IM3

INTEGRATED MULTISECTOR MULTISCALE MODELING

Advancing scenario discovery to identify impacts and consequential dynamics for complex multi-actor human-natural systems

Antonia Hadjimichael, Patrick M. Reed, Julianne D. Quinn, Chris R. Vernon, Travis Thurber

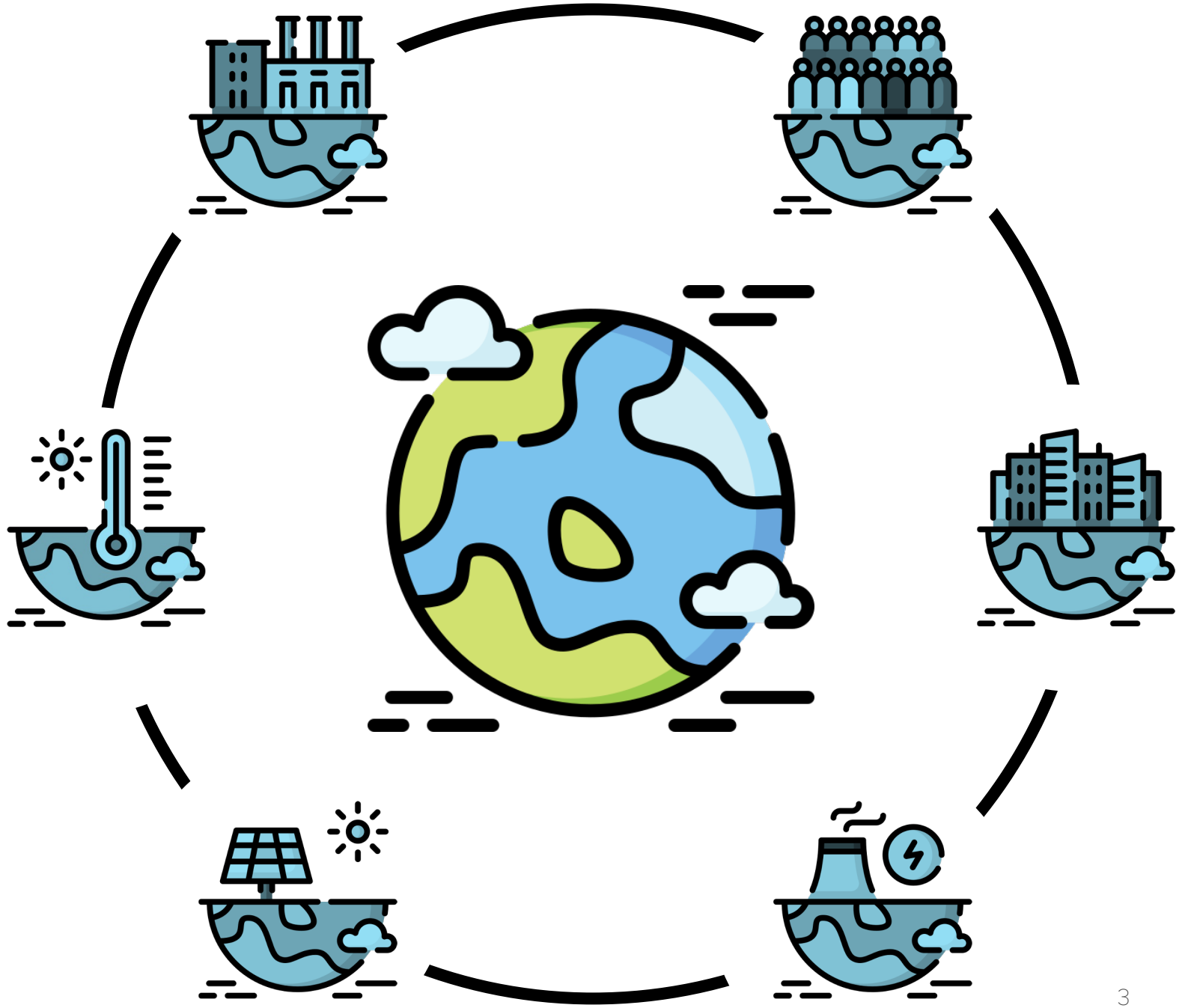
This research is supported by the U.S. Department of Energy, Office of Science, as part of research in MultiSector Dynamics, Earth and Environmental System Modeling Program

Motivation

- **Human-natural systems:** dynamic two-way interactions between human components (e.g., economic, social) and natural (e.g., hydrologic, atmospheric, biological, geological)
- When **planning** for human-natural systems, there exists a tension between ensuring **rigorous assessment** of **complexity** and **uncertainty**, as well as **usability** of outcomes
- This talk presents a **framework** for **narrative scenario discovery** to address this gap

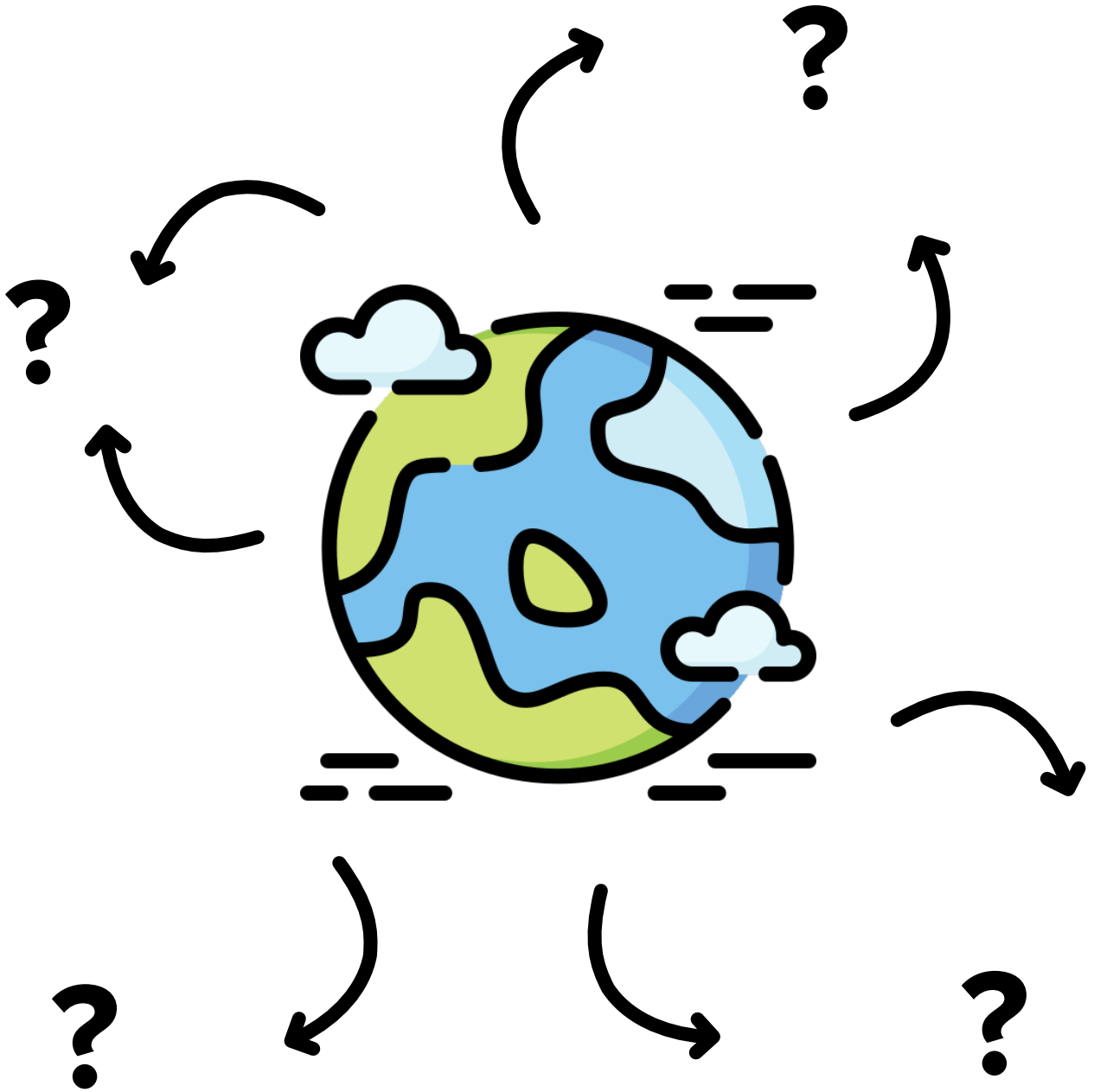
IM3

Human-natural systems are shaped by many complex feedbacks and interactions



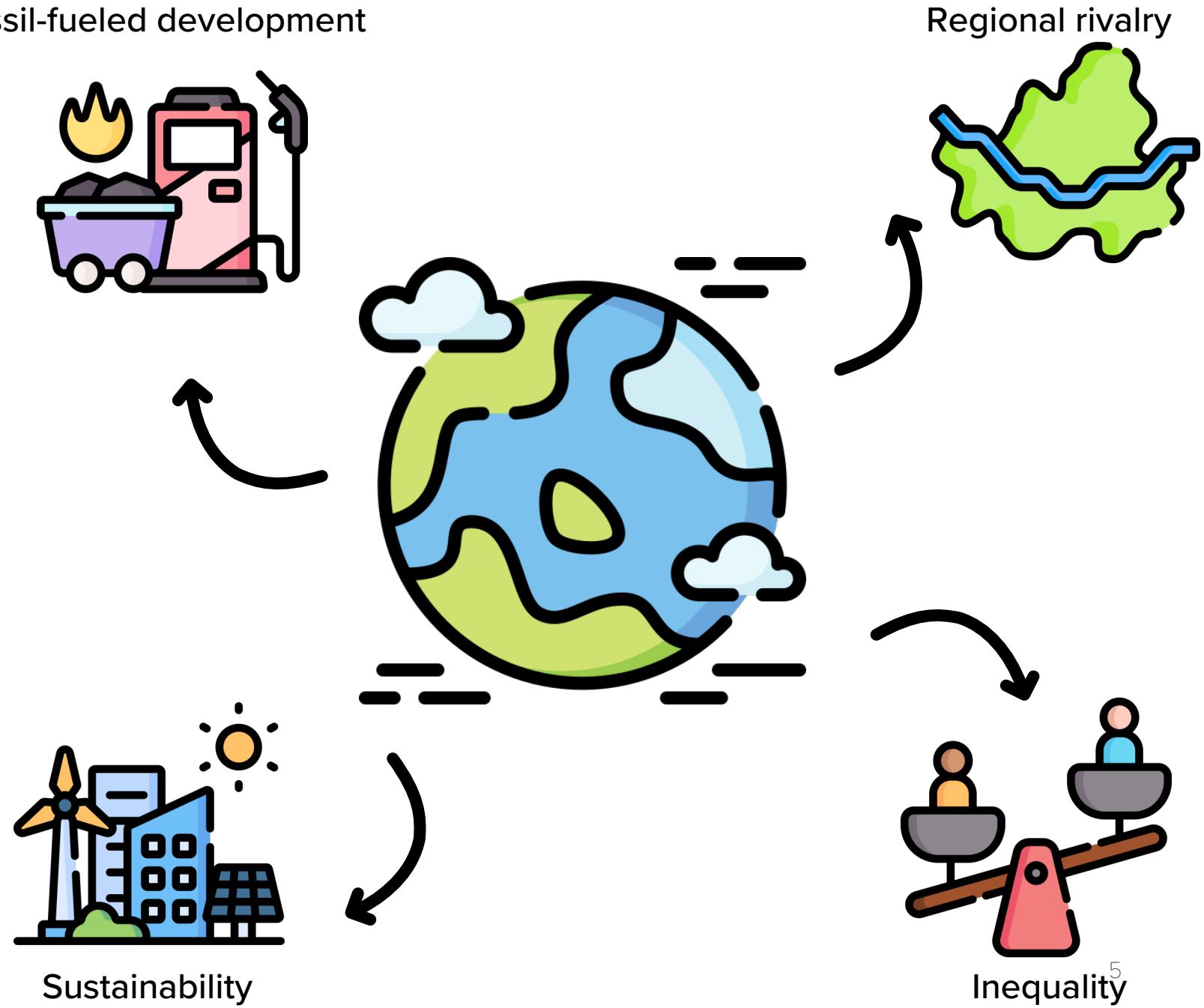
IM3

Deep uncertainties confound our assessment, especially when looking into the future



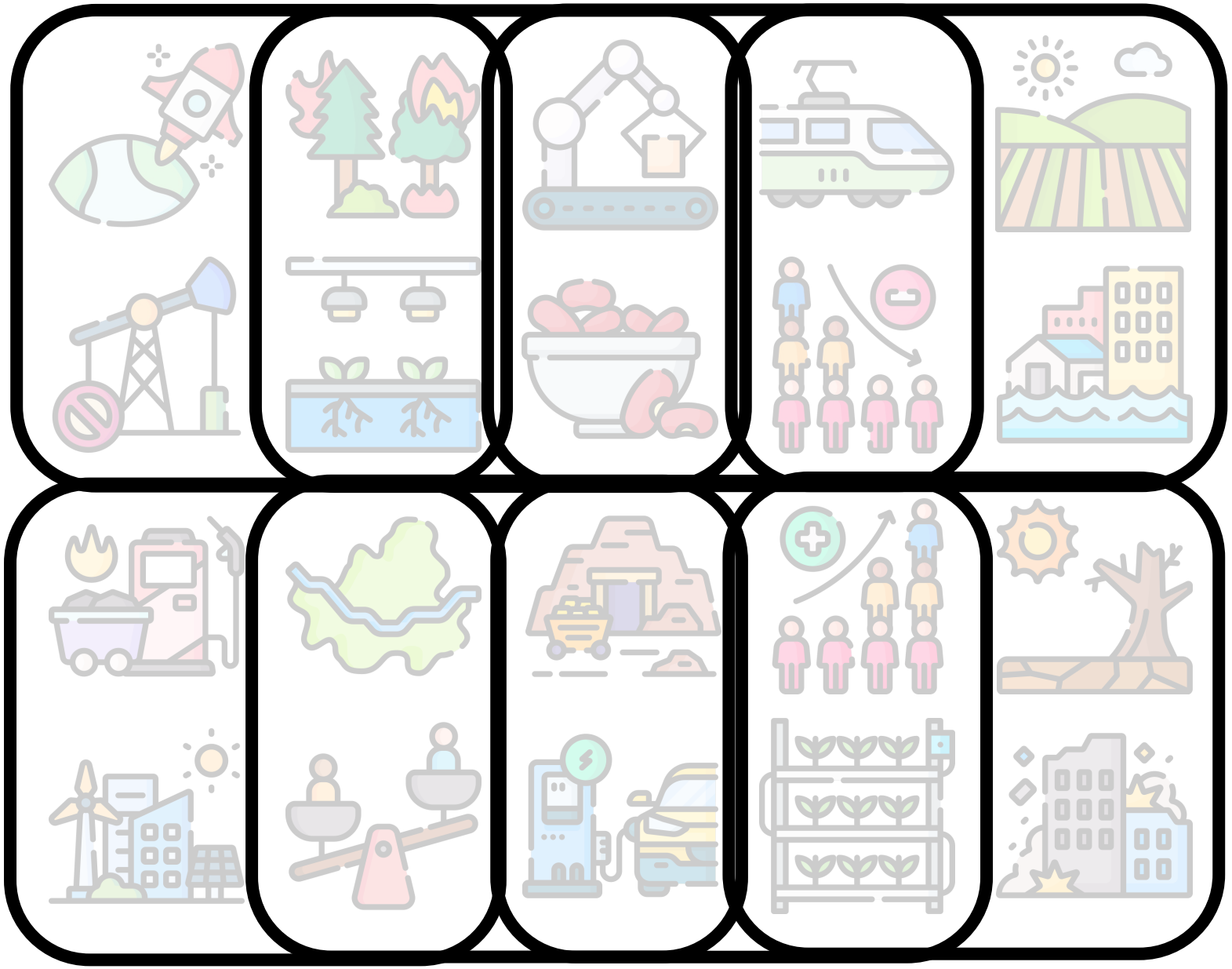
IM3

Scenarios help us reduce this complexity to narrative descriptions of the future



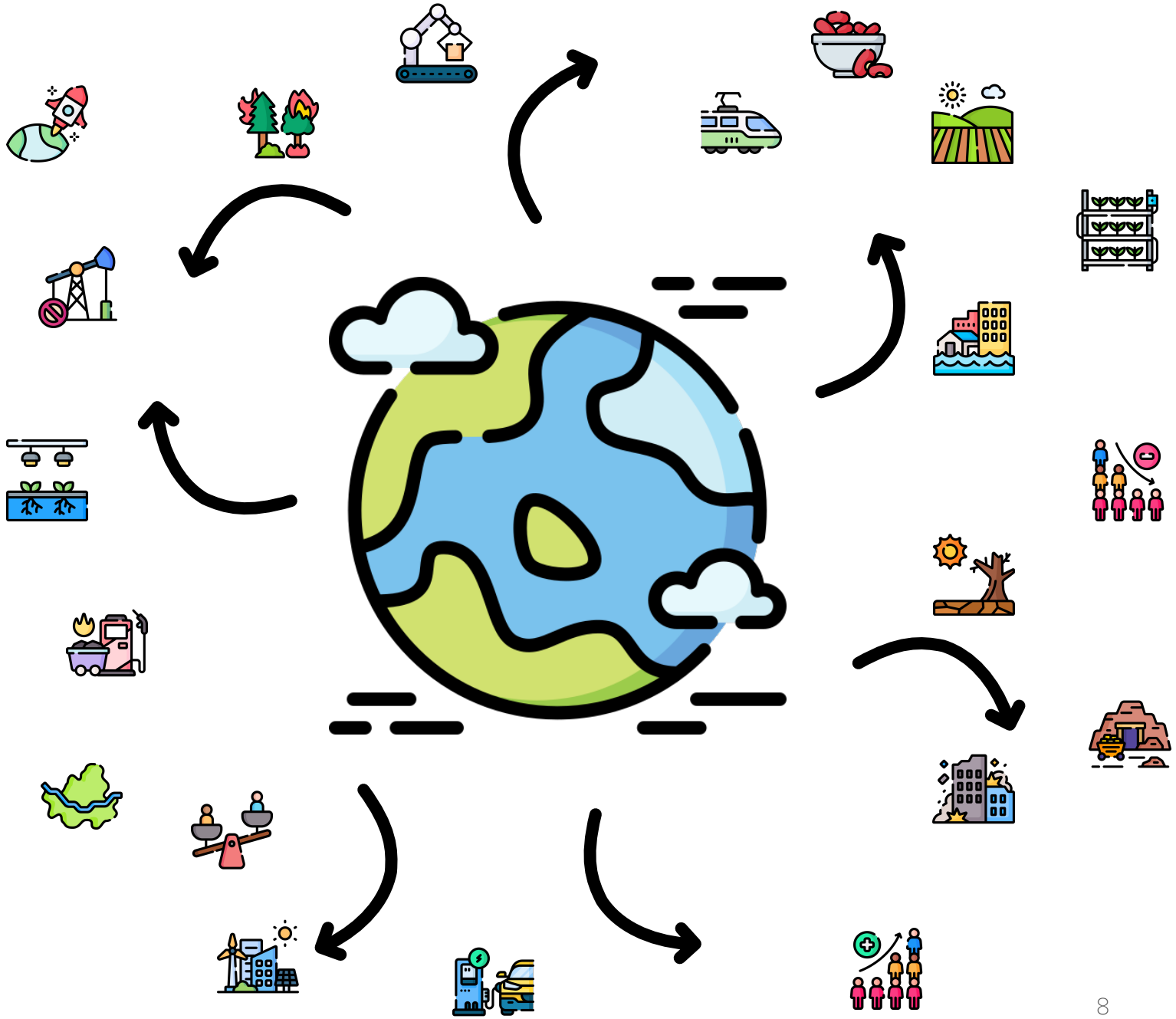
But they bring several problems: they only represent a **small number** of all the future possibilities

But they bring several problems: they might be **biased** by those involved in crafting them

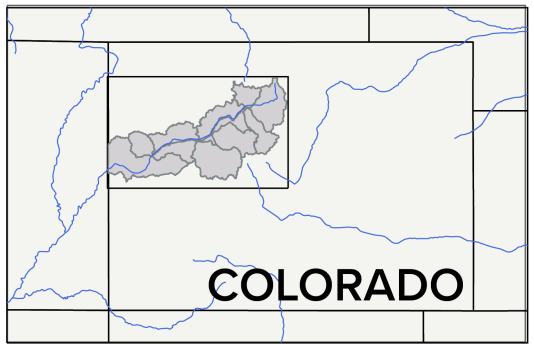


IM3

Exploratory modeling approaches try to overcome this by investigating large numbers of hypothetical futures

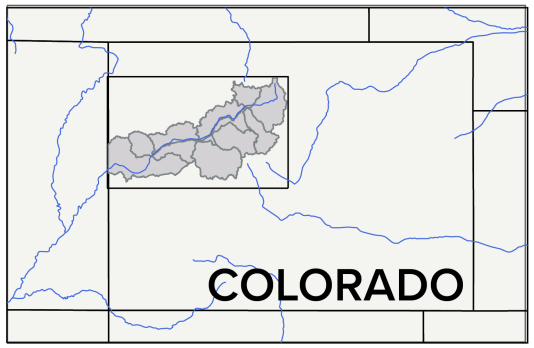


The Upper Colorado River Basin (UCRB)



Cumulative yearly statistics of the Colorado Division of Water Resources (2012)

The Upper Colorado River Basin (UCRB)



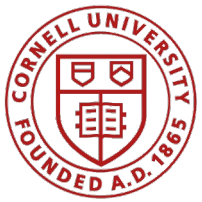
Prior-appropriation doctrine:
Each diversion with level of seniority and decreed flow

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

IM3

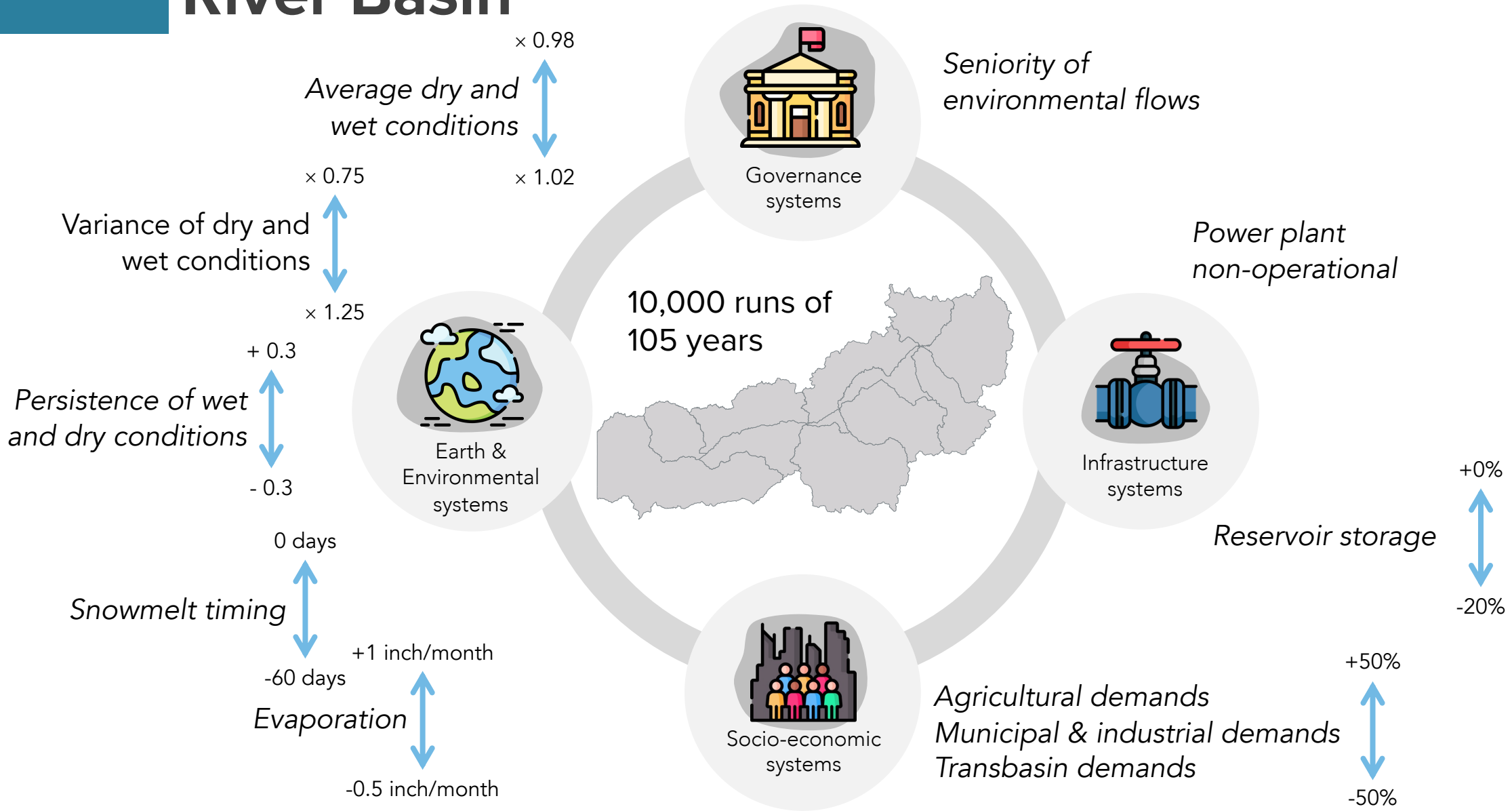
- How **vulnerable** are these water users to future climatic stress, increasing water demands and other uncertain drivers?

- Can we identify which **stressors** are most consequential for these users and under what conditions?

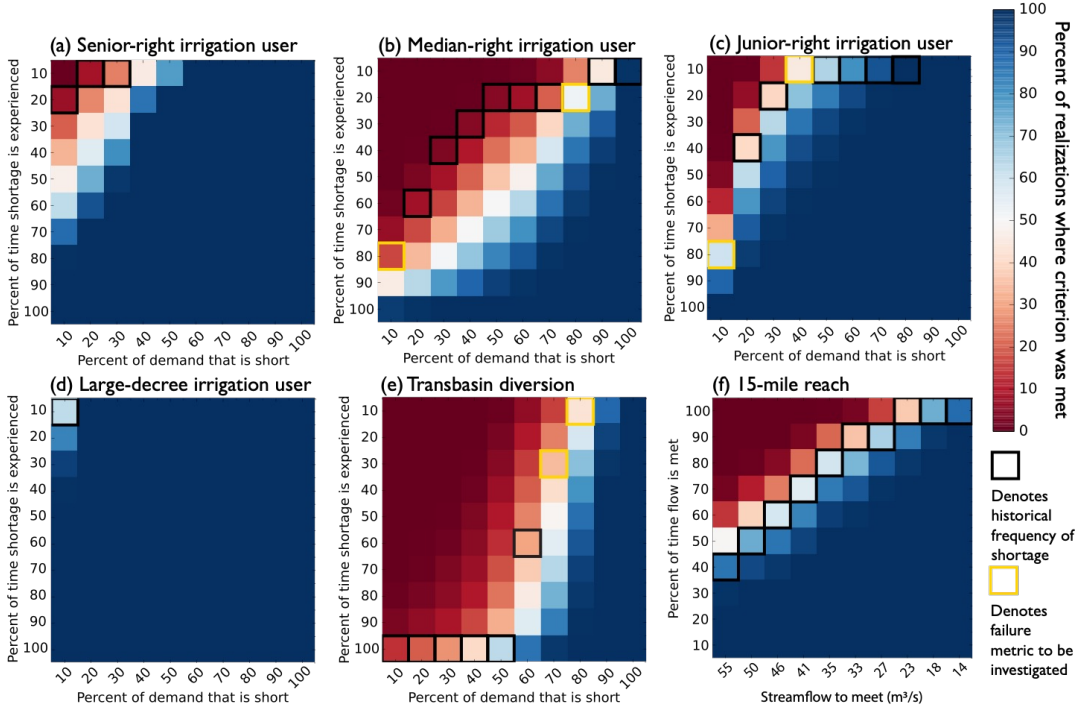


COLORADO
Colorado Water Conservation Board
Department of Natural Resources

Exploratory experiment for the Upper Colorado River Basin

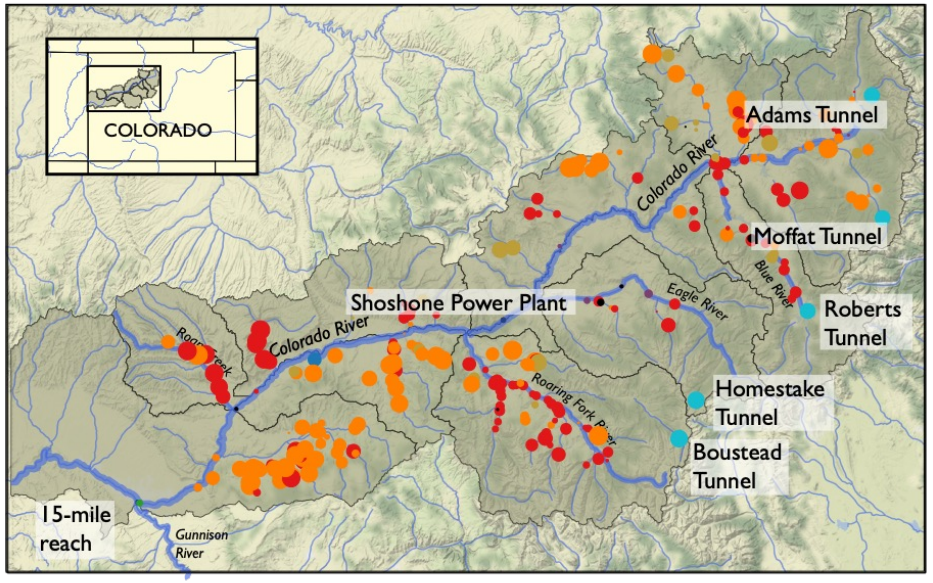


Exploratory experiment for the Upper Colorado River Basin



Assessed conditions result in very different impacts to water users in the basin

Spatial distribution of single most important factor affecting the frequency of a 2002-level shortage



Earth's Future

Research Article | Open Access

Defining Robustness, Vulnerabilities, and Consequential Scenarios for Diverse Stakeholder Interests in Institutionally Complex River Basins

Antonia Hadjimichael, Julianne Quinn, Erin Wilson, Patrick Reed, Leon Basdekas, David Yates, Michelle Garrison

First published: 12 May 2020 | https://doi.org/10.1029/2020EF001503 | Citations: 20

Water Resources Research

Research Article | Free Access

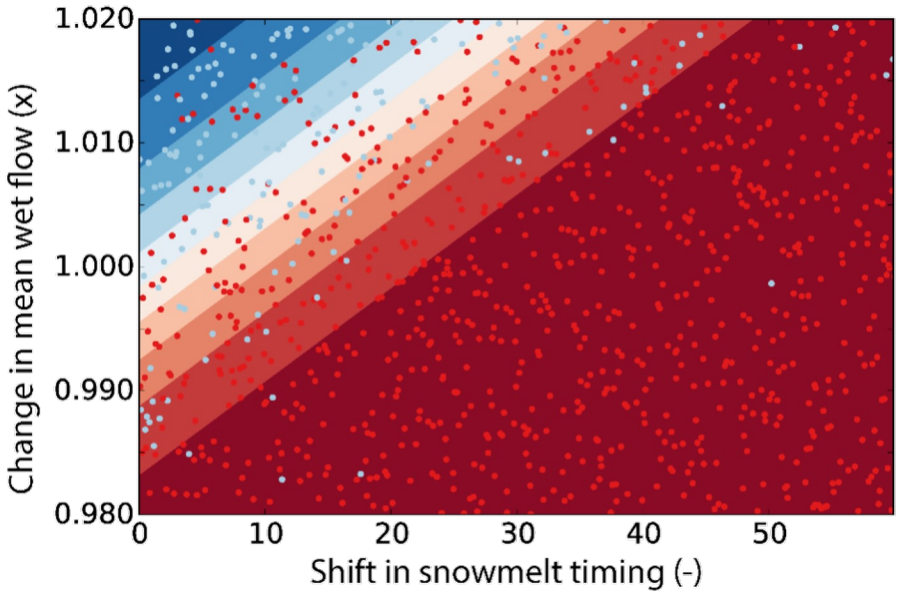
Advancing Diagnostic Model Evaluation to Better Understand Water Shortage Mechanisms in Institutionally Complex River Basins

Antonia Hadjimichael, Julianne Quinn, Patrick Reed

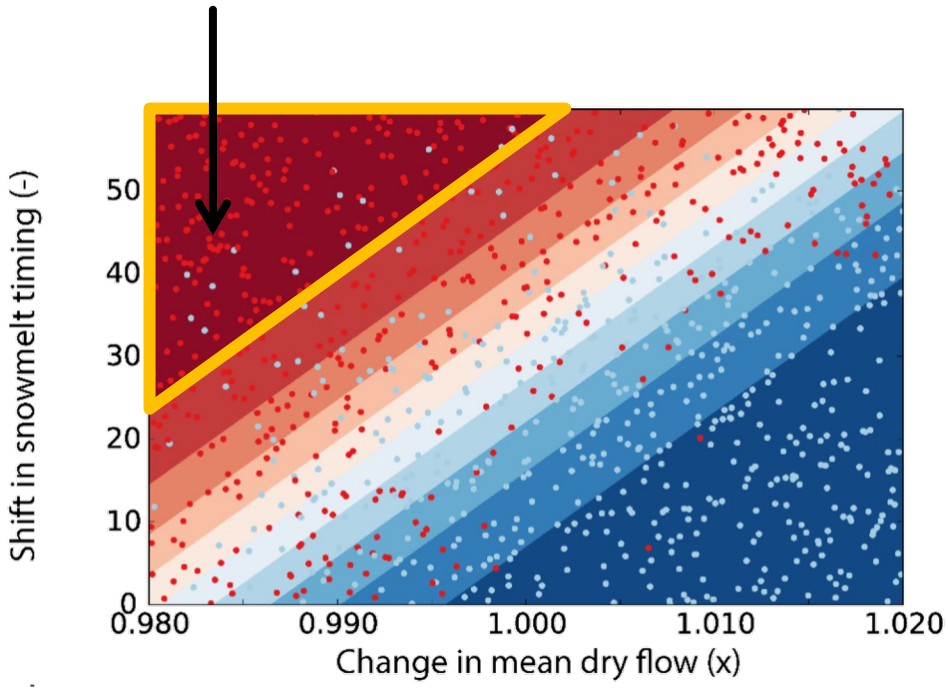
First published: 05 October 2020 |

Discovery of consequential scenarios for different users

Classify potential futures into ‘successes’ and ‘failures’ using uncertain factors as predictors



Earlier snowmelt combined with reduced dry flows increases shortages

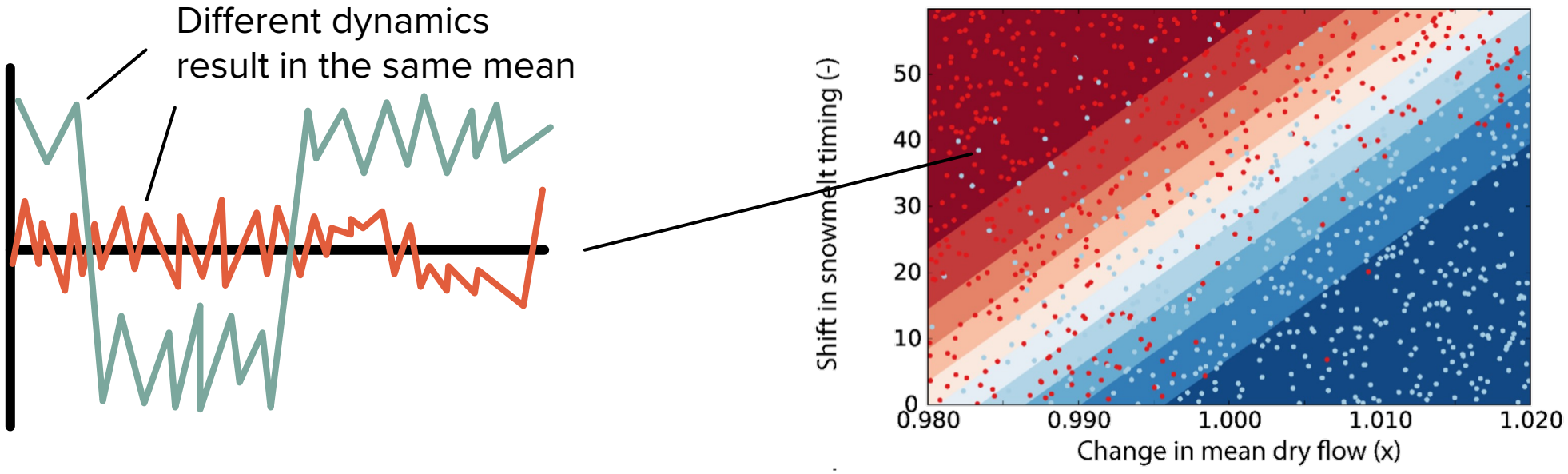


Probability of success

100% 0%

But this faces a couple problems

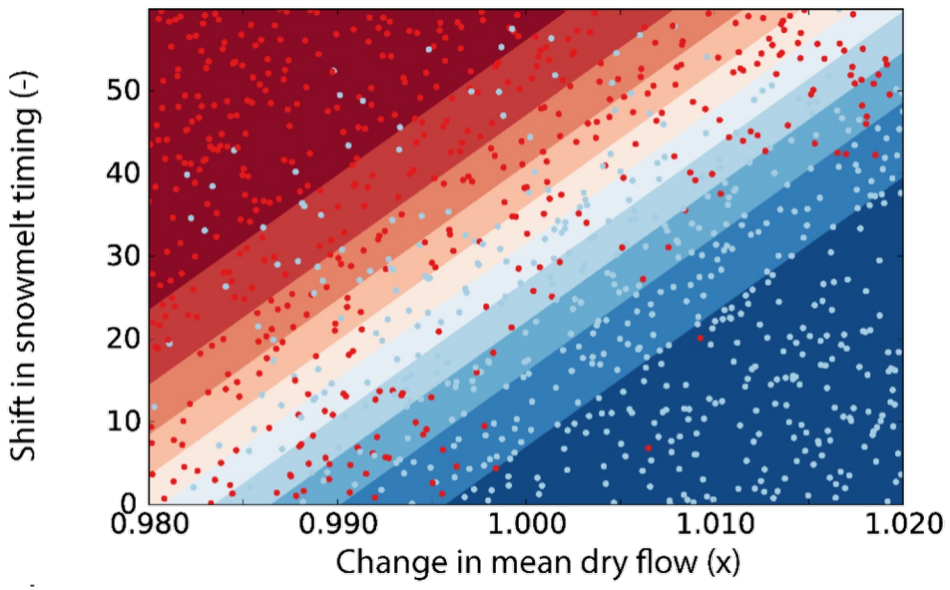
1. We don't keep track of **key dynamic processes** that result in each scenario's failure



But this faces a couple problems

2. We lose the **narrative simplicity** of a small number of key scenarios

"Of course we'll make a decision ...
once we have considered the 5243 factors."

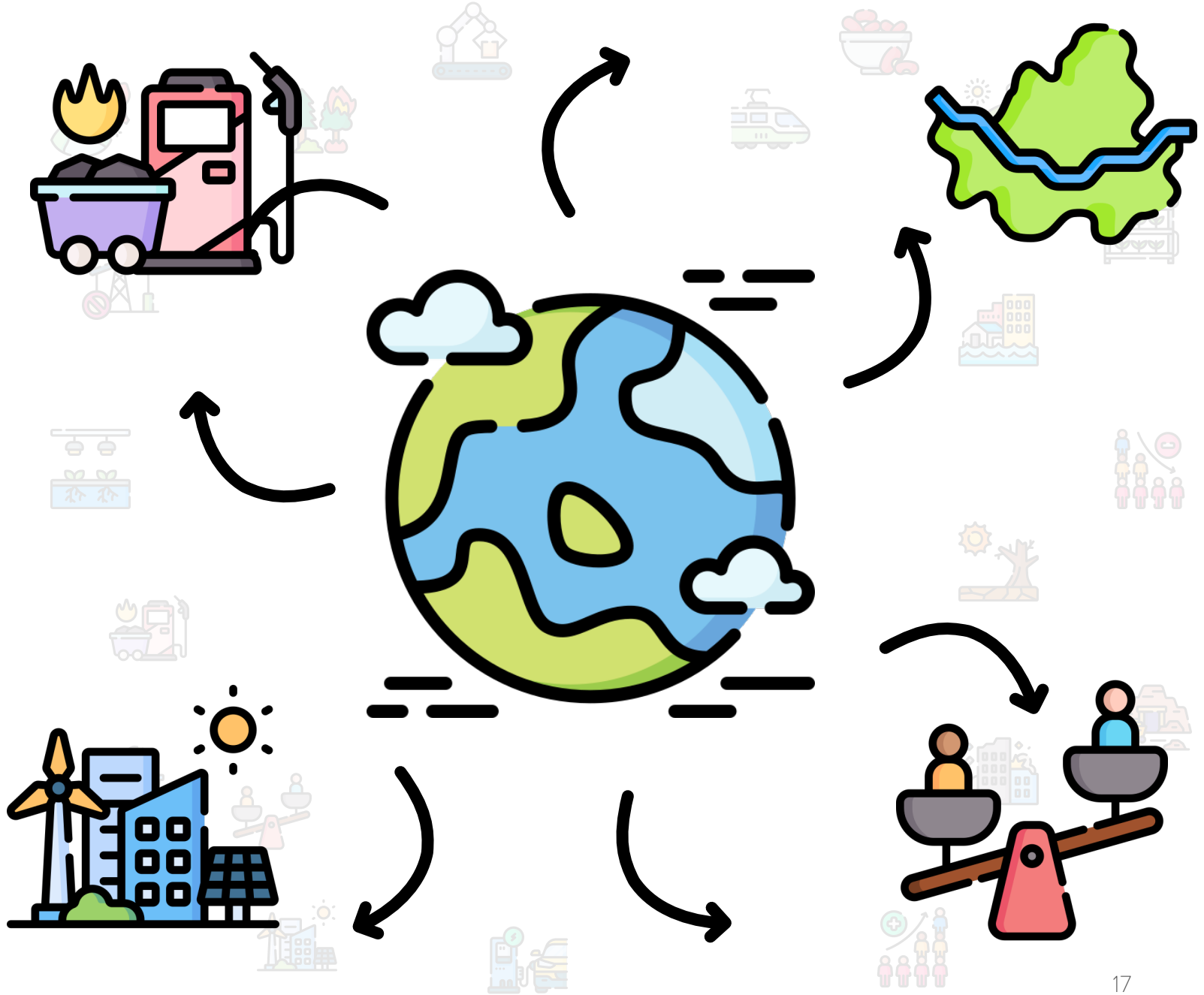


IM3

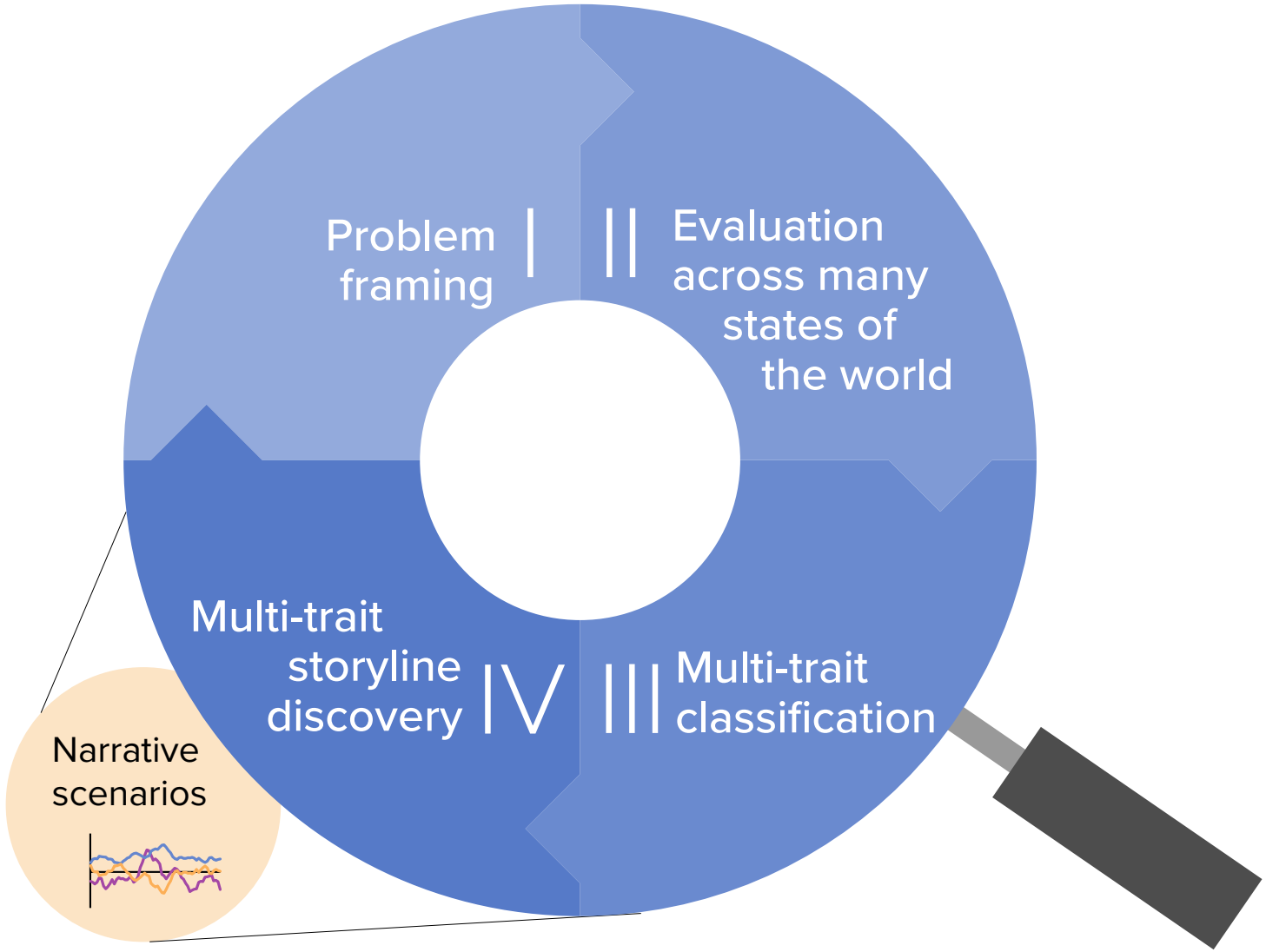
So, we want to utilize the **analytical rigor** provided by **exploratory modeling**

...to establish **narrative scenarios** that describe key **impacts**

...while keeping track of fundamental **dynamic processes** that get us there.

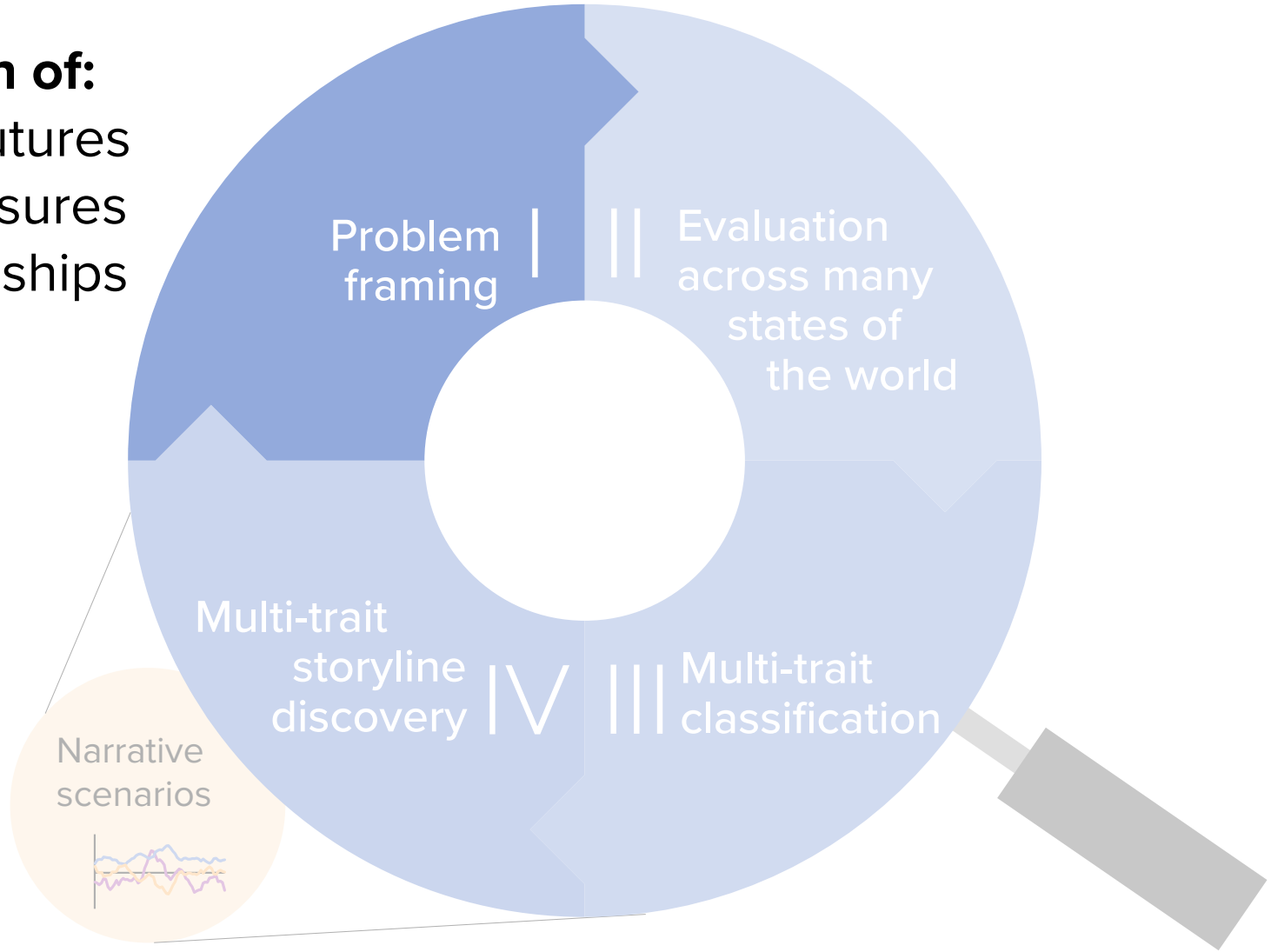


FRamework for Narrative Scenarios and Impact Classification (FRNSIC)

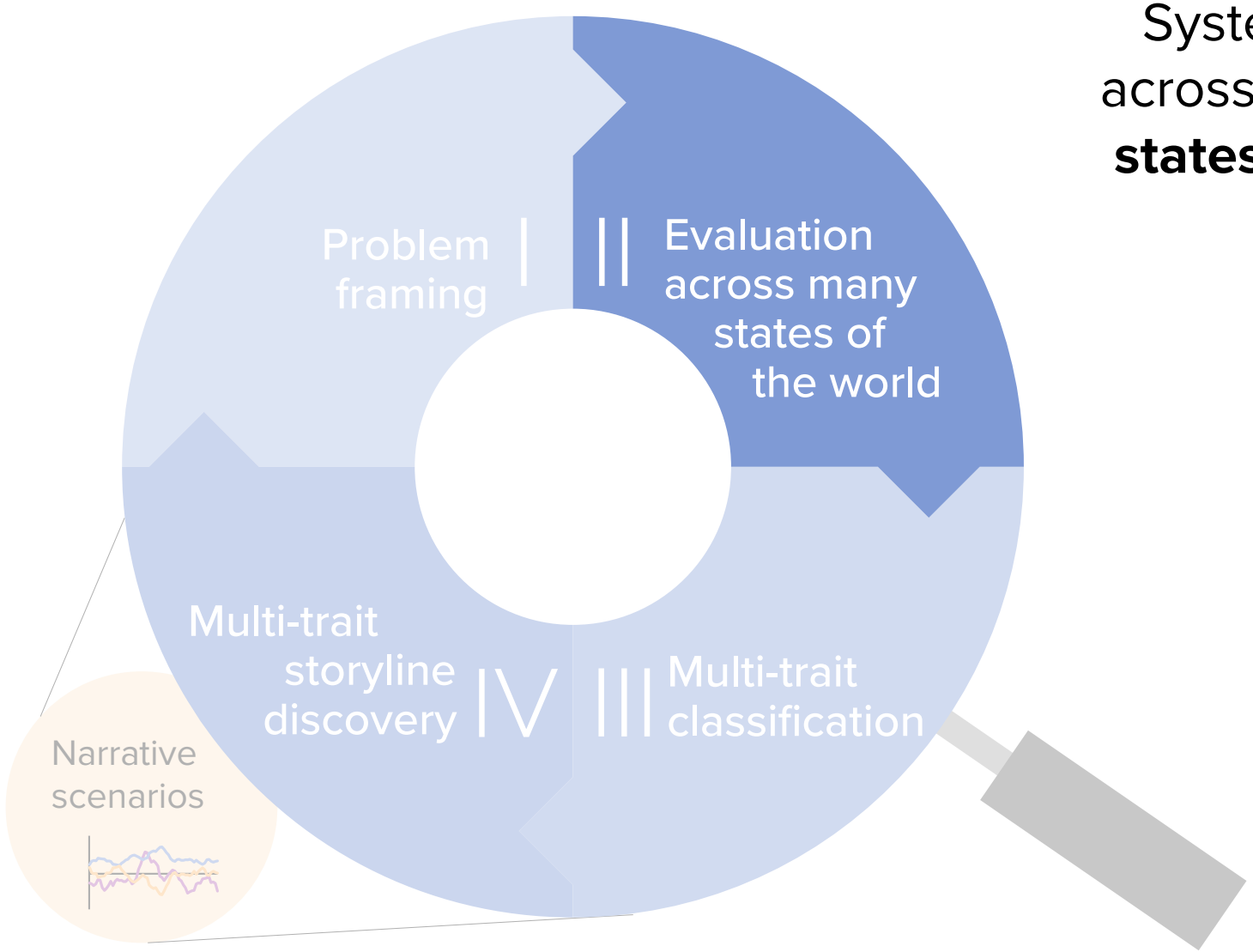


FRamework for Narrative Scenarios and Impact Classification (FRNSIC)

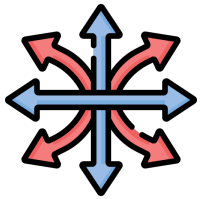
Formulation of:
Uncertain futures
Impact measures
Key relationships



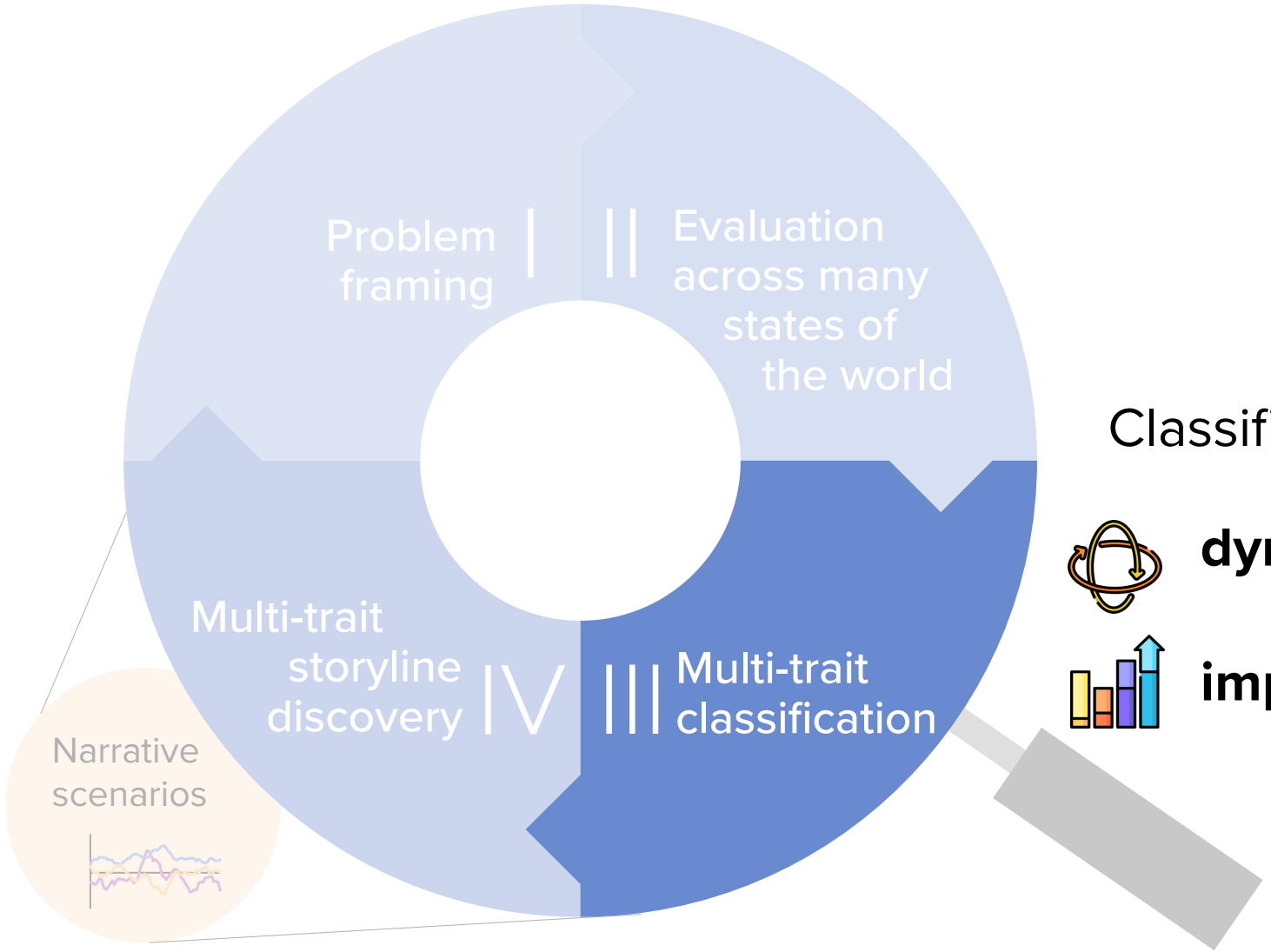
FRamework for Narrative Scenarios and Impact Classification (FRNSIC)



System simulation across all candidate **states of the world**



FRamework for Narrative Scenarios and Impact Classification (FRNSIC)



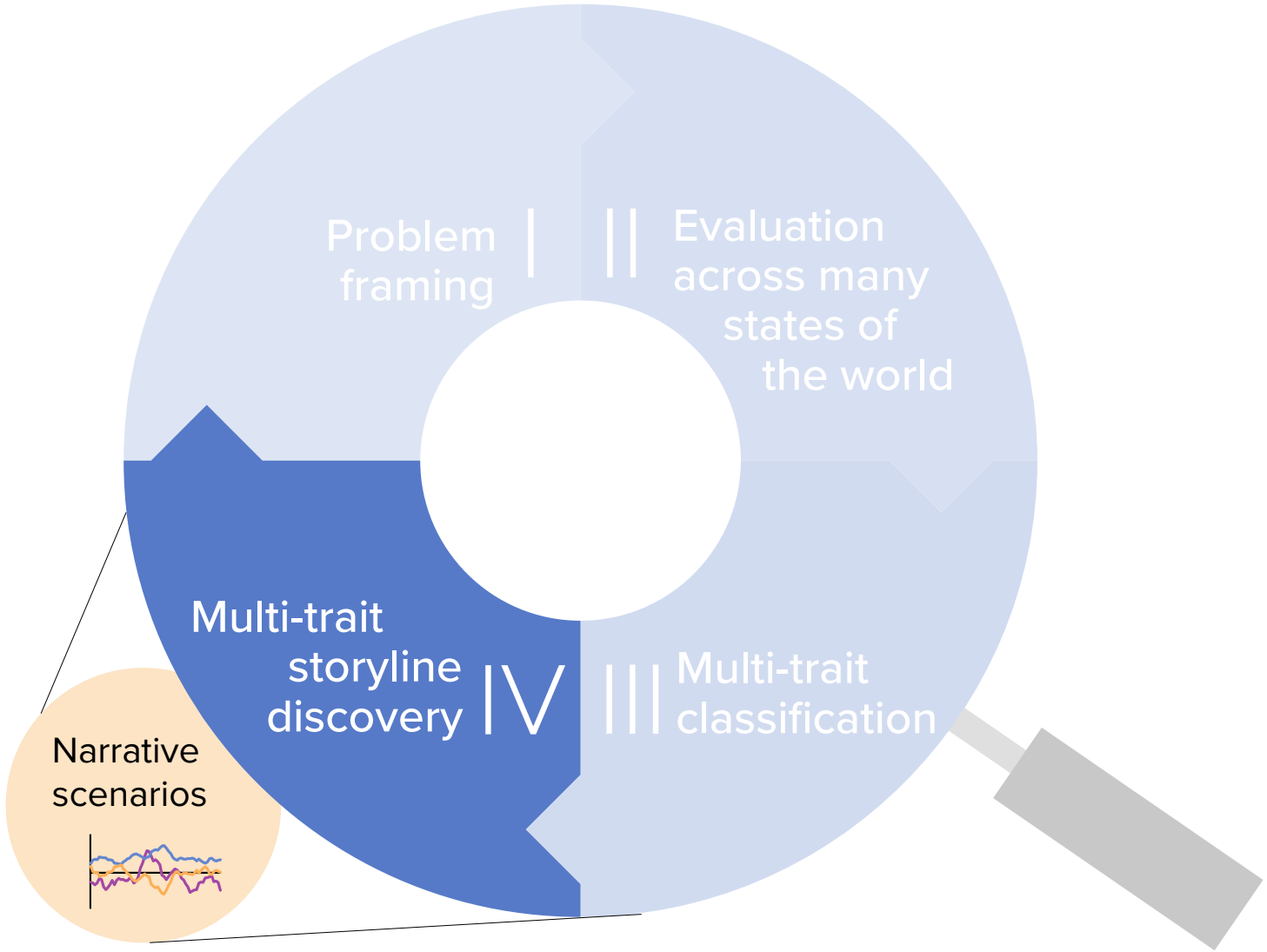
Classification of:

dynamic properties

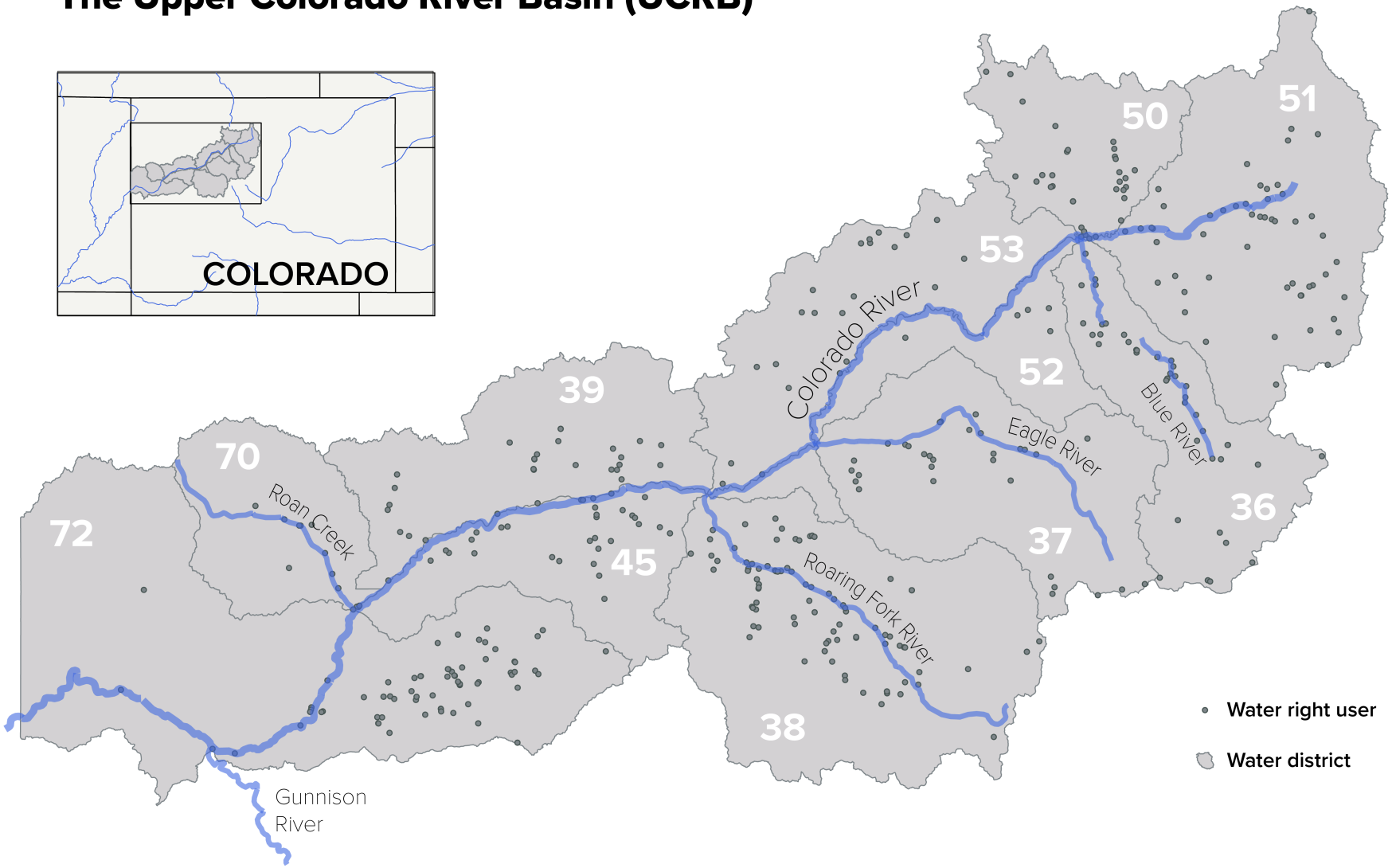
impact groups

FRamework for Narrative Scenarios and Impact Classification (FRNSIC)

Identification of **narrative scenarios** of dynamic states and impacts



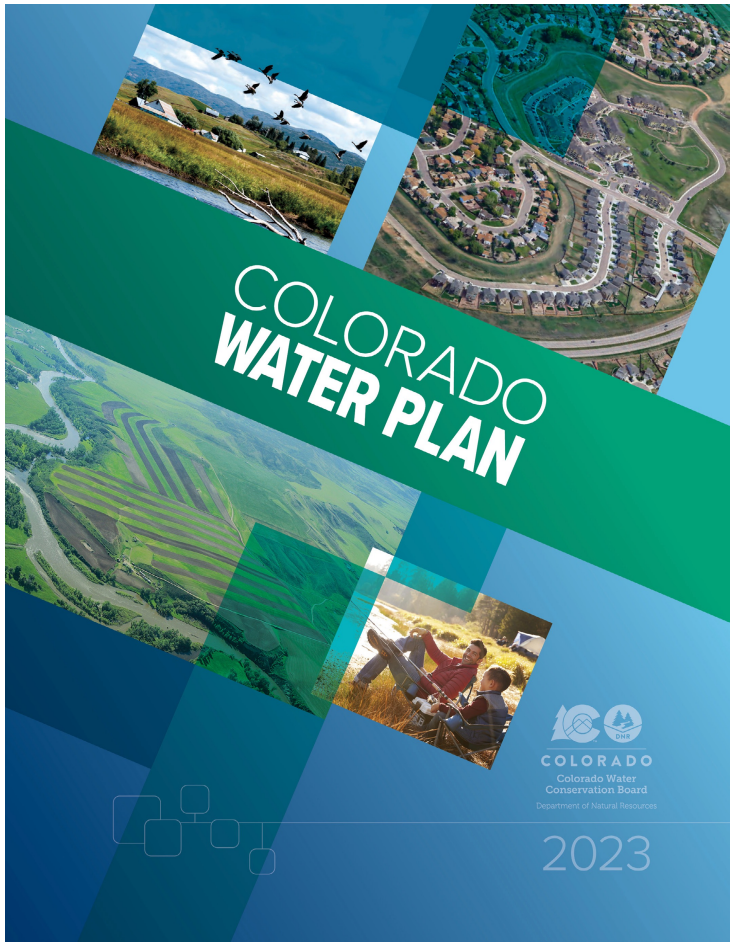
The Upper Colorado River Basin (UCRB)

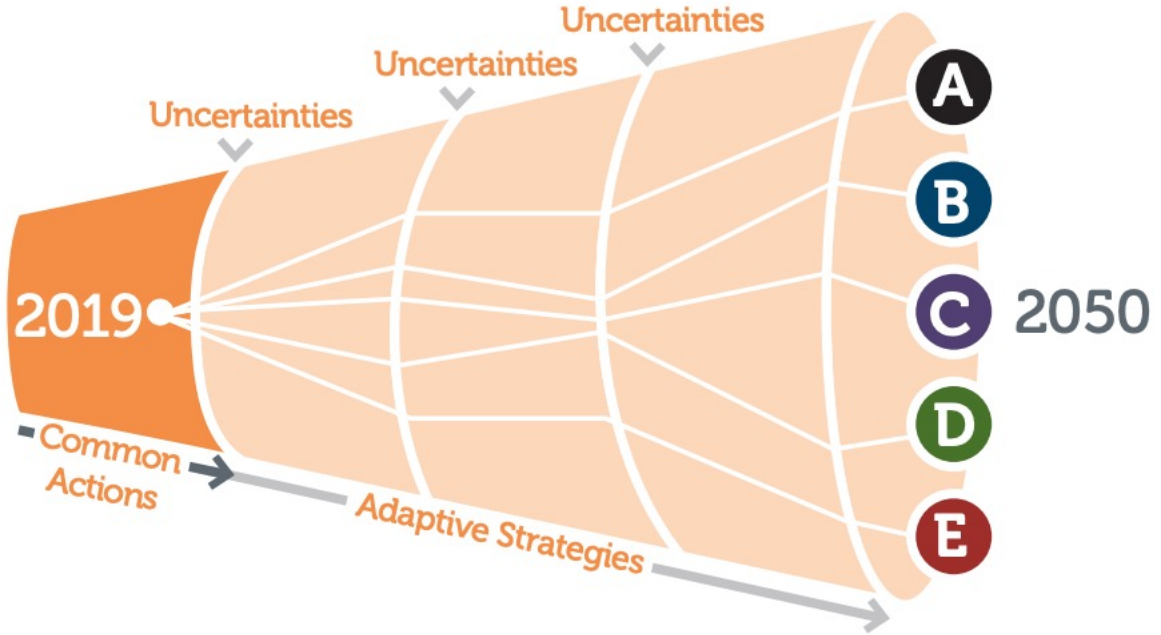


Demonstrate **hypothetical** planning context where the FRNSIC might be used

Low water levels of Lake Granby on Friday, May 14, 2021, in Granby.
Hugh Carey, The Colorado Sun

Narrative planning scenarios

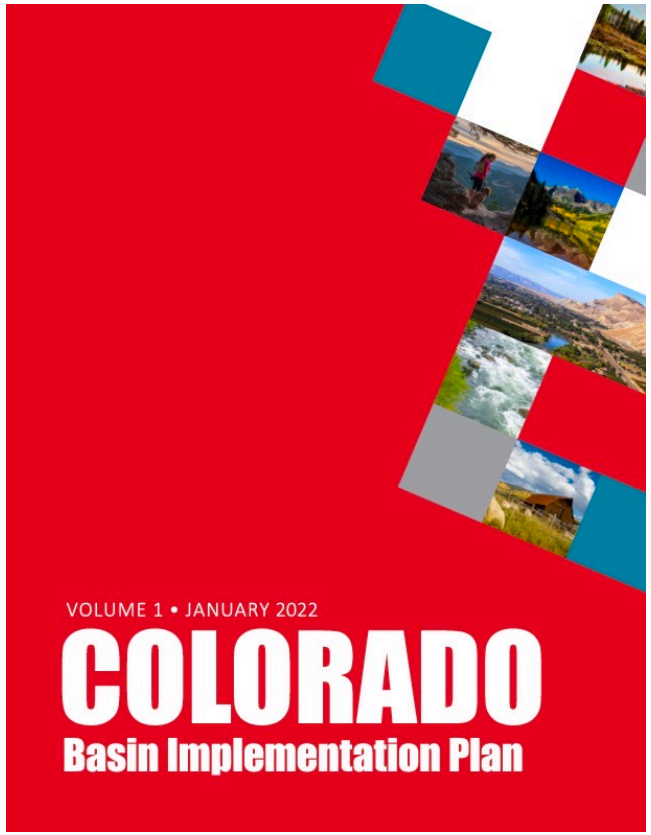




Scenarios describe **key driver** assumptions (no impacts)

A Business as Usual	B Weak Economy	C Cooperative Growth	D Adaptive Innovation	E Hot Growth
Water Supply ●●●	Water Supply ●●●	Water Supply ●●	Water Supply ●	Water Supply ●
Climate Status 🌡🌡	Climate Status 🌡🌡	Climate Status 🌡🌡🌡	Climate Status 🌡🌡🌡🌡	Climate Status 🌡🌡🌡🌡
Social Values 🌳🌳🌳	Social Values 🌳🌳🌳	Social Values 🌳🌳🌳🌳🌳	Social Values 🌳🌳🌳🌳🌳	Social Values 🌳
Agri. Needs 🚰🚰	Agri. Needs 🚰🚰🚰	Agri. Needs 🚰🚰🚰🚰	Agri. Needs 🚰🚰🚰🚰	Agri. Needs 🚰🚰🚰🚰🚰
M&I Needs 🚰🚰🚰	M&I Needs 🚰	M&I Needs 🚰🚰	M&I Needs 🚰🚰🚰🚰	M&I Needs 🚰🚰🚰🚰🚰

Implementing the Water Plan in the UCRB and local concerns



- Charged with **water planning** for the Colorado River Basin within Colorado.
- As part of a statewide initiative to develop Colorado's Water Plan, completed its own **Basin Implementation Plan** to address water needs within the basin.
- Allocates **funding** to address the basin's water challenges.
- Members include people from **agriculture**, **domestic water providers**, **environmental** and **recreation** entities, **state agencies**, and interested **citizens**.

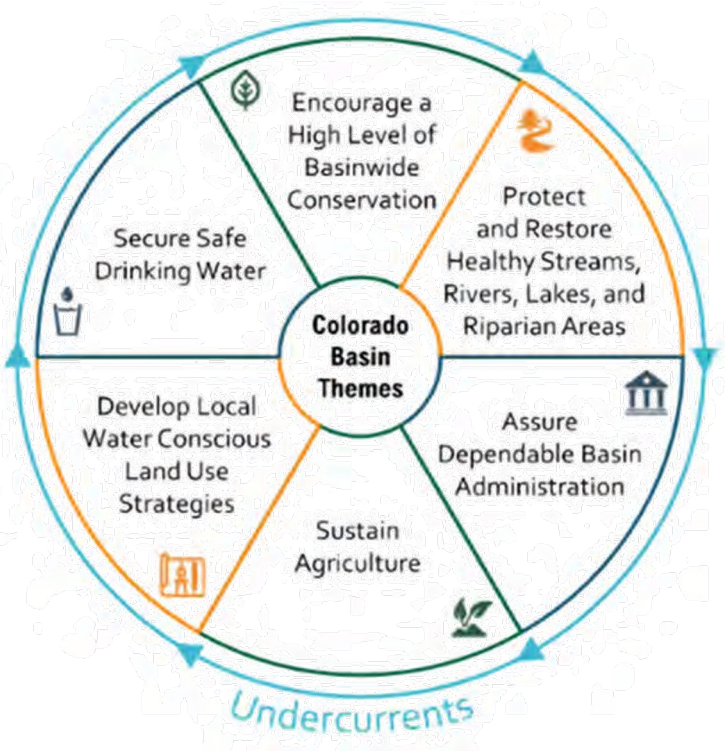
https://www.coloradobasinroundtable.org/about/

IM3

COLORADO BASIN ROUNDTABLE

Table 1. Key Future Water Management Issues and Challenges in the Colorado Basin

AGRICULTURE	WATERSHED	MUNICIPAL AND INDUSTRIAL	COMPACTS, ADMINISTRATION, AND REGULATORY
• Despite the importance of agriculture, con ued urbaniza on of agricultural lands could reduce irrigated acres in the Colorado Basin. • The value of agriculture in the basin is o en understated; it is a cri cal component of the basin's economy.	• In an uncertain future, maintaining ows suppor ve of recre on and the environment is vital. These are major drivers in the Colorado Basin and are important for economic health and quality of life.	• Development of condi onal transbasin water rights and poten al full use of exis g transbasin diversions is a concern, and the e ct on in-basin supplies in the Colorado Basin must be considered.	• There is concern over a poten al compact shortage during severe and sustained drought and the poten al e cts to in-basin supplies. Demand management to conserve water per the recently signed Drought Con gency Plan is a pressing issue.



We're interested in how **sustained and severe droughts** might impact our **local water users** across the different UCRB **regions**

We are also concerned with meeting our **federal obligations** to downstream users

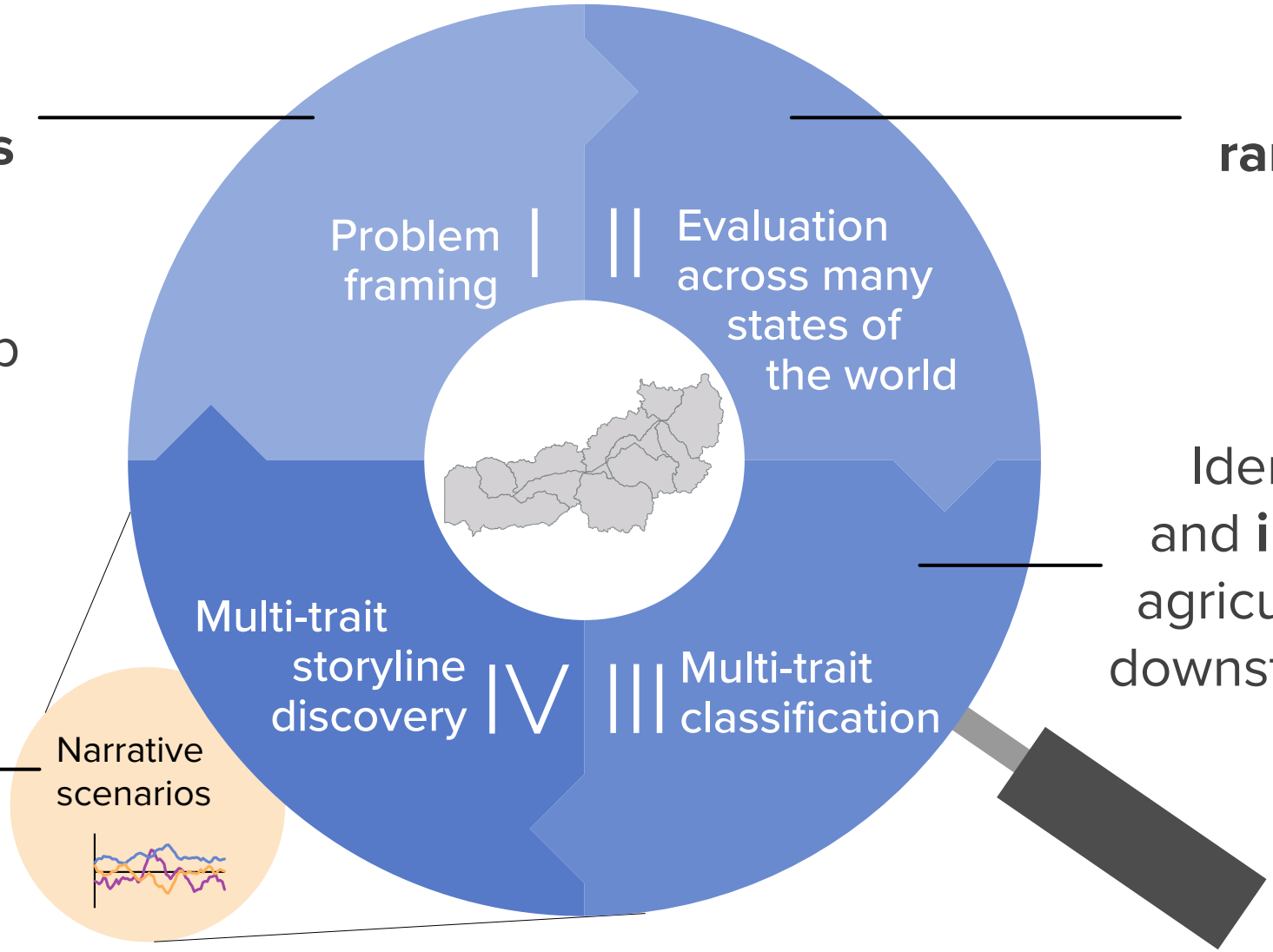
There's a broad range of possible **uncertain futures**

* not actual members of the Colorado Basin Roundtable

Using FRNSIC in a hypothetical planning context for the UCRB

Identify **drought planning scenarios** that capture **key local impacts** and their **drivers** to help inform **future adaptation**

Scenarios are **narrative** descriptions of both

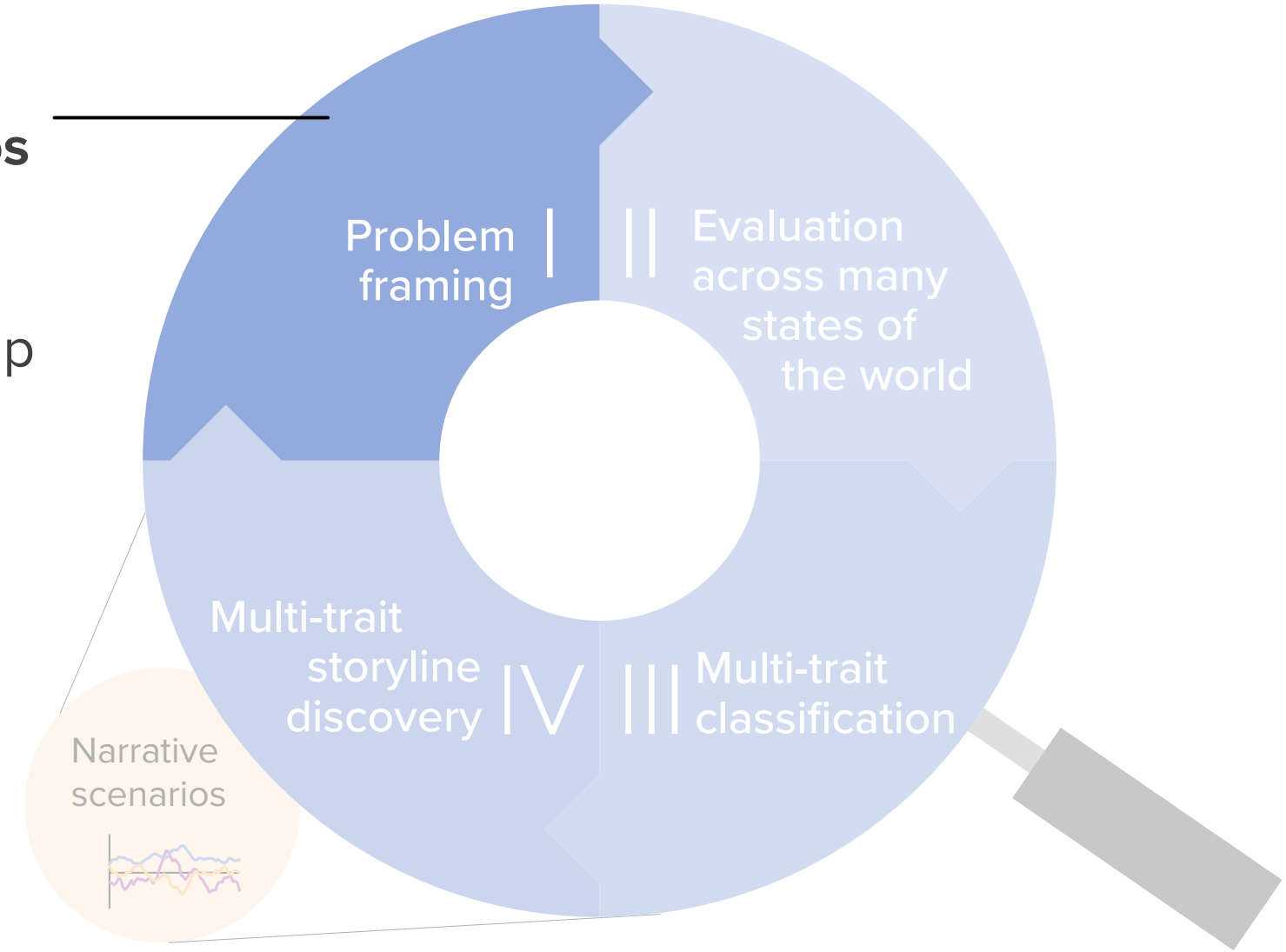


Consider **broad range** of plausible drought futures

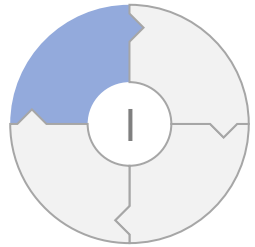
Identify key **drivers** and **impacts** on local agricultural users and downstream deliveries

Using FRNSIC in a hypothetical planning context for the UCRB

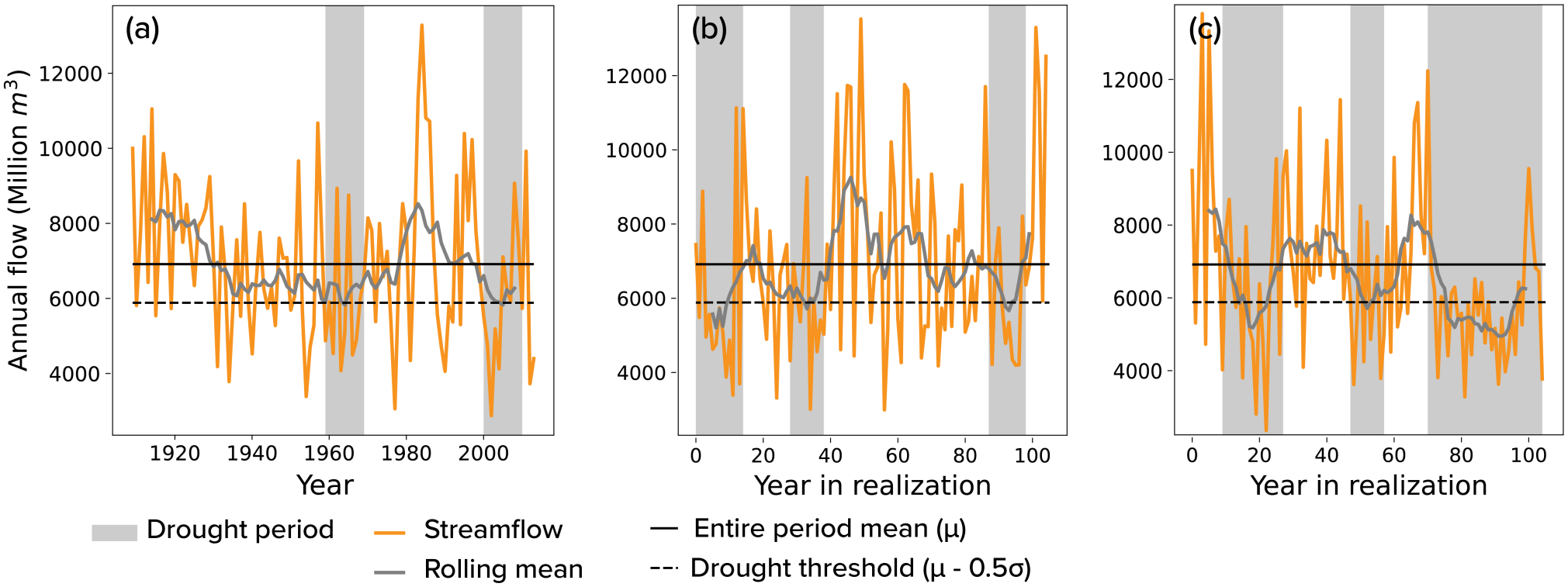
Identify **drought planning scenarios** that capture **key local impacts** and their **drivers** to help inform **future adaptation**



Exploring internal variability gives rise to previously unseen drought conditions



Historical observations **Synthetically generated flows**

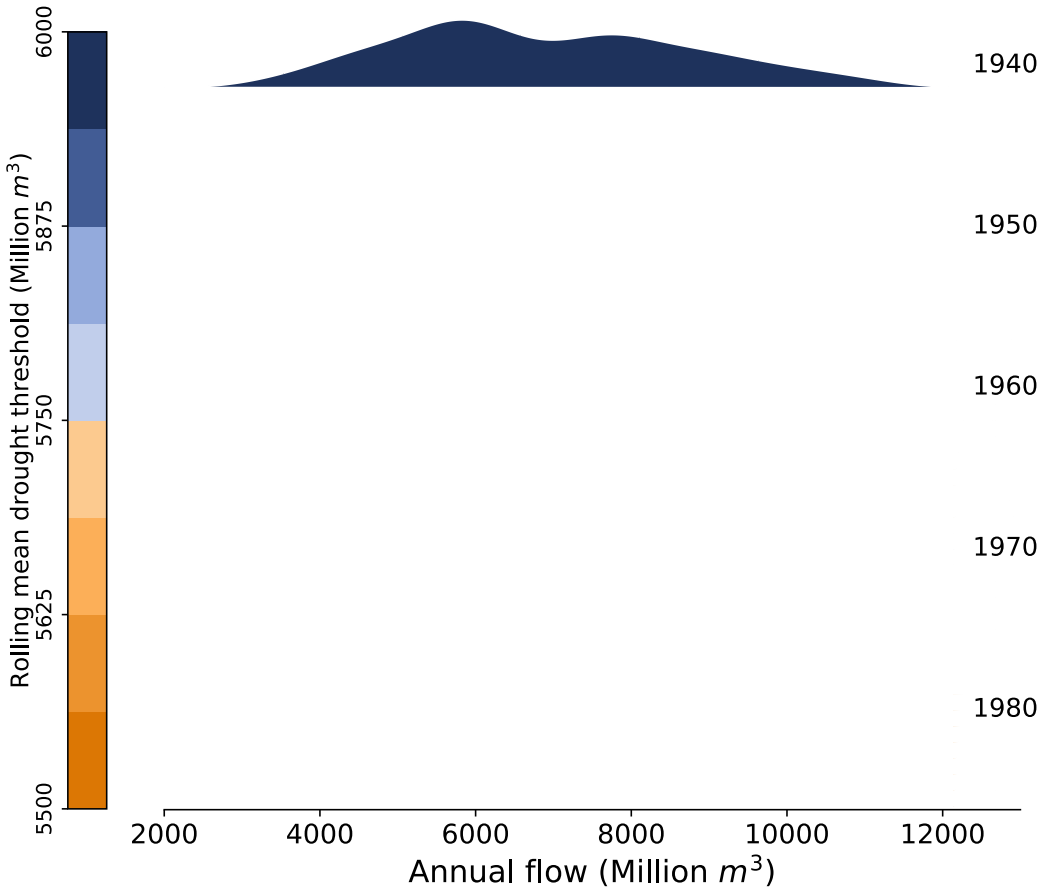


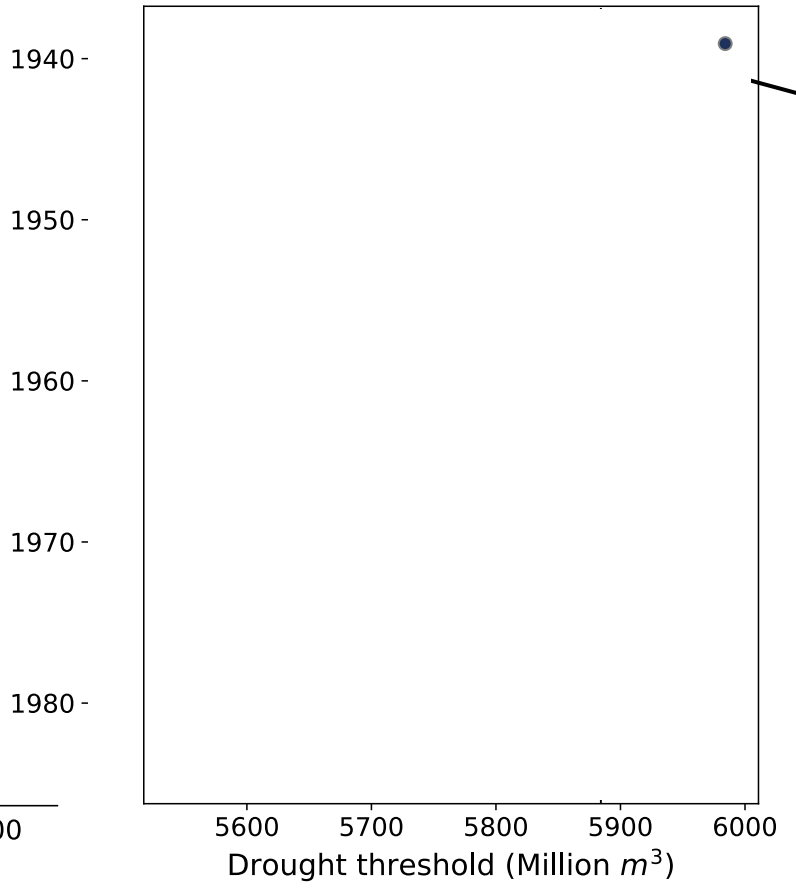
Synthetic streamflow sequences with **same statistical properties** can show **more decades** of **drought** than those experienced

Changing system properties affect how we classify drought

Different periods might experience **different distributions of conditions**

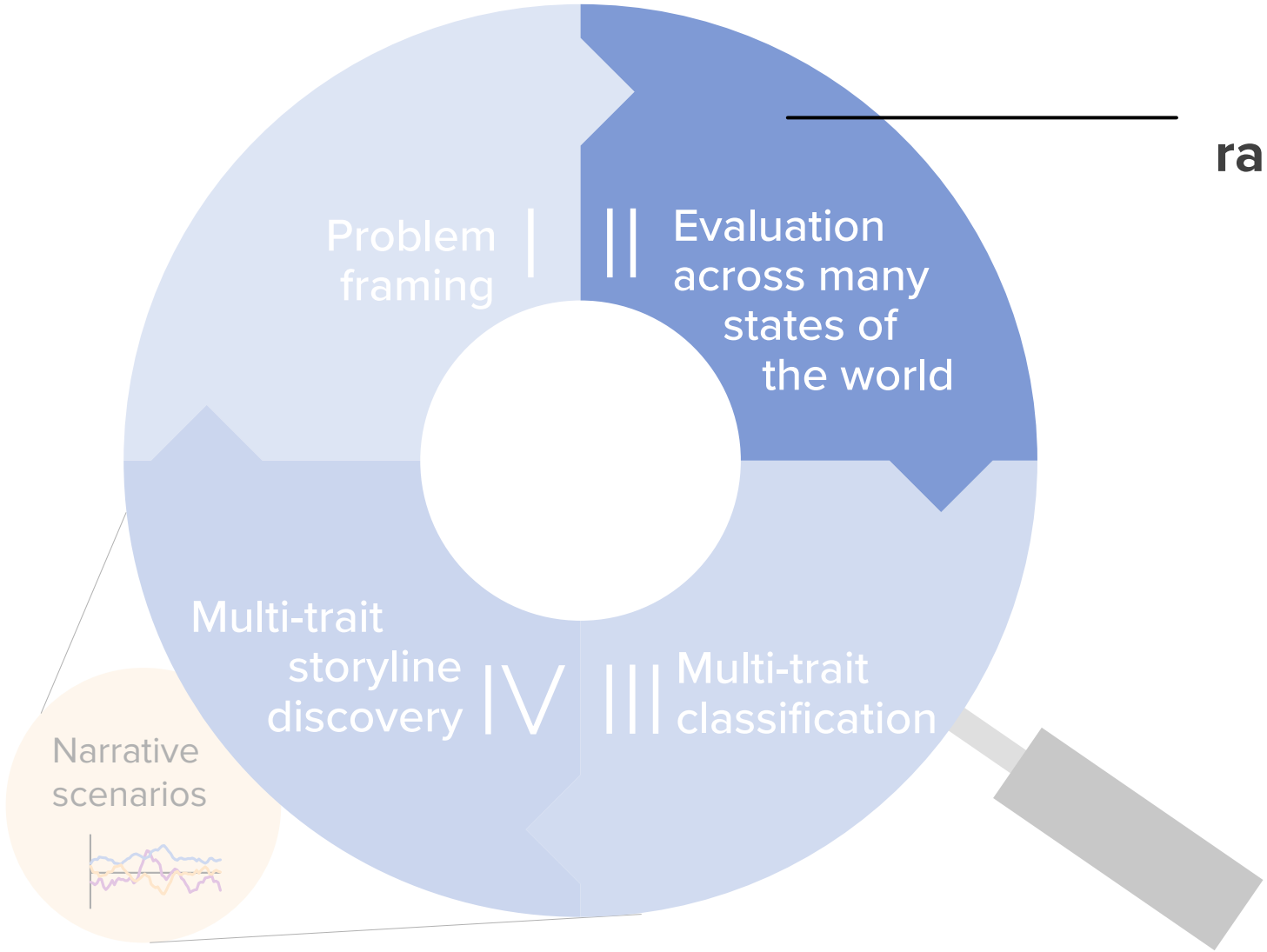
Rolling windows of streamflow





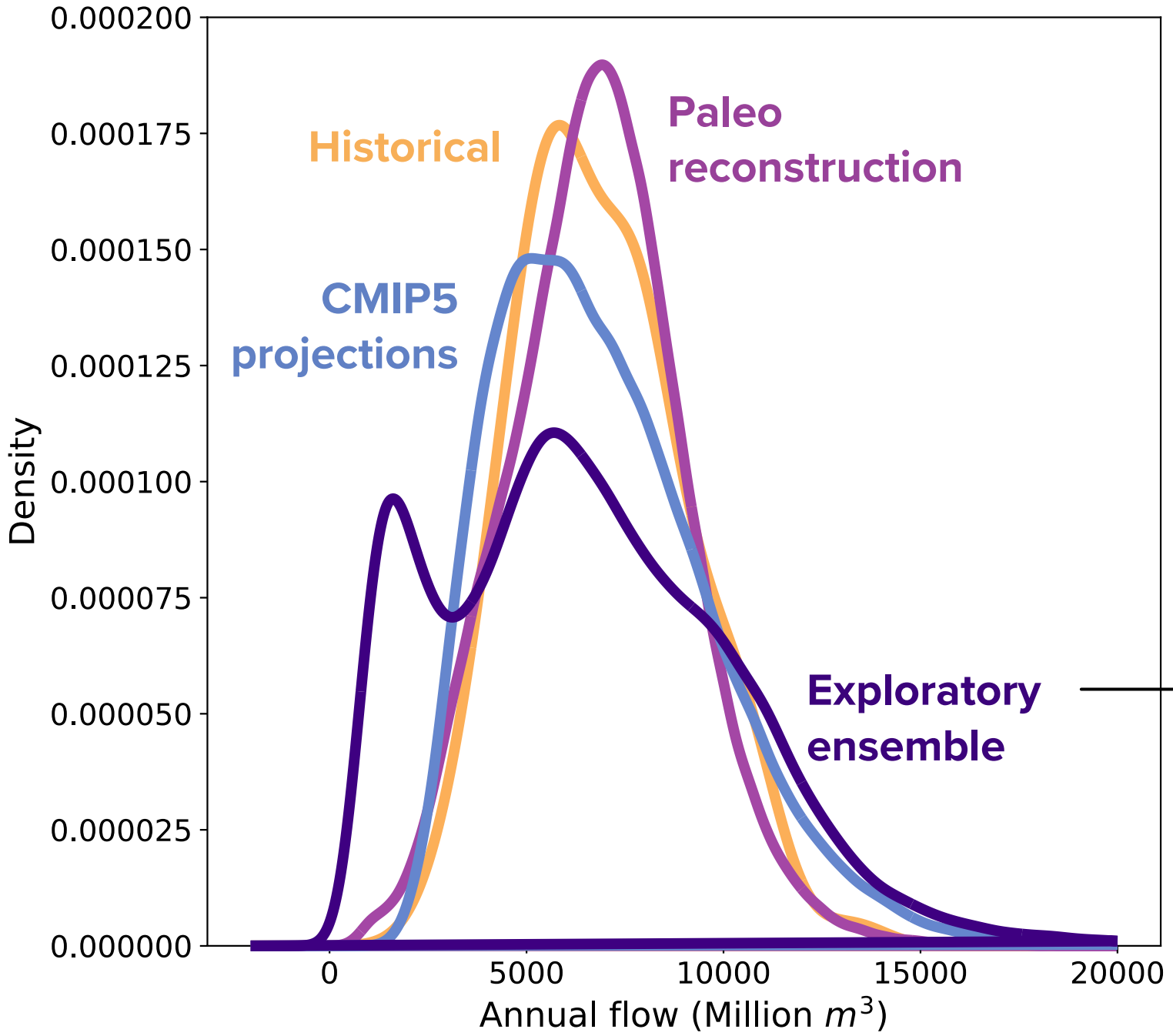
Establishing a **drought threshold** during a **wet** period would mean **more drought years** are classified in the future.

FRamework for Narrative Scenarios and Impact Classification (FRNSIC)



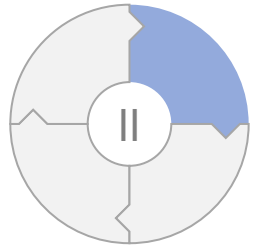
Consider **broad range** of plausible drought futures

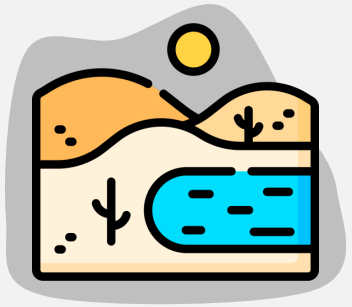
Explore effects of both how **internal variability** and **changing properties**



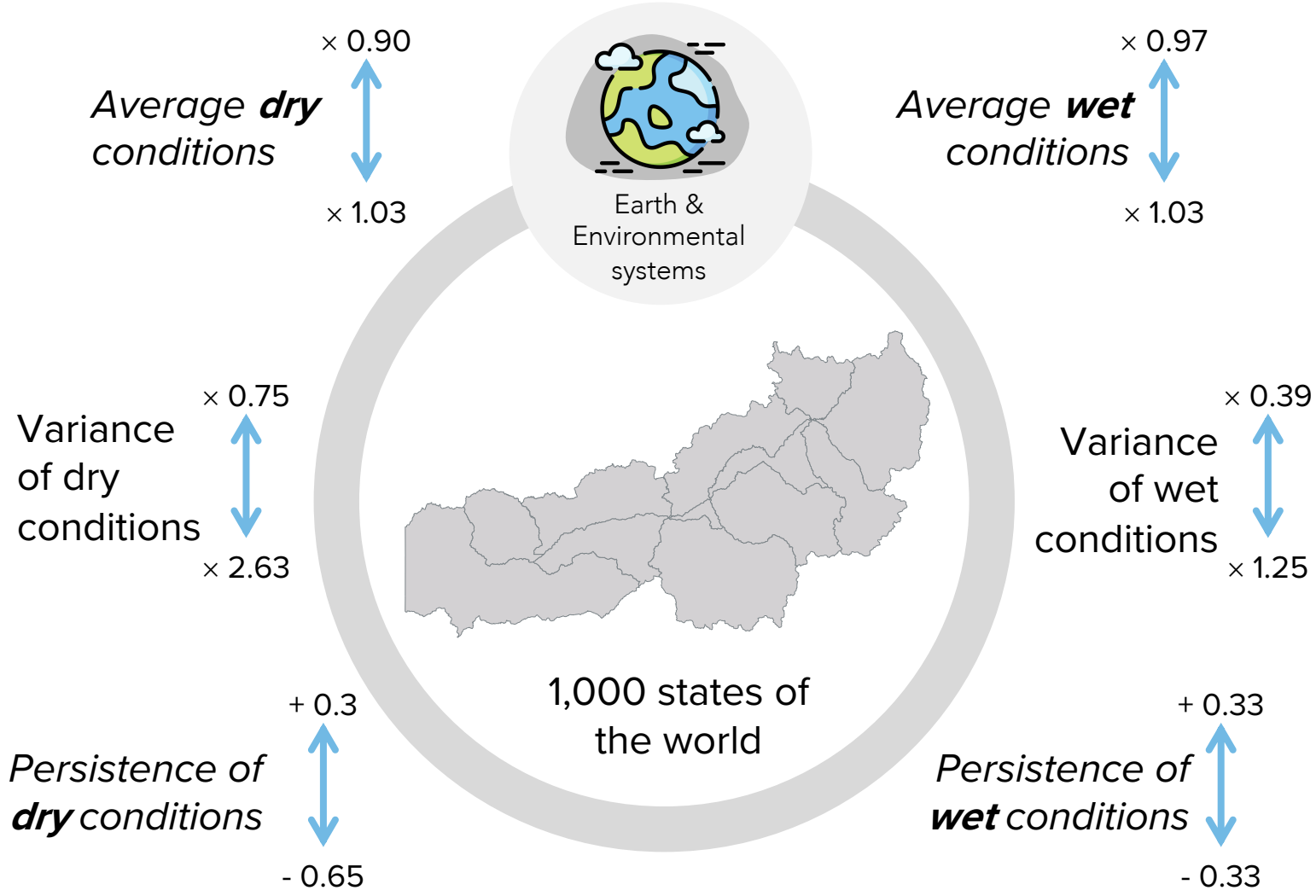
Intentionally enveloping history and projections

Statistically varying dry and wet properties of streamflow



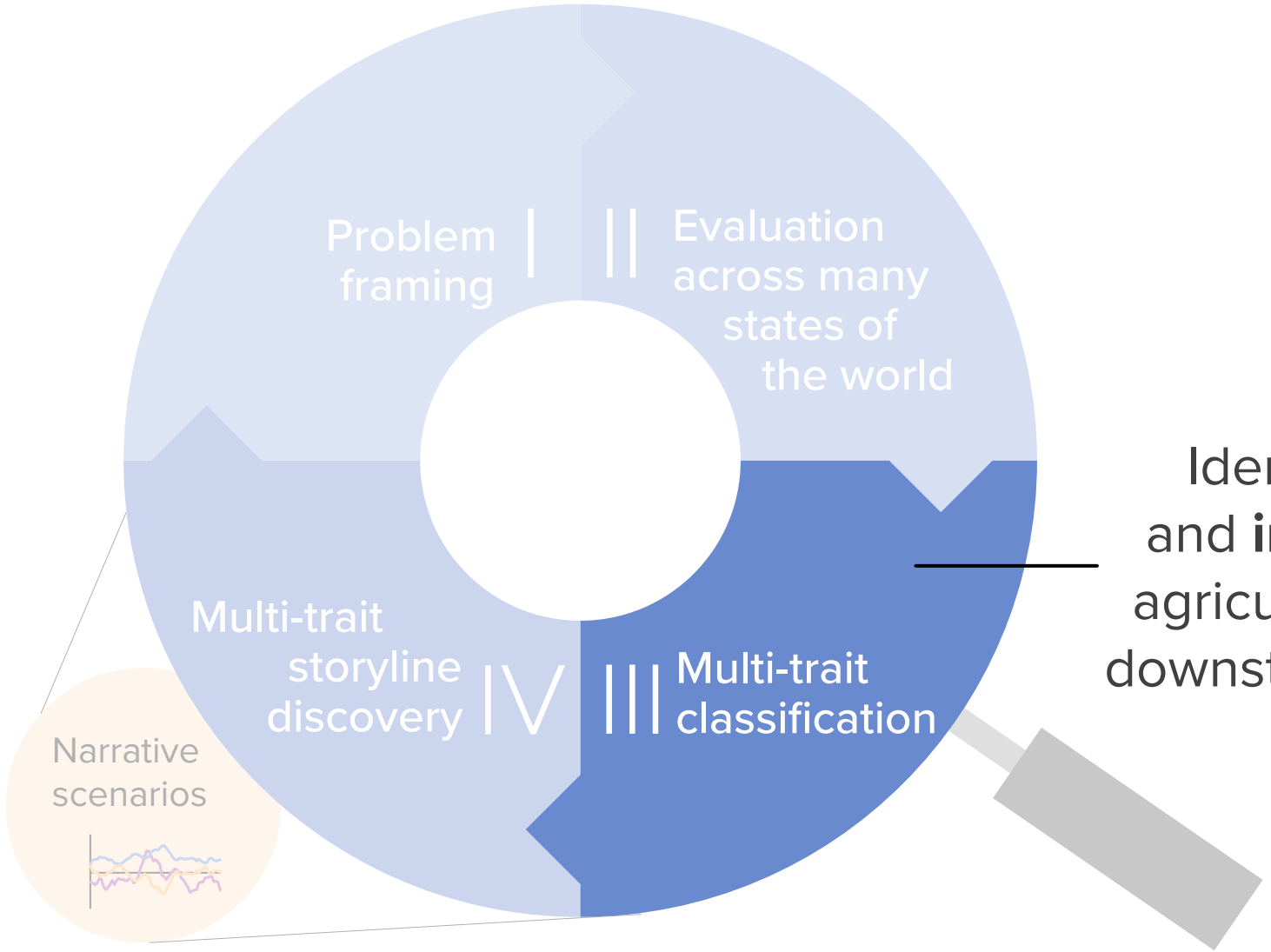


Streamflow properties under **dry** conditions



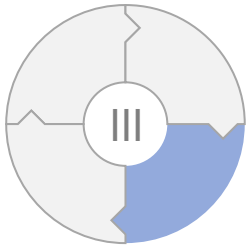
Streamflow properties under **wet** conditions

FRamework for Narrative Scenarios and Impact Classification (FRNSIC)



Identify key **drivers** and **impacts** on local agricultural users and downstream deliveries

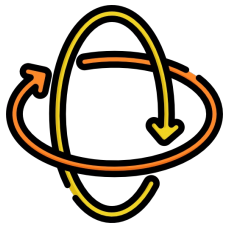
Classify temporal dynamics of each SOW



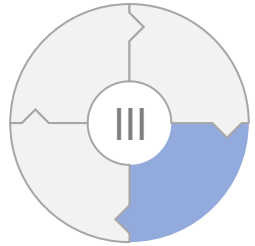
SOWs with the same **variability** in dry conditions as historical experience

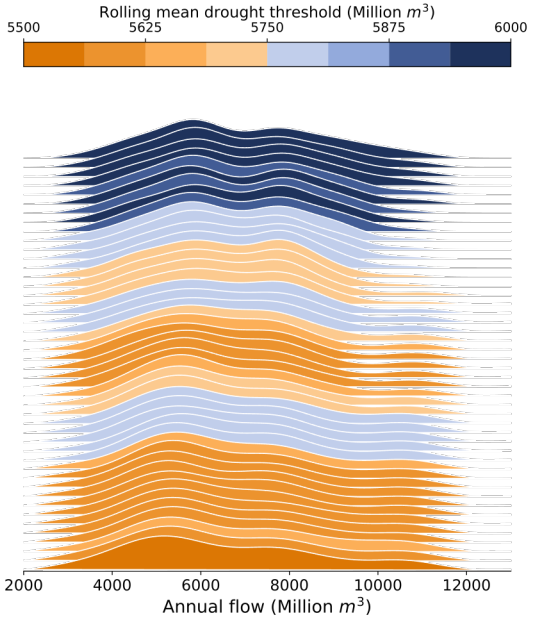
SOWs with the same **average** dry conditions as historical experience

SOWs with as many **drought years** as historical experience



Classify temporal dynamics of each SOW





Variance

$$VS = \{s_{i,j} \in S | 0.76 \leq \sigma_{d_i} \leq 1.38\}$$

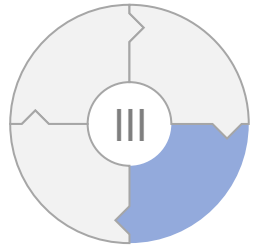
Average

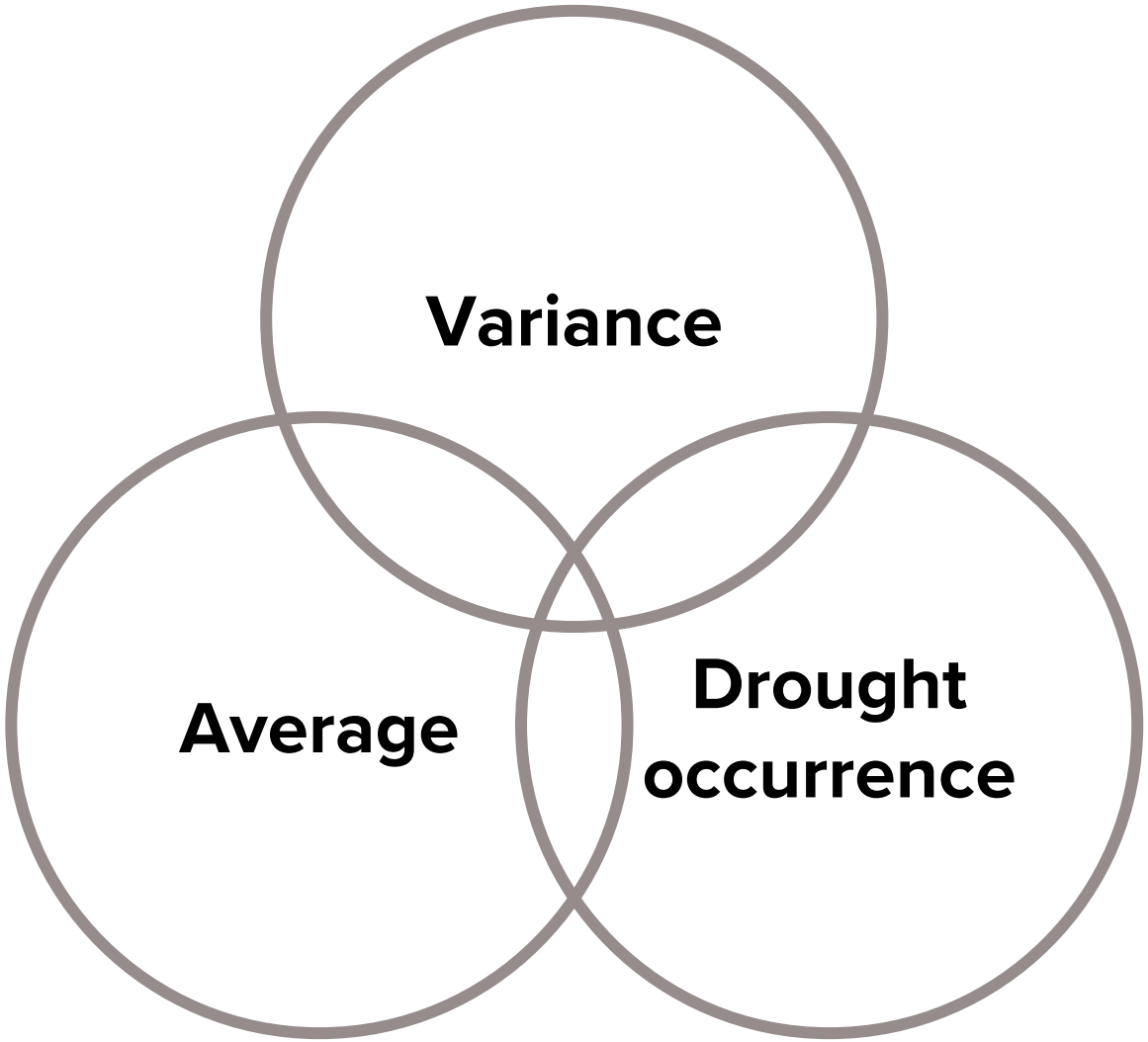
$$MS = \{s_{i,j} \in S | 0.99 \leq \mu_{d_i} \leq 1.01\}$$

Drought occurrence

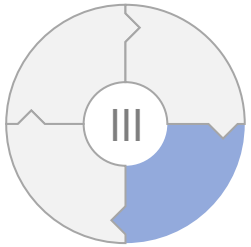
$$DS = \{s_{i,j} \in S | d_{i,j} \leq 30\}$$

Classify temporal dynamics of each SOW

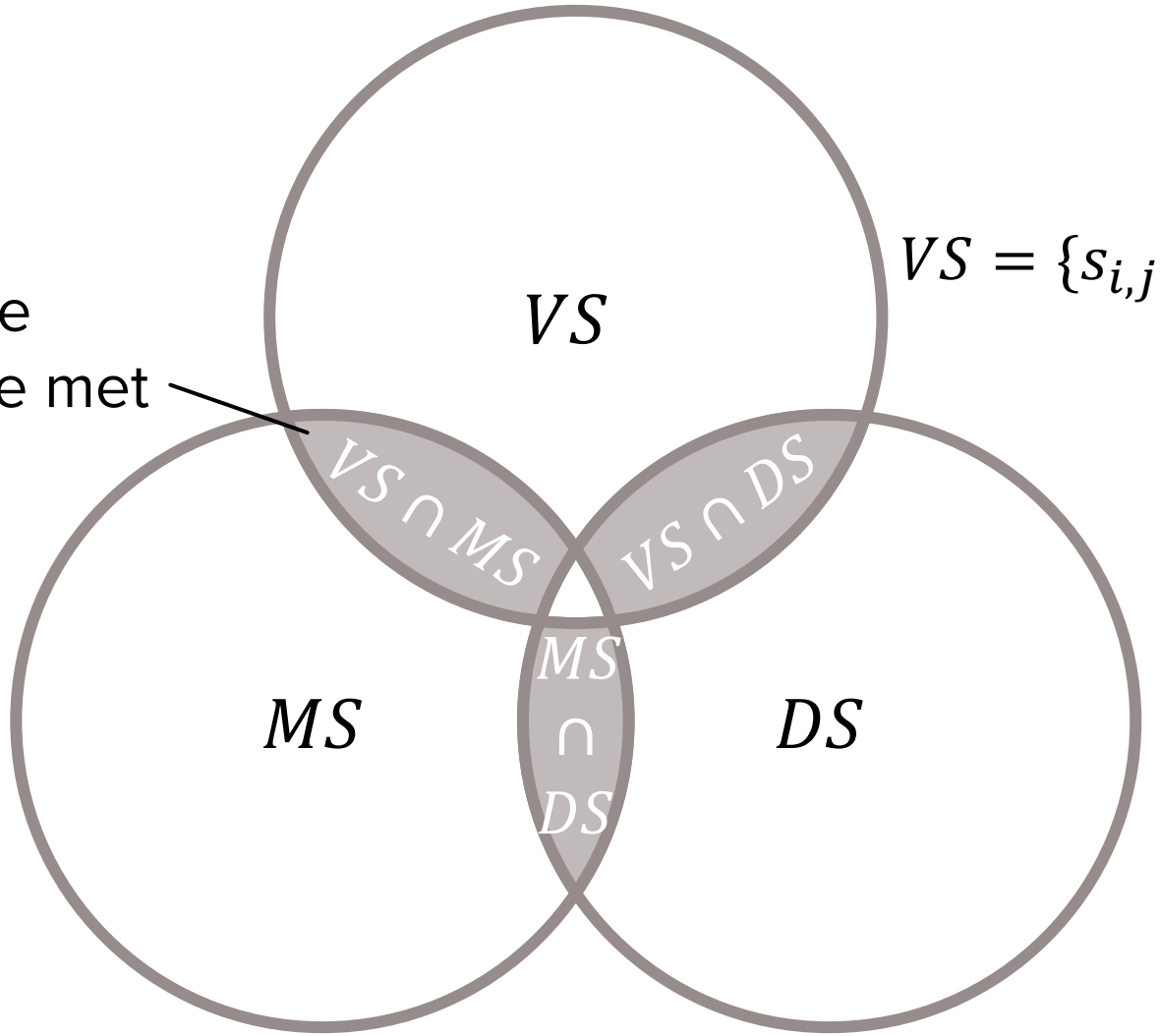




Classify temporal dynamics of each SOW



Overlap sets where both conditions are met



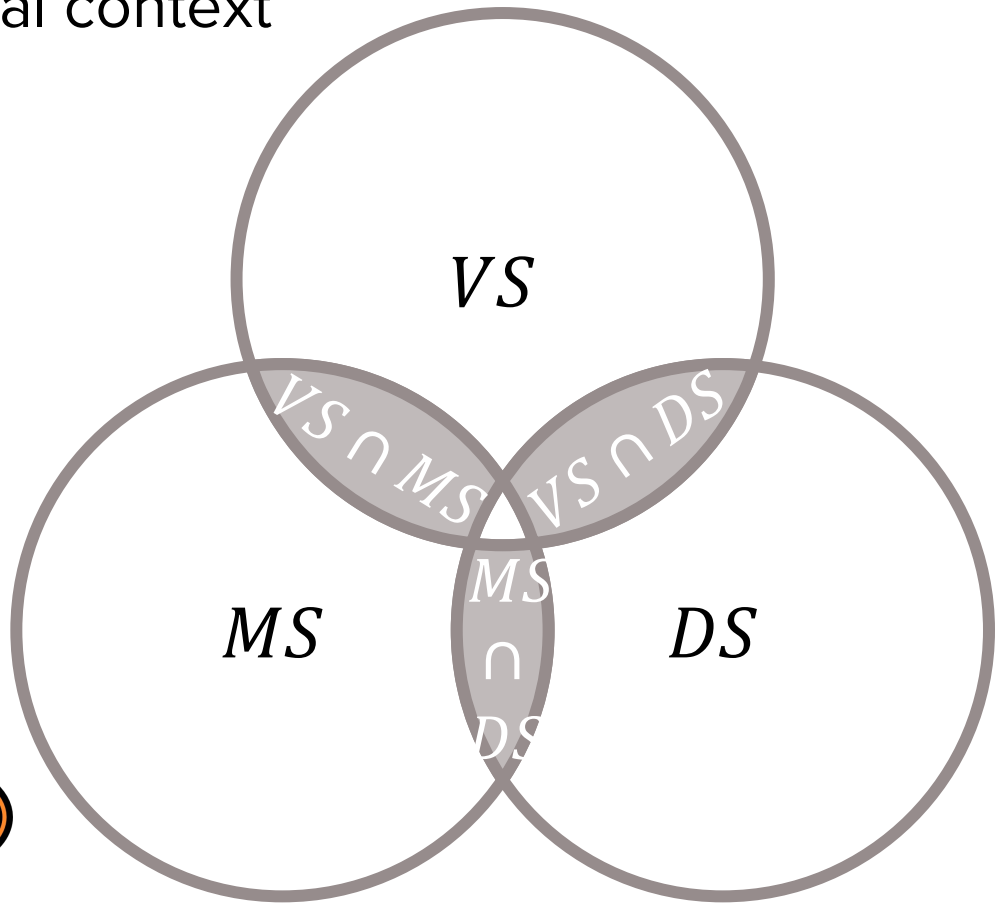
$$VS = \{s_{i,j} \in S | 0.76 \leq \sigma_{d_i} \leq 1.38\}$$

$$MS = \{s_{i,j} \in S | 0.99 \leq \mu_{d_i} \leq 1.01\}$$

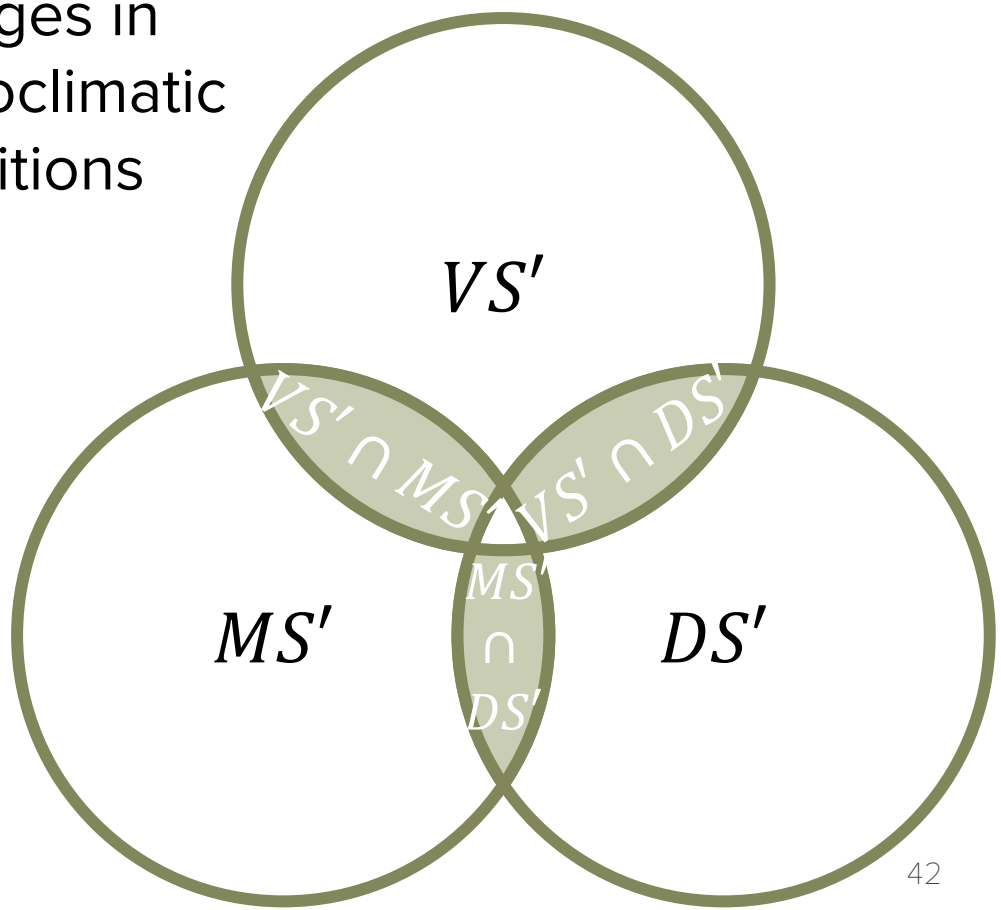
$$DS = \{s_{i,j} \in S | d_{i,j} \leq 30\}$$

Classify temporal dynamics of each SOW

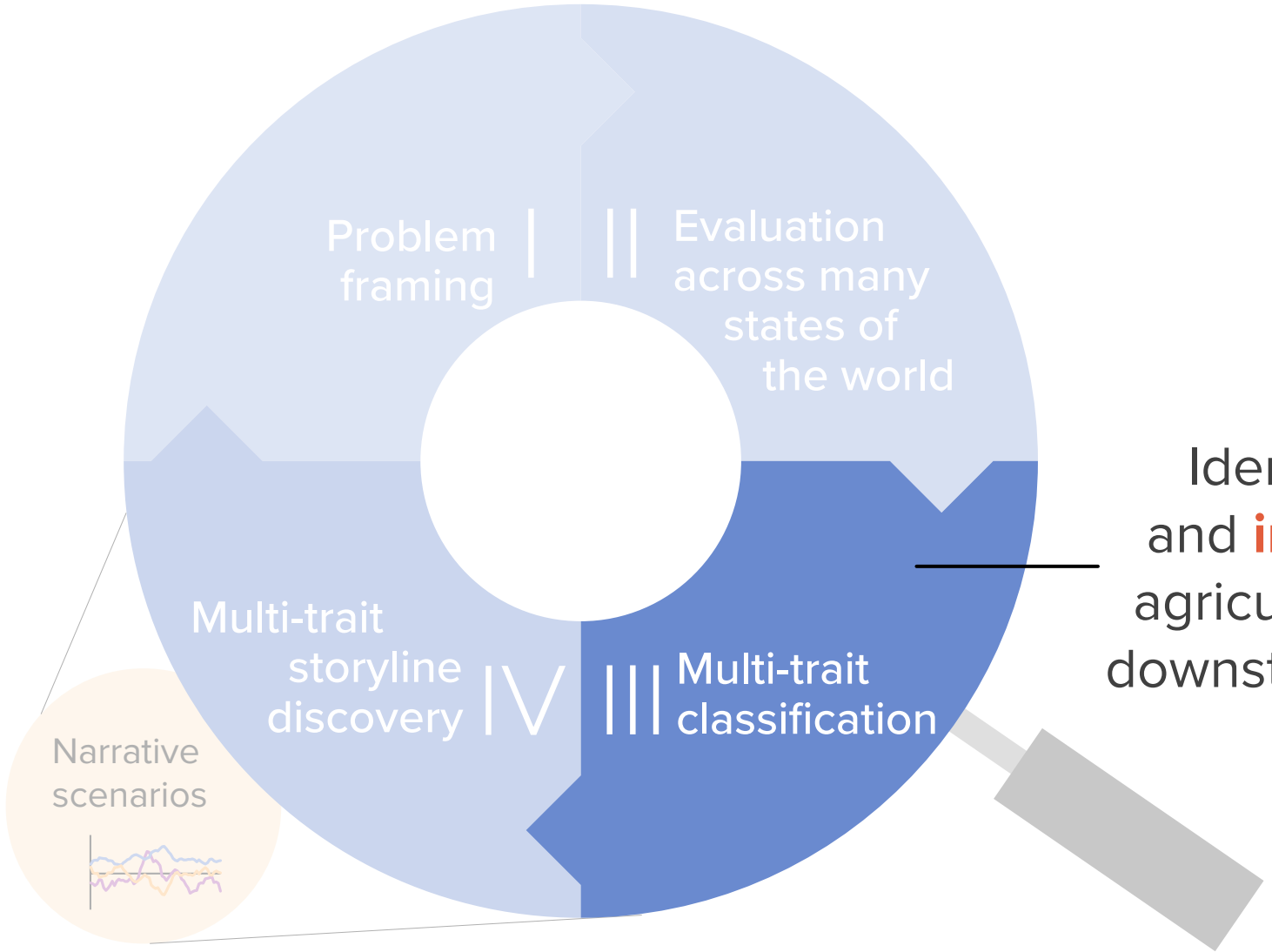
SOWs within the experienced historical context



SOWs with plausible changes in hydroclimatic conditions

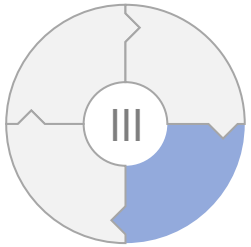


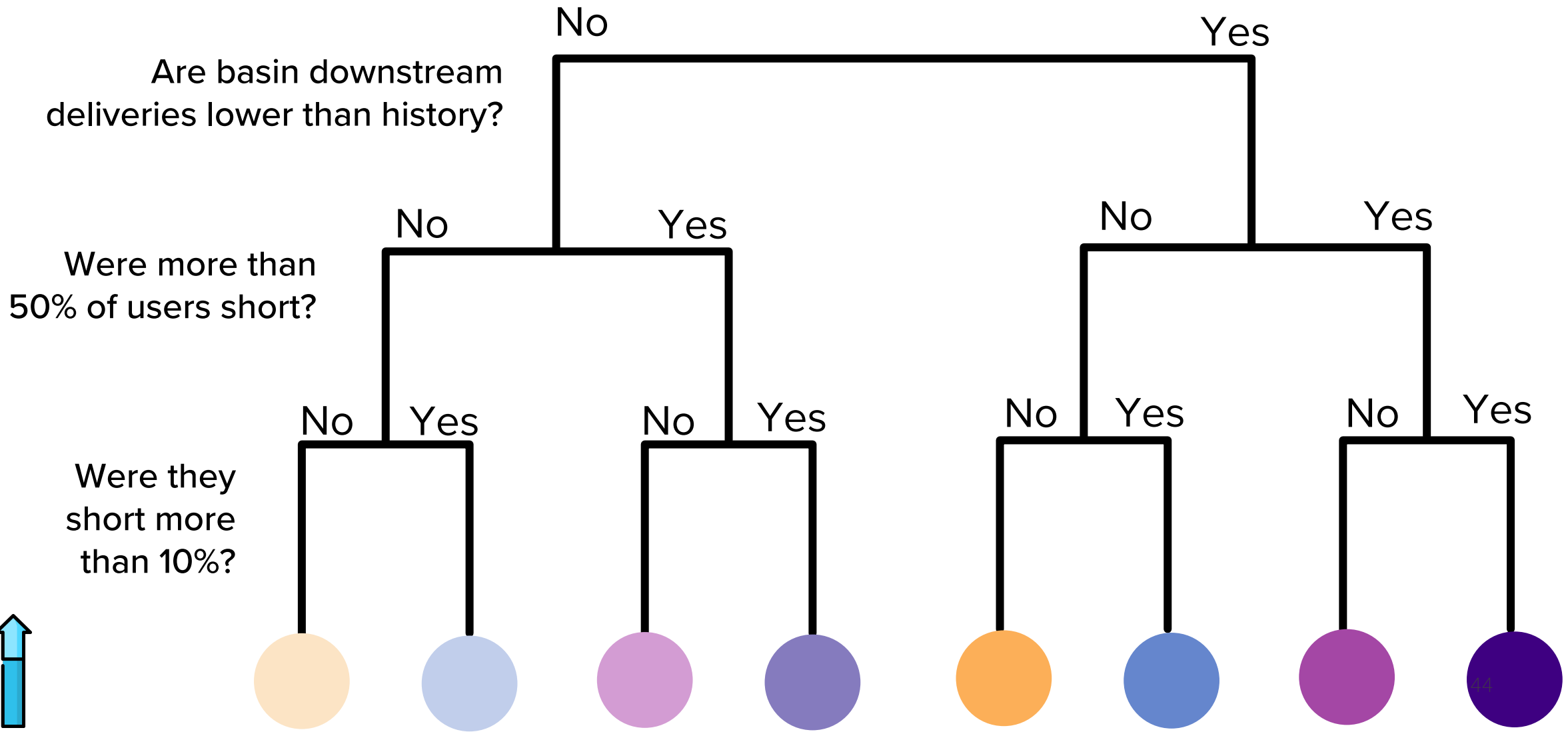
FRamework for Narrative Scenarios and Impact Classification (FRNSIC)



Identify key **drivers** and **impacts** on local agricultural users and downstream deliveries

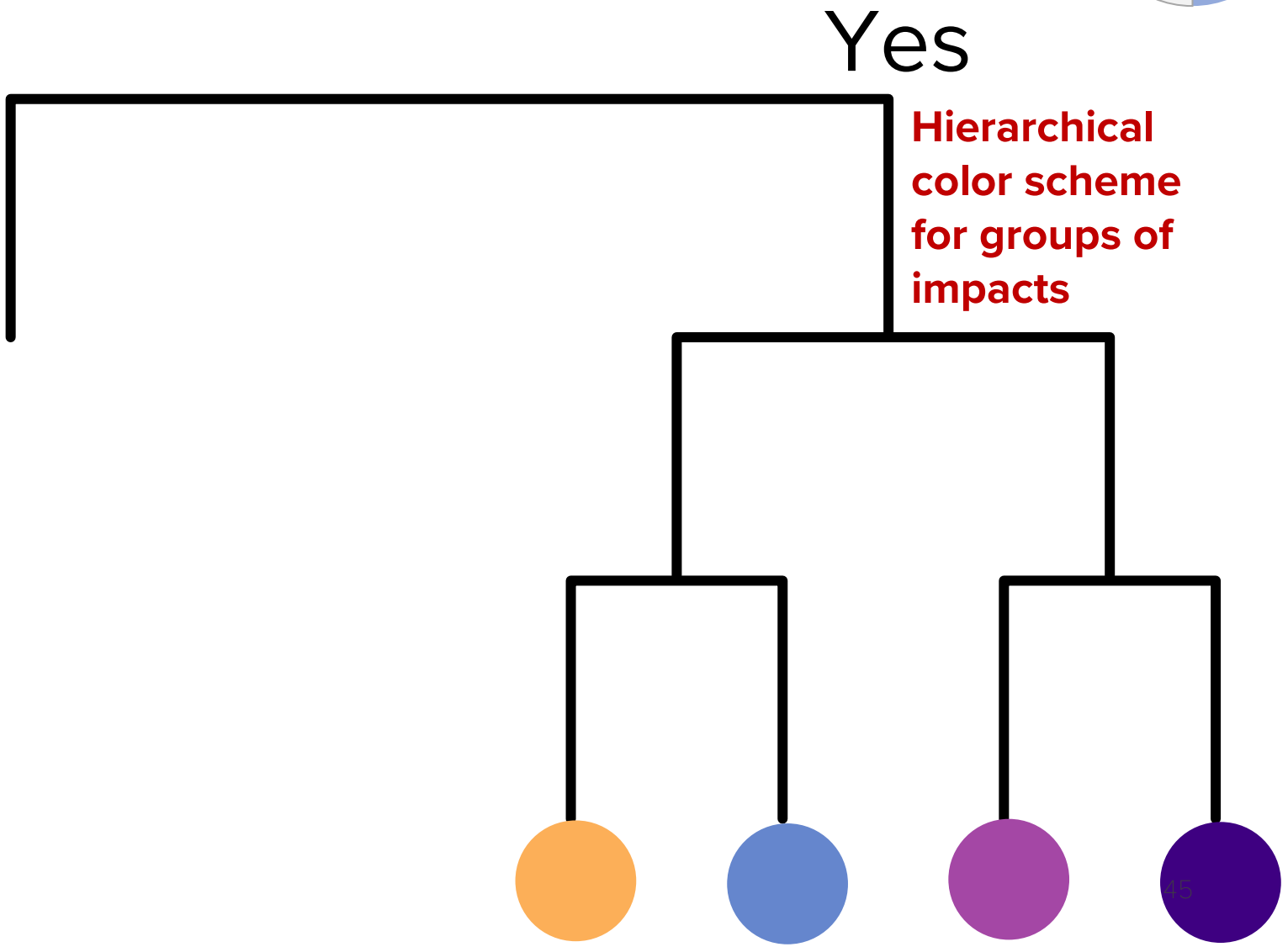
Classify impacts of each SOW



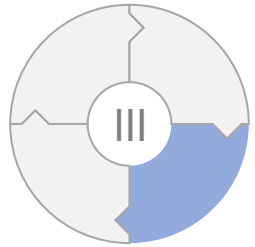


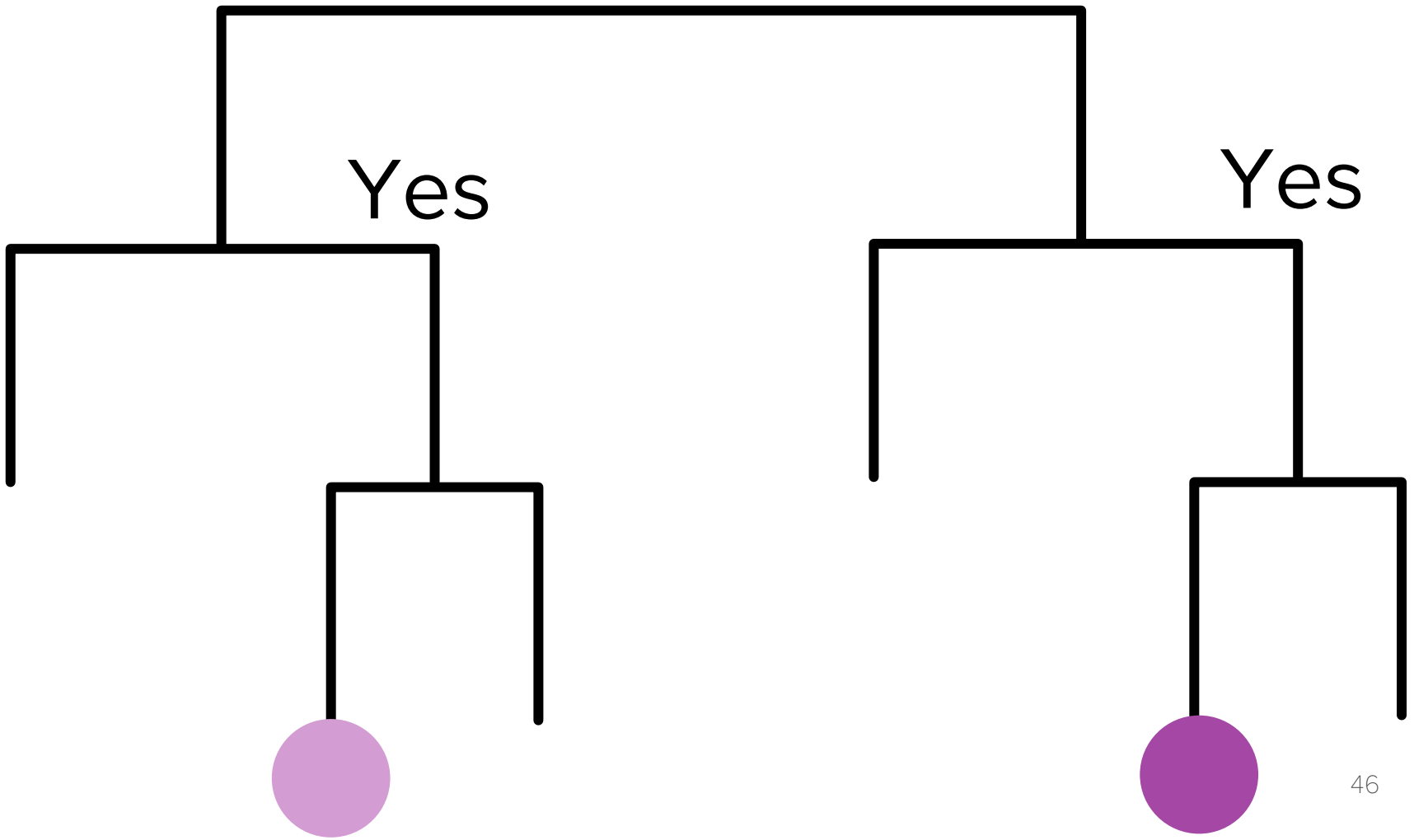
Classify impacts of each SOW

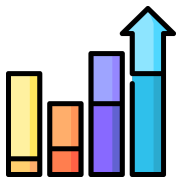
Are basin downstream deliveries lower than history?



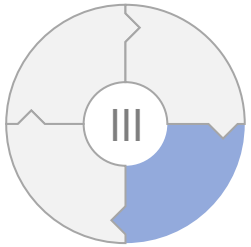
Classify impacts of each SOW

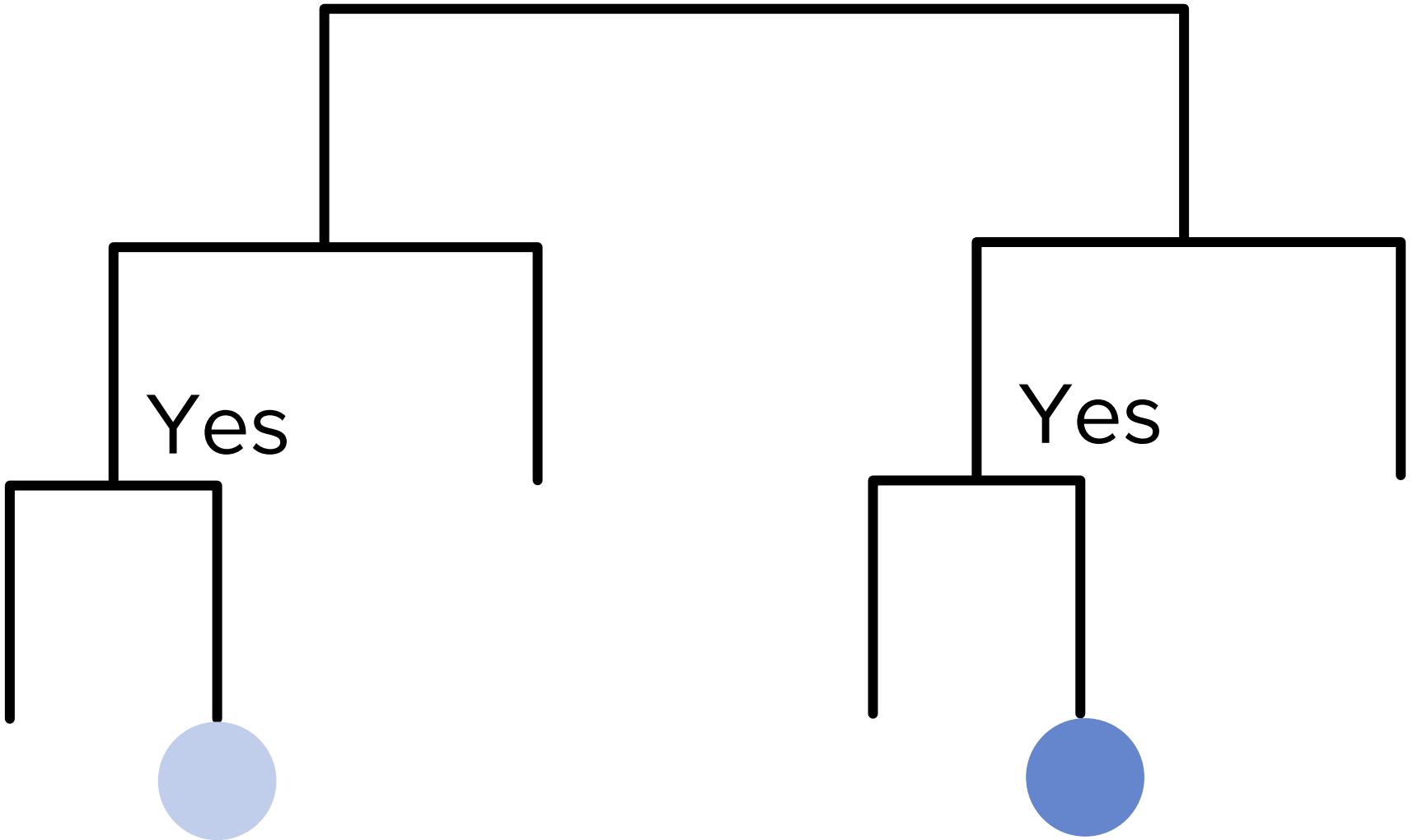


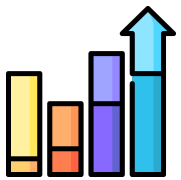




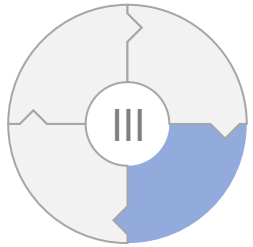
Classify impacts of each SOW

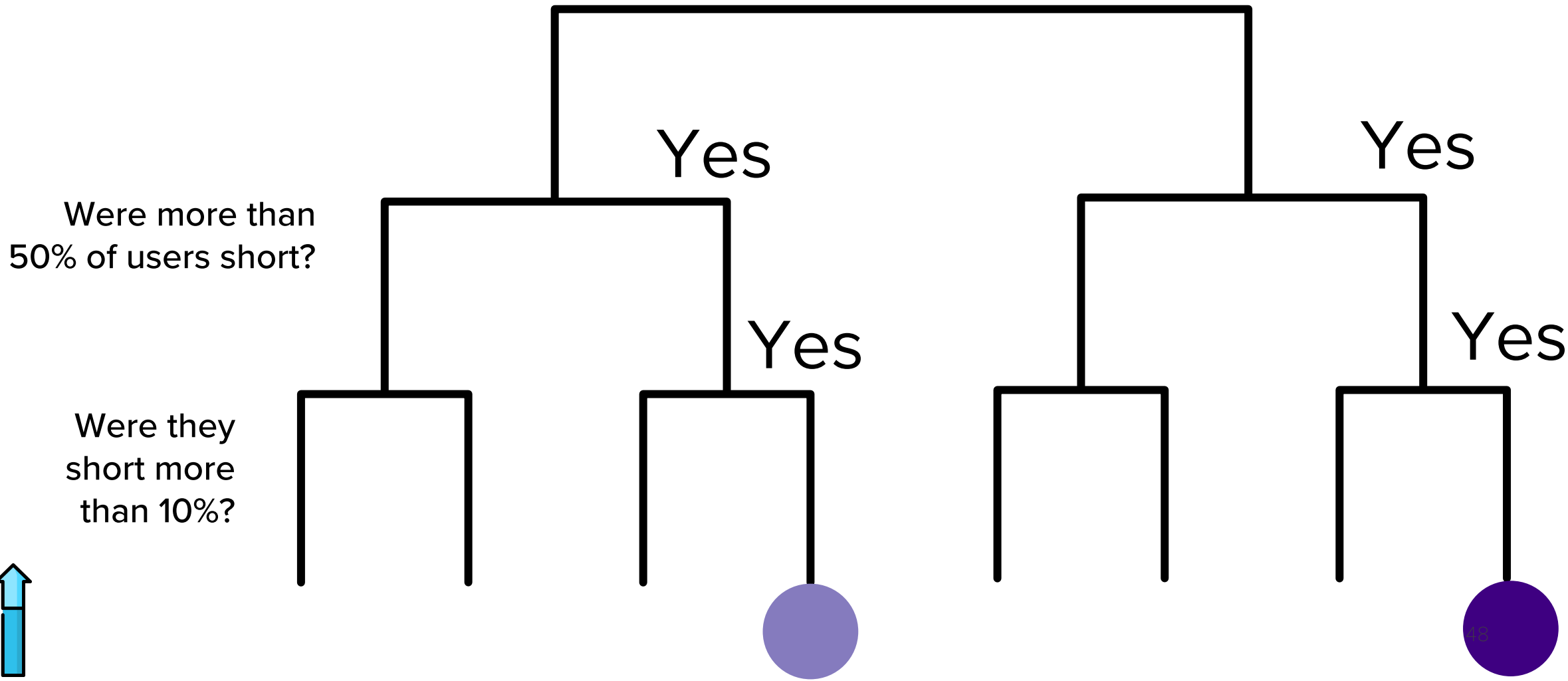


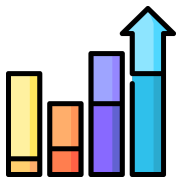




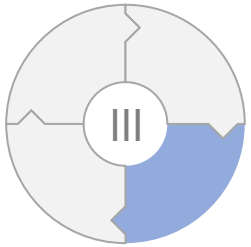
Classify impacts of each SOW

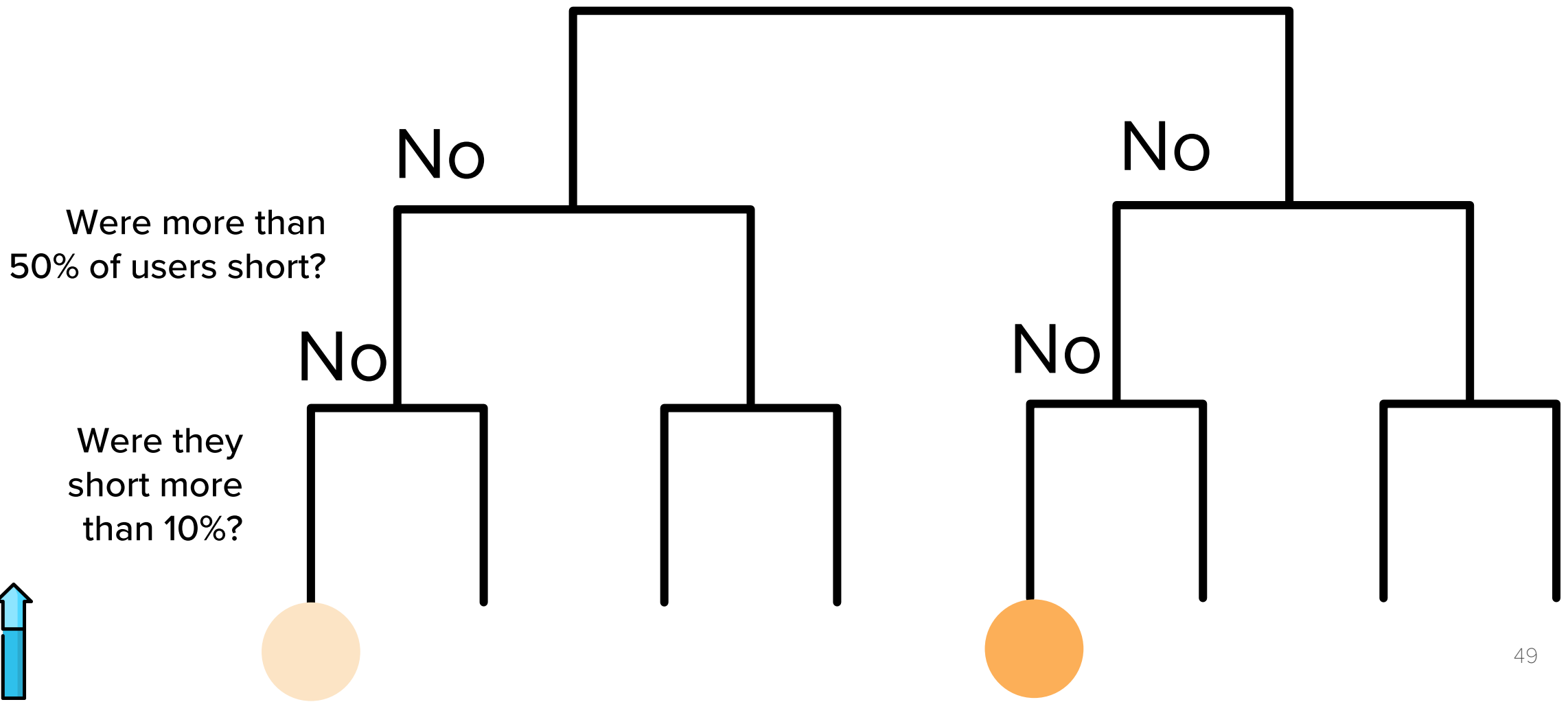


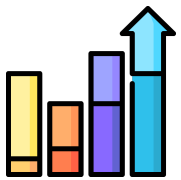




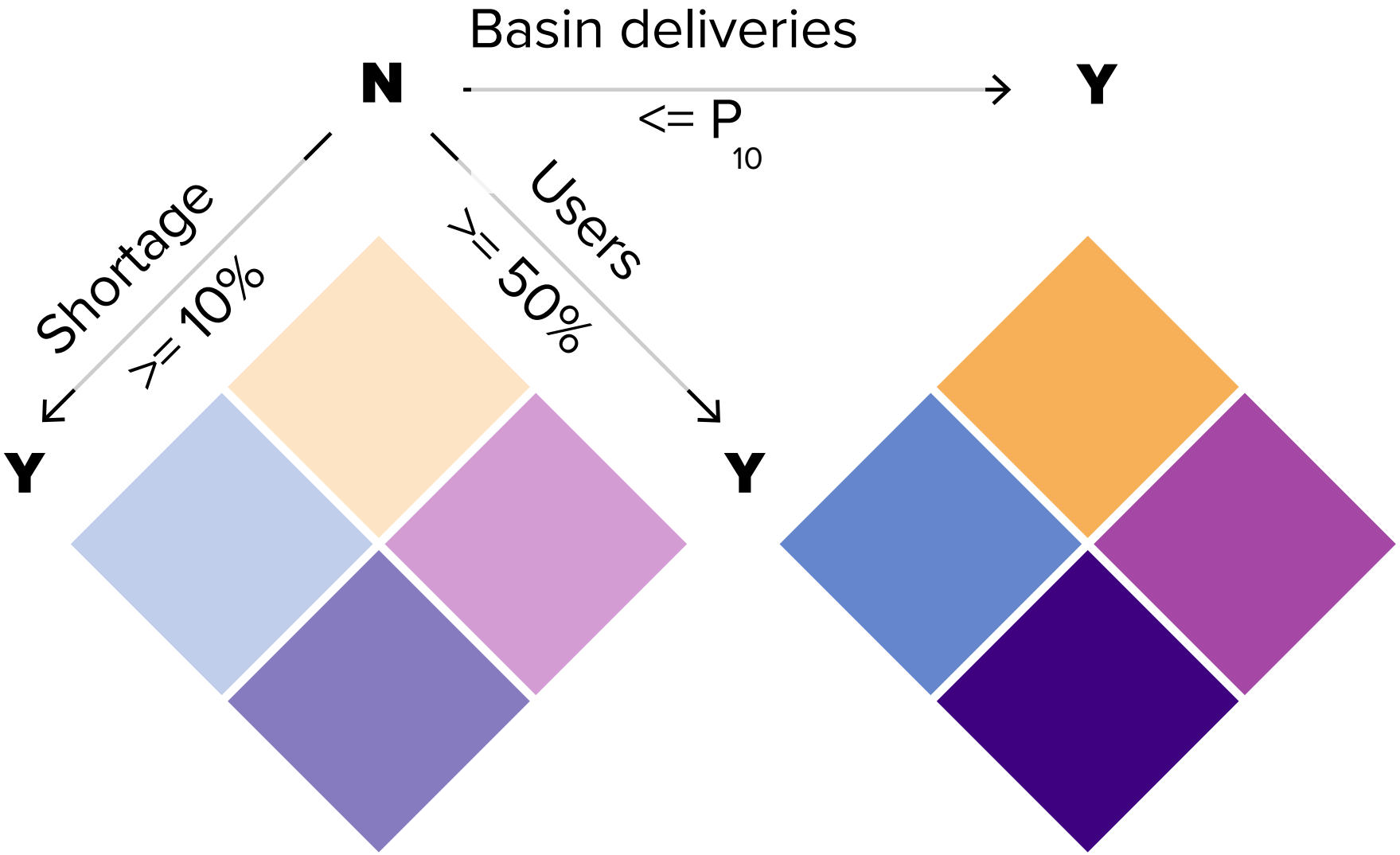
Classify impacts of each SOW





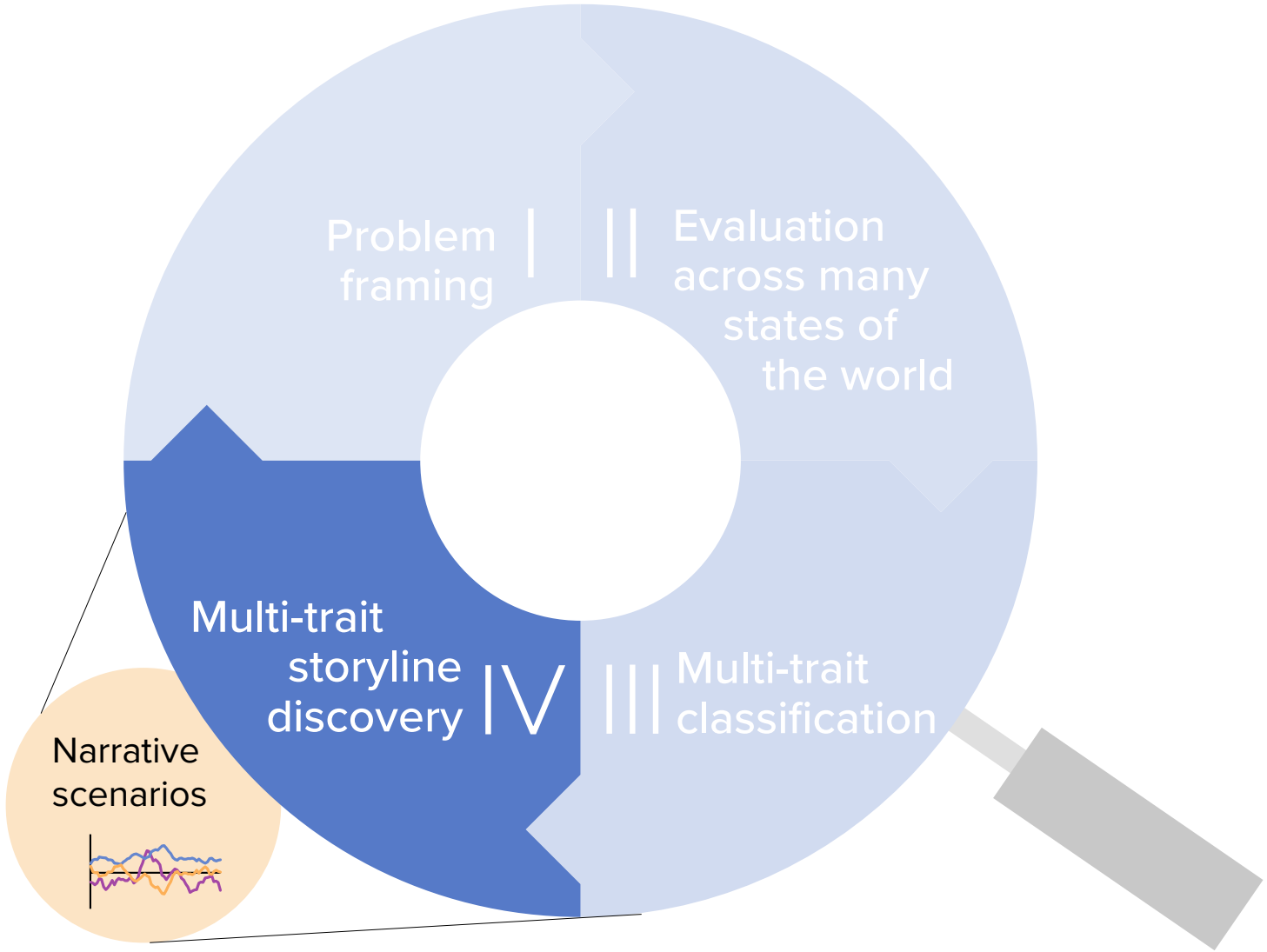


Classify impacts of each SOW

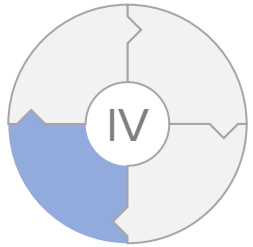


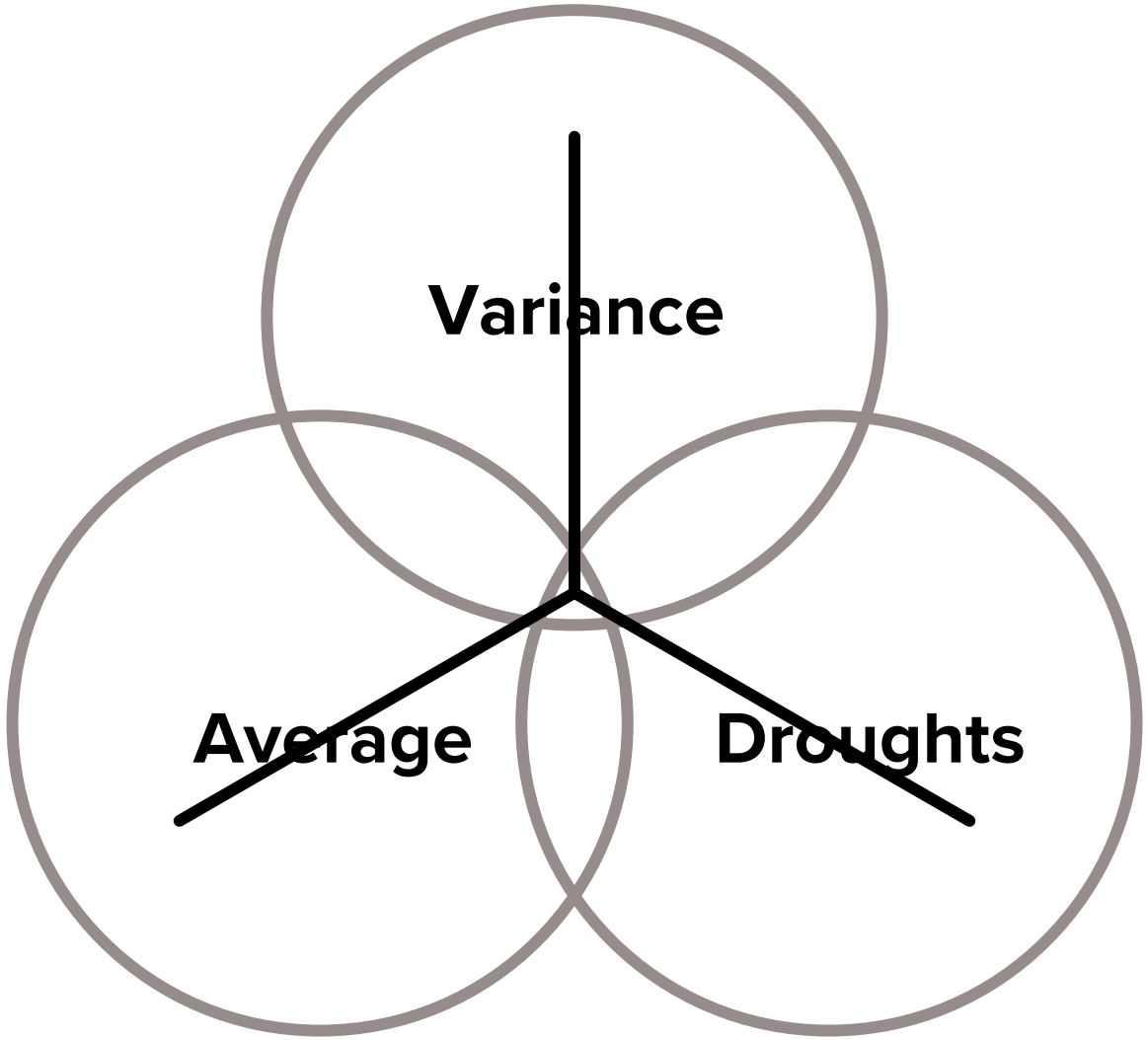
FRamework for Narrative Scenarios and Impact Classification (FRNSIC)

Identification of **narrative scenarios** of dynamic states and impacts

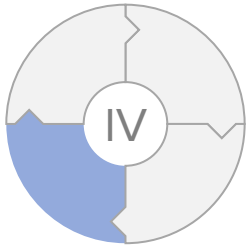


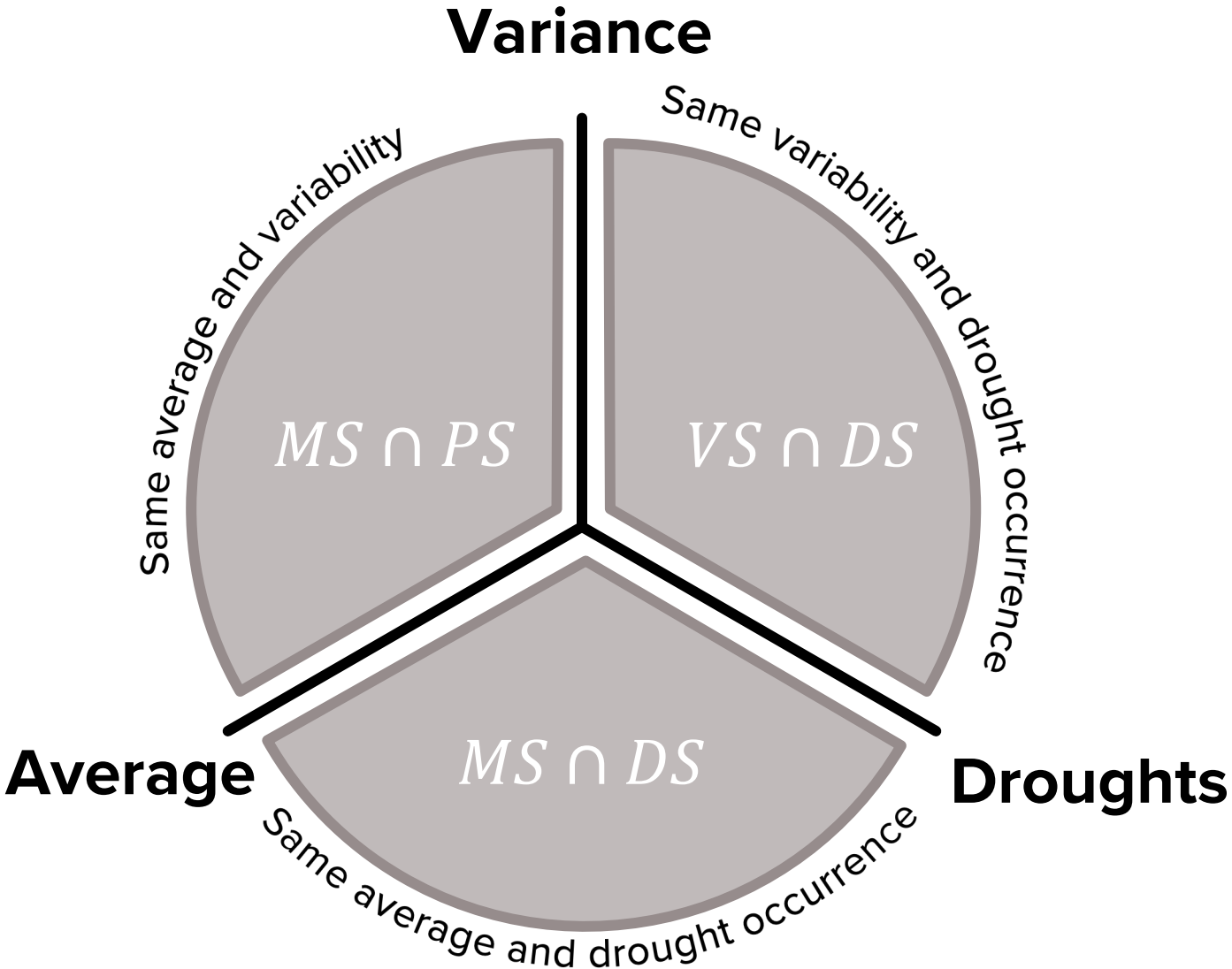
Combining both to identify narrative storylines



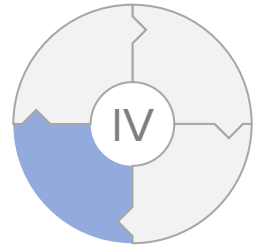


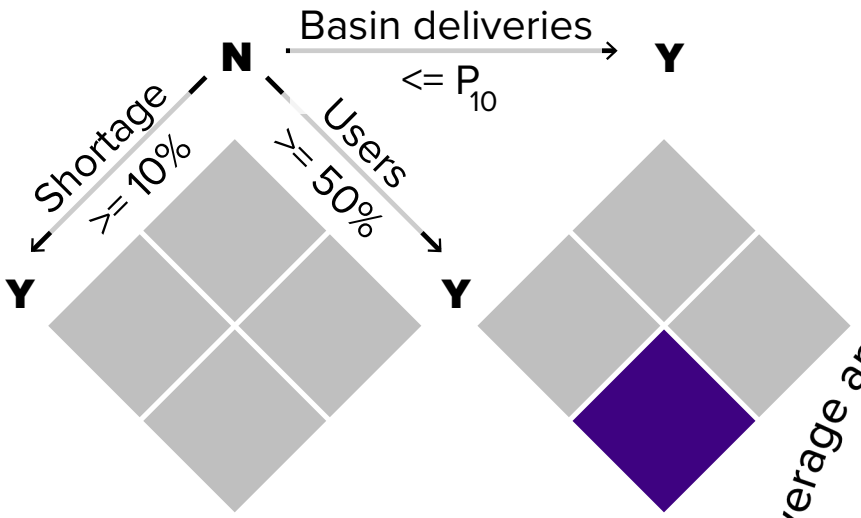
Combining both to identify narrative storylines



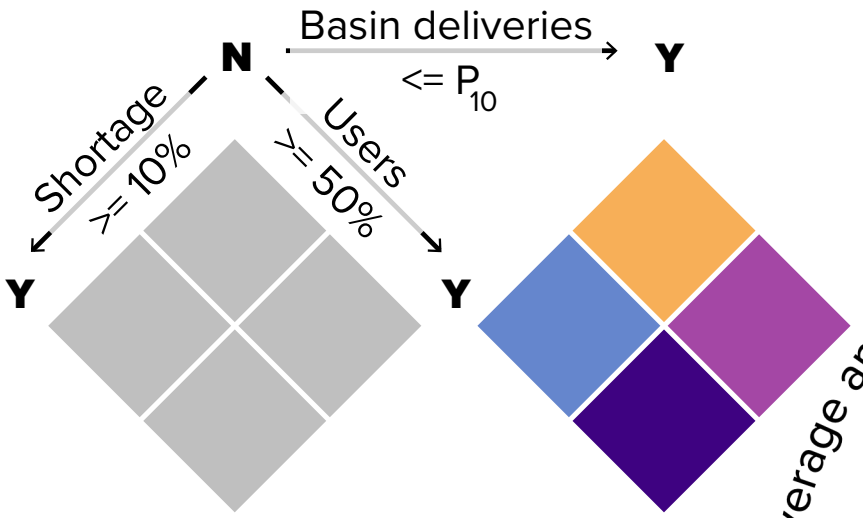


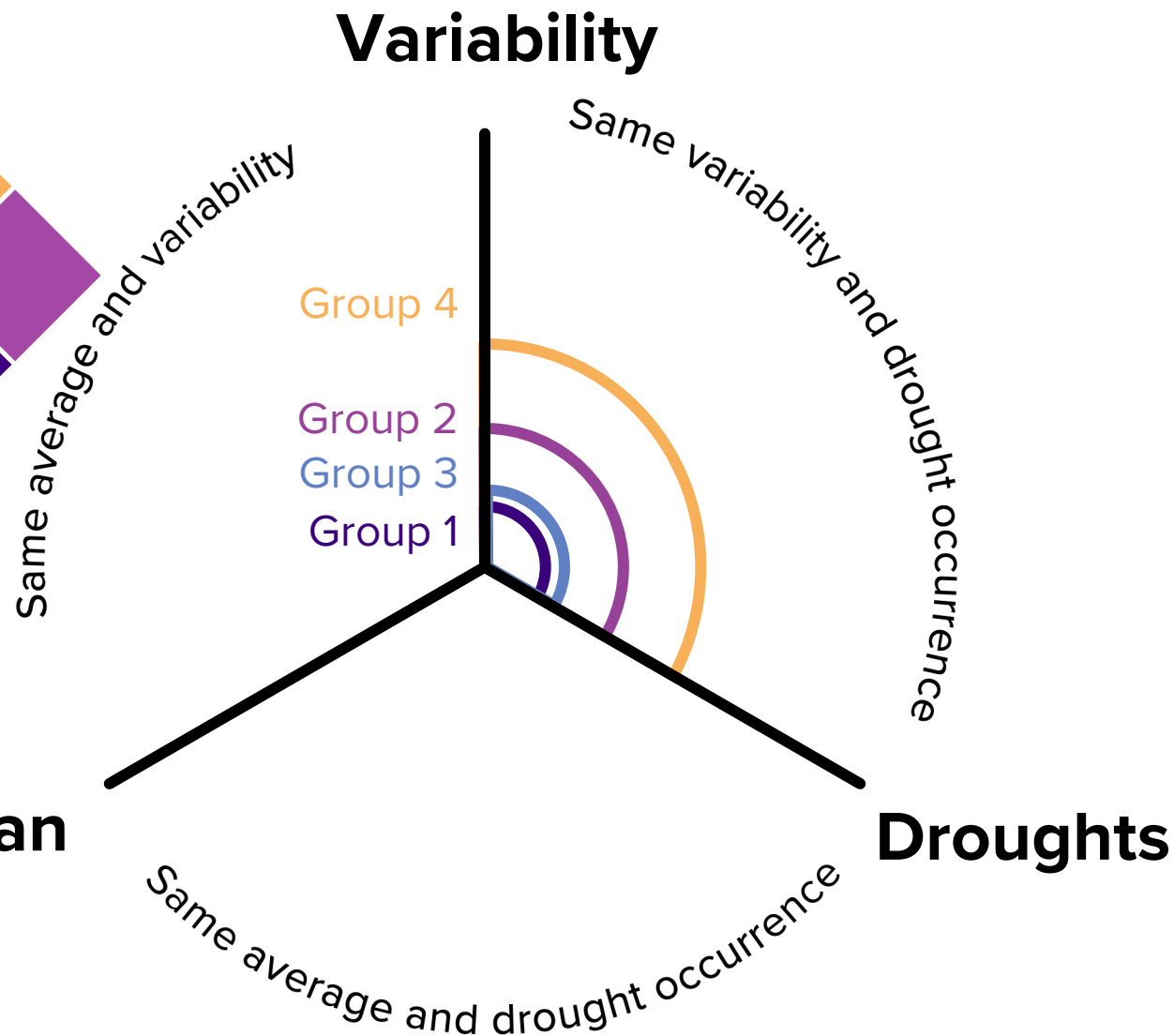
Combining both to identify narrative storylines



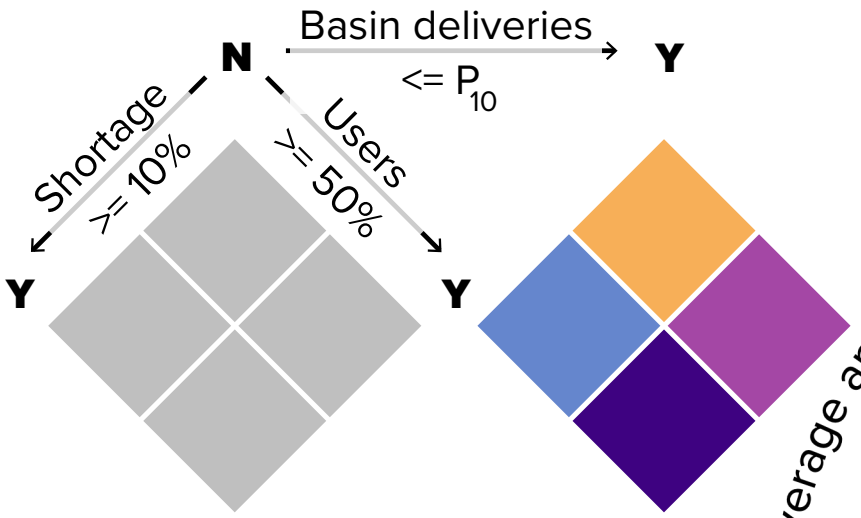


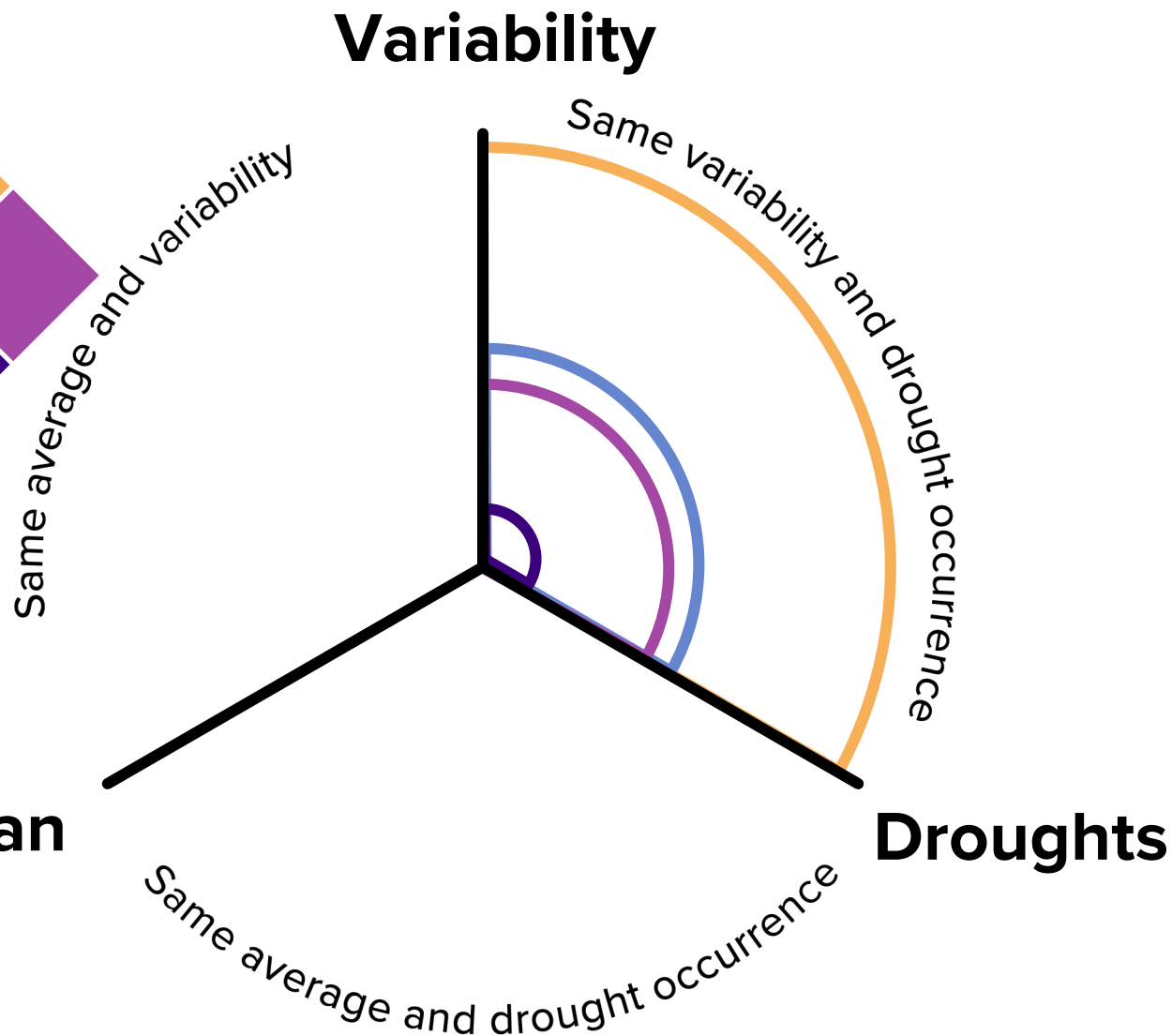
Summarizing changes in Impacts



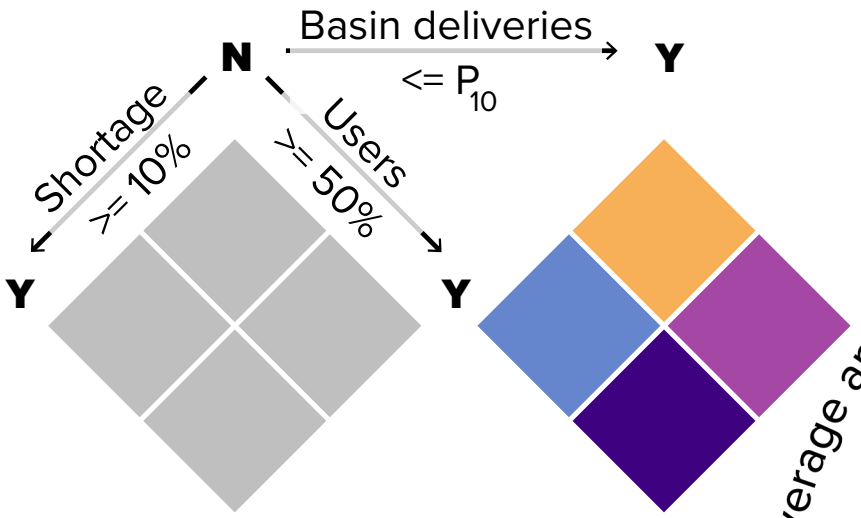


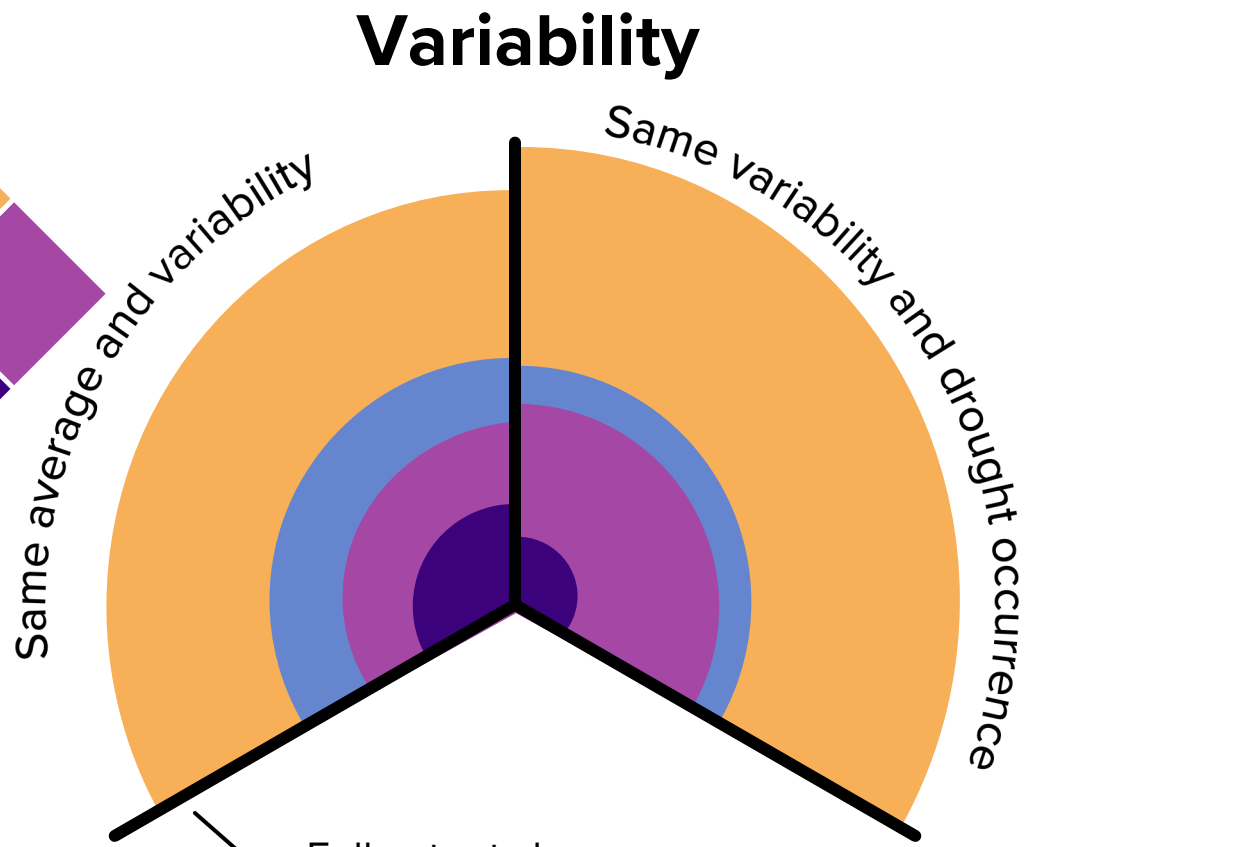
Summarizing changes in Impacts





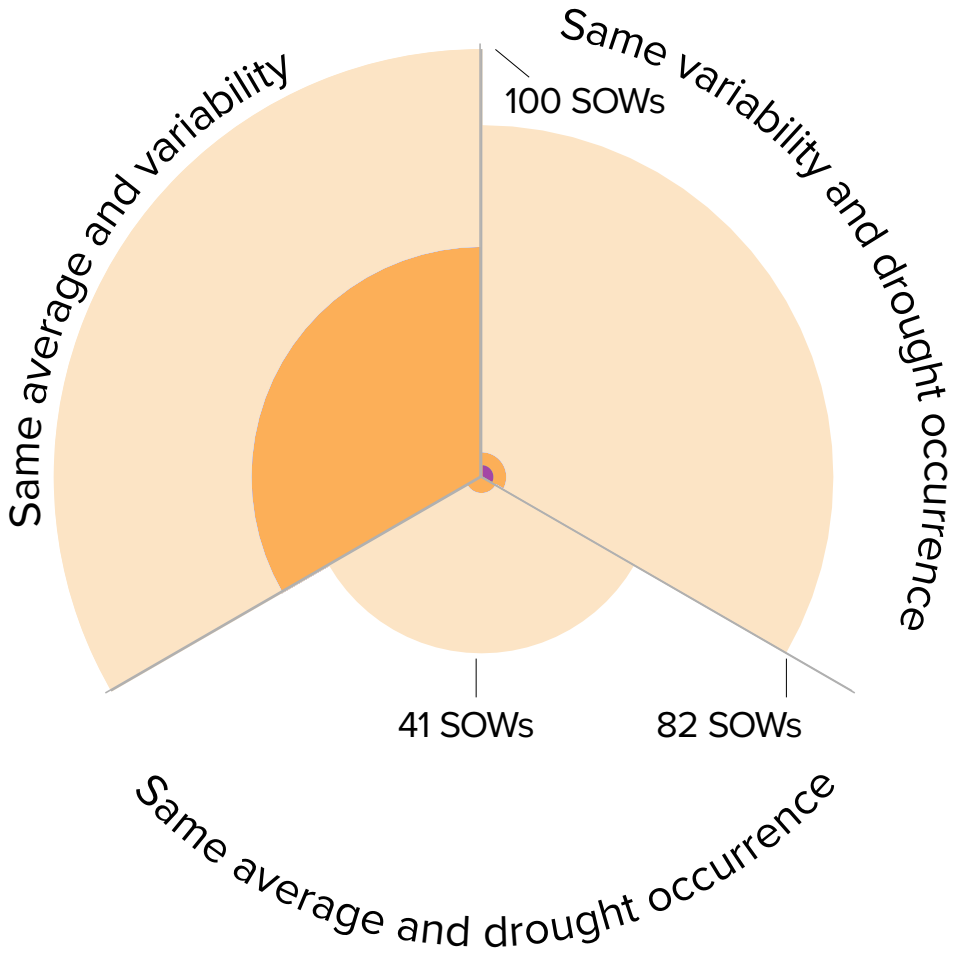
Summarizing changes in Impacts





Implications for UCRB

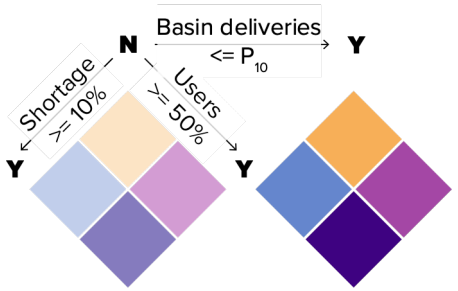
SOWs within the experienced historical context

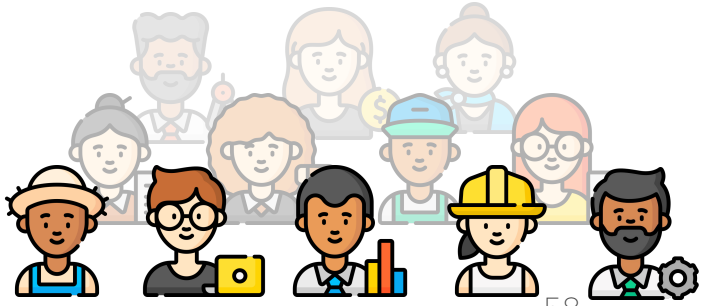


If planners expect future conditions to be like the past

Most SOWs do not meet any of the impact criteria

Some only affect deliveries or an increased number of users





* not actual members of the Colorado Basin Roundtable

Implications for UCRB

SOWs within the experienced historical context

Same average and variability

Same

Same average and drought occurrence

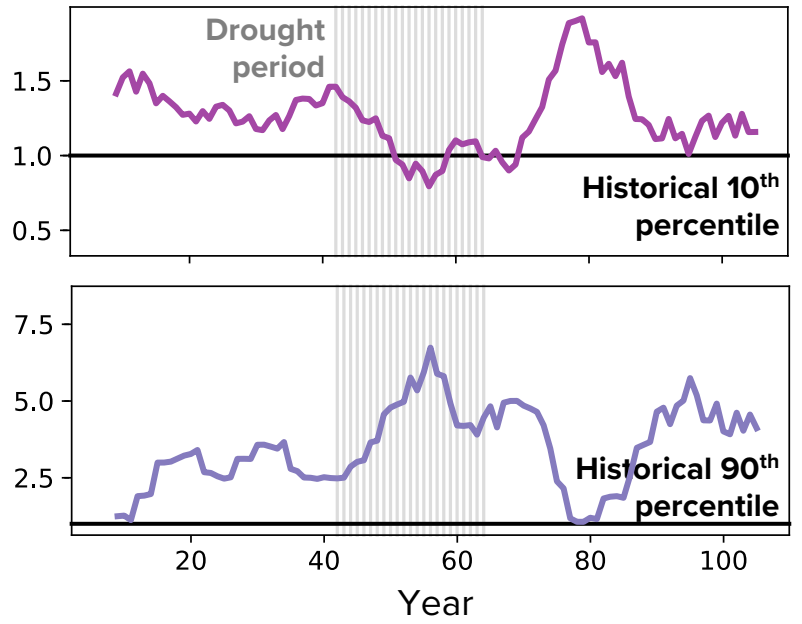
The Unknown Normal

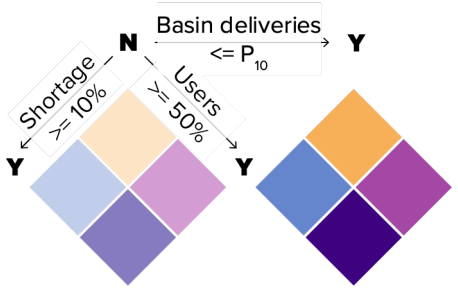
- Downstream **deliveries drop** below historical worst 10
- Basin **shortages accumulate** to over 5 times the historical worst 10

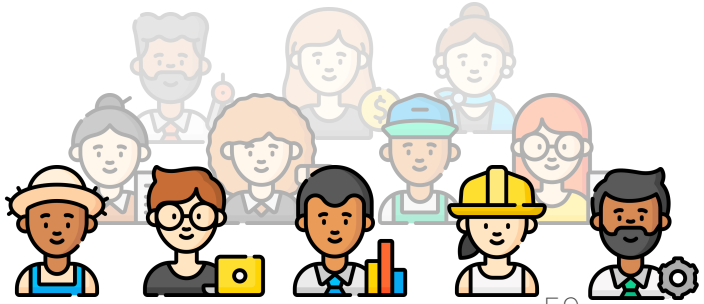
If planners expect future conditions to be like the past

Basin deliveries downstream
(x historical 10th percentile)

Cumulative basin shortages
(x historical 90th percentile)



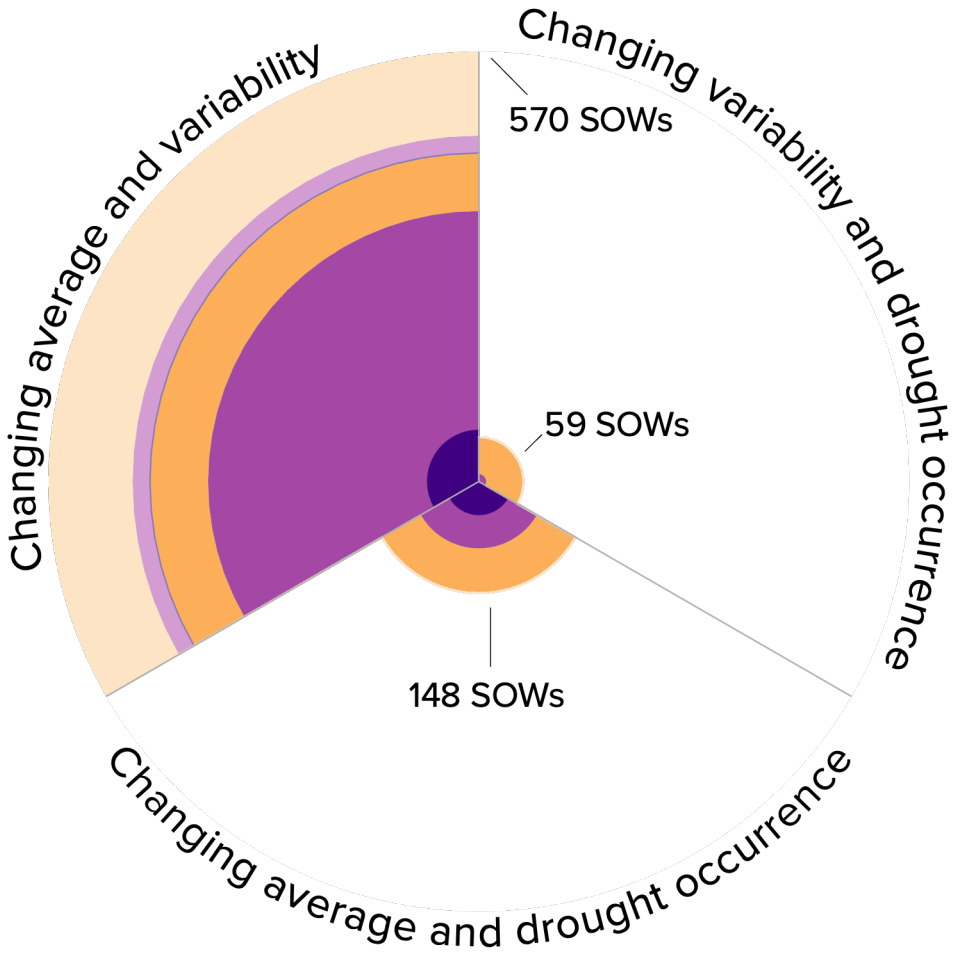




* not actual members of the Colorado Basin Roundtable

Implications for UCRB

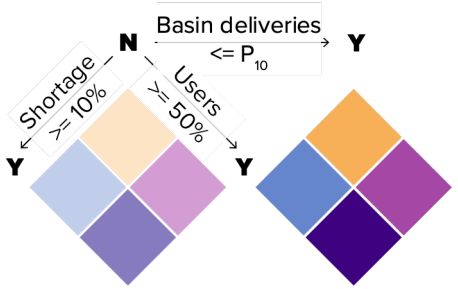
SOWs with plausible changes in hydroclimatic conditions

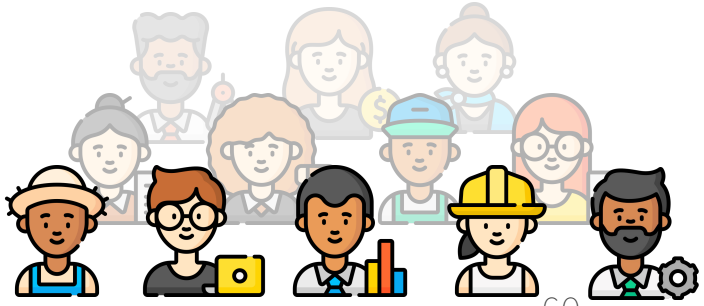


If planners expect future conditions to **change**

A lot more of the SOWs in our ensemble have these dynamic properties

Much more **severe impacts**, including SOWs with impacts in all three groups





* not actual members of the Colorado Basin Roundtable

Implications for UCRB

SOWs with plausible changes in hydroclimatic conditions

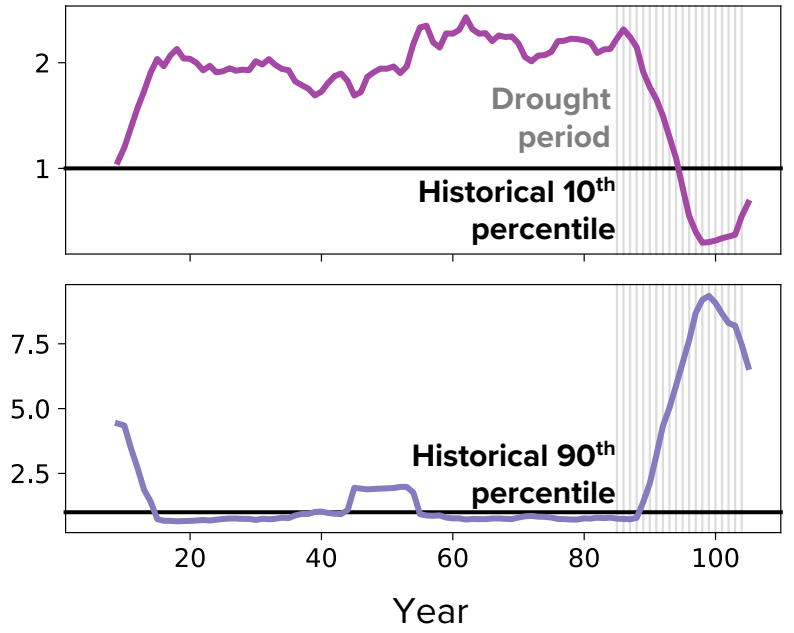
If planners expect future conditions to **change**

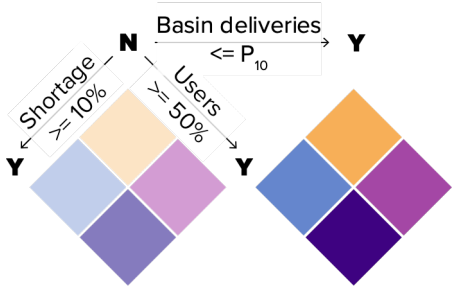
The Unforeseen Struggles:

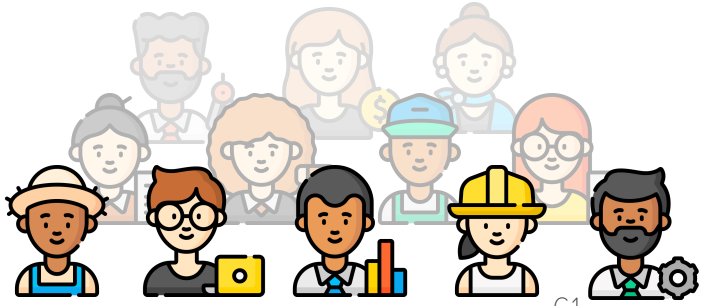
Similar but exacerbated impacts to deliveries and local shortages

Basin deliveries downstream *(x historical 10th percentile)*

Cumulative basin shortages *(x historical 90th percentile)*

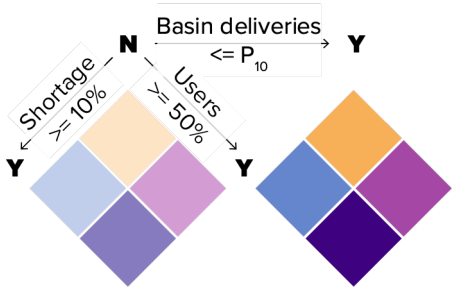


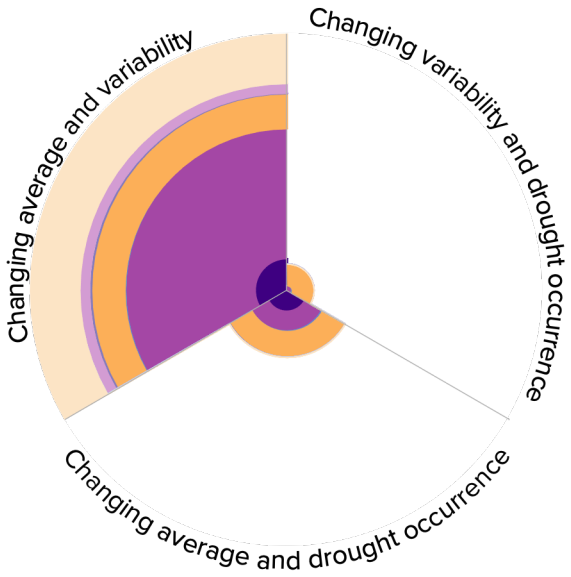




* not actual members of the Colorado Basin Roundtable

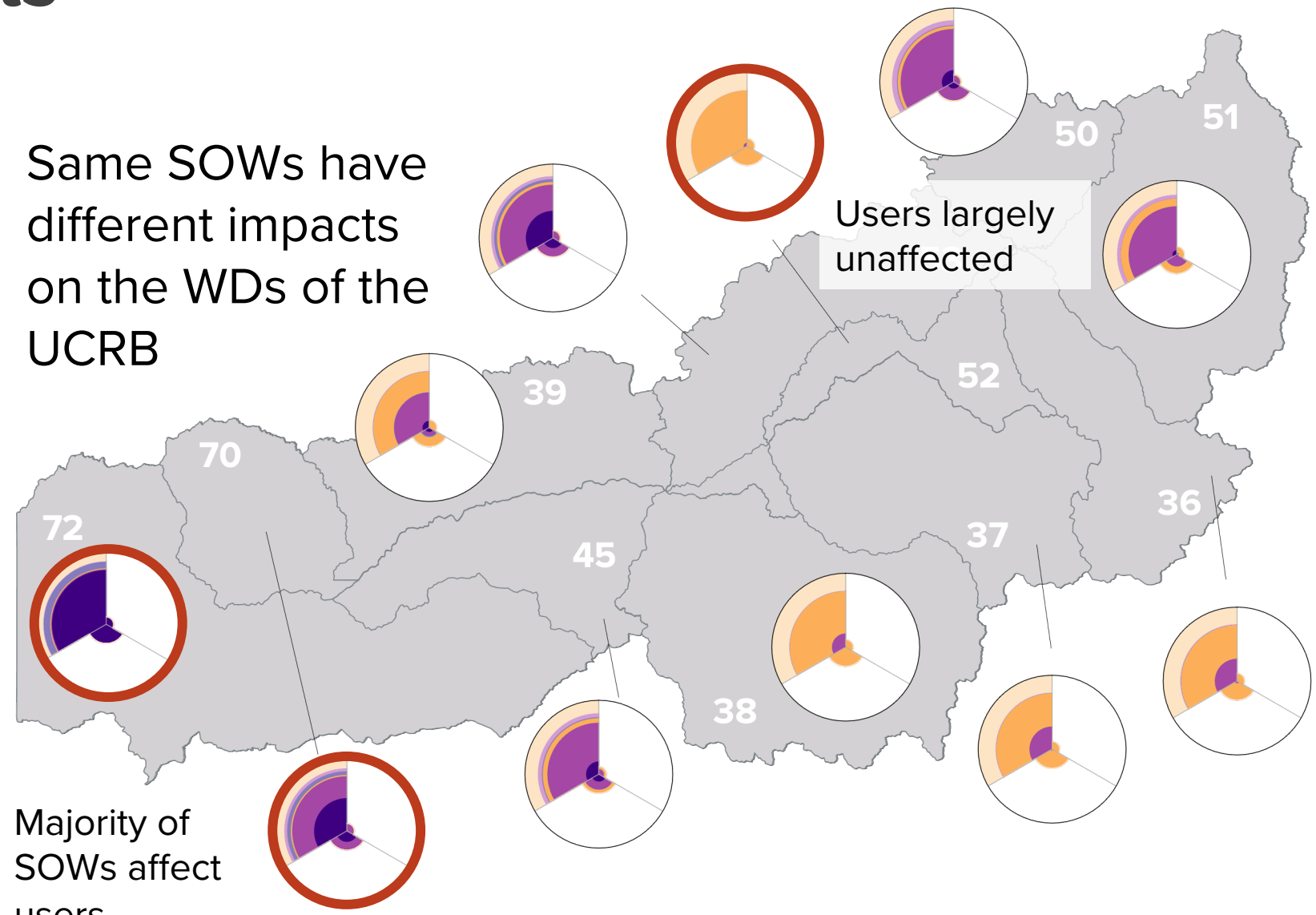
Distribution of impacts across water districts

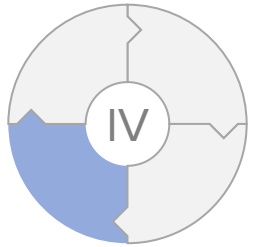




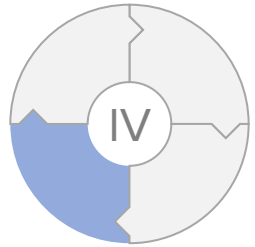
SOWs with plausible changes in hydroclimatic conditions

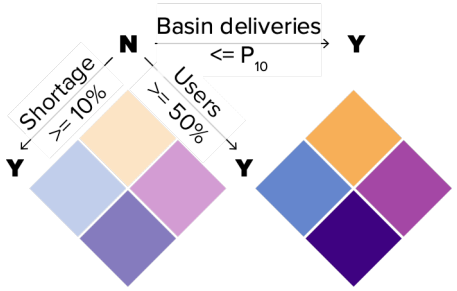
Same SOWs have different impacts on the WDs of the UCRB

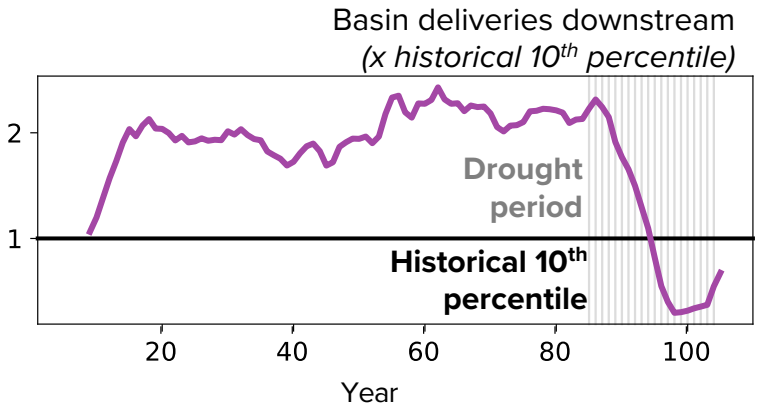


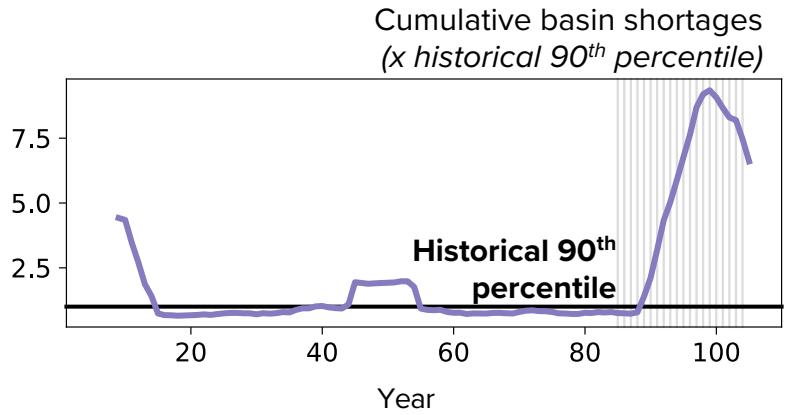


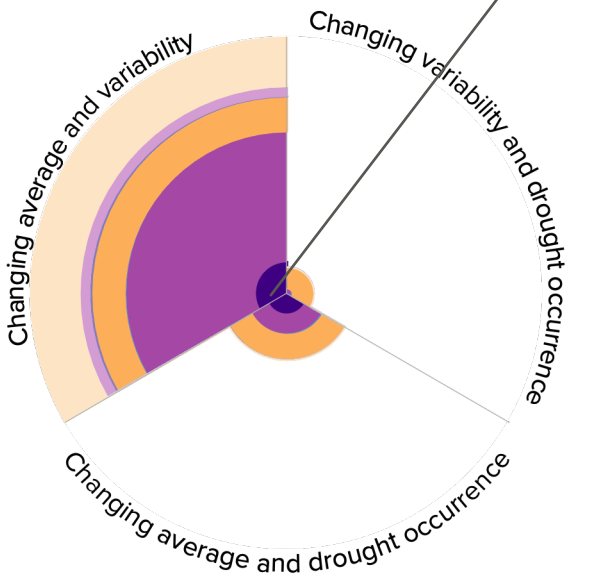
The Unforeseen Struggles across scales

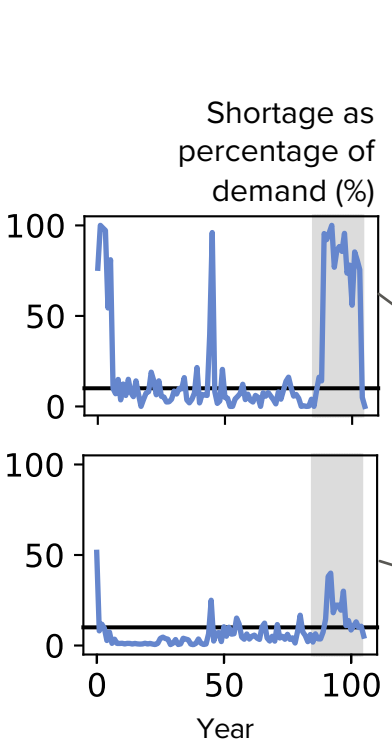


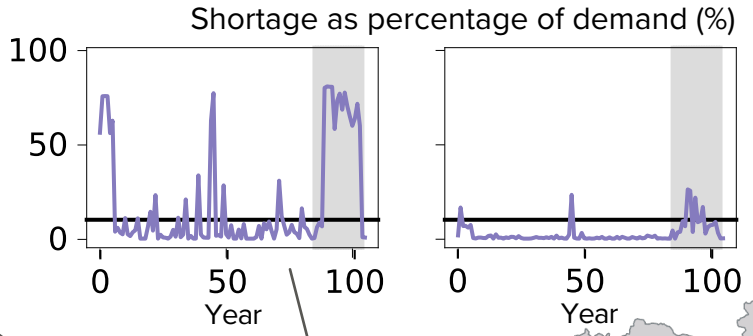






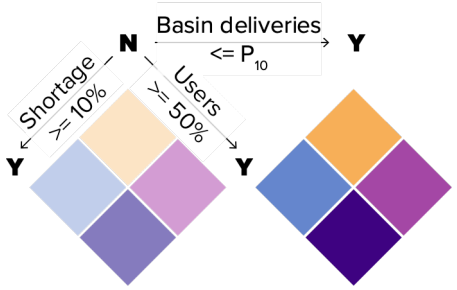




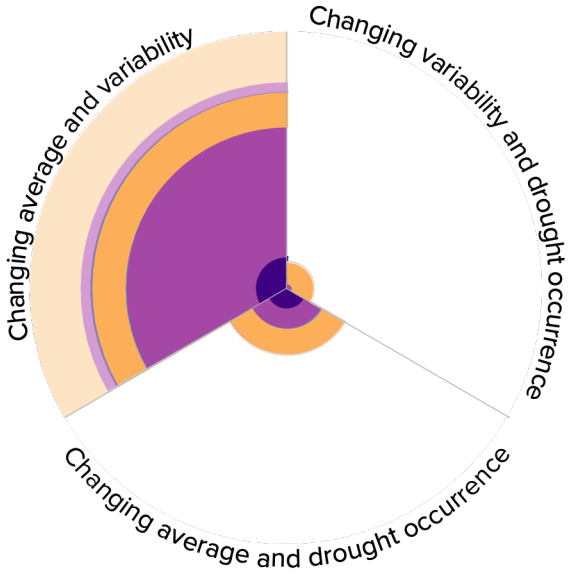


SOWs with plausible changes in hydroclimatic conditions

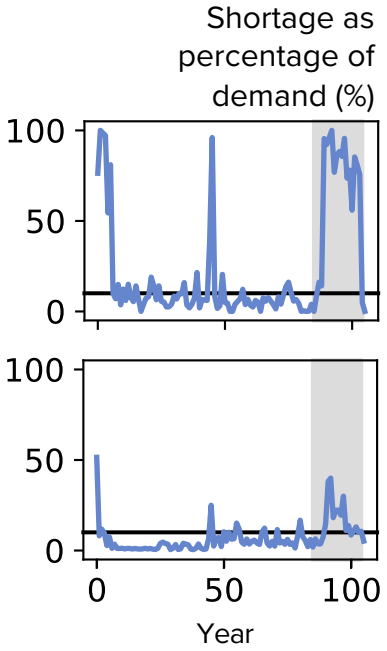
Do these thresholds represent everyone's risk aversion?

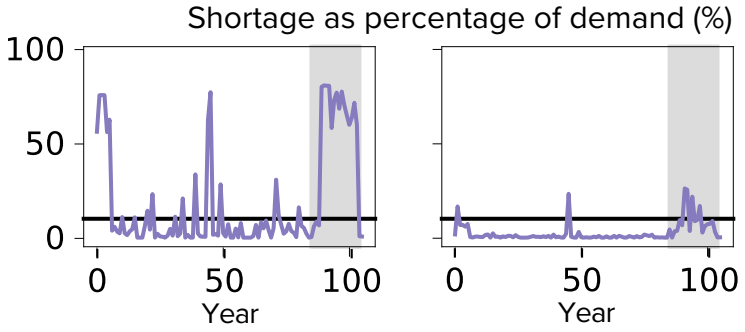


Examine the implications of alternative performance metrics on the discovery of consequential scenarios



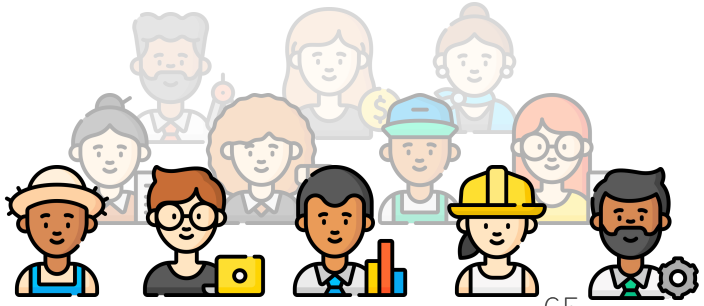
SOWs with plausible changes in hydroclimatic conditions





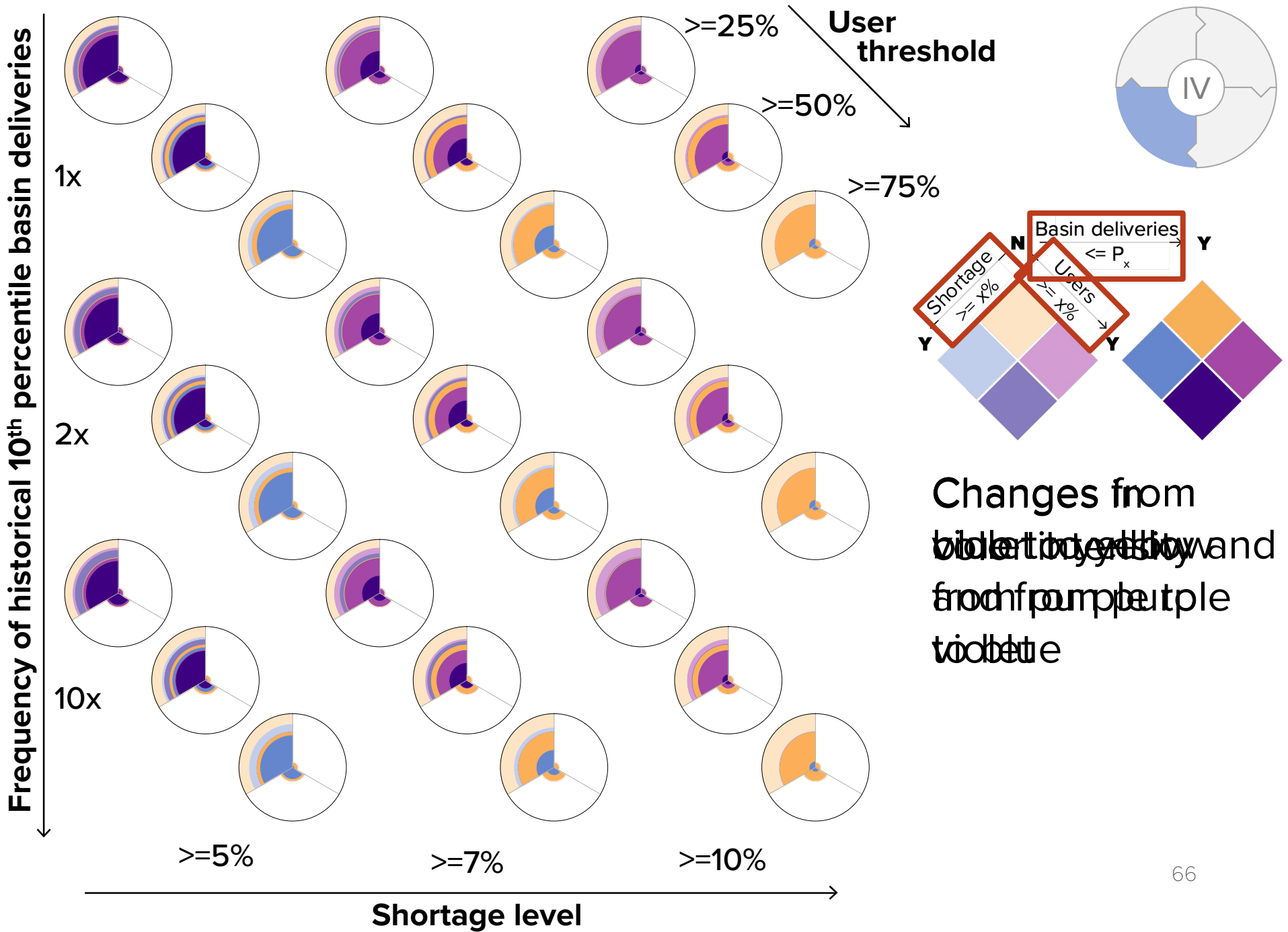
If too many water users in our district are short, it jeopardizes local jobs.

My senior right is never short, so a 10% shortage is catastrophic!



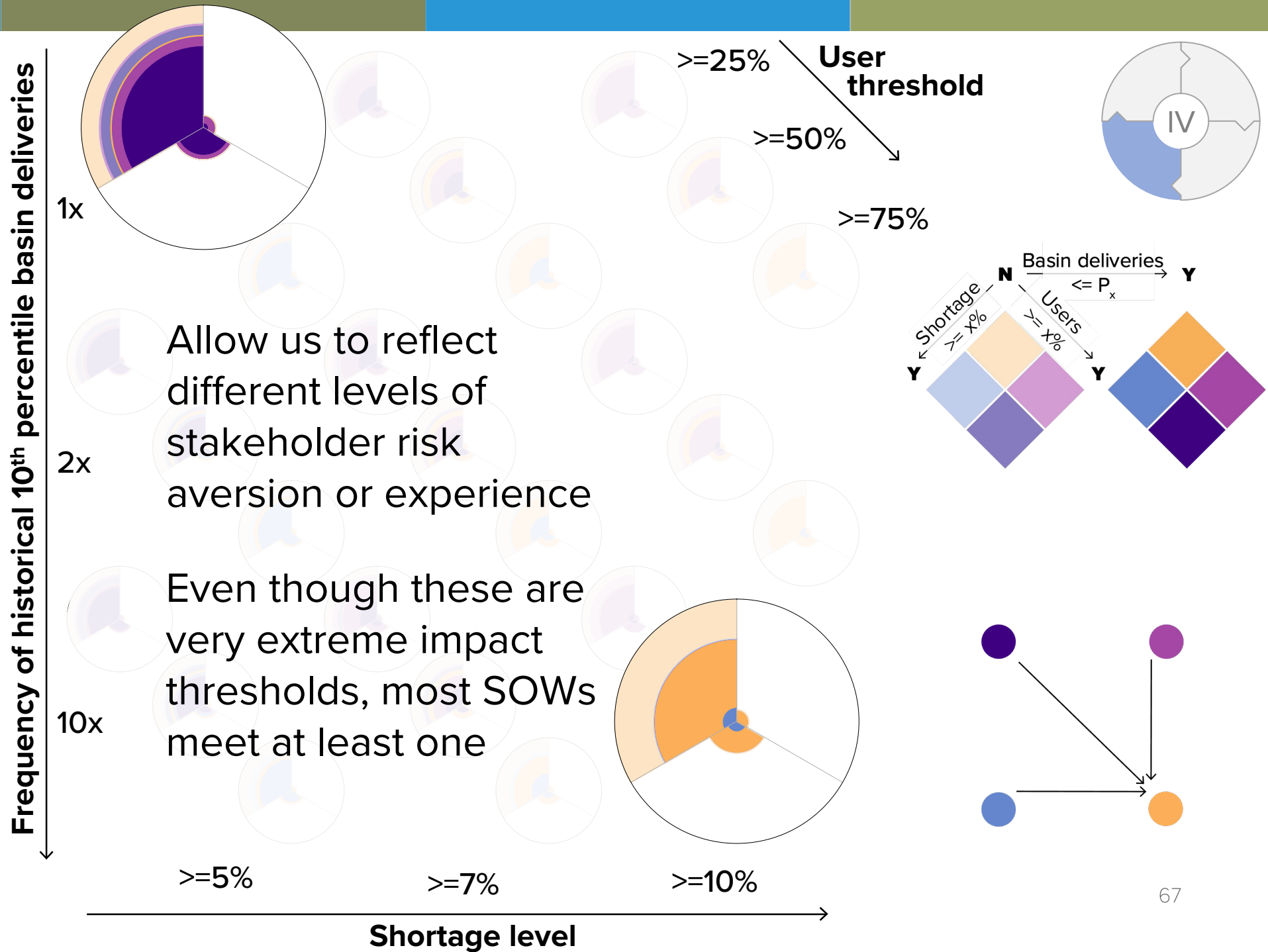
* not actual members of the Colorado Basin Roundtable

Distribution of impacts across different thresholds



Changes from

Distribution of impacts across different thresholds



Allow us to reflect different levels of stakeholder risk aversion or experience

Even though these are very extreme impact thresholds, most SOWs meet at least one

Take-home messages

- FRNSIC addresses a gap between the **rigor** of exploratory modeling and the **usability** of traditional narrative scenarios
- Narrative **scenarios** capture both **dynamic** properties and **impact** groups
- Examining alternative combinations of impact thresholds allows us to address **decision-relevance** for systems with **many actors**

IM3

INTEGRATED MULTISECTOR MULTISCALE MODELING

Thank you!

Find me at:

hadjimichael@psu.edu

https://www.hadjimichael.info/

@a_hadjimichael

This research is supported by the U.S. Department of Energy, Office of Science, as part of research in MultiSector Dynamics, Earth and Environmental System Modeling Program

Hydrologic Model - Synthetic Generator

AGU PUBLICATIONS

Water Resources Research

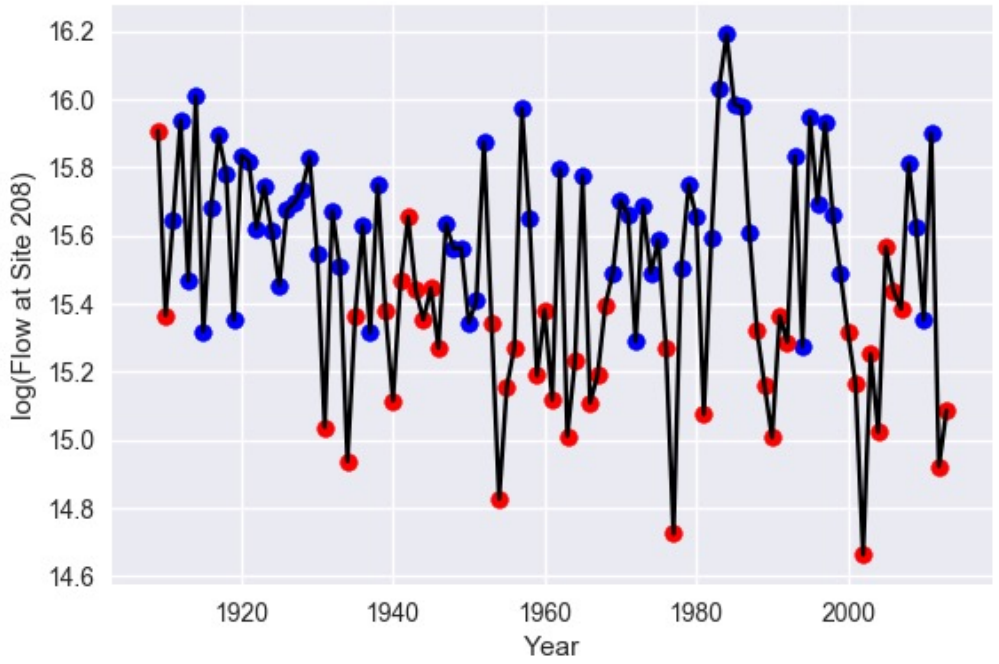
RESEARCH ARTICLE

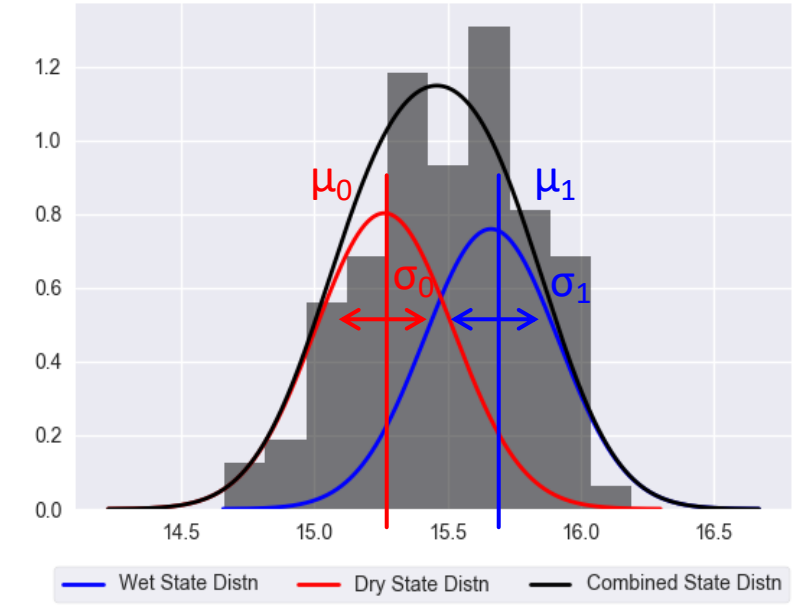
10.1002/2014WR015567

A hidden Markov model combined with climate indices for multidecadal streamflow simulation

C. Bracken[1,2], B. Rajagopalan[1,3], and E. Zagona[1,4]

- Dry state
- Wet state



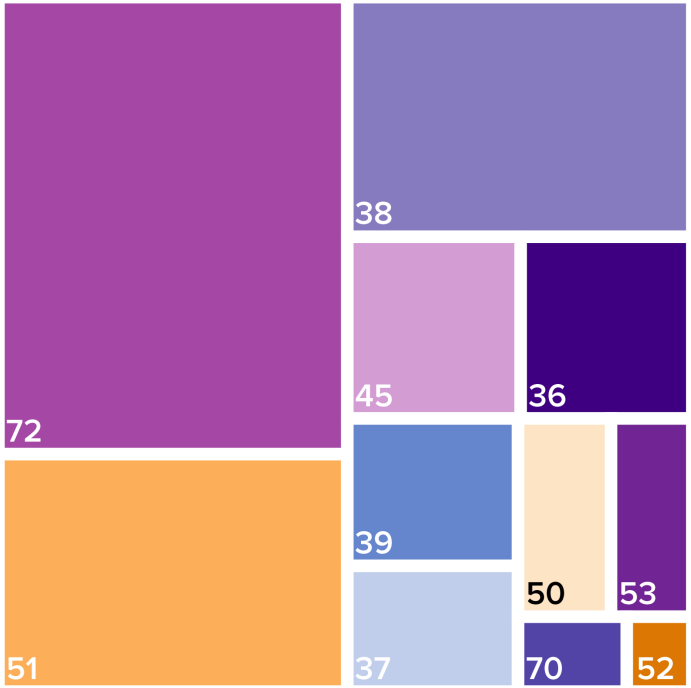


	Dry State	Wet State
Dry State	$p_{00} = 0.68$	$p_{01} = 0.32$
Wet State	$p_{10} = 0.35$	$p_{11} = 0.65$

Historical distribution of demands and shortages

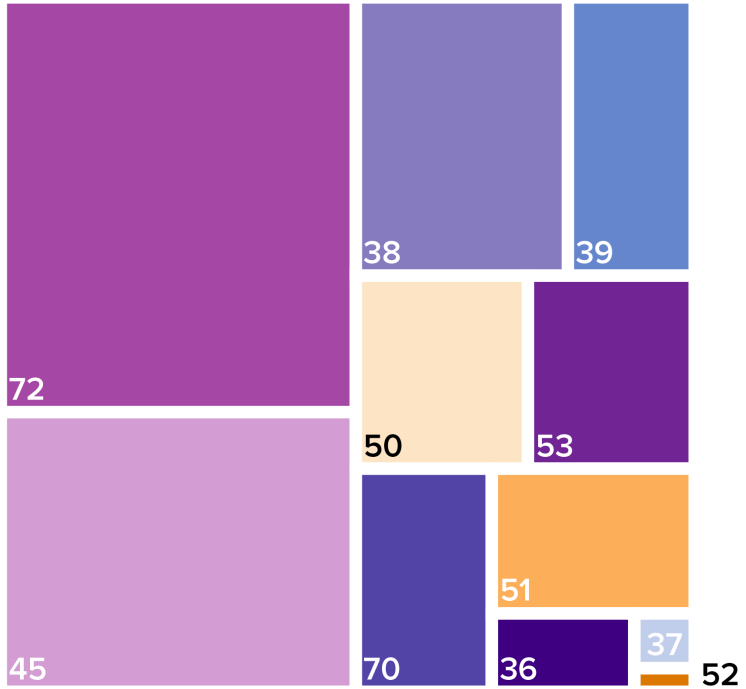
Demands and shortages are disporportionally shared among water districts

(a) Share of demands



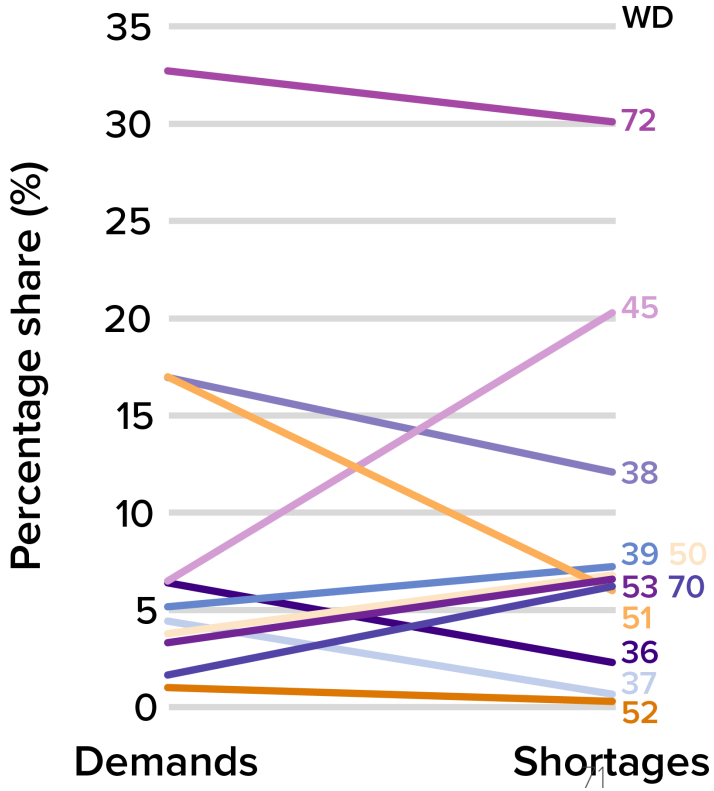
Total: 3309 Million m^3

(b) Share of shortages

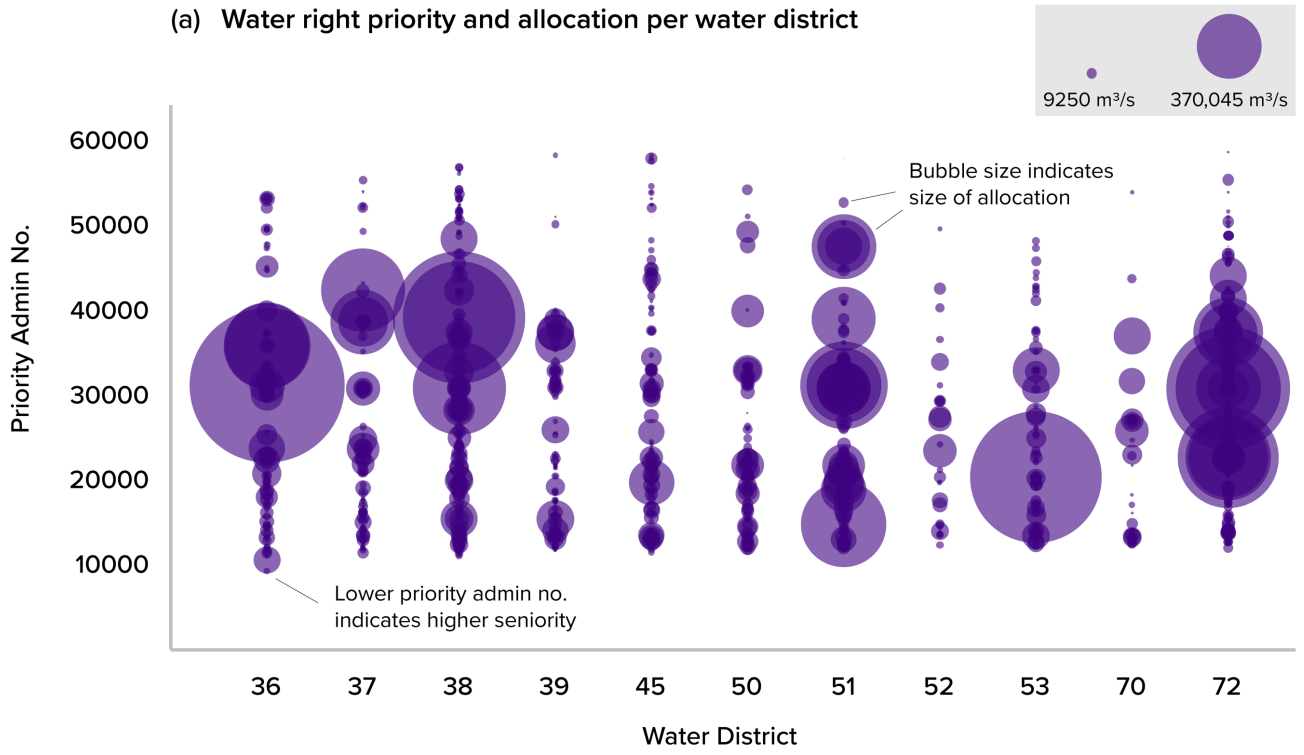


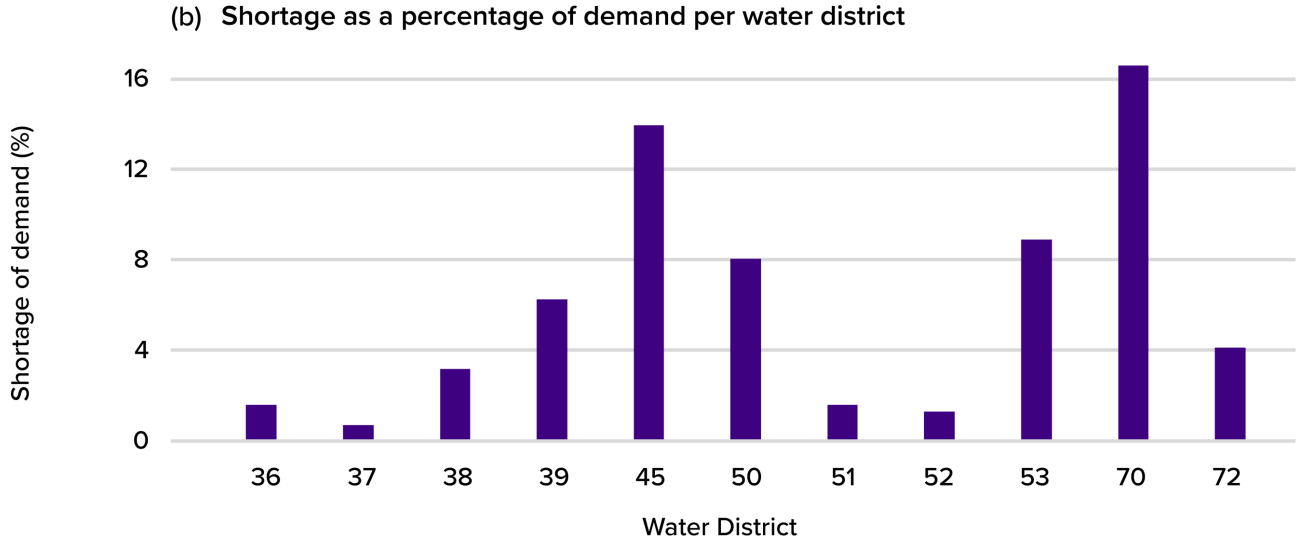
Total: 148 Million m^3

(c) Change in share



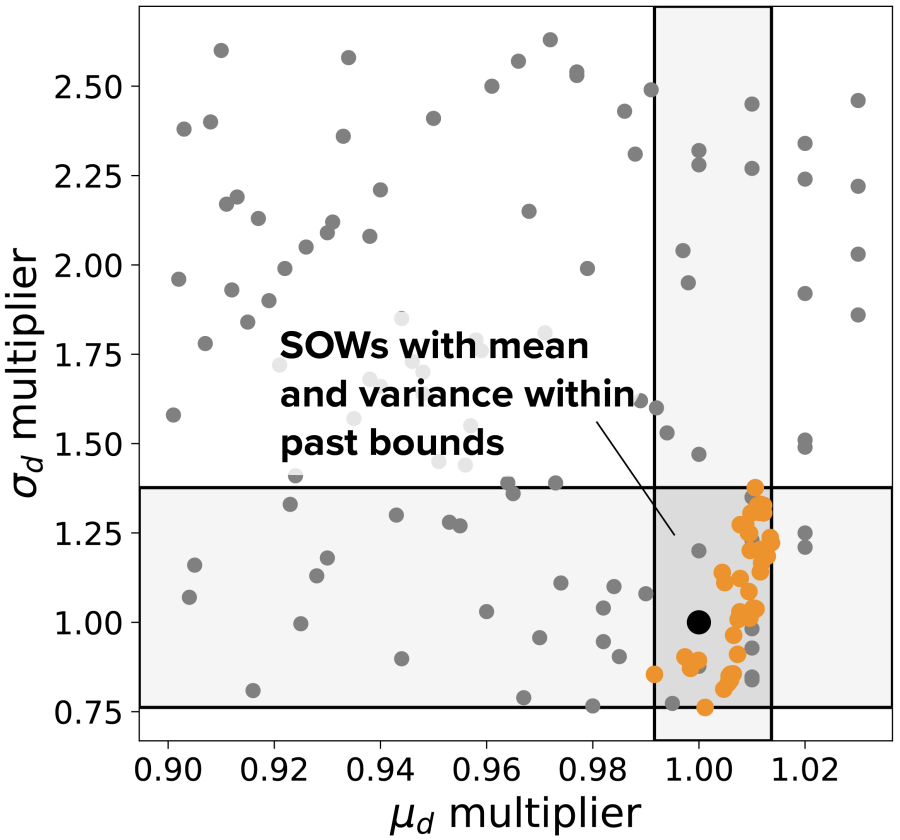
...partly, but not entirely explained by water rights



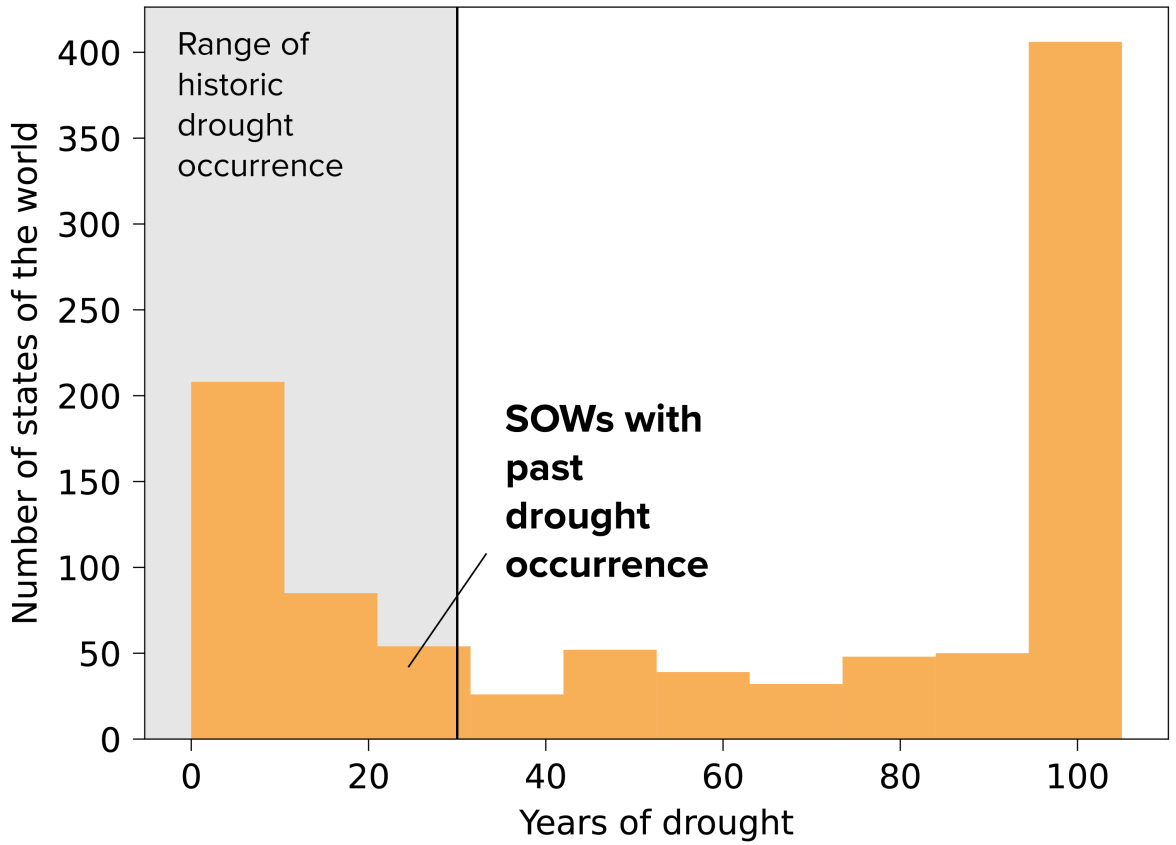


Thresholds to classify SOWs within the historical context

(a) Classification based on variance and mean



(b) Classification based on drought occurrence



- Values based on recent historical observations
- Values using rolling 60-year windows of historical observations
- State of the world values in entire Latin Hypercube Sample