

Advancing adaptive decision-making through an Environmental Water Manager (EWM) role to enhance the ecological resilience of Western U.S. river systems

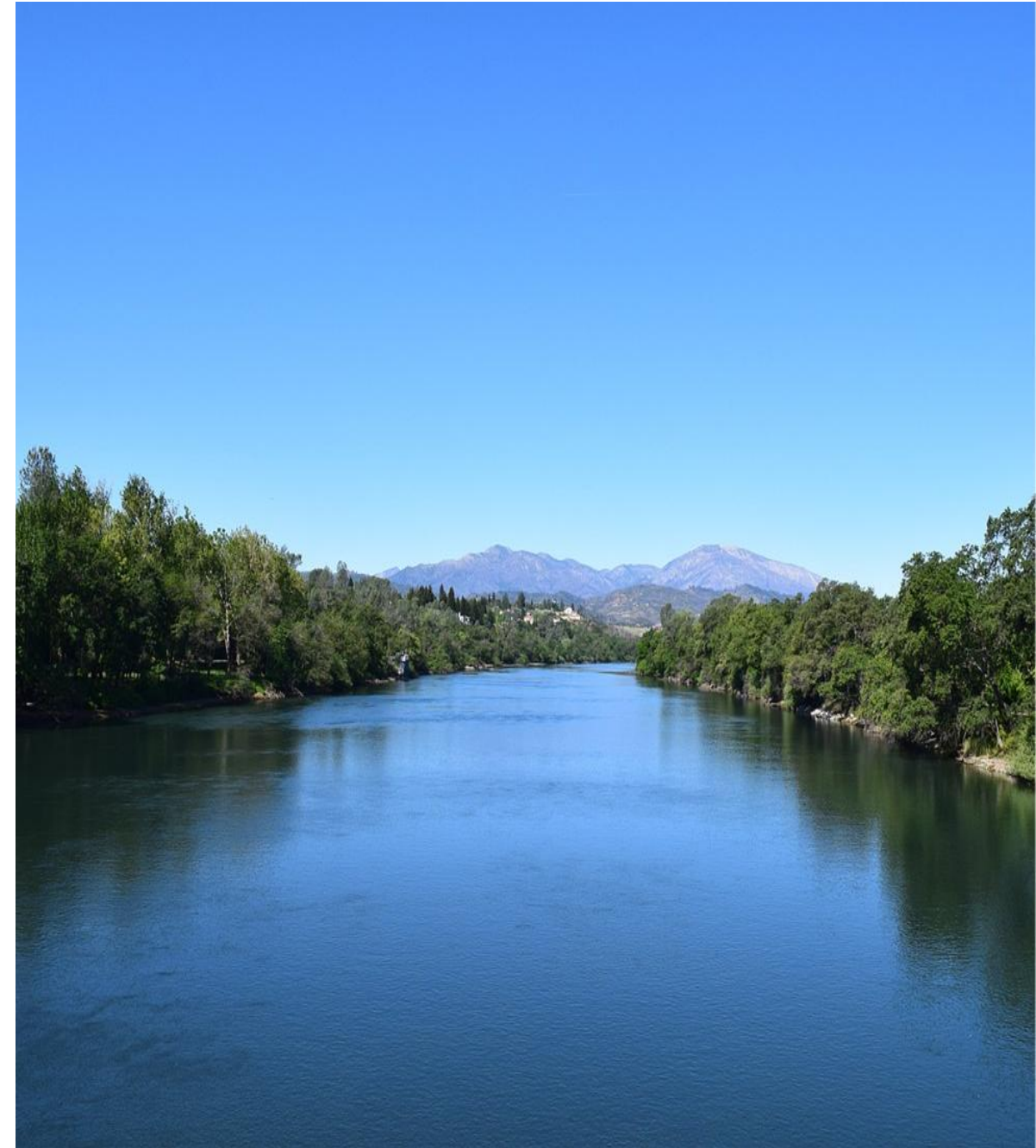
California Water and Environmental Modeling
Forum (CWEMF) Annual Meeting
April 21, 2026

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Hall³, Patrick Reed²

¹Center for Western Weather & Water Extremes (CW3E)

²Cornell University

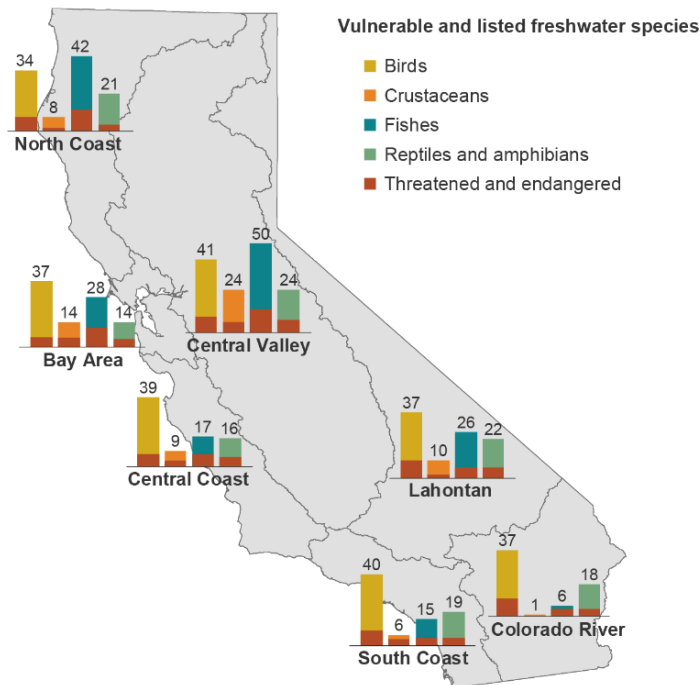
³Environmental Defense Fund



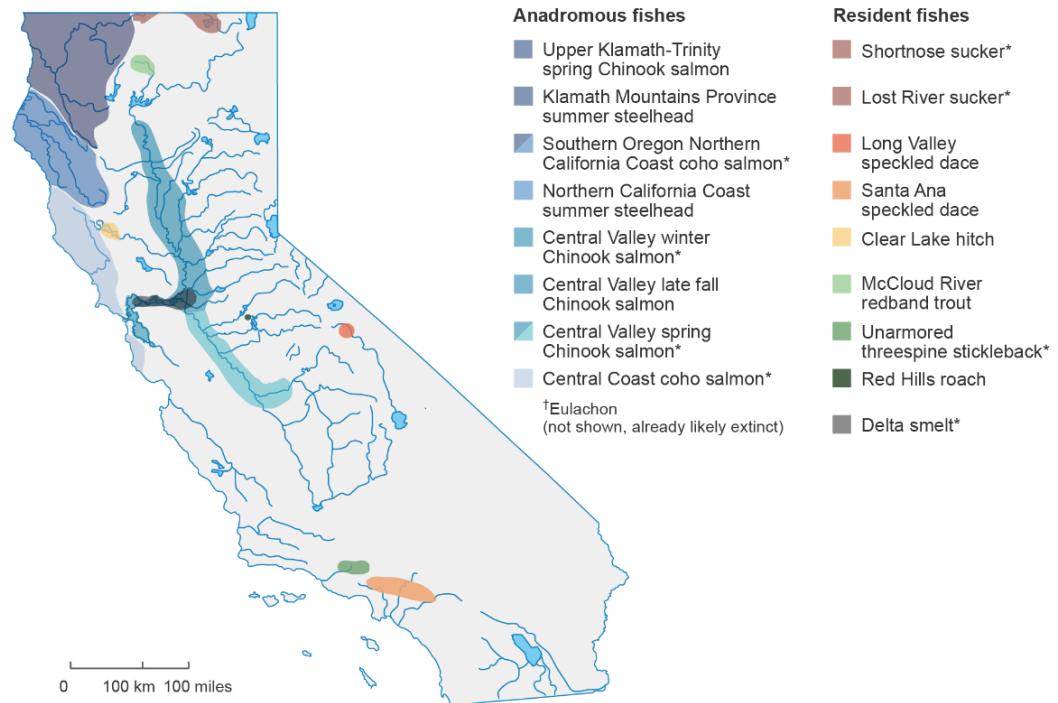
Western U.S. freshwater ecosystem challenges

‘The heavy reliance upon ESAs to manage *freshwater ecosystems*—and native biodiversity in general—is **not working**. They are specifically designed to prevent extinction...They are **not** designed or implemented to manage ecosystems for **multiple objectives**...’ (Mount et al., 2019)

CA freshwater species under ESA



CA freshwater species vulnerable to extinction in next major drought



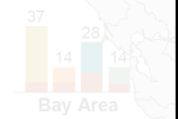
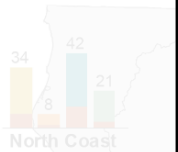
Western U.S. freshwater ecosystem challenges

‘The heavy reliance upon ESAs to manage *freshwater ecosystems*—and native biodiversity in general—is **not working**. They are specifically designed to prevent extinction...They are **not** designed or implemented to manage

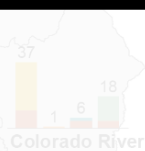
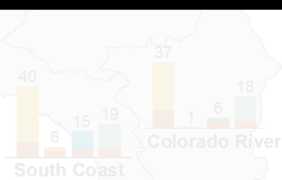
‘...a **new strategy** for river system management is needed. This new strategy is underscored by the oft-cited **paradox** that *more human intervention* is needed to restore ecological balance to systems that were originally *unbalanced by human actions*’

Brodeur et al., *In Press*

CA fresh



Centr



0 100 km 100 miles

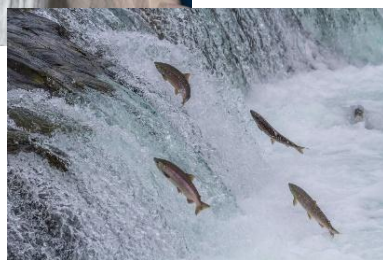
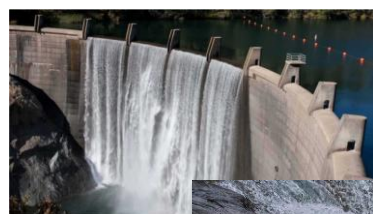
An Environmental Water Manager as a potential solution

Daily

Adaptive actions across multiple timescales

Annual+

Real-time response to ecological conditions



Long term management of ecological water
(Protect, Maintain, Recover, Enhance)

Examples of environmental watering objectives under different planning scenarios

			
Drought	Dry	Average	Wet to very wet
Main objective: PROTECT > Avoid critical loss > Maintain key refuges > Avoid catastrophic events	Main objective: MAINTAIN > Maintain river functioning with reduced reproductive capacity > Maintain key functions of high priority wetlands > Manage within dry-spell tolerances	Main objective: RECOVER > Improve ecological health and resilience > Improve recruitment opportunities for key animal and plant species	Main objective: ENHANCE > Restore key floodplain and wetland linkages > Enhance recruitment opportunities for key animal and plant species

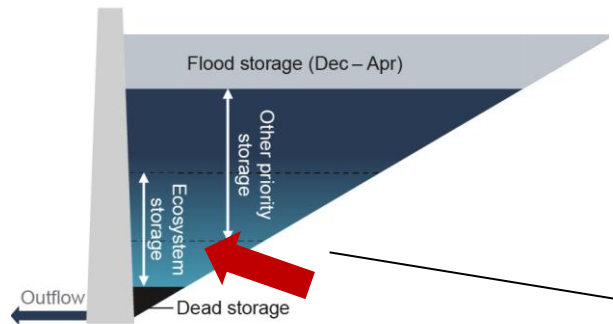
Mount et al., 2016

An Environmental Water Manager (EWM) as a potential solution

Translating environmental flows science to adaptive river system management

Environmental flow strategies

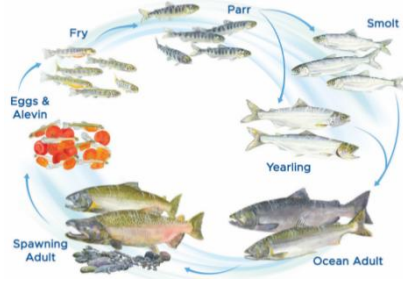
Environmental Water Budget



Ecosystem Based Management Structure



Function



Environmental Water Manager (EWM)



Environmental Water Budget (EWB)¹

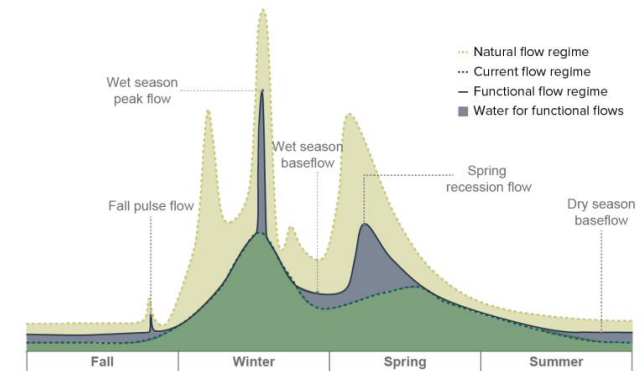


Ecosystem Based Management (EBM)¹

*Brodeur et al., 2026;
Mount et al., 2019*

Environmental flow objectives

Functional Flows



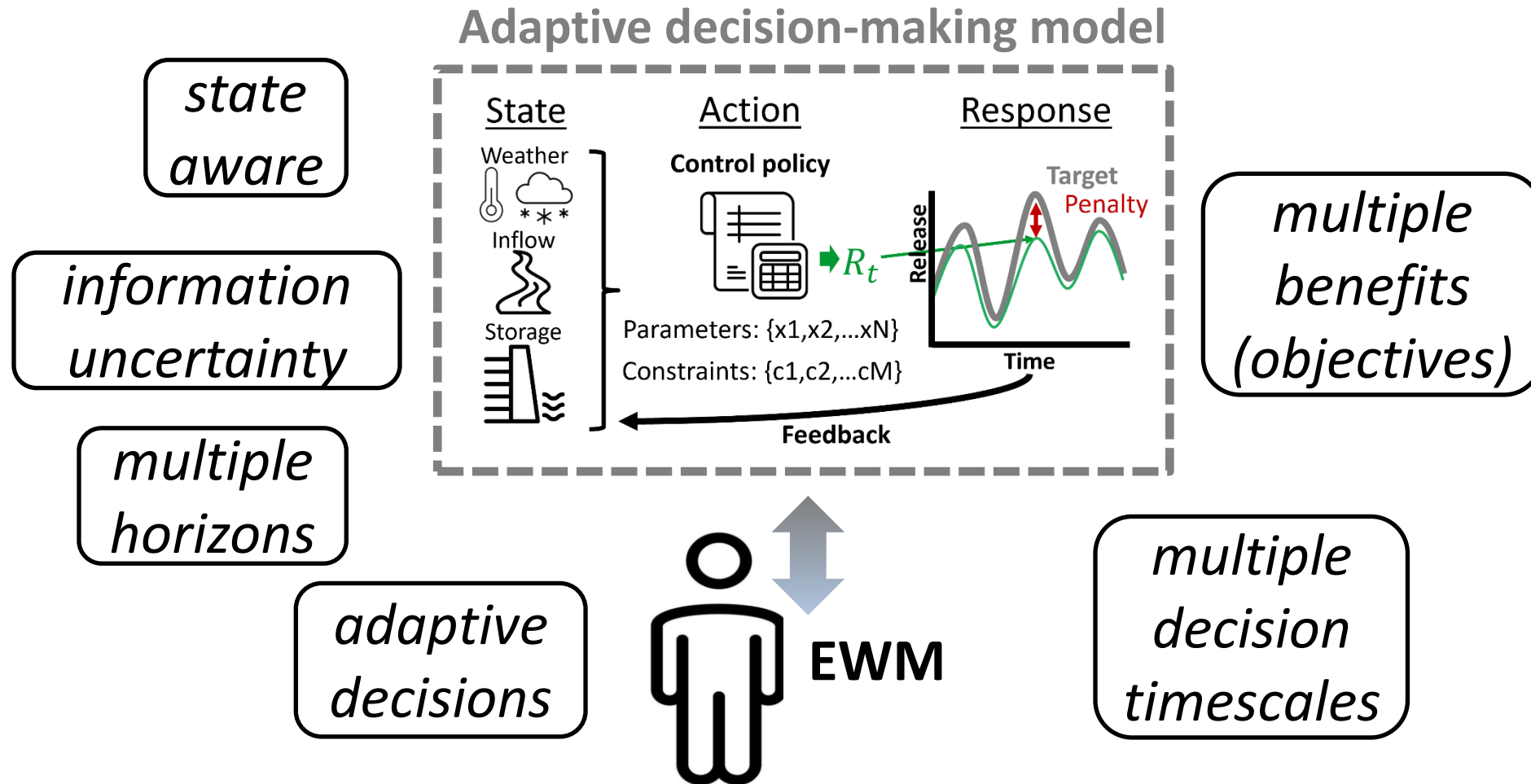
Water Quality



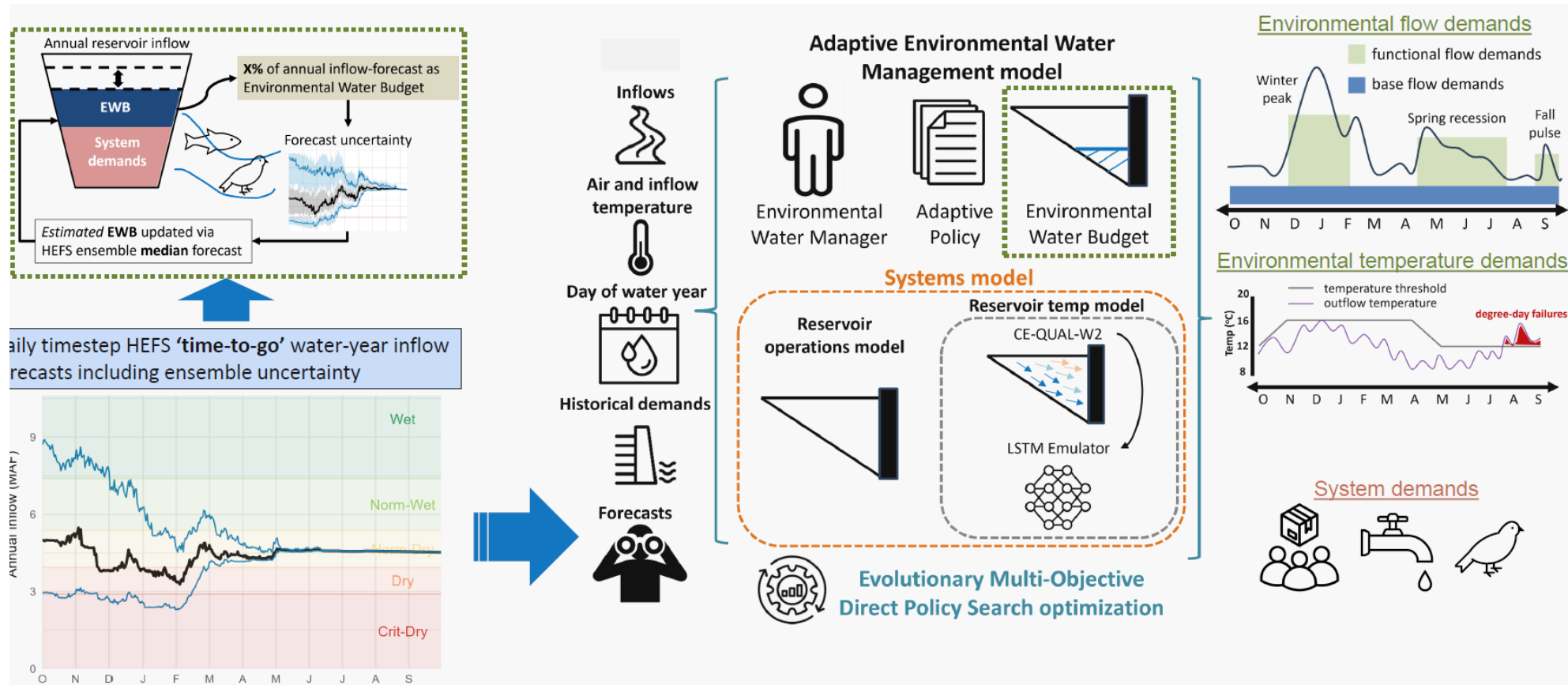
Steelhead trout

Chinook salmon

Understanding EWM potential through an adaptive decision-making modeling framework



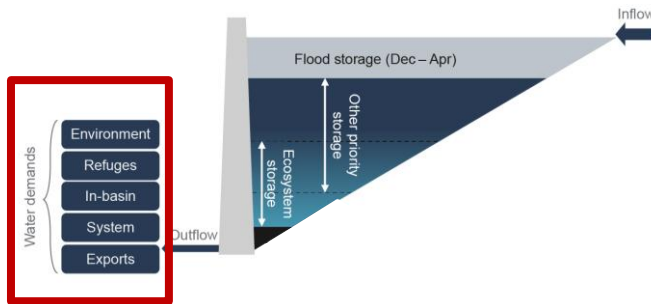
An environmental water management model to simulate EWM adaptive decision-making



Core elements of the adaptive environmental water management model

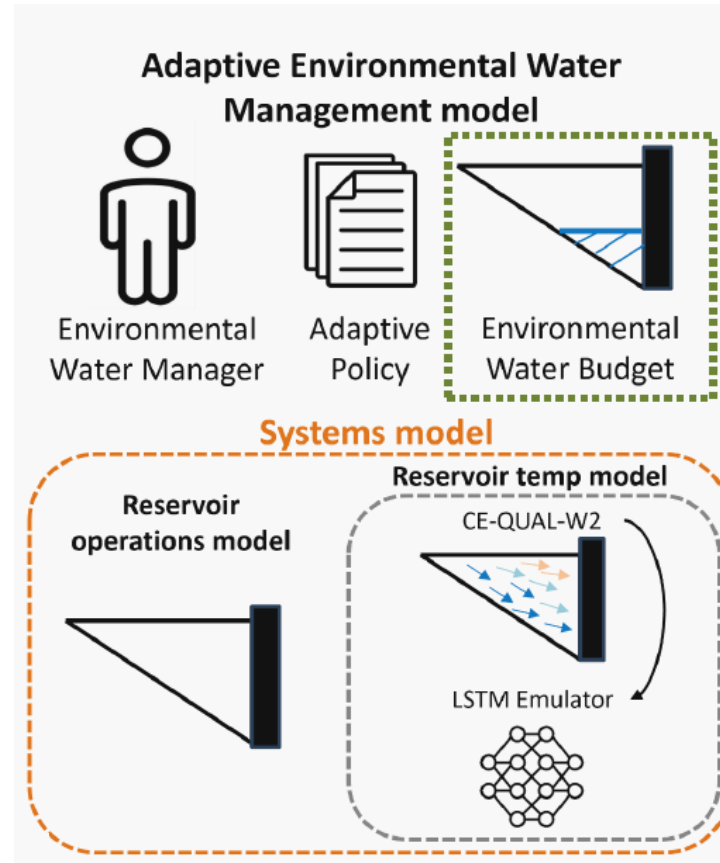
Reservoir simulation model

Stylized representation
of Shasta reservoir

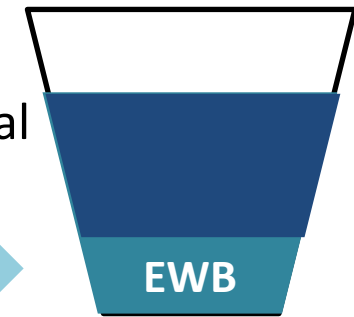


Historical Shasta demands

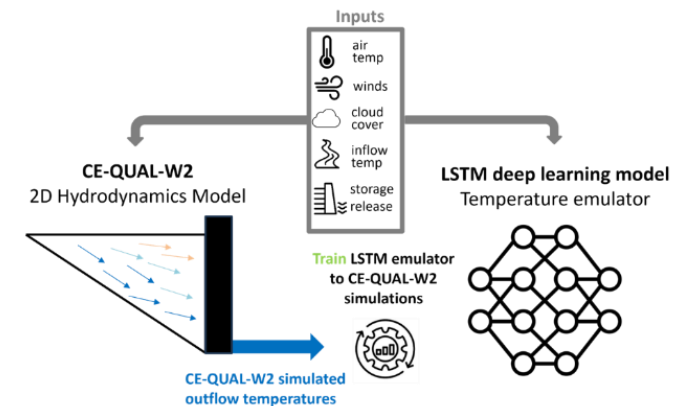
Null et al. 2024



20% Annual
Inflow



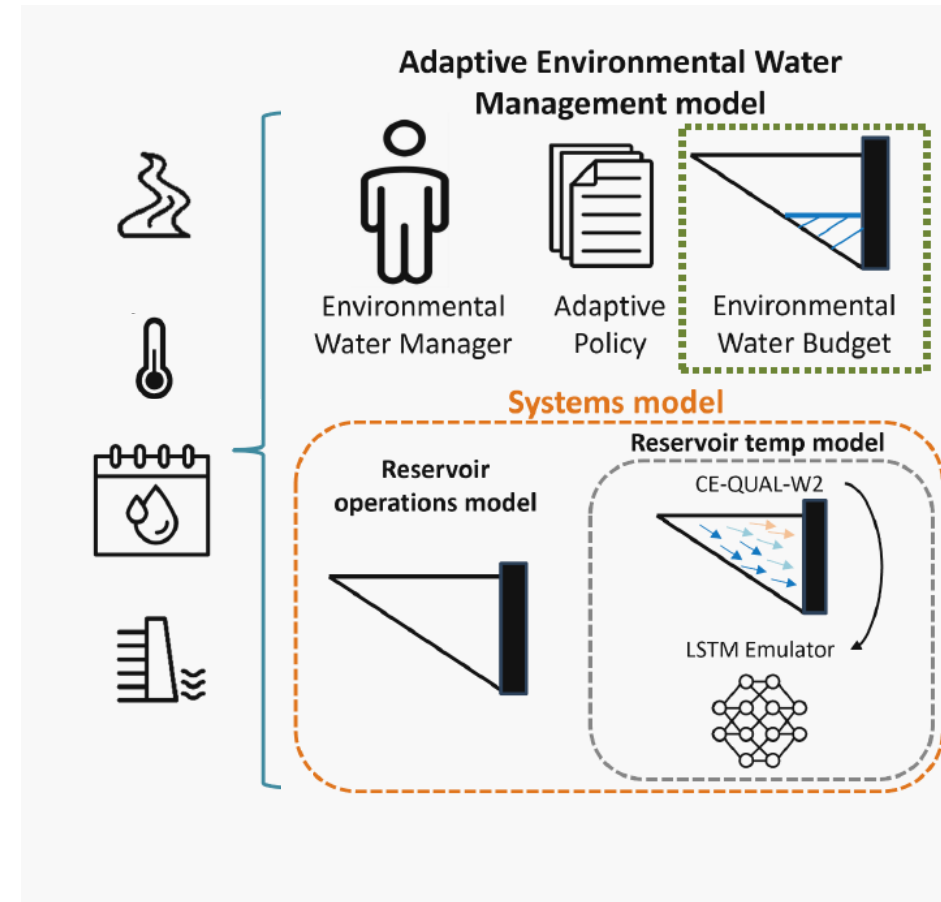
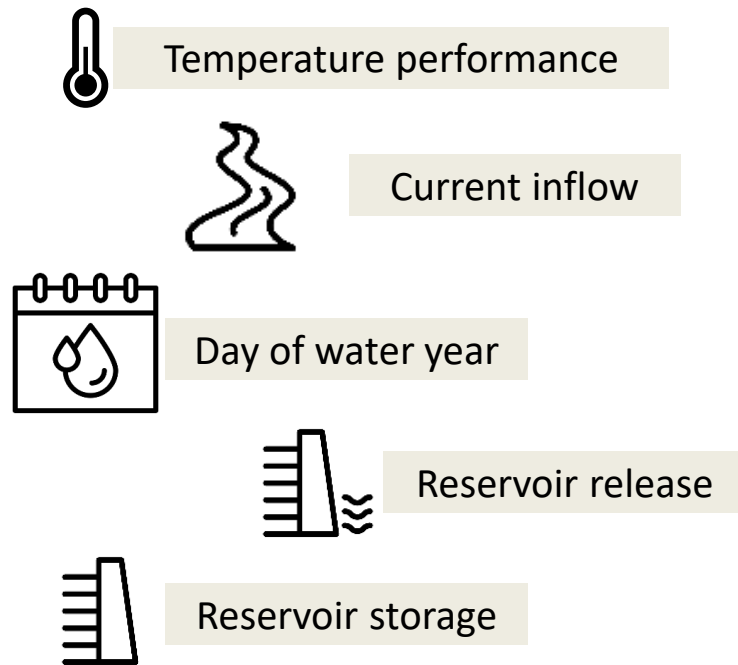
ML emulator approach
for water temperature



Core elements of the adaptive environmental water management model

Model inputs

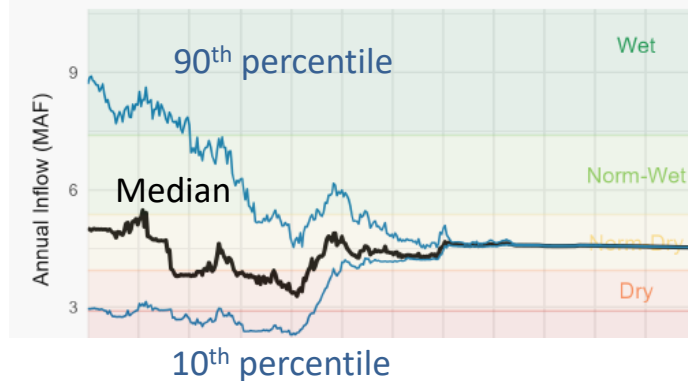
System States



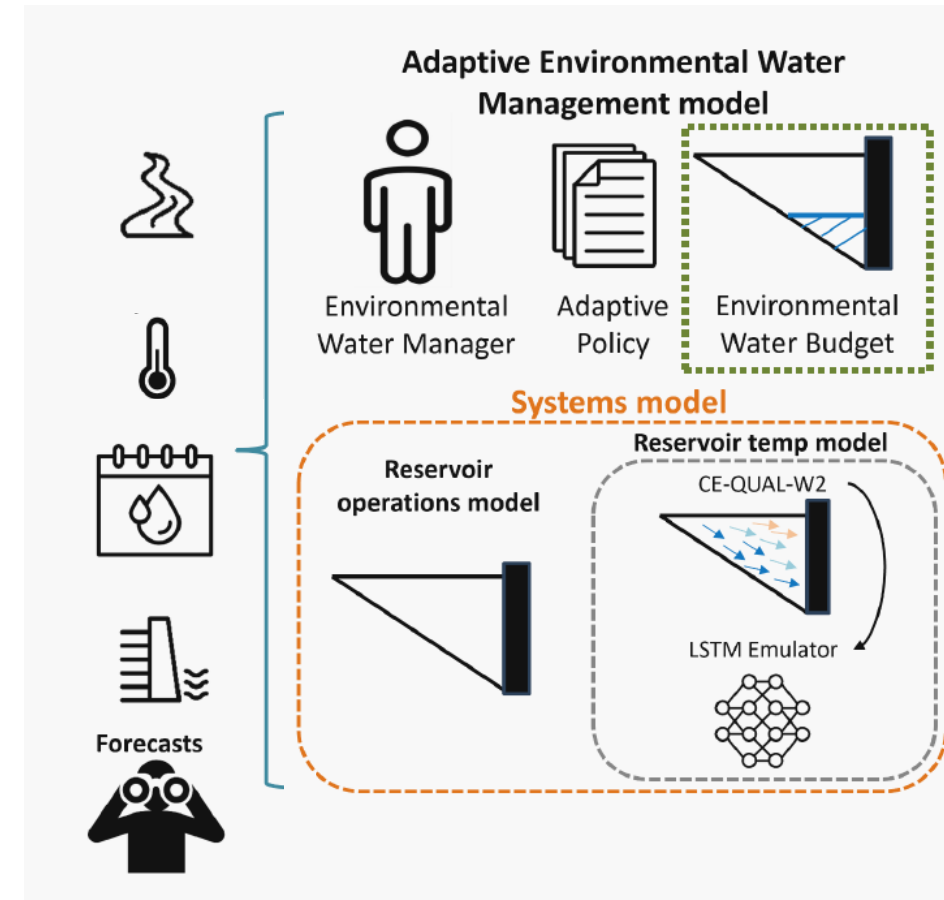
Core elements of the adaptive environmental water management model

Forecasted System States

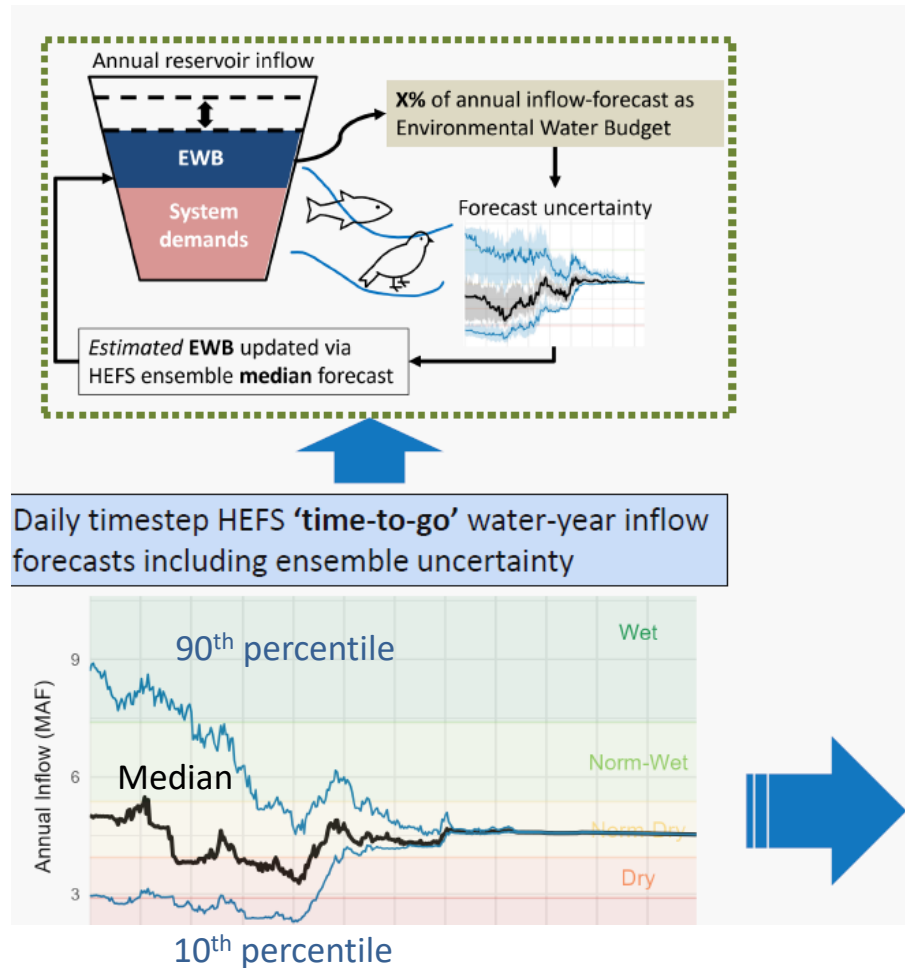
Daily timestep HEFS 'time-to-go' water-year inflow forecasts including ensemble uncertainty



Model inputs



Core elements of the adaptive environmental water management model



Model inputs

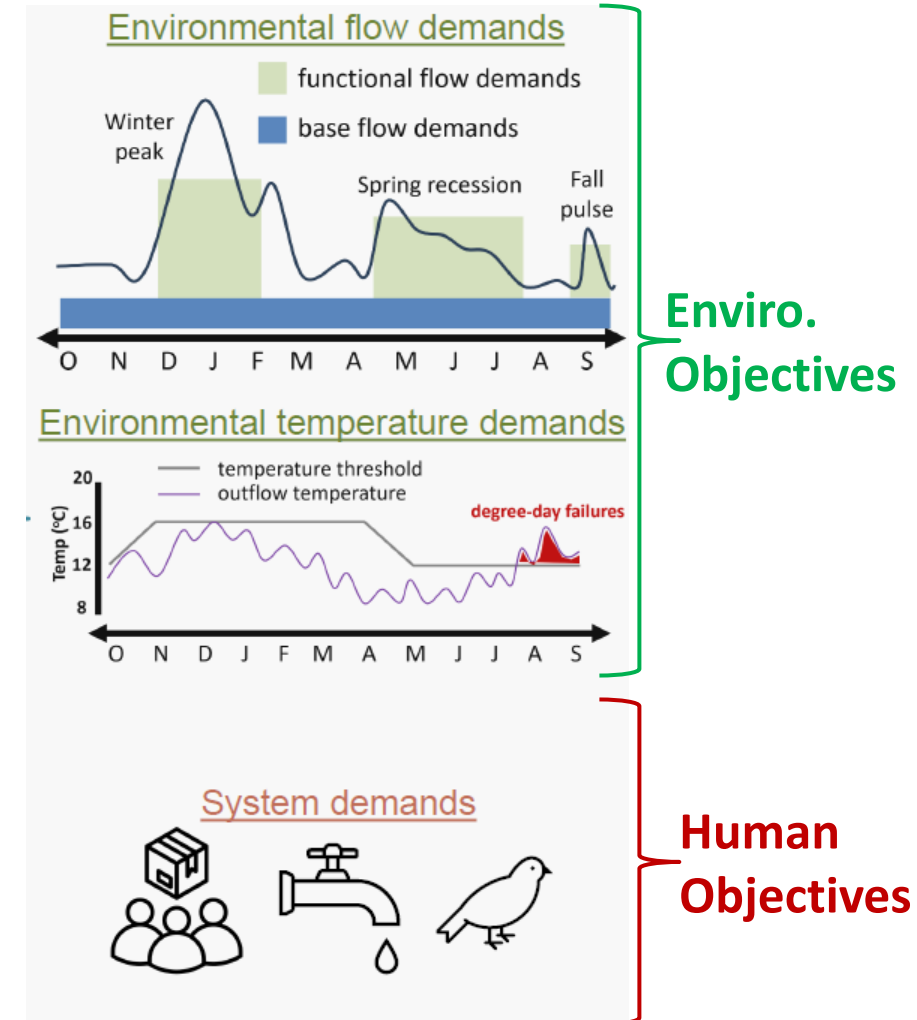
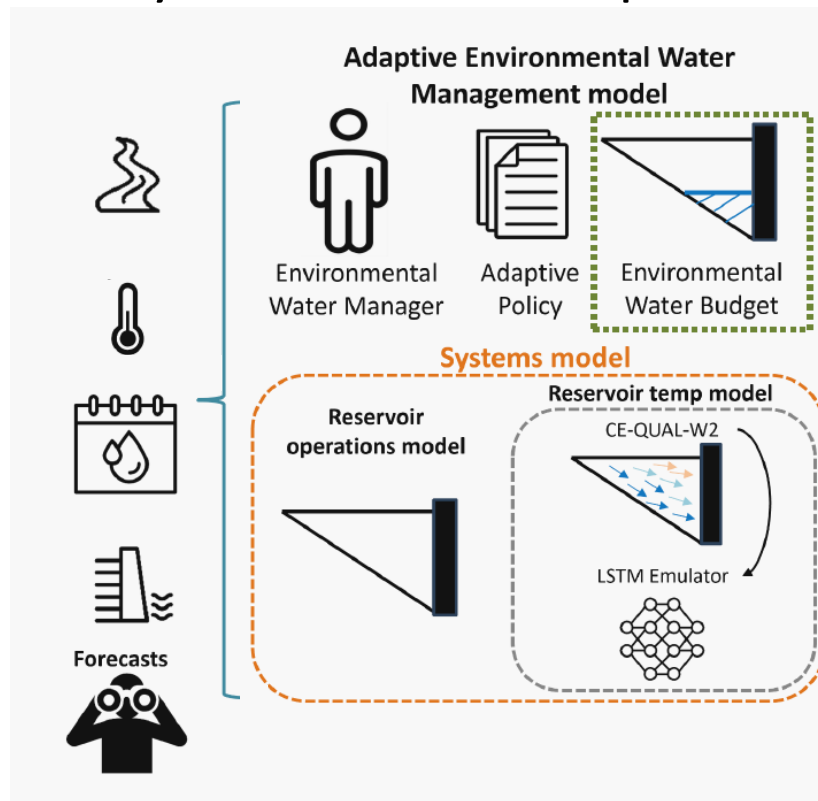
Long-range forecast uncertainty is **both** an *explicit decision-making input* to the model as well as a *key element* of model state information.

Specifically, *how much environmental water budget is left for the year* is an uncertain quantity determined by forecasts, emulating **real-world** context

Core elements of the adaptive environmental water management model

System objectives

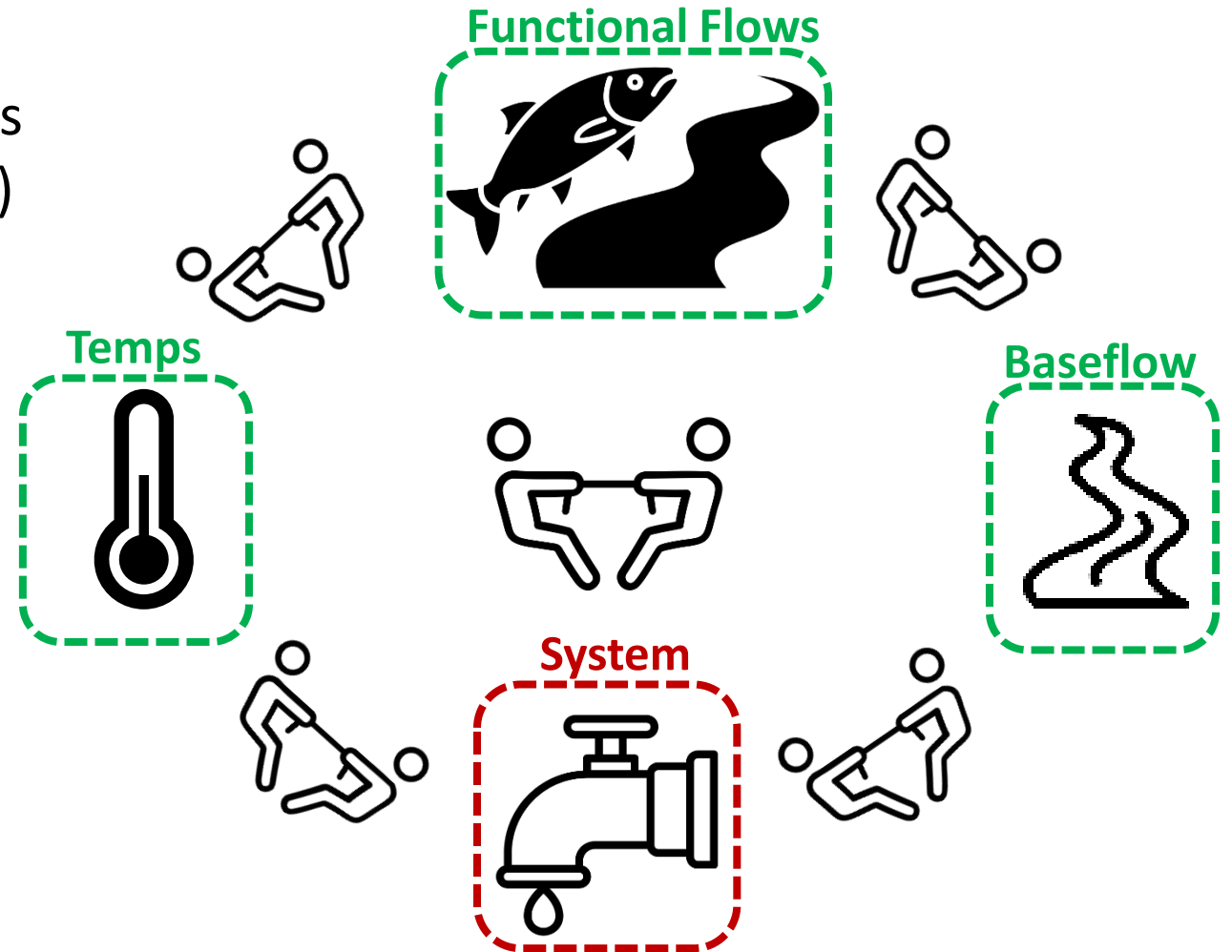
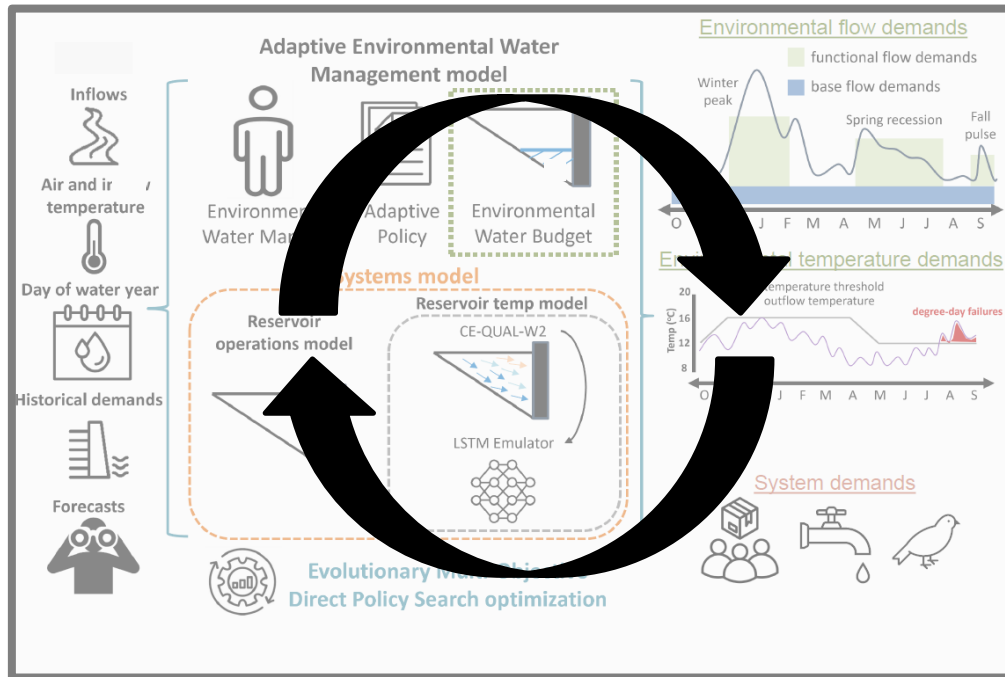
Systems model + inputs



Exploring adaptive management solutions

System optimization

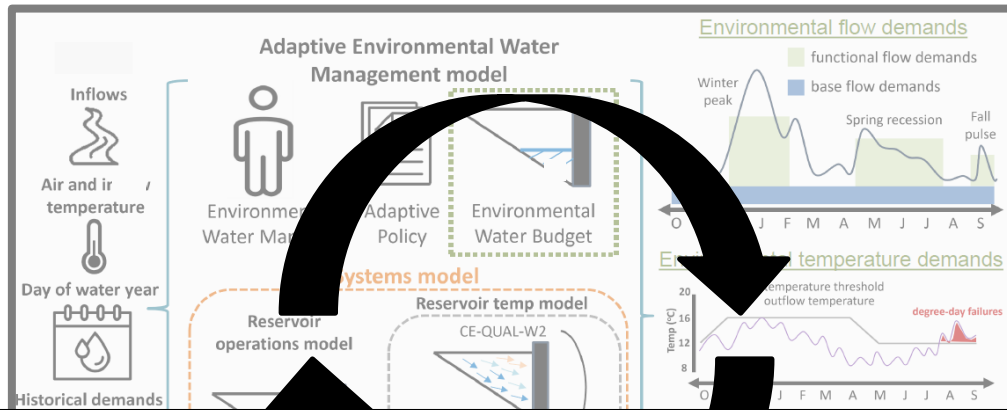
Find the set of optimal tradeoff solutions across 4 objectives (3 **Enviro** + 1 **Human**)



Exploring adaptive management solutions

System optimization

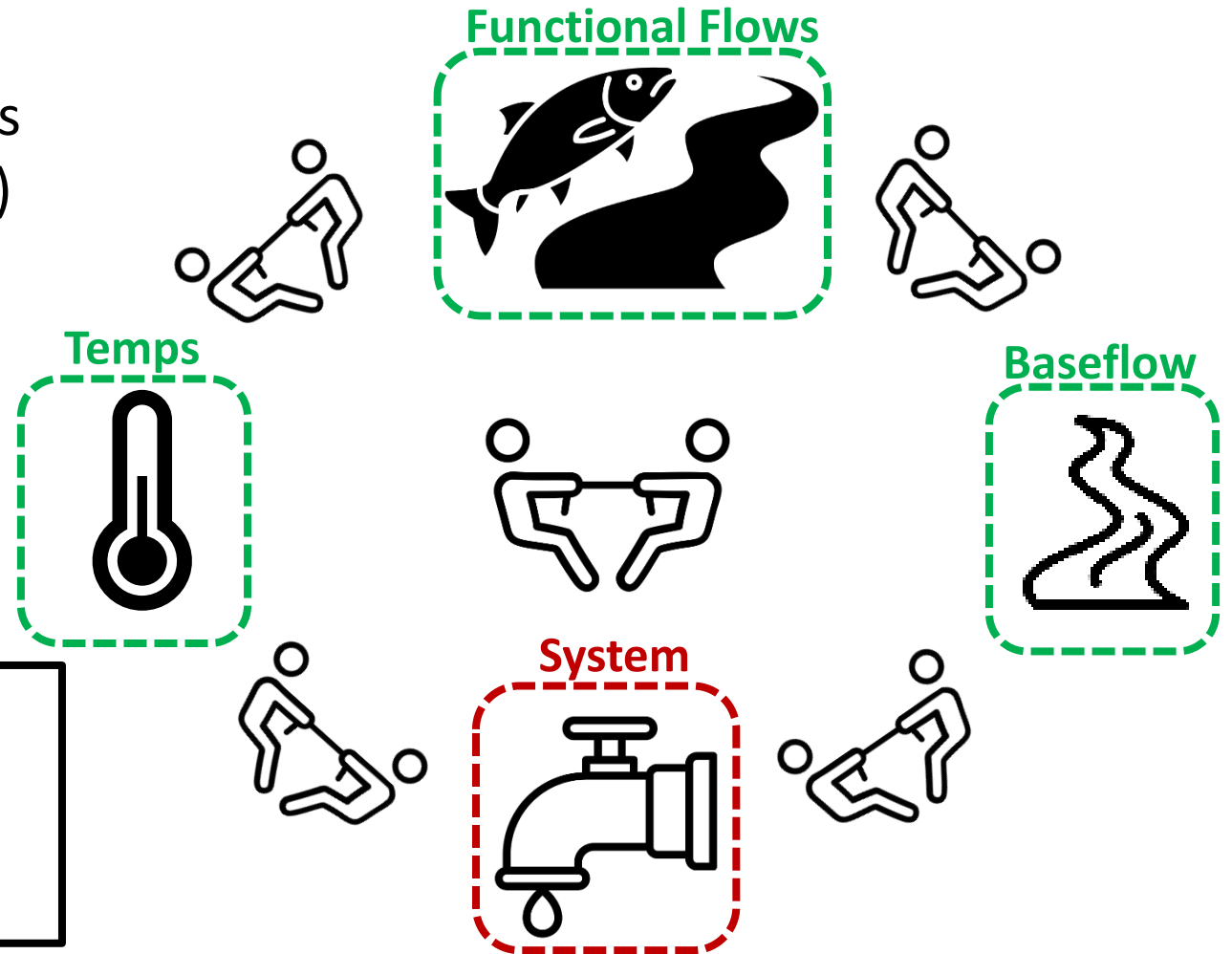
Find the set of optimal tradeoff solutions across 4 objectives (3 **Enviro** + 1 **Human**)



Borg evolutionary optimization algorithm:

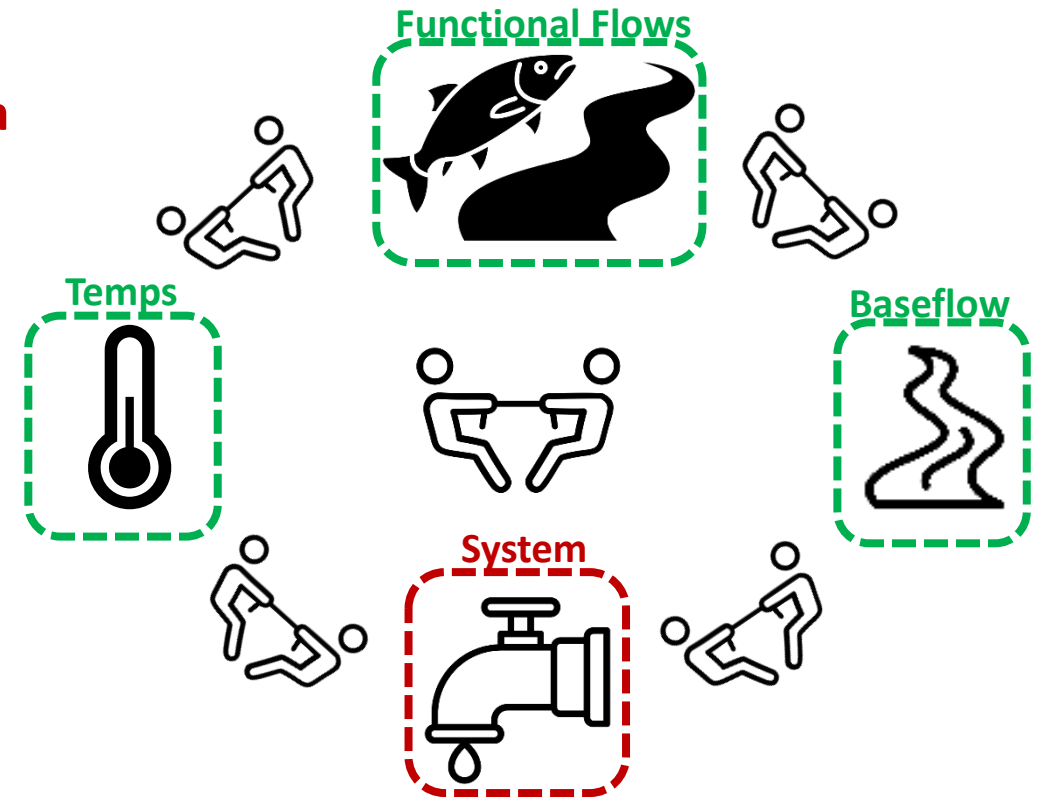
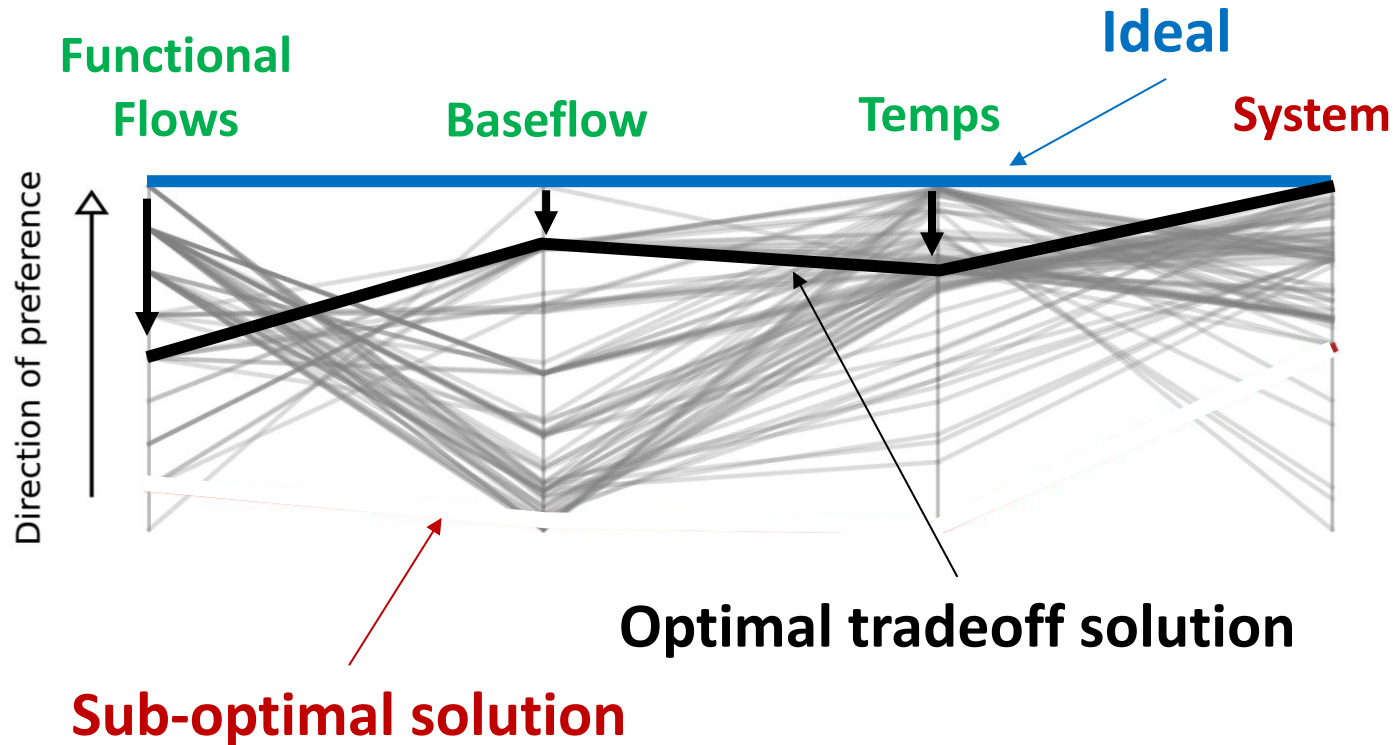
- State-of-the-science for complex, high-dimensional optimization problems

Hadka & Reed, 2013

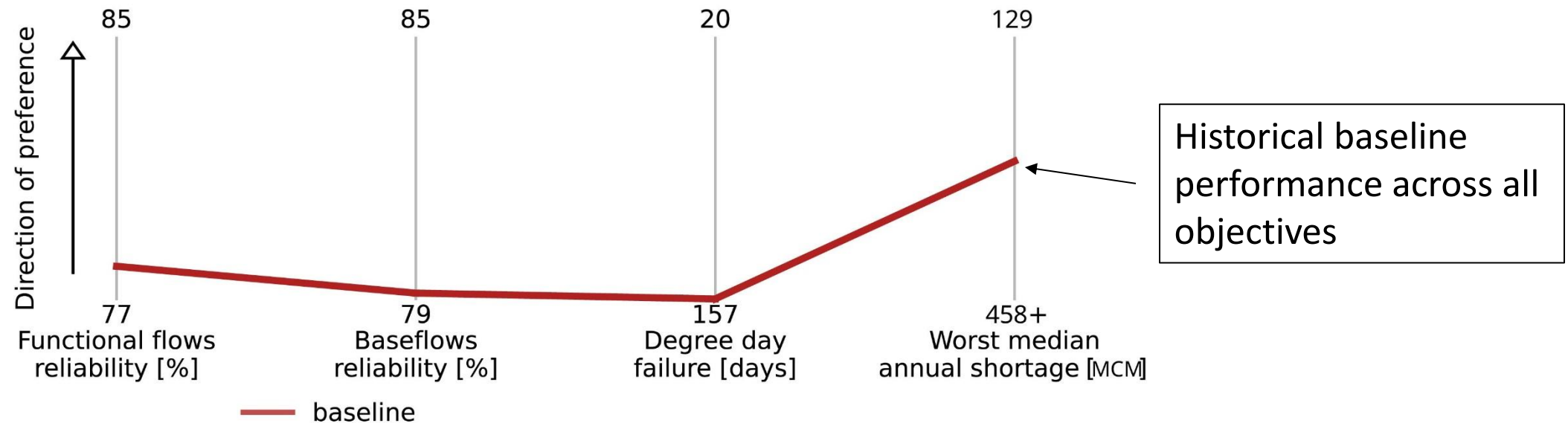


Exploring adaptive management solutions

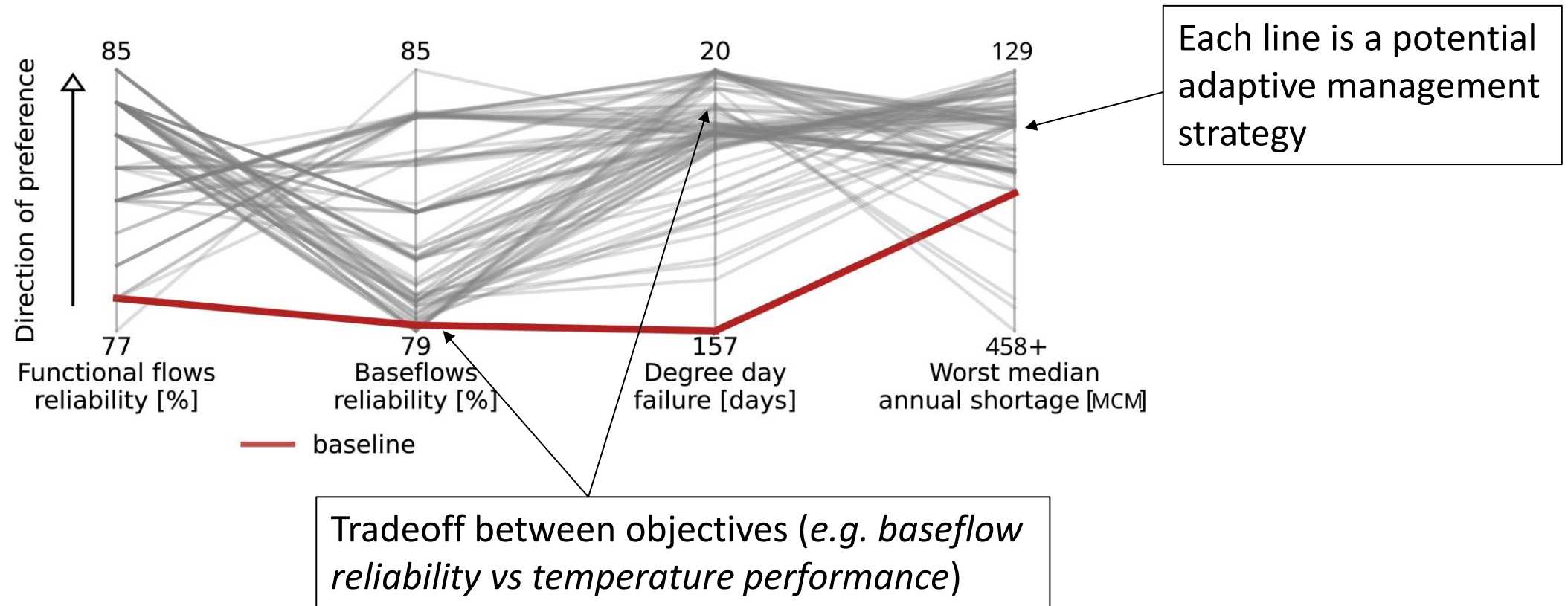
Parallel axis plot to visualize tradeoffs



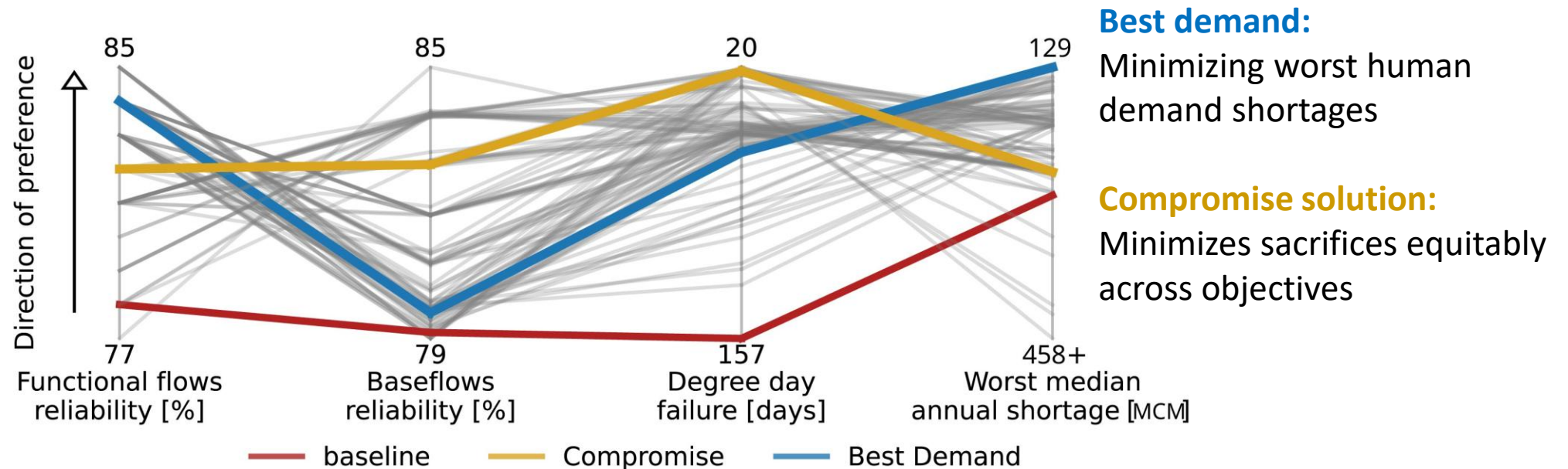
EWM adaptive environmental water management insights: Tradeoffs between system objectives



EWM adaptive environmental water management insights: Tradeoffs between system objectives

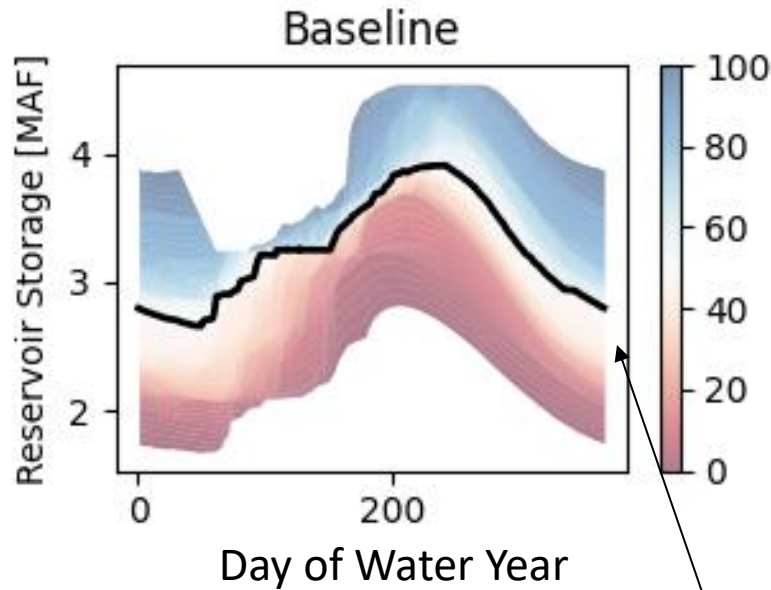


EWM adaptive environmental water management insights: Tradeoffs between system objectives



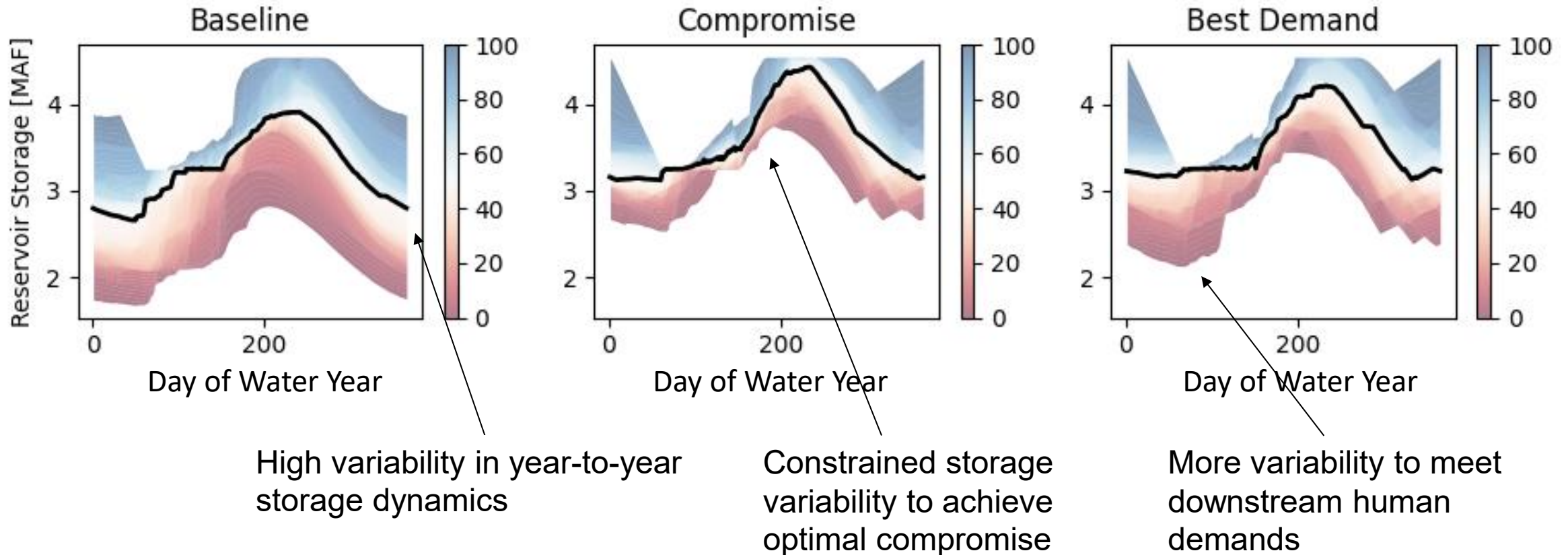
We can select solutions with different management preferences to understand the impact on system tradeoffs, *human vs environmental* and *environmental vs environmental*

EWM adaptive environmental water management insights: System dynamics for different management strategies

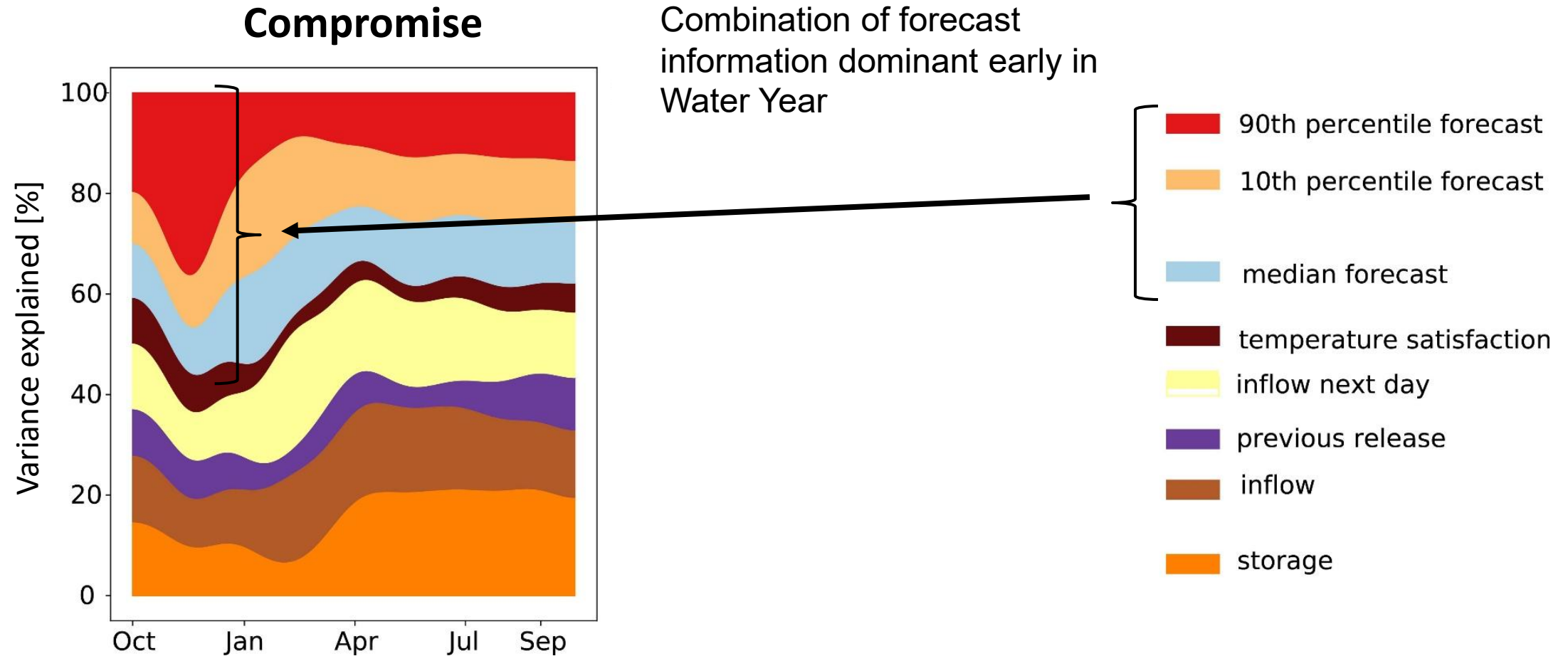


High variability in year-to-year
storage dynamics

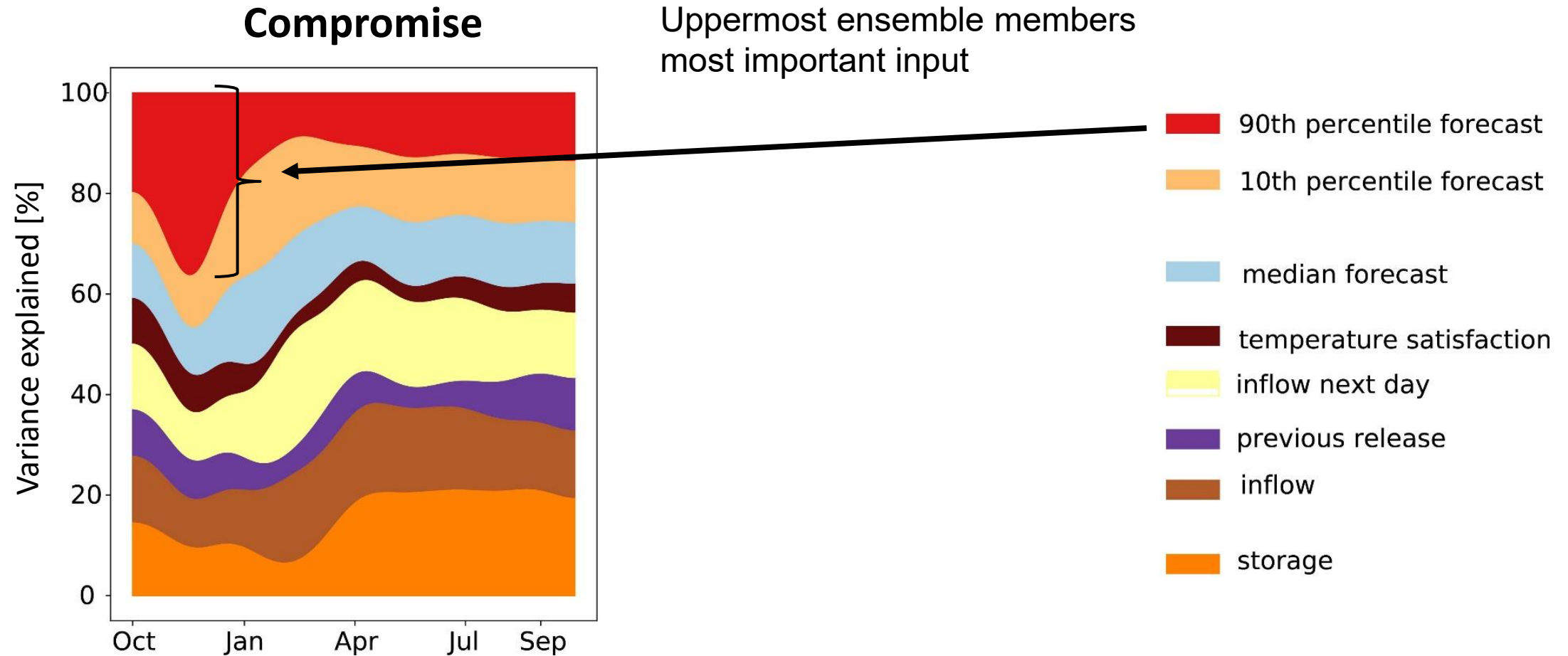
EWM adaptive environmental water management insights: System dynamics for different management strategies



EWM adaptive environmental water management insights: The time-varying value of information sources

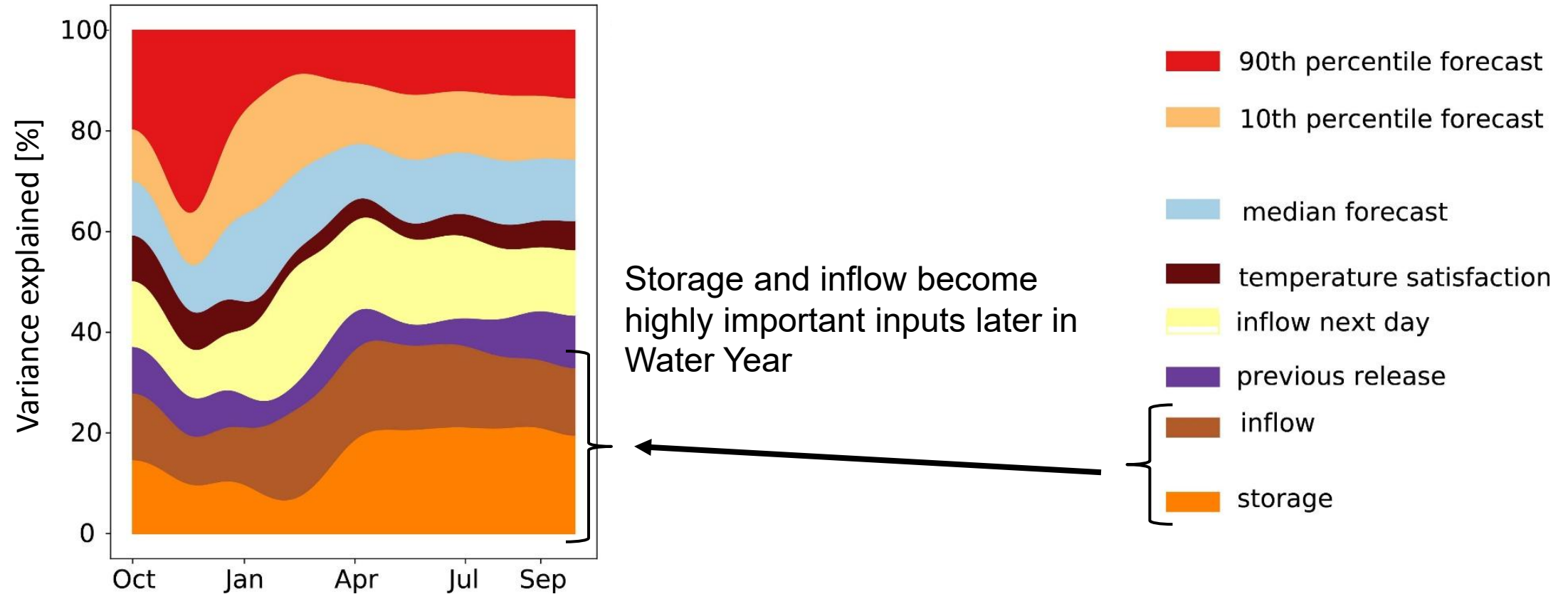


EWM adaptive environmental water management insights: The time-varying value of information sources

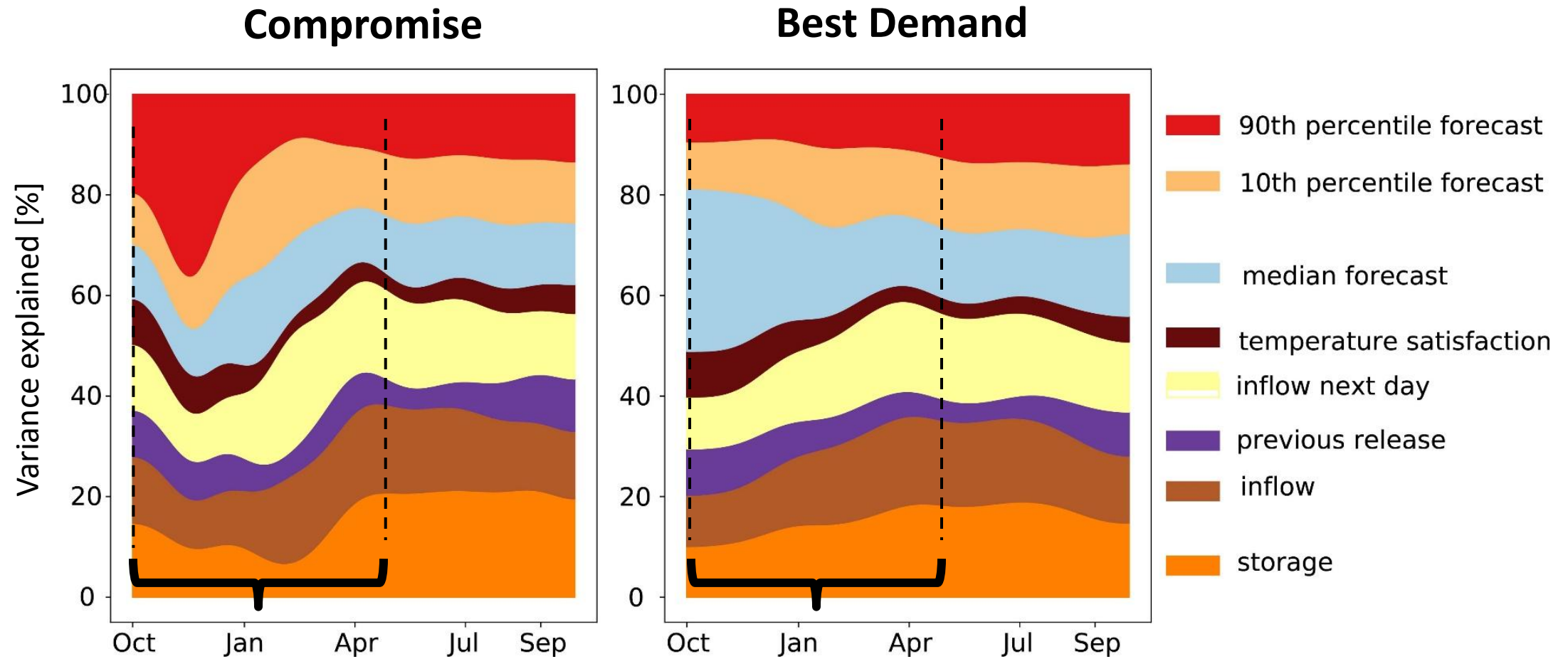


EWM adaptive environmental water management insights: The time-varying value of information sources

Compromise

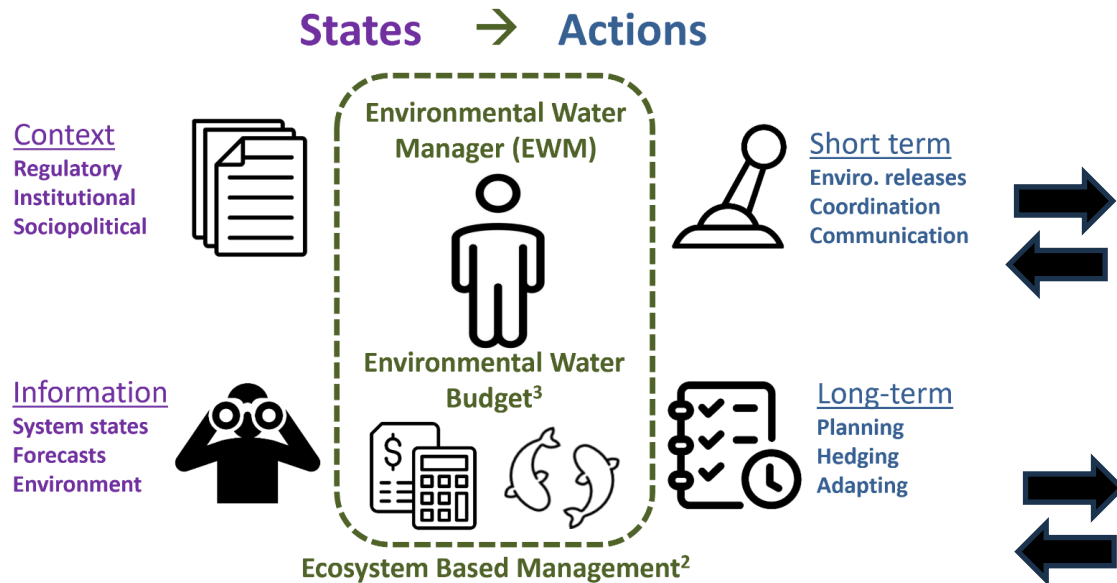


EWM adaptive environmental water management insights: The time-varying value of information sources

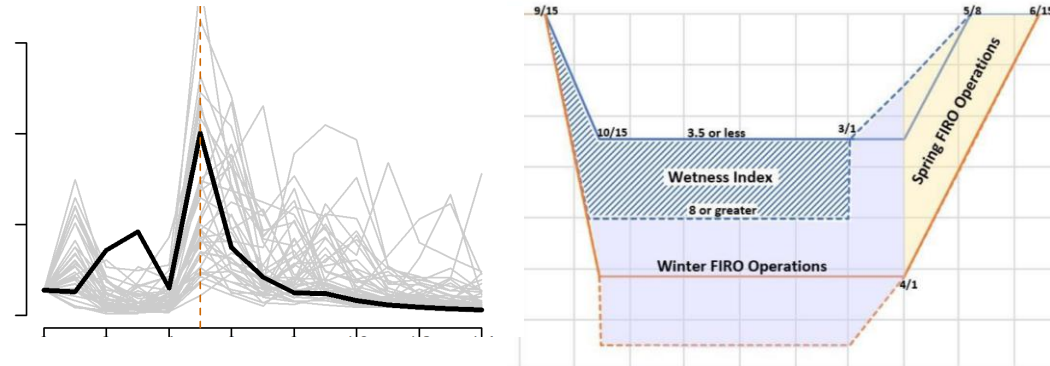


Time-varying, value-of-information dynamics differ
between adaptive management strategies

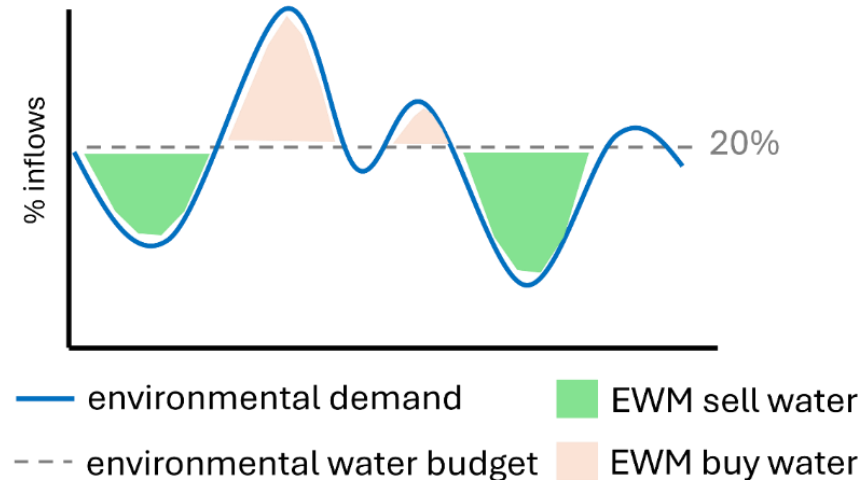
Future Work: Synergies w/emerging strategies



Forecast Informed Reservoir Operations (FIRO)



Environmental water markets



Synergies

- Modeling tools and strategies
- Institutional and operational flexibility
- Improvements to water supply reliability for the environment

Key takeaways

- An Environmental Water Manager (EWM) is a potential solution to *maximize the ecological performance* of managed river systems
- Exploring potential EWM benefits via models requires representation of *state-aware, multi-timescale* actions across multiple human and environmental objectives
- Our *adaptive environmental water management model* enables this exploration through novel coupling of water systems and quality models and the integration of forecast information
- We can develop insights into *system tradeoffs, system dynamics*, and the *value of information* under different adaptive environmental water management strategies

Questions?

Reference:

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- Null, S. E., Zeff, H., Mount, J., Gray, B., Sturrock, A. M., Sencan, G., Dybala, K., & Thompson, B. (2024). Storing and managing water for the environment is more efficient than mimicking natural flows. *Nature Communications*, 15(1), 5462. <https://doi.org/10.1038/s41467-024-49770-4>
- Sunkara, S. V., Brodeur, Z., Penny, G., Hall, M., & Reed, P. (n.d.). Enhancing adaptive reservoir management across multiple decision horizons to better balance human and ecosystem objectives. *In preparation*
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Additional Slides

Global freshwater ecosystem challenges

‘Freshwater ecosystems cover <1% of earth’s surface, but host ~1/3 of vertebrate species and 10% of all species’ (Tickner et al., 2020)



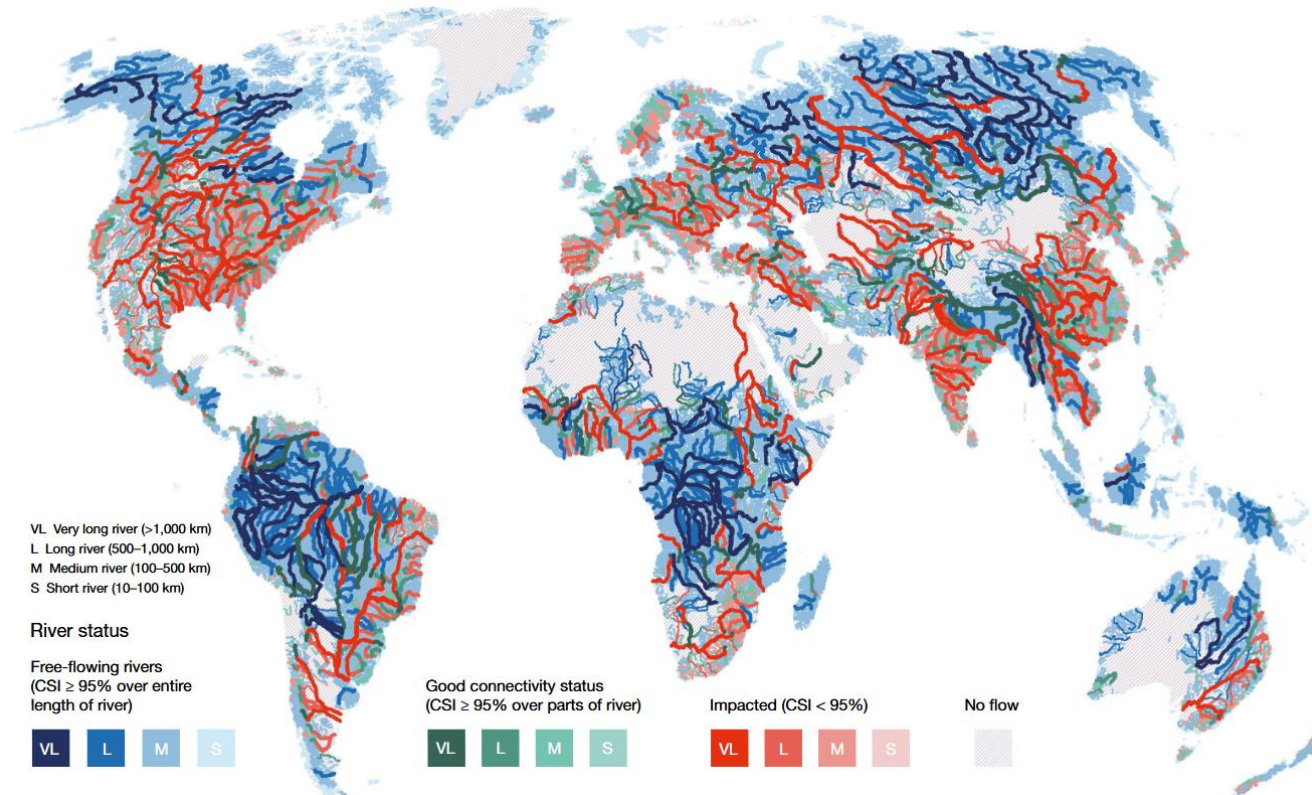
‘Riverine ecosystems provide services to **billions of people**, yet remain among the most *undervalued*, *overexploited*, and *degraded* ecosystems worldwide’ (Arthington et al., 2024)

Global freshwater ecosystem challenges

‘...an estimated ~**50%** of the global river volume is currently altered by either flow regulation or fragmentation, the pending construction of ~3,700 major hydropower dams is expected to **increase** this percentage to **93%**’ (Barbarossa et al., 2020)

Free-
flowing
rivers

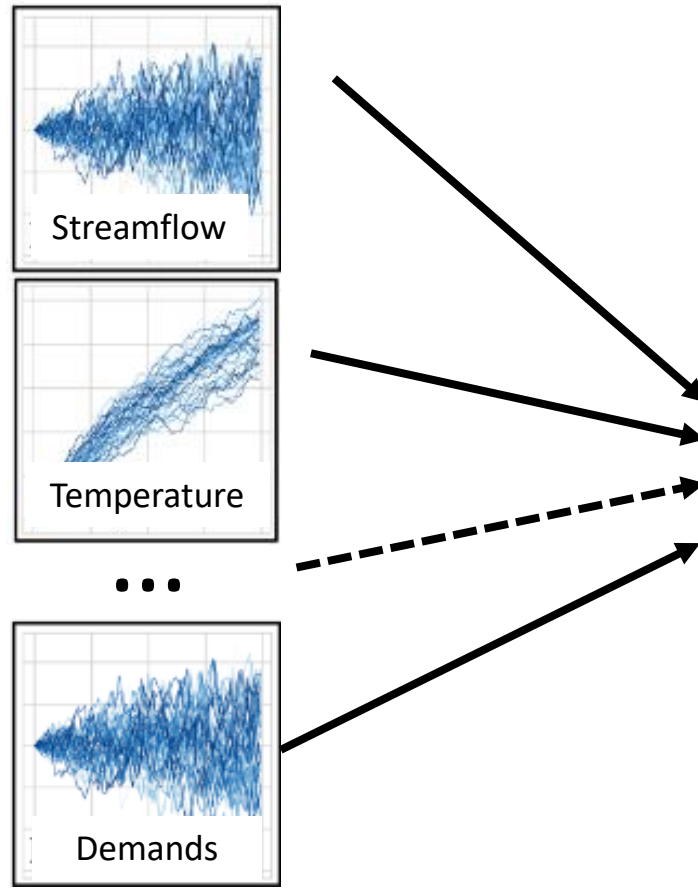
Highly
altered
rivers



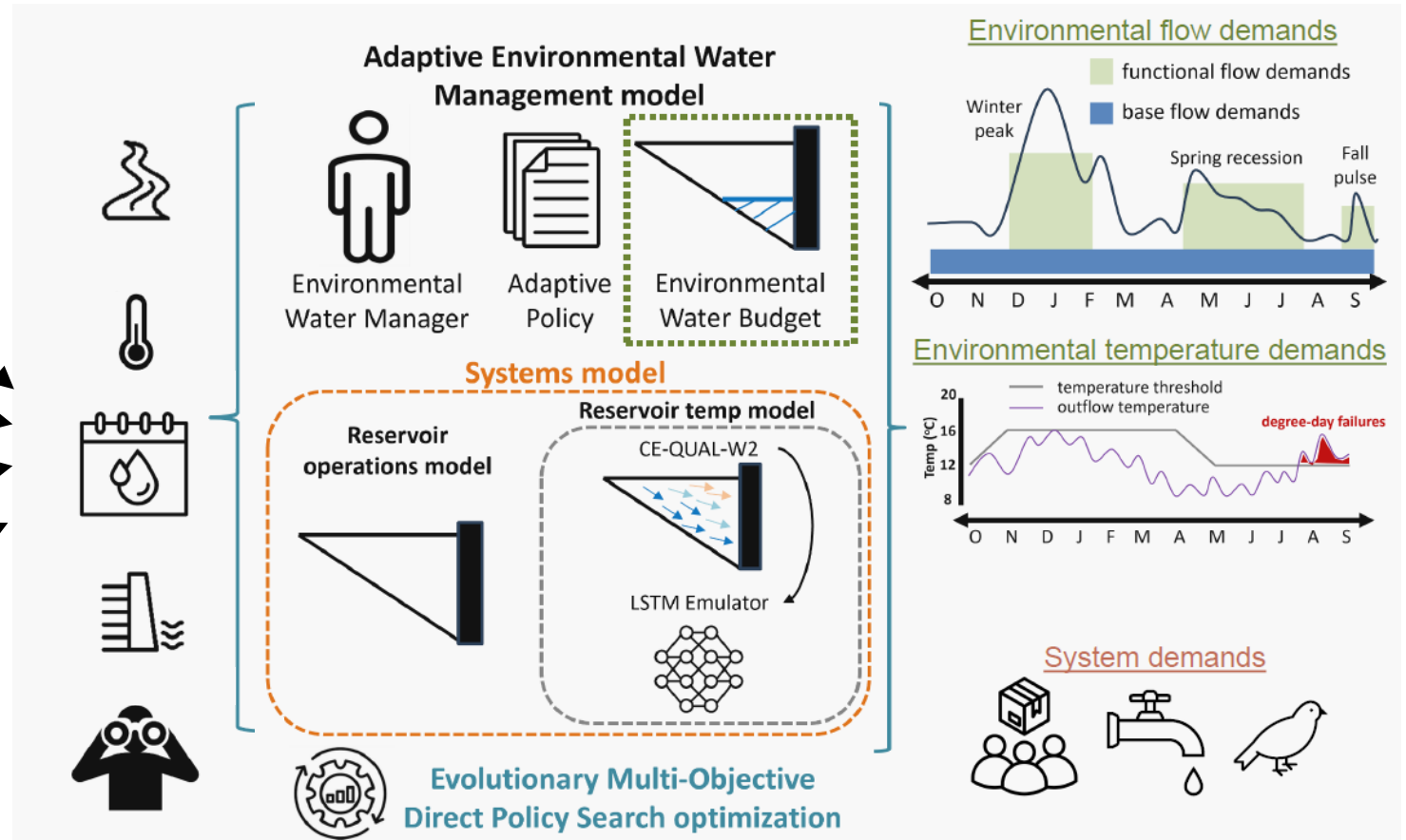
Grill et al., 2019

Future Work: Stochastic scenario development and EWM robustness

Stochastic inputs



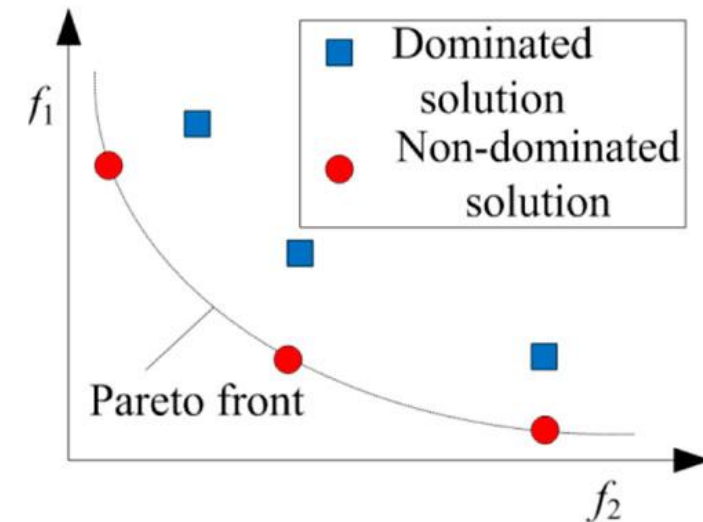
EWM adaptive decision-making robustness



Core elements of the adaptive environmental water management model

System optimization

Find the set of non-dominated solutions across 4 objectives (3 Enviro + 1 Human)

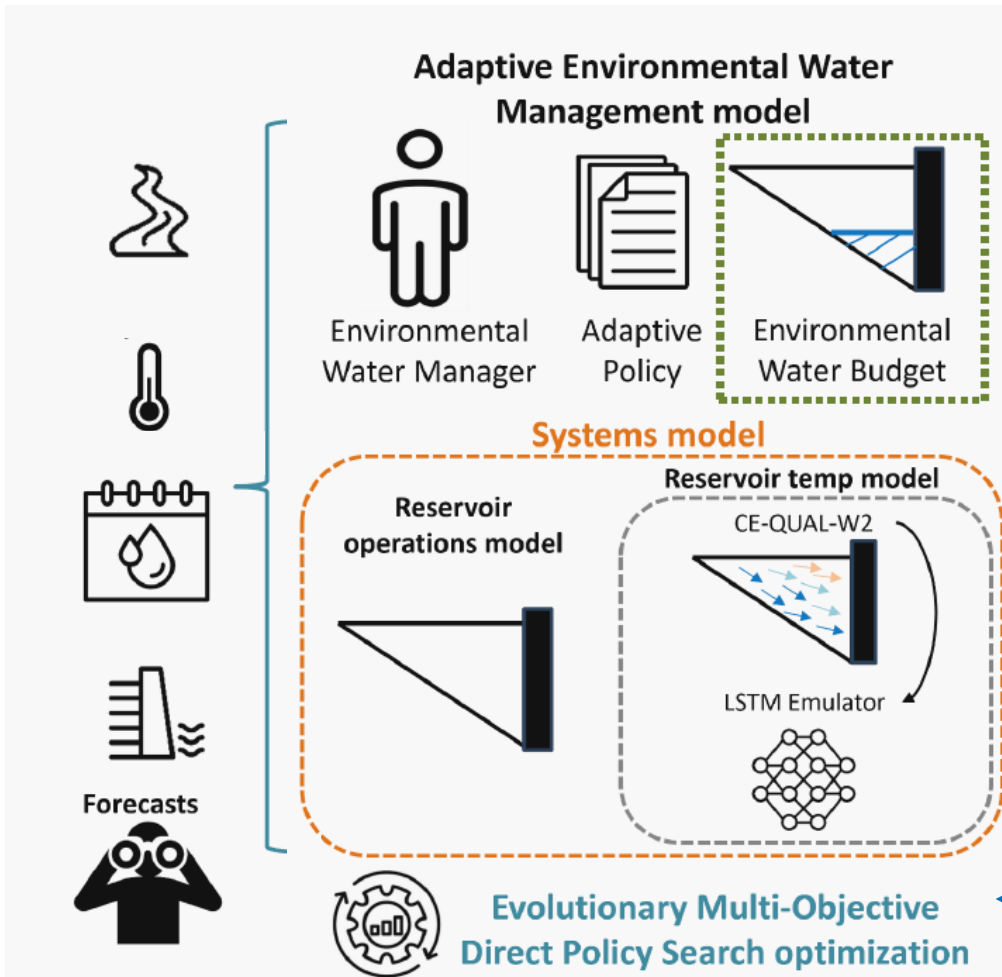


Borg evolutionary optimization algorithm:

- State-of-the-science for complex, high-dimensional optimization problems

Hadka and Reed, 2013

Sunkara et al., In Preparation



Future Work: Real-world applications

Willamette River System

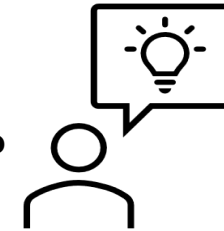


- System contains 13 USACE dams
- On the docket for major FIRO implementation effort starting 2026
- Large variety of environmental water management challenges

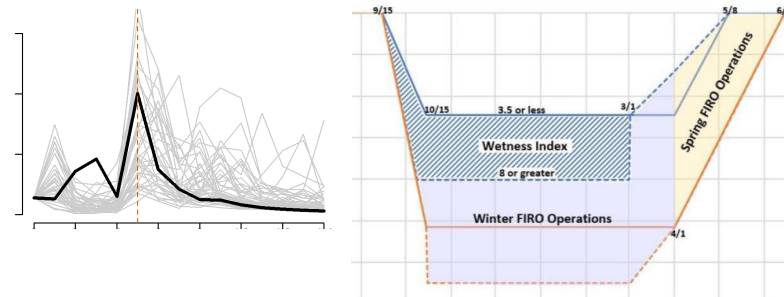
Environmental Water Management



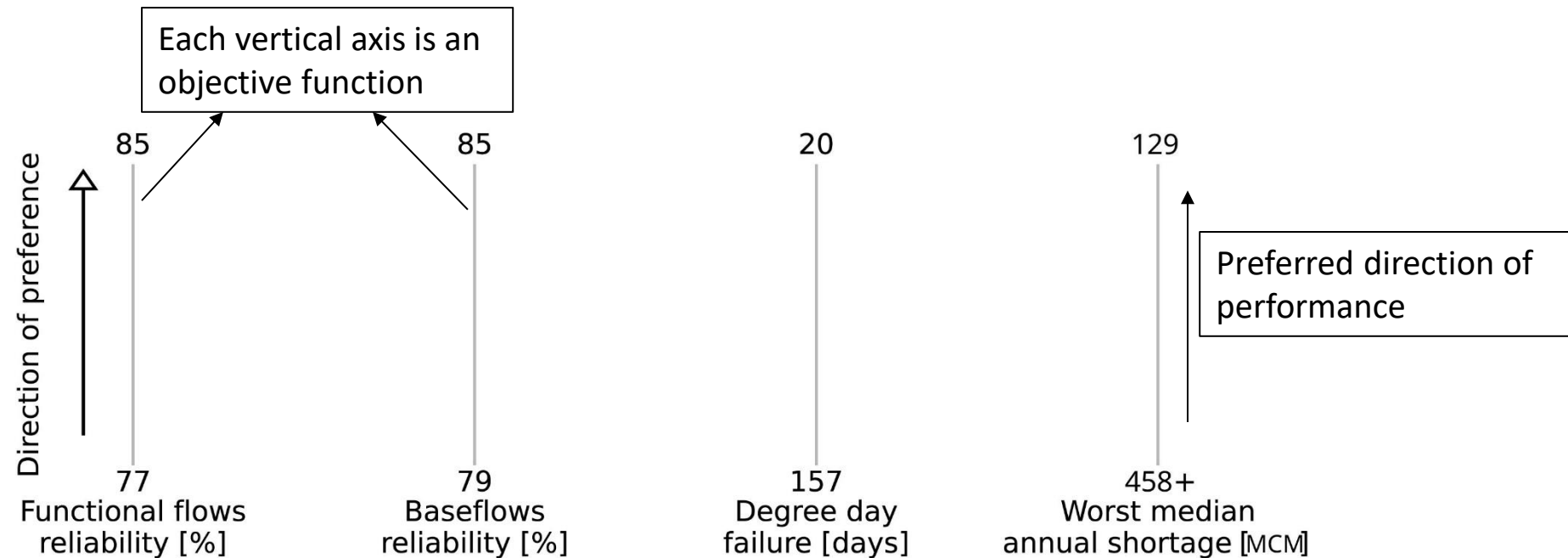
EWM
impacts?



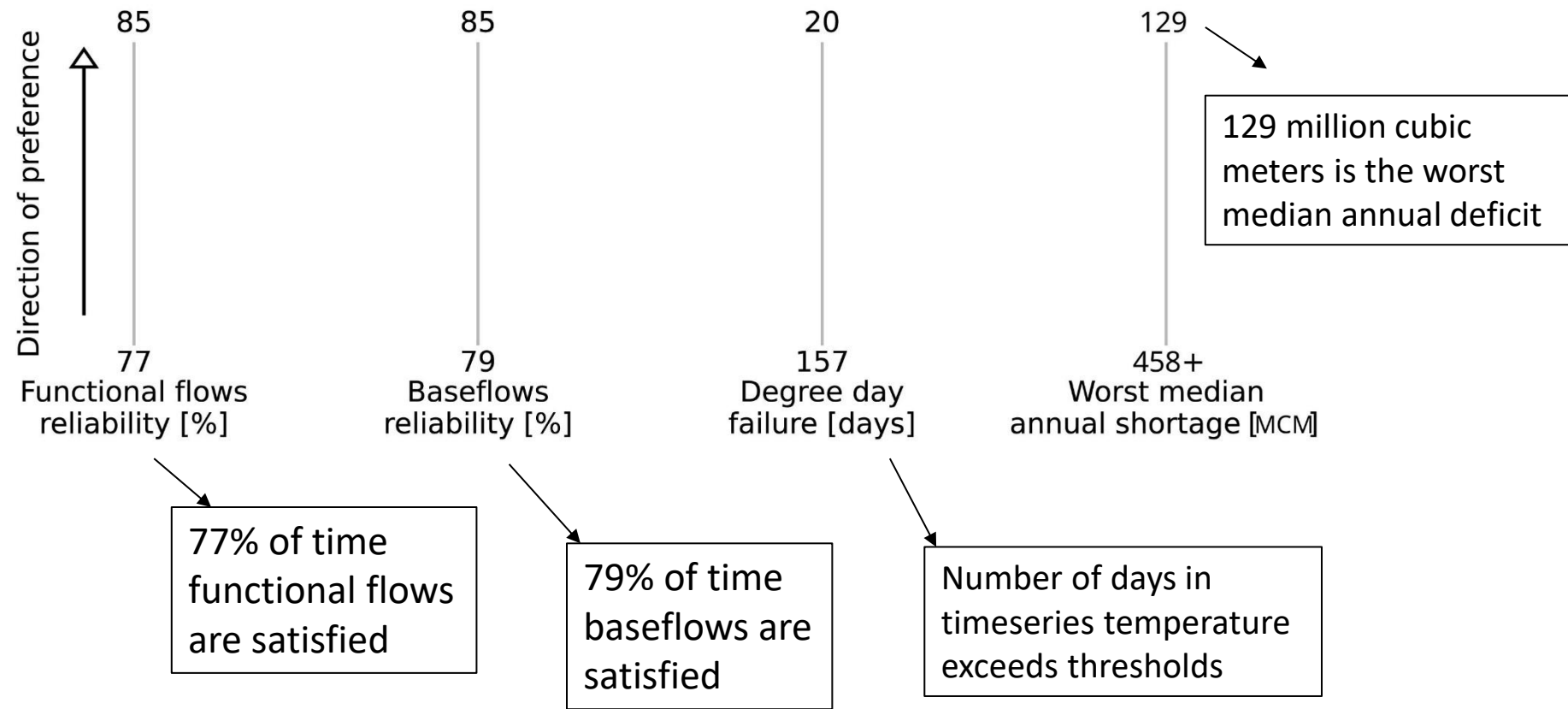
Forecast Informed Reservoir Operations



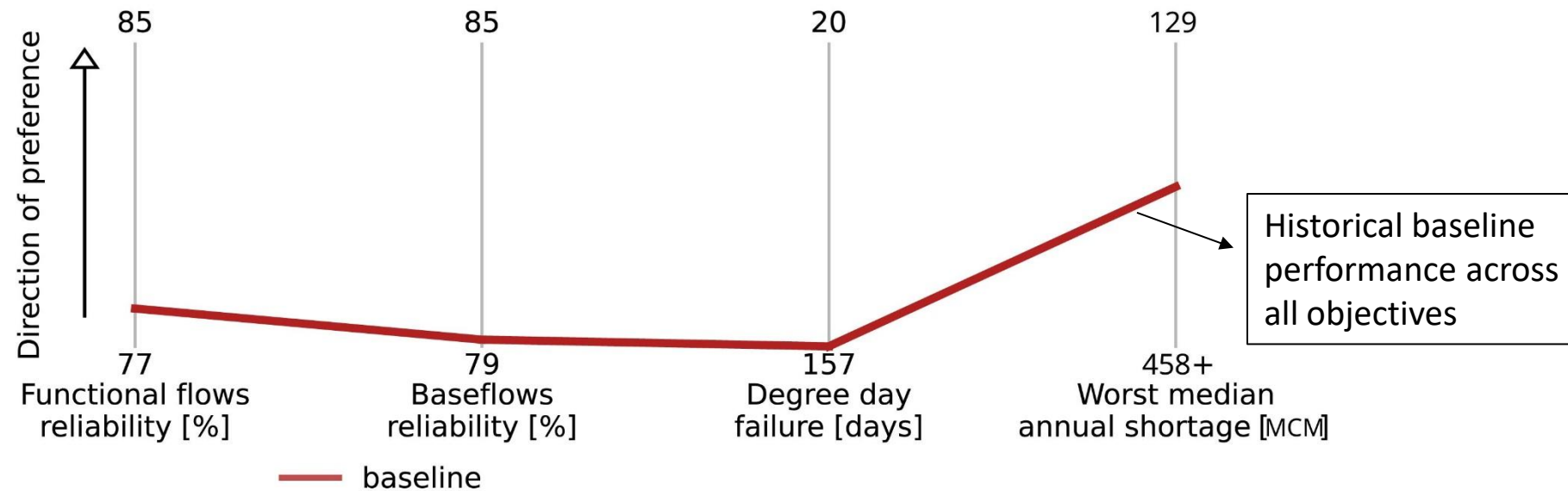
Alternative EWM policies identified through optimization



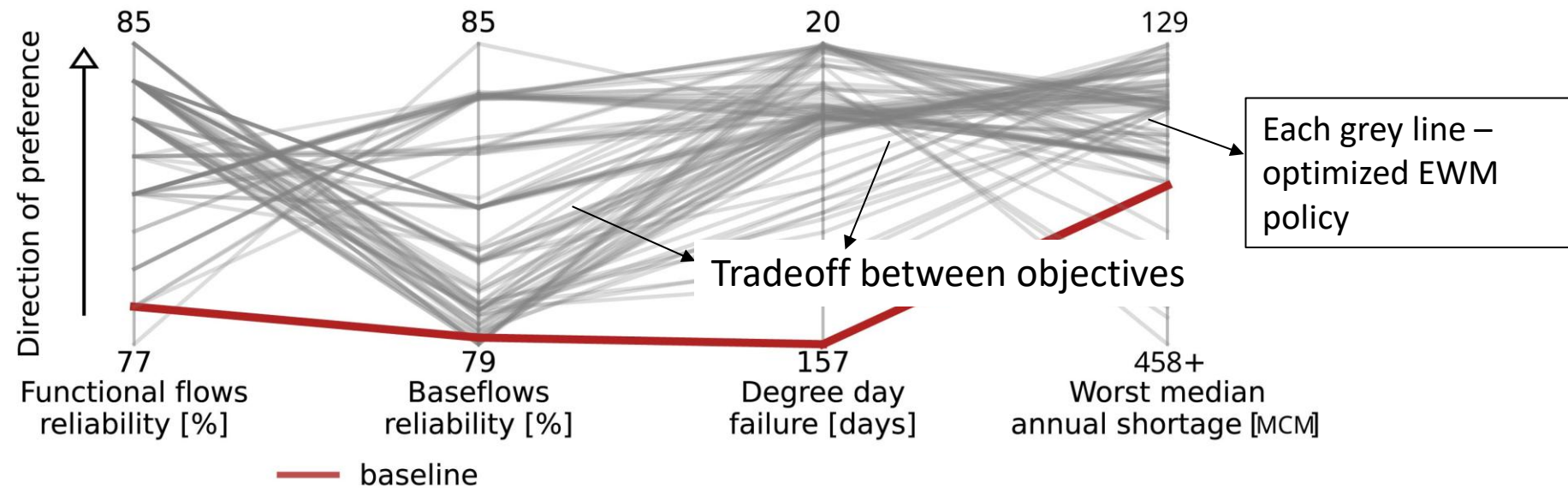
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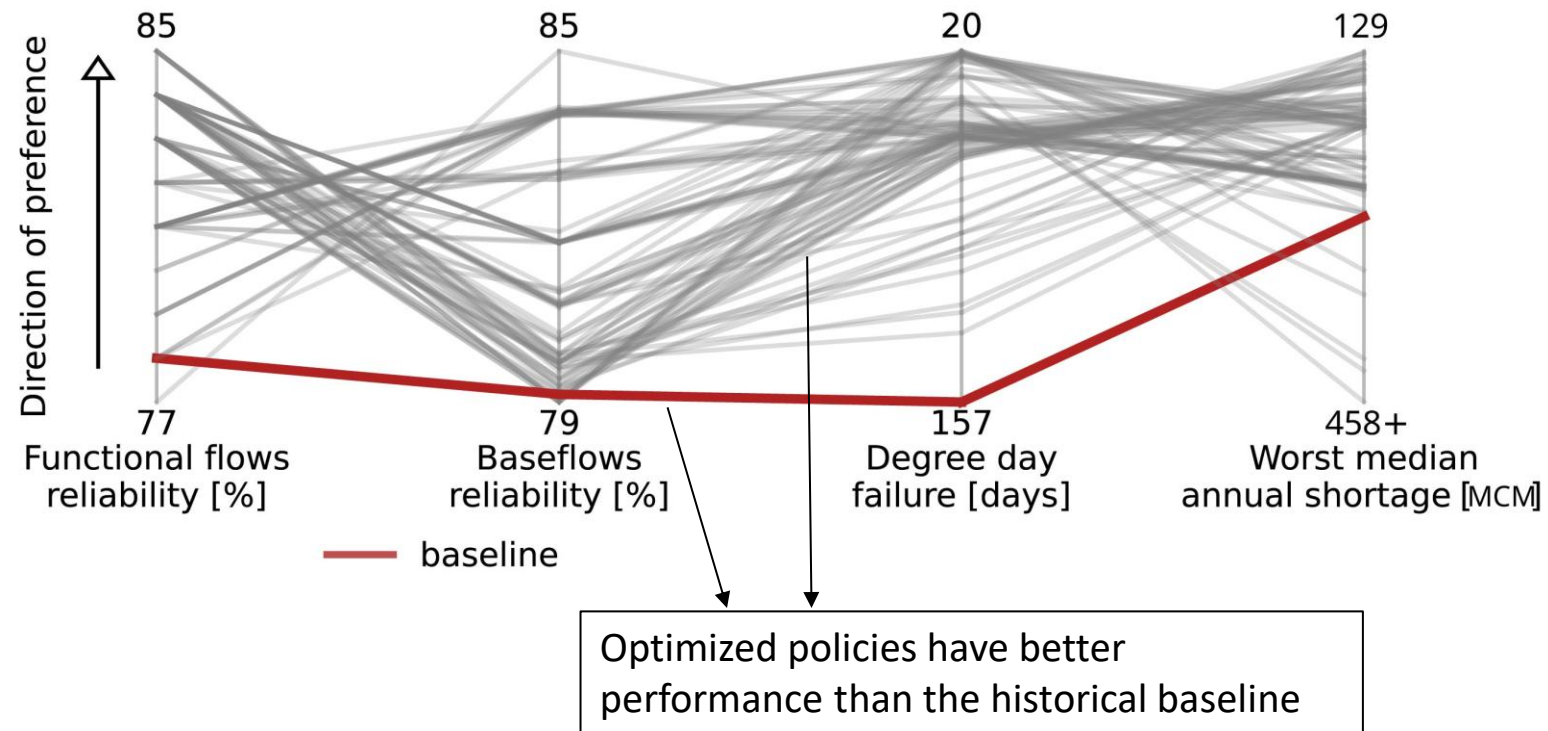
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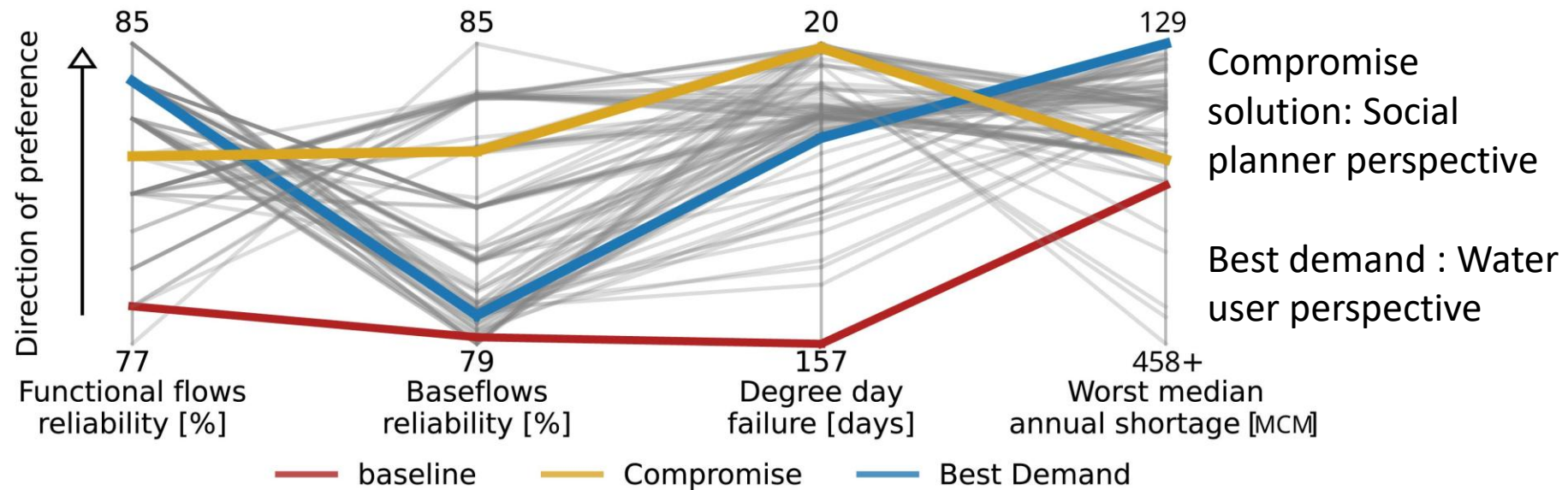
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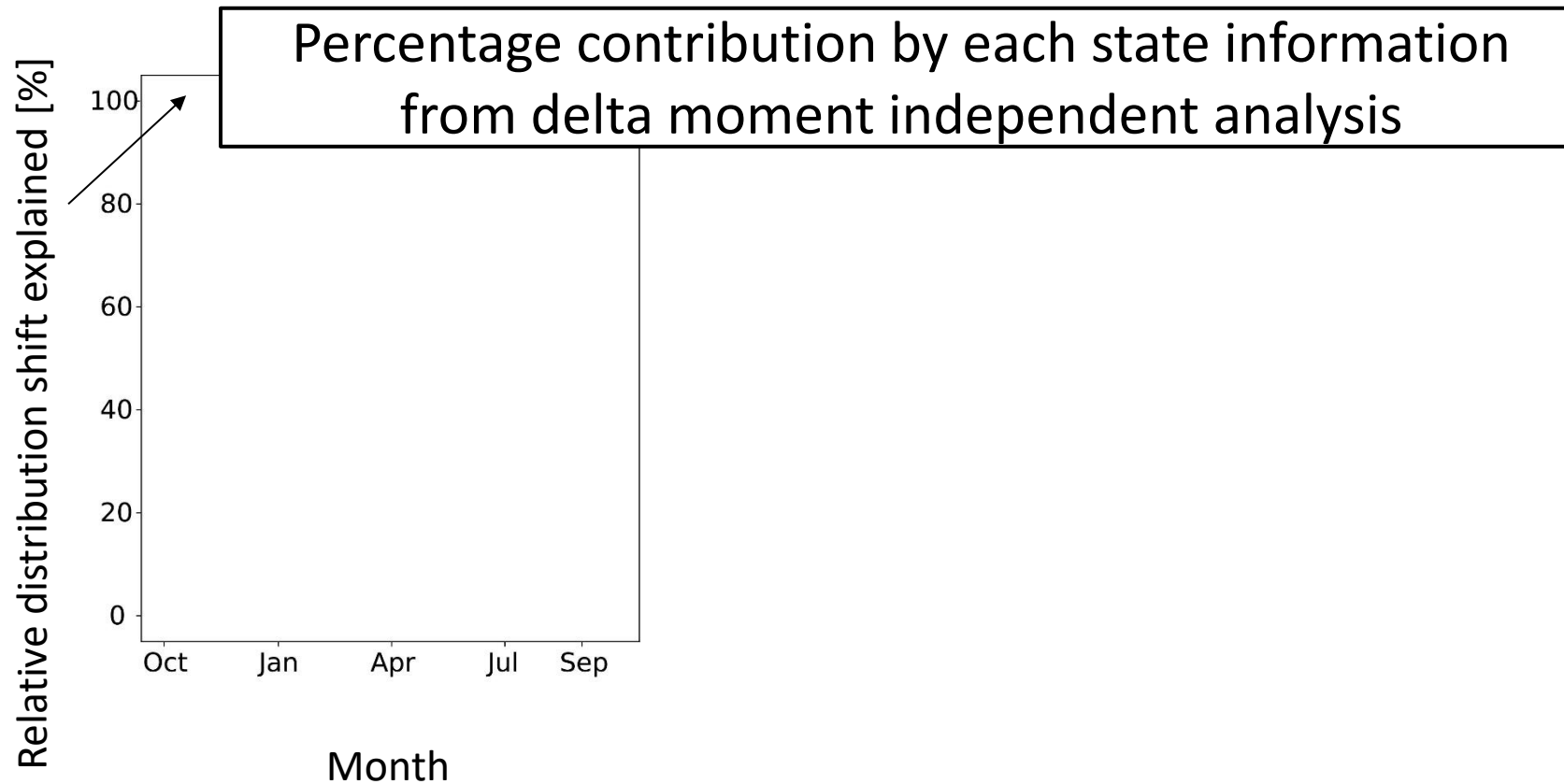
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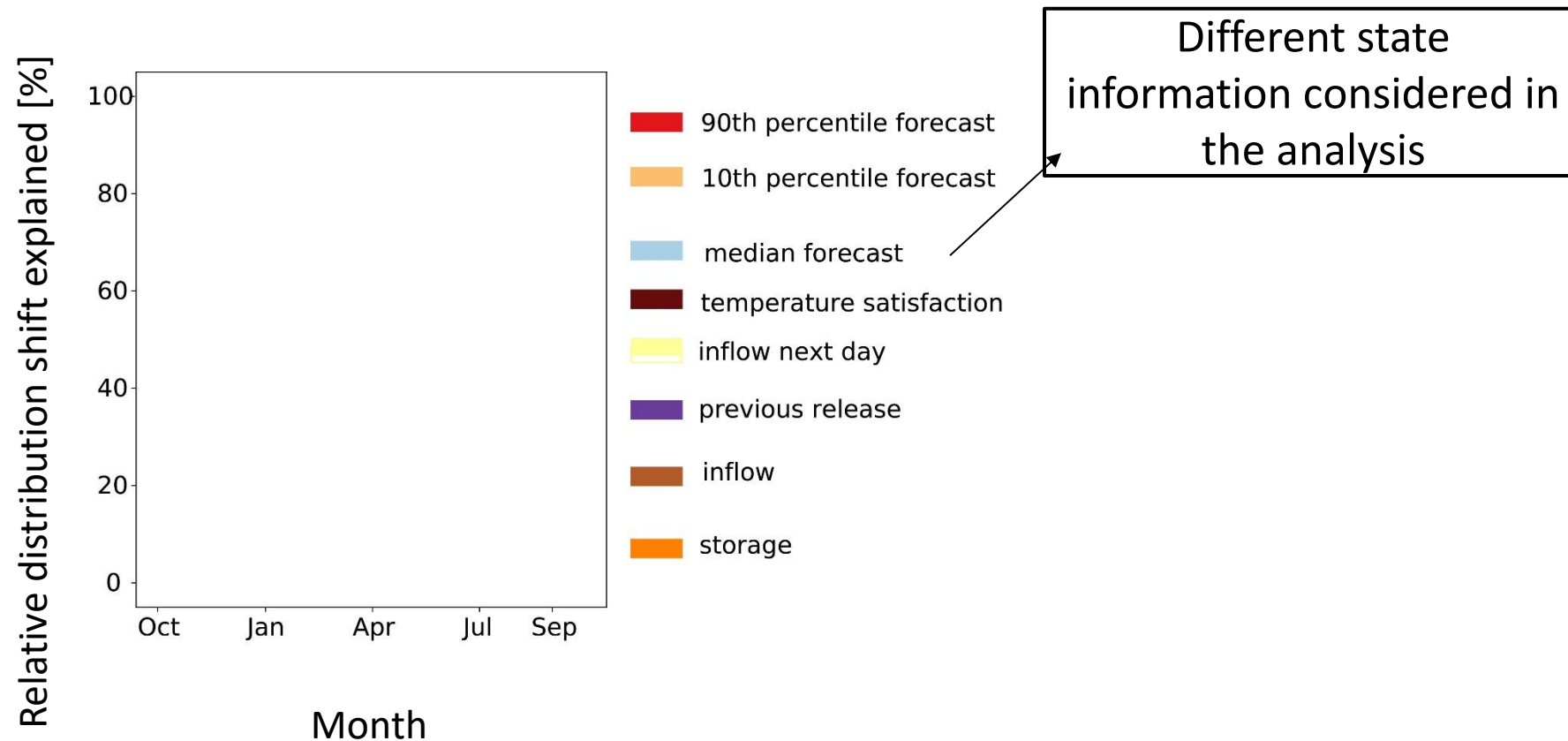
We select two solutions for further exploration



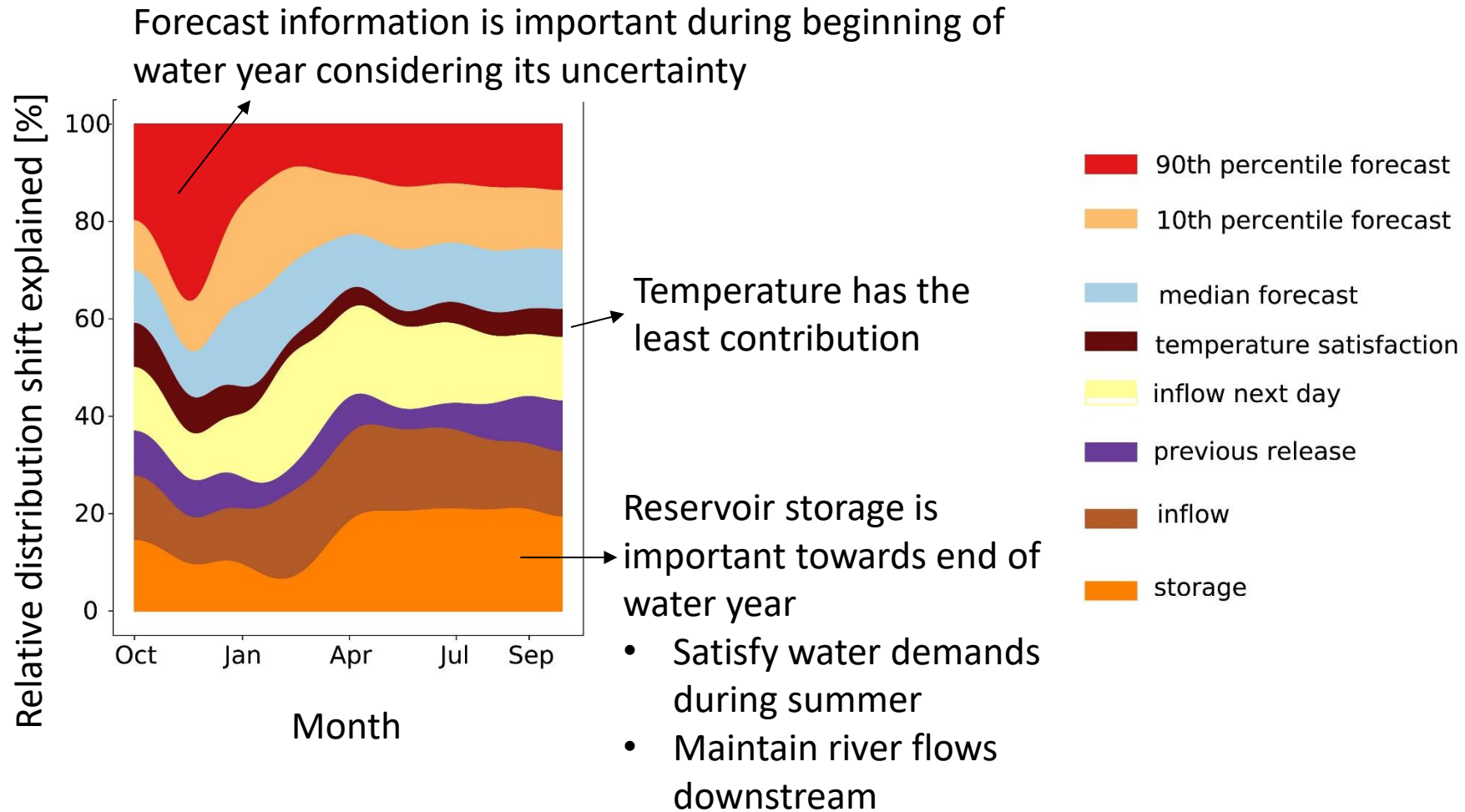
Variation in importance of state information for compromise policy



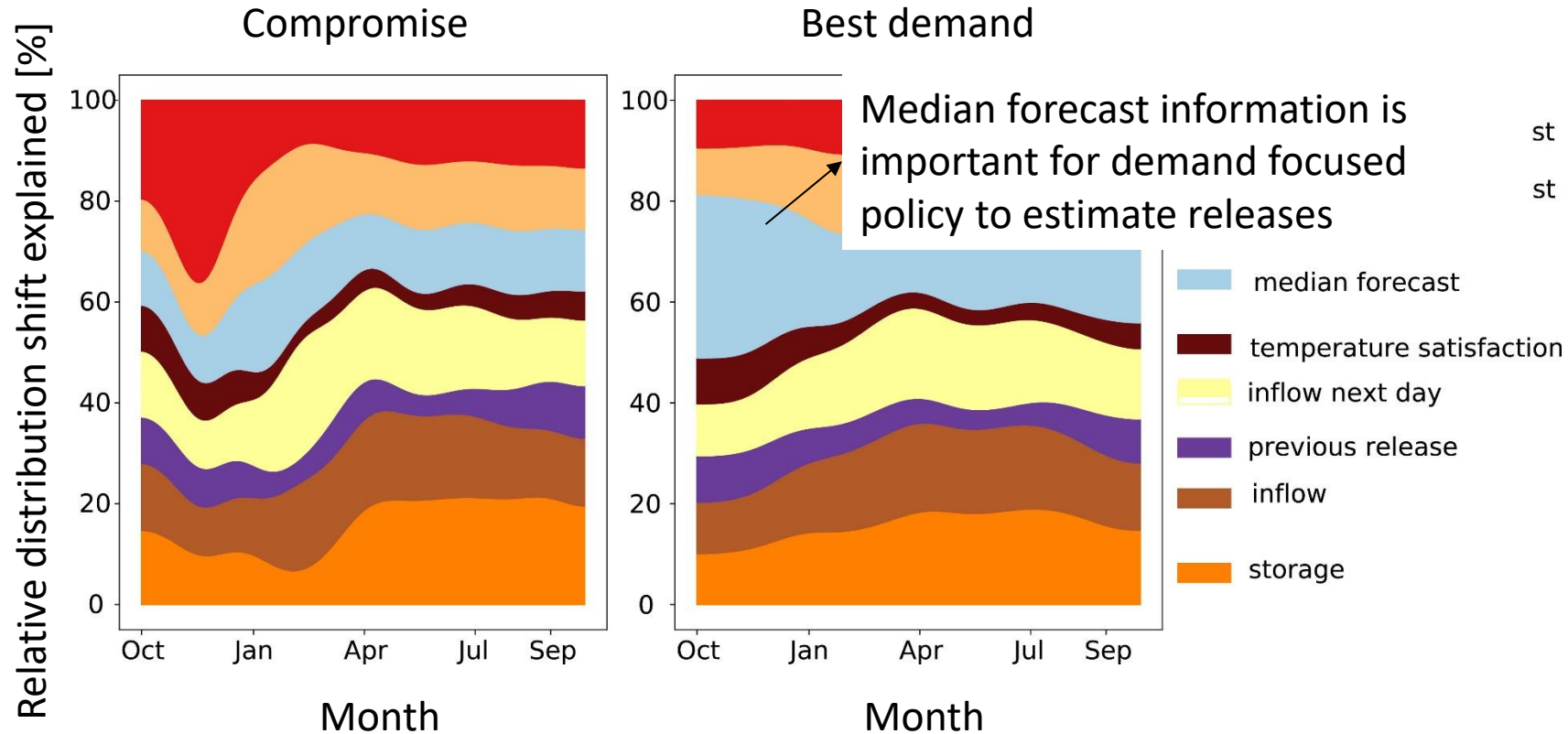
Variation in importance of state information for compromise policy



Variation in importance of state information for compromise policy

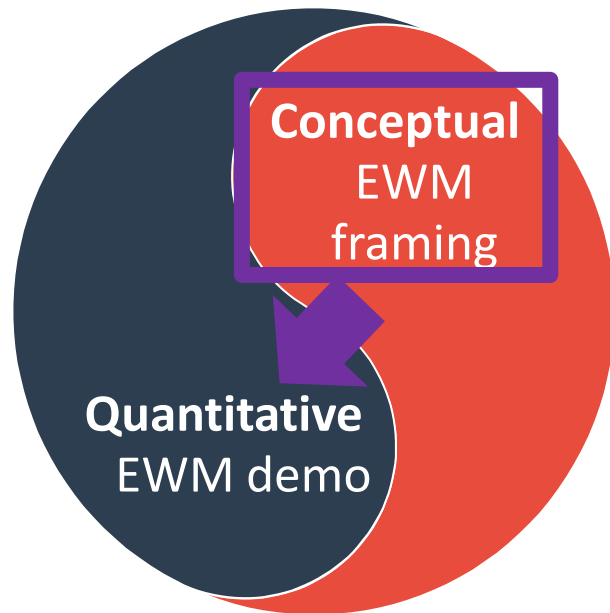


Variation in importance of state information for compromise and best demand policy



Building off an EWM conceptual framework

Project efforts



EWM Conceptual Framework

States → Actions

Context
Regulatory
Institutional
Sociopolitical



Information
System states
Forecasts
Environment



Environmental Water
Manager (EWM)



Environmental Water
Budget³



Ecosystem Based Management²

Brodeur et al., In Review



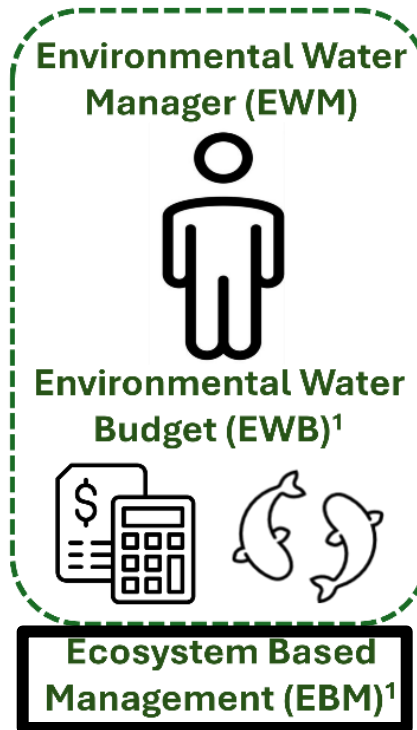
Short term
Enviro. releases
Coordination
Communication



Long-term
Planning
Hedging
Adapting

EWM elements: Ecosystem-Based Management

States → Actions



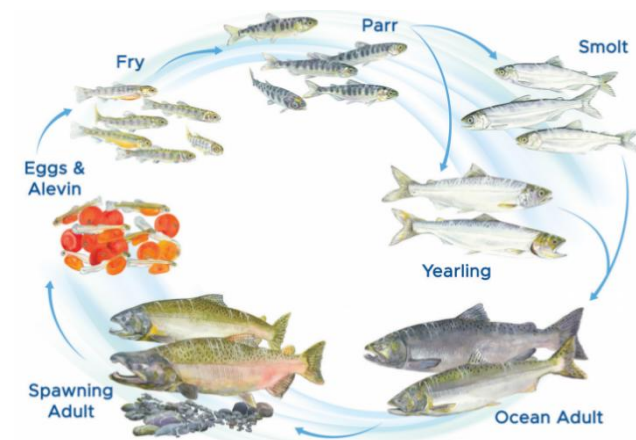
EBM is a management strategy that:

- leverages *flexible and robust* governance structures
- targets *improved ecosystem conditions* for biodiversity
- accounts for *coupled natural-human system* dynamics
- prioritizes *multi-benefit* actions over species-specific

Ecosystem structure



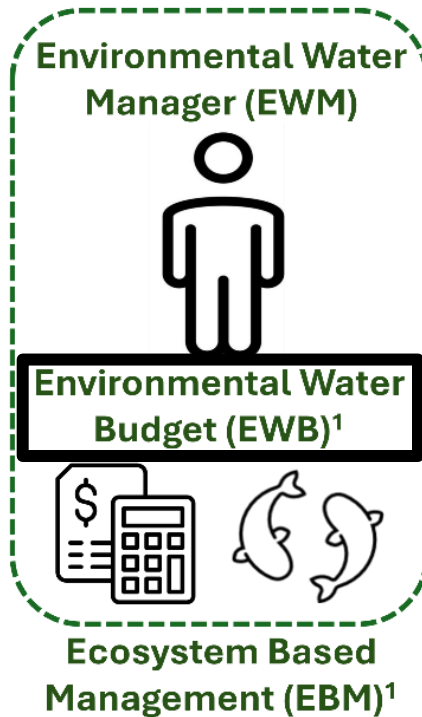
Ecosystem function



(Mount et al., 2019)

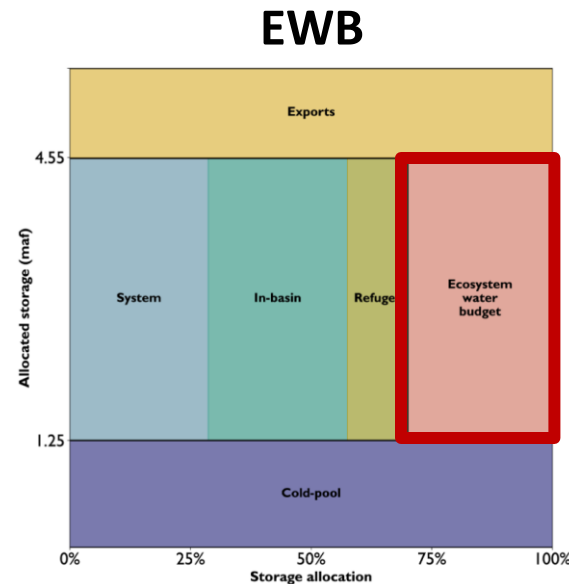
EWM elements: Environmental Water Budget

States → Actions

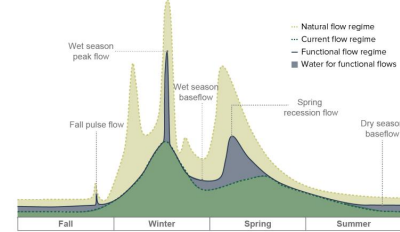


EBM benefits from an **EWB**:

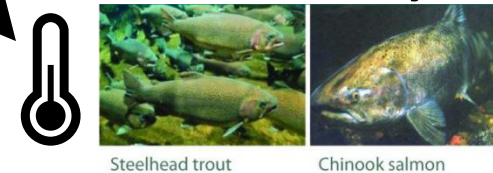
- prescribed volume of water w/*senior water right*
- dedicated *solely* for environmental purposes
- should include *both storage and inflow capacity*
- can be adaptively allocated with the *quantity, quality, and timing* for the greatest ecosystem benefits



Functional Flows

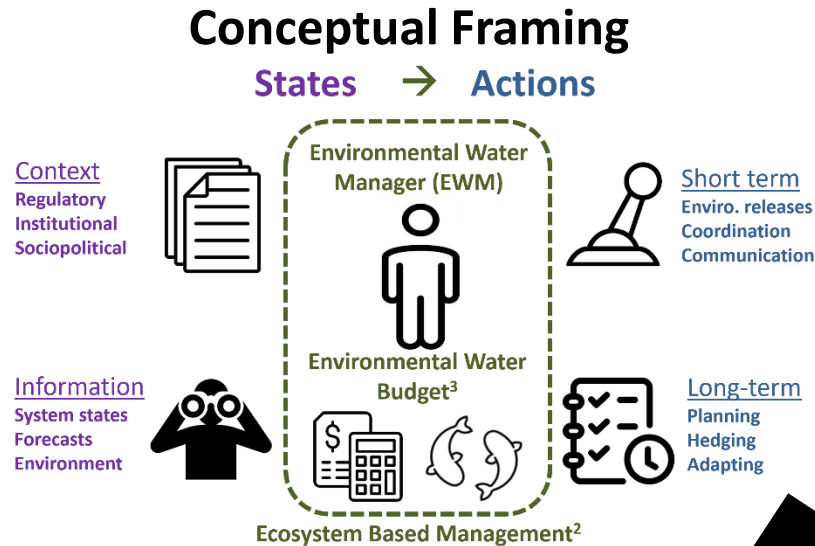


Water Quality



(Mount et al., 2019; Null et al., 2024)

Translating the EWM concept to a pilot model



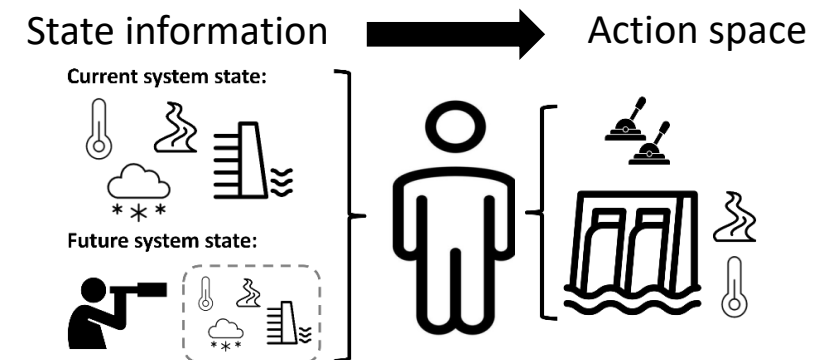
Modeling opportunities:

- *Adaptive* decision-making frameworks
- Systems model *coupling* strategies
- Uncertainty *aware* optimization
- Advanced *hindcast* datasets

Modeling challenges:

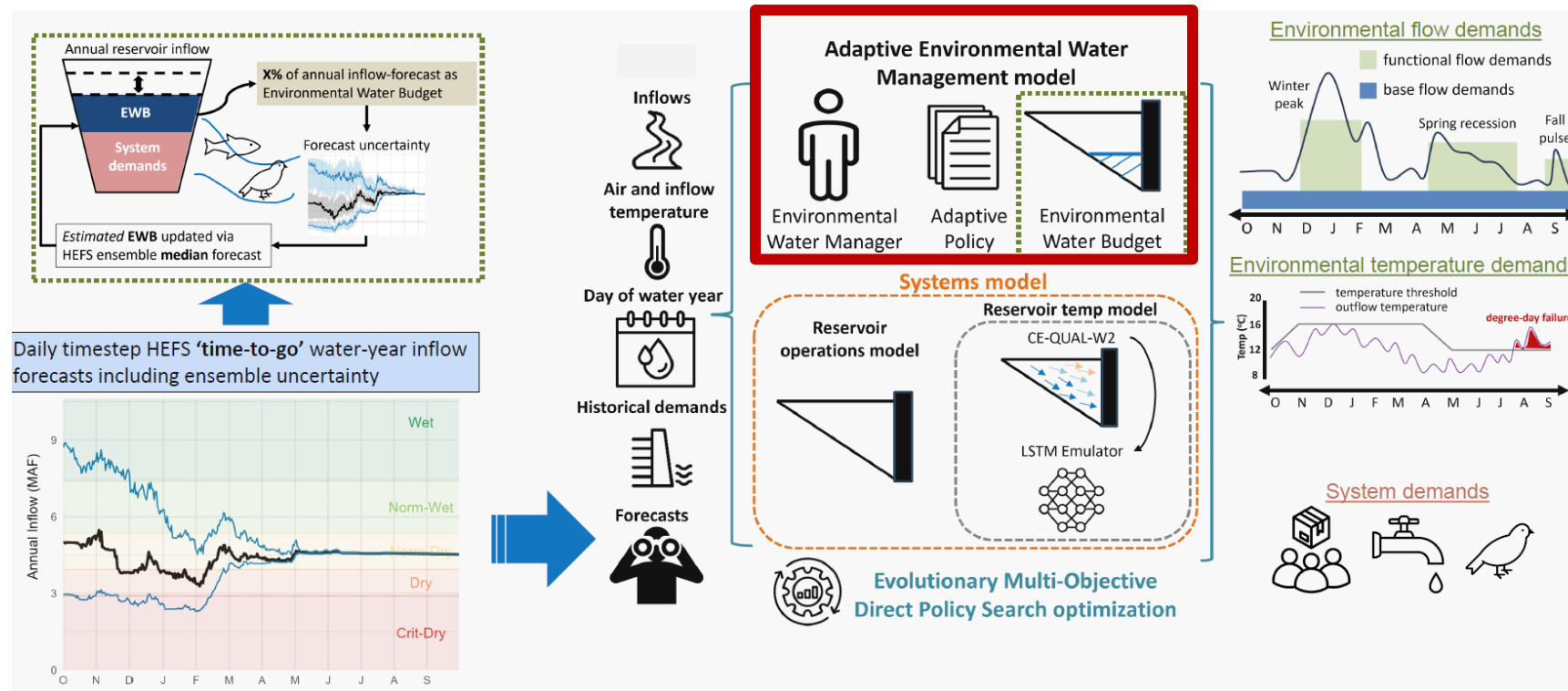
- *State-aware, adaptive* agent
- Actions across *multiple timescales* for *multiple benefits*
- Uses information *across* time-horizons (current obs → long-range forecasts)
- Informational *uncertainty*

Modeling problem formulation



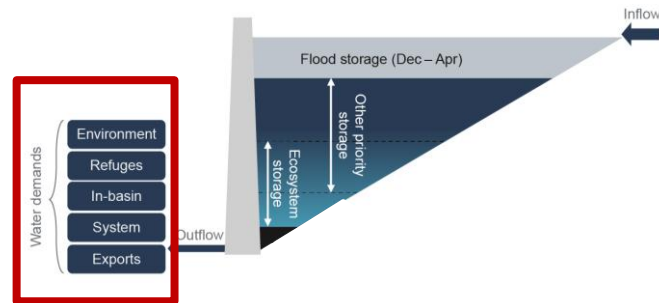
Abstracting the EWM with EMODPS

We utilize EMODPS to explore *EWM* adaptive environmental water management strategies and *interrogate* their outcomes



Simulation model setup

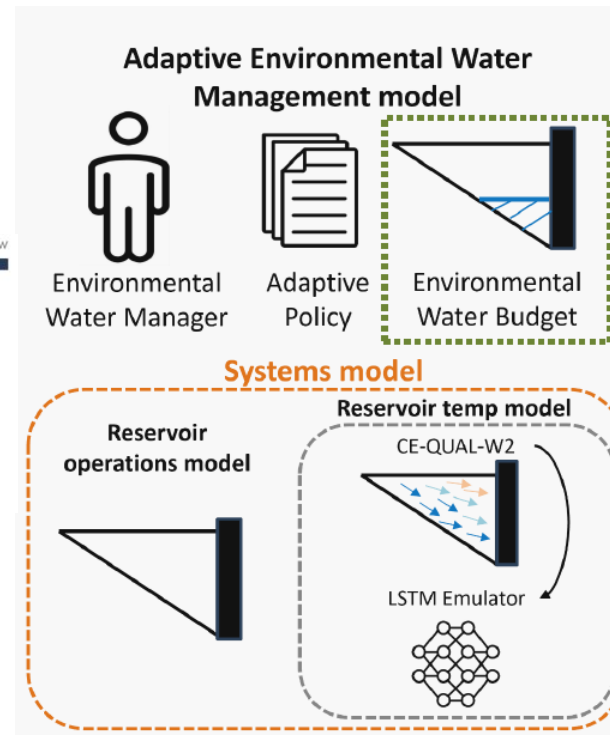
Stylized representation
of Shasta reservoir



Historical Shasta demands

Null et al. 2024

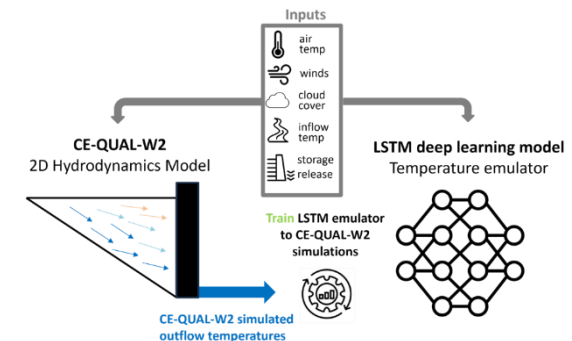
Simulation modeling framework



20%
Annual
Inflow



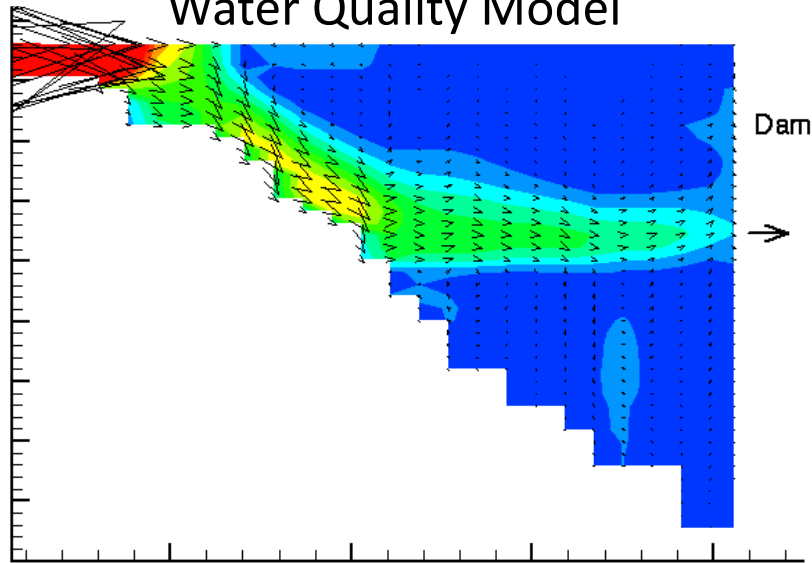
ML emulator approach
for water temperature



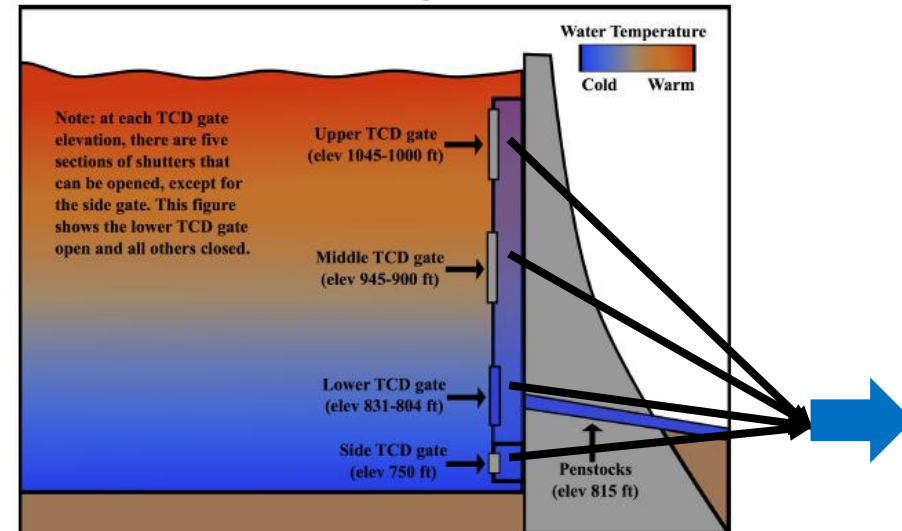
High resolution temperature model: CE-QUAL-W2

We first develop a high-resolution temperature model with a representation of Shasta Reservoir's Thermal Control Device (TCD)

CE-QUAL-W2 Hydrodynamic & Water Quality Model



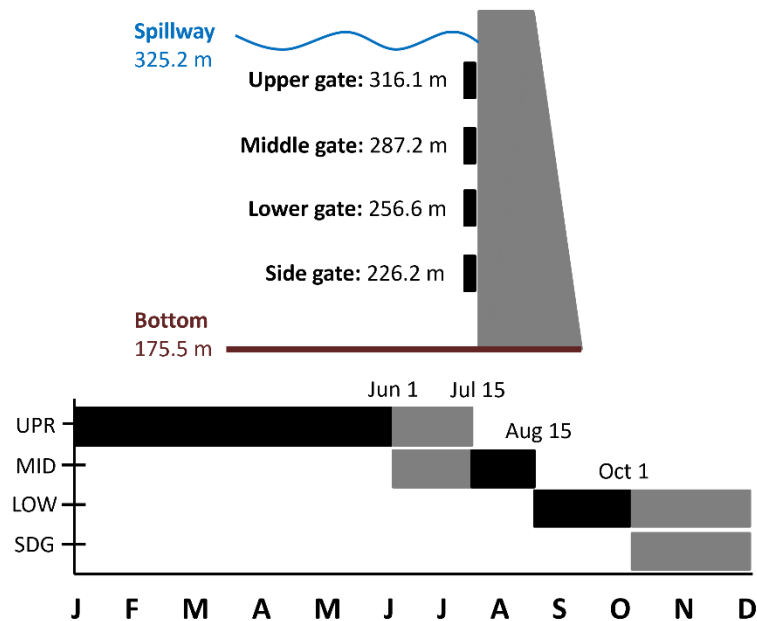
Shasta Thermal Control Device (TCD) diagram



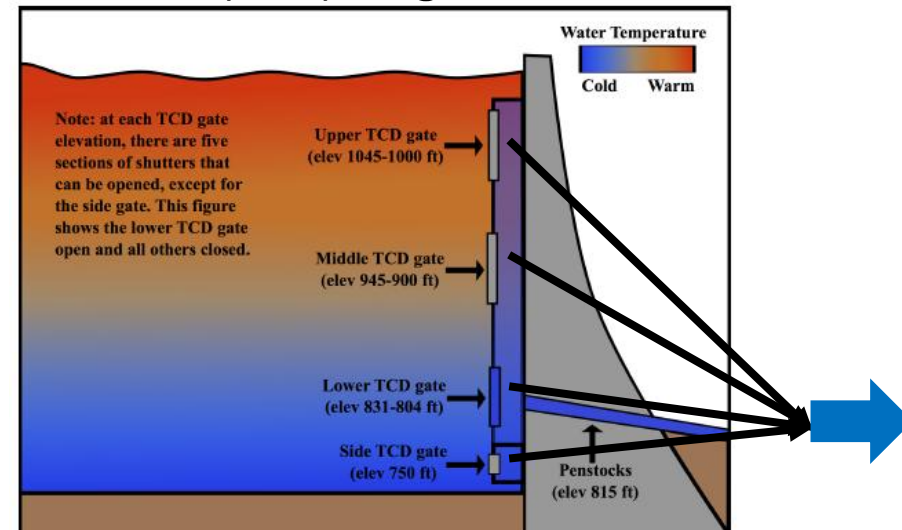
High resolution temperature model: CE-QUAL-W2

We implement a plausible, 'cold pool conserving' rule-based selective withdrawal scheme

Rule-based TCD scheme



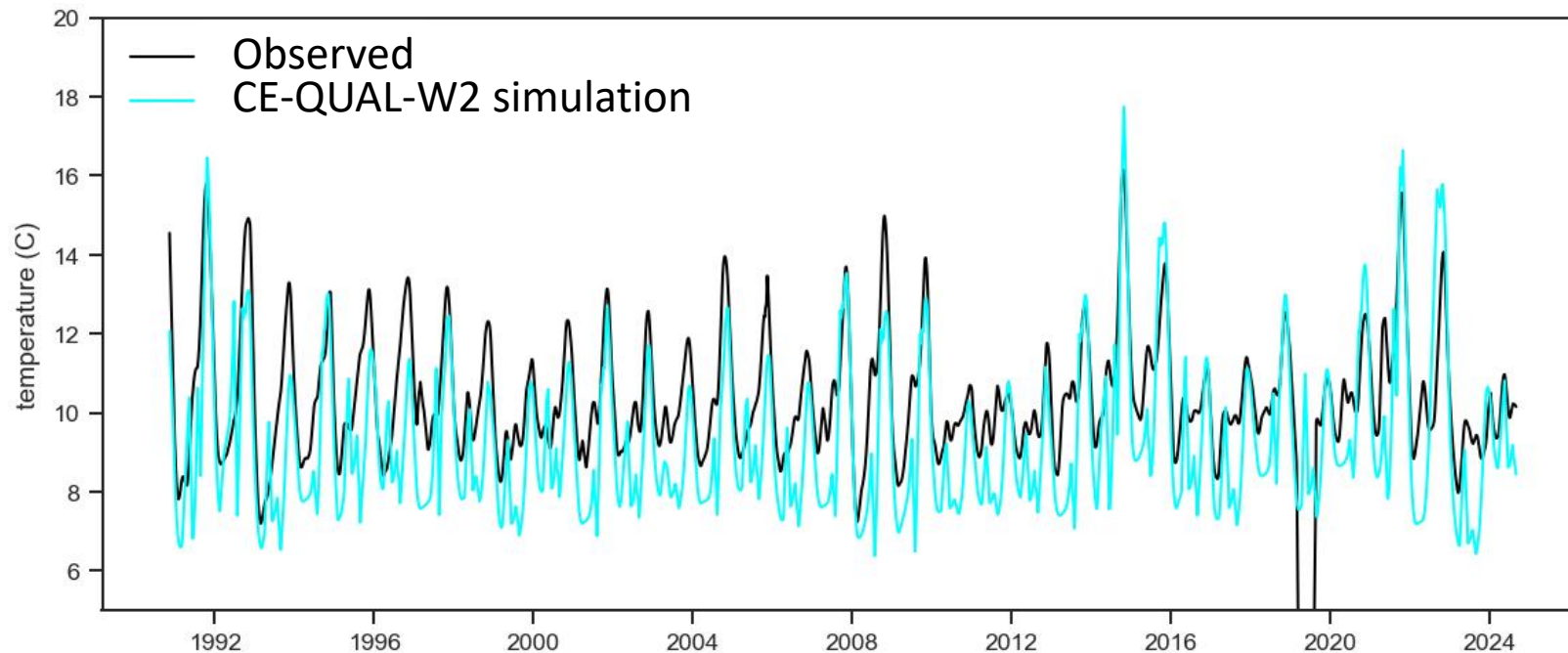
Shasta Thermal Control Device (TCD) diagram



High resolution temperature model: CE-QUAL-W2

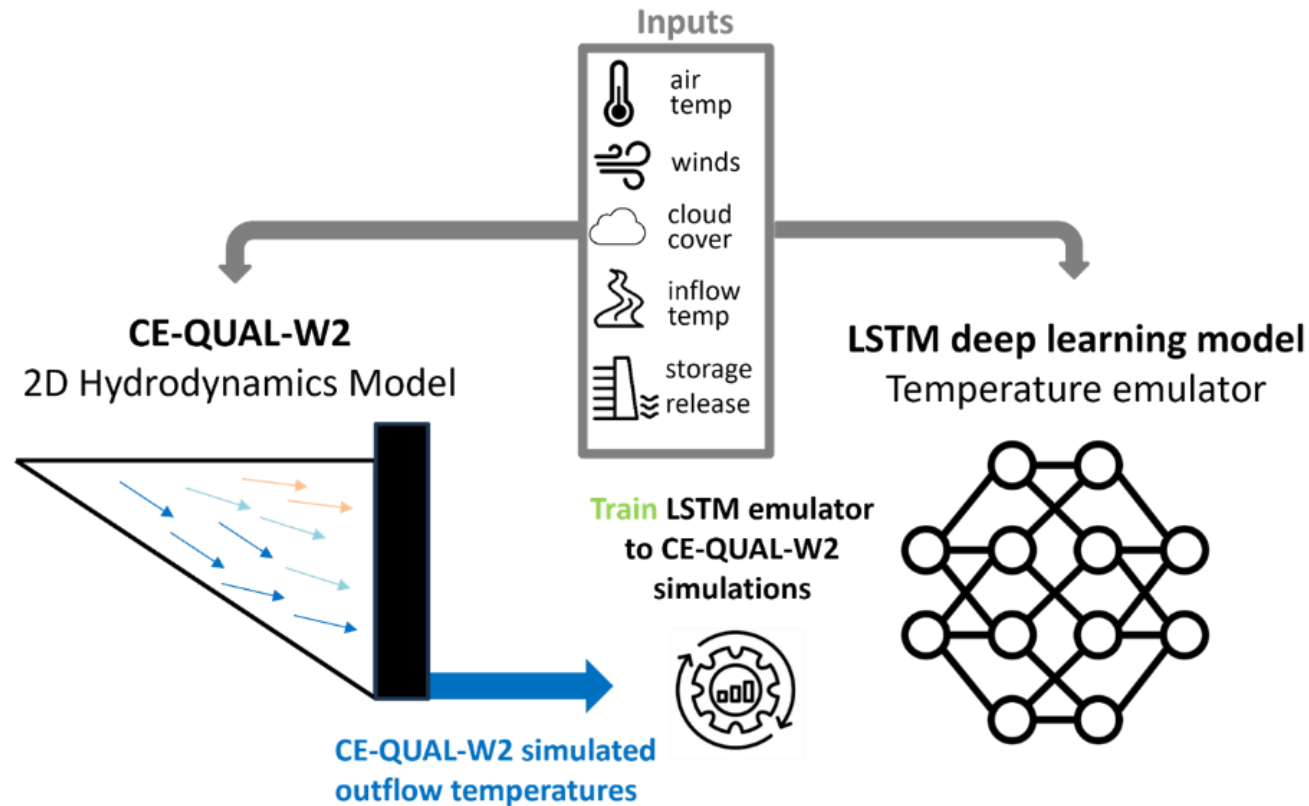
Simulations from this model capture Shasta observed dynamics well with a bit of low bias*

*Note: There is no historical record of actual TCD decisions



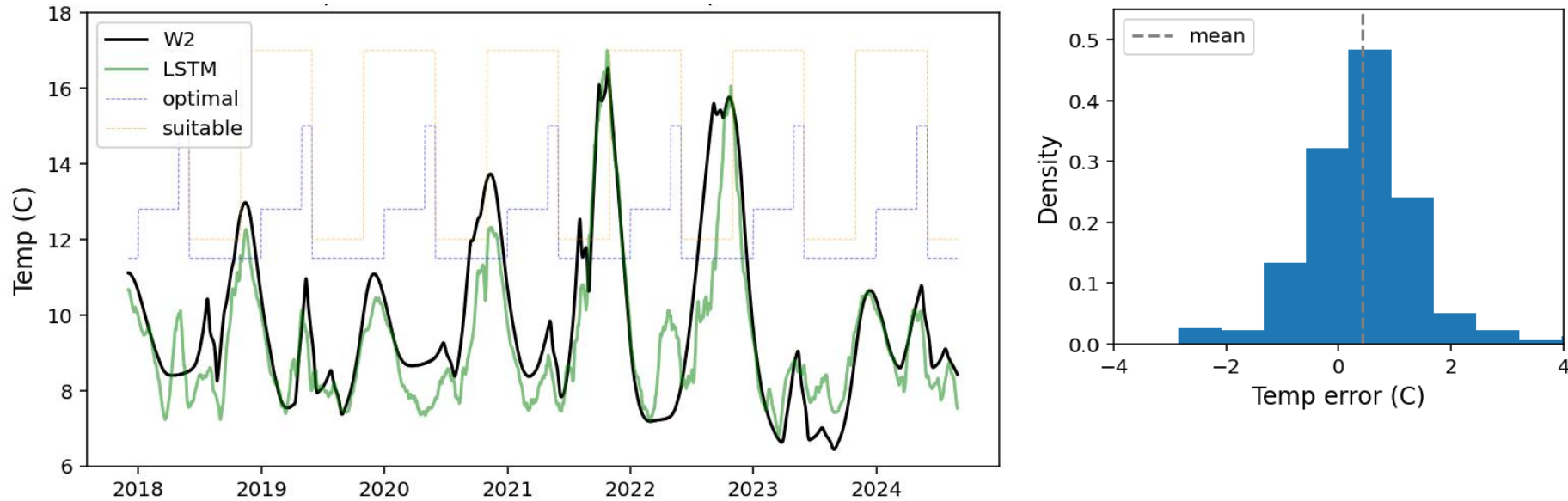
Lightweight LSTM temperature emulator

We fit a computationally efficient deep learning emulator to the outputs of the high-resolution temperature model using the same inputs



Lightweight LSTM temperature emulator

Out-of-sample testing

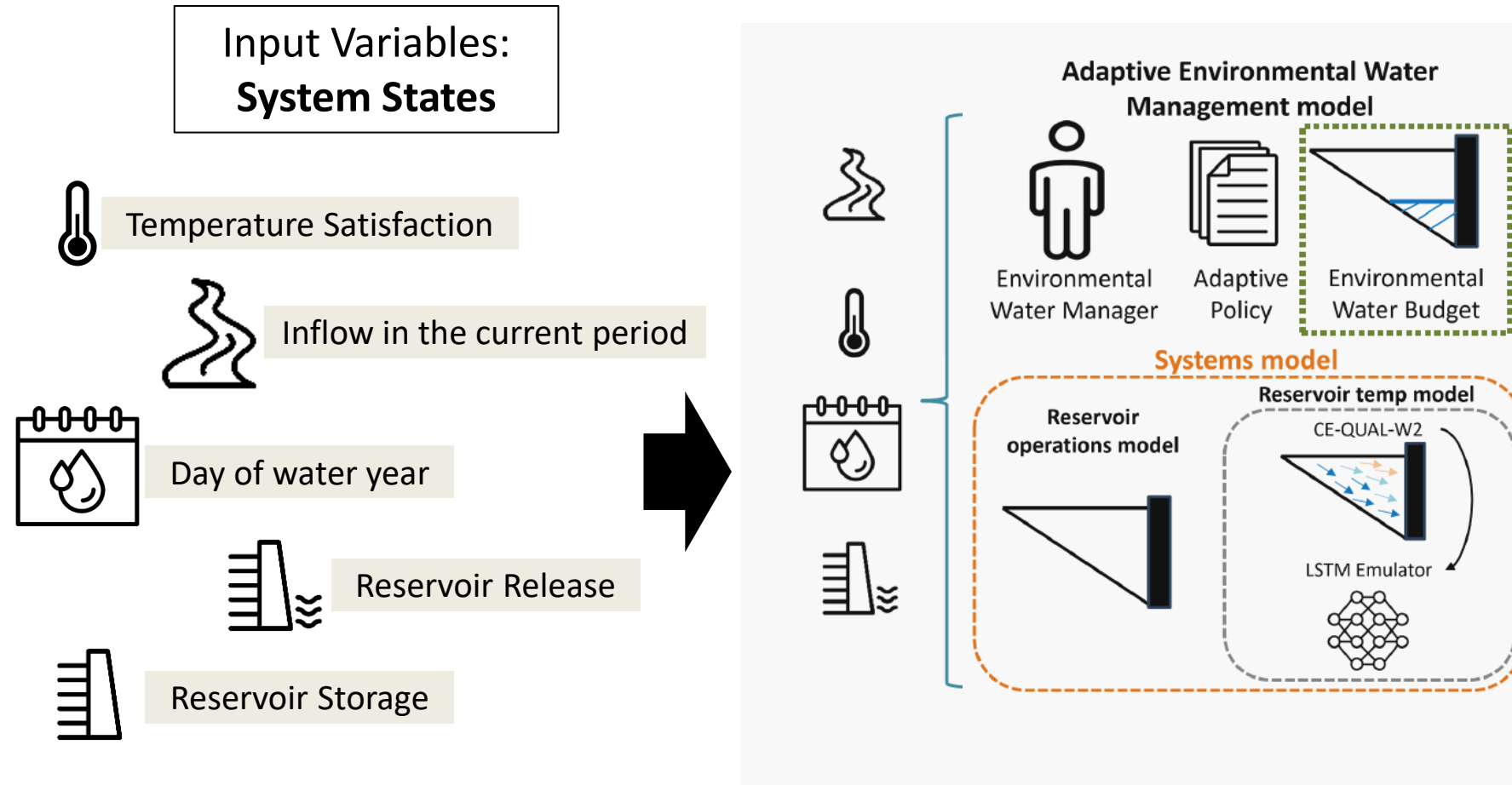


Computational tractability:

CE-QUAL-W2 runtime: ~15 min

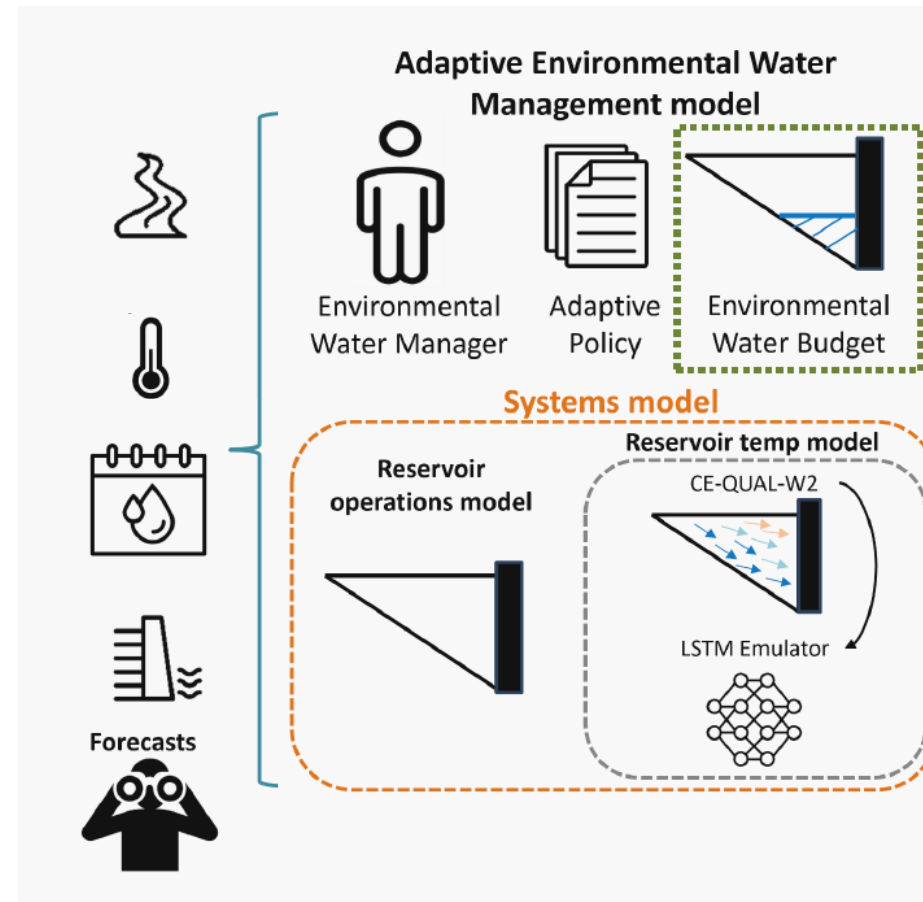
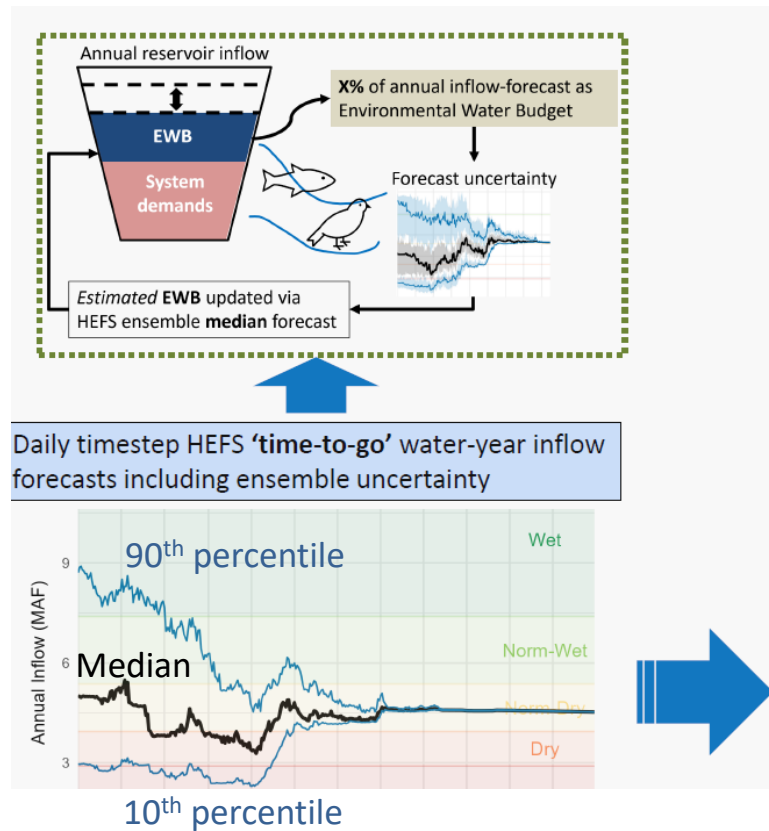
LSTM runtime (prediction): <<<1 sec

EWM EMODPS input variables



EWM EMODPS input variables

Input Variables: Time-to-go forecasts



'Time-to-go' forecast usage

Real-world

(San Joaquin River Restoration Program)



Table 1: 2023 Restoration flow allocation history

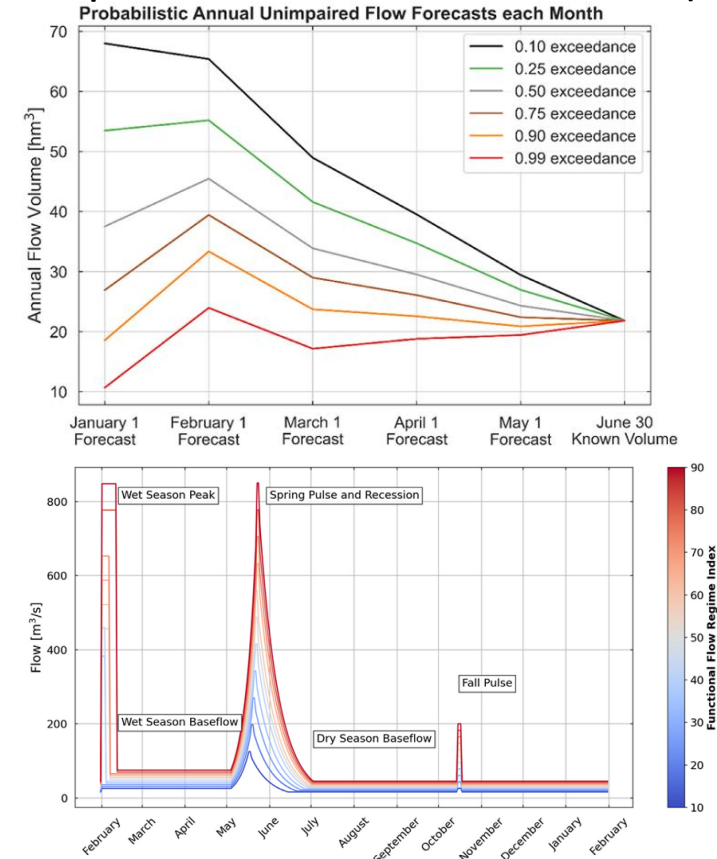
Allocation Type	Issue Date	Forecast Blending Applied	Unimpaired Runoff Forecast (at forecast exceedance)	Year Type	Restoration Allocation at Gravelly Ford	Restoration Flows and URFs Released
Initial	January 20, 2023	0/100	3,403 TAF (at 50%)	Wet	556.542 TAF	0 (through January 19, 2023)
Updated	February 17, 2023	30/70	3,080 TAF (at 50%)	Wet	557.038 TAF	167.564 (through February 16, 2023)
Updated	March 14, 2023	0/100	4,537 TAF (at 50%)	Wet	557.038 TAF	179.992 (through March 13, 2023)
Updated	April 20, 2023	60/40 (0/0+50/+100/+200 offset)	4,569 TAF (at 50%)	Wet	557.038 TAF	212.083 (through April 20, 2023)
Final	May 18, 2023	50/50	4,664 TAF (at 50%)	Wet	557.038 TAF	408.525 (through May 15, 2023)

Johnson, 2024

Water year type updates based on WY forecasts

Research

(Adaptive Function Flows Model)



Yarnell et al., 2024

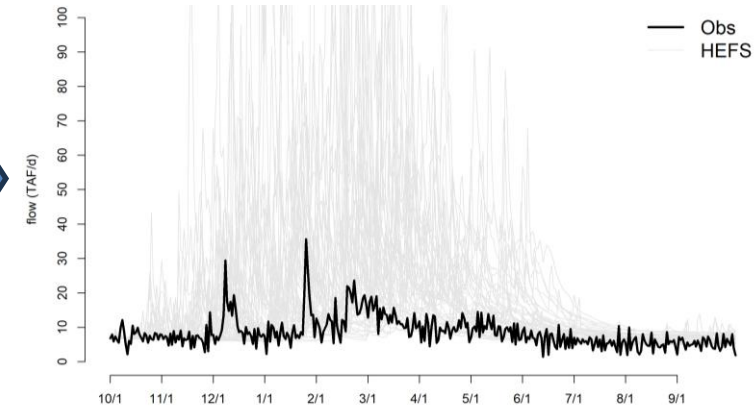
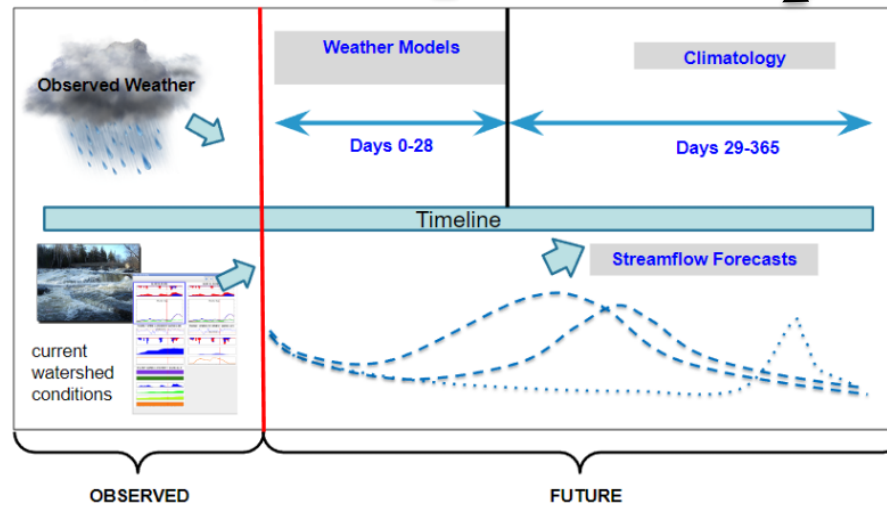
HEFS hindcast dataset for Shasta (1989-2023)

Daily historical observations (1990-2023)

Daily NOAA/NCEP Global Ensemble Forecast (GEFS) version 12 hindcasts (1990-2023)

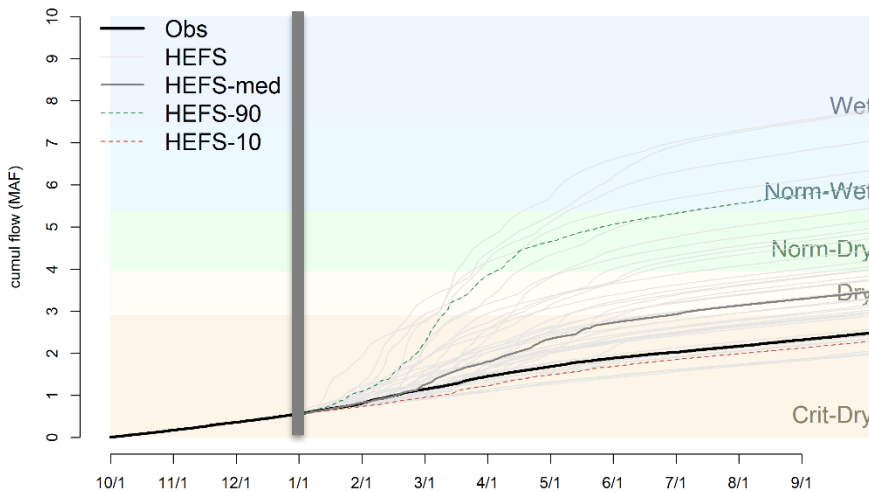
1980-2022 daily climatology of temp/precip

365-day forecast
(1993-10-01 example)

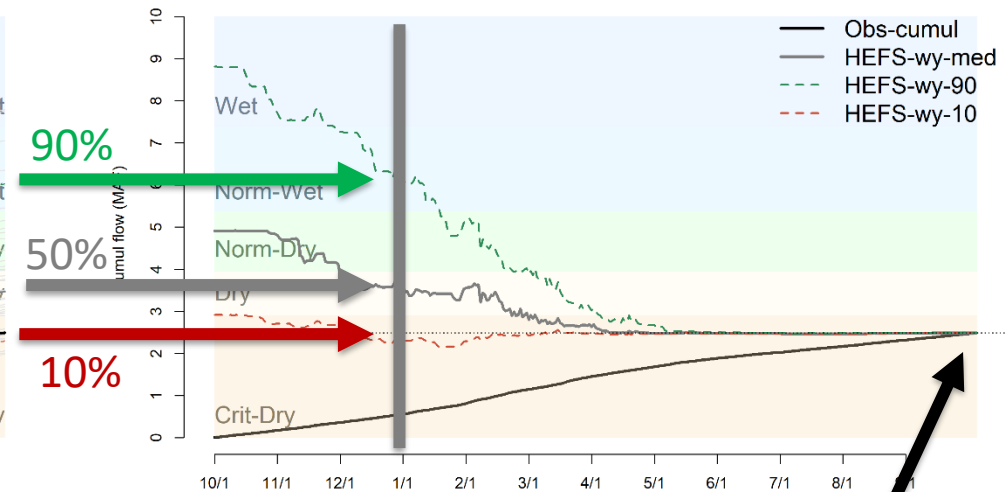


Time-to-go WY forecasts

**Cumulative forecast for WY
2021 – Jan 1**



**Time to go forecast for
WY 2021 – Jan 1**



Inflow observed (e.g. 90-day observed inflow @ Jan 1)

+

Inflow projected (e.g. 275 day HEFS cumulative forecast @ Jan 1)

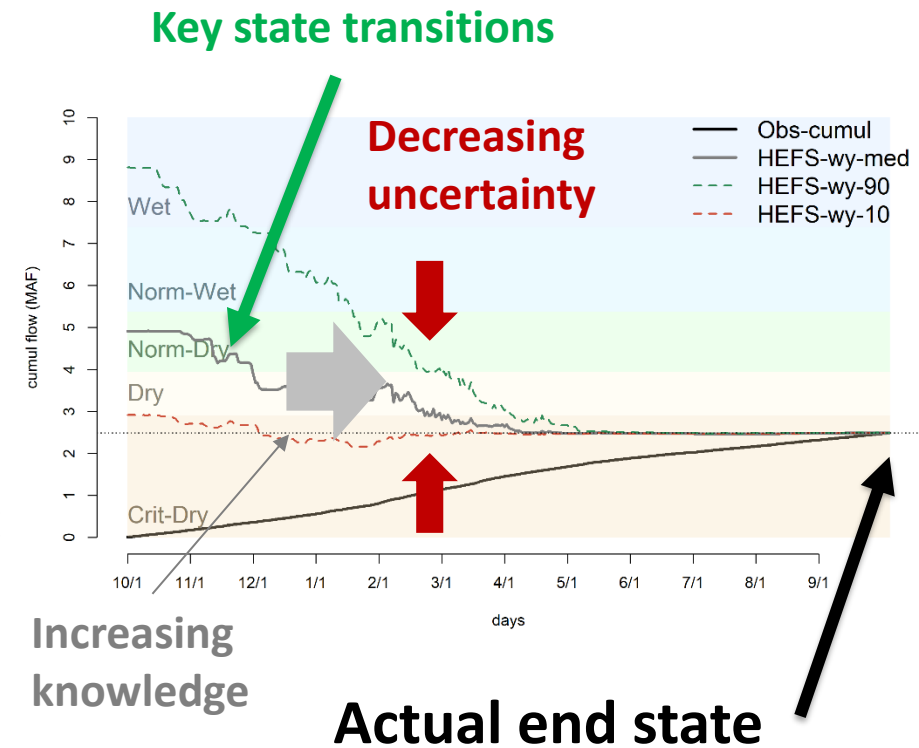
Predicting this:
End of WY
cumul inflows

Time-to-go WY forecasts

Under WY typing framework, shows:

- **Real-world uncertainty** about WY water supply outcomes
- **Decrease of uncertainty** as WY end approaches
- Key **transition** periods for knowledge uncertainty

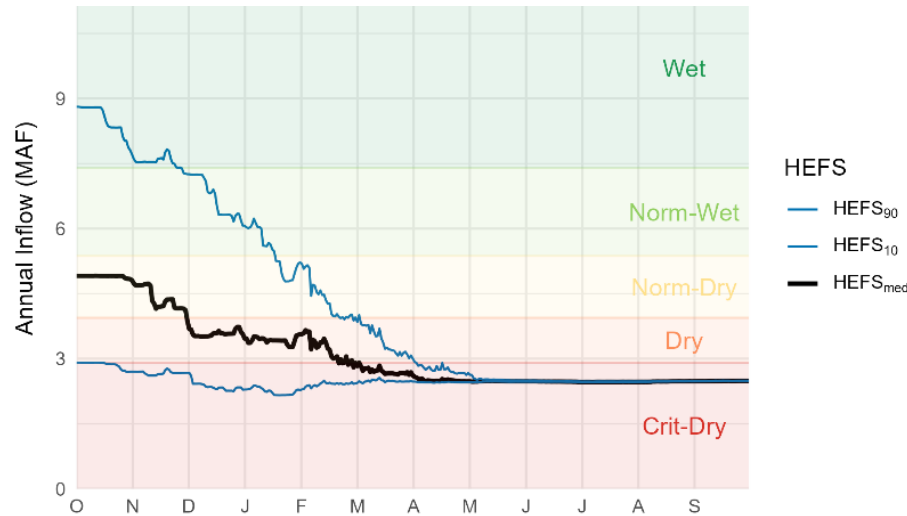
Can be a *realistic representation* of an EWM's water supply knowledge at any state in 30-yr historical record



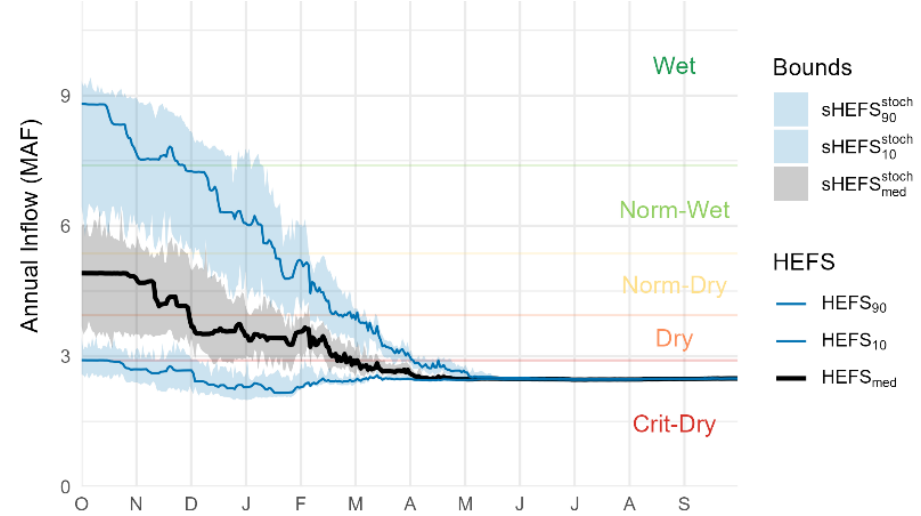
Time-to-go stochastic forecasts

To support time varying sensitivity analysis, we developed a stochastic resampling technique to produce 100 random forecast samples for 1990-2023

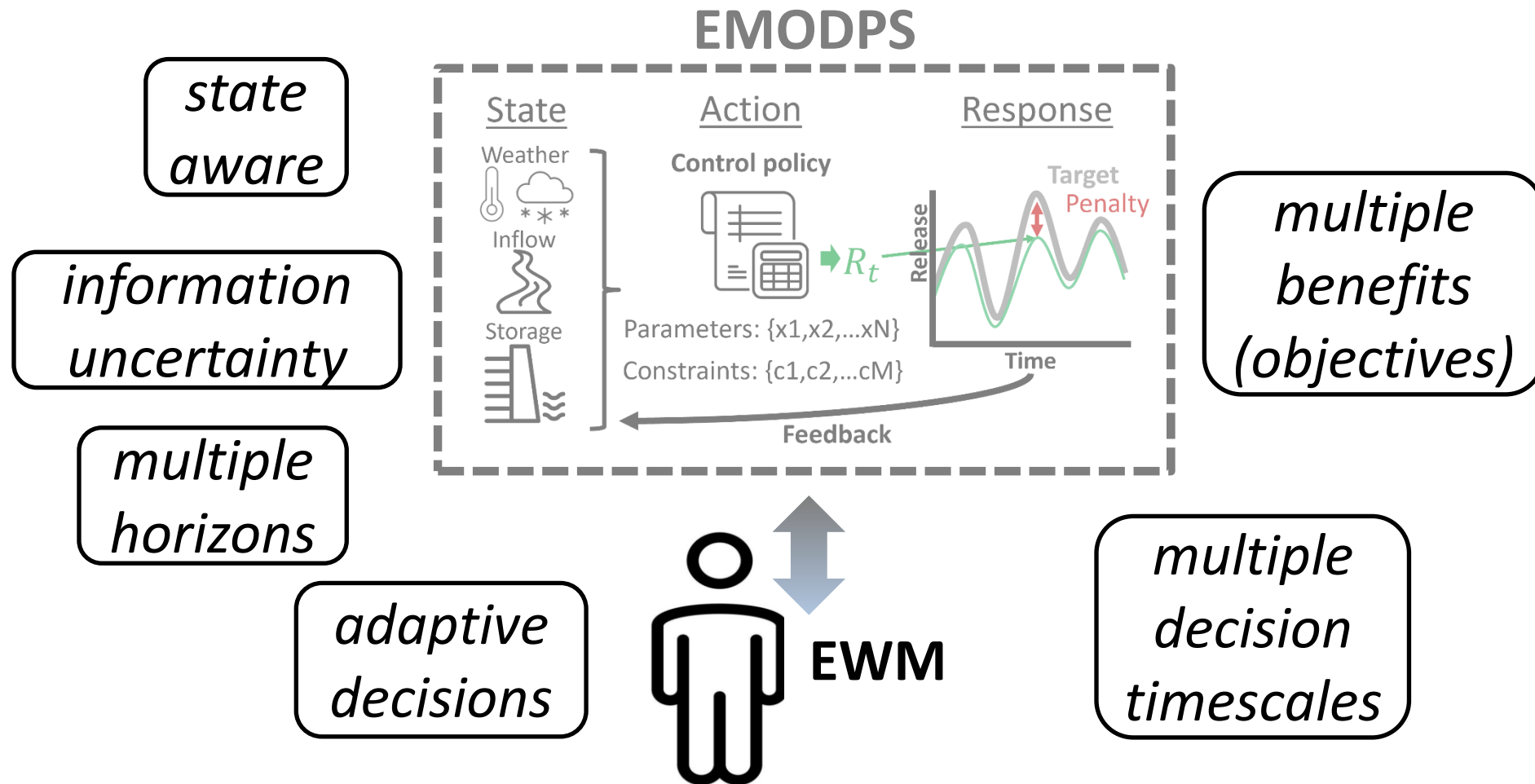
**HEFS time-to-go hindcast
(WY 2021)**



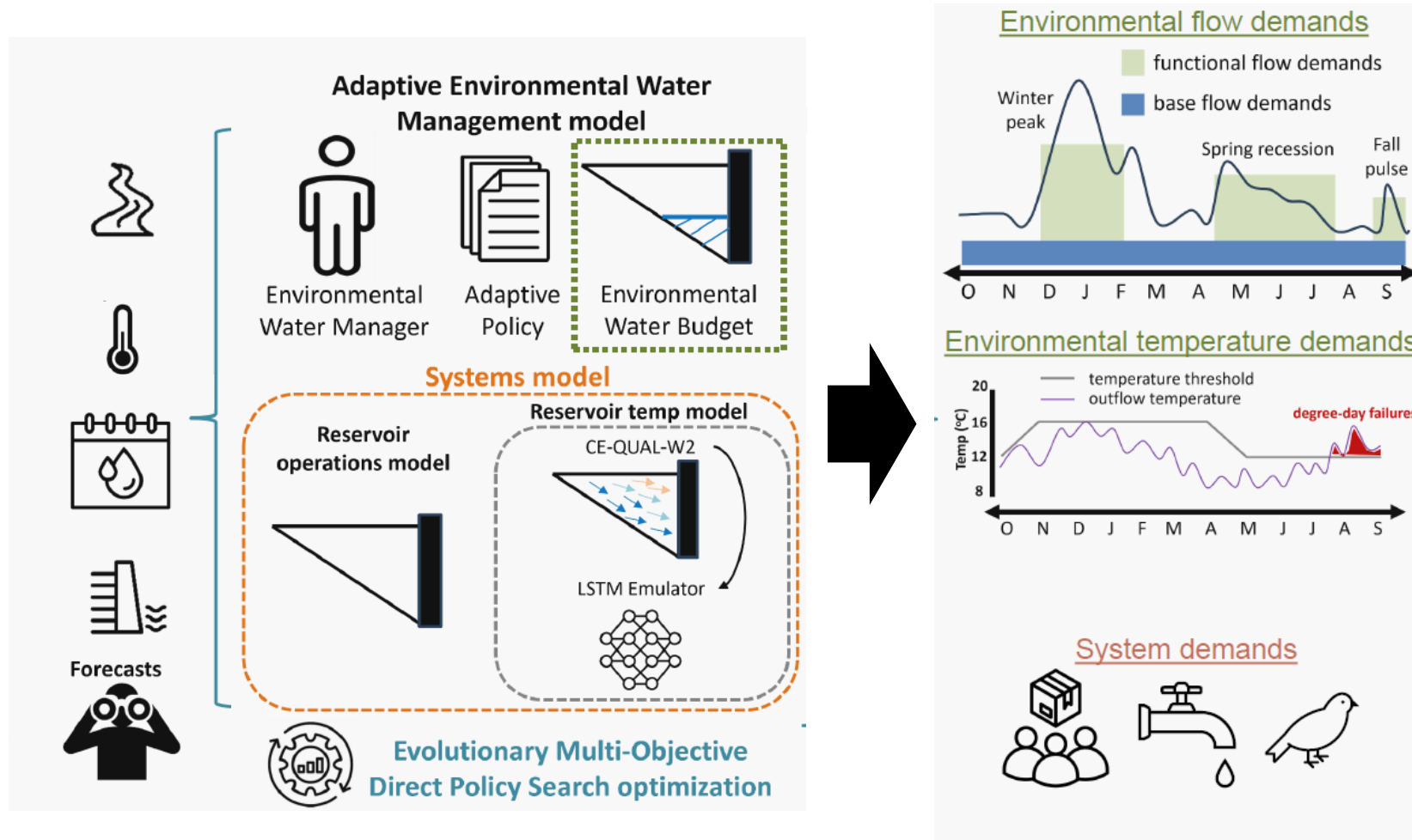
**Uncertainty bounds of stochastic HEFS
(WY 2021)**



EWM adaptive management through EMODPS

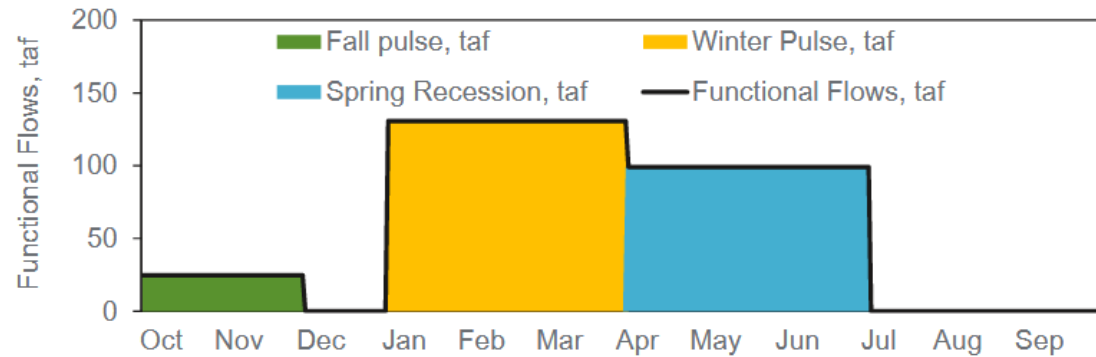


EWM EMODPS multiple objectives



EWM objective function formulation

1. Functional flows (water quantity)

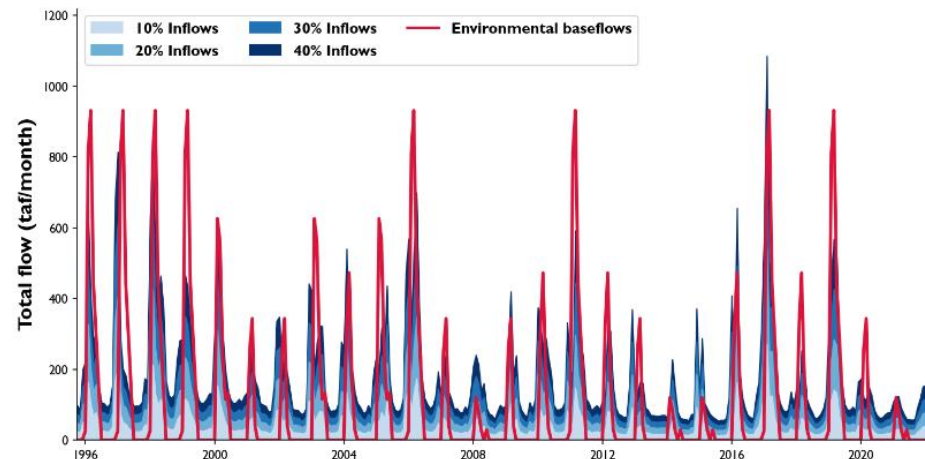


Maximize the *reliability* of functional flow satisfaction

$$J_{func} = \frac{\sum S_t}{T}$$



2. Minimum baseflows (water quantity)



Maximize the *reliability* of minimum baseflow satisfaction

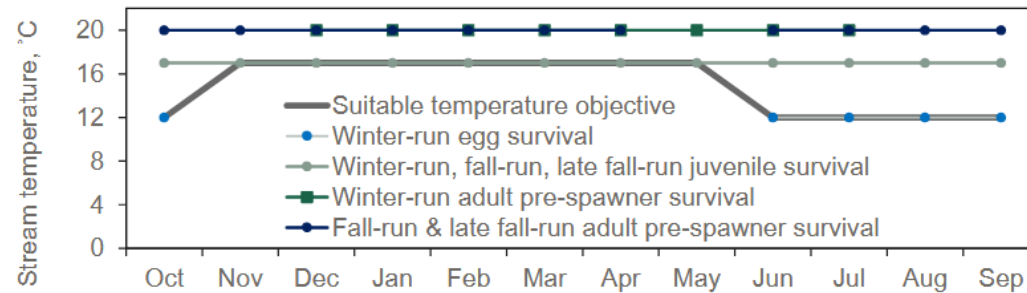
$$J_{bflow} = \frac{\sum B_t}{T}$$



EWM objective function formulation

3. Temperature objective (water quality)

a) Water temperature objectives for suitable habitat



Minimize the accumulated degree day *failure*

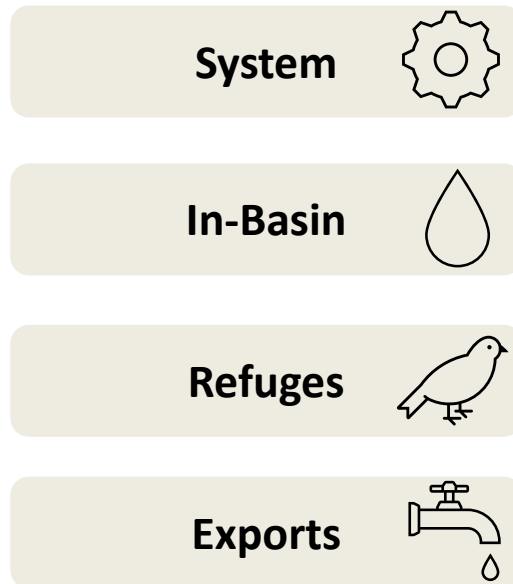
$$J_{temp} = \sum temp_t < temp_limit$$



Accumulated degree day failure = sum of days with outflow temperature > suitable temperature threshold for cold-water salmonids

EWM objective function formulation

4. Demand Satisfaction



J_{dmd} = Minimize worst **median annual deficit** across all demand types

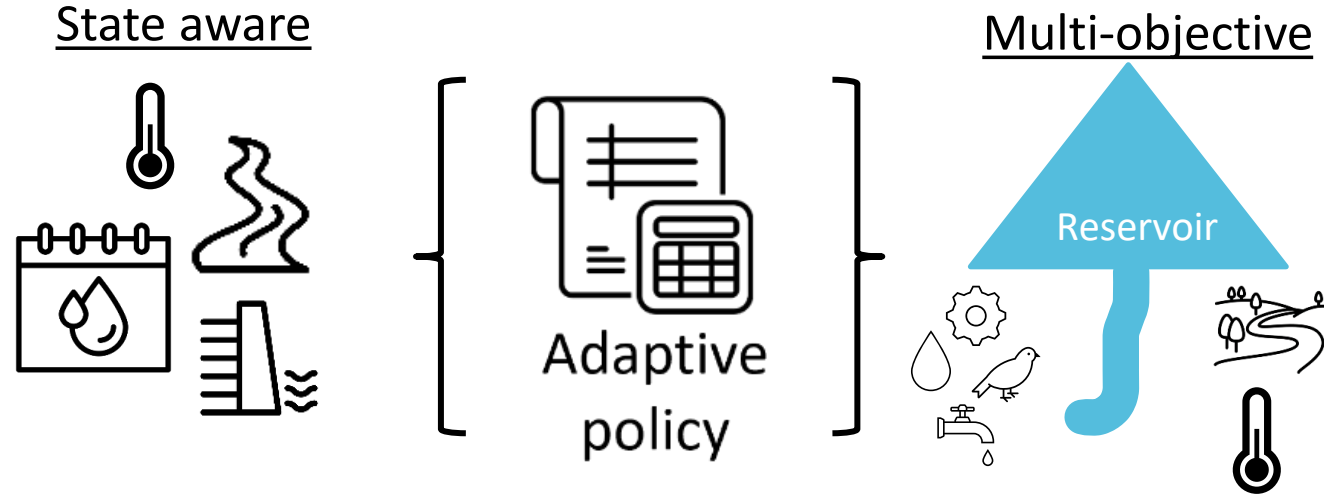
Deficit is the difference between water supply and demand

Demands are determined by water year type

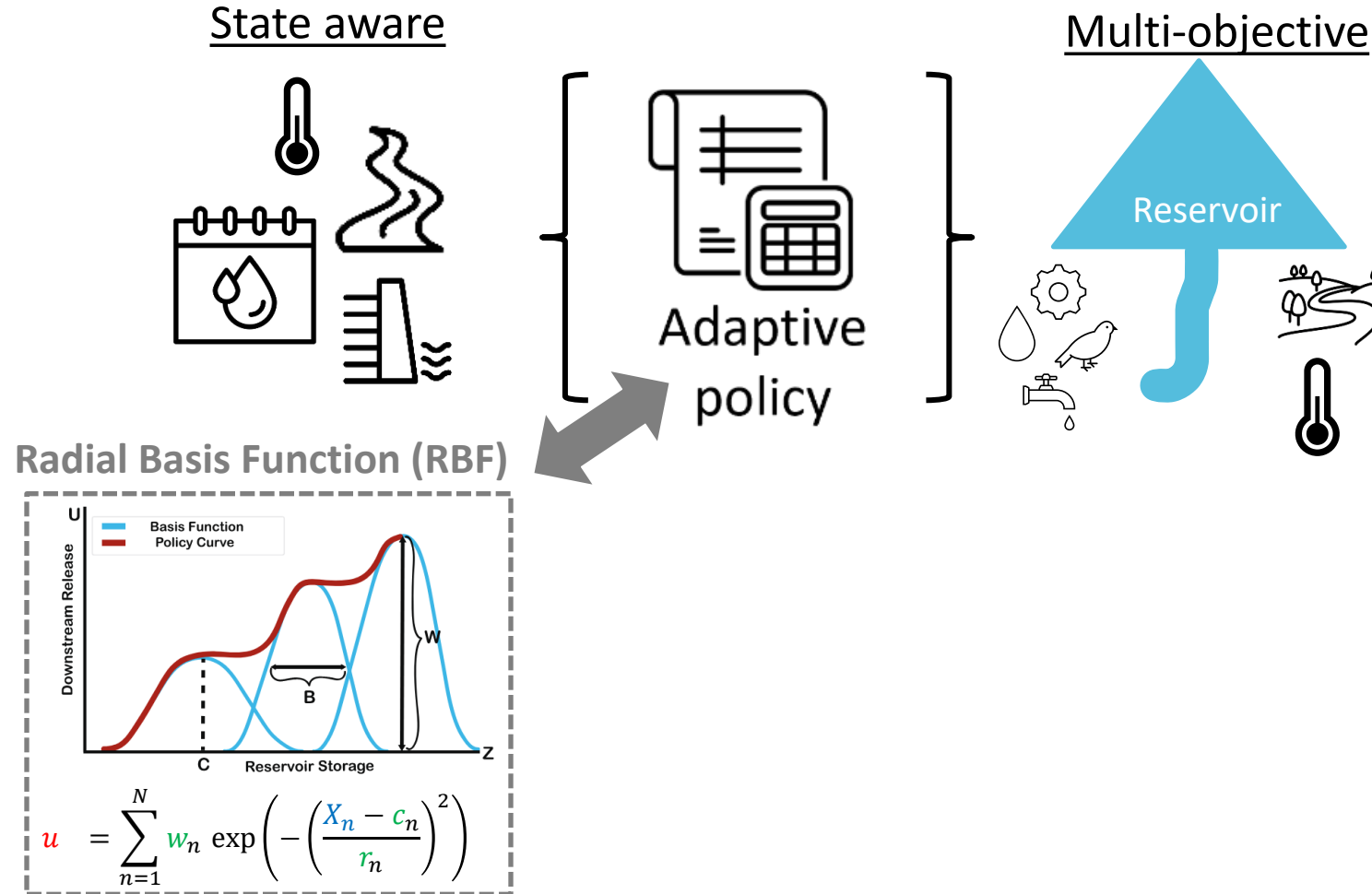
$$\theta^* = \operatorname{argmin}_{\theta} J(\theta)$$

$$J = \begin{bmatrix} -J_{func} \\ -J_{bflow} \\ -J_{temp} \\ -J_{dmd} \end{bmatrix}$$

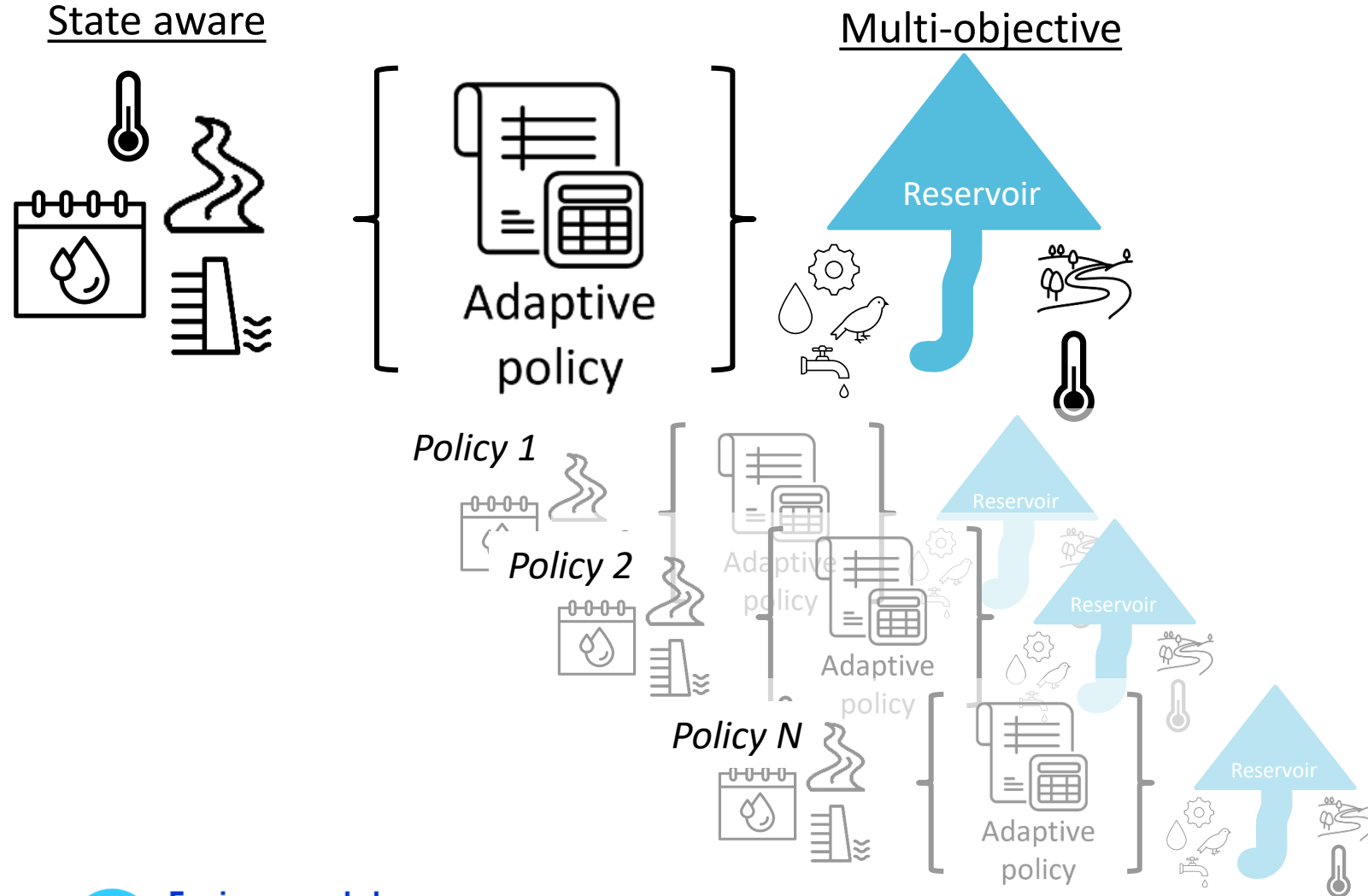
EMODPS to explore alternative EWM adaptive policies



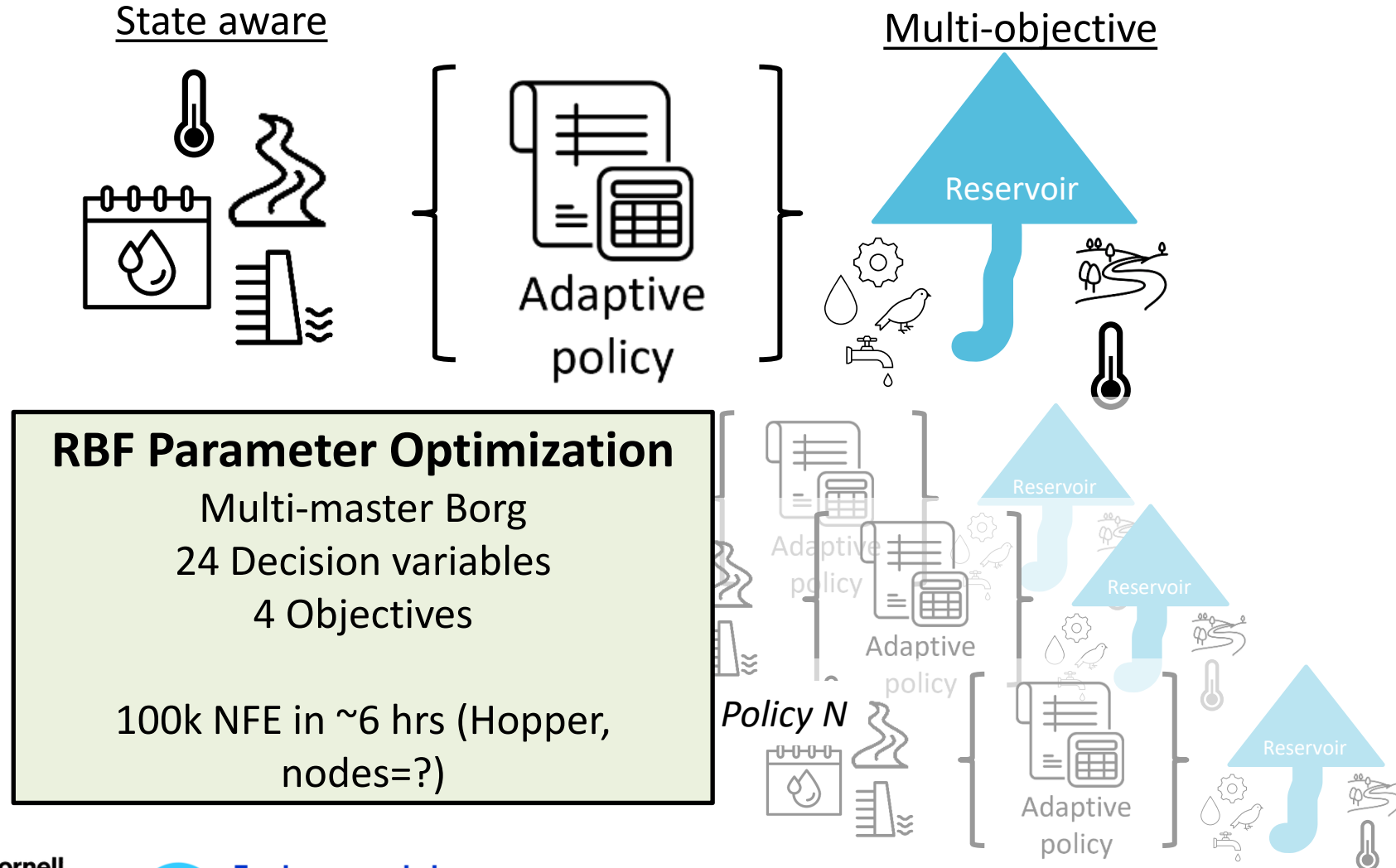
EMODPS to explore alternative EWM adaptive policies



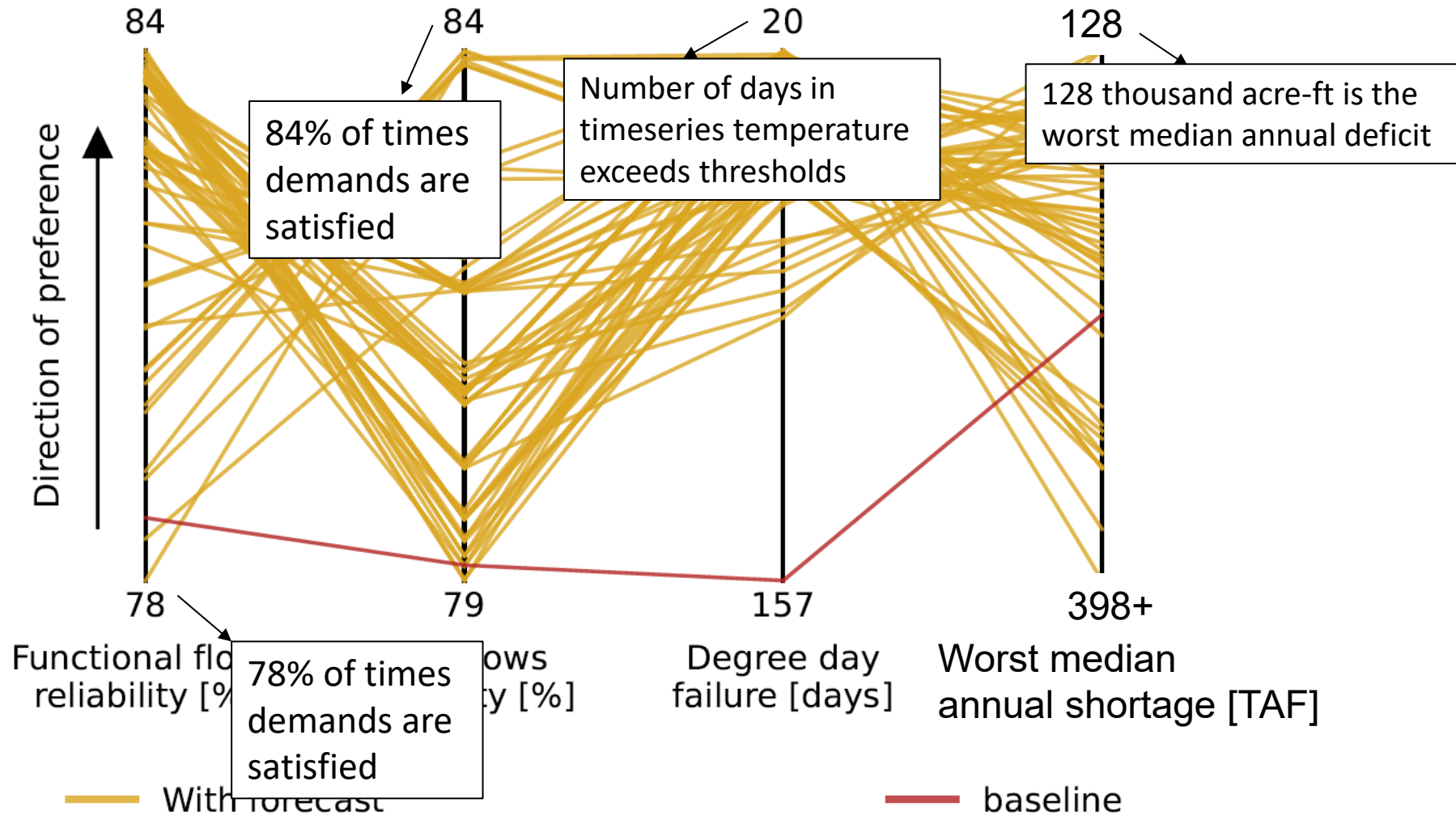
EMODPS to explore alternative EWM adaptive policies



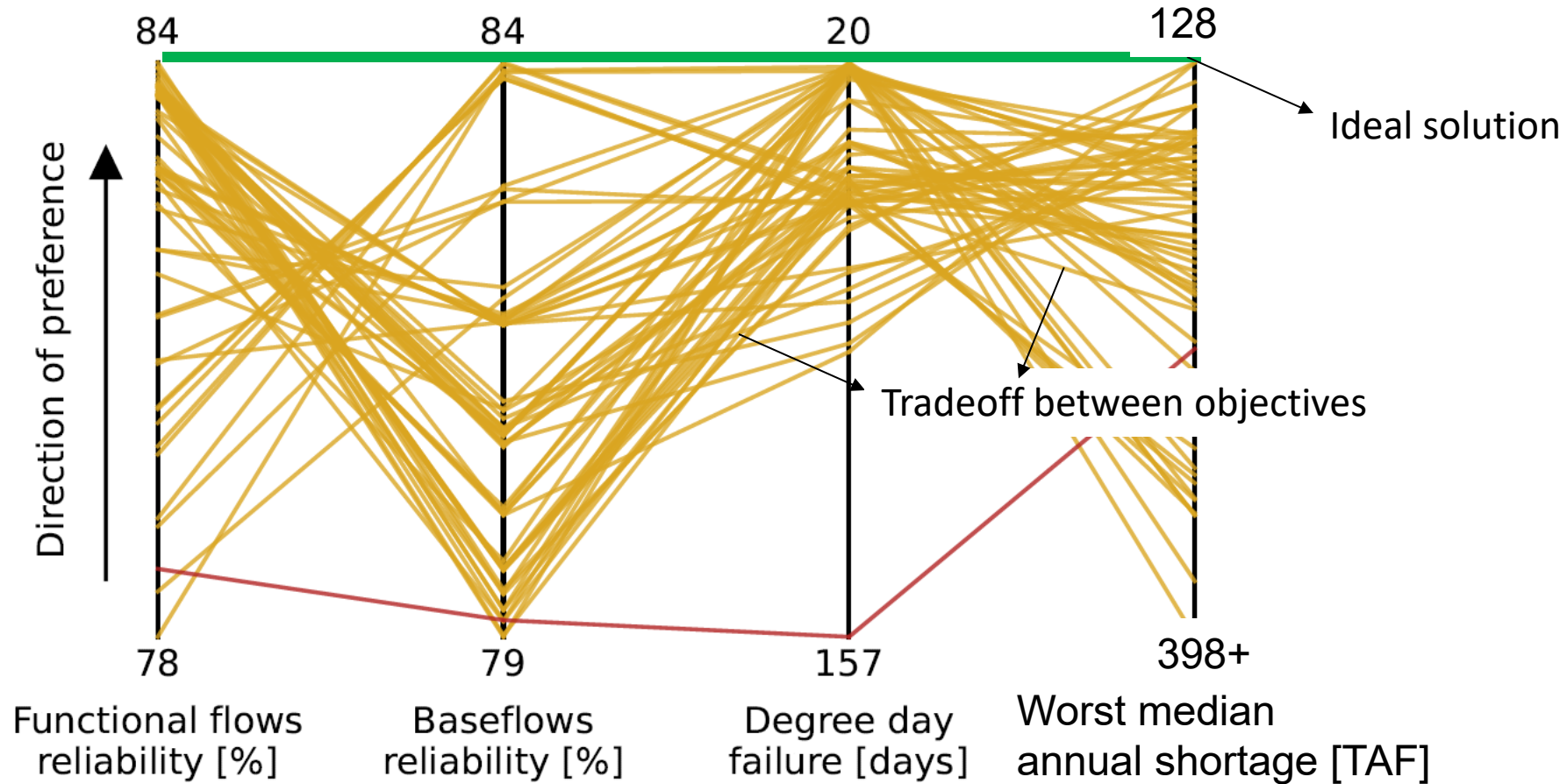
EMODPS to explore alternative EWM adaptive policies



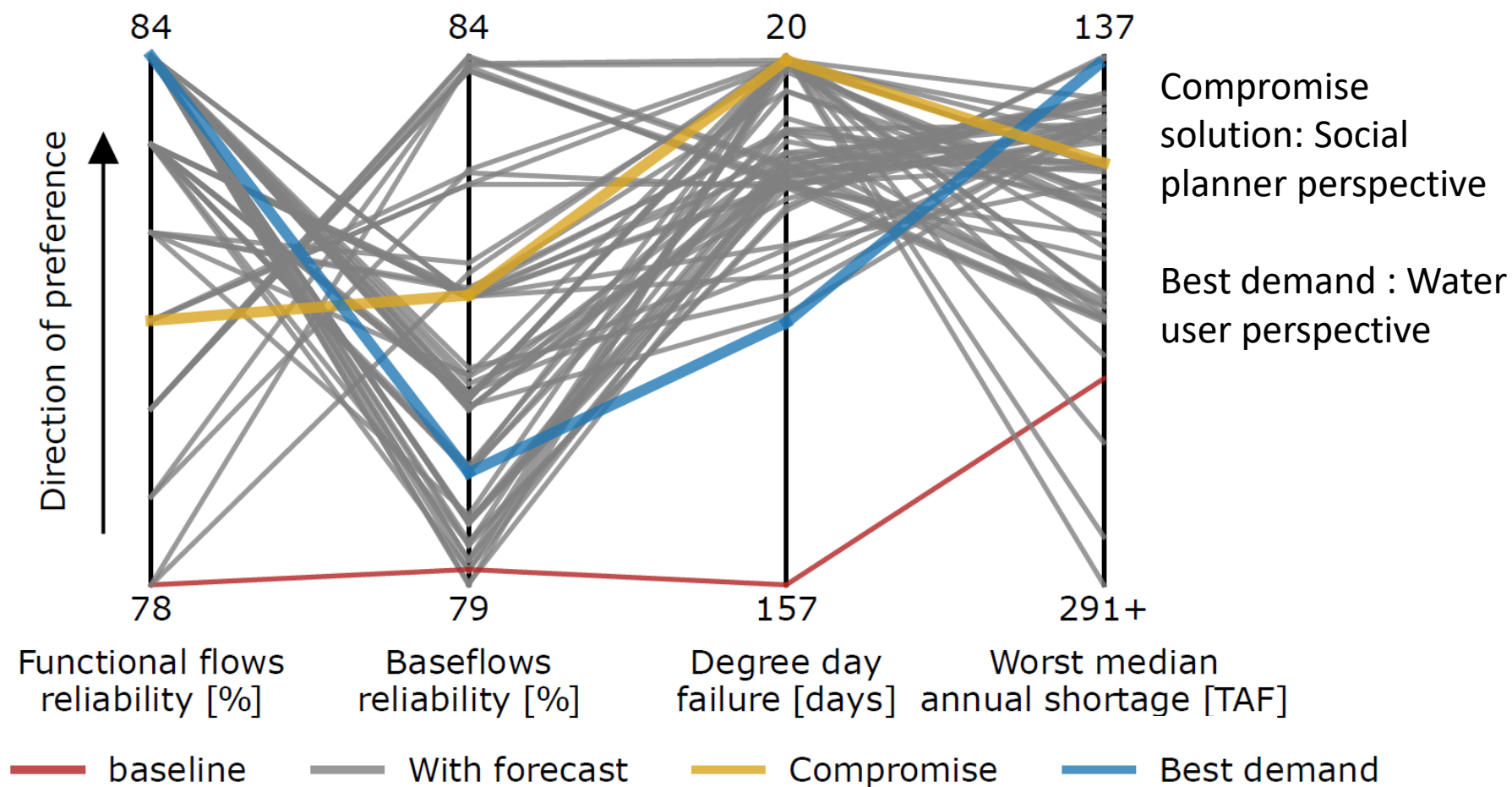
Optimization results: 4 objectives



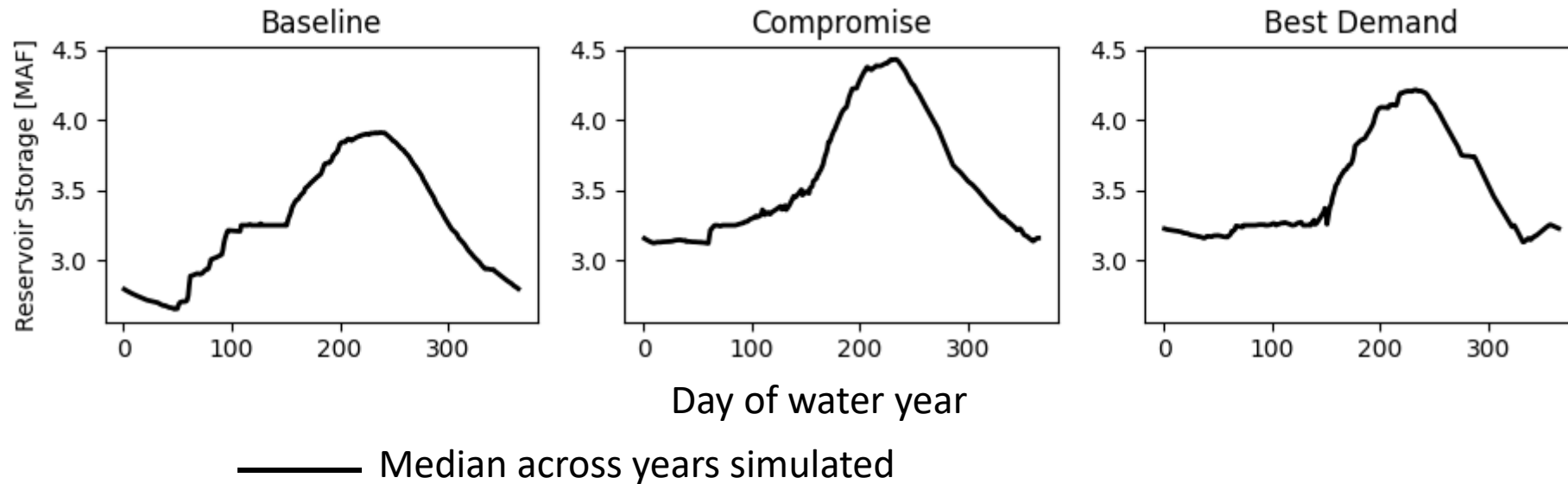
Optimization results: 4 objectives



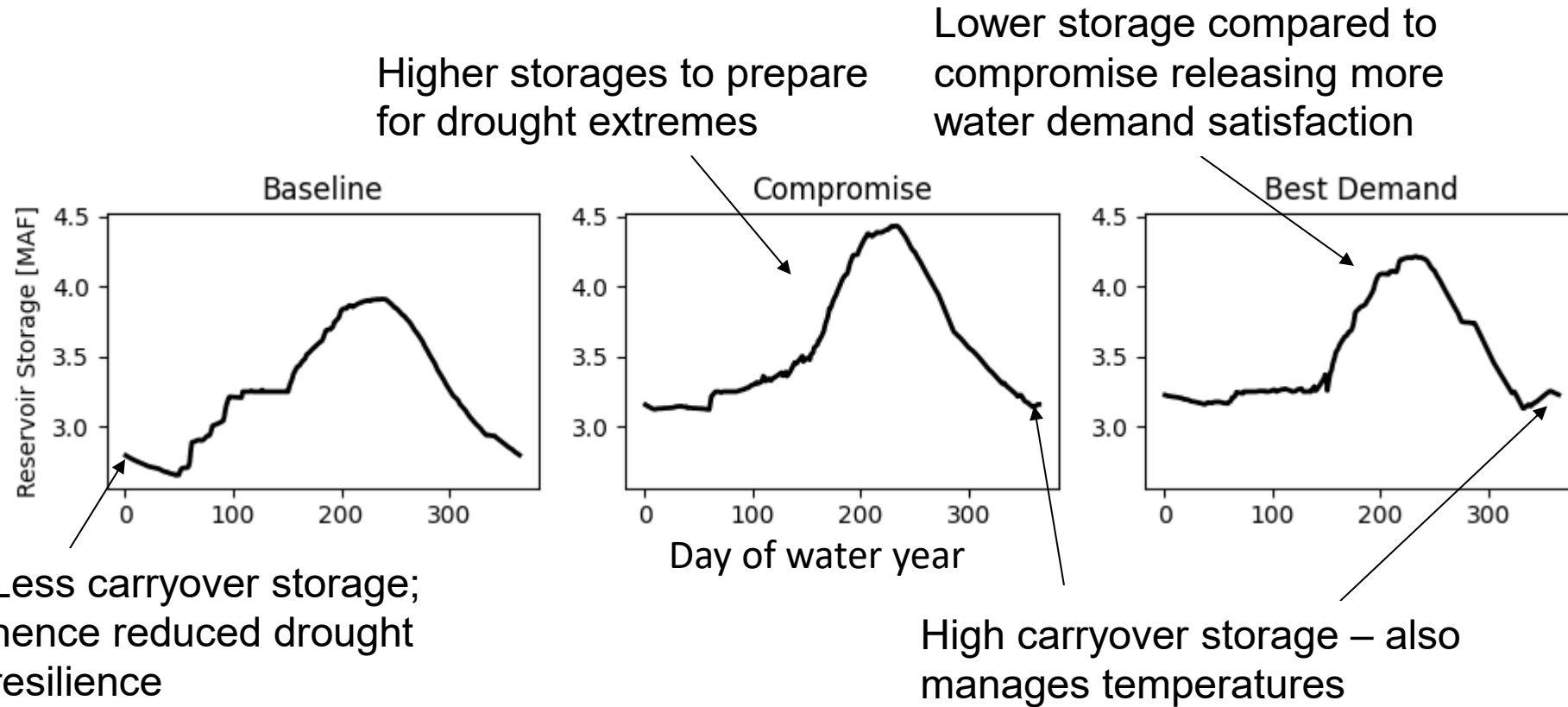
Explore 2 selected solutions and Baseline



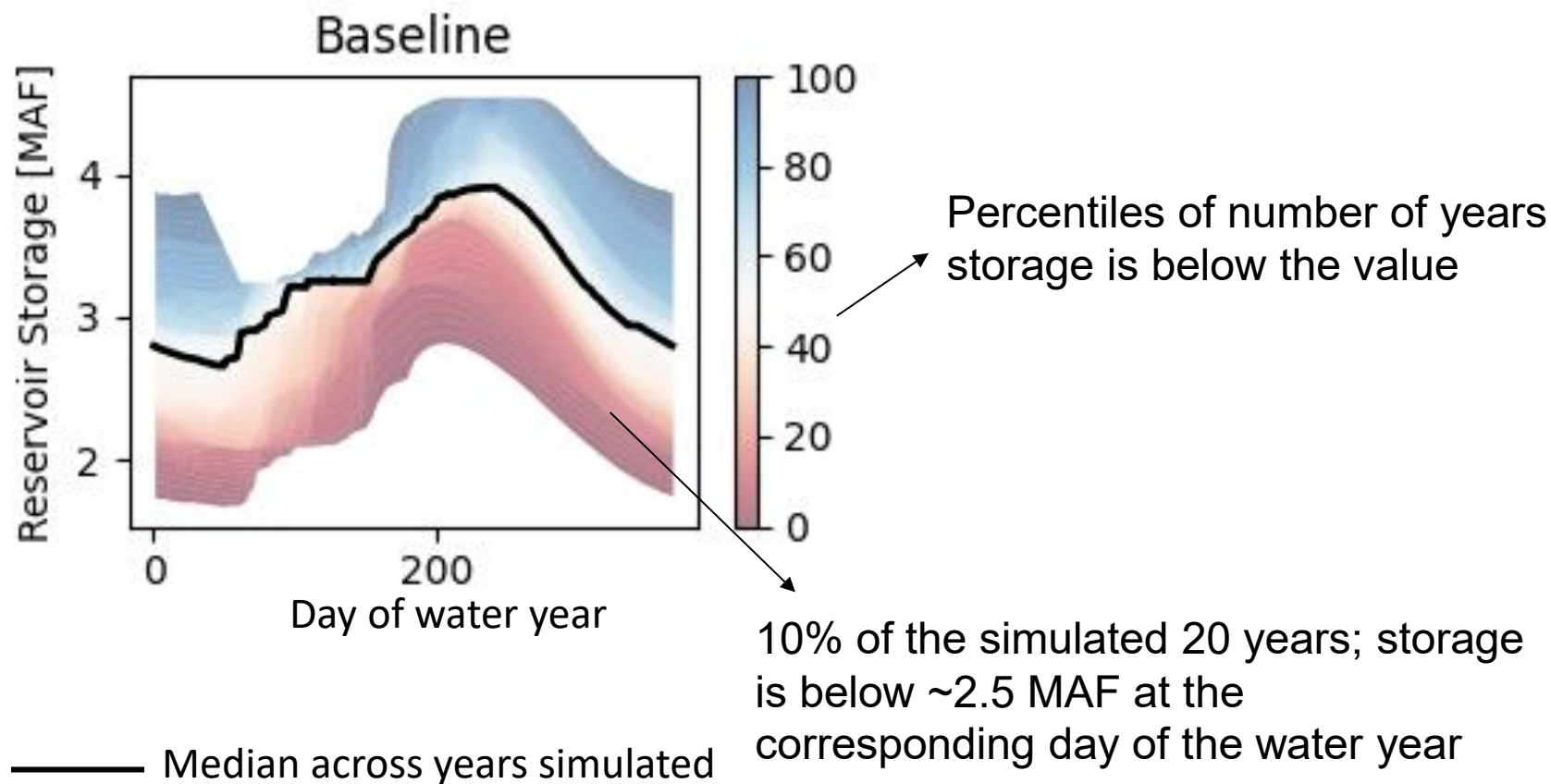
System dynamics for the selected solutions



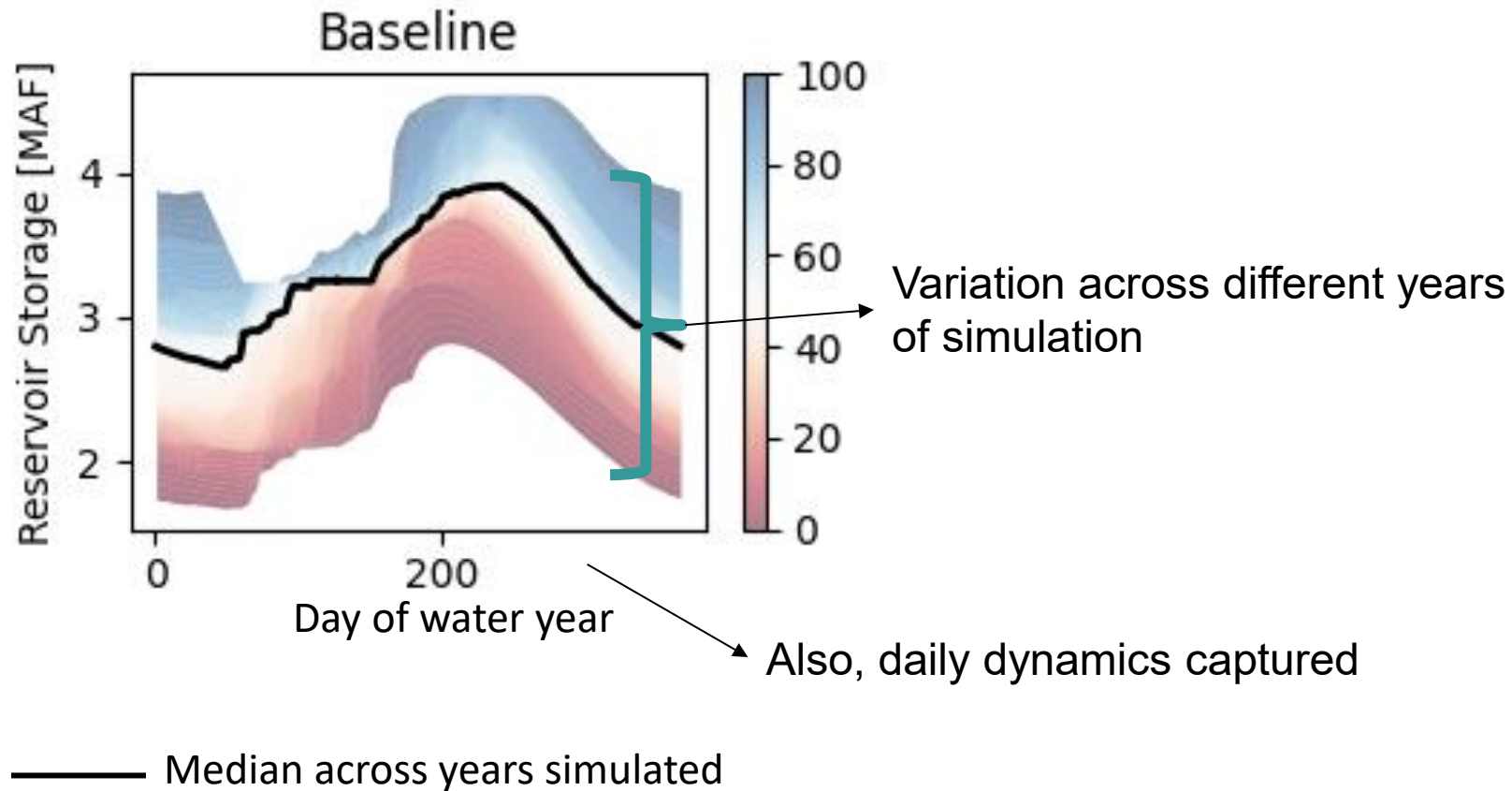
System dynamics for the selected solutions



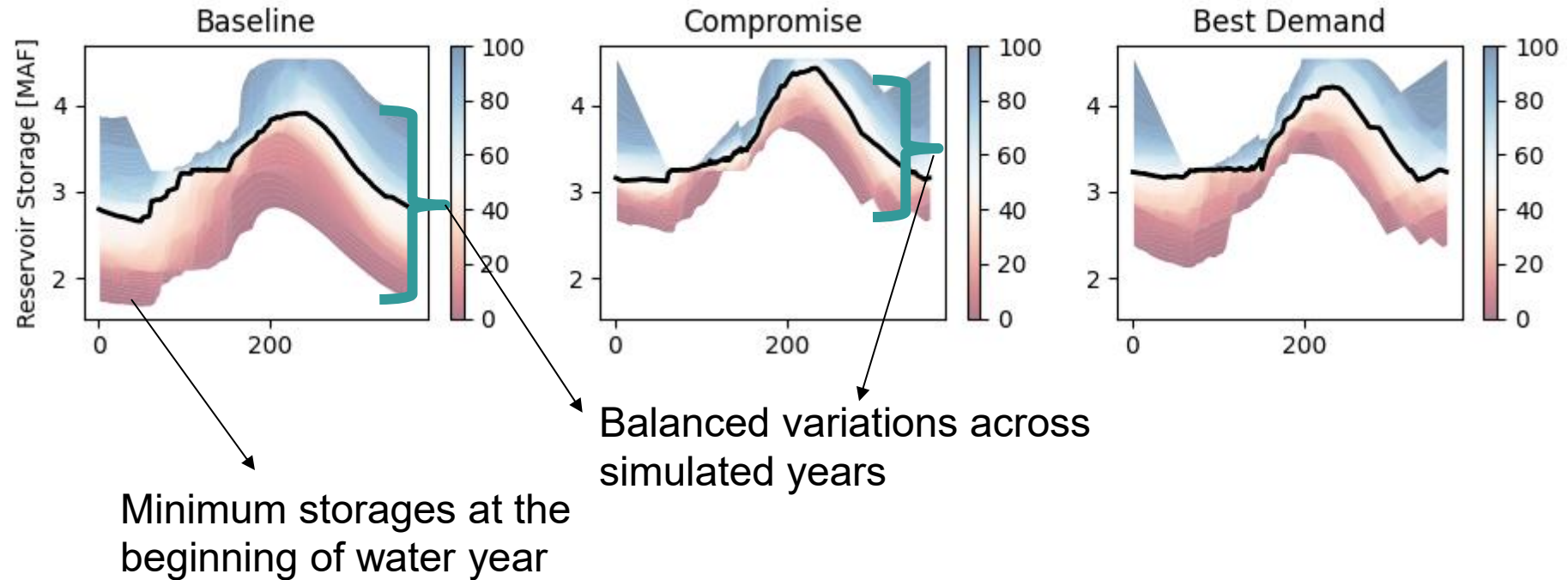
System dynamics for the selected solutions



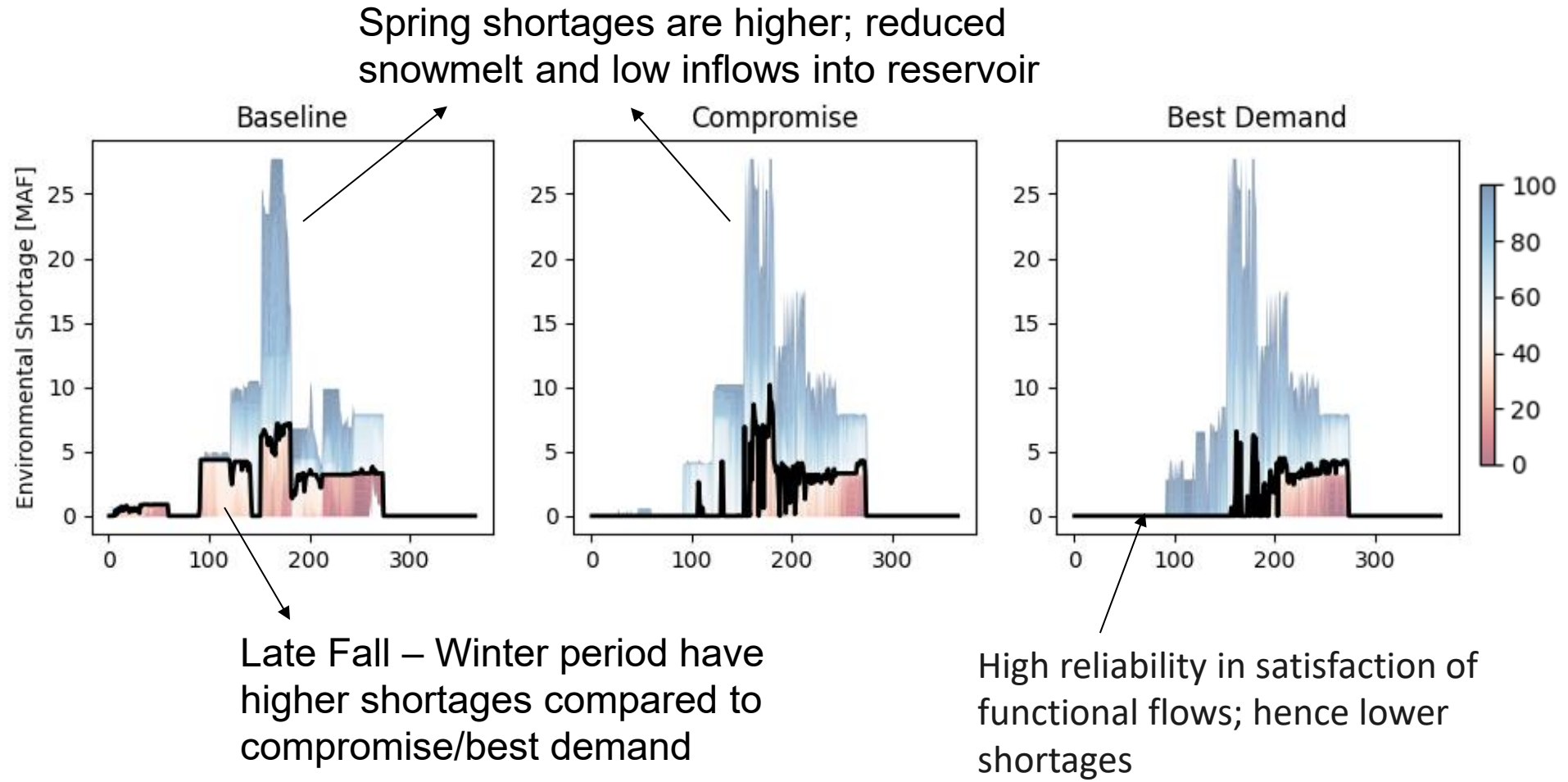
System dynamics for the selected solutions



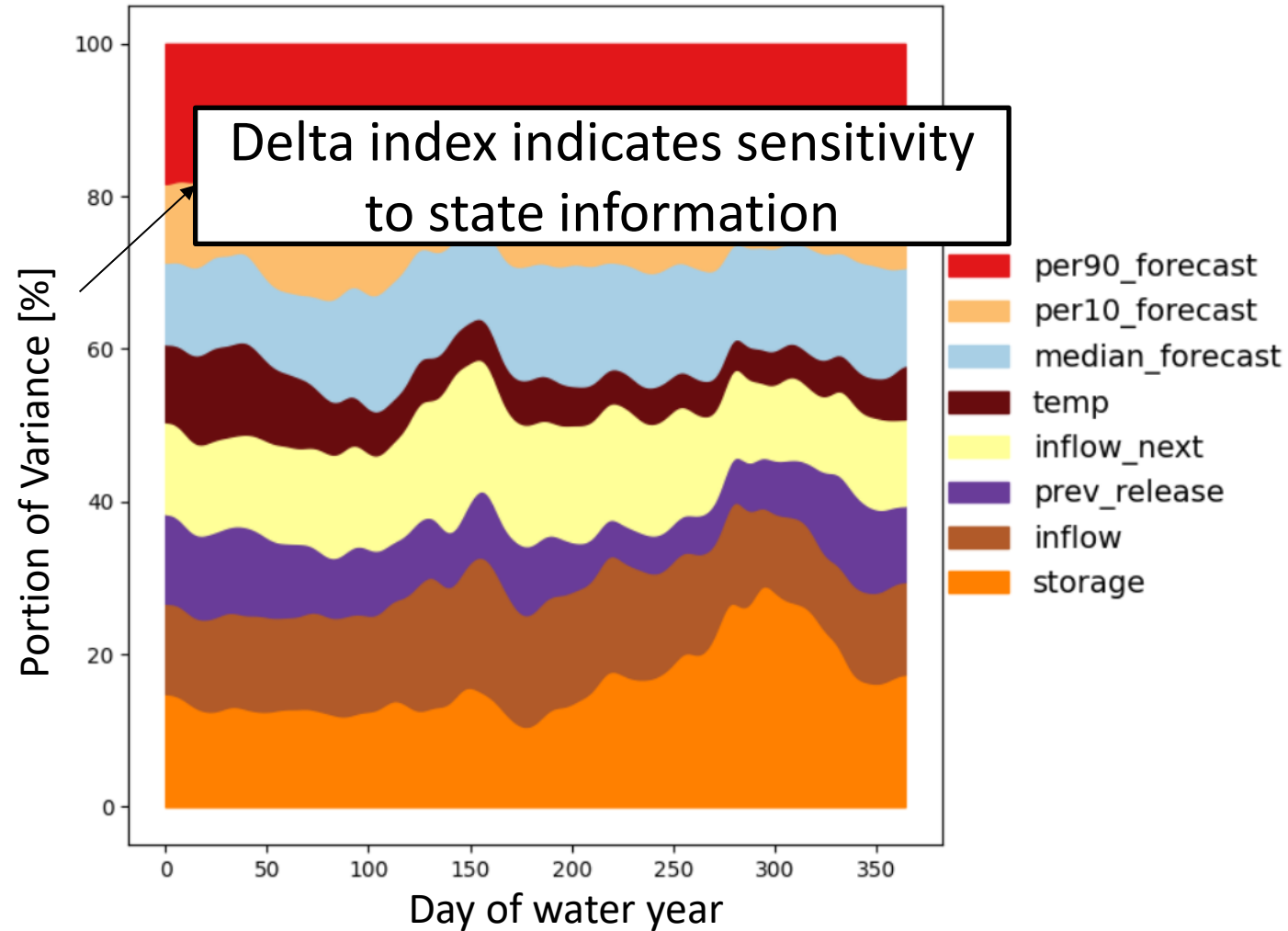
System dynamics for the selected solutions



Environmental water shortages

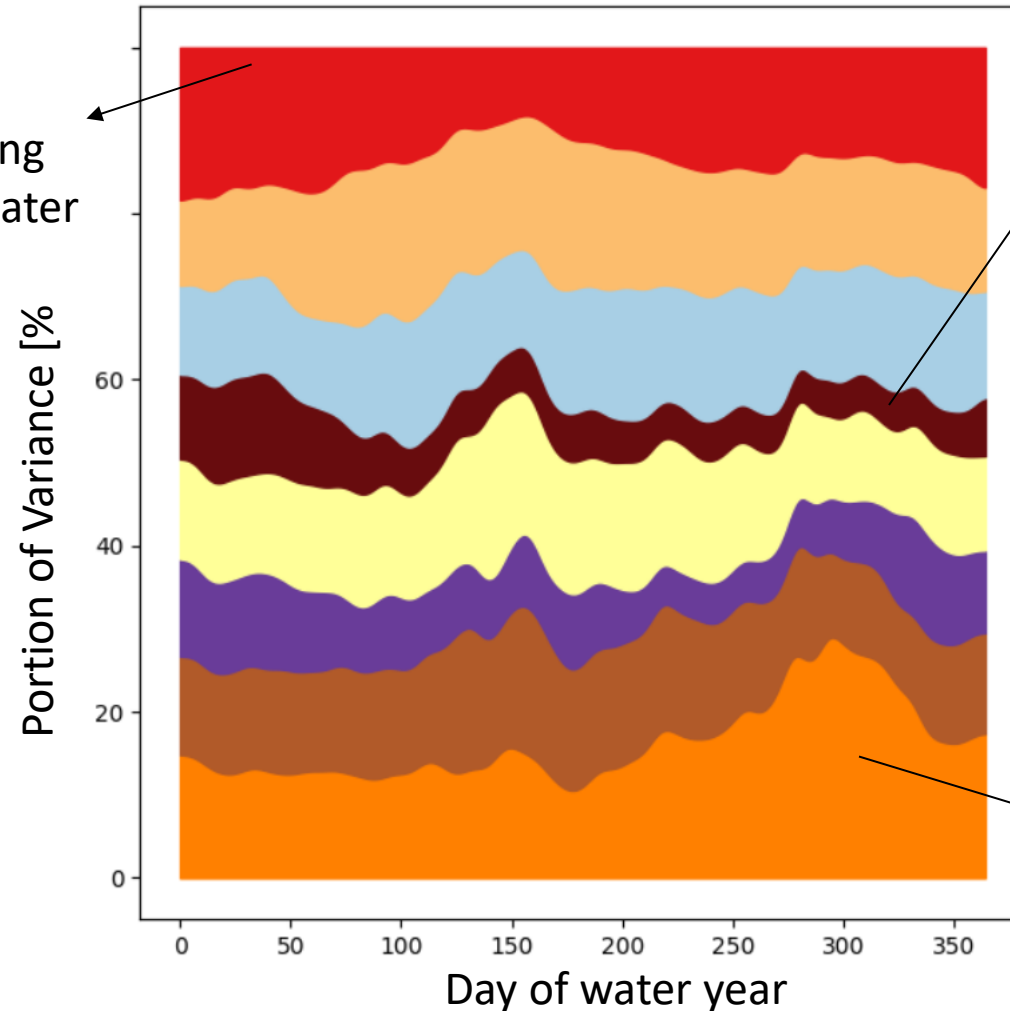


Variation in importance of state information for compromise solution



Variation in importance of state information for compromise solution

Forecast information is important during beginning of water year

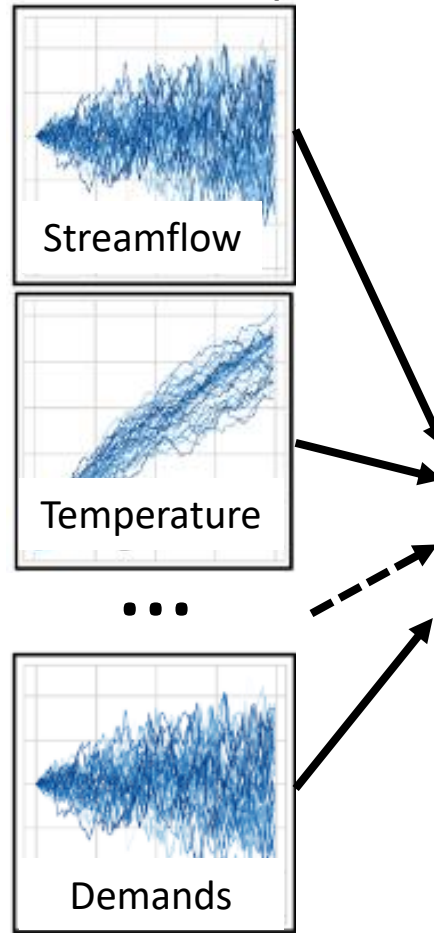


Temperature has the least contribution

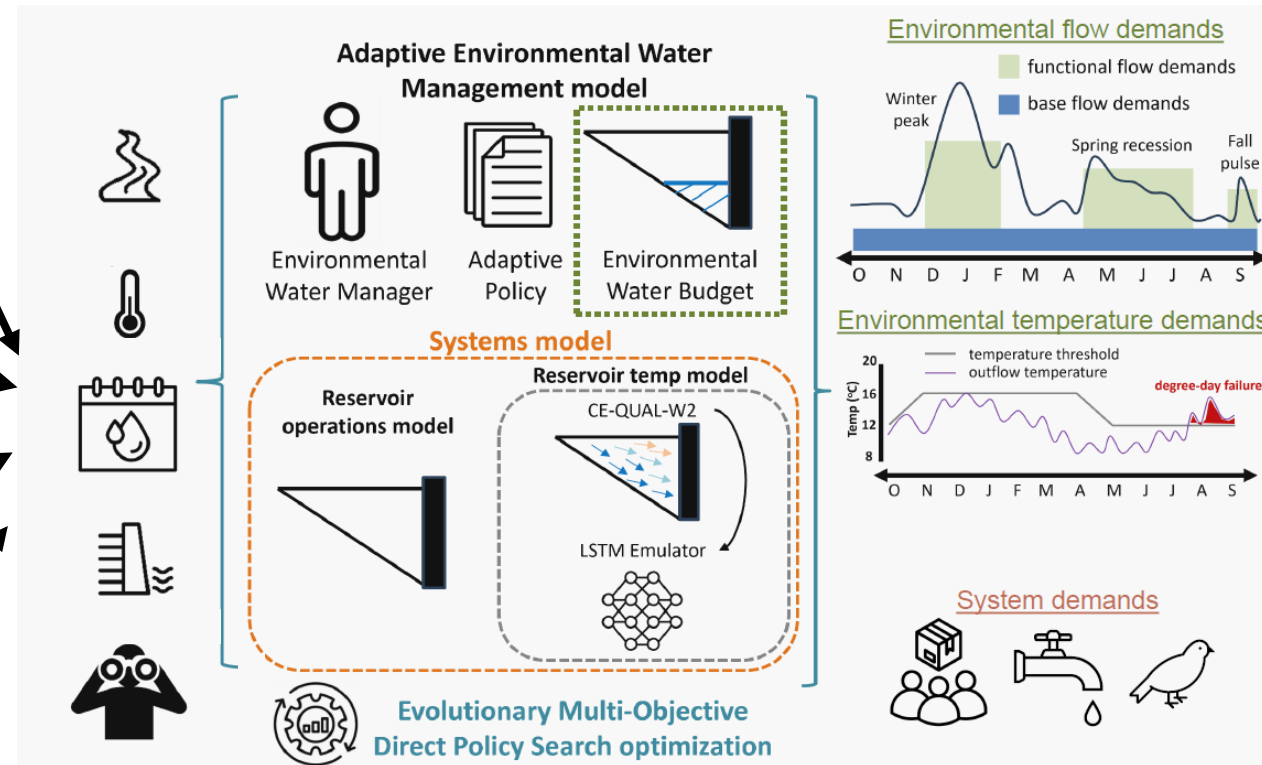
Reservoir storage is important towards end of water year

Future Work: Stochastic scenario development and EWM robustness

Stochastic inputs

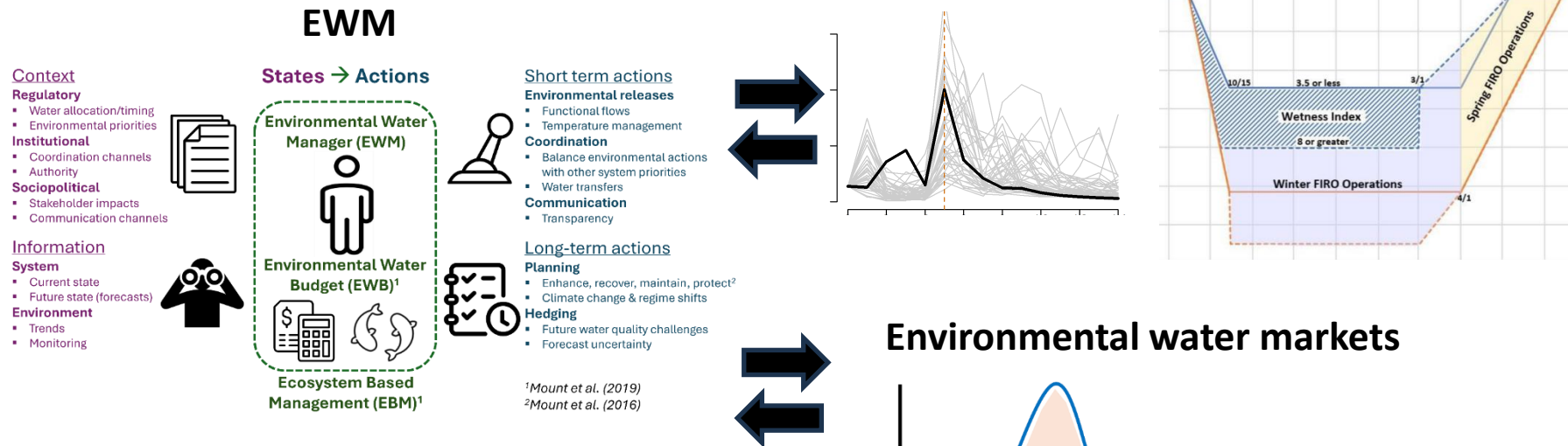


EWM adaptive decision-making robustness



Future Work: Synergies w/emerging strategies

Forecast Informed Reservoir Operations (FIRO)



Synergies

- Modeling tools and strategies
- Institutional and operational flexibility
- Improvements to water supply reliability for the environment

Future Work: Real-world applications

Willamette River System

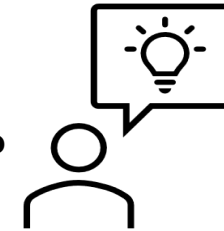


- System contains 13 USACE dams
- On the docket for major FIRO implementation effort starting 2026
- Large variety of environmental water management challenges

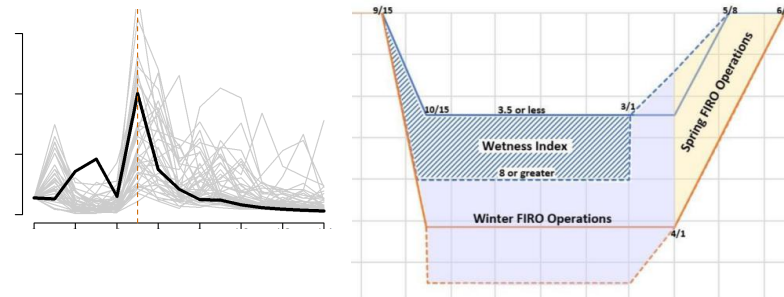
Environmental Water Management



EWM
impacts?



Forecast Informed Reservoir Operations



Discussion

Reference:

Alexander, C. A. D., Robinson, D. C. E., & Poulsen, F. (2014). *Application of the Ecological Flows Tool to Complement Water Planning Efforts in the Delta & Sacramento River: Multi-Species Effects Analysis & Ecological Flow Criteria* (p. 228). The Nature Conservancy.

Brodeur, Z., Sunkara, S. V., Penny, G., Hall, M., & Reed, P. (n.d.). Facilitating adaptive management for river system ecological resilience: Advancing an Environmental Water Manager role. *In submission, Journal of Water Resources Planning and Management* (October 2025)

Doering, K., Quinn, J., Reed, P. M., & Steinschneider, S. (2021). Diagnosing the Time-Varying Value of Forecasts in Multiobjective Reservoir Control. *Journal of Water Resources Planning and Management*, 147(7), 04021031. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0001386](https://doi.org/10.1061/(ASCE)WR.1943-5452.0001386)

Giuliani, M., Castelletti, A., Pianosi, F., Mason, E., & Reed, P. M. (2016). Curses, Tradeoffs, and Scalable Management: Advancing Evolutionary Multiobjective Direct Policy Search to Improve Water Reservoir Operations. *Journal of Water Resources Planning and Management*, 142(2). [https://doi.org/10.1061/\(asce\)wr.1943-5452.0000570](https://doi.org/10.1061/(asce)wr.1943-5452.0000570)

Null, S. E., Zeff, H., Mount, J., Gray, B., Sturrock, A. M., Sencan, G., Dybala, K., & Thompson, B. (2024). Storing and managing water for the environment is more efficient than mimicking natural flows. *Nature Communications*, 15(1), 5462. <https://doi.org/10.1038/s41467-024-49770-4>

SPA & USBR (2023). *Sites Reservoir Project: Final Environmental Impact Report/Environmental Impact Statement* (No. 2001112009; p. 1997). Sites Project Authority (SPA) and U.S. Bureau of Reclamation (USBR).