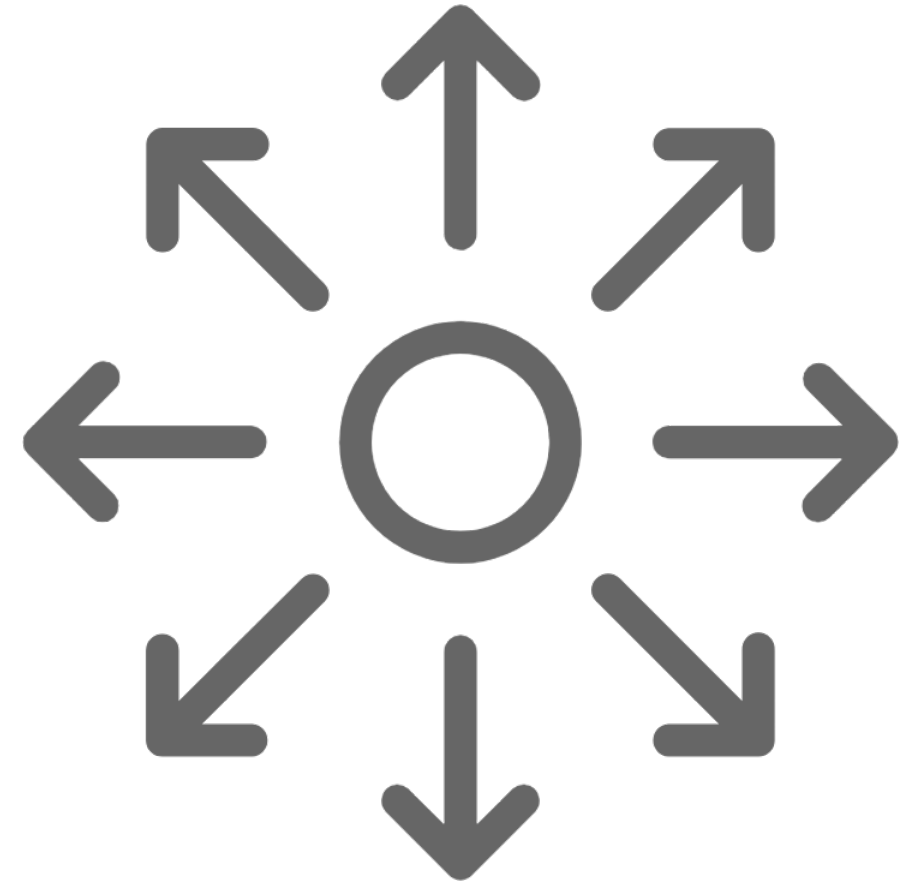
Water demand forecasts for Seattle, Washington



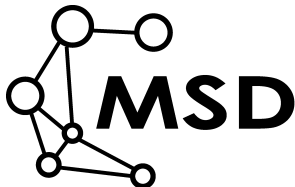
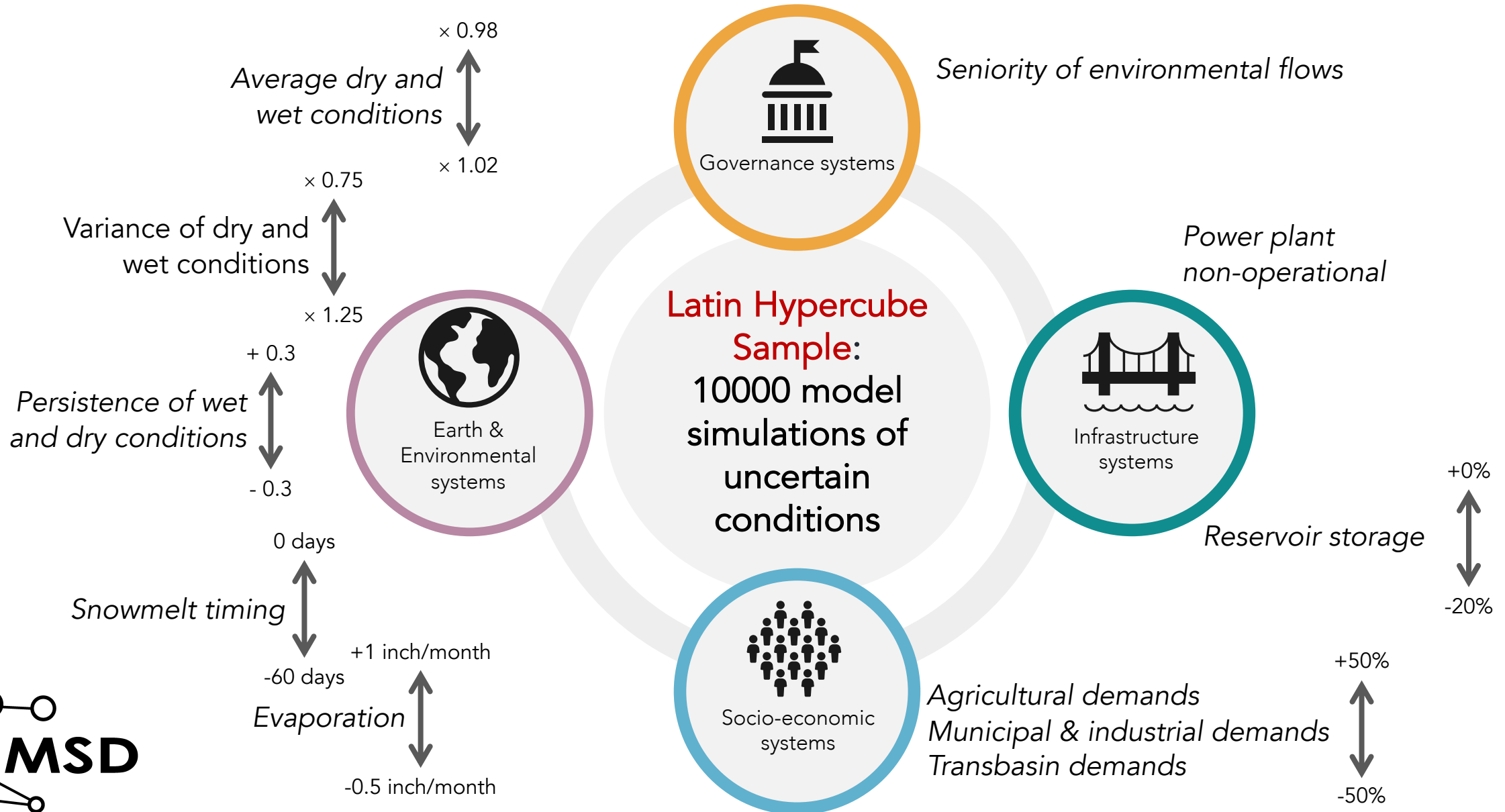
A Community Guide for Evaluating Future Urban Water Demand (2016). Pacific Institute

# Exploratory modeling

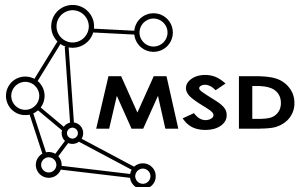
Sampling over ensembles of computational experiments that represent a **large number of plausible assumptions** about the future.



# Exploratory experiment

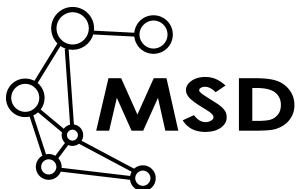
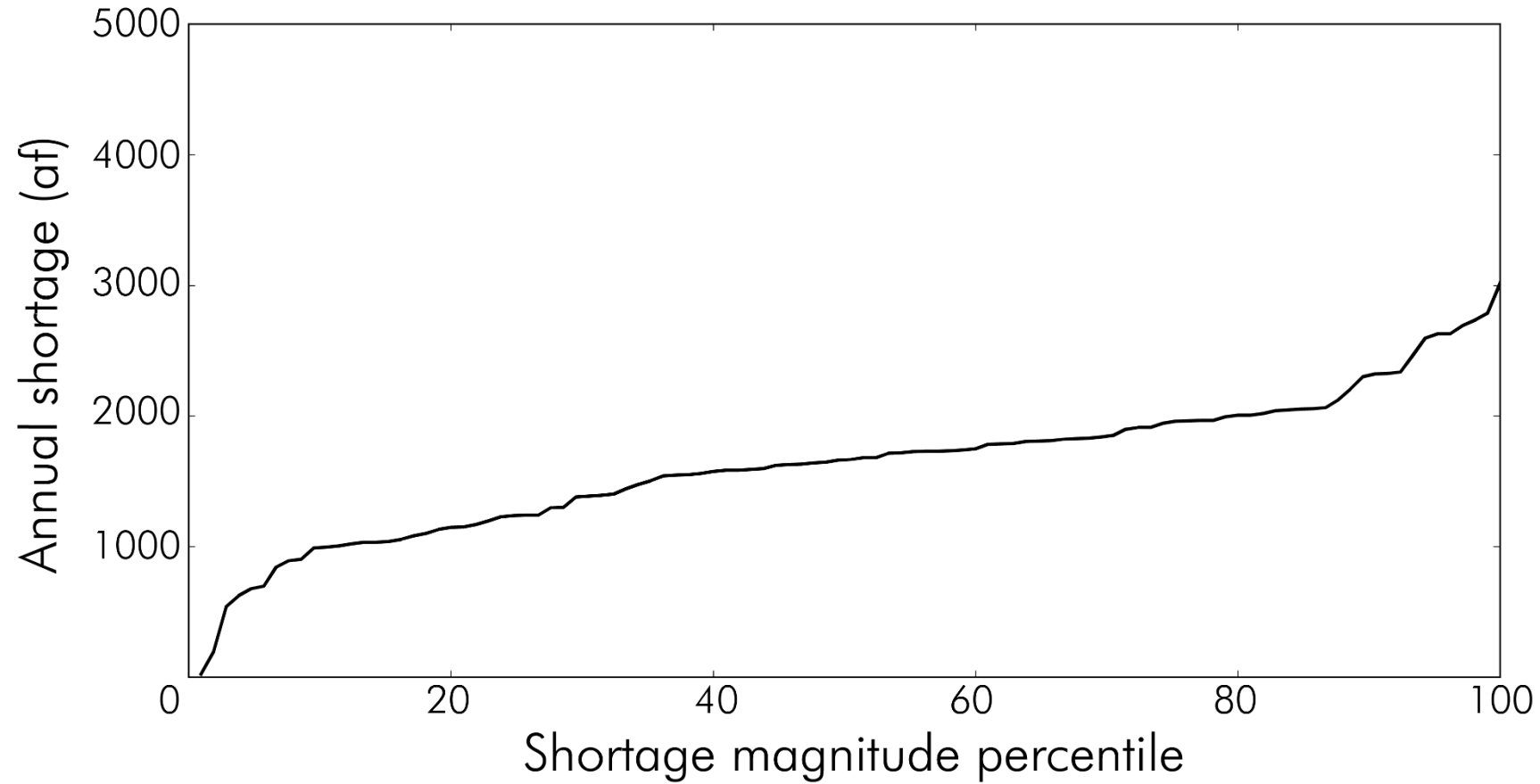


How does this experiment  
affect water users?



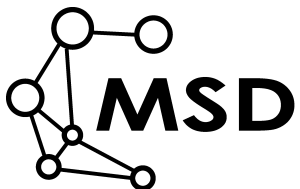
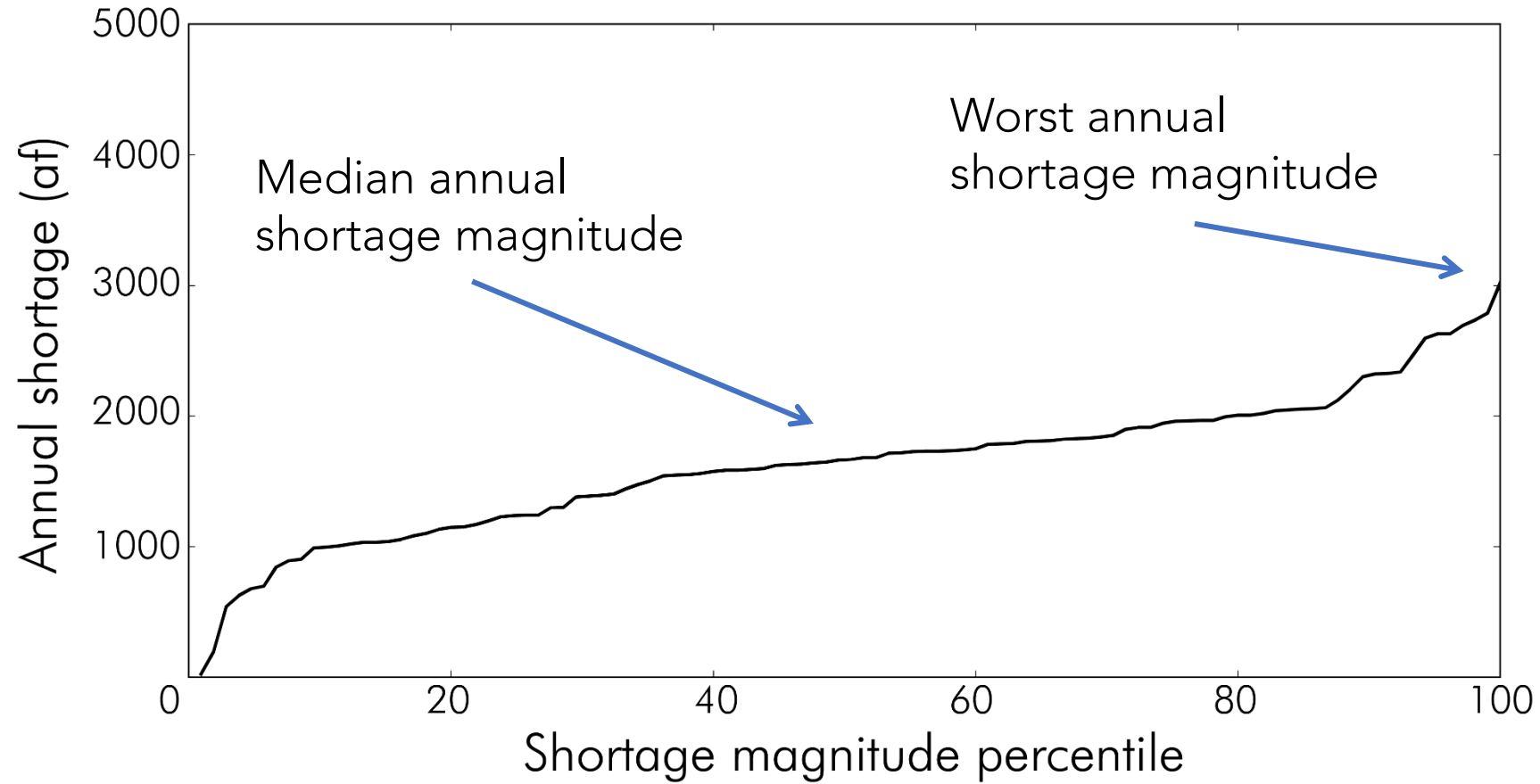
# Shortage magnitudes for an irrigation site

Rank all annual shortages experienced  
in the 105-year record



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Rank all annual shortages experienced  
in the 105-year record

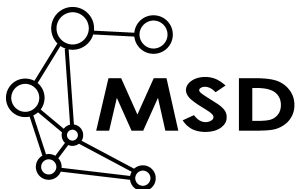
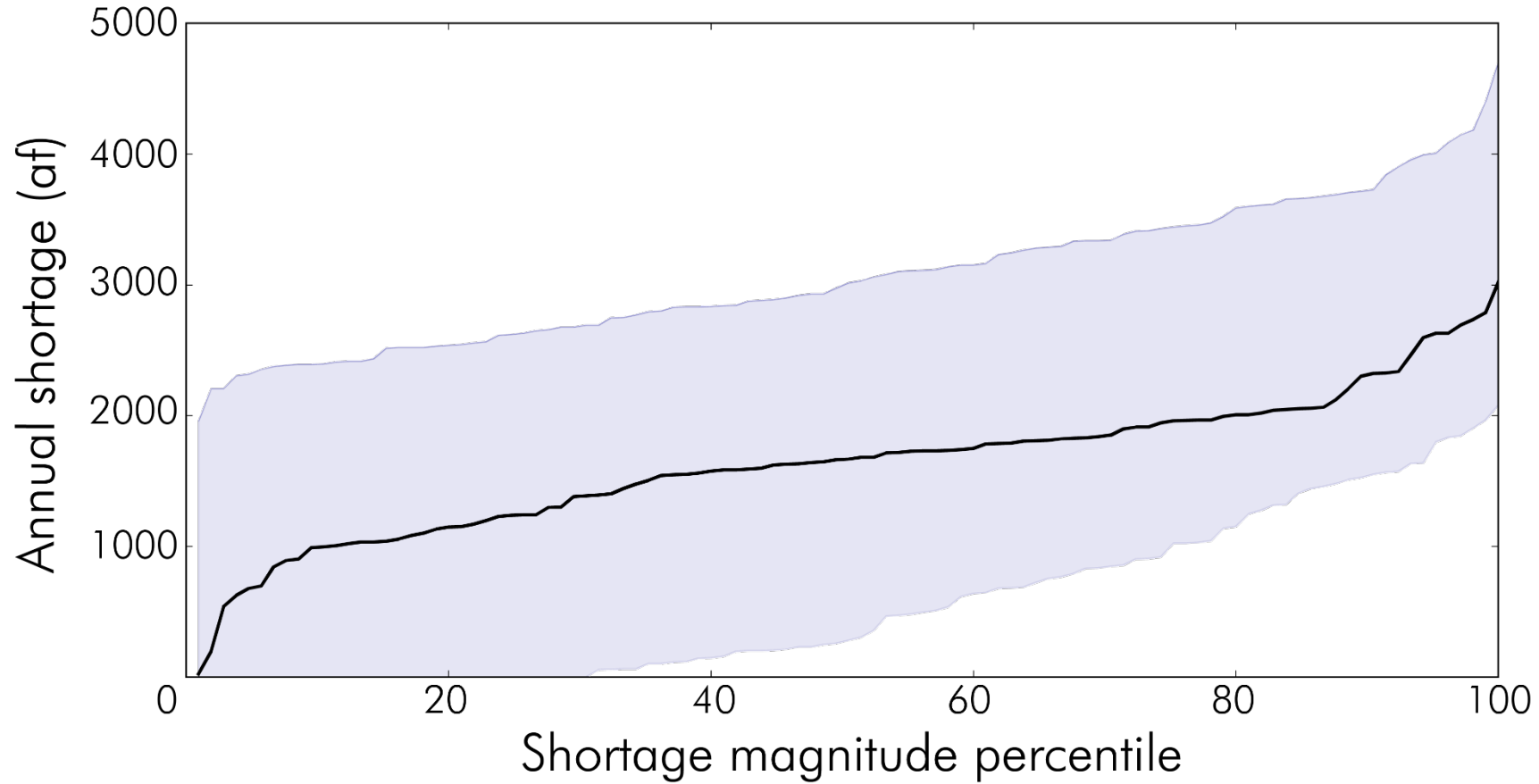




# Shortage magnitudes for an irrigation site

Perform experiment

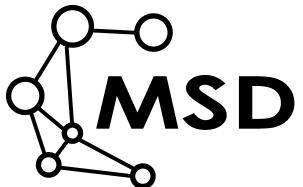
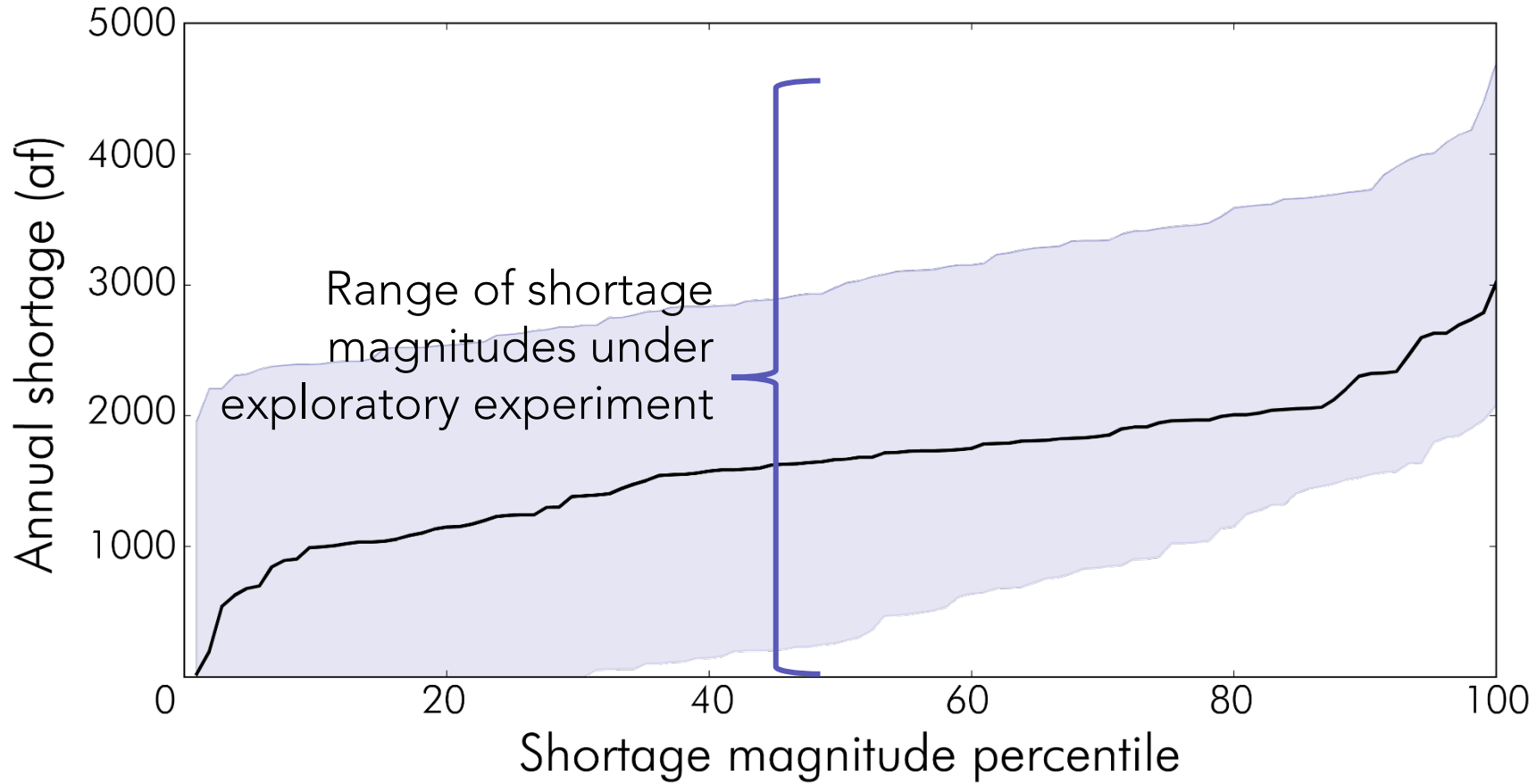
Extract all 105-year sequences and rank as before



# Shortage magnitudes for an irrigation site

Perform experiment

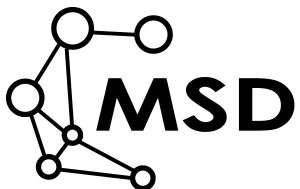
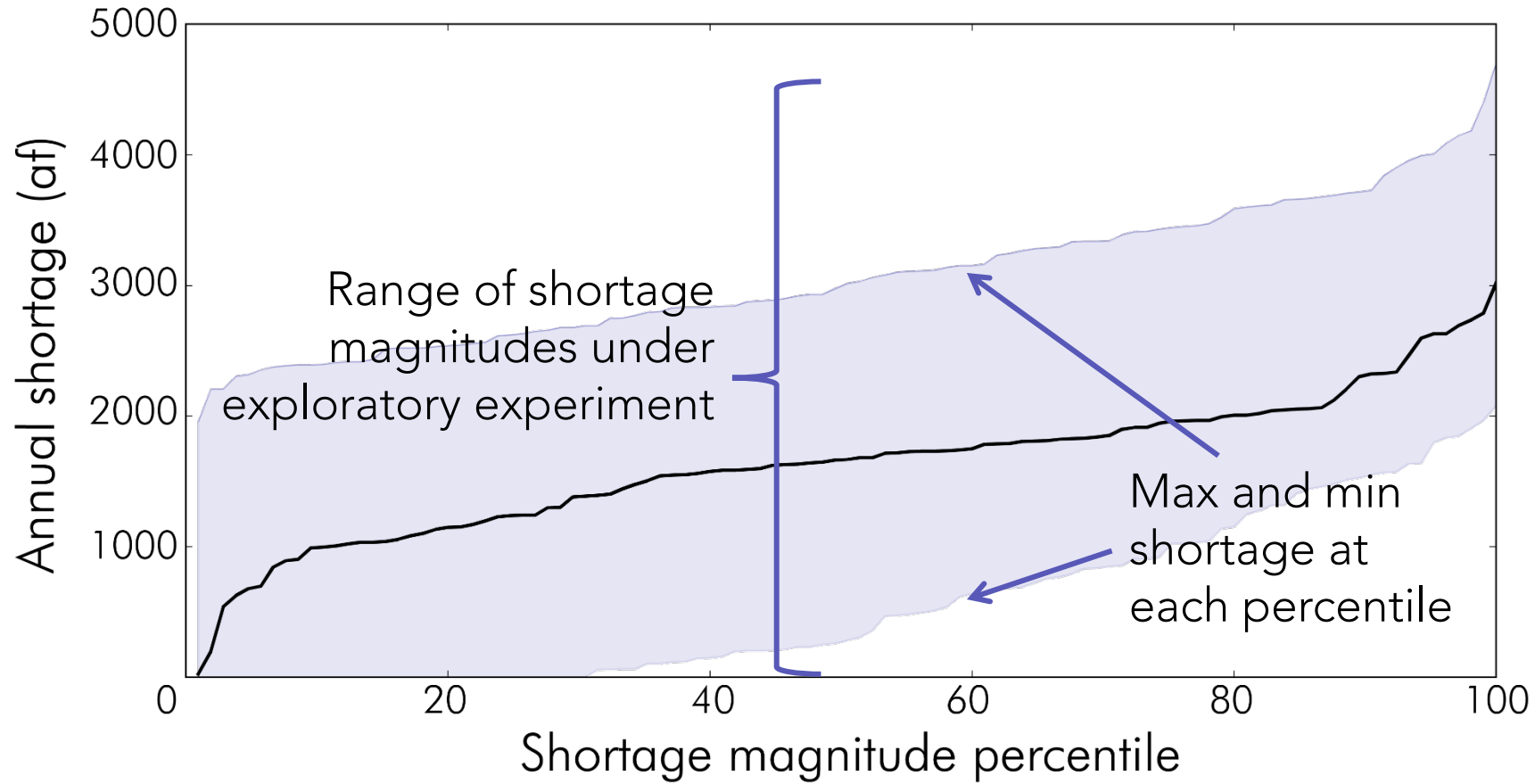
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# Shortage magnitudes for an irrigation site

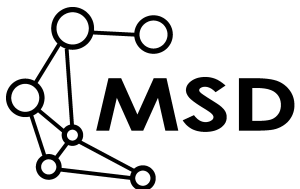
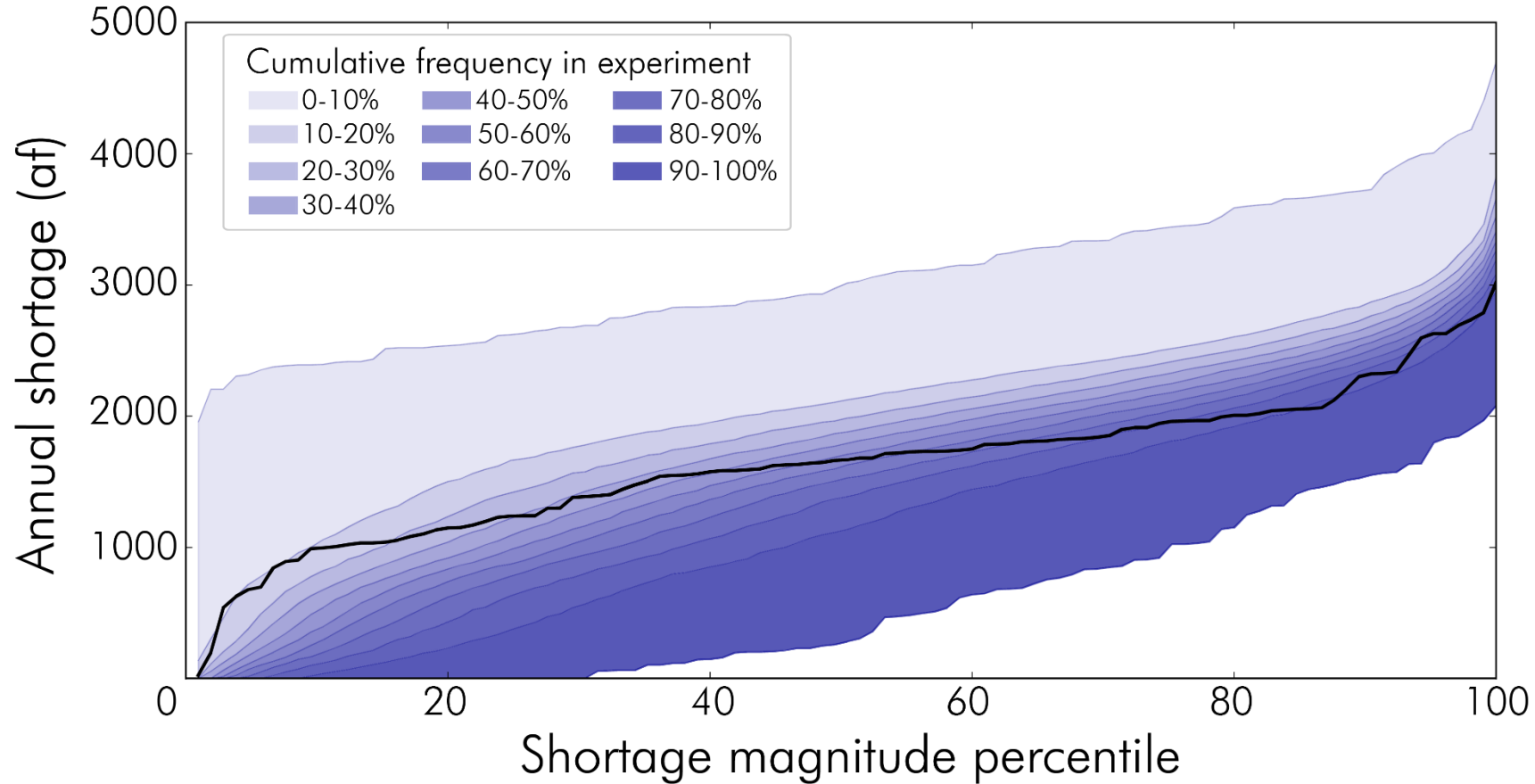
Perform experiment

Extract all 105-year sequences and rank as before



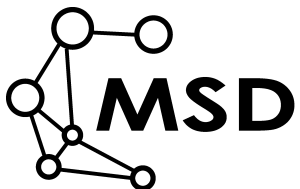
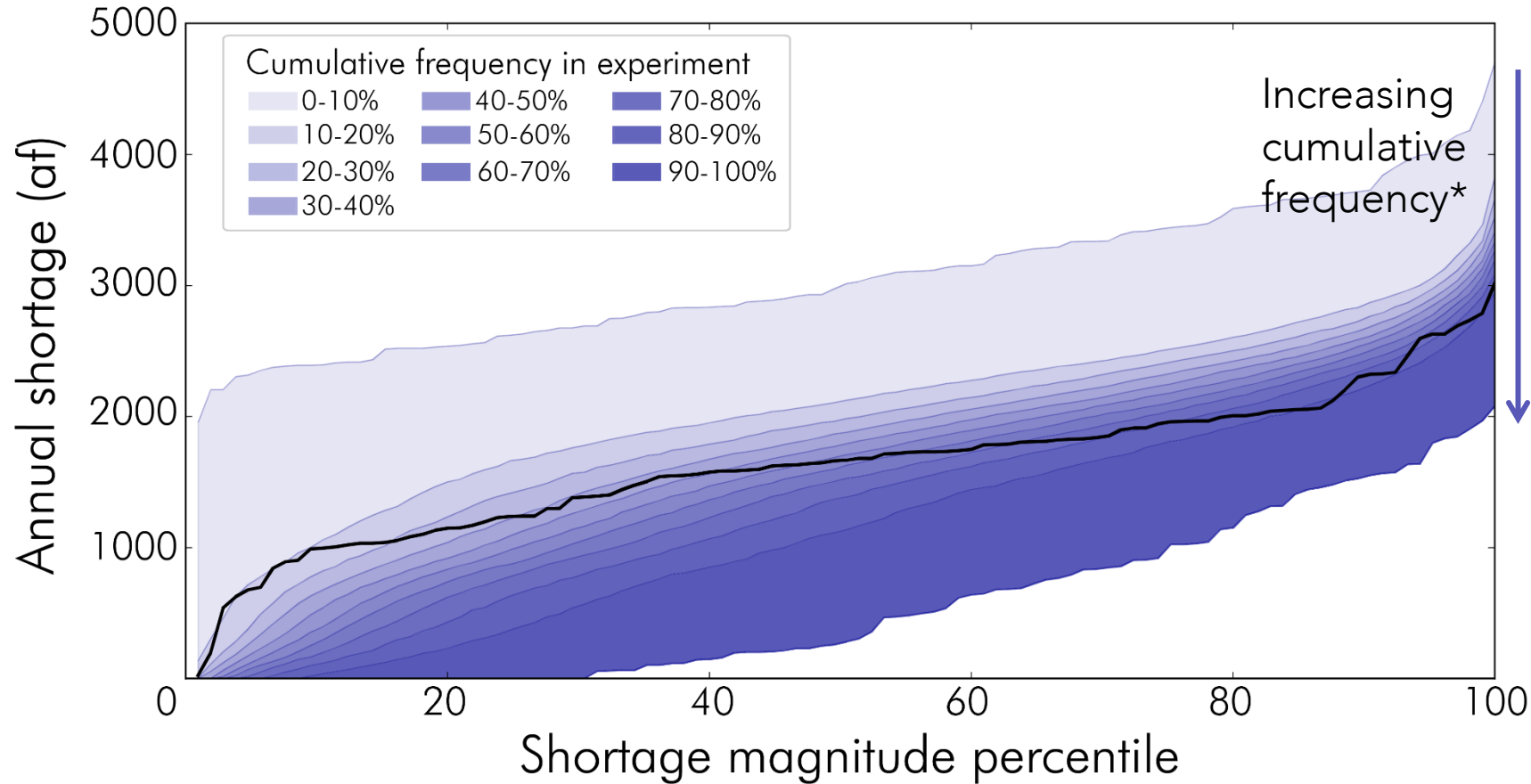
# Shortage magnitudes for an irrigation site

Repeat for all percentiles in experiment ensemble



# Shortage magnitudes for an irrigation site

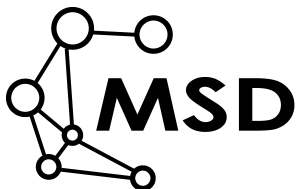
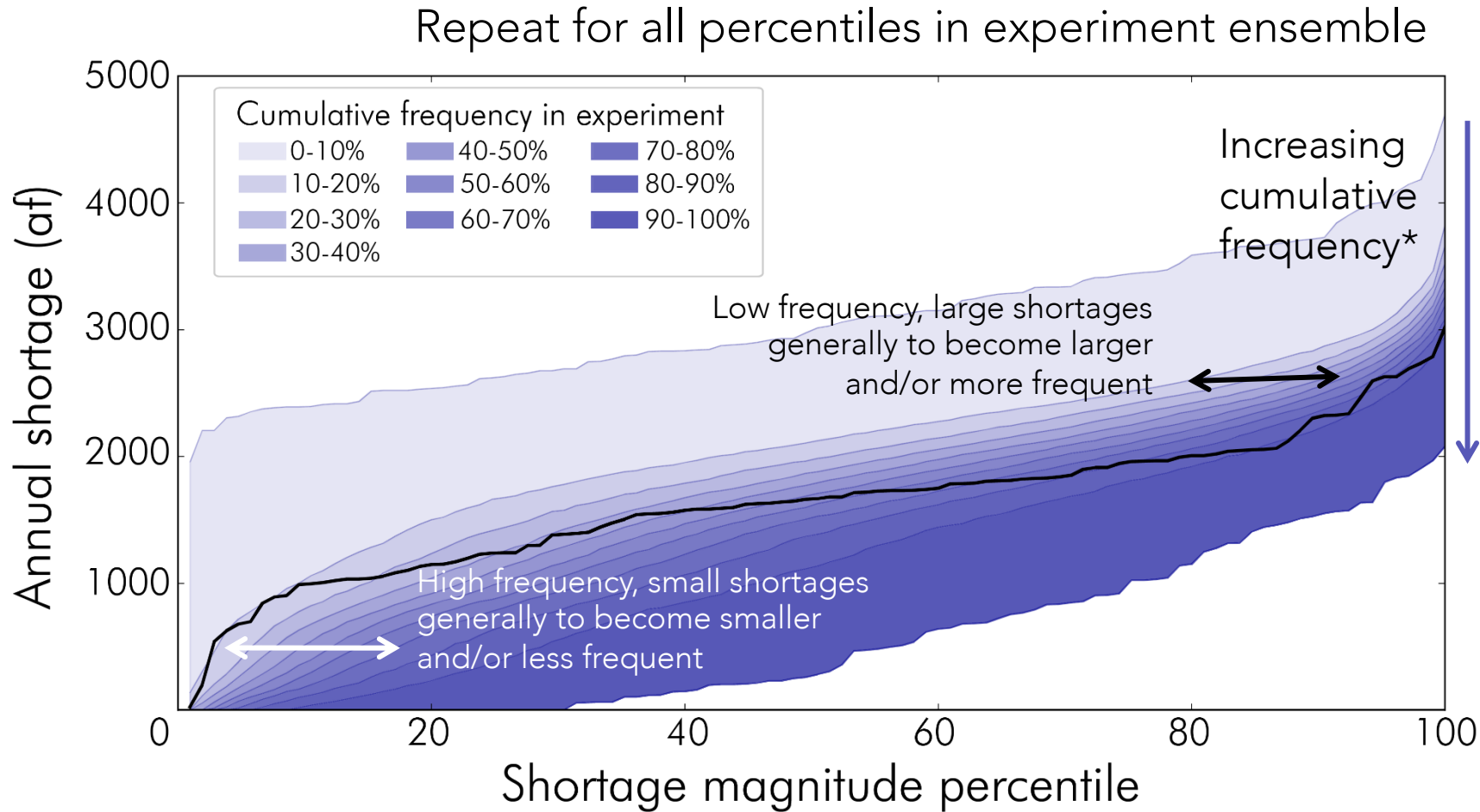
Repeat for all percentiles in experiment ensemble



\*Conditional on the sample (ranges and distributions)



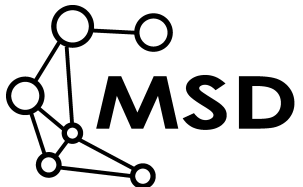
# Shortage magnitudes for an irrigation site



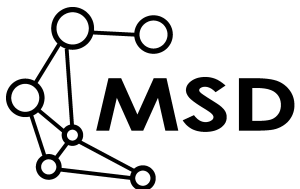
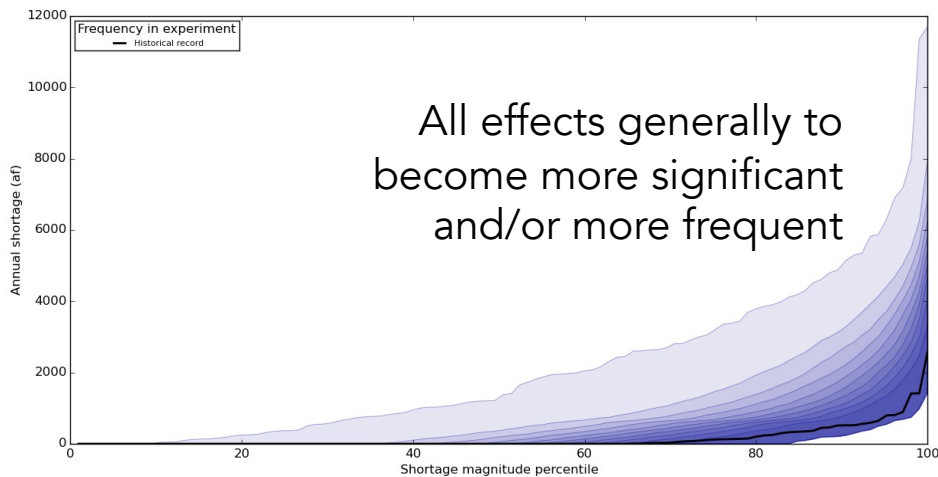
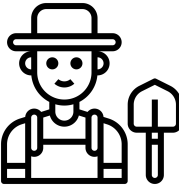
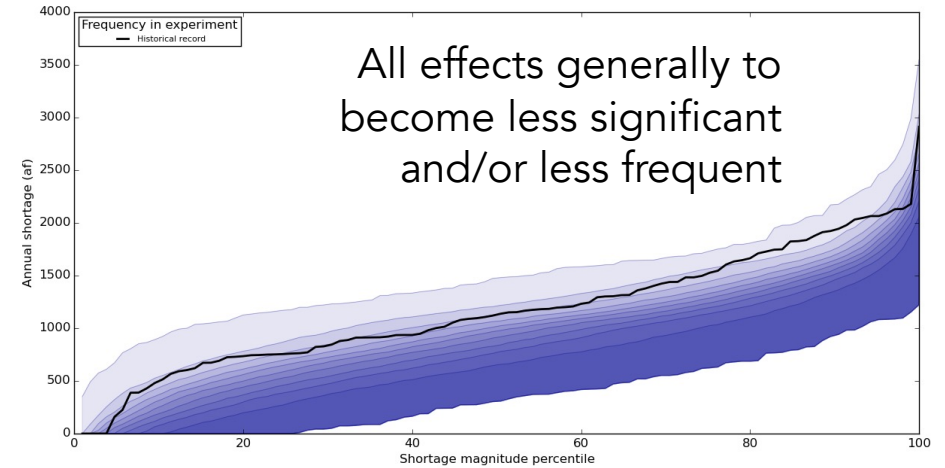
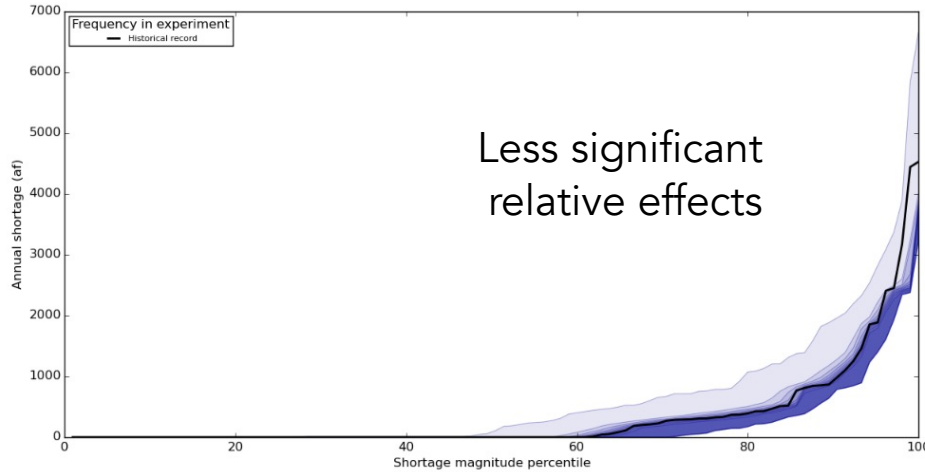
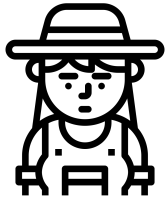
\*Conditional on the sample (ranges and distributions)



Are these effects common  
among other sites?



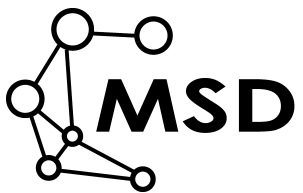
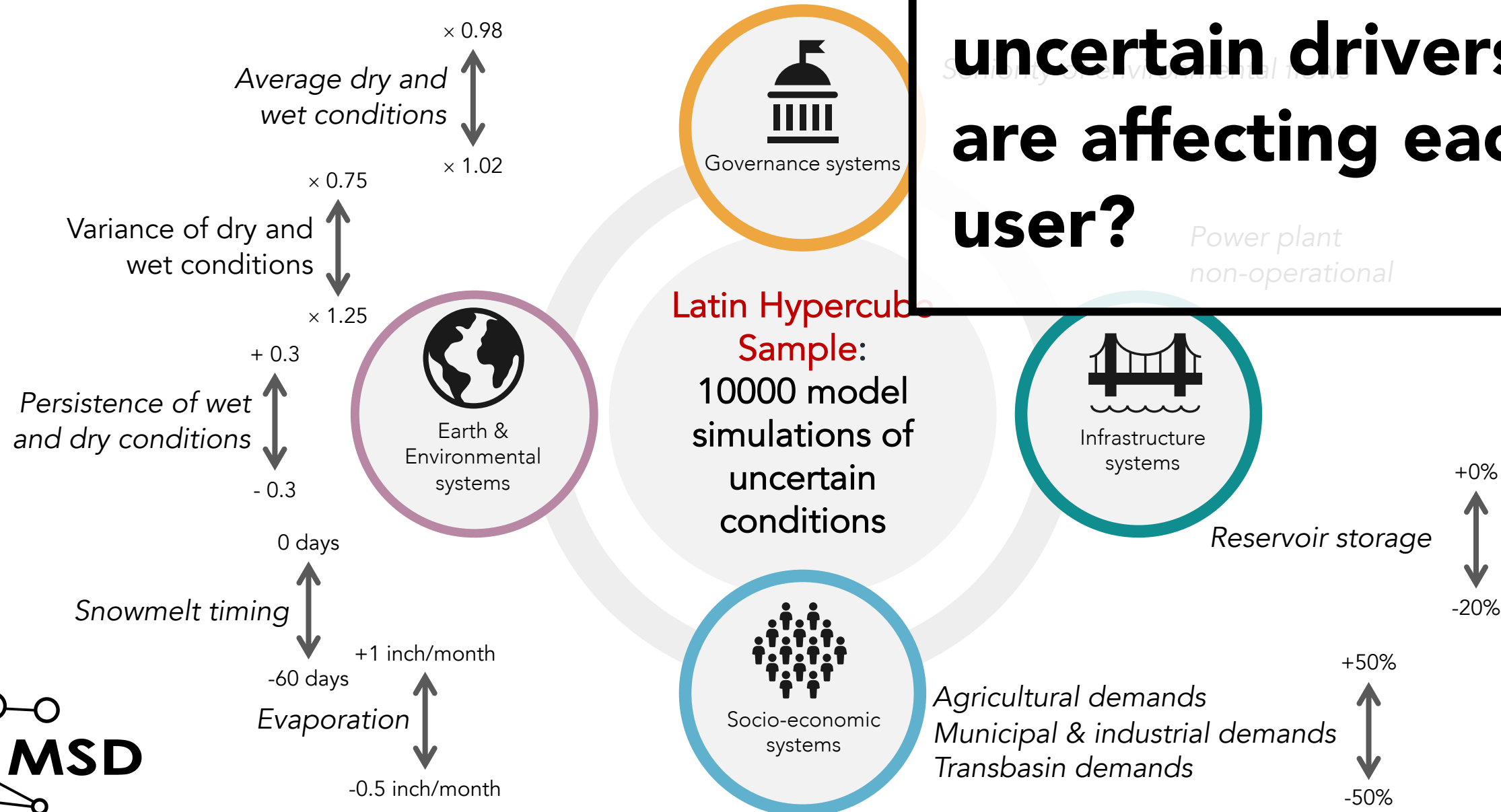
# Different users experience different impacts



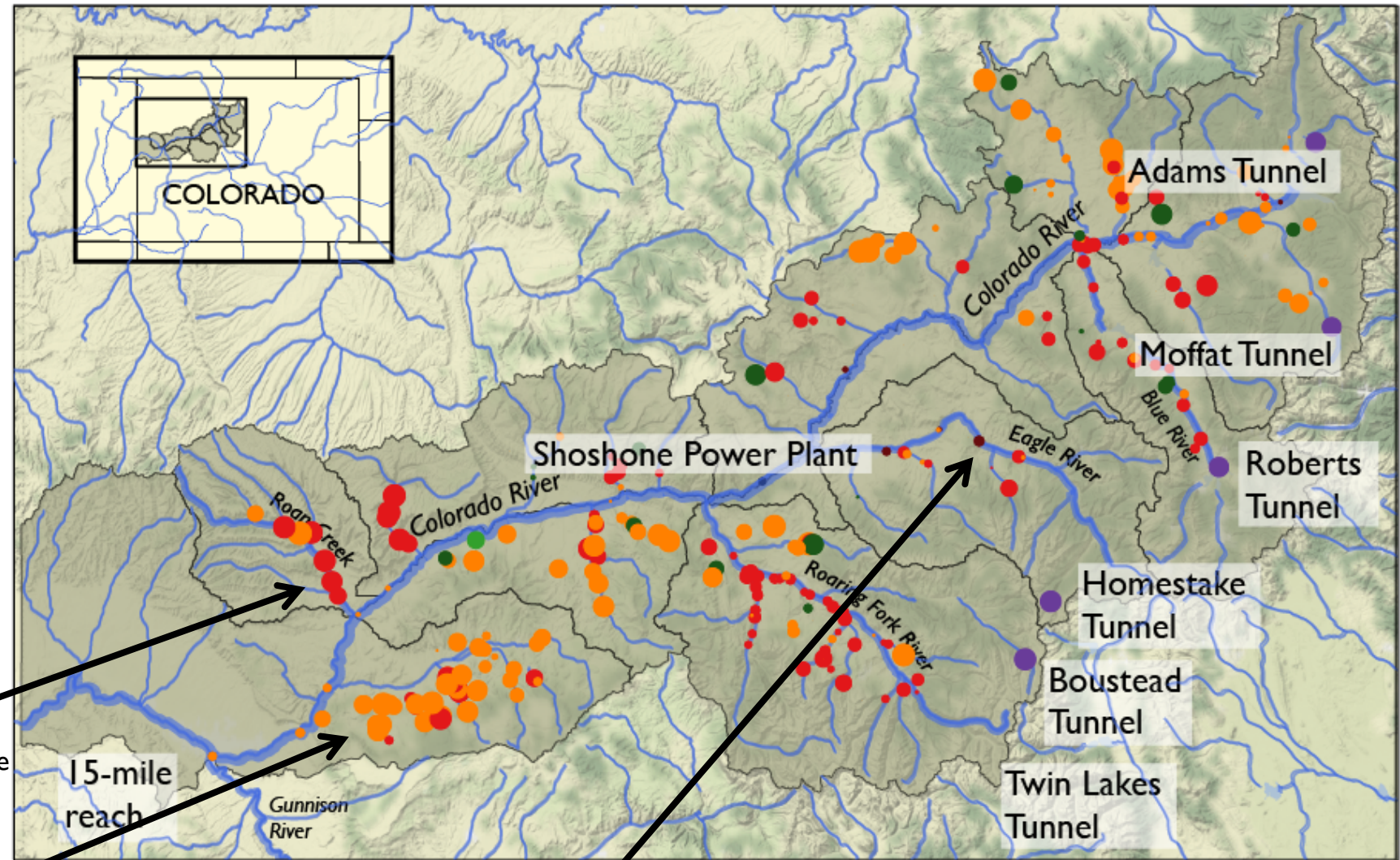


# Exploratory experiment

**Which of these uncertain drivers are affecting each user?**



# Different kinds of drivers shape impacts

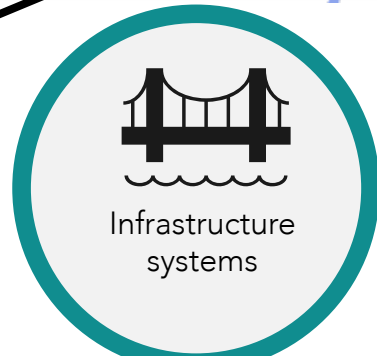


- Dry flow variance
- Evaporation
- Wet flow variance
- Dry flow persistence

- Mean wet flow
- Mean dry flow
- Wet flow persistence
- Snowmelt timing



- Irrigation demand
- Transbasin demand
- M&I demand



- Power plant operational
- Reservoir loss

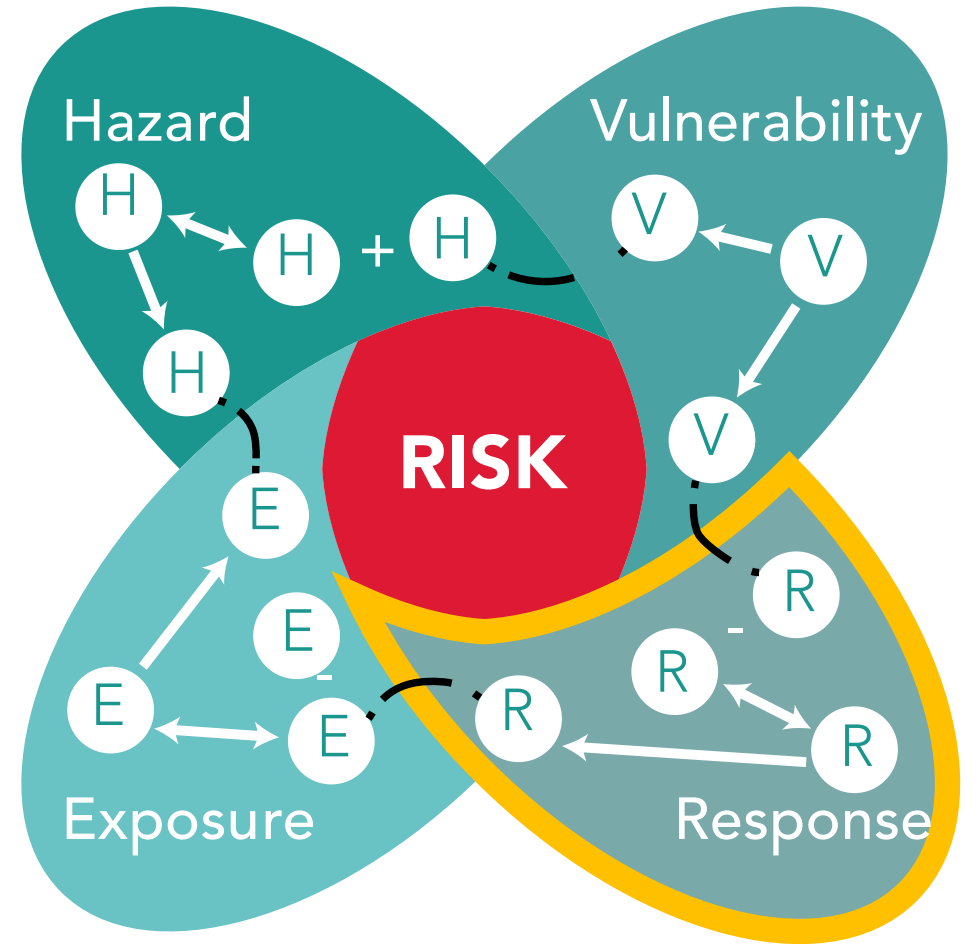


- Environmental right seniority

# Currently expanding...

Previous work has focused more on impacts, by accounting for (some) drivers of hazard, vulnerability and exposure.


But what about **human response**?



# Adapting to changing conditions

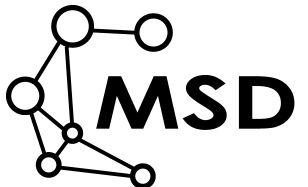
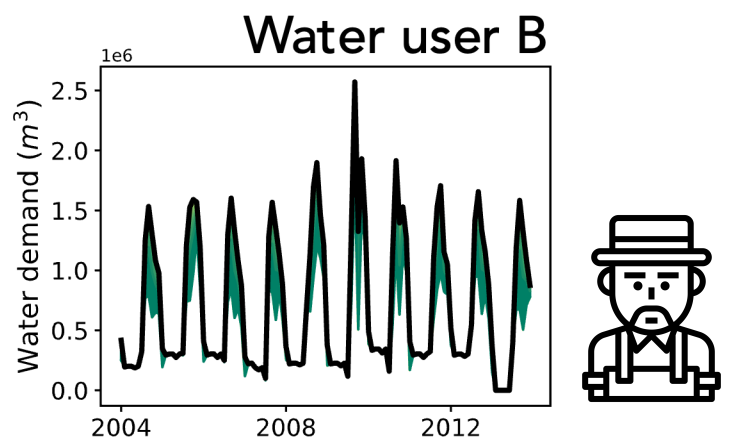
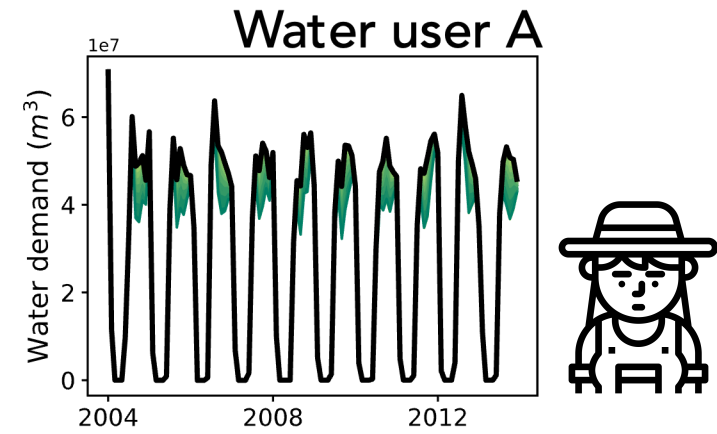
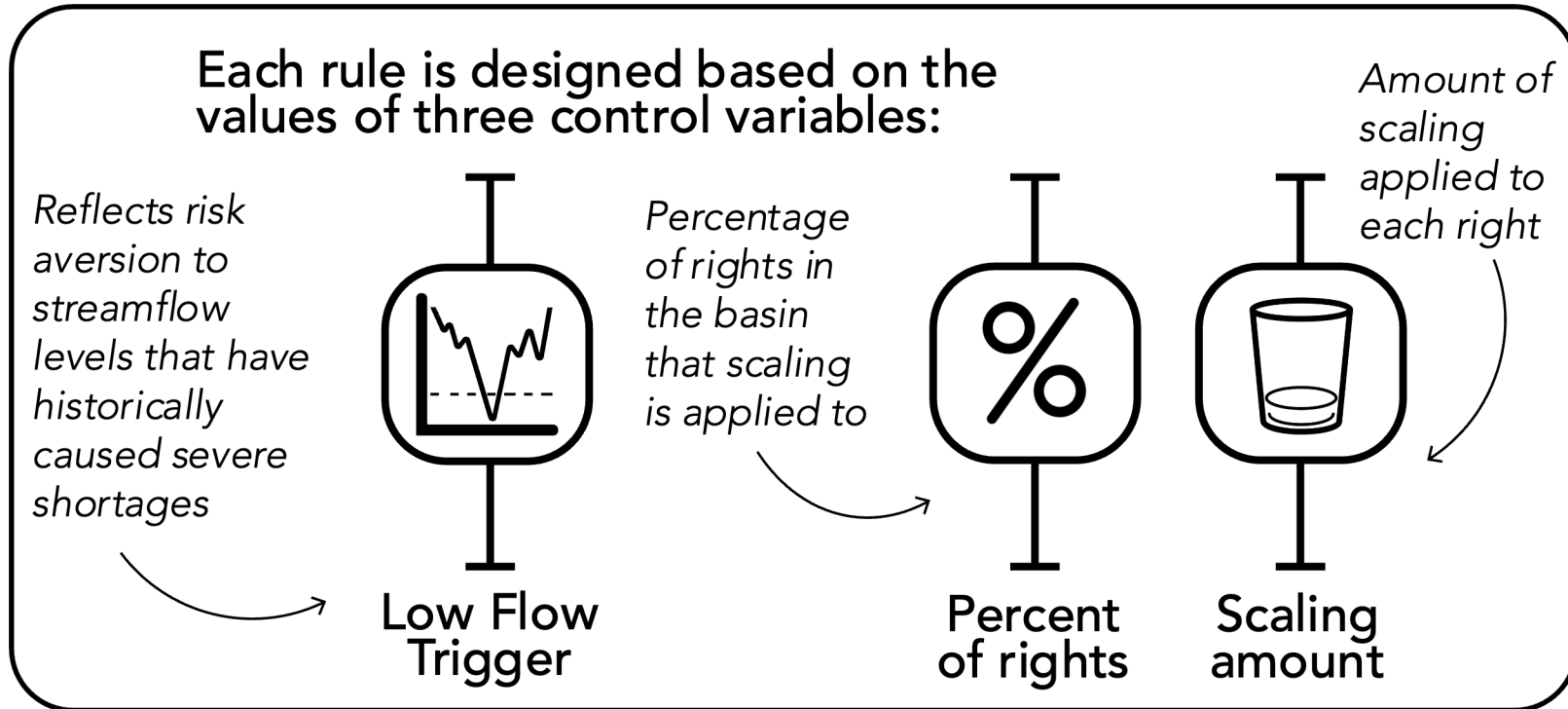
Water utilities and individuals have been buying water rights to safeguard their supply

Water conservation efforts are reducing demands



FOR SALE  
WATER  
719-849-8565

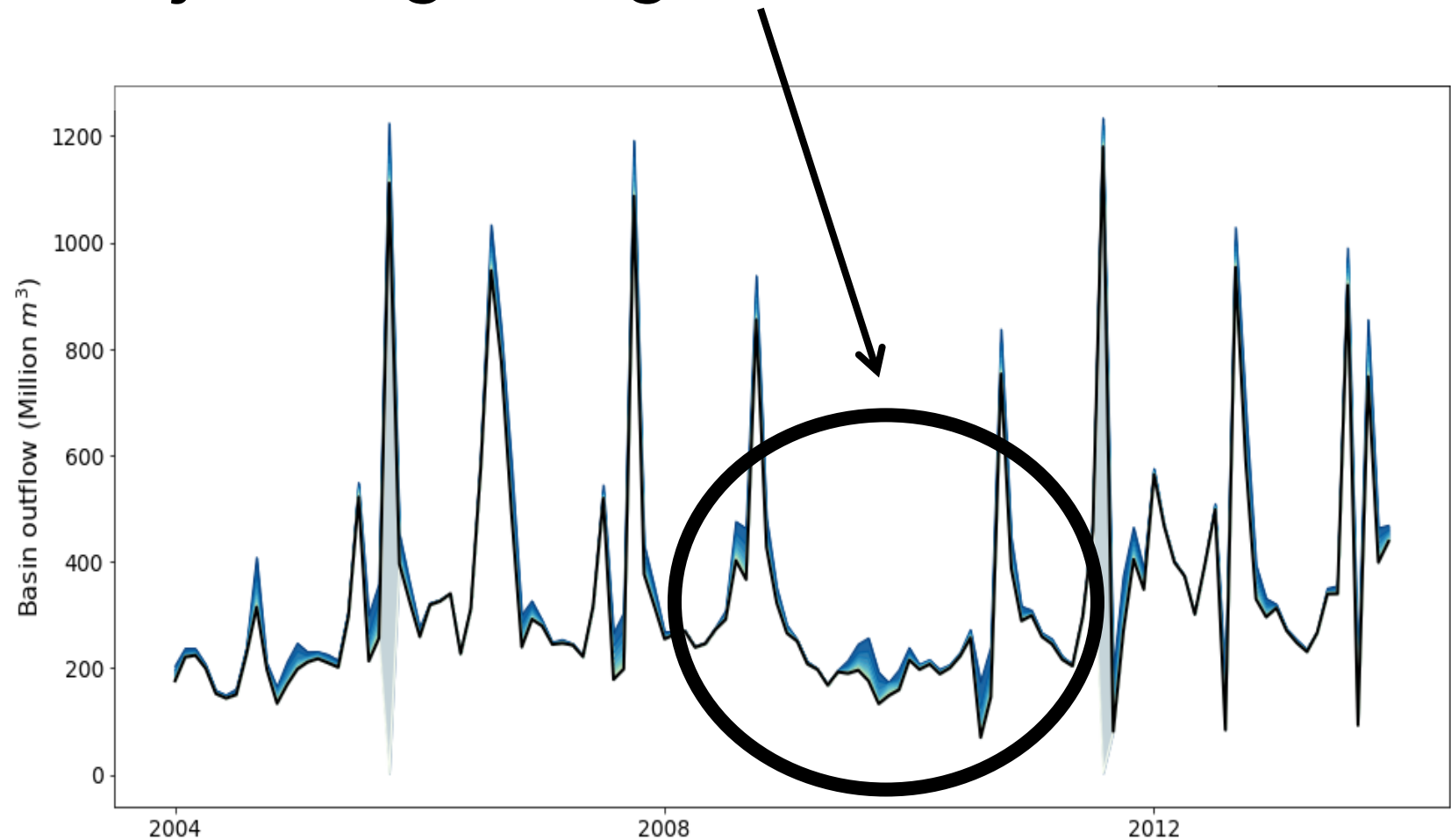
# Create 600 exploratory adaptive demand scaling rules tailored to each user



# Effects on water availability

Preliminary results show positive effect on increasing available water, especially during droughts

Effect is limited under increasingly stressed conditions



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at this year's **DMDU Meeting 9-11 November, 2022**



# Thank you for your attention!



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