

Motivation & Background

Sedento Valley

DU Pathways IU

Computational Challenges

Performance & Robustness

Performance degradation

Sensitivity analysis

Key Takeaways

Accounting for human implementation uncertainties in the discovery of robust water supply infrastructure pathways using evolutionary multi-objective reinforcement learning (eMORL)

Lillian Lau[1], Patrick Reed[1], and David Gold[2]

EGU General Assembly 2026 | May 5th

[1] Cornell University, [2] Utrecht University

This presentation participates in OSPP

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5-minute Lightning Tour

Animate

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Water utilities are challenged by hydroclimatic extremes, uncertain demands, and financial constraints

fluence

The Most Overlooked Risk in Water Infrastructure? Time.

FLUENCE NEWS TEAM

FRIDAY, FEBRUARY 13, 2026

Extreme drought impacts three North Carolina counties

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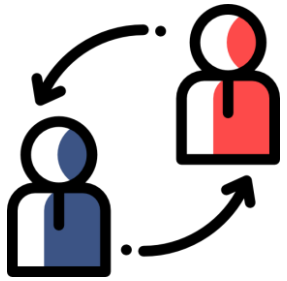
By Reuters

January 20, 2026 2:03 PM EST · Updated January 20, 2026

Regional cooperation promise **improved resource efficiency**, added **flexibility**, and **limited financial risks**, but…

Coordinate weekly drought management actions





Share water to achieve economies of scale

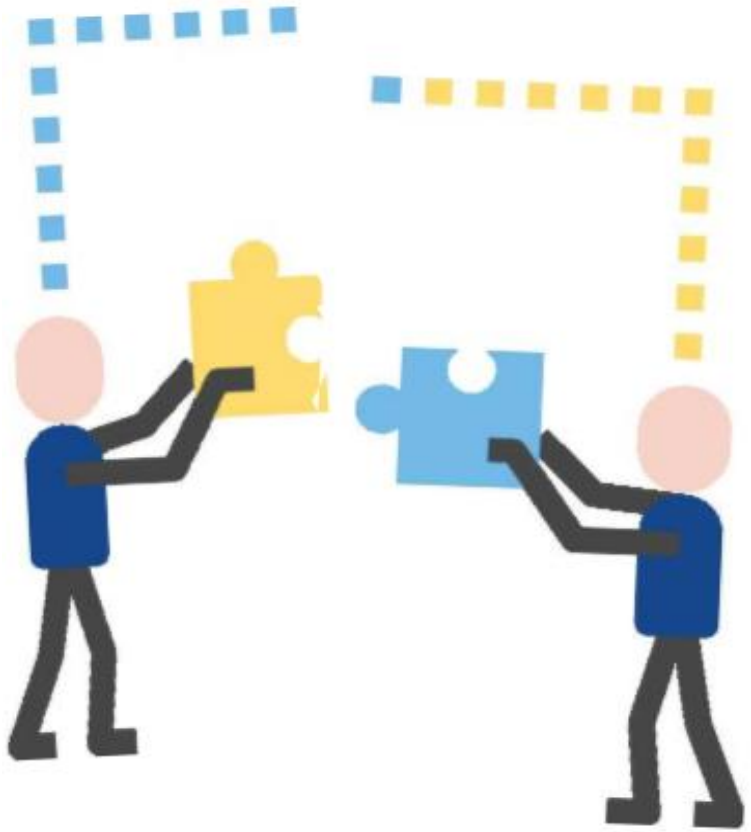
Regionalization



Co-invest to mitigate financial pressures over decades

Find out more here

Regional cooperation can expose utilities to **implementation uncertainty** that **degrade individual and collective robustness**



Implementation uncertainty

> *Uncertainty caused by the deviations from a prescribed portfolio of actions or decision variables*

Motivating Questions



How does **explicitly accounting for implementation uncertainty under challenging scenarios** change the **number** and **diversity** of pathway strategies discovered?



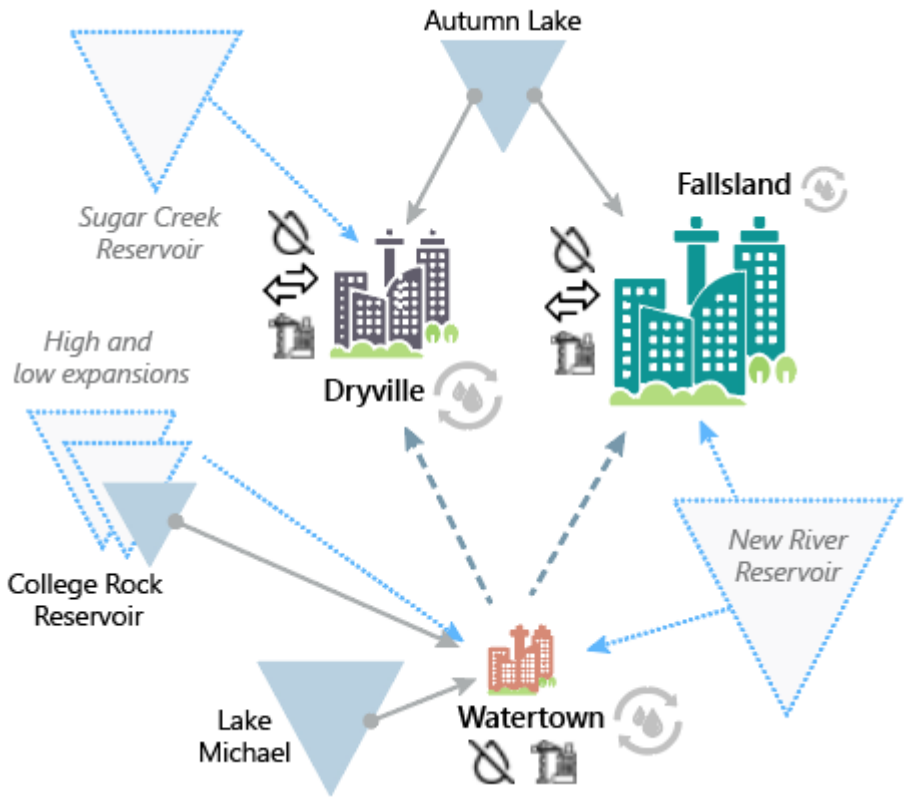
Can such pathway strategies uncertainty **avoid performance degradation** and **maintain high robustness** when exposed to imperfect implementation?



How do **vulnerabilities to implementation uncertainty manifest** across cooperating parties under selected compromise pathway strategies?

The Sedento Valley Benchmarking Test Case

Sedento Valley Schematic



Three utilities: **Watertown**, **Dryville**, and **Fallsland**

Each utility can take the following actions:

- Restrict water
- Purchase treated transfers
- Co-invest in new supply infrastructure

The utilities need to each meet **five performance objectives**

Five performance objectives per utility



Reliability



Restriction frequency



Infrastructure net present cost



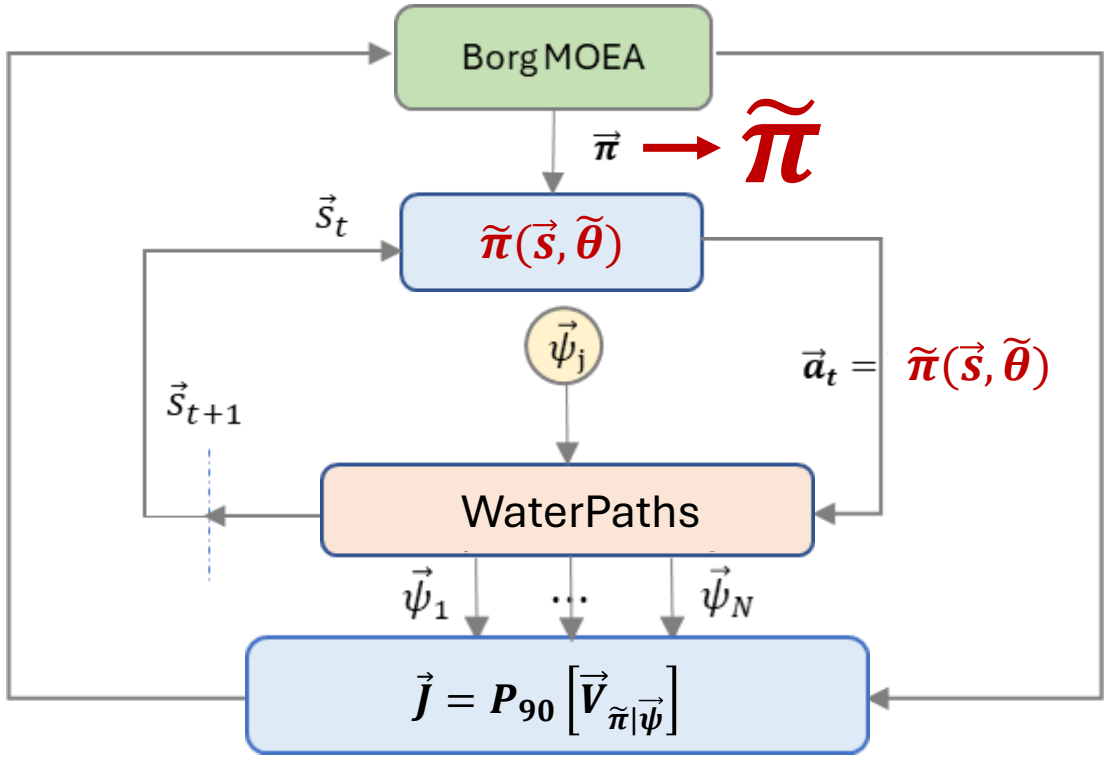
Peak financial cost



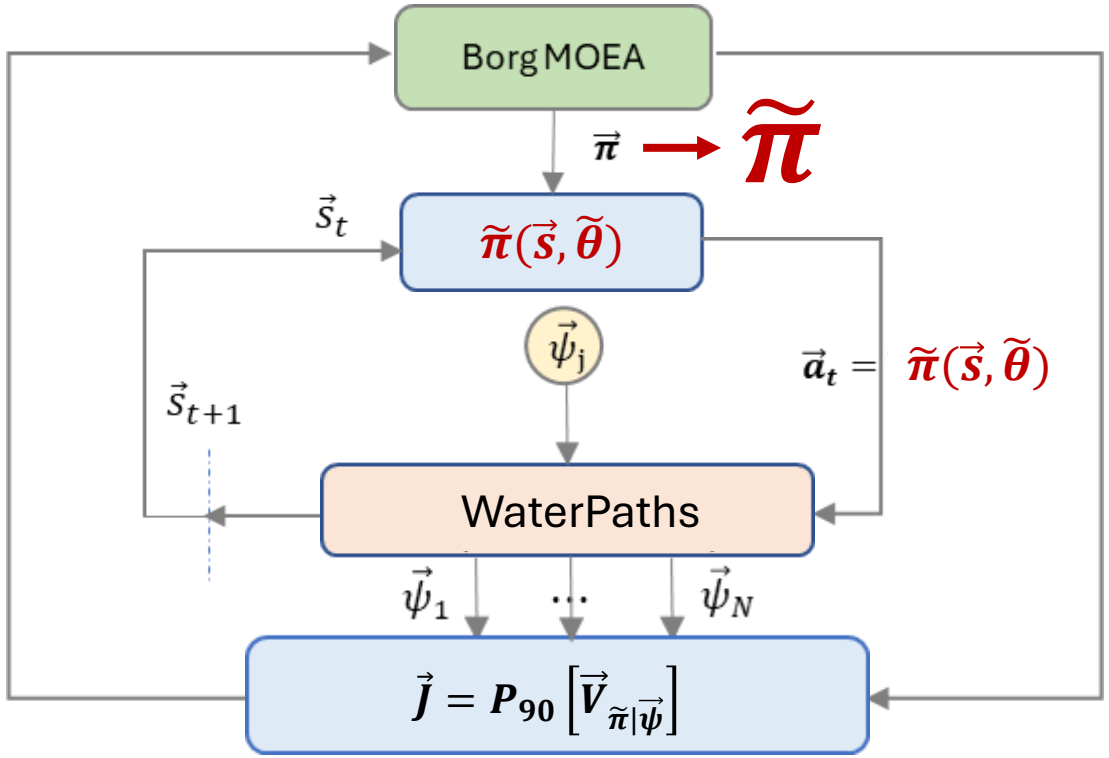
Drought mitigation cost

Find out more here

DU Pathways IU: An eMORL framework that allows utilities to meet their performance objectives under implementation uncertainty



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Water-use restrictions (RT)

Treated transfers (TT)

Infrastructure construction (INF)

Actions exposed to perturbations ρ within a $\pm$ 4% range

Find out more here

The computational experiment was conducted using the NERSC Perlmutter HPC System



Access to over **10,000 node hours** on the Perlmutter System at NERSC:

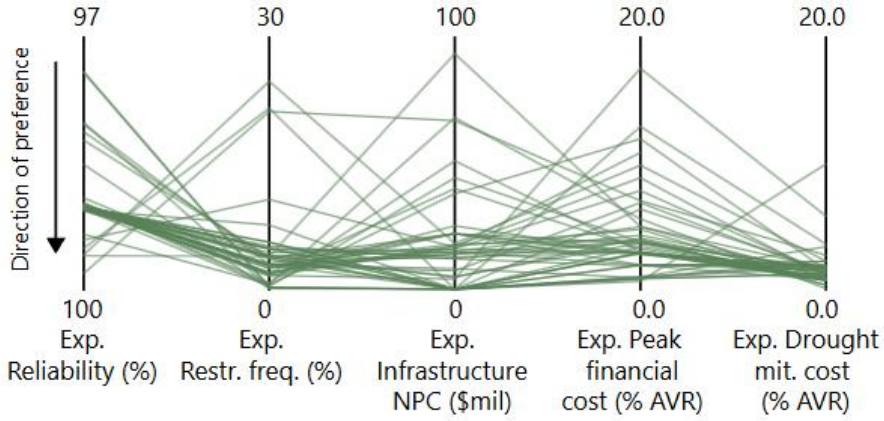
- 3,072 2x AMD EPYC 7763 CPU Nodes
- 1,536 TB of storage

Find out more here

The DU Pathways IU approach discovers a **larger, more diverse set of high performing strategies** under challenging conditions

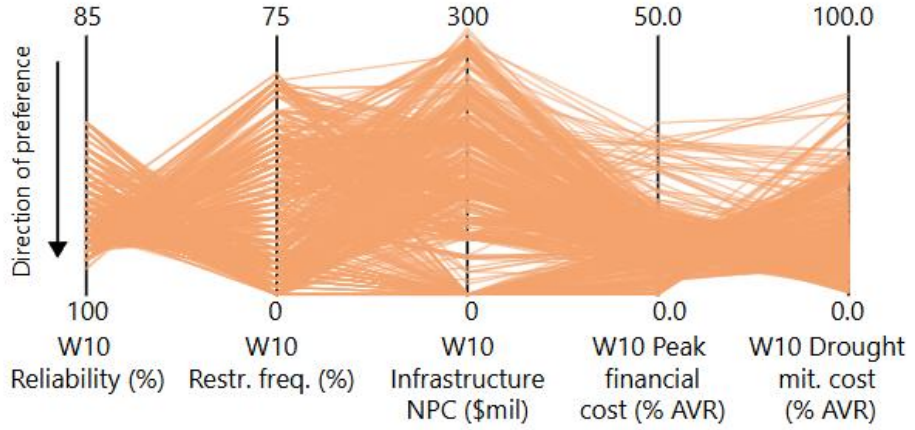
Baseline pathway strategies

46 pathway strategies *that achieve high performance under expected conditions*



IU pathway strategies

628 pathway strategies *that achieve moderate-to-high performance under challenging conditions*



Find out more here

We stress-test the pathway strategies across a **wider set of deeply uncertain states of the world (DU SOWs) to assess robustness**



REL > 98%



RF < 10%

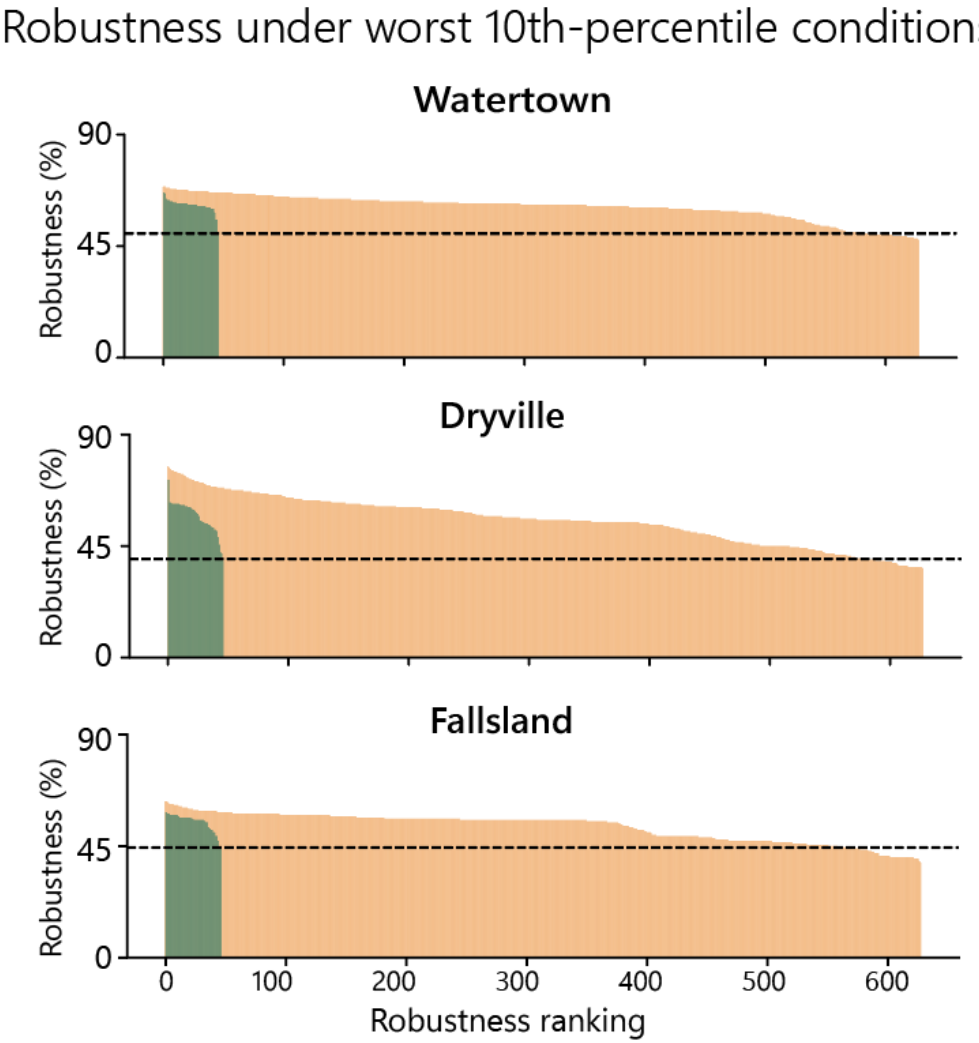


DMC < 10%

Satisficing robustness

The percentage of DU SOWs in which **all three satisficing criteria are met**

The IU pathway strategies that account for implementation uncertainty can **better adapt to deep uncertainty** and **achieve higher robustness**



The IU pathway strategies **largely attain higher robustness** than their baseline counterparts

More **frequent use of cooperative mechanism** allow them to **adapt to challenging, unforeseen scenarios**

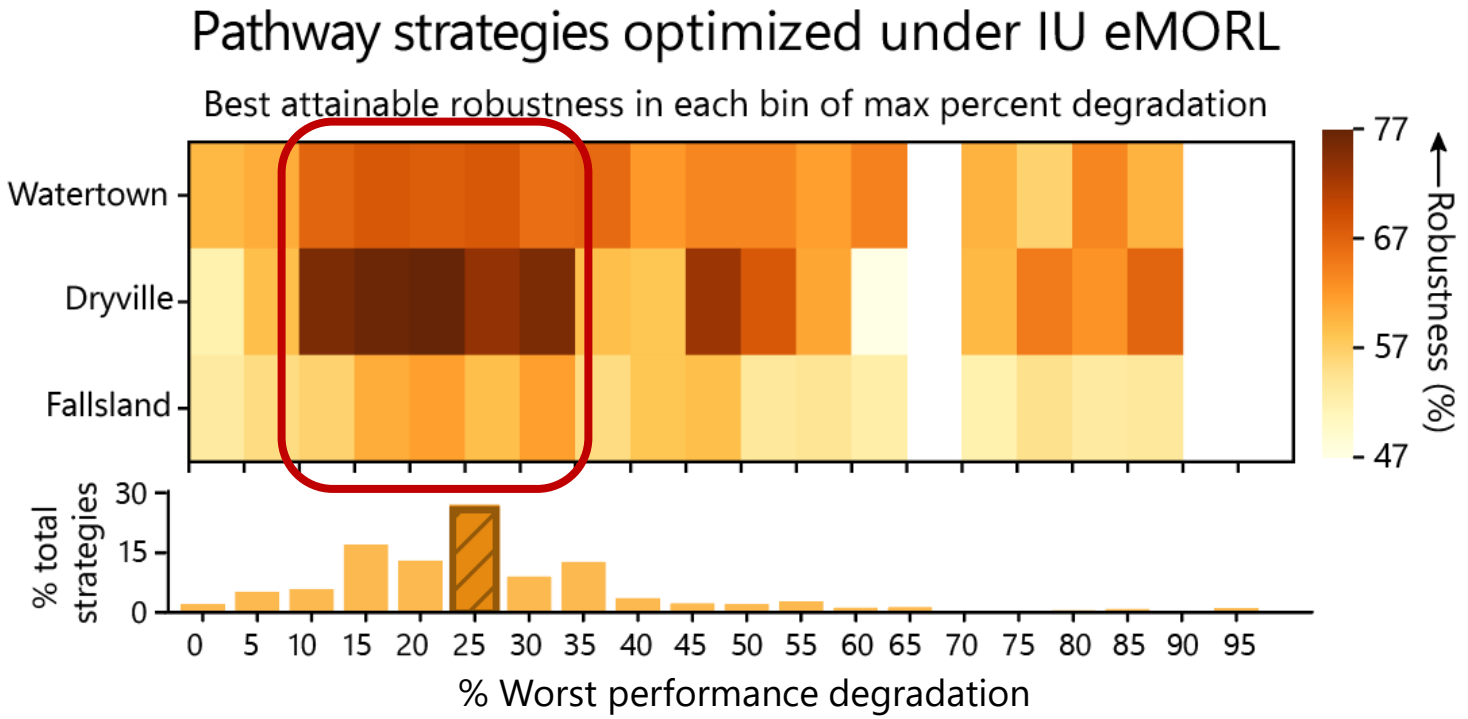
Find out more here

They also **experience limited performance degradation when exposed to implementation uncertainty** while achieving high robustness

Performance degradation

The **maximum percentage decrease in performance** under implementation uncertainty

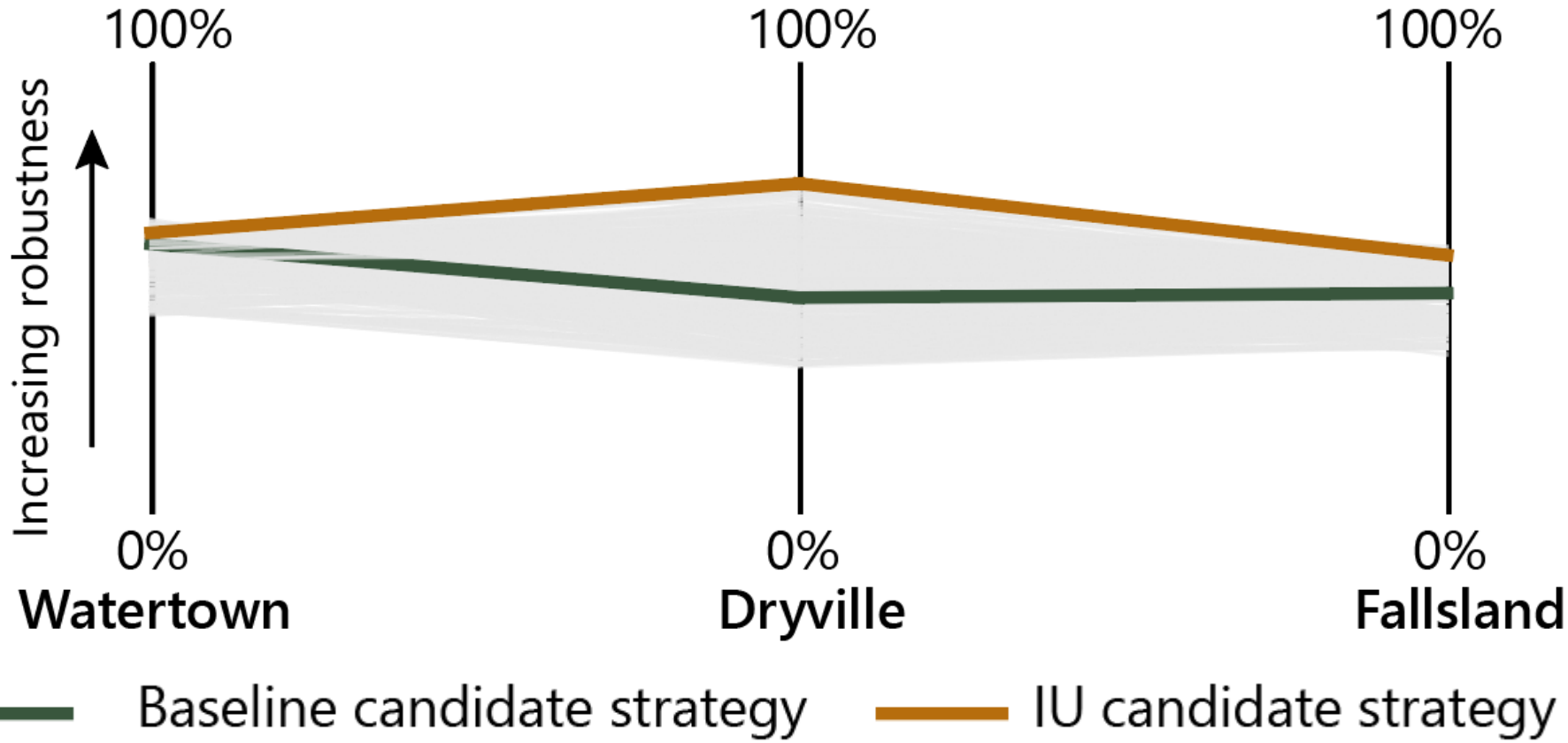
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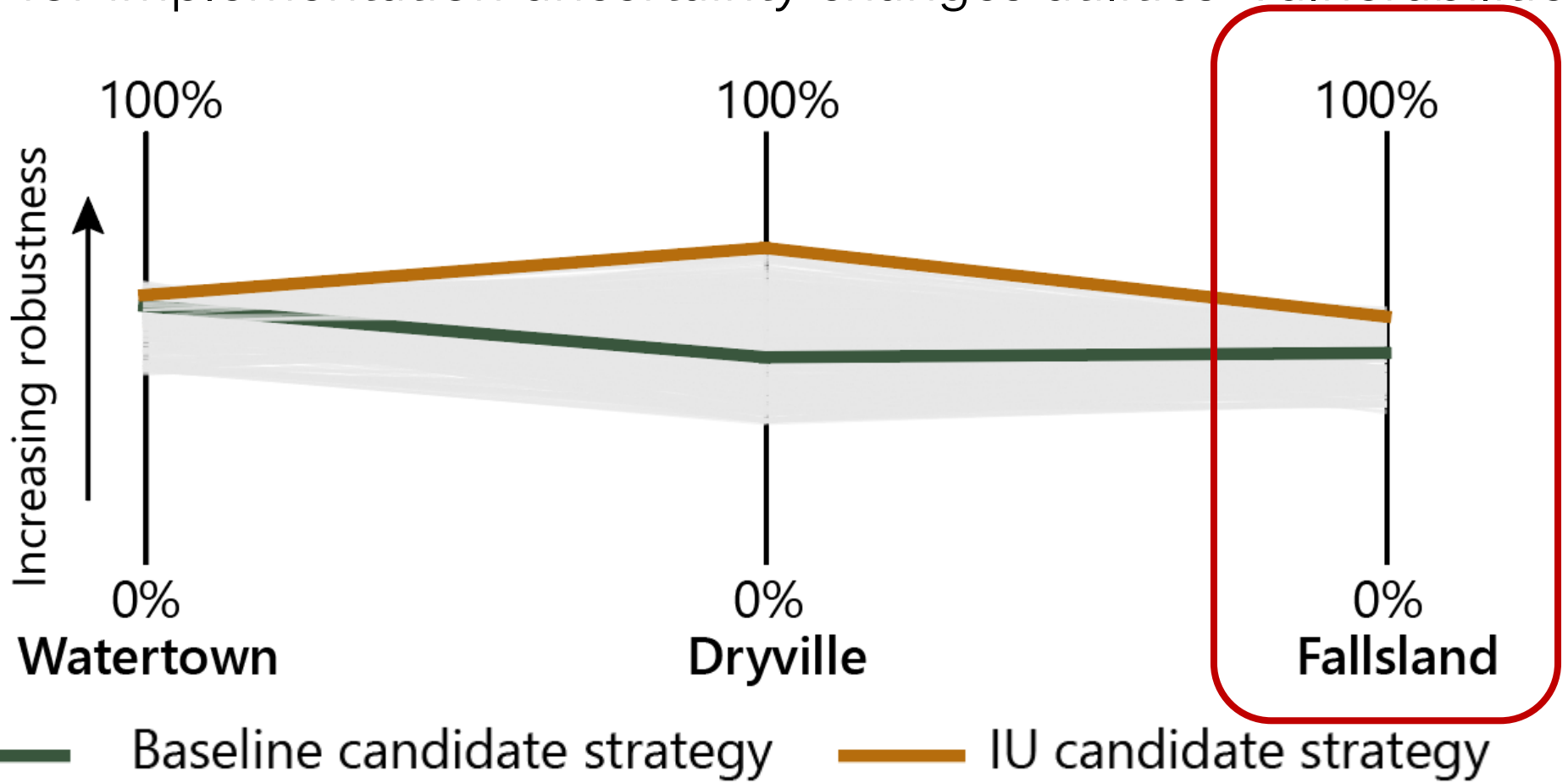
The IU pathway strategies can both **maintain high robustness and limited performance change** when exposed to implementation uncertainty

Find out more here

We select a **Social Planner strategy for Fallsland** to understand how accounting for implementation uncertainty changes utilities' vulnerabilities



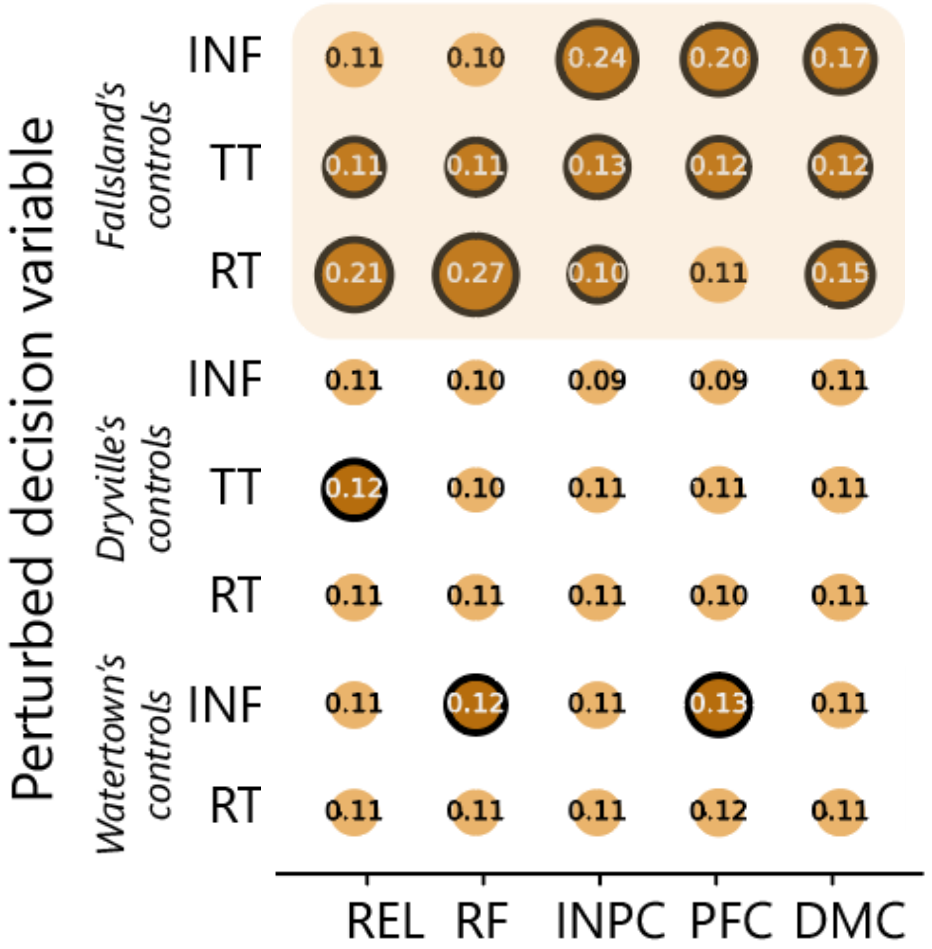
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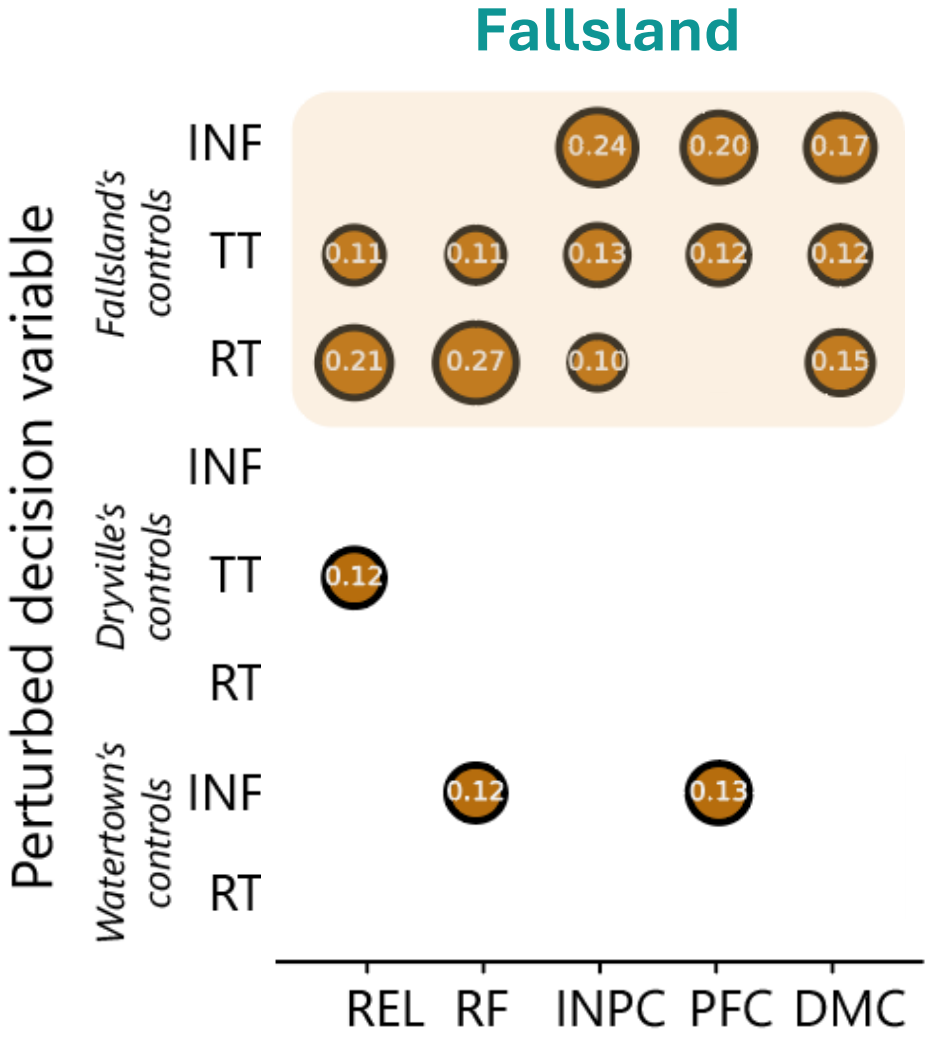
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The **IU strategy** affords utilities **better control** over their individual performance, **reducing vulnerability to implementation uncertainty**

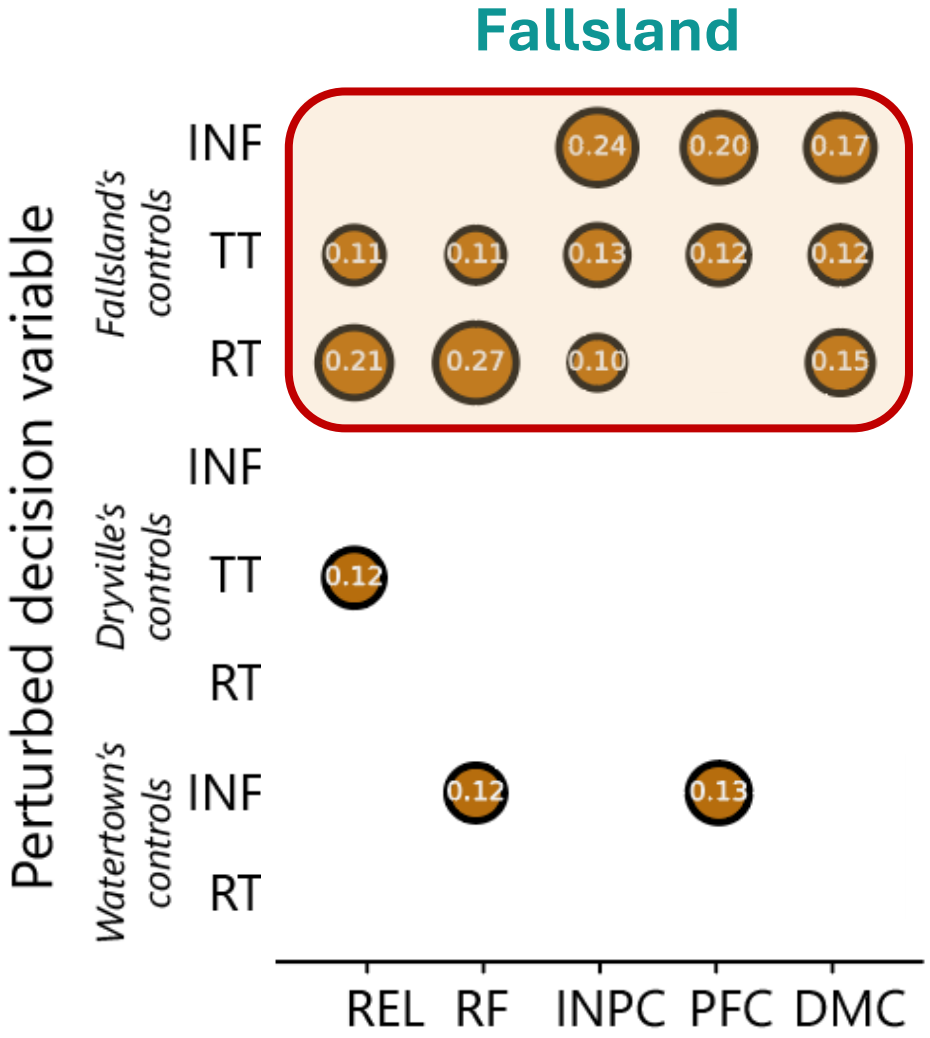
Fallsland



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Fallsland **benefits both from regional cooperation and an improved ability to maintain high performance** when implementation uncertainty is considered

Find out more here

Key Takeaways



DU Pathways (IU) facilitates the discovery of a **more diverse set of highly cooperative pathway strategies** that **generalize well** under both expected and challenging conditions



Such policies are also **more robust** and **maintain high performance under deviations** from the original strategy, affording utilities **more agency** over their decisions



This **improves transparency** into how human-driven **implementation uncertainty drives potential future conflicts**, facilitating acknowledgement and joint mitigation.

Motivation and Background

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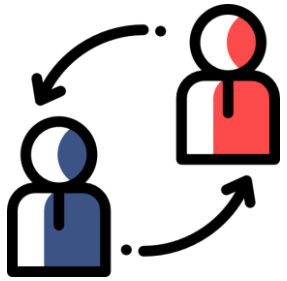
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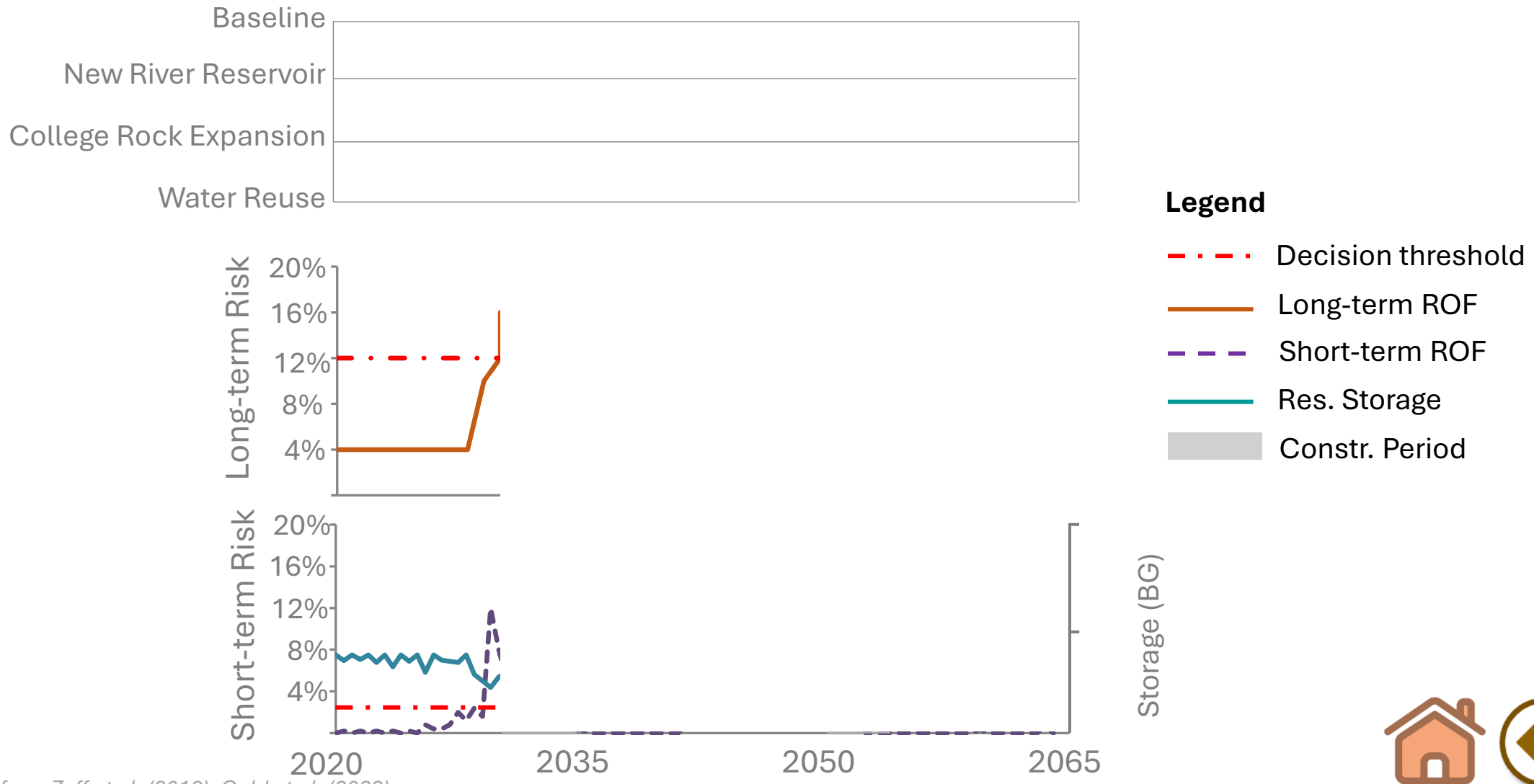
Share water to achieve economies of scale

Regionalization



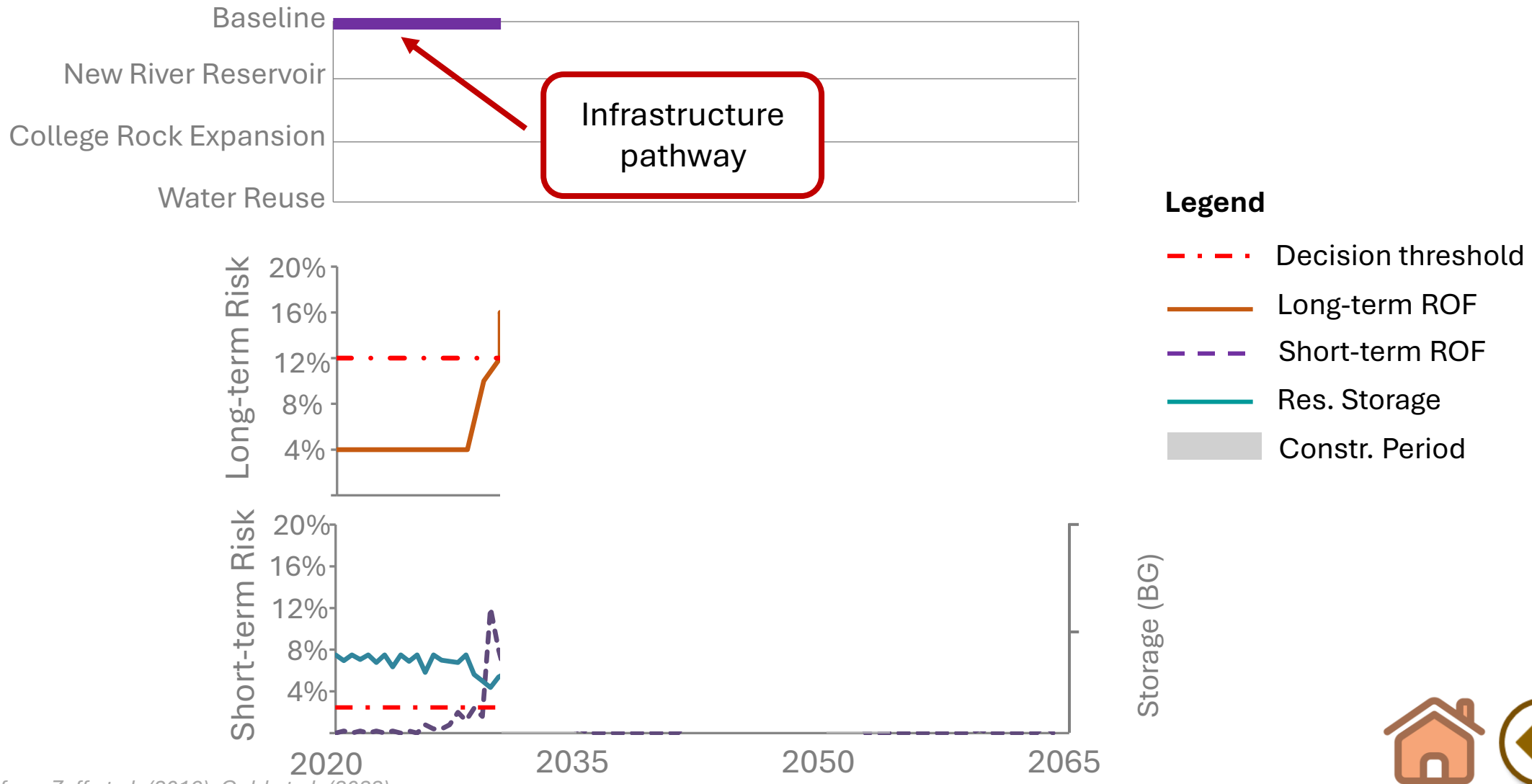
Co-invest to mitigate financial pressures over decades

Recent innovations enable utilities to **realize the benefits of regional cooperation** using **state-aware infrastructure investment pathways**



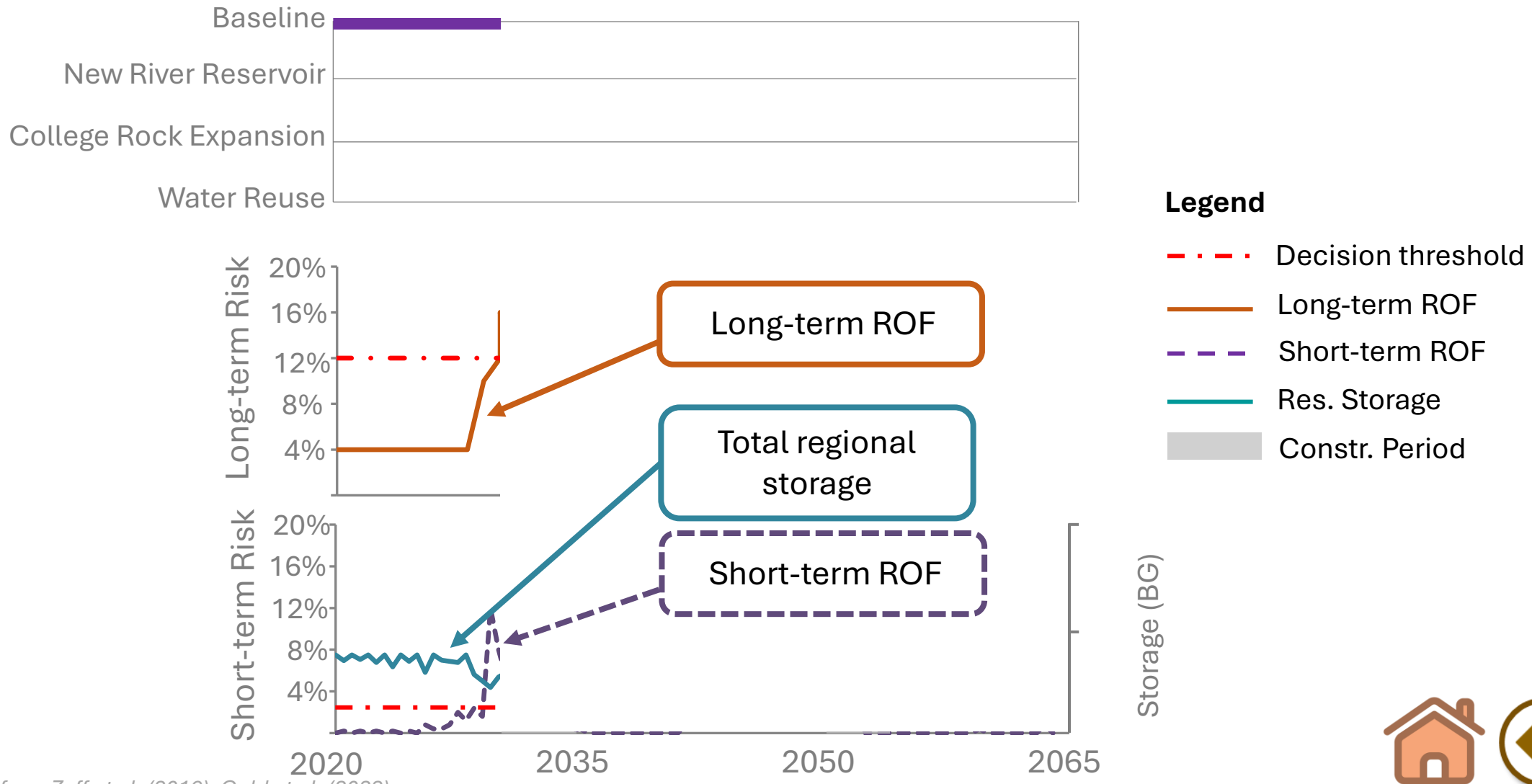
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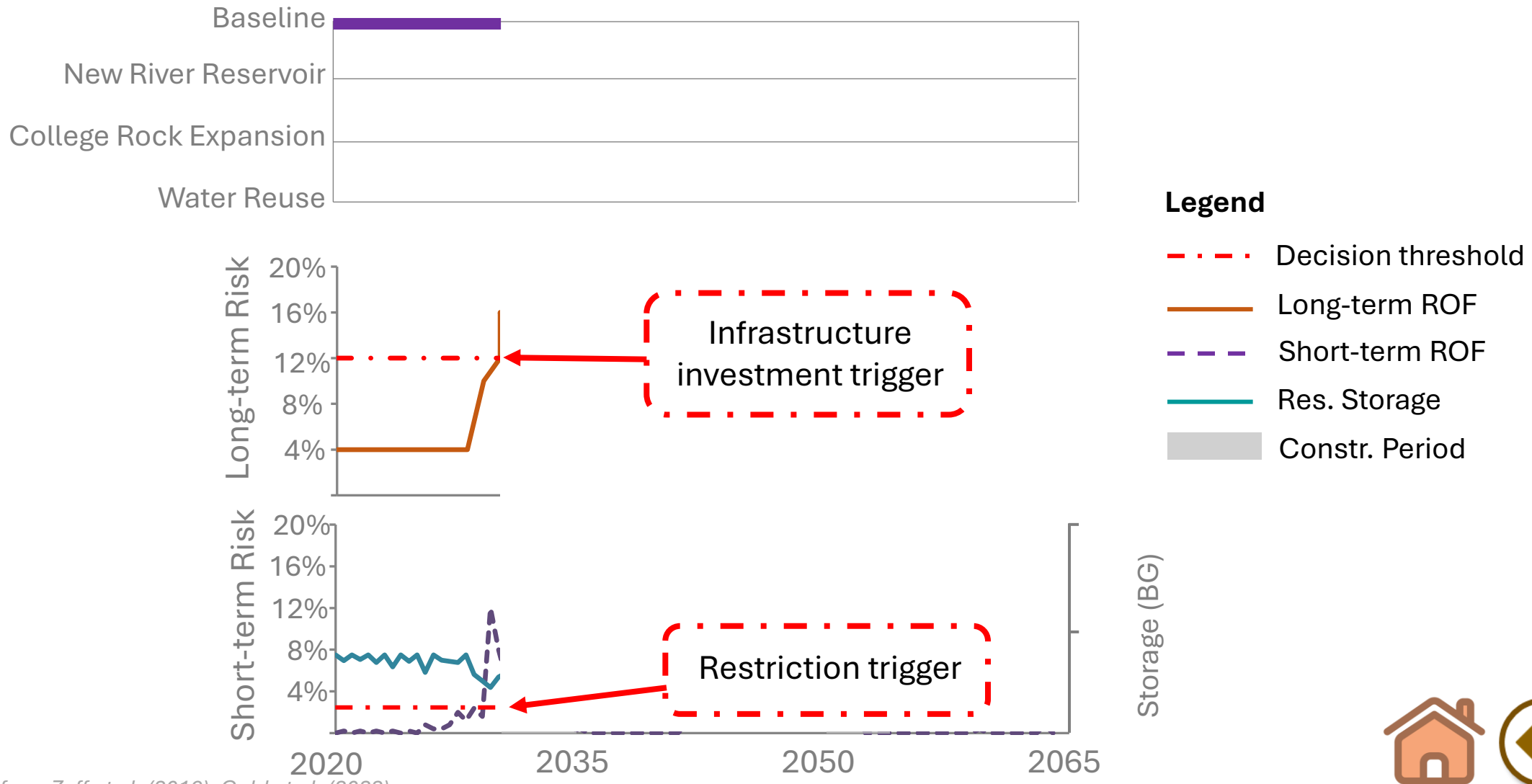
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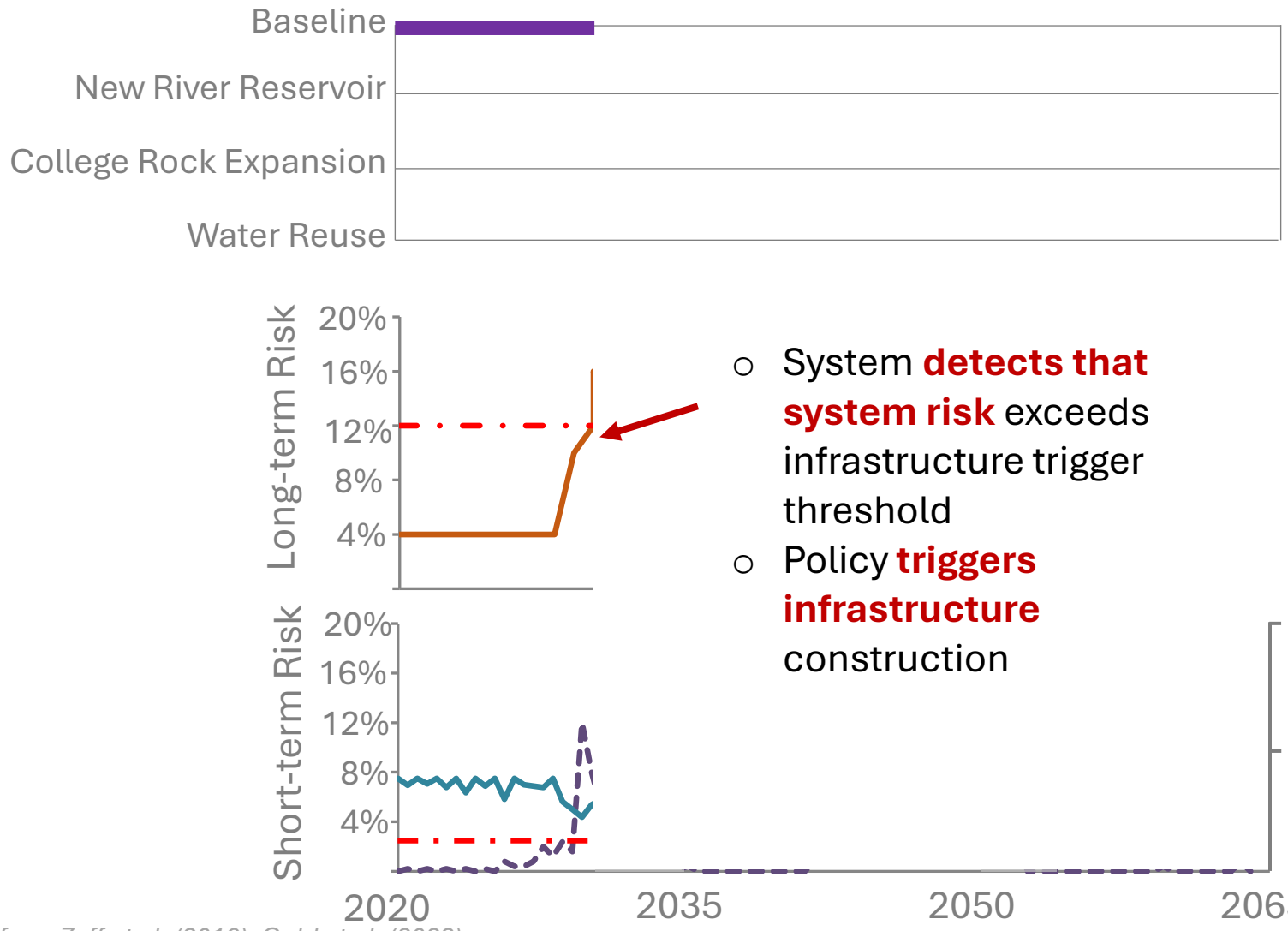
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Recent innovations enable utilities to **realize the benefits of regional cooperation** using **state-aware infrastructure investment pathways**



- System **detects that system risk** exceeds infrastructure trigger threshold
- Policy **triggers infrastructure** construction

Legend

- Decision threshold
- Long-term ROF
- Short-term ROF
- Res. Storage
- Constr. Period

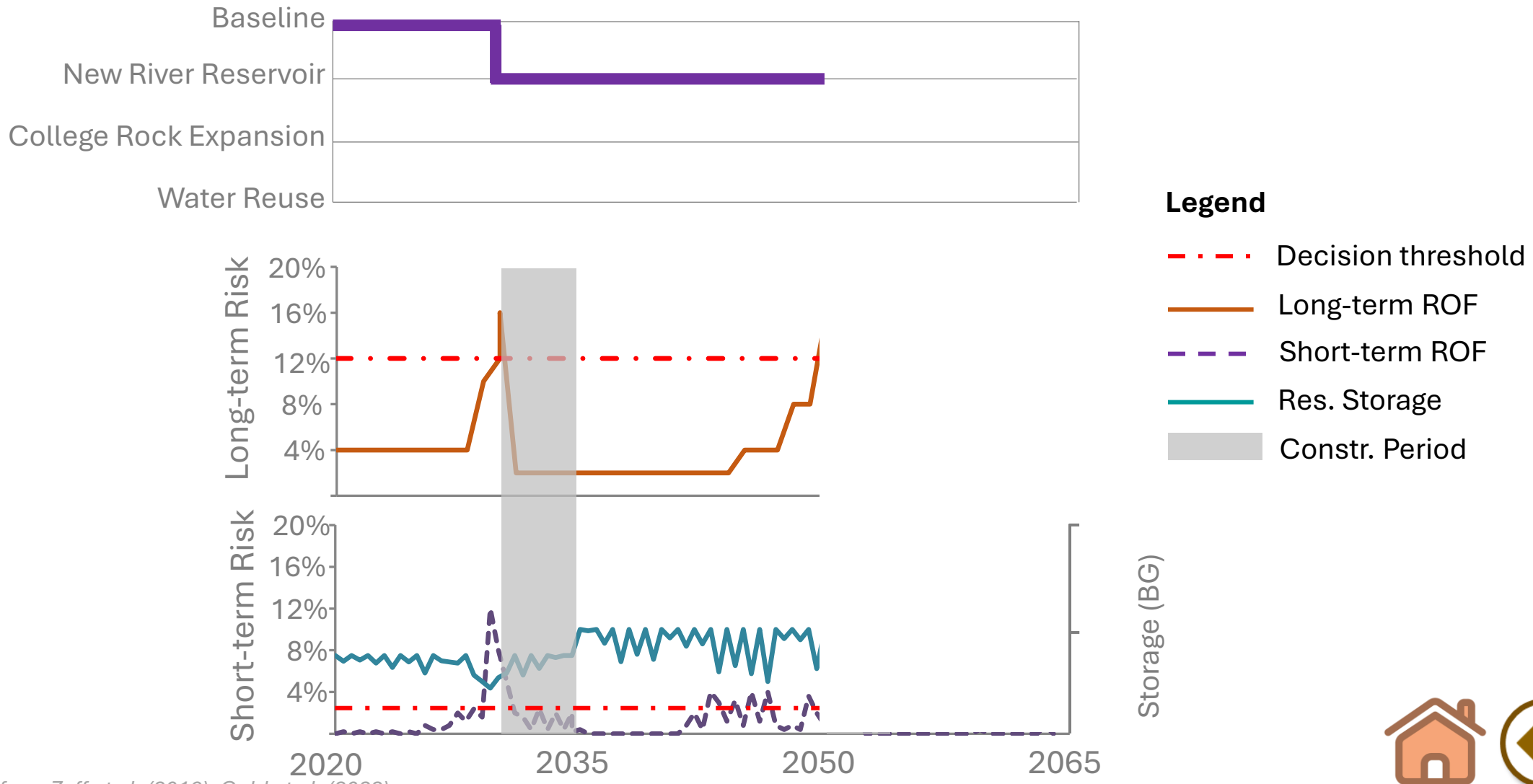
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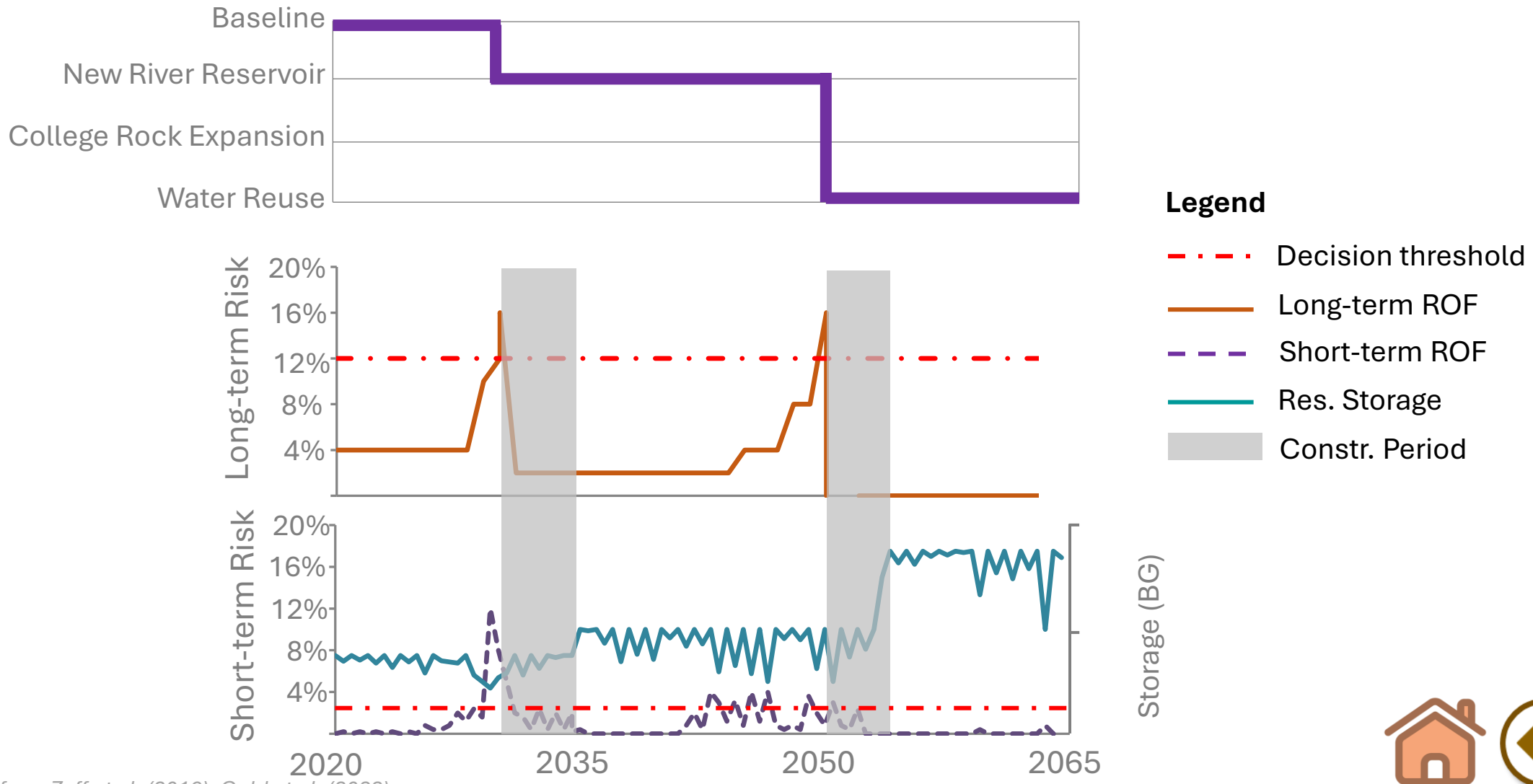
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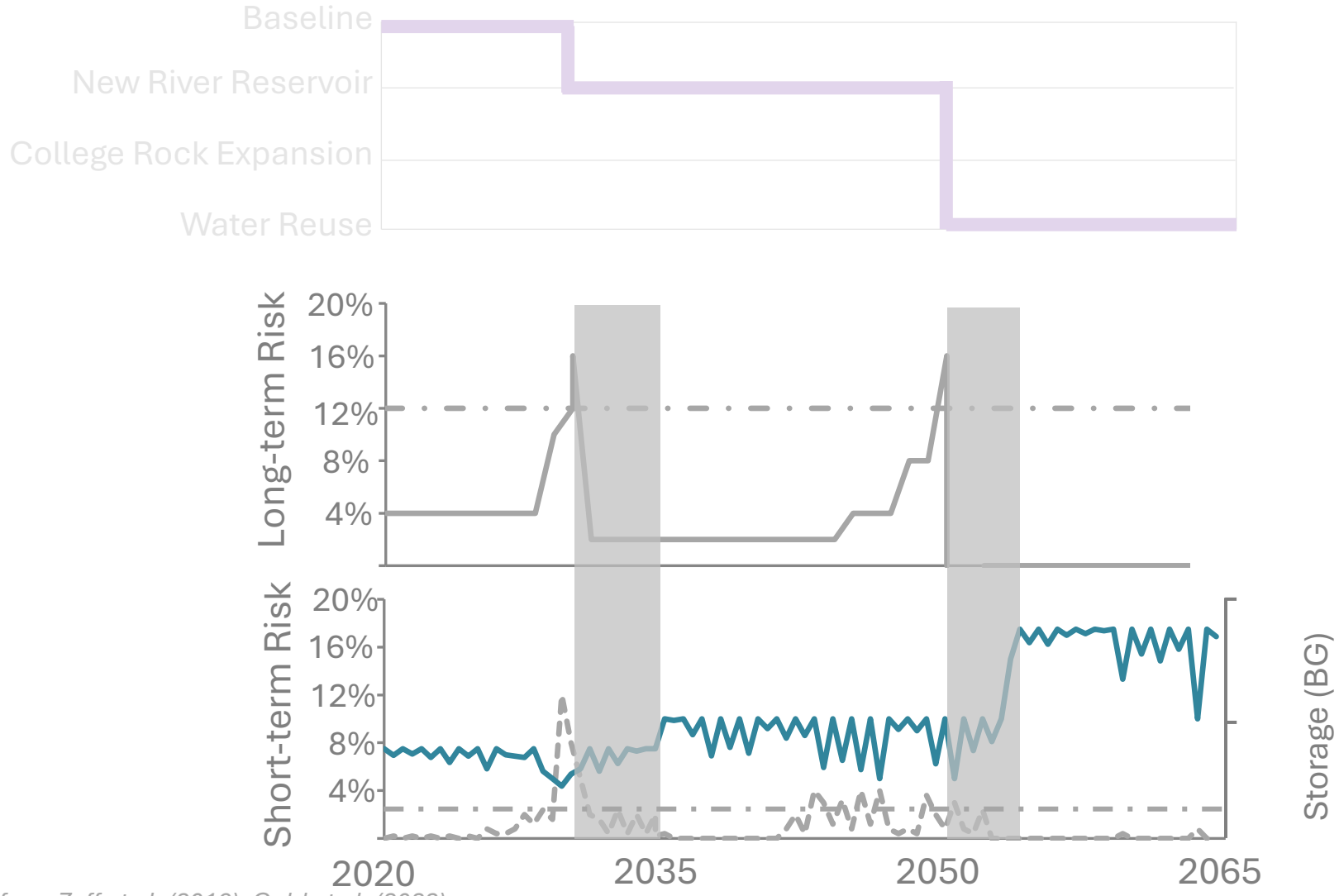
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Recent innovations enable utilities to **realize the benefits of regional cooperation** using **state-aware infrastructure investment pathways**



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When implementing investment pathways, utilities need to **manage risks** driven by **deeply uncertain storage**, **demand**, and **infrastructure timings**

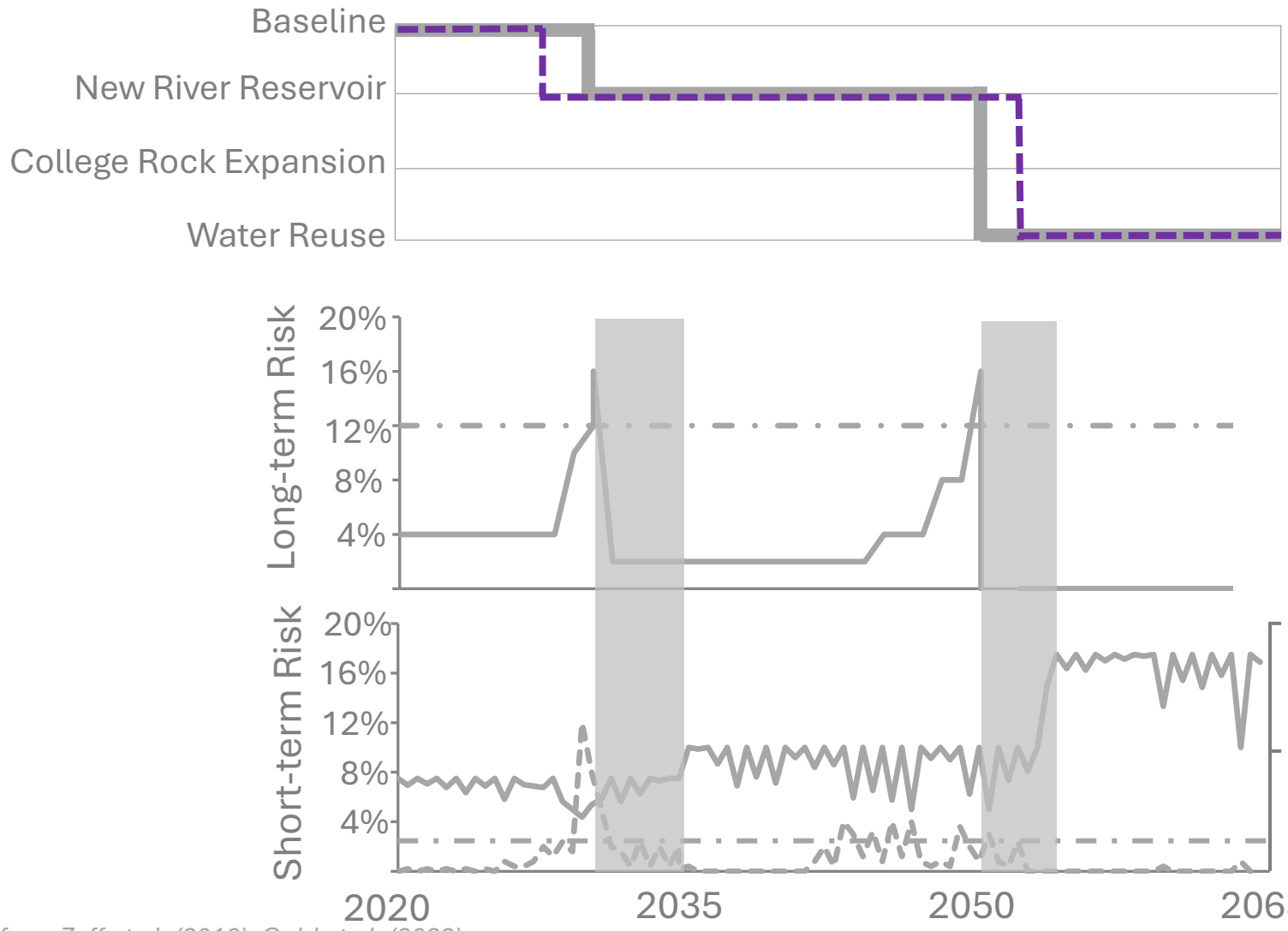


Deep uncertainty in

- Streamflows
- Demands
- Evaporation

Adapted from Zeff et al. (2016), Gold et al. (2022)

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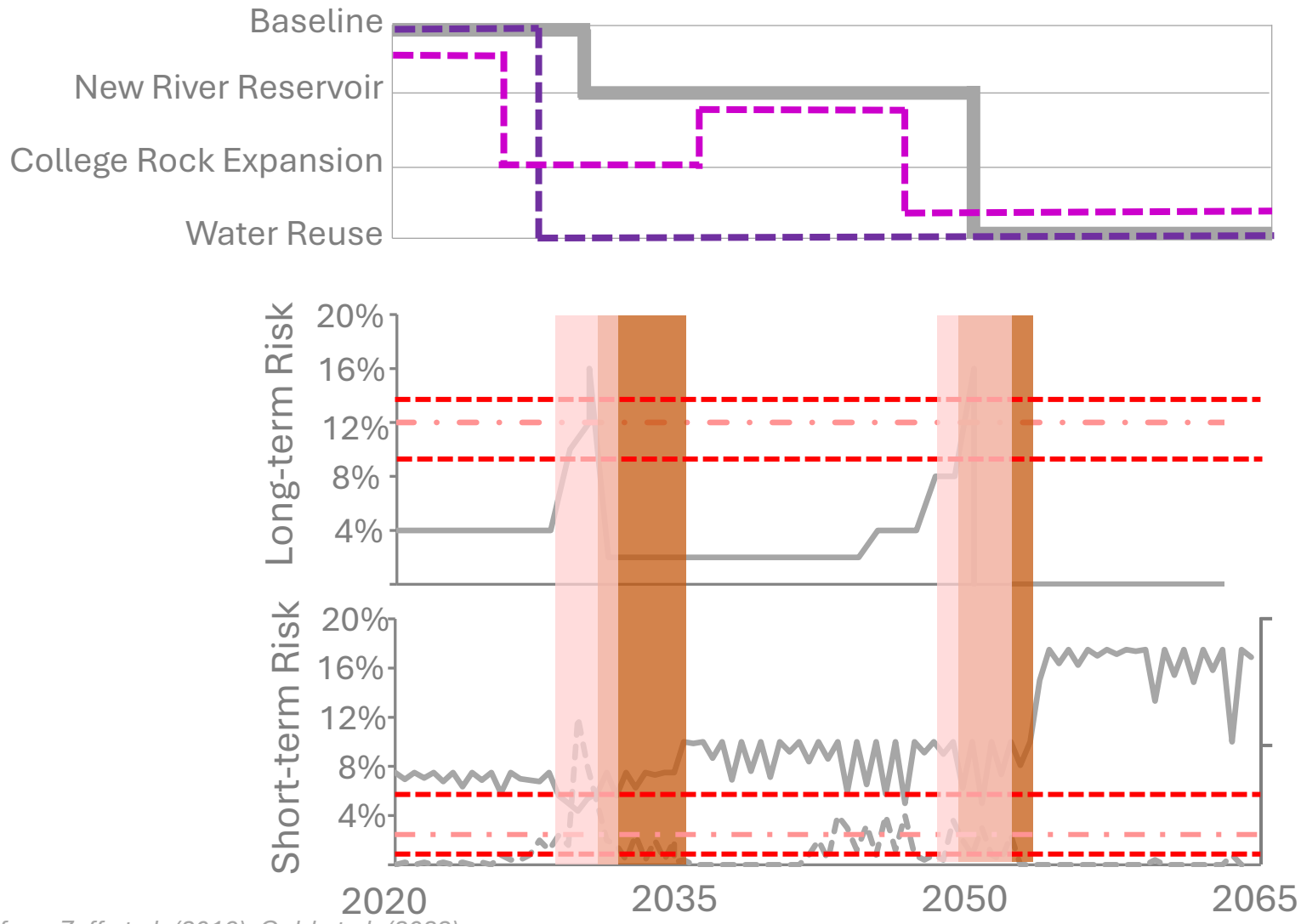


Deep uncertainty in

- Construction timing
- Permitting time
- Bond terms
- Interest rates

Adapted from Zeff et al. (2016), Gold et al. (2022)

Regional cooperation can expose utilities to **implementation uncertainty** that **degrade individual and collective robustness**



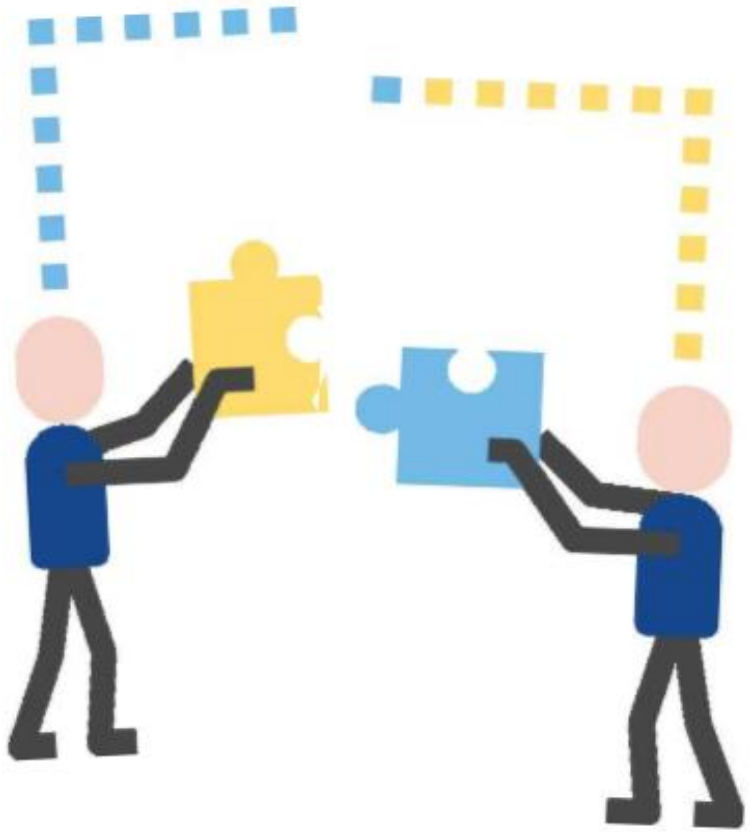
Deep uncertainty in

Strategy implementation

Adapted from Zeff et al. (2016), Gold et al. (2022)

Back to Tour

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Implementation uncertainty

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Motivating Questions



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The Sedento Valley

The Sedento Valley Benchmarking Test Case

Sedento Valley Schematic

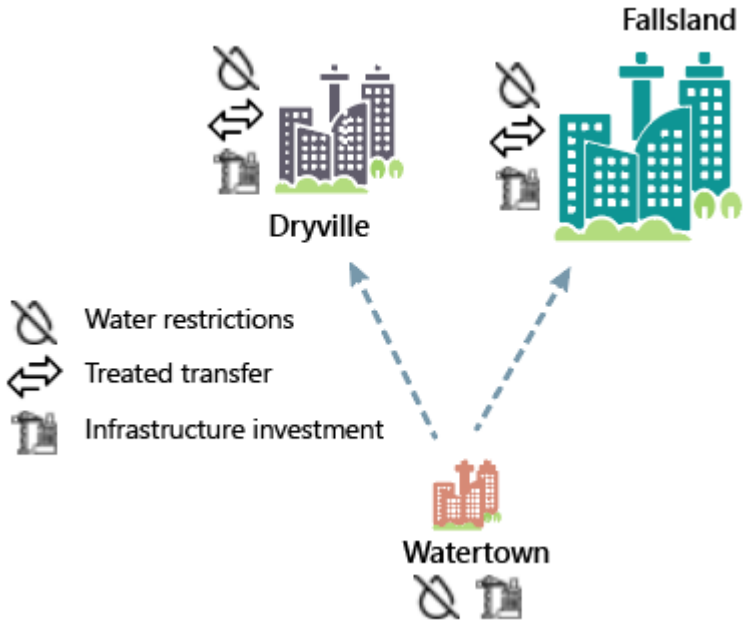


Three utilities:

- **Watertown**
- **Dryville**
- **Fallsland**

The Sedento Valley Benchmarking Test Case

Sedento Valley Schematic



Three possible planning and drought mitigation actions



Water-use restrictions (RT)



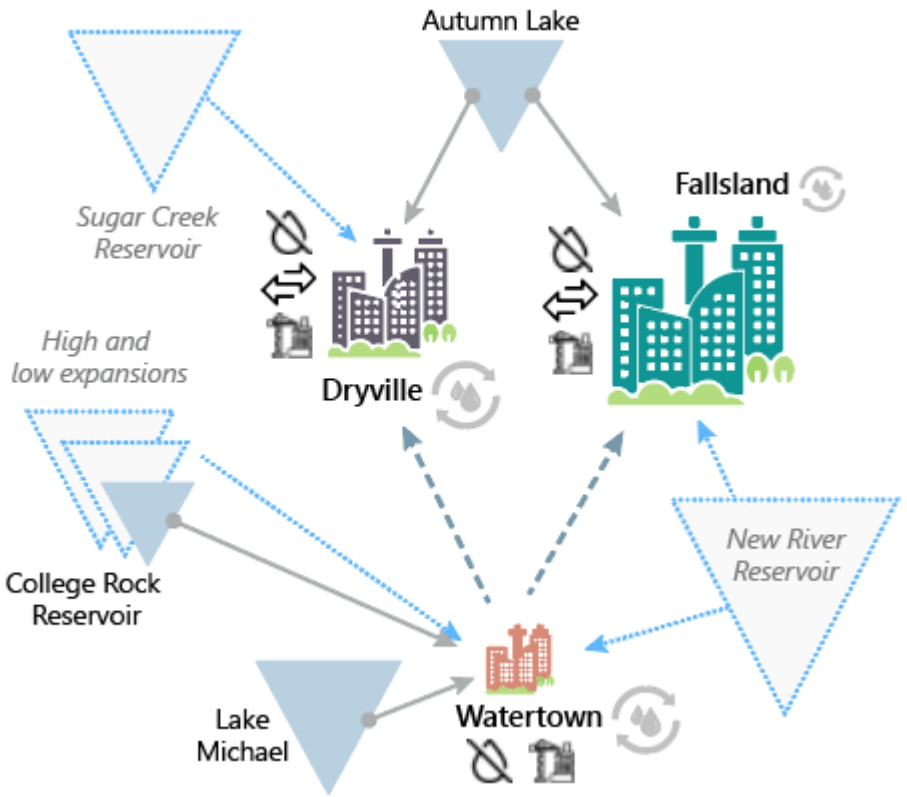
Treated transfers (TT)



Infrastructure construction (INF)

The Sedento Valley Benchmarking Test Case

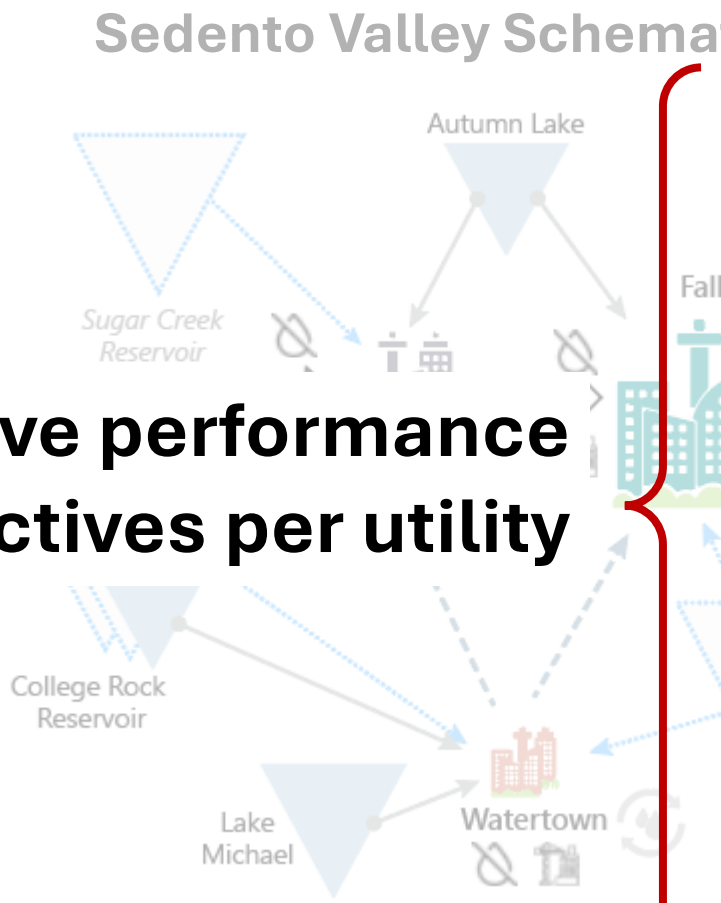
Sedento Valley Schematic



Types of new infrastructure:

- Water reuse facilities
- New reservoirs
- Reservoir expansions

The Sedento Valley Benchmarking Test Case



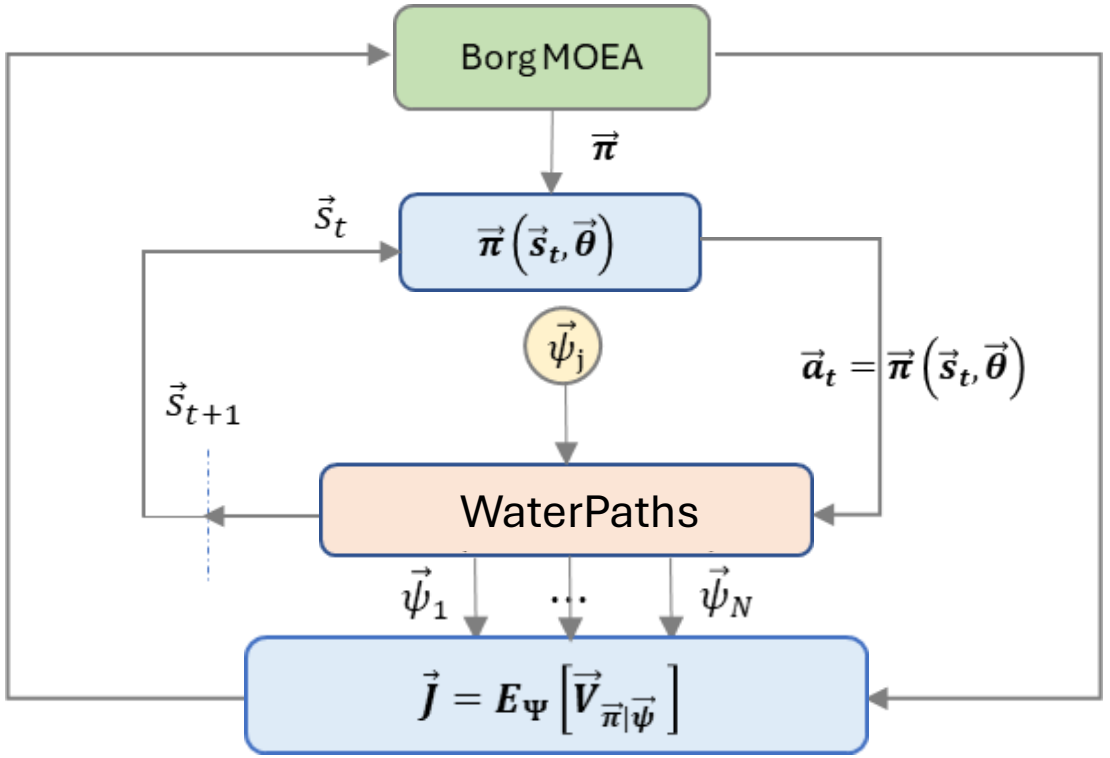
Five performance objectives per utility

- **Reliability**
- **Restriction frequency**
- **Infrastructure net present cost**
- **Peak financial cost**
- **Drought mitigation cost**

Back to Tour

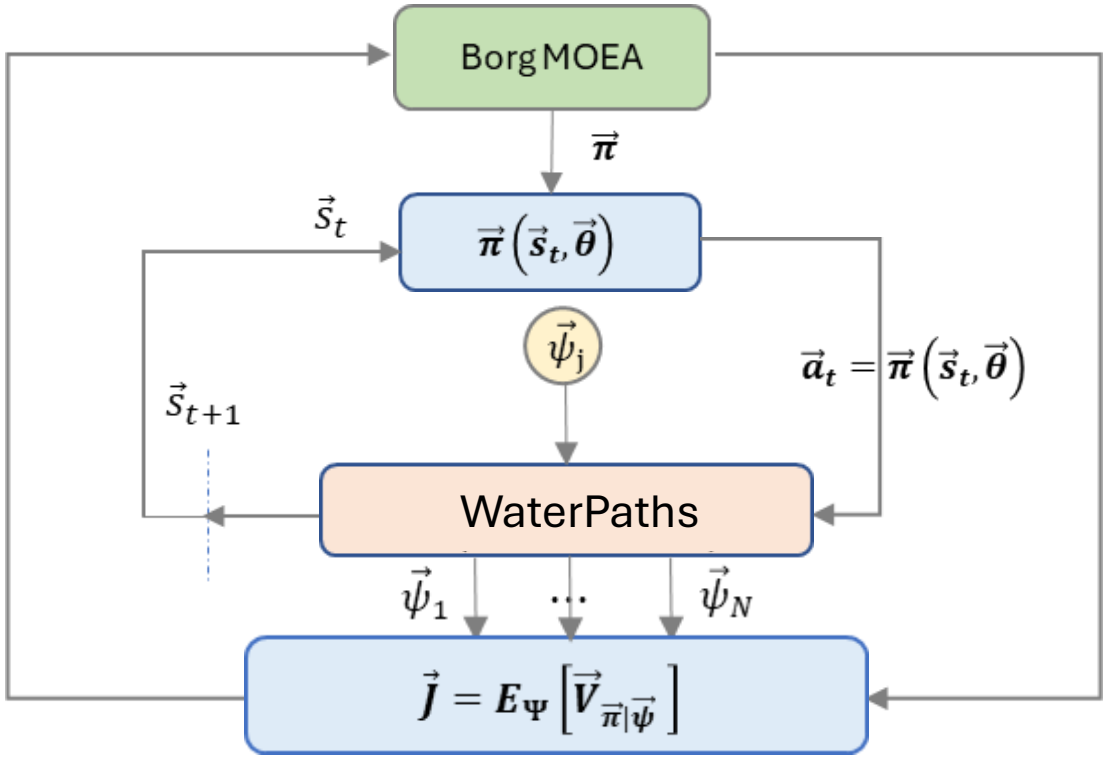
Deeply Uncertain Pathways under Implementation Uncertainty (DU Pathways IU)

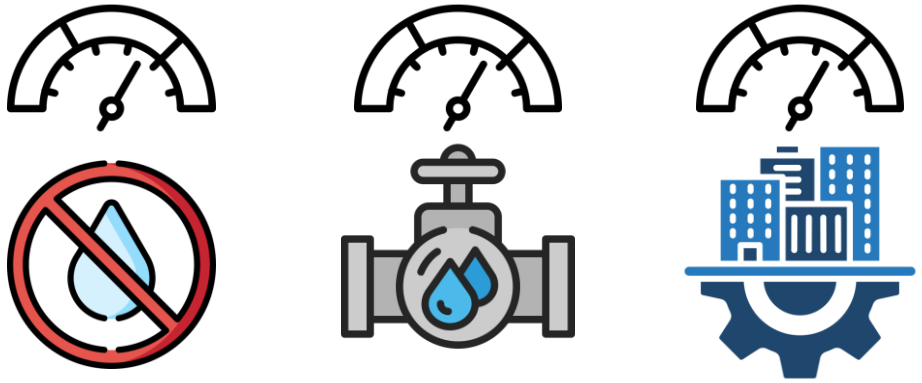
DU Pathways exploits evolutionary **multi-objective reinforcement learning (eMORL)** to discover robust pathway strategies



Leverage **MOEAs** to **discover policies** to **coordinate** planning and management **actions**

DU Pathways exploits evolutionary **multi-objective reinforcement learning (eMORL)** to discover robust pathway strategies





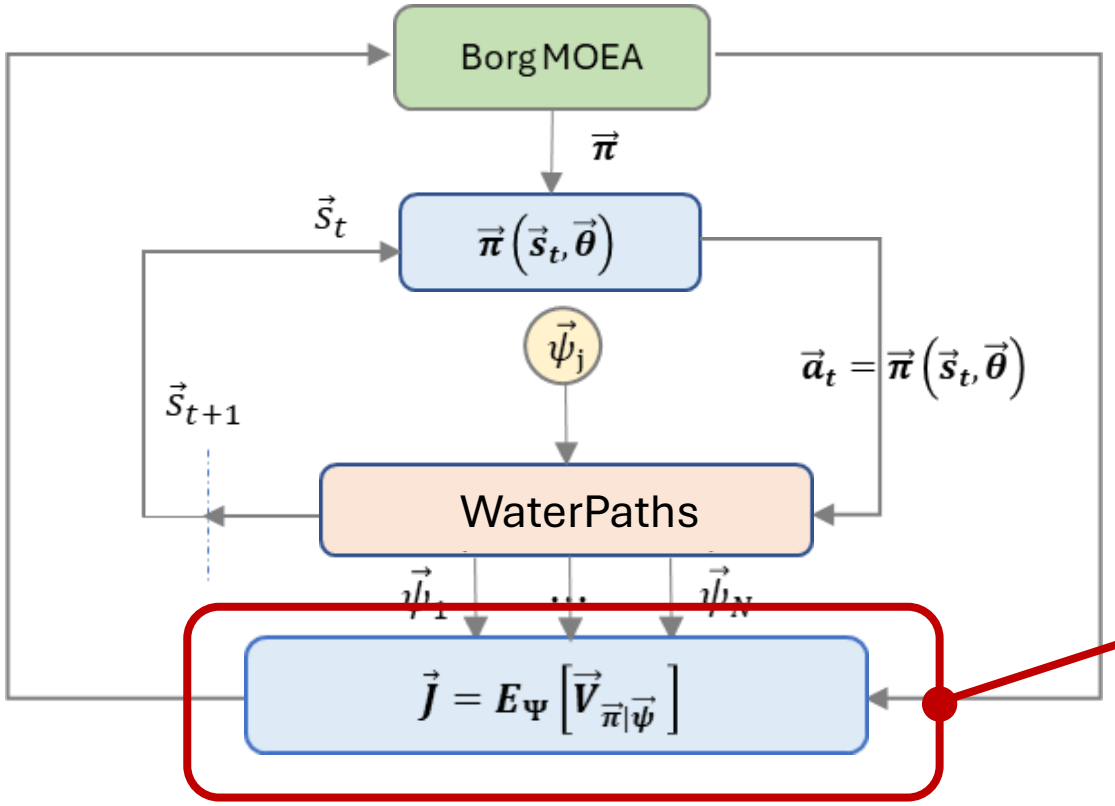
Water-use restrictions (RT)

Treated transfers (TT)

Infrastructure construction (INF)

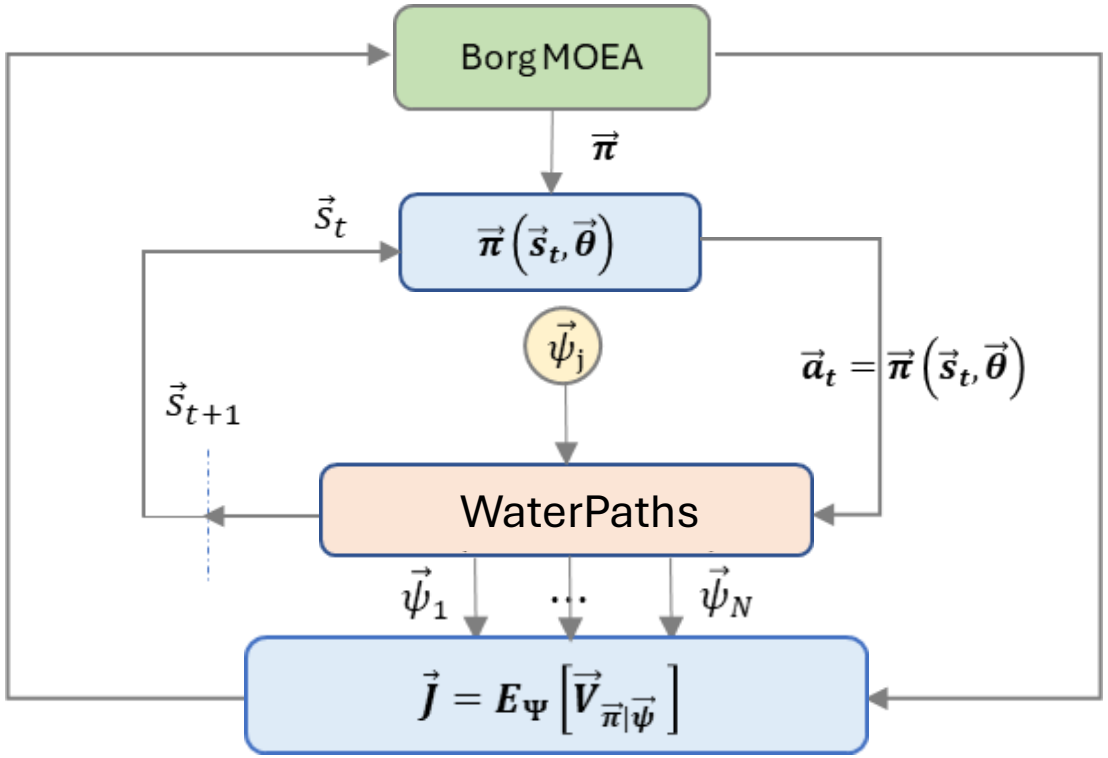
Portfolio of actions

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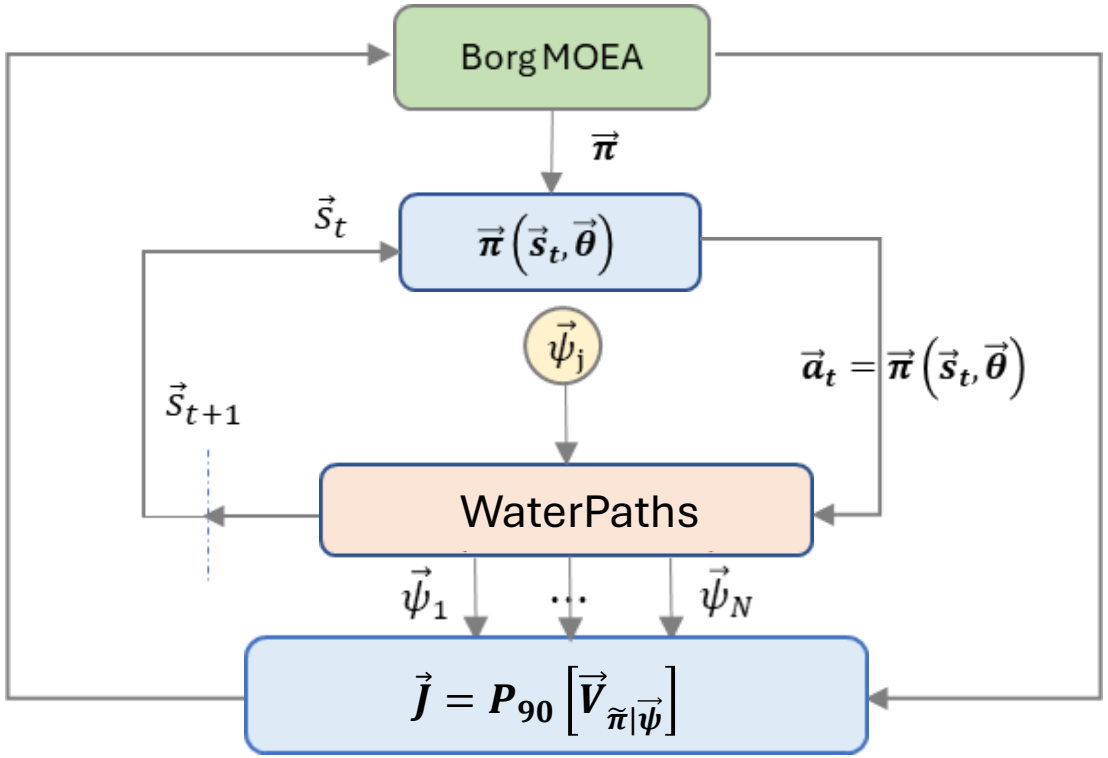
Actions taken must meet five supply and financial performance objectives **under expected conditions**

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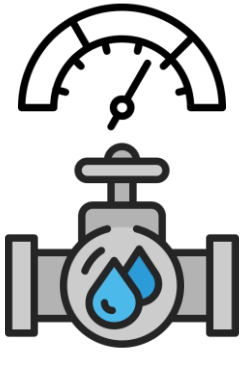
This approach assumes **perfect strategy implementation** under expected future conditions

Deeply Uncertain Pathways under Implementation Uncertainty (DU Pathways IU) accounts for **implementation uncertainty** under **challenging conditions**





Water-use restrictions (RT)

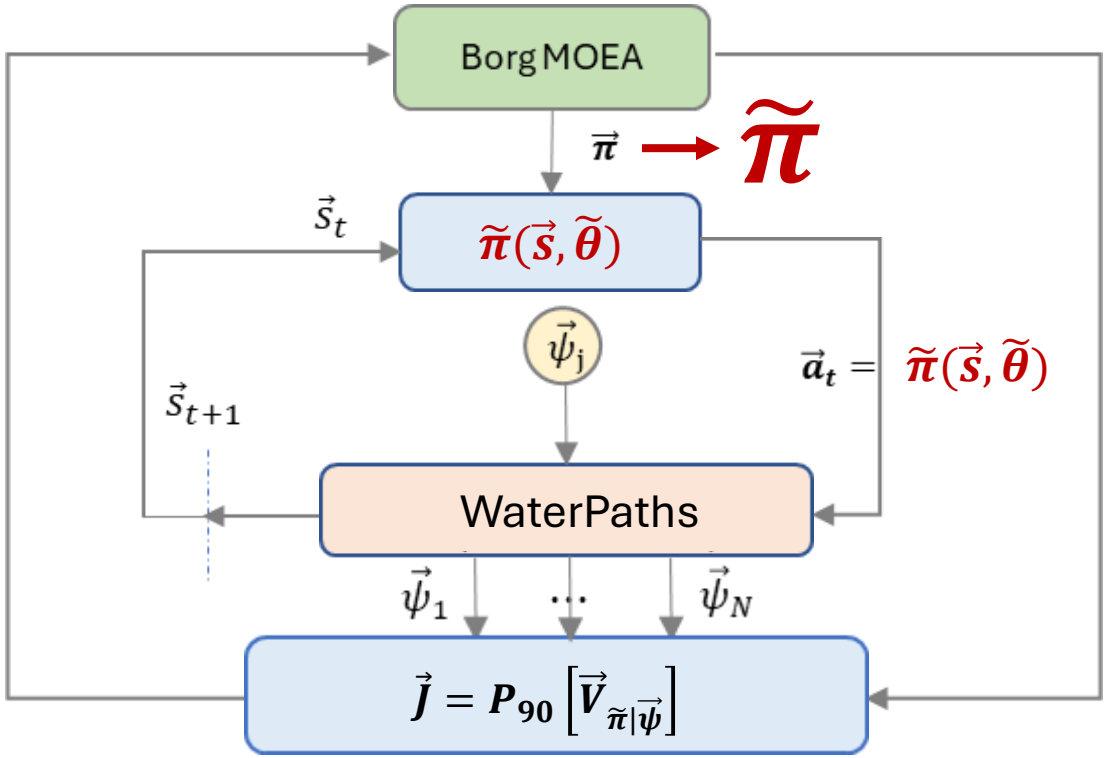


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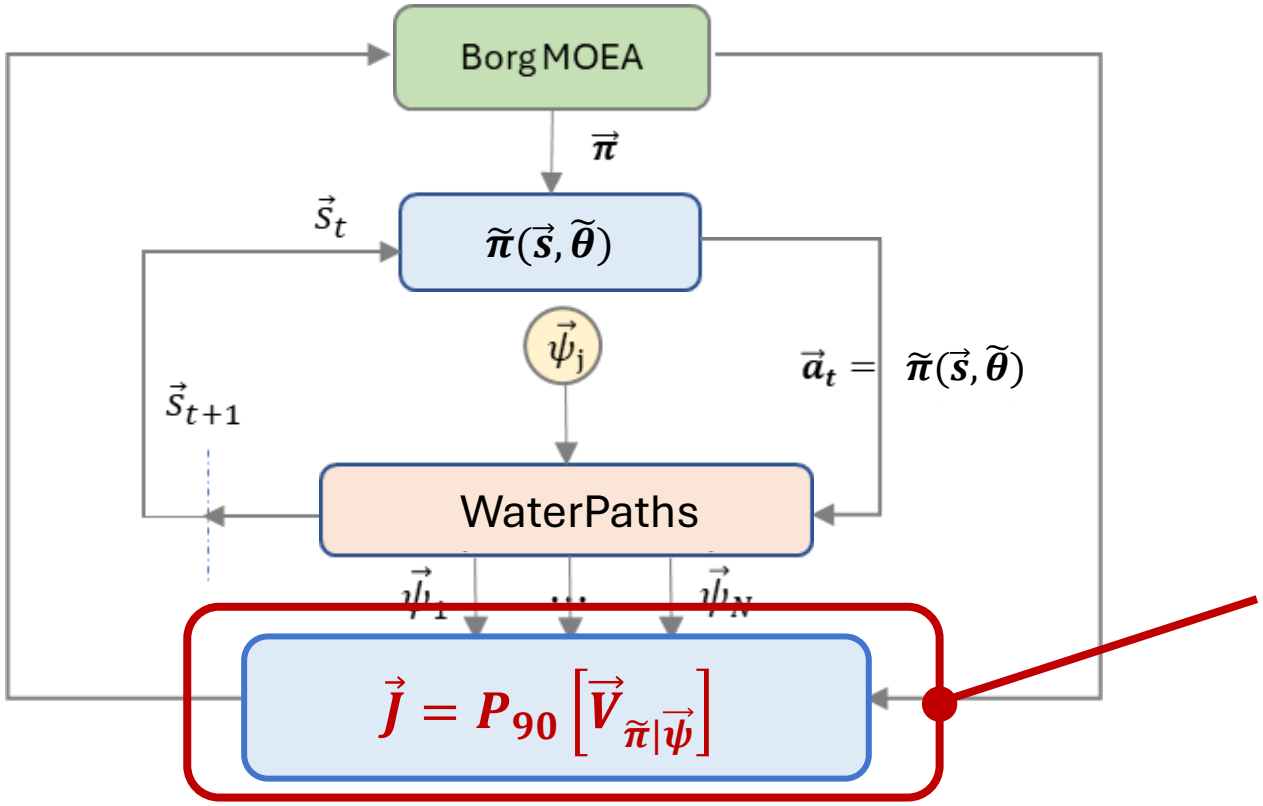
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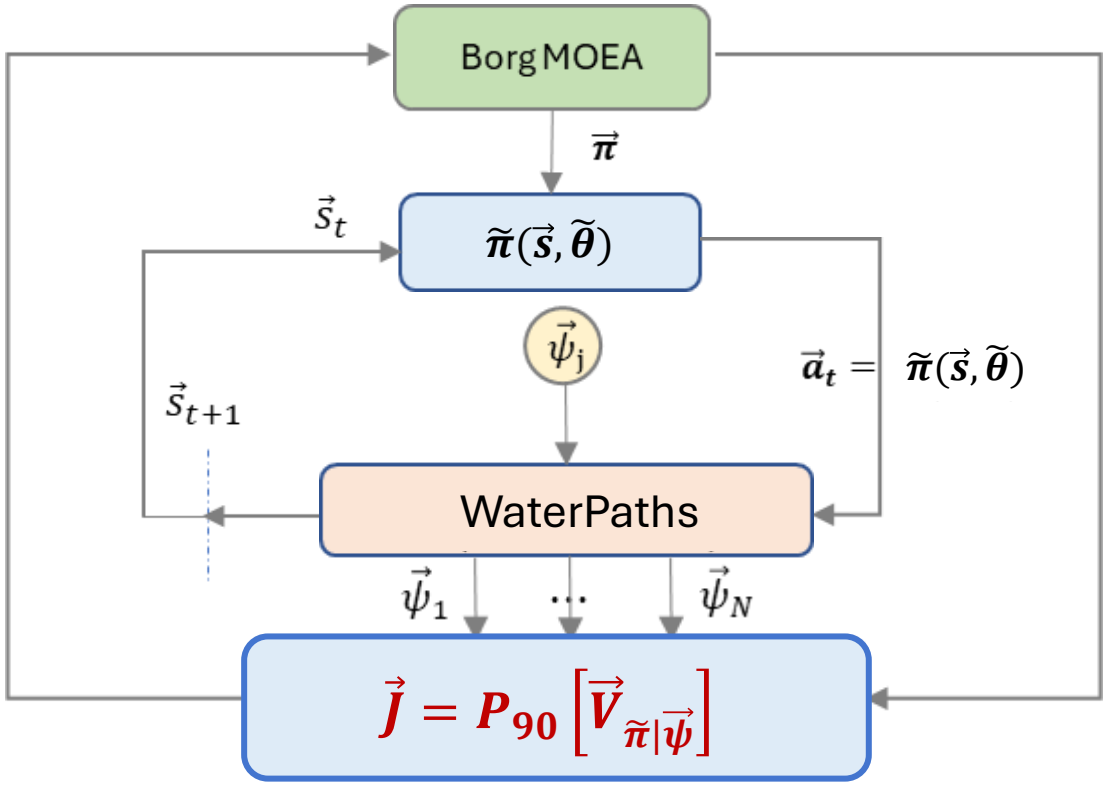
Actions exposed to perturbations ρ within a $\pm$ 4% range

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Actions taken must meet five supply and financial performance objectives **under challenging conditions**

Deeply Uncertain Pathways under Implementation Uncertainty (DU Pathways IU) accounts for **implementation uncertainty** under **challenging conditions**



This approach assumes **imperfect strategy implementation** under challenging future conditions

Two rival framings: Baseline DU eMORL vs IU DU eMORL under implementation uncertainty

Baseline DU eMORL

Assumptions

- Perfect strategy implementation
- Expected future conditions

Hypothesis

Pathway strategies perform well under expected conditions but perform poorly under challenging conditions

IU DU eMORL

Assumptions

- Imperfect strategy implementation
- Challenging future conditions

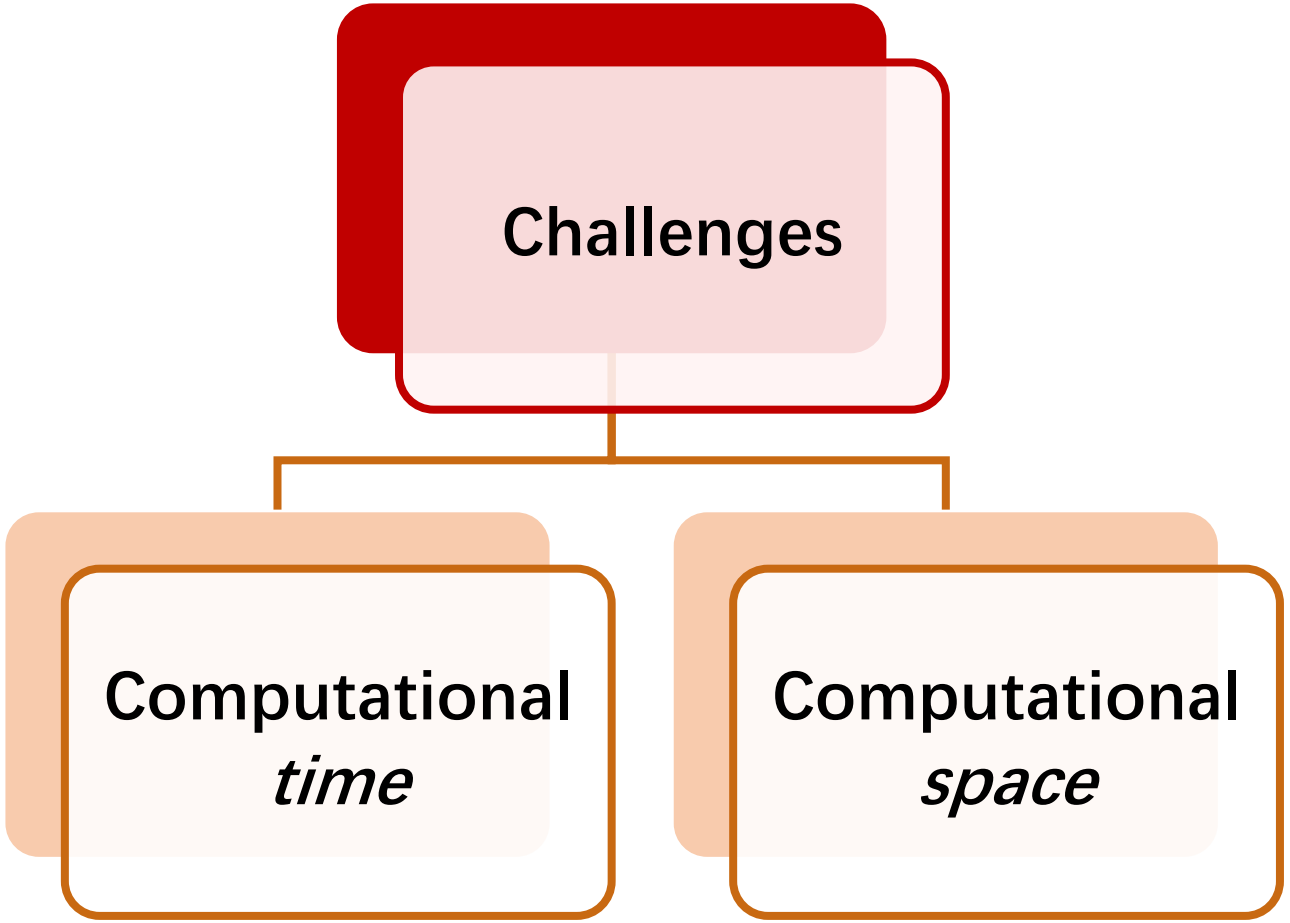
Hypothesis

More pathway strategies discovered perform well under worst 10th percentile conditions and can adapt to reduce regrets in expected DU conditions

Back to Tour

Computational Challenges

Accounting for implementation uncertainty is **computationally expensive** and requires a **significant amount of storage**



Hybrid shared and distributed memory parallelization scheme for efficient simulation-optimization



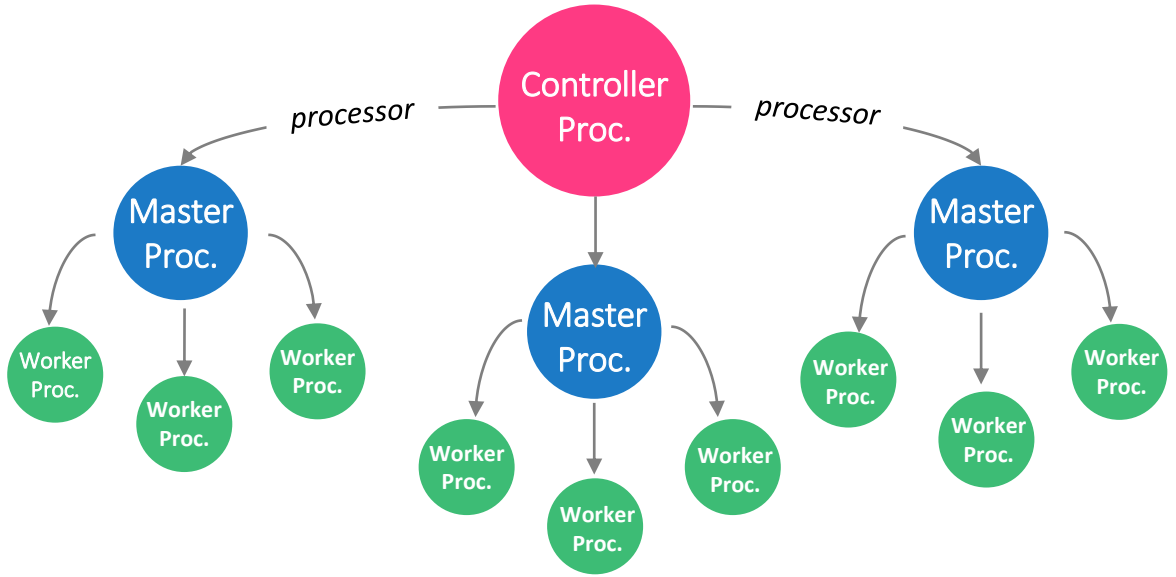
Access to over **10,000 node hours** on the Perlmutter System at NERSC:

- 3,072 dual-core AMD EPYC 7763 CPU Nodes
- 1,536 TB of storage

Hybrid shared and distributed memory parallelization scheme for efficient simulation-optimization

Optimization with Multi-Master Borg MOEA

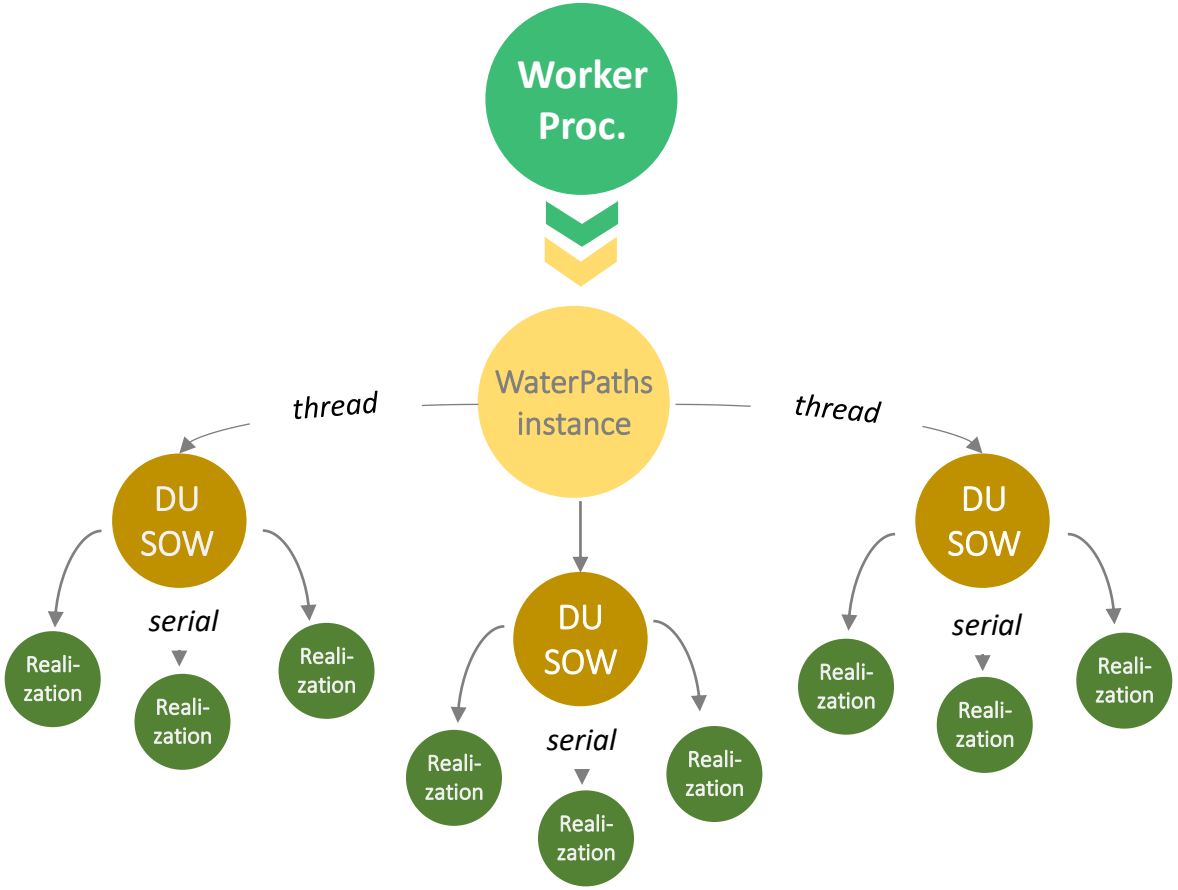
Distributed memory parallelization



Hybrid shared and distributed memory parallelization scheme for efficient simulation-optimization

Simulation with WaterPaths

Shared memory parallelization

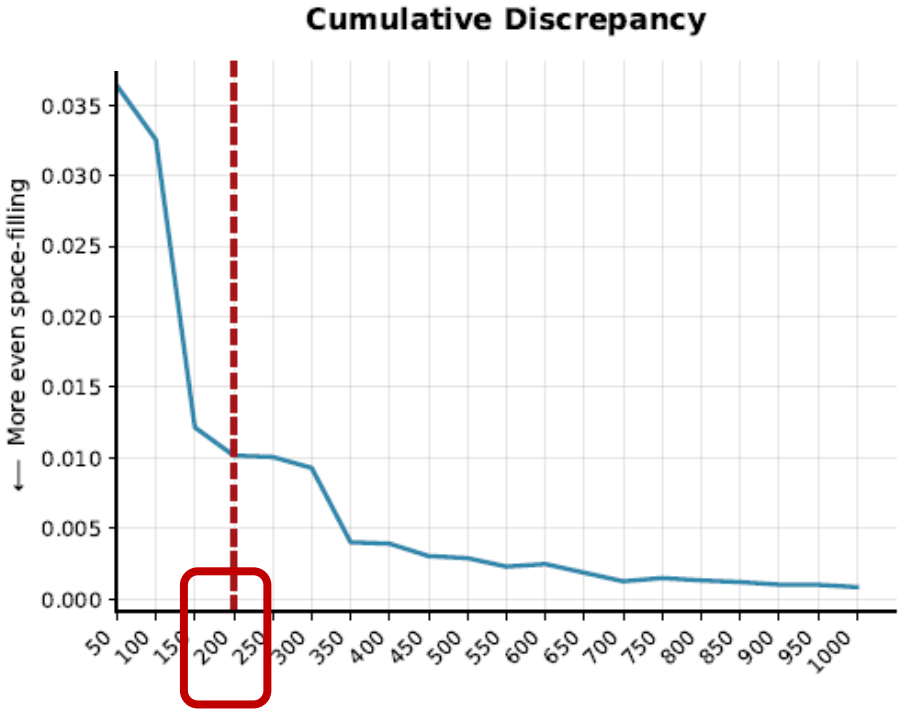


Reduce the number of Latin Hypercube samples while maintaining distributional similarity

Reduce the number of Latin Hypercube samples while maintaining distributional similarity

1 **Cumulative discrepancy (CD)**

Compares the **spread of points** across the space between two samples



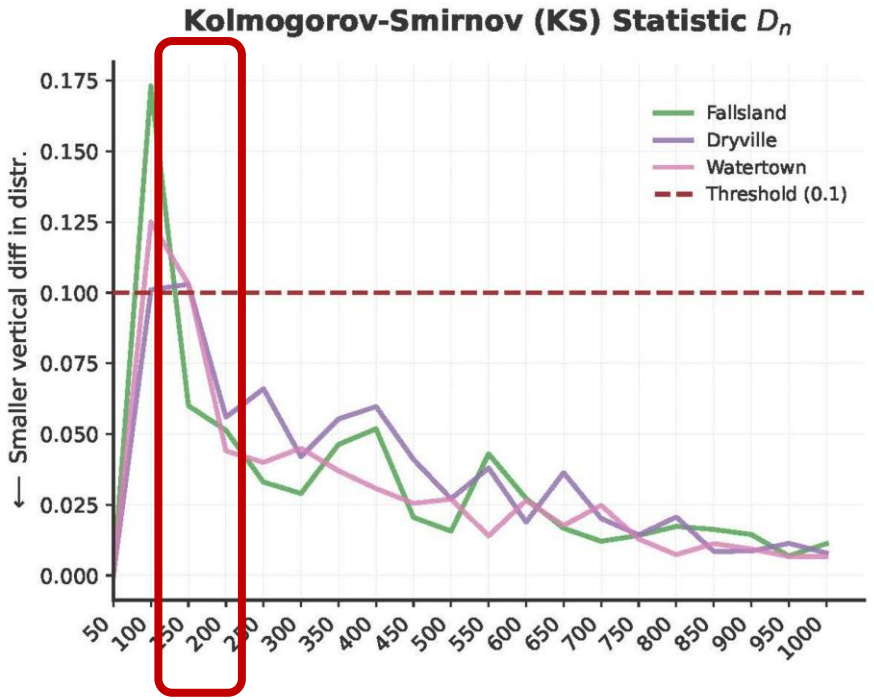
Min sample size: 200

Reduce the number of Latin Hypercube samples while maintaining distributional similarity

1. **Cumulative discrepancy (CD)**

2. **Kolmogorov-Smirnov (KS) statistic**

   Measure's the smaller set's ability to preserve the distribution of the larger set

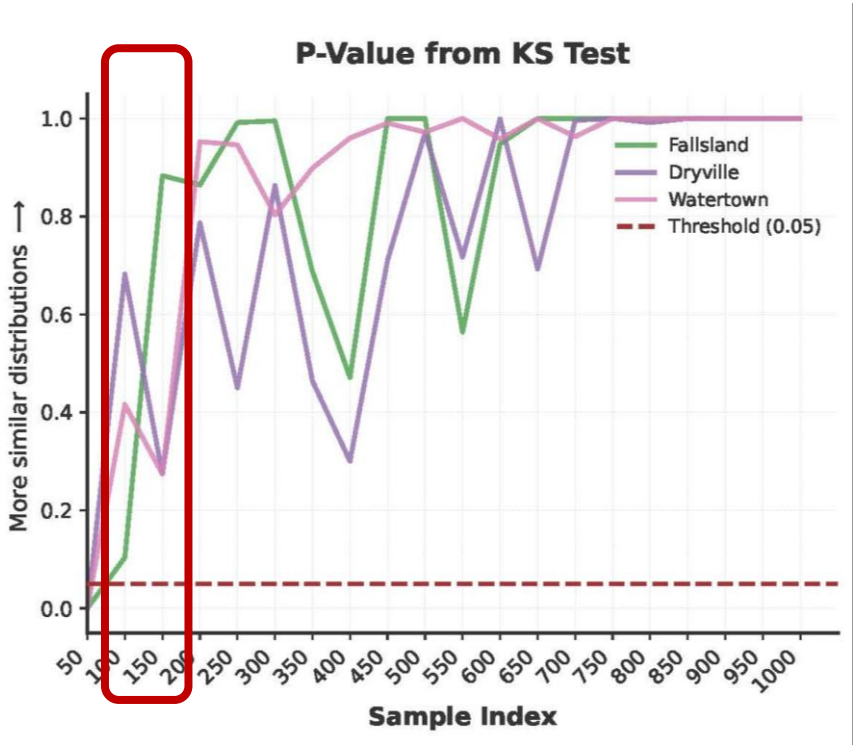


Min sample size: 200

Reduce the number of Latin Hypercube samples while maintaining distributional similarity

1. **Cumulative discrepancy (CD)**
2. **Kolmogorov-Smirnov (KS) statistic**
3. ***p*-value**

   Measures if the smaller subset is significantly different from the larger set



Min sample size: 150

Transition to **scientific file compression formats** to reduce space and computational efficiency

Inputs | n-Hydroclimatic timeseries of 45 years' worth of weekly demands, inflows, and evaporation data

Outputs | Multidimensional 45 years' worth of weekly state variable information

Parquet

Combination of approaches result in **two orders' magnitude reduction** in required storage space and computational time

Approach	Reasoning
Sample reduction	Number of future scenarios decreased from 1,000 to 200
Hybrid shared-distributed memory parallelization	Efficient distribution of workload between WaterPaths simulation and MM Borg MOEA optimization
Efficient file compression formats	Input files updated from CSV to Parquet or HDF5
Load balancing and profiling	Ensures all available computational resources are being simultaneously used

Combination of approaches result in **two orders' magnitude reduction** in required storage space and computational time

Approach	Reasoning
Load balancing and profiling	Ensures all available computational resources are being simultaneously used

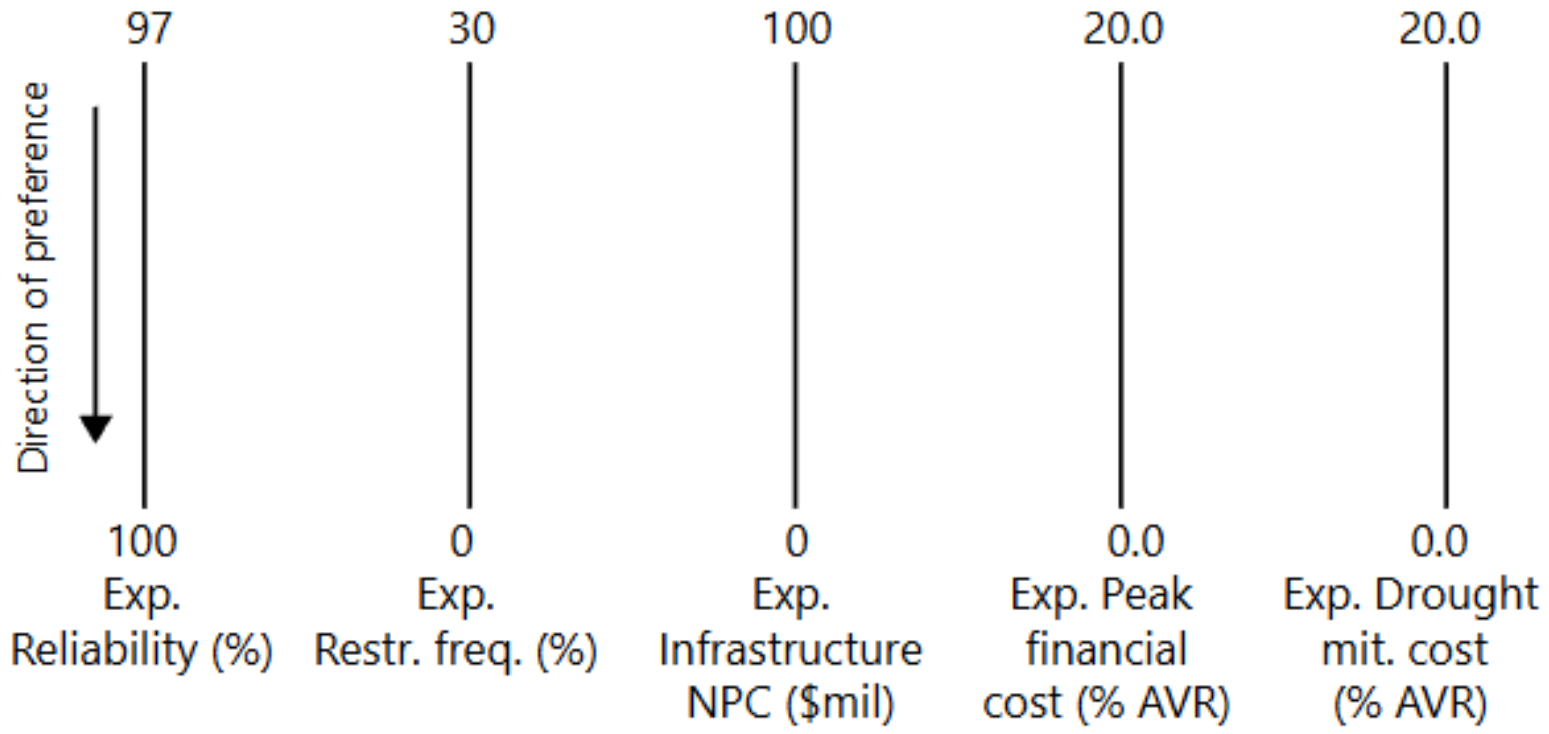
Two orders of magnitude

- reduction in computational requirements from **8.0×10^5 to 6.6×10^3 node hours**
- reduction in total input *and* output file storage required from **6,382 TB to 20.1 TB**

Back to Tour

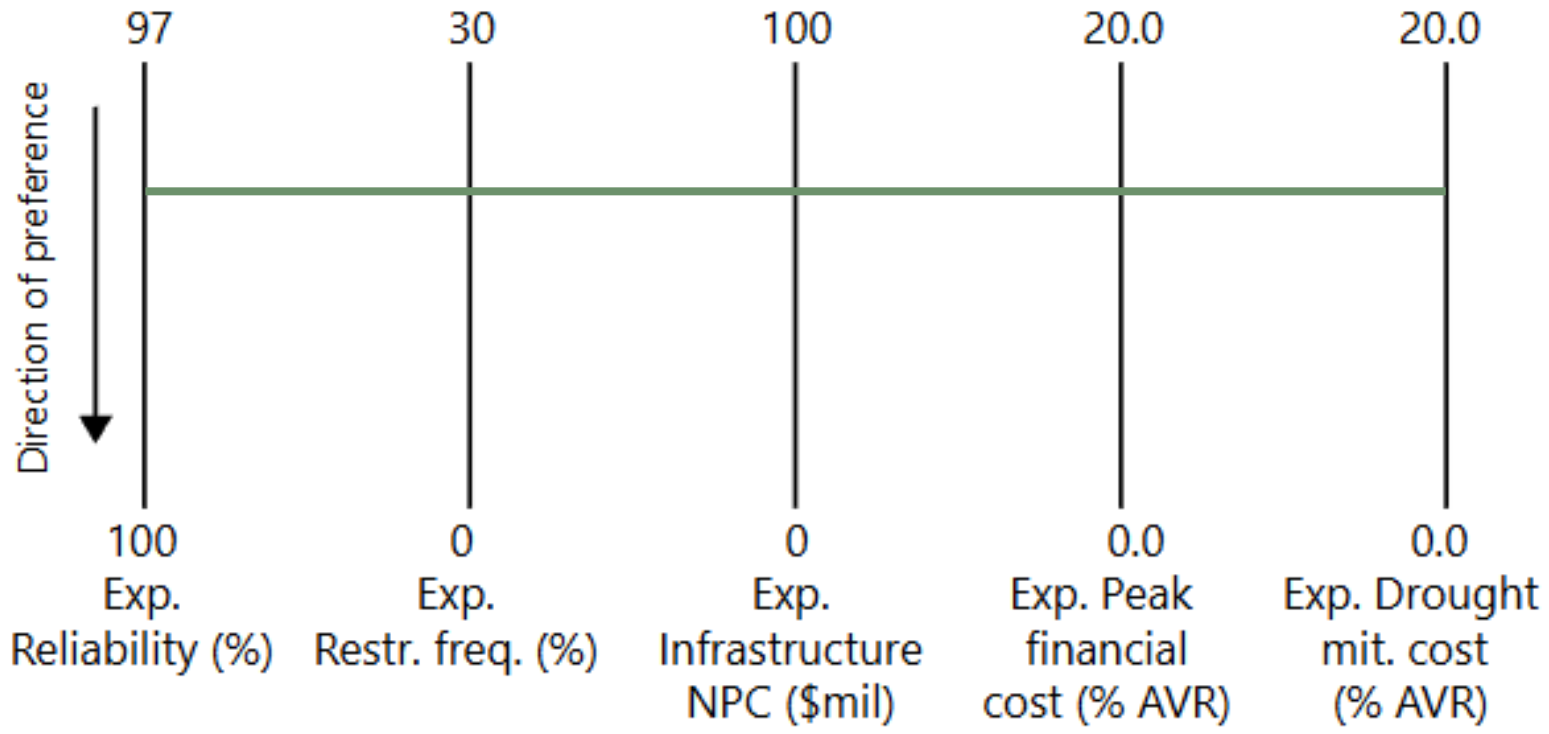
Results and Discussion

Incorporating implementation uncertainty and accounting for challenging future conditions yield a **larger, more diverse set of high-performing pathway strategies**



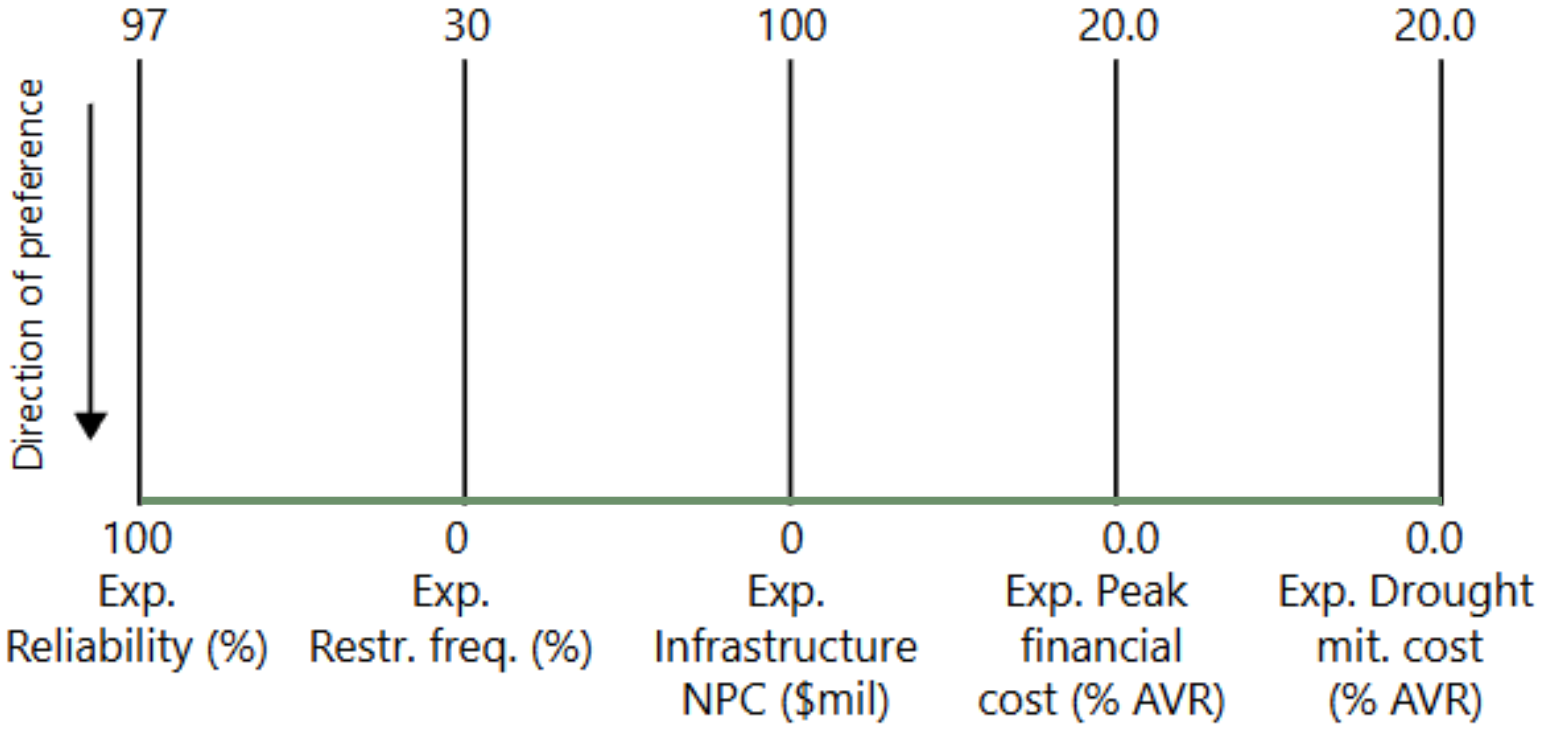
One vertical axis → one objective

Incorporating implementation uncertainty and accounting for challenging future conditions yield a **larger, more diverse set of high-performing pathway strategies**



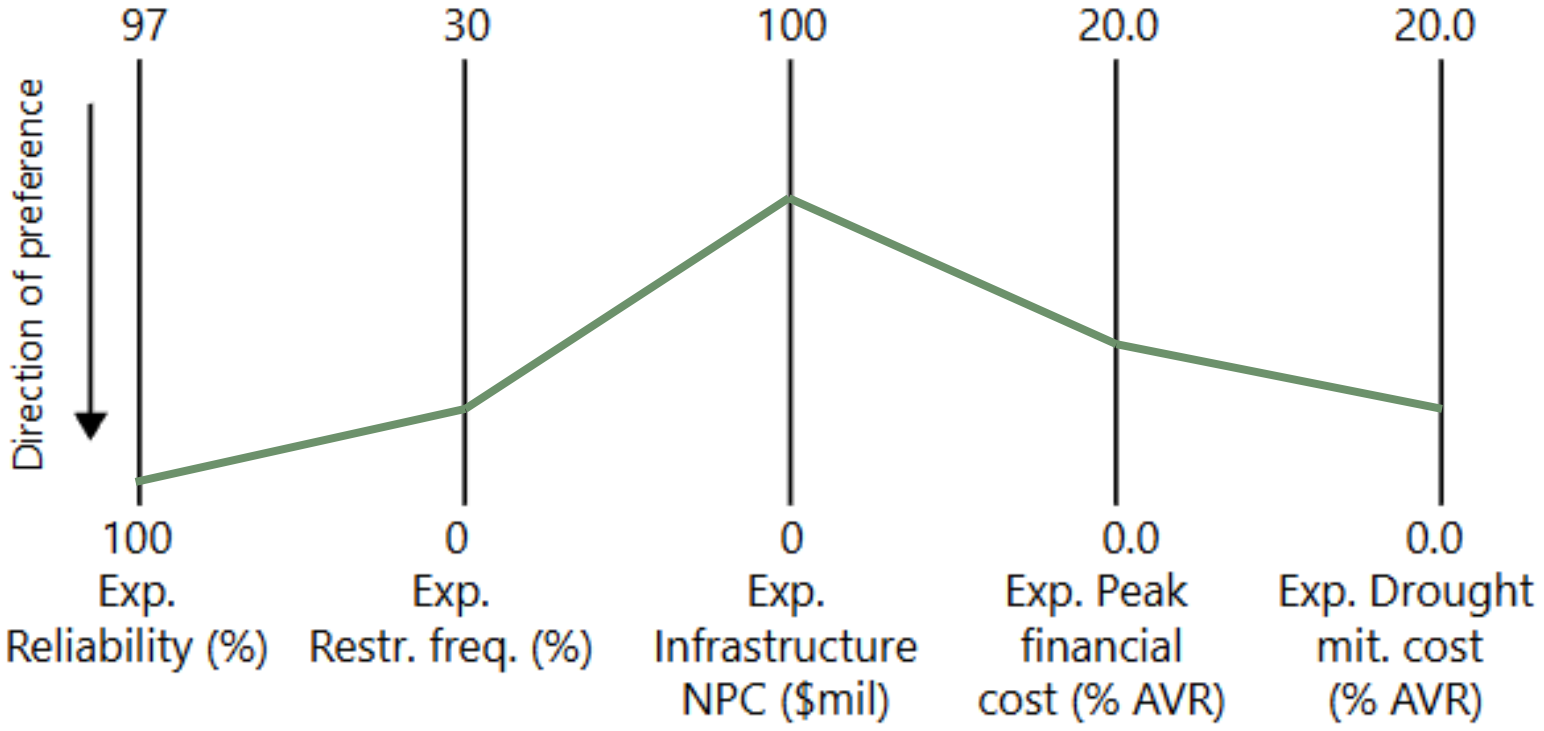
One vertical axis → one objective

Incorporating implementation uncertainty and accounting for challenging future conditions yield a **larger, more diverse set of high-performing pathway strategies**



Lower position on axis → better performance

Incorporating implementation uncertainty and accounting for challenging future conditions yield a **larger, more diverse set of high-performing pathway strategies**

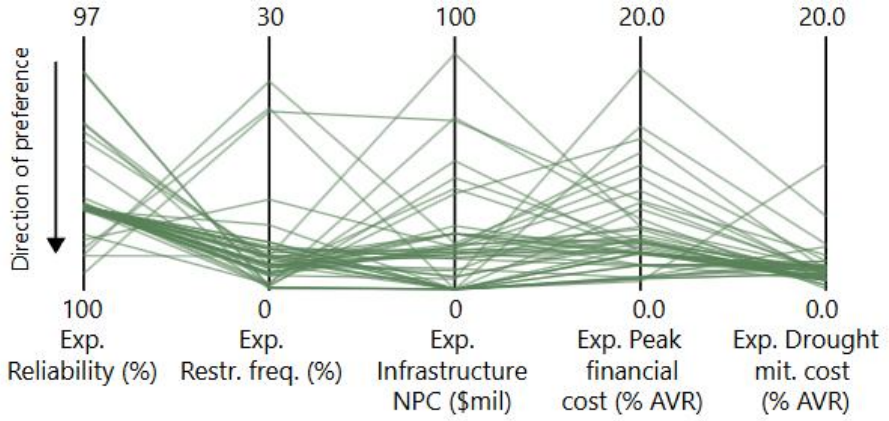


Steeper diagonal → more significant tradeoffs

Comparing pathway strategies discovered using baseline and IU DU eMORL framings illustrate **differences in strategy quantity and quality**

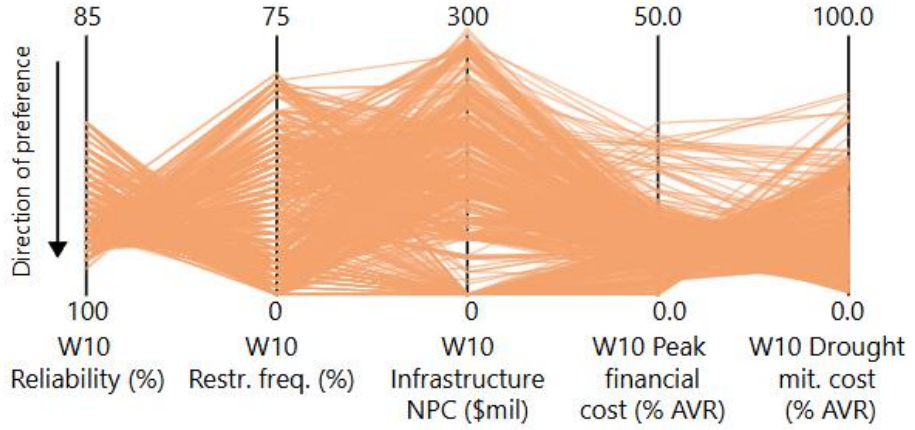
Baseline pathway strategies

46 pathway strategies *that achieve high performance under expected conditions*

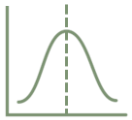


IU pathway strategies

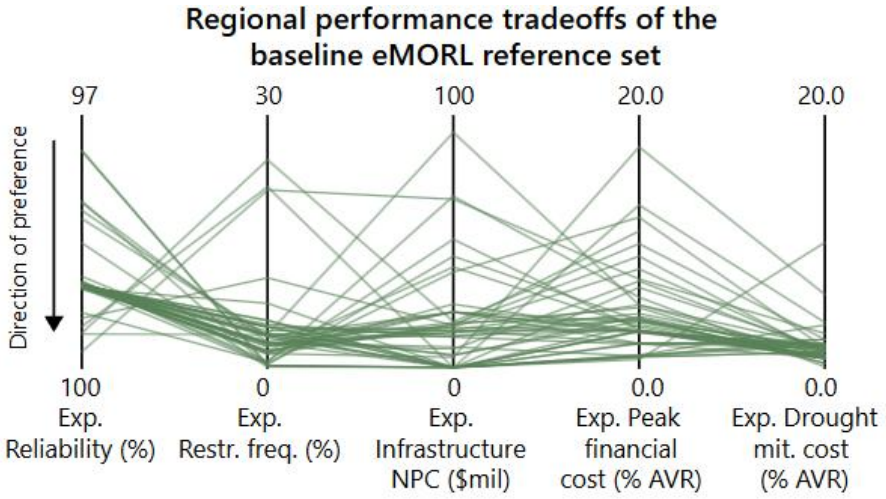
628 pathway strategies *that achieve moderate-to-high performance under challenging conditions*



Comparing pathway strategies discovered using baseline and IU DU eMORL framings illustrate **differences in strategy quantity and quality**

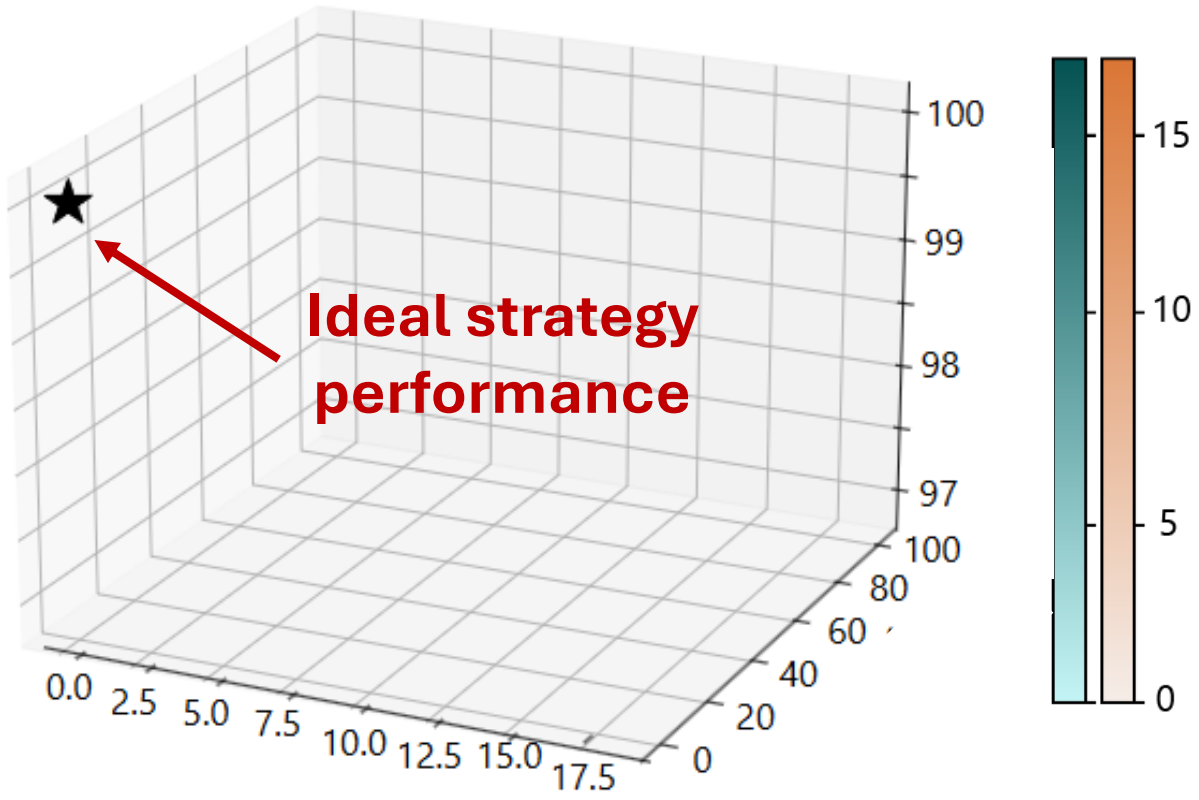


Baseline DU eMORL



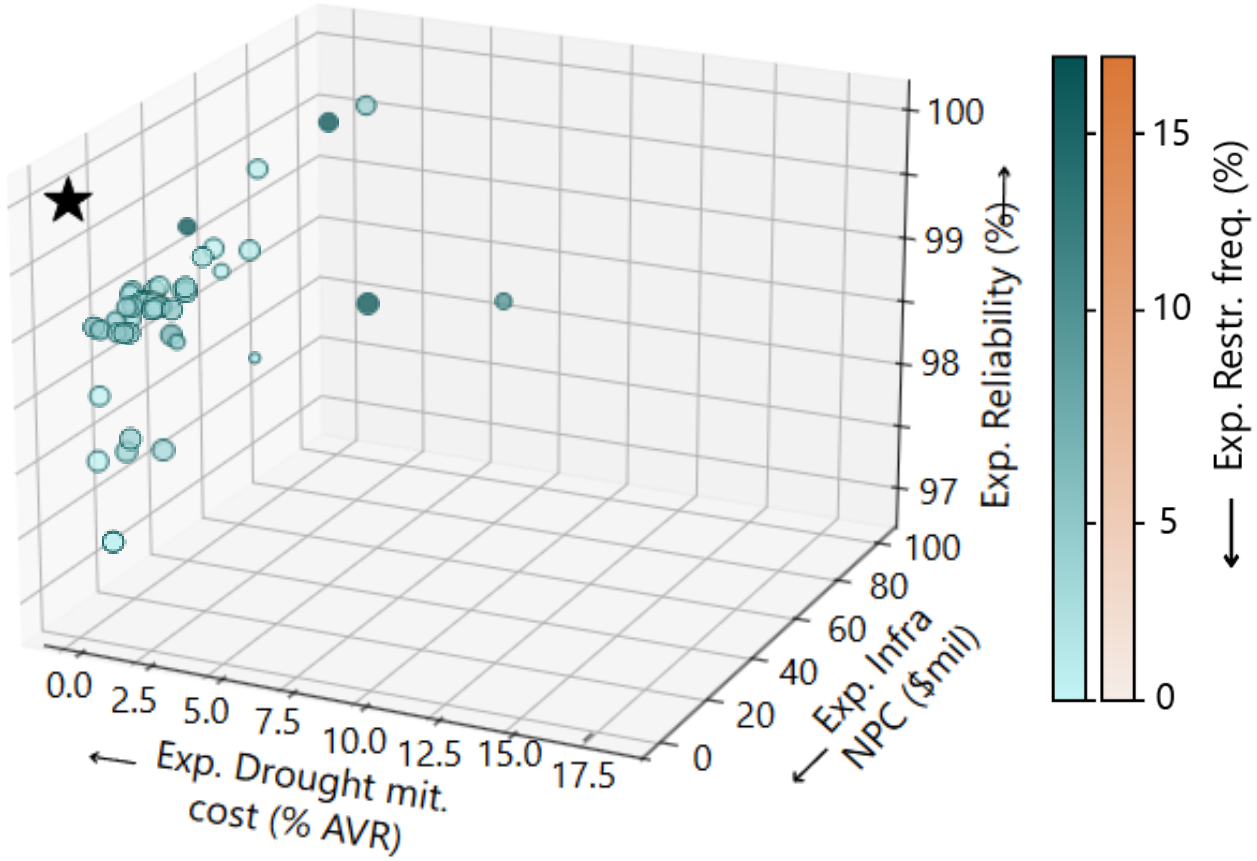
The baseline DU eMORL pathway strategies achieve **high supply reliability and financial performance under expected conditions**

Baseline DU eMORL



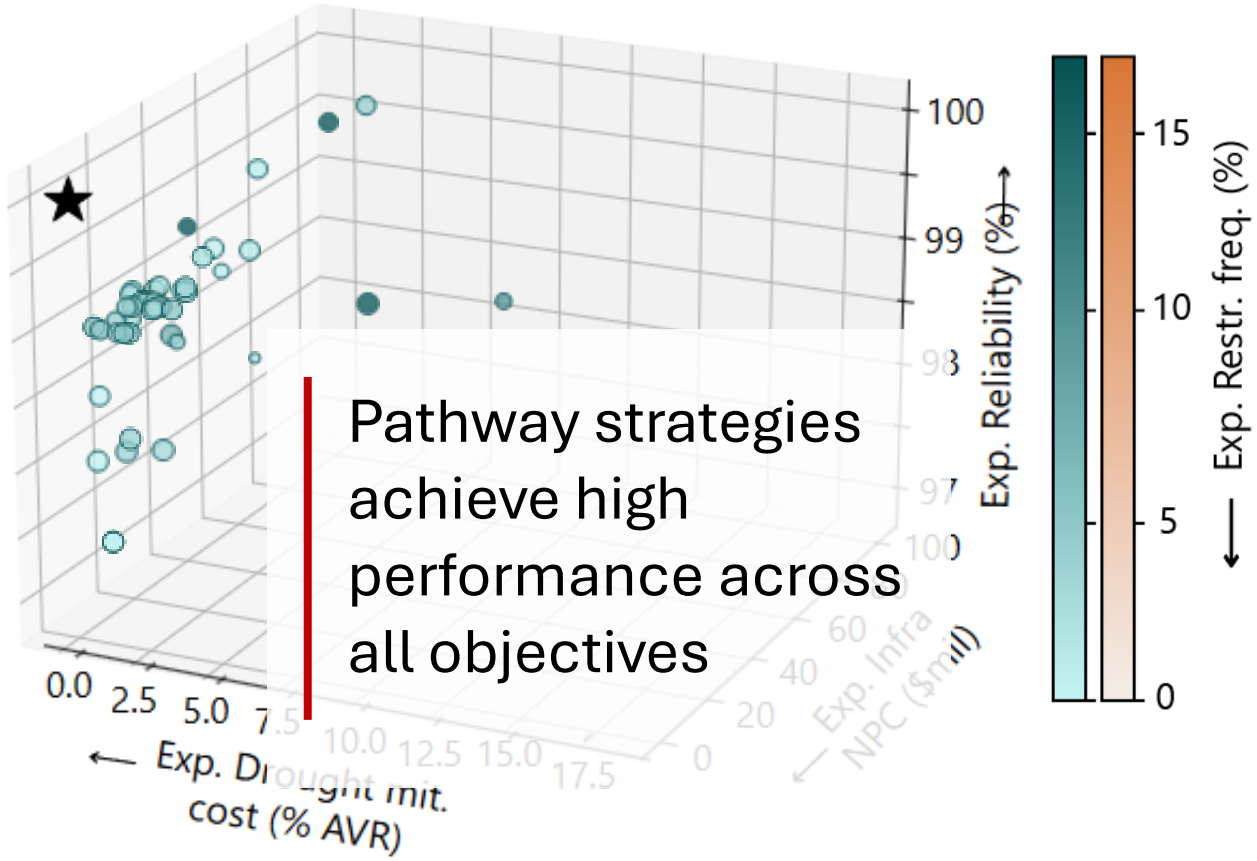
The baseline DU eMORL pathway strategies achieve **high supply reliability and financial performance under expected conditions**

Baseline DU eMORL



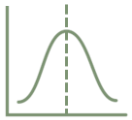
The baseline DU eMORL pathway strategies achieve **high supply reliability and financial performance under expected conditions**

Baseline DU eMORL

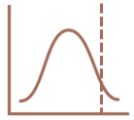


Pathway strategies achieve high performance across all objectives

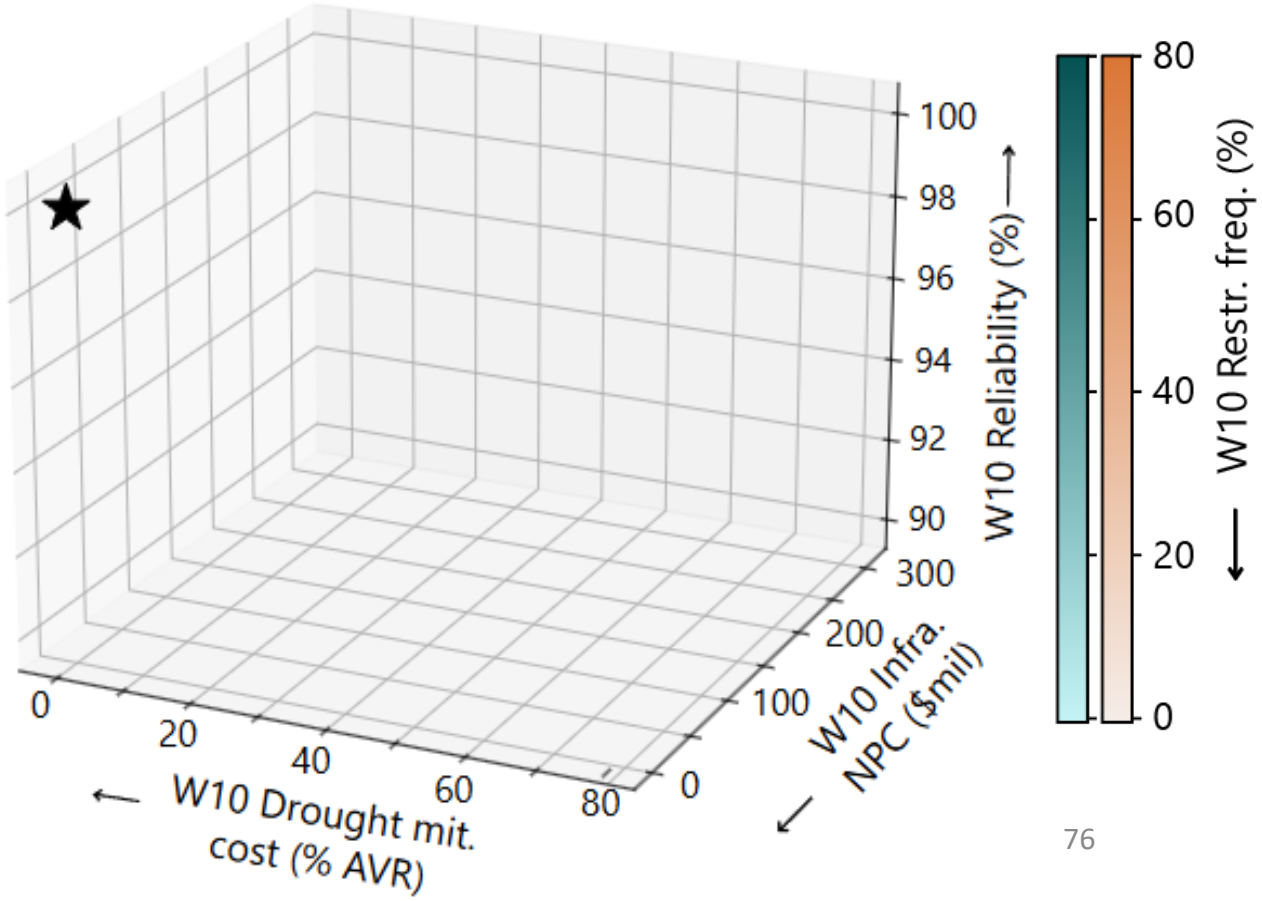
These strategies **struggle to generalize** under the **more challenging IU DU eMORL framing,** resulting in decreased performance



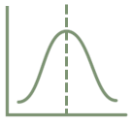
Baseline DU eMORL



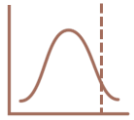
IU DU eMORL



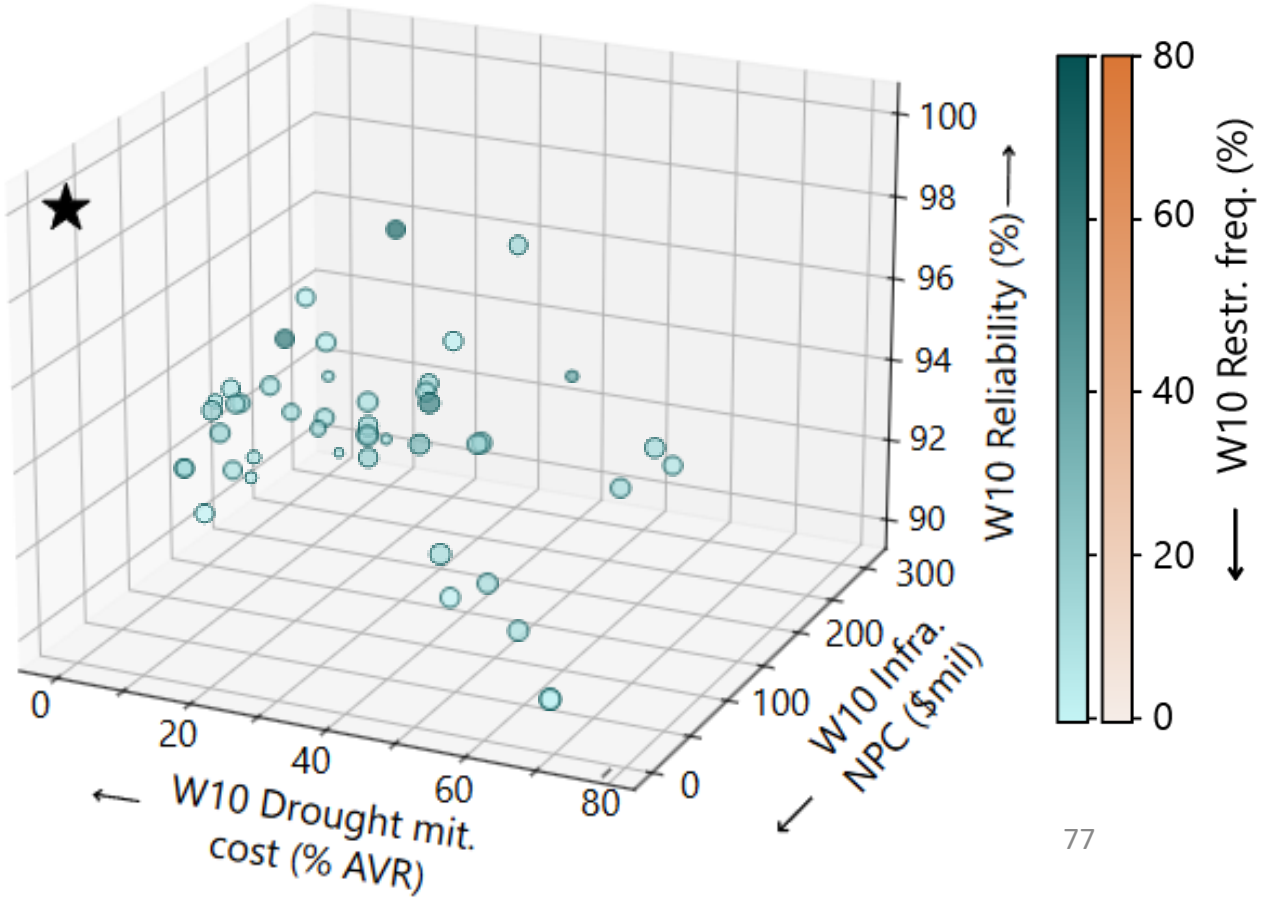
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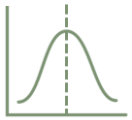
Baseline DU eMORL



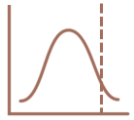
IU DU eMORL



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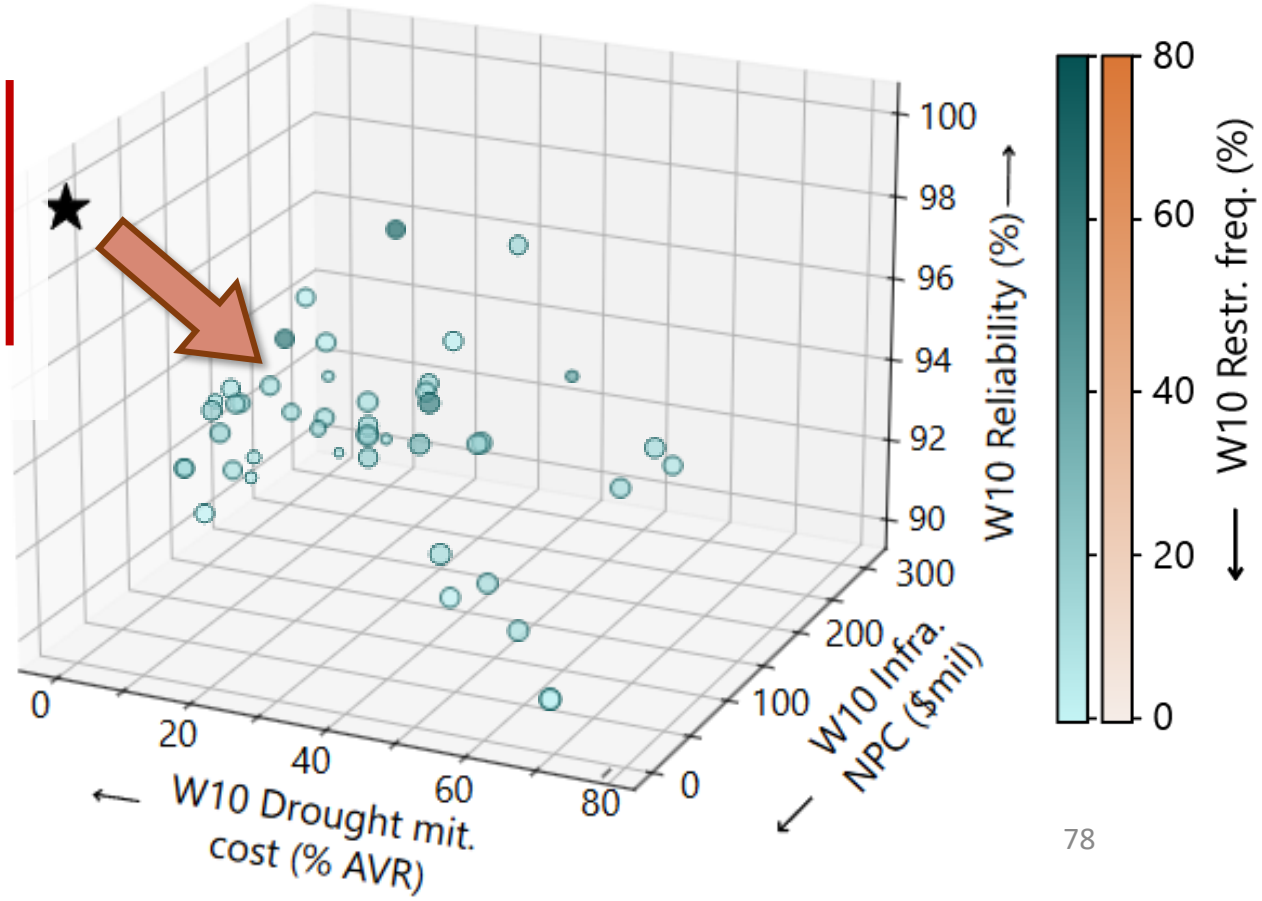


Baseline DU eMORL

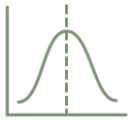


IU DU eMORL

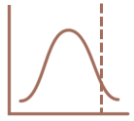
Pathway strategies move further from ideal point



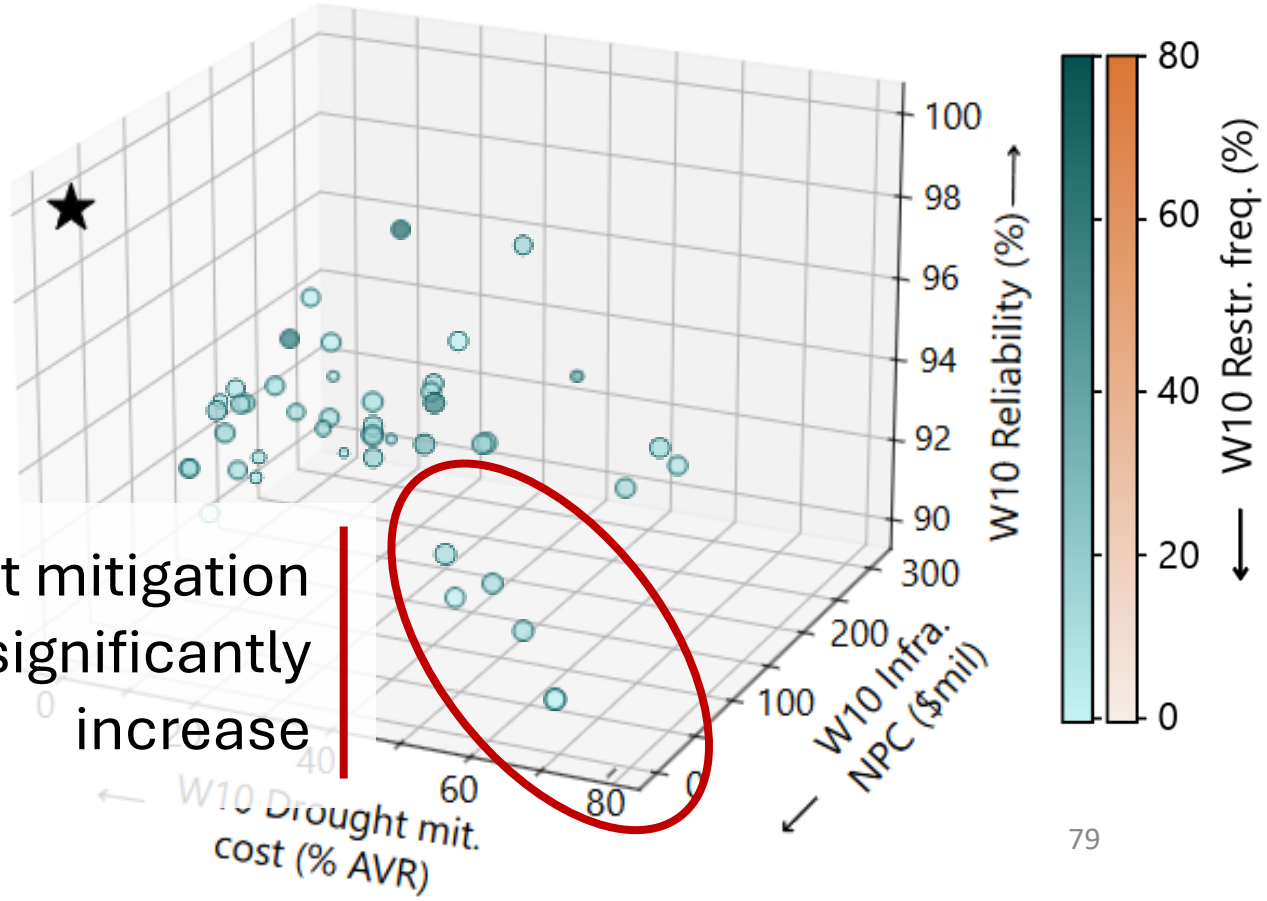
These strategies **struggle to generalize** under the **more challenging IU DU eMORL framing,** resulting in decreased performance



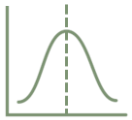
Baseline DU eMORL



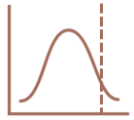
IU DU eMORL



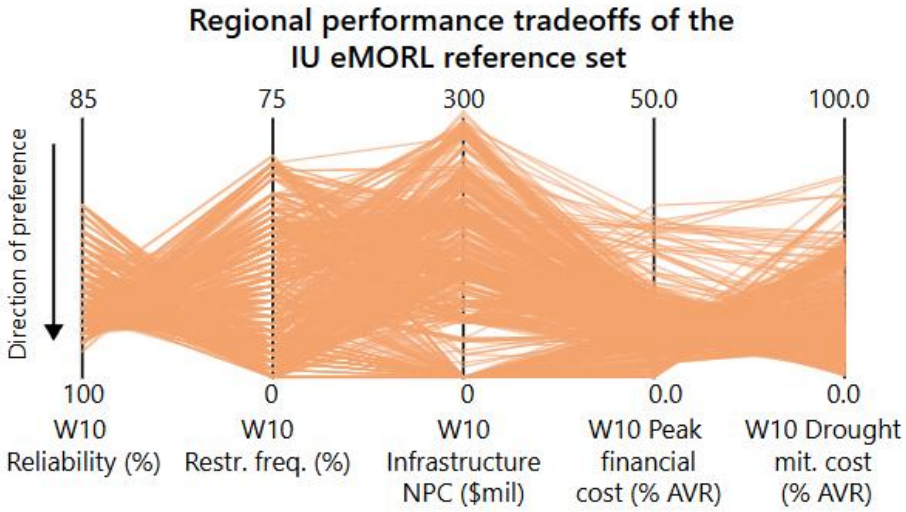
The **larger set of IU pathway strategies** achieves high performance **under both extreme and expected future conditions**



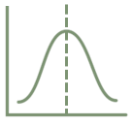
Baseline DU eMORL



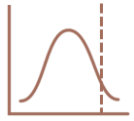
IU DU eMORL



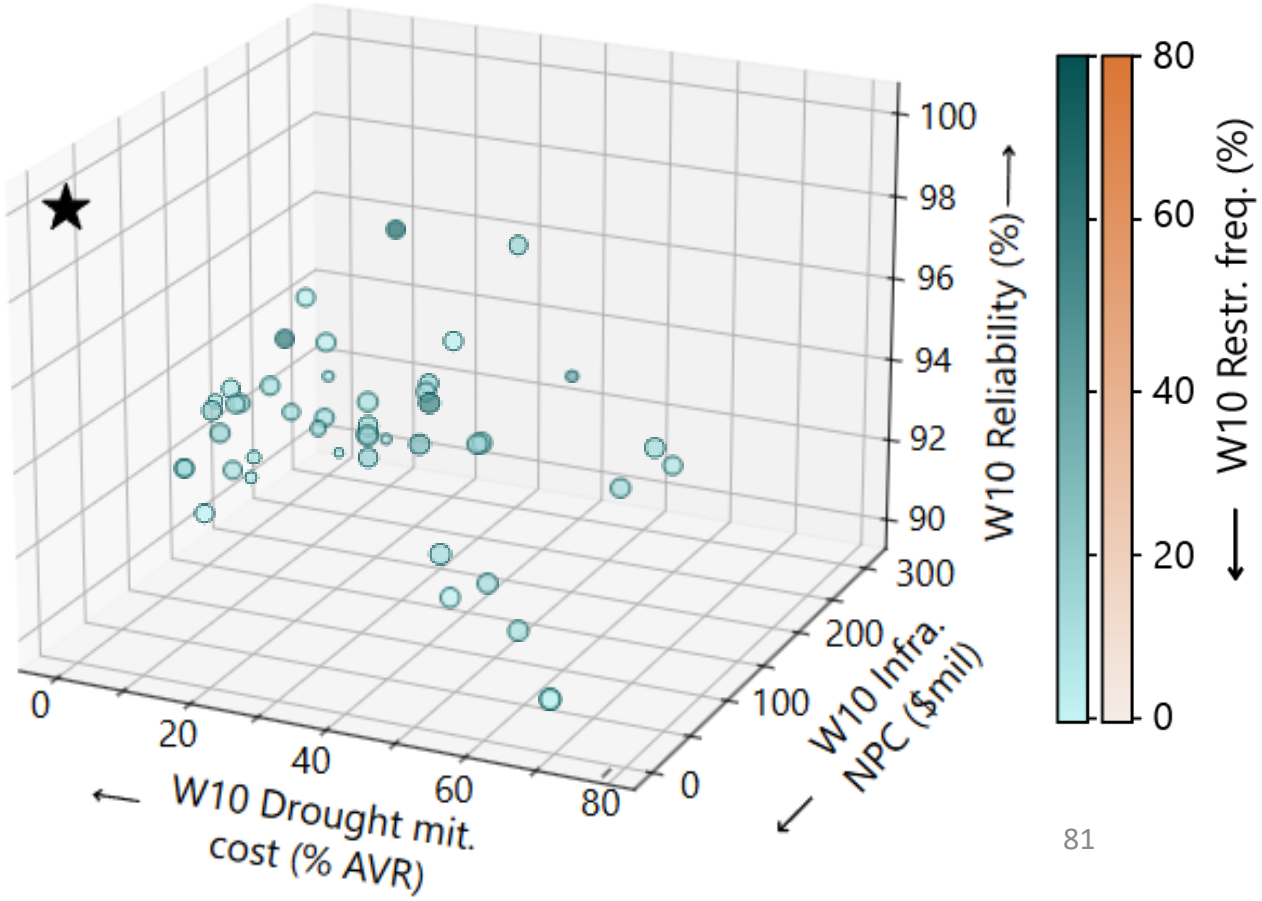
The **larger set of IU pathway strategies** achieves high performance **under both extreme and expected future conditions**



Baseline DU eMORL



IU DU eMORL

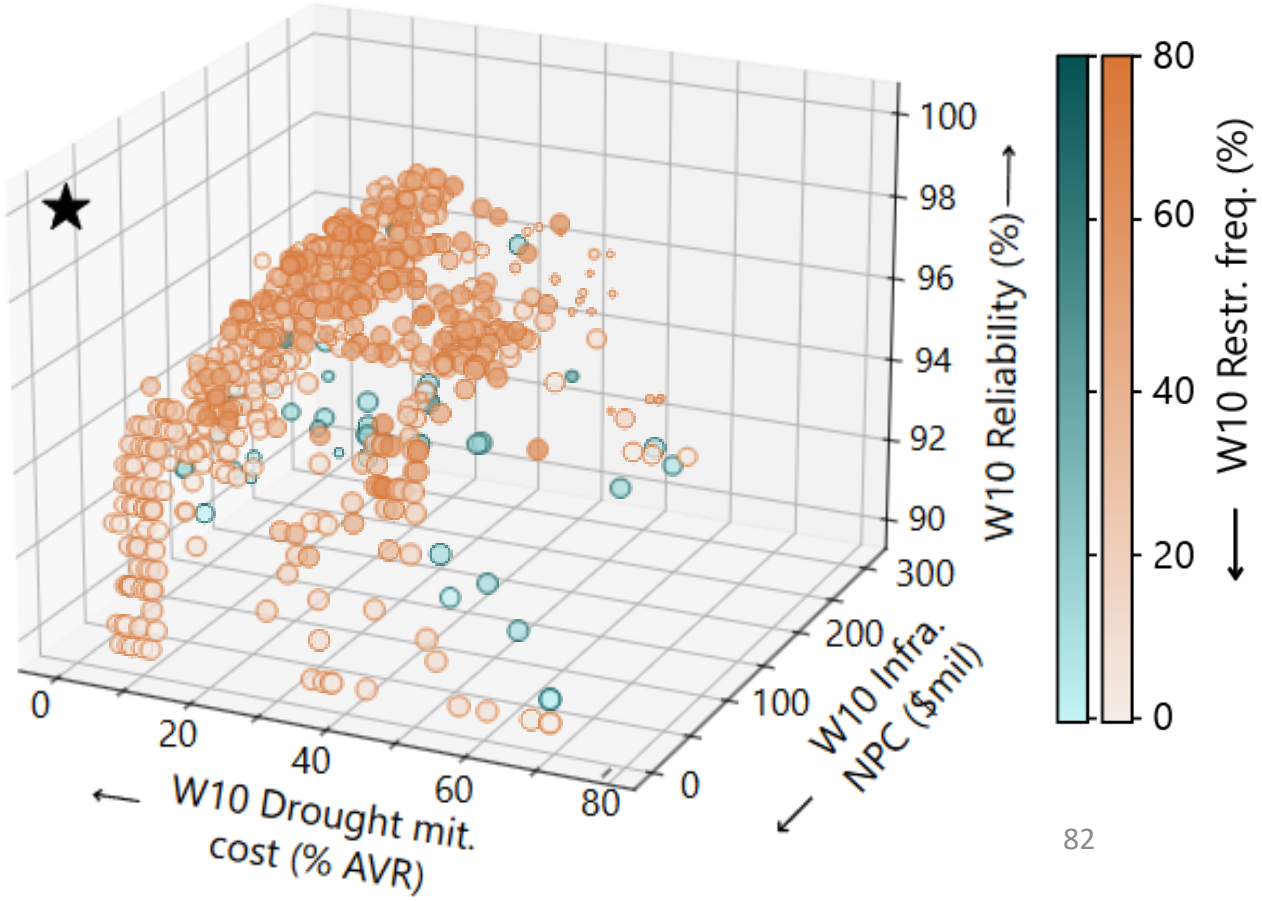


The **larger set of IU pathway strategies** achieves high performance **under both extreme and expected future conditions**

Baseline DU eMORL

IU DU eMORL

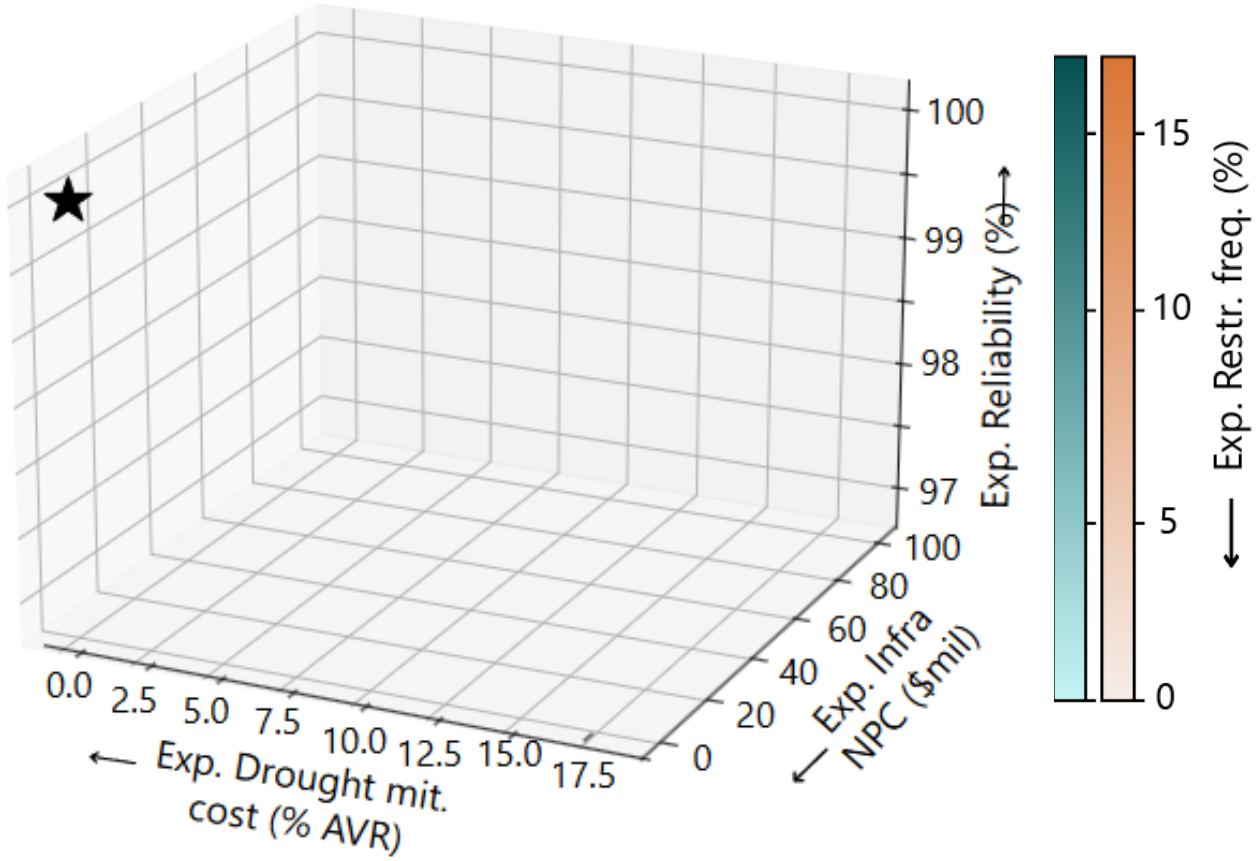
The IU pathway strategies strongly outperform the baseline strategies under challenging conditions



The **larger set of IU pathway strategies** achieves high performance **under both extreme and expected future conditions**

Baseline DU eMORL

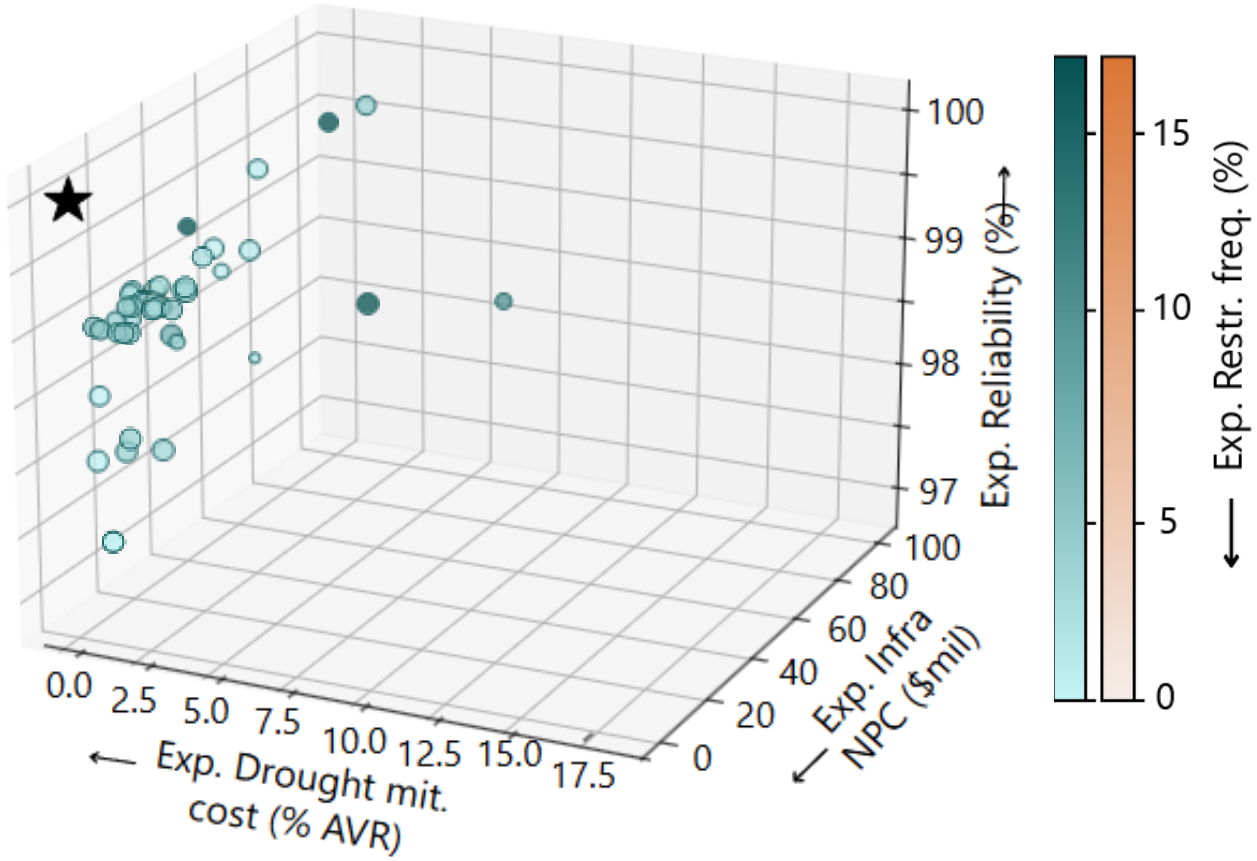
IU DU eMORL



The **larger set of IU pathway strategies** achieves high performance **under both extreme and expected future conditions**

Baseline DU eMORL

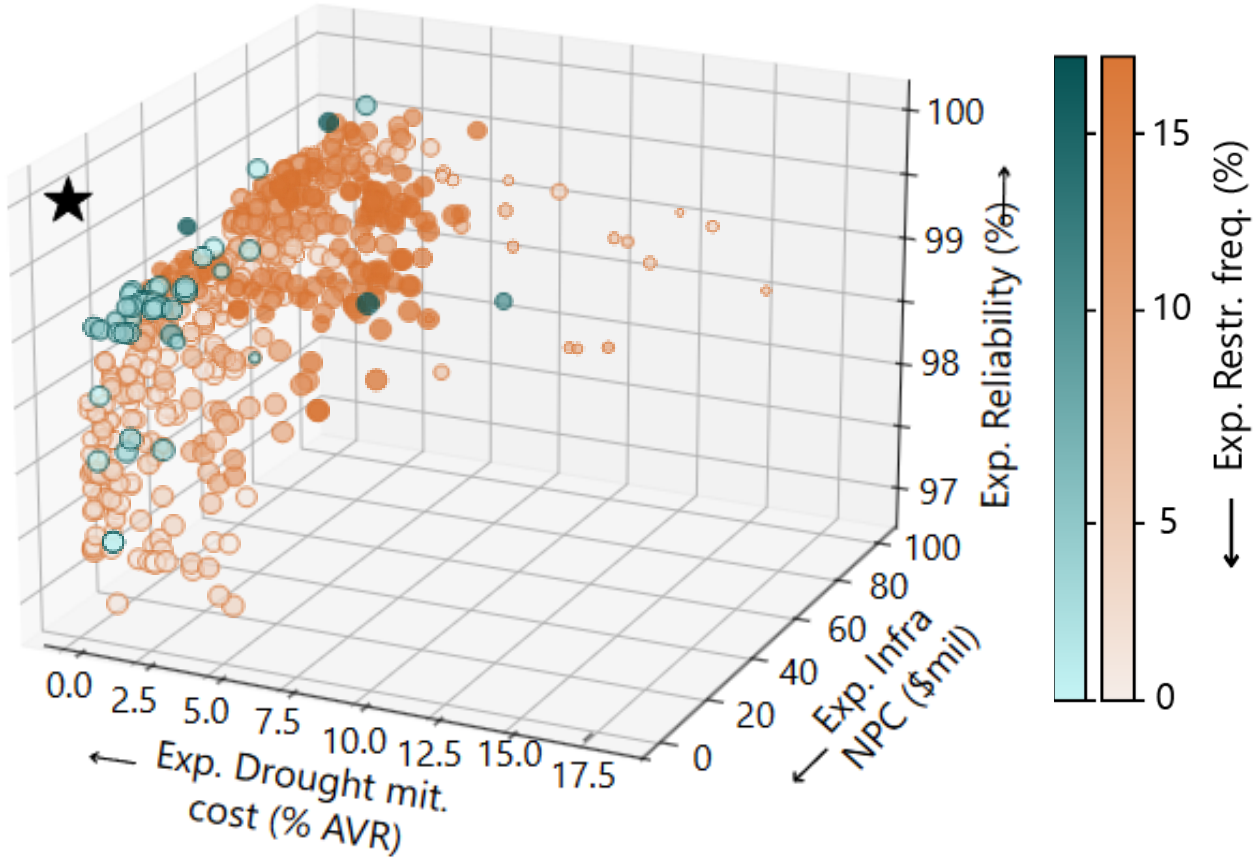
IU DU eMORL



The **larger set of IU pathway strategies** achieves high performance **under both extreme and expected future conditions**

Baseline DU eMORL

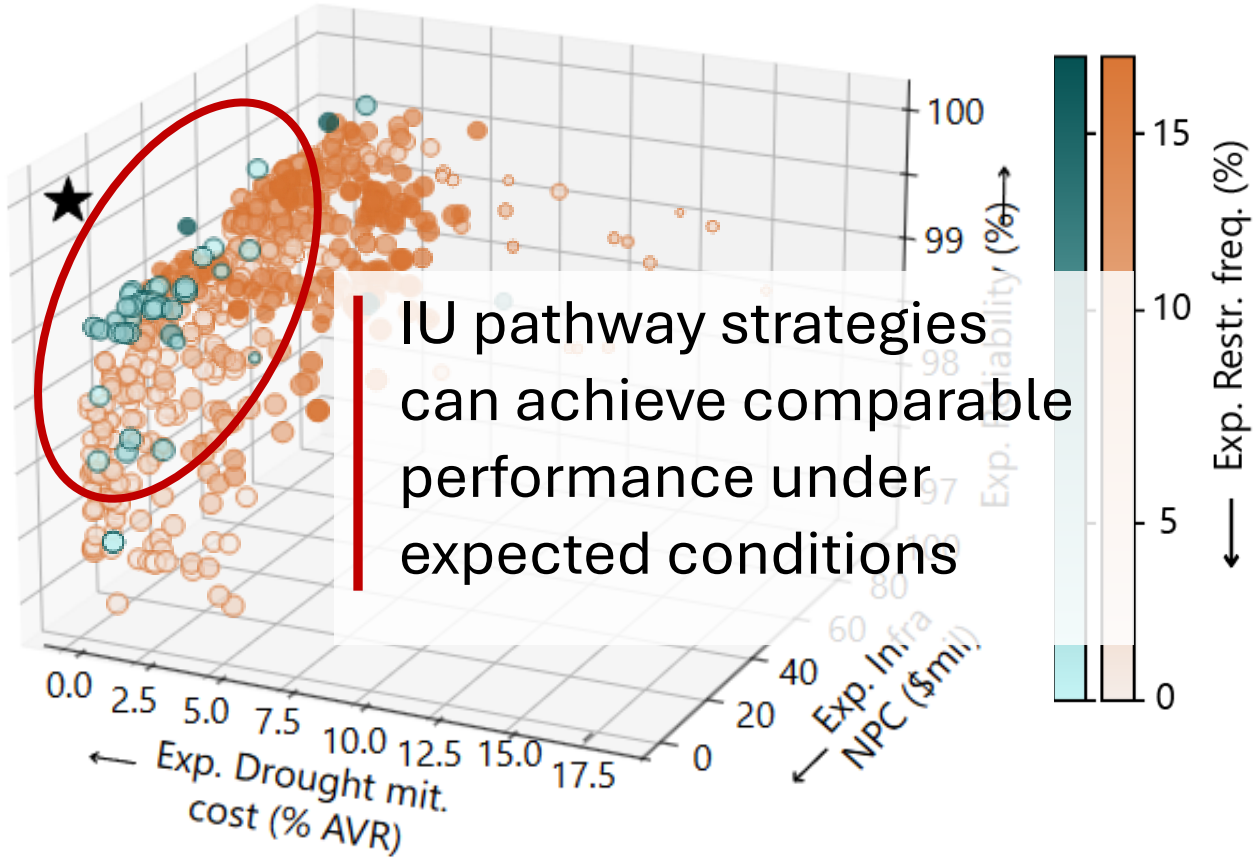
IU DU eMORL



The **larger set of IU pathway strategies** achieves high performance **under both extreme and expected future conditions**

Baseline DU eMORL

IU DU eMORL



IU pathway strategies can achieve comparable performance under expected conditions

Back to Tour

We stress-test the pathway strategies across a **wider set of deeply uncertain states of the world (DU SOWs) to assess robustness**



REL > 98%



RF < 10%

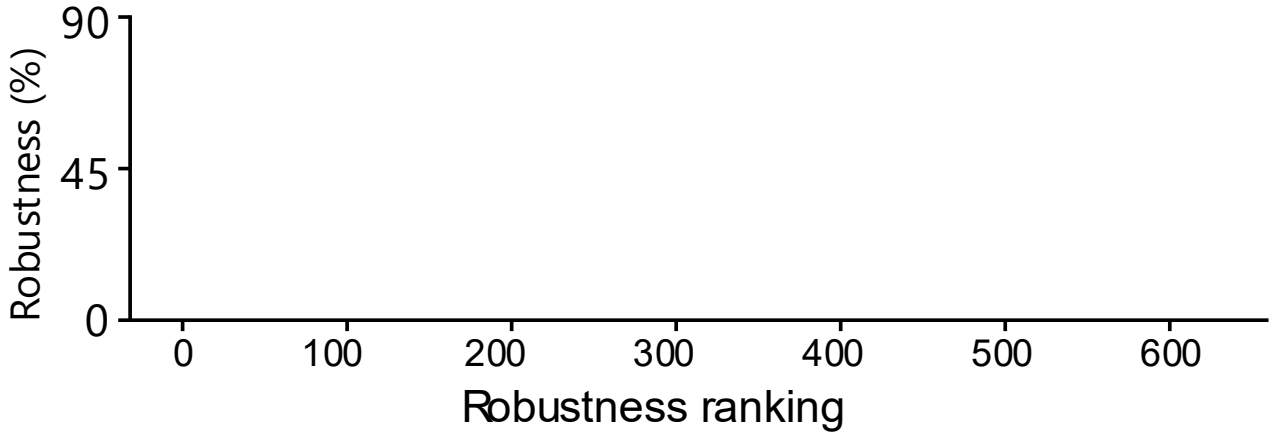


DMC < 10%

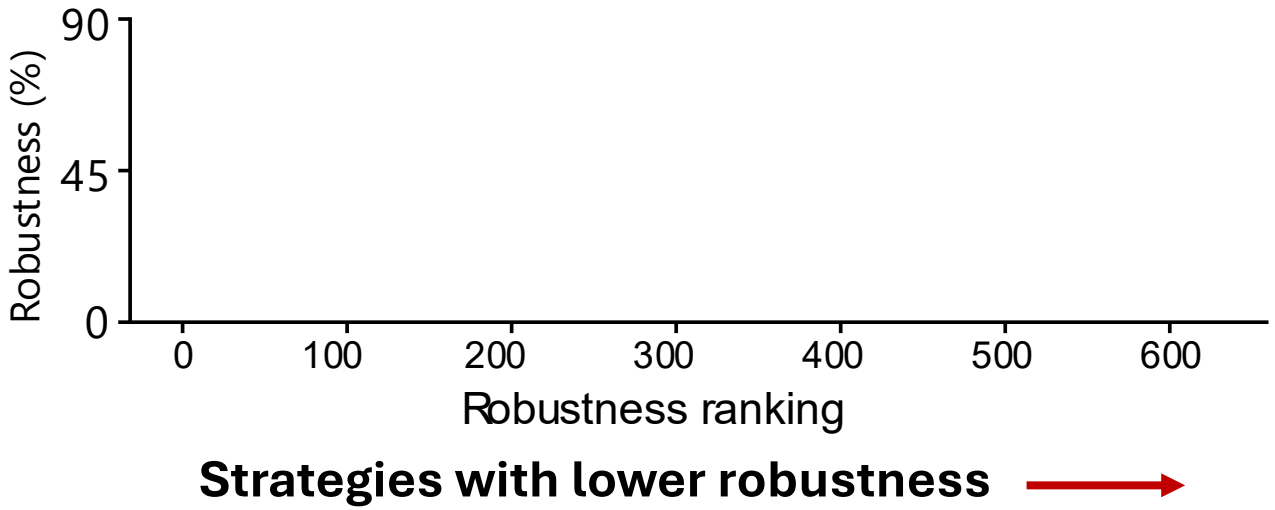
Satisficing robustness

The percentage of DU SOWs in which **all three satisficing criteria are met**

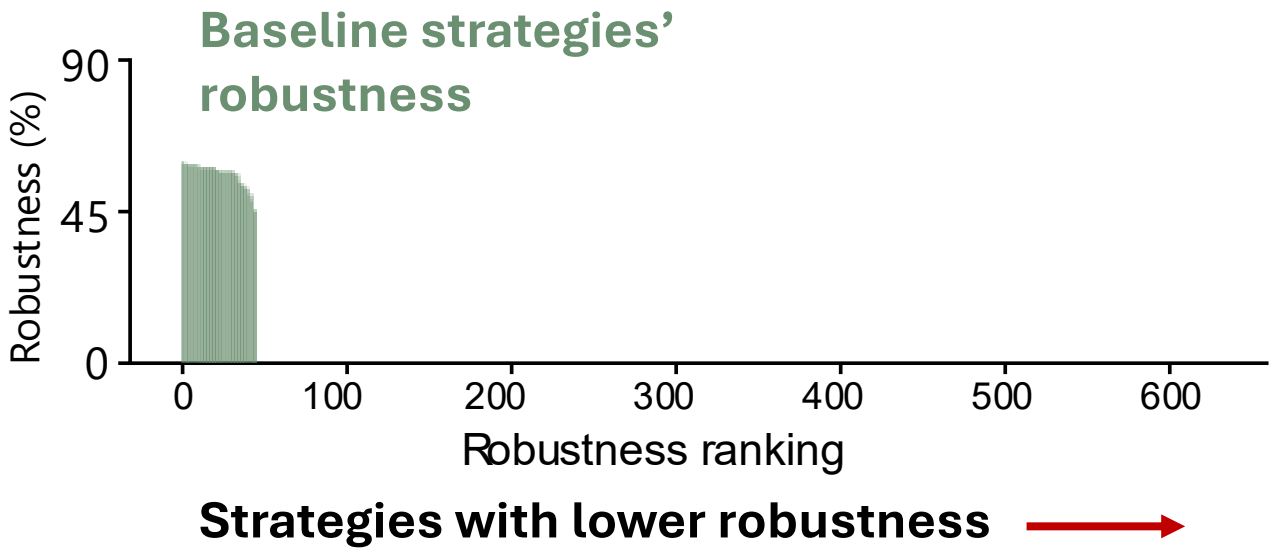
Pathway strategies that directly account for implementation uncertainty allows them to **better adapt to deep uncertainty** and **achieve higher robustness**



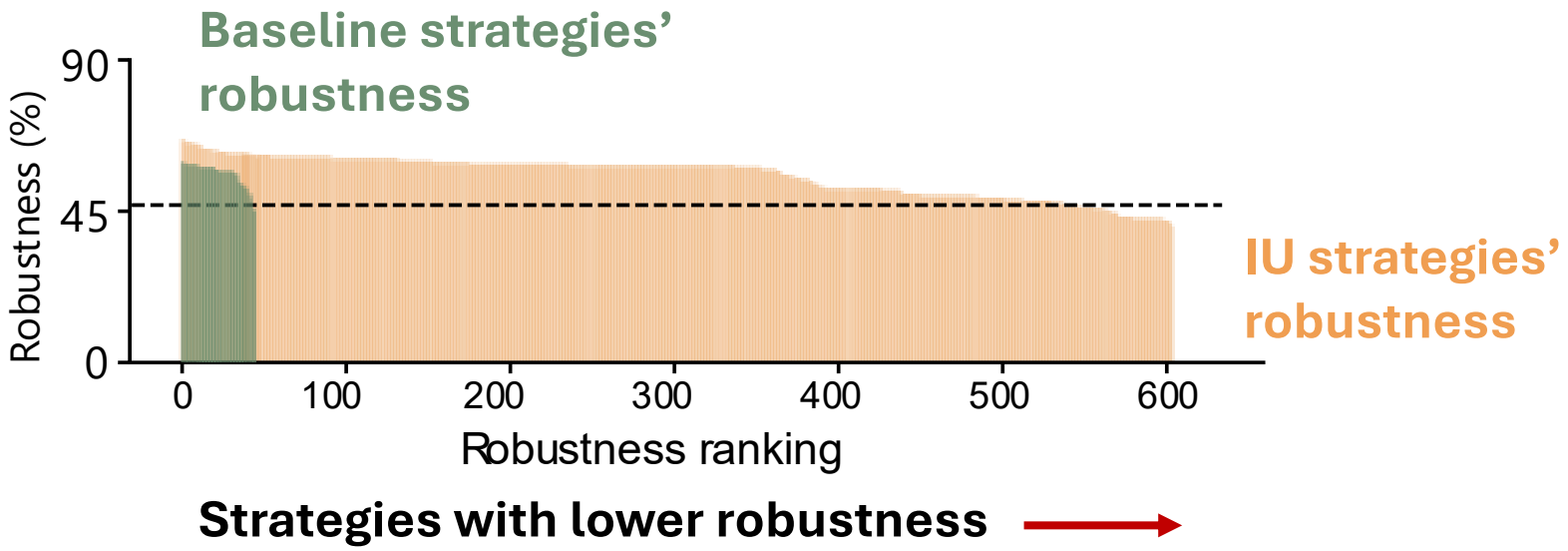
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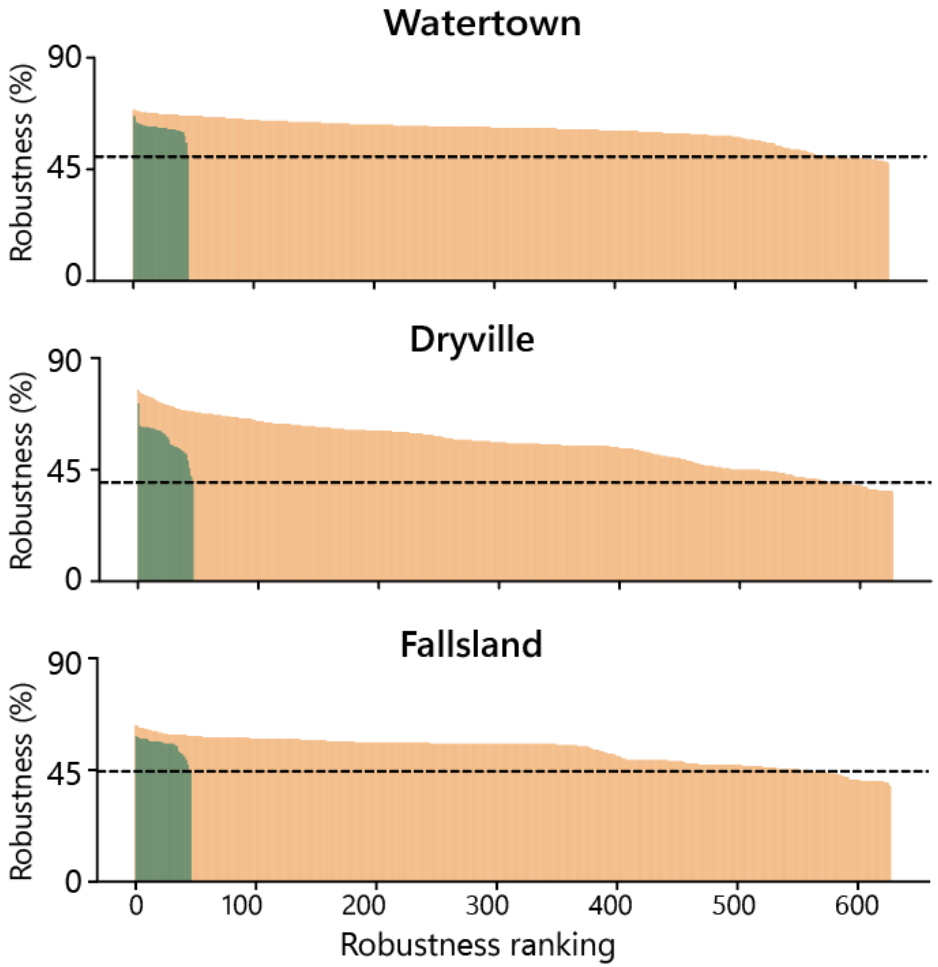


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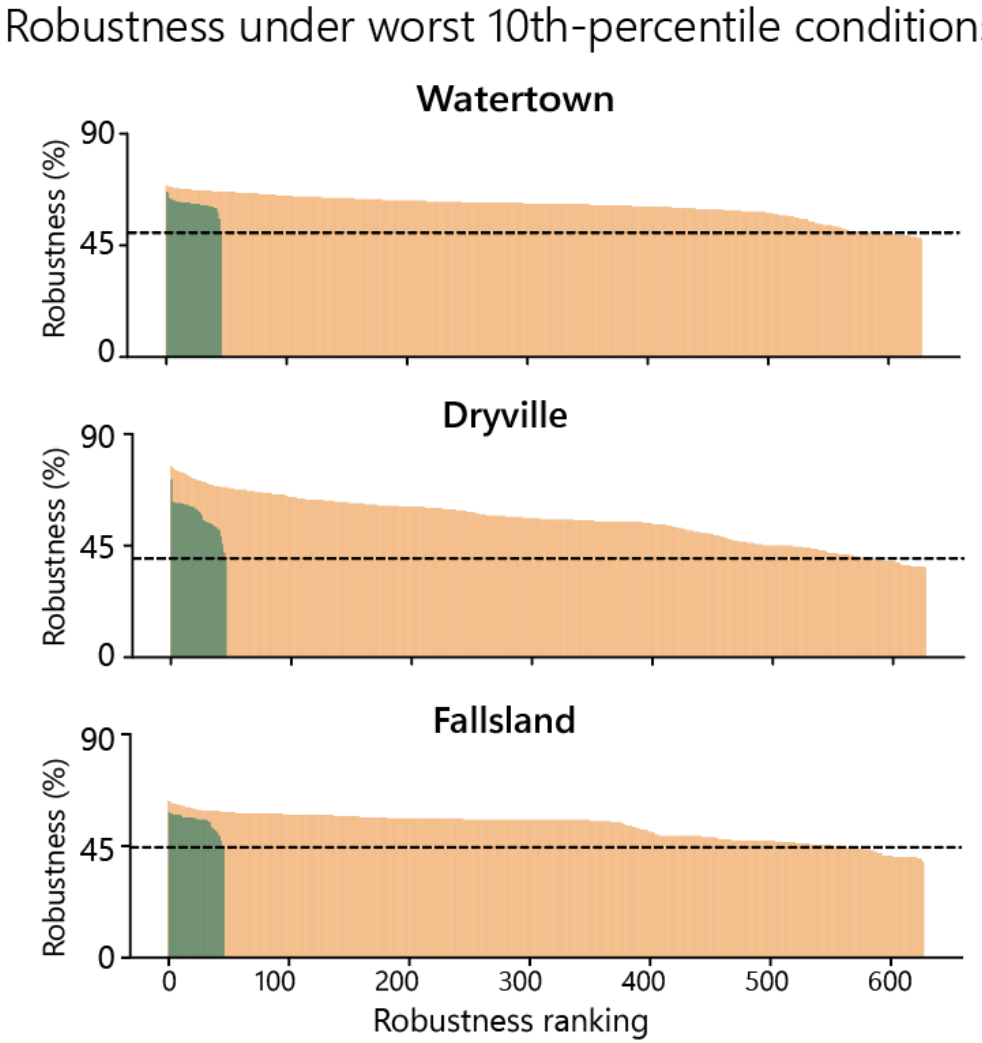


Pathway strategies that directly account for implementation uncertainty allows them to **better adapt to deep uncertainty** and **achieve higher robustness**

Robustness under worst 10th-percentile conditions



Pathway strategies that directly account for implementation uncertainty allows them to **better adapt to deep uncertainty** and **achieve higher robustness**

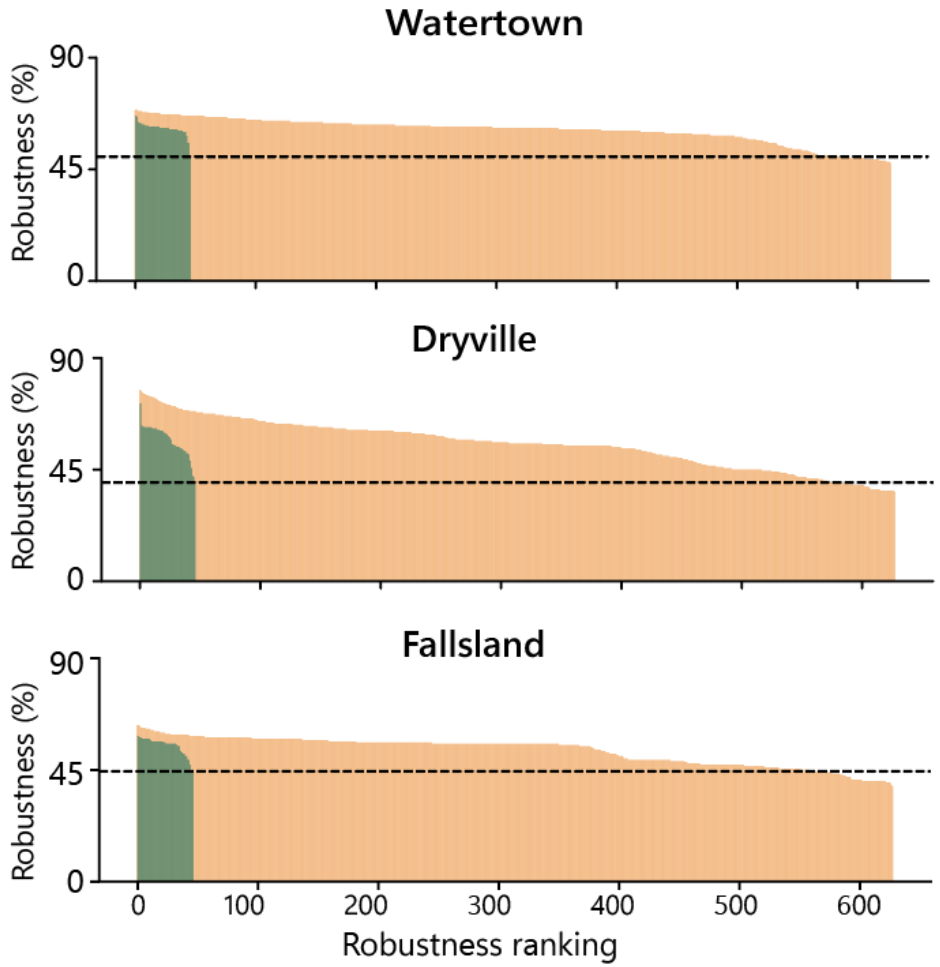


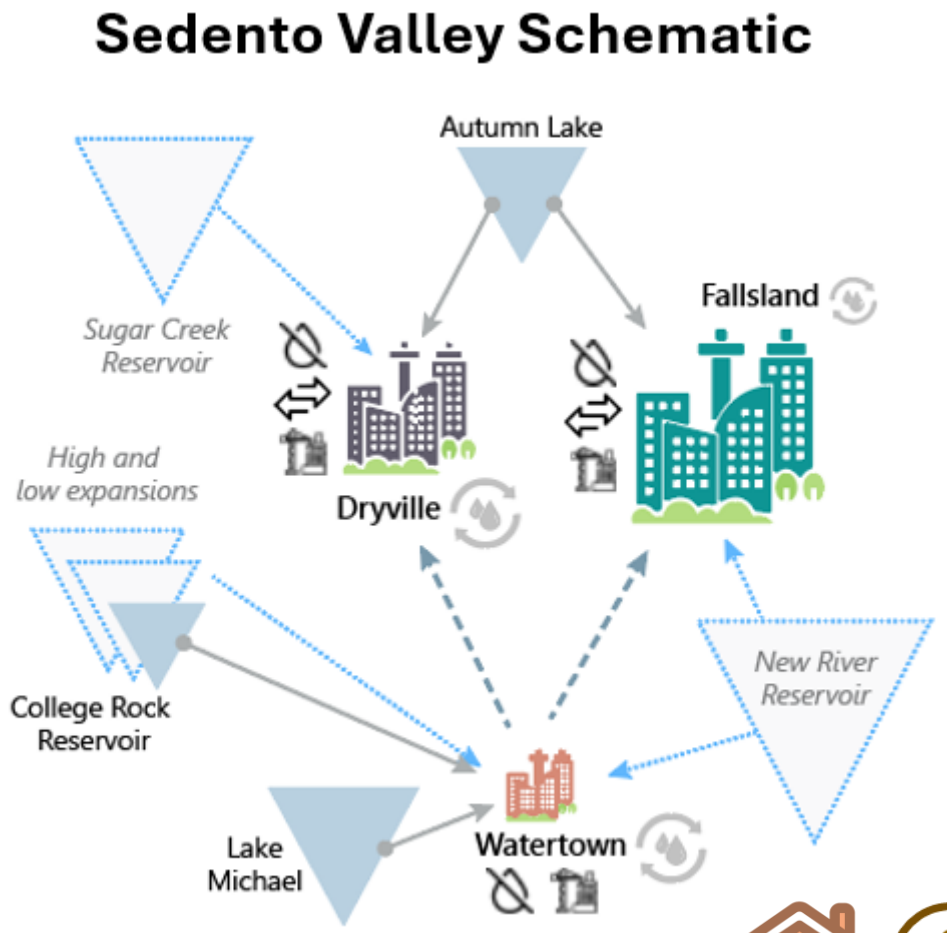
The IU pathway strategies **largely attain higher robustness** than their baseline counterparts

More **frequent use of cooperative mechanism** allow them to **adapt to challenging, unforeseen scenarios**

Pathway strategies that directly account for implementation uncertainty allows them to **better adapt to deep uncertainty** and **achieve higher robustness**

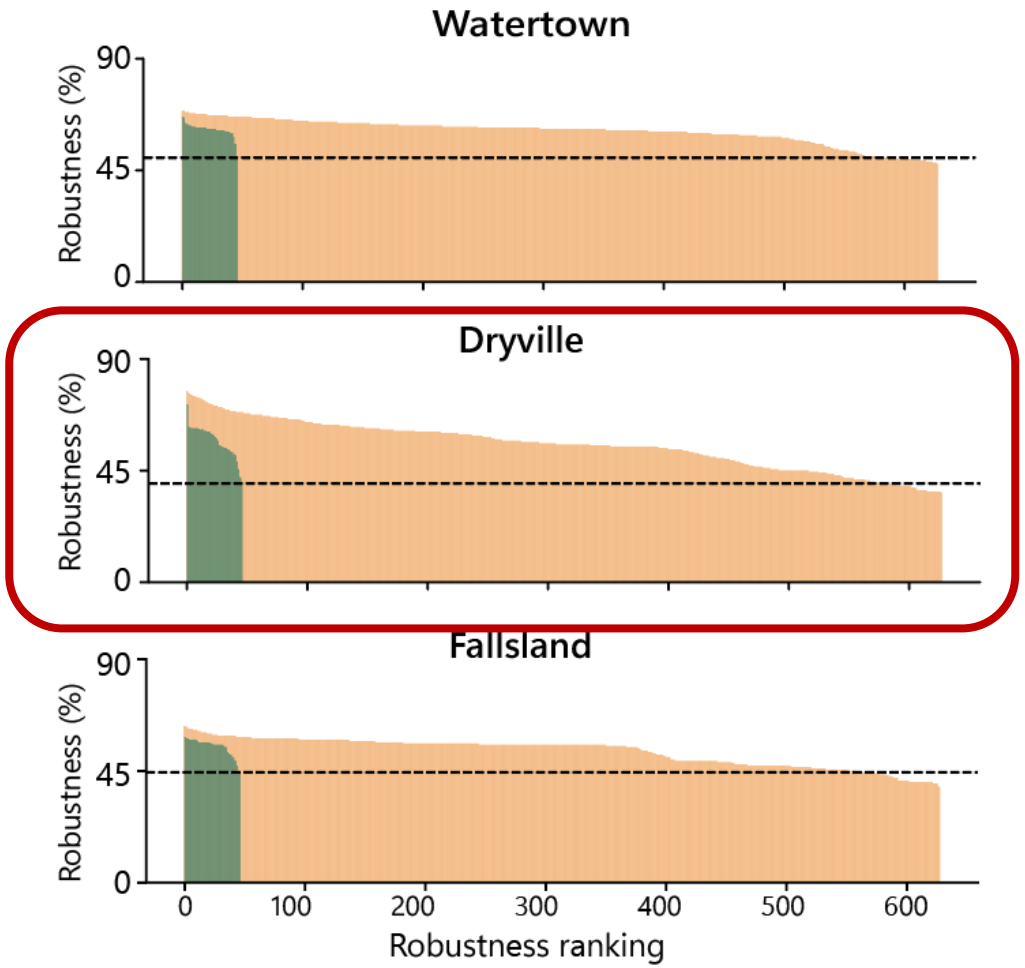
Robustness under worst 10th-percentile conditions



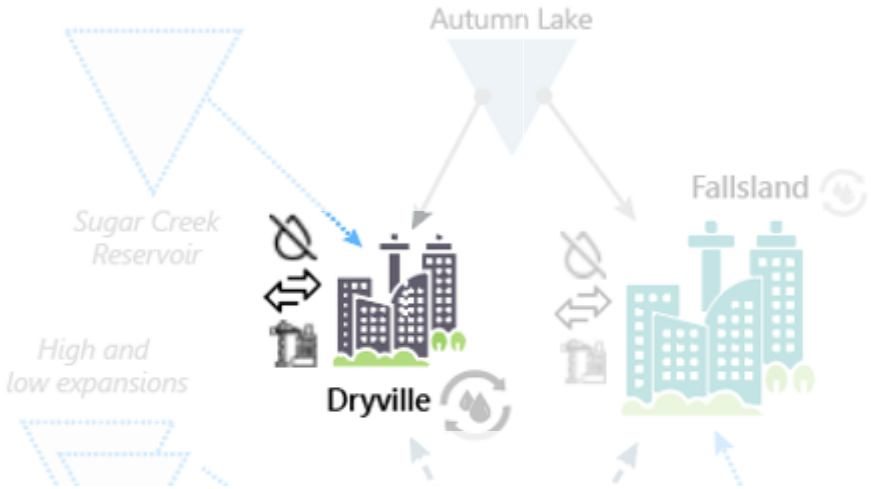


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Robustness under worst 10th-percentile conditions



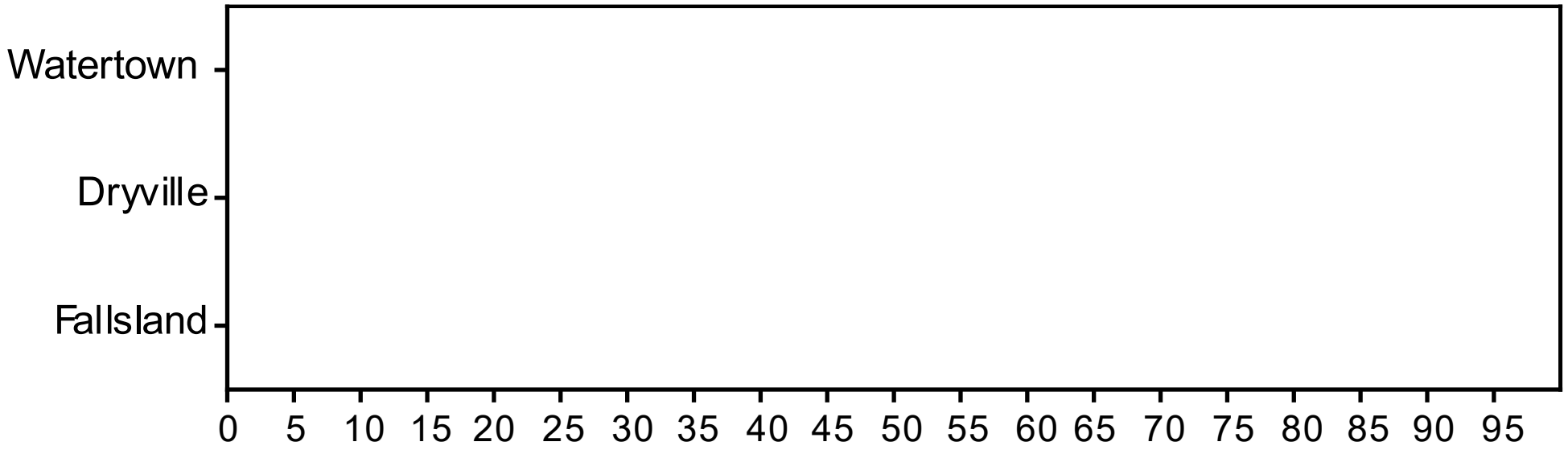
Sedento Valley Schematic



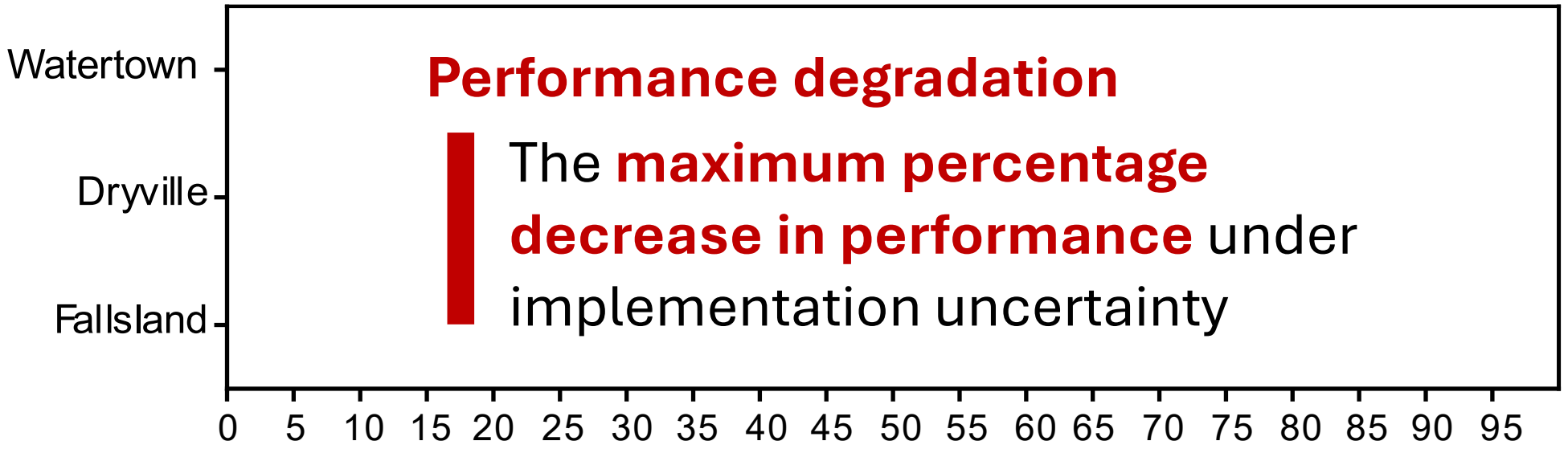
Robustness gains felt most by utilities **dependent on short-term cooperation**

Back to Tour

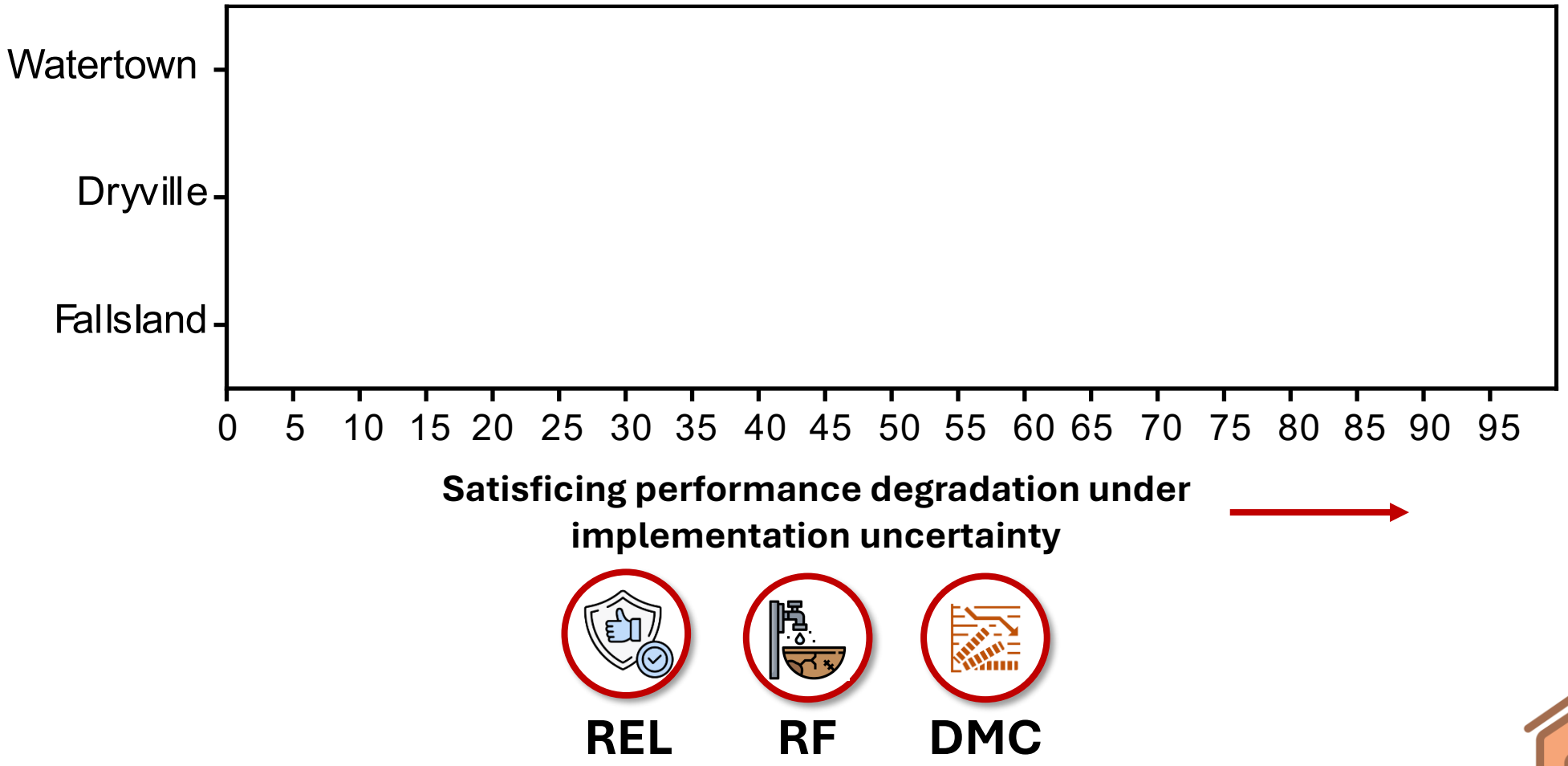
The strategies are also **better able to avoid performance degradation driven by implementation uncertainty**



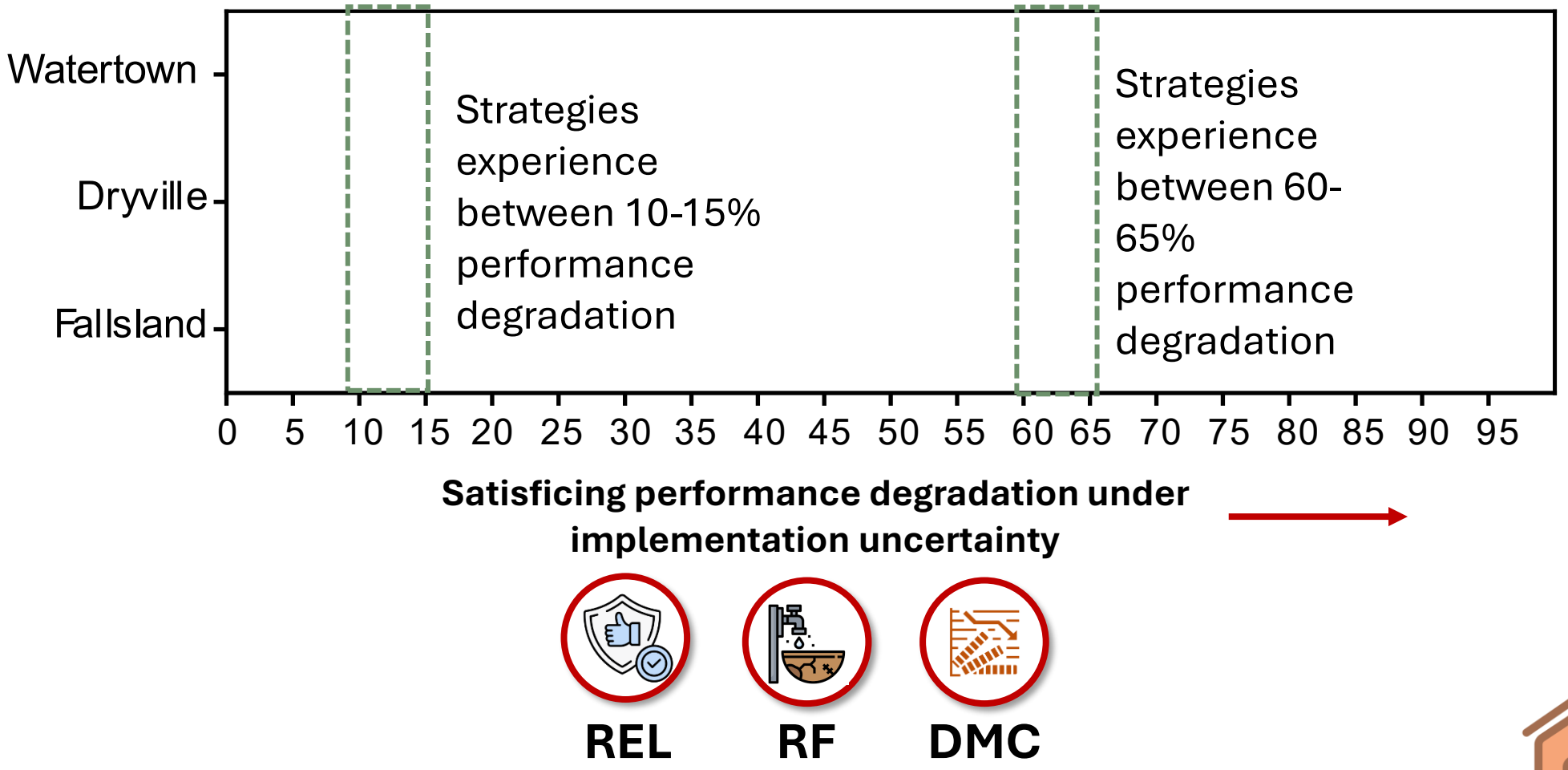
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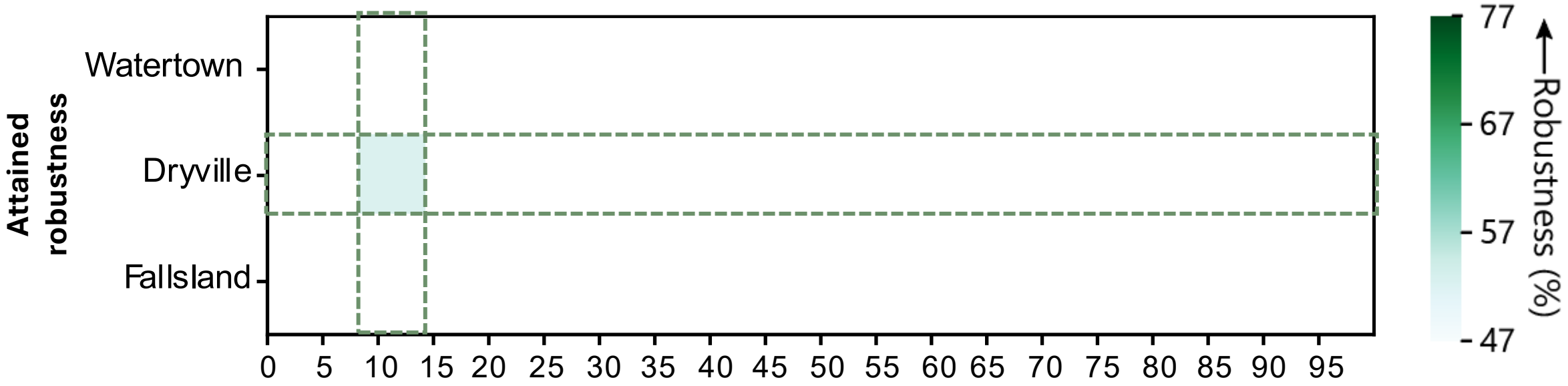
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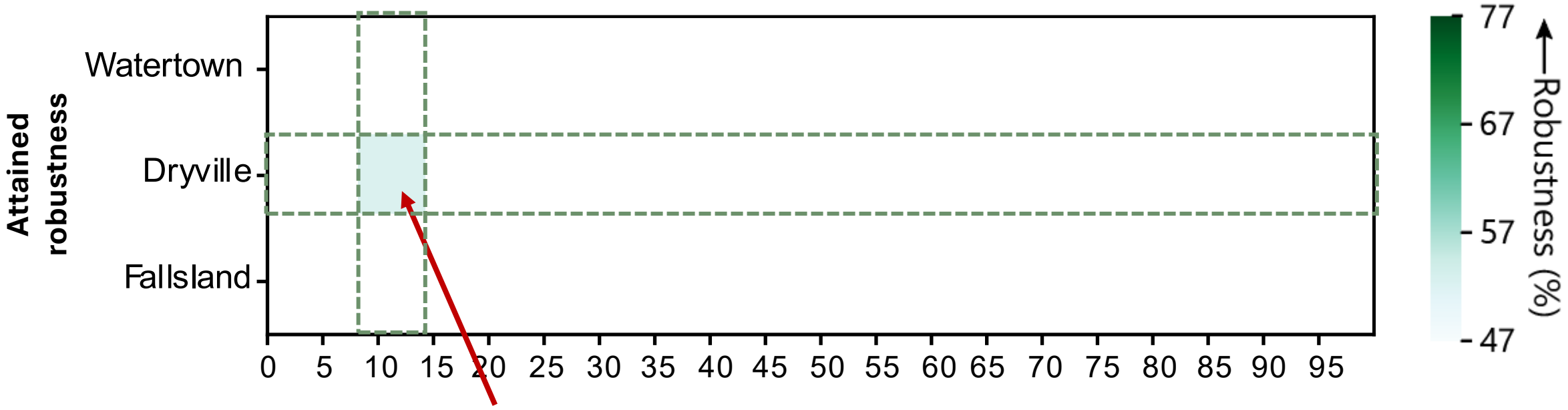
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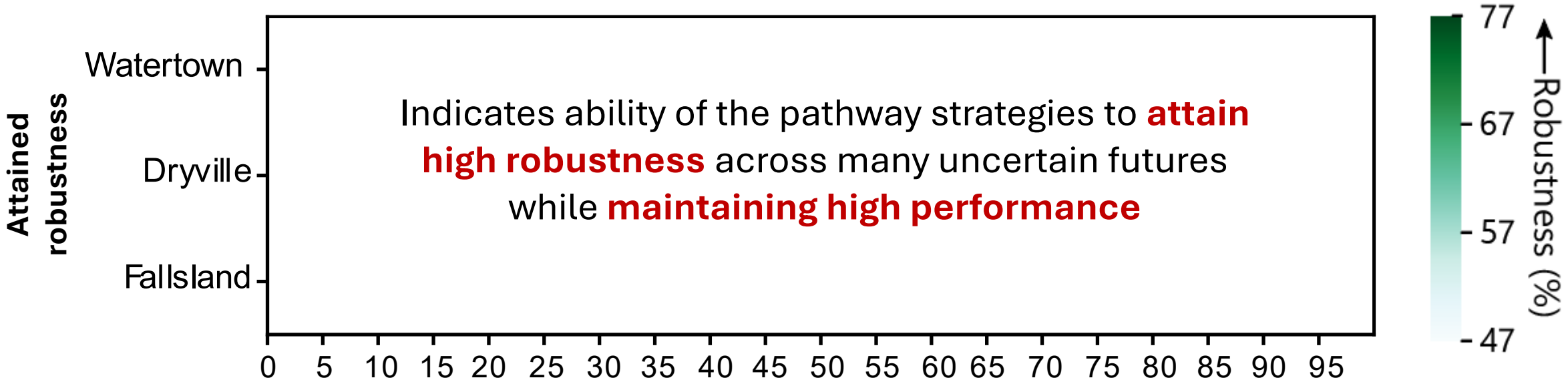


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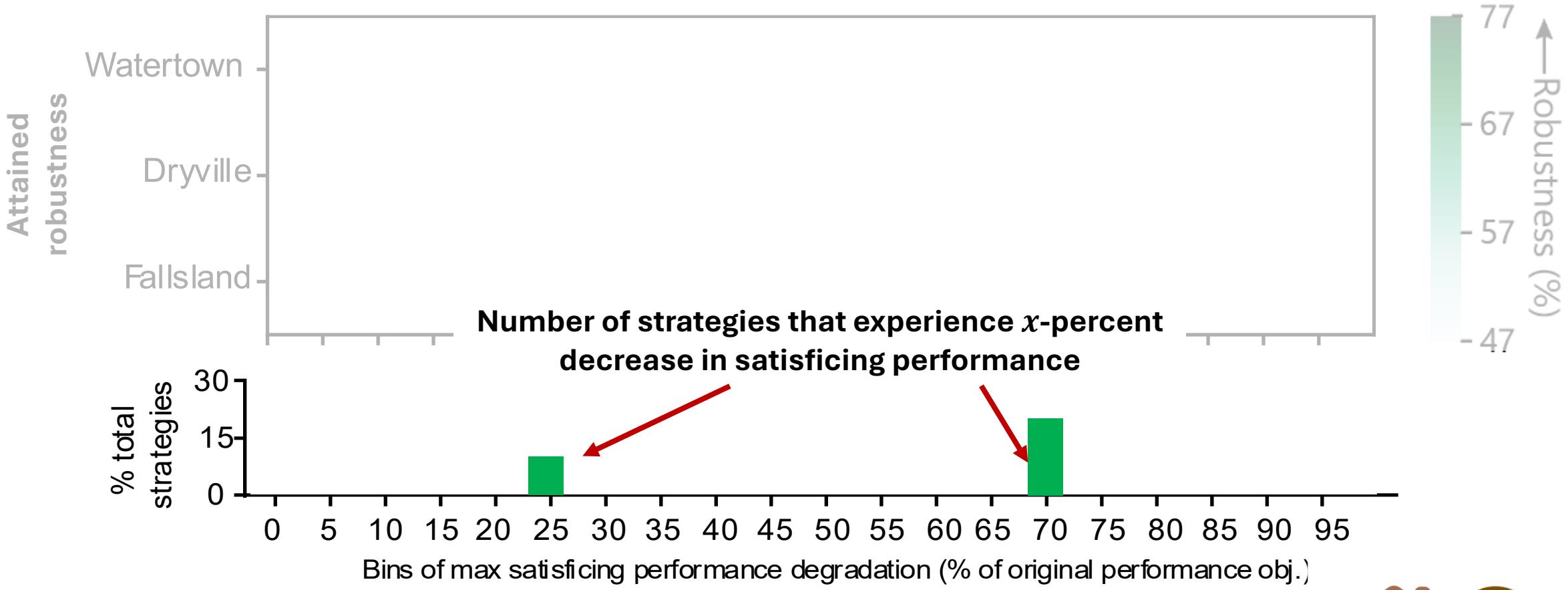


Dryville's strategies that experience a **10-15% performance degradation** also attain a **robustness of ~50%**

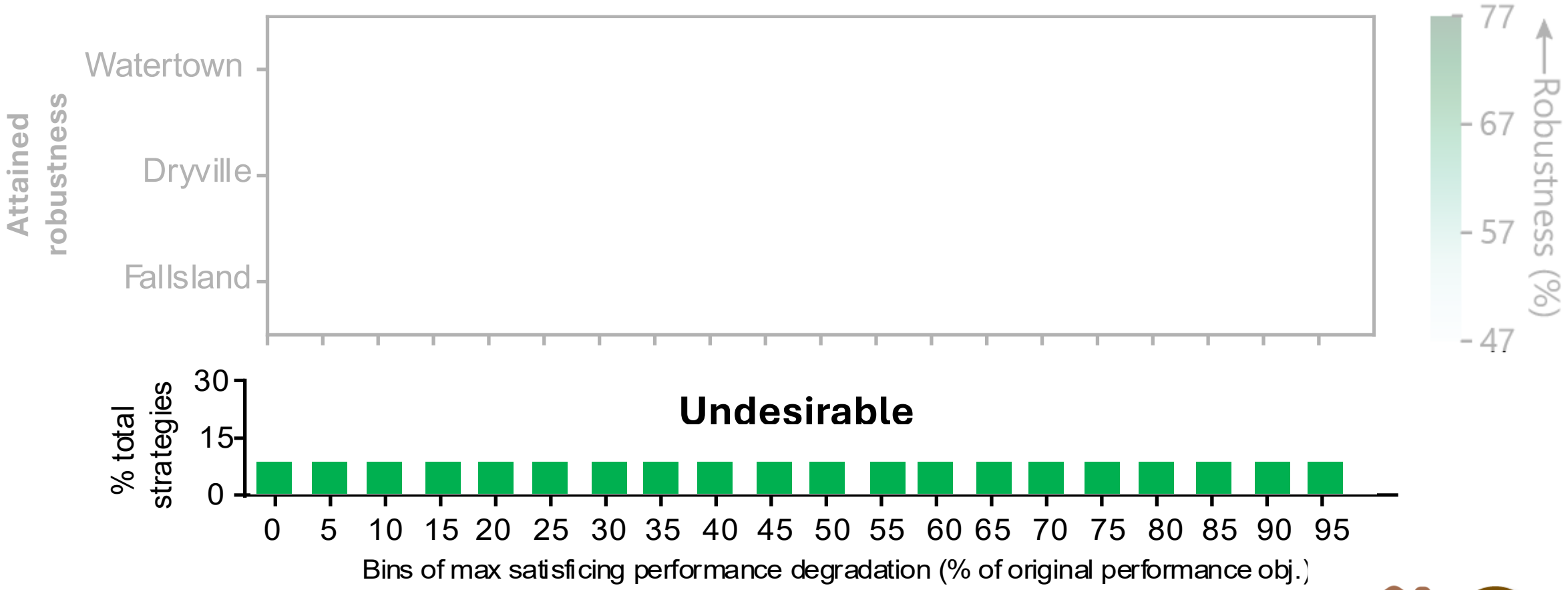
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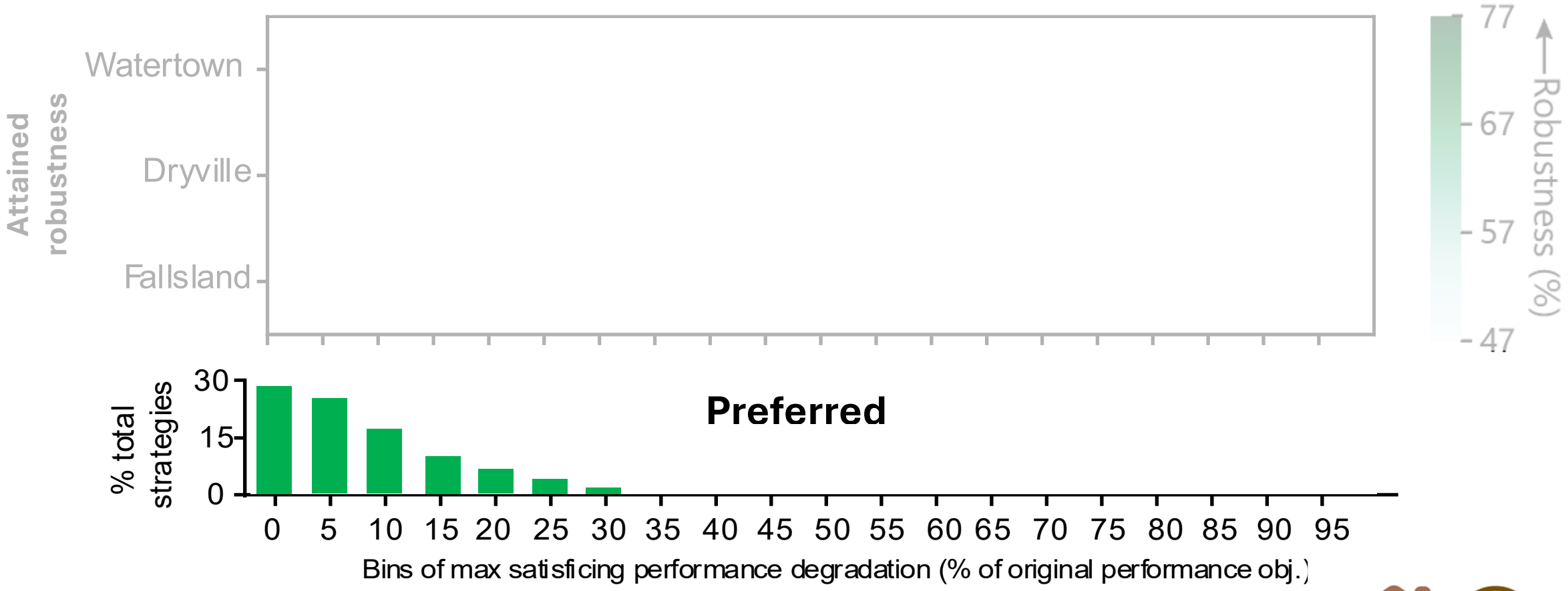
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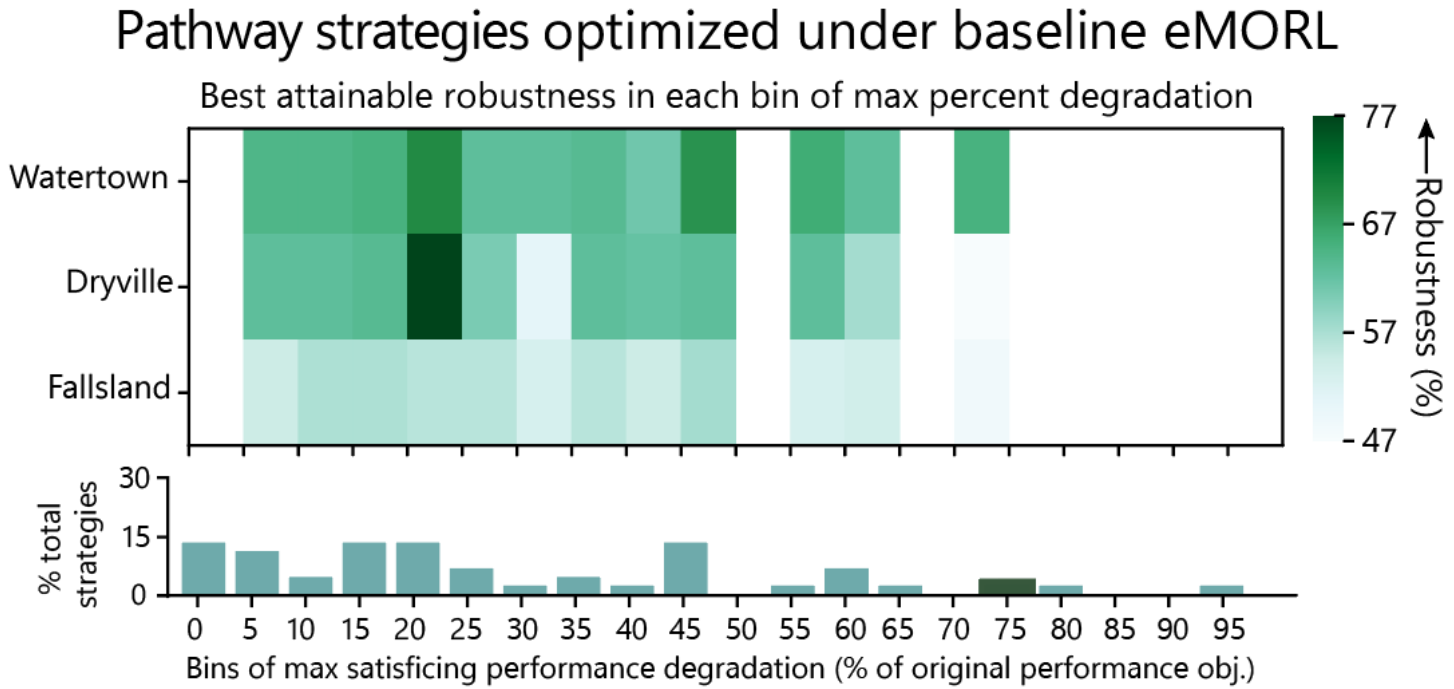
The strategies are also **better able to avoid performance degradation driven by implementation uncertainty**



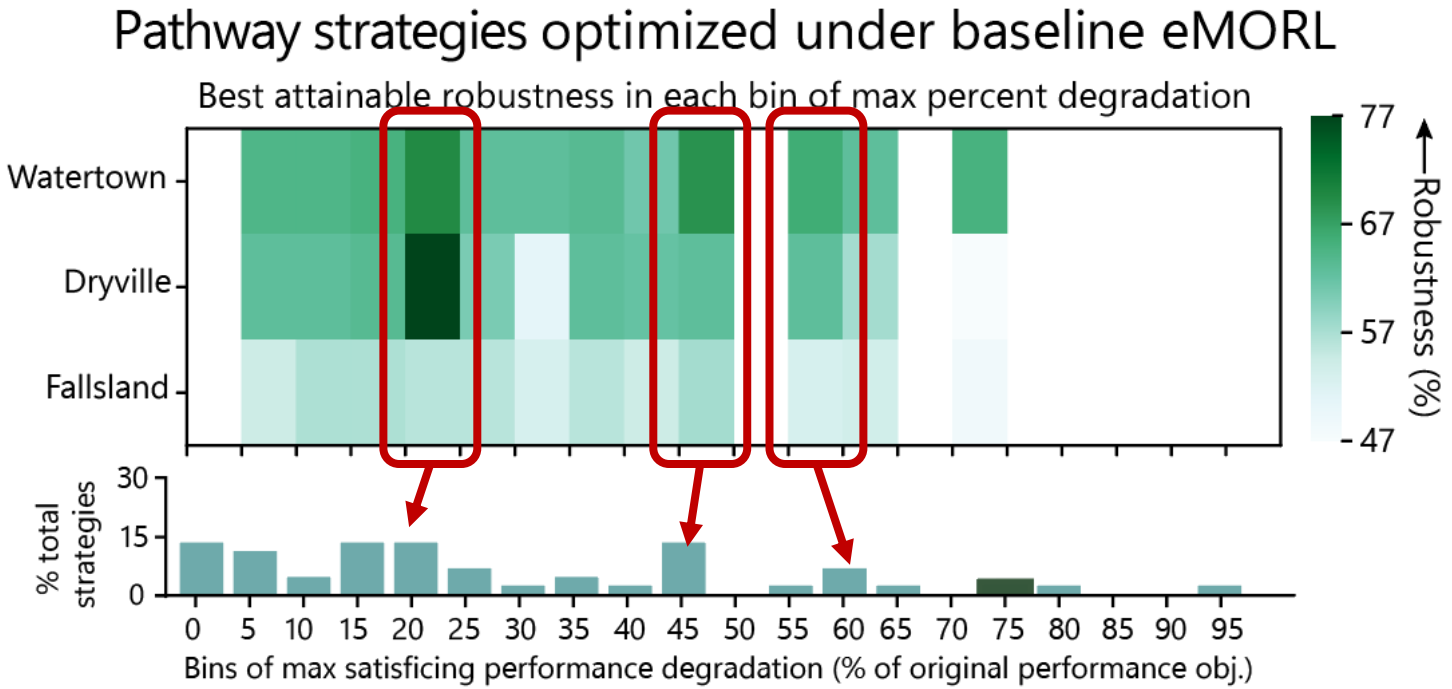
The strategies are also **better able to avoid performance degradation driven by implementation uncertainty**



Baseline vs IU pathway strategies: **The tradeoff between high robustness and limited performance degradation**

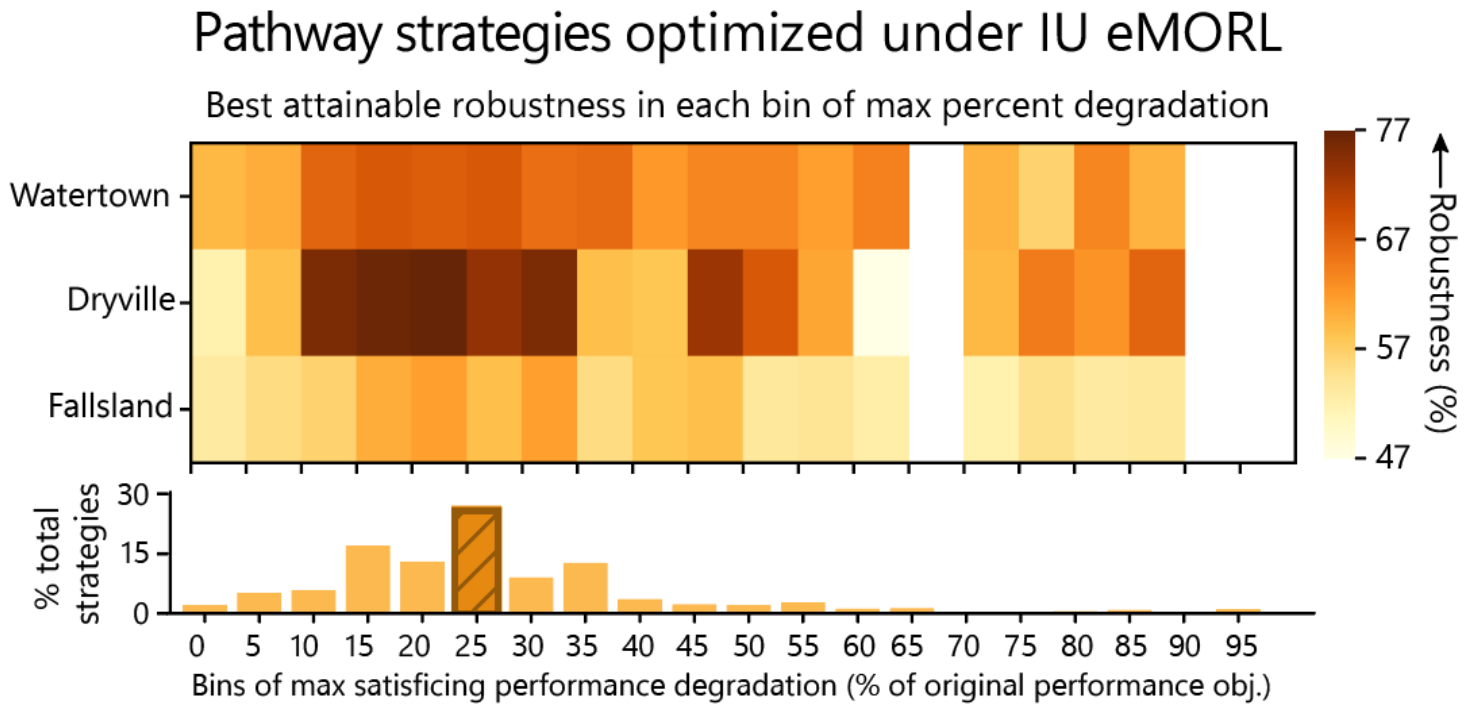


Baseline vs IU pathway strategies: **The tradeoff between high robustness and limited performance degradation**

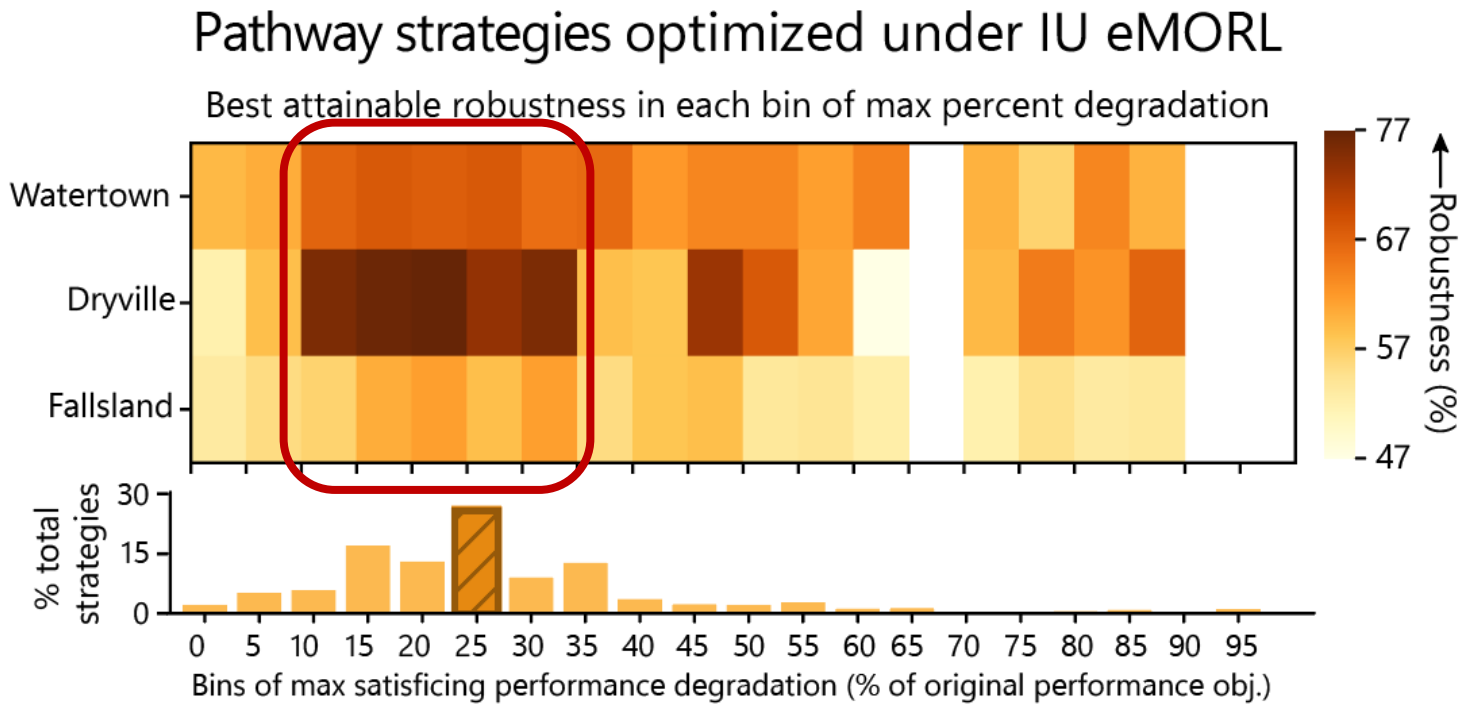


The baseline strategies **experience a wide range of performance degradation** when directly exposed to implementation uncertainty

Baseline vs IU pathway strategies: The tradeoff between high robustness and limited performance degradation



Baseline vs IU pathway strategies: The tradeoff between high robustness and limited performance degradation



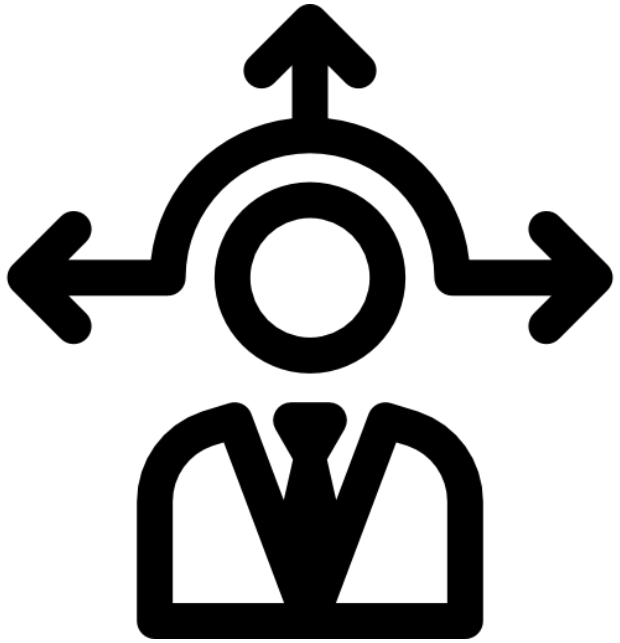
The IU pathway strategies can both **maintain high robustness and limited performance change** when exposed to implementation uncertainty

Back to Tour

The "Social Planner" strategy: Minimizing regional dissatisfaction by maximizing regional robustness

Prioritizes regional cooperation over individual benefits

May favor parties with the least access to resources



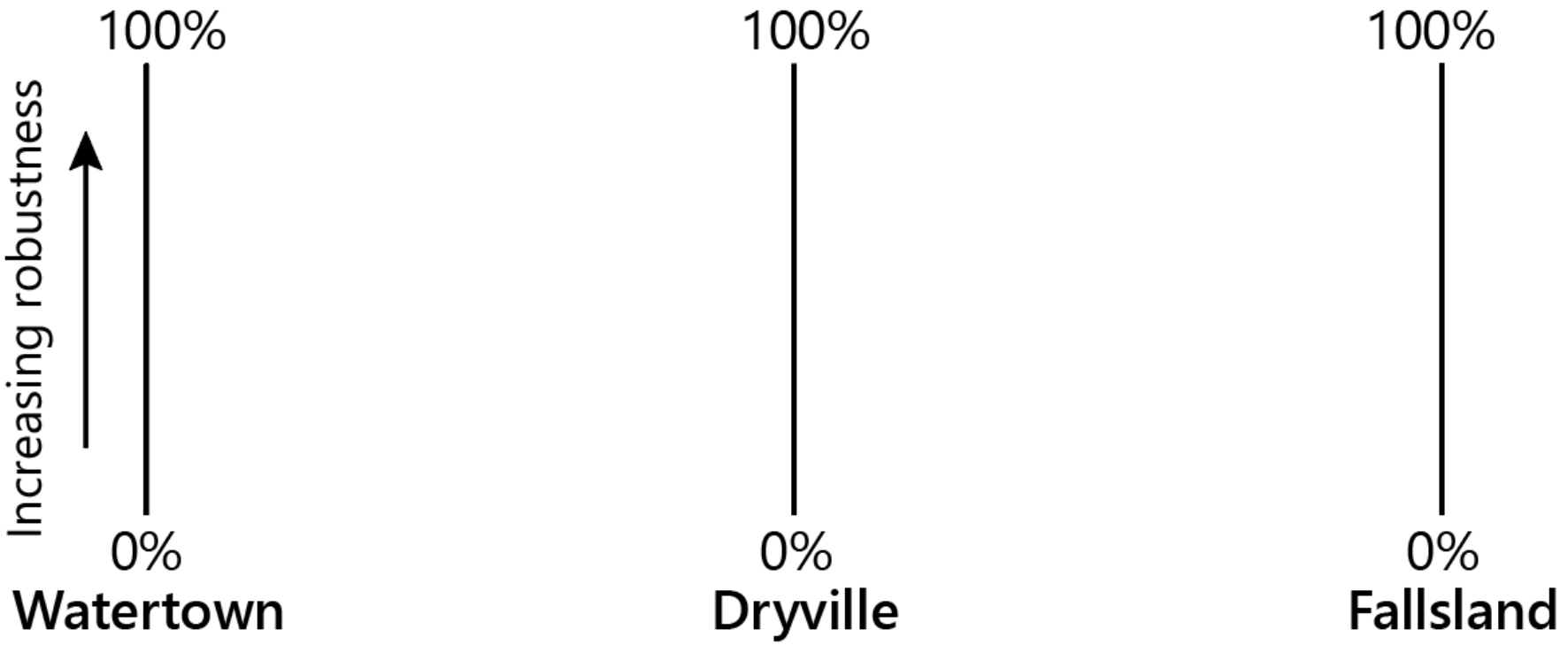
Strong investment in shared infrastructure

Benevolent Central Planner

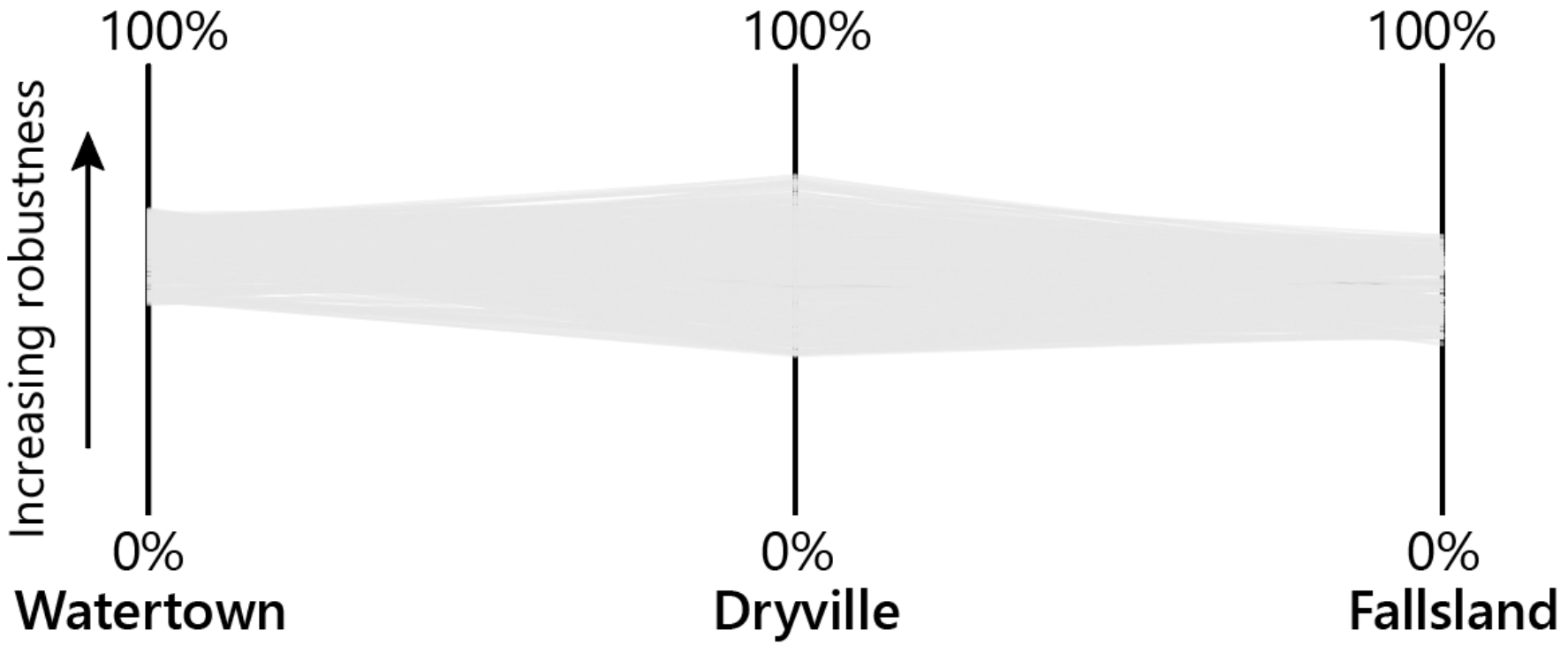
[1] Read, L., Madani, K. and Inanloo, B. (2014) 'Optimality versus stability in water resource allocation', *Journal of Environmental Management*, 133, pp. 343–354. doi:10.1016/j.jenvman.2013.11.045.

[2] Gold, D. F., Reed, P. M., Gorelick, D. E., & Characklis, G. W. (2022). Power and pathways: Exploring robustness, cooperative stability, and power relationships in regional infrastructure investment and water supply management portfolio pathways. Earth's Future, 10, e2021EF002472. https://doi.org/10.1029/2021EF002472

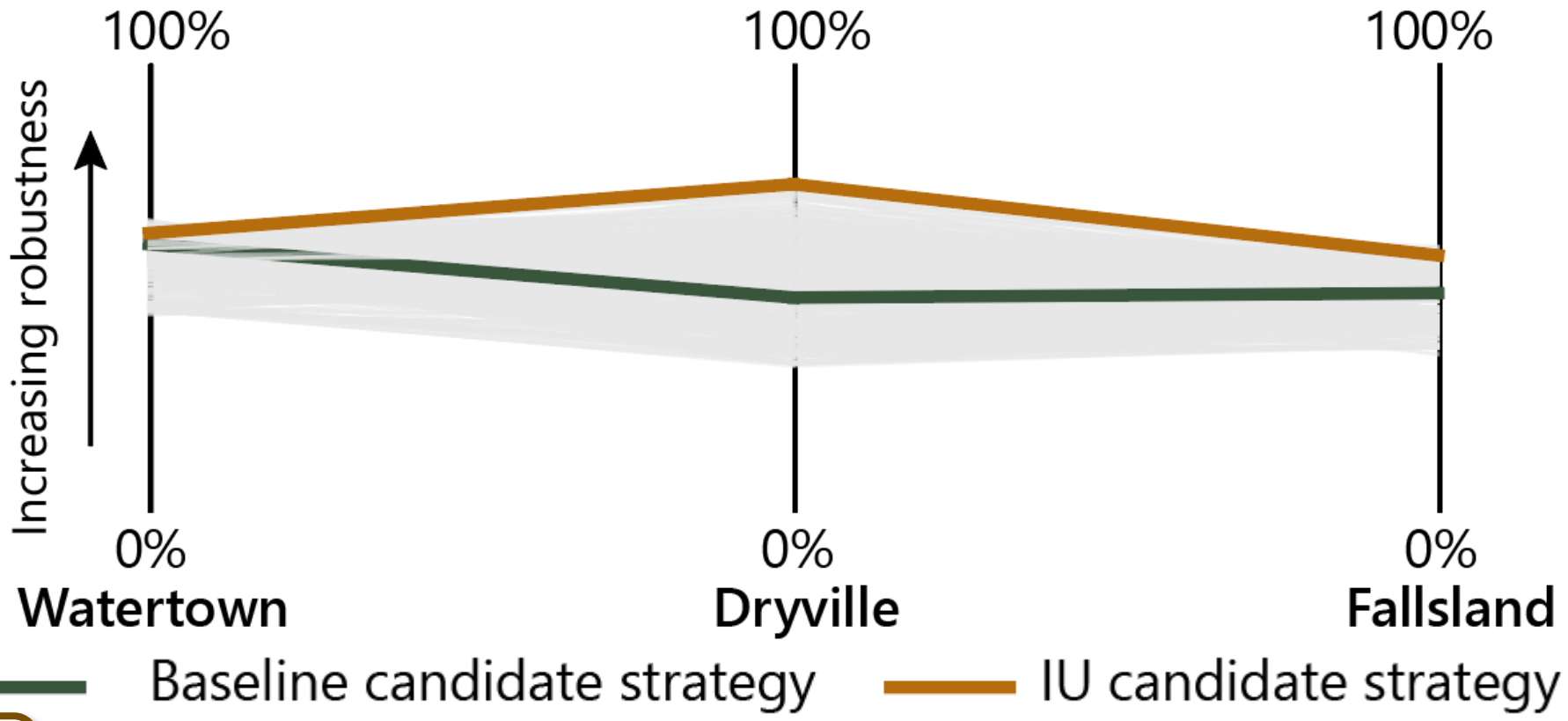
The "Social Planner" strategy: Minimizing regional dissatisfaction by maximizing regional robustness



The "Social Planner" strategy: Minimizing regional dissatisfaction by maximizing regional robustness

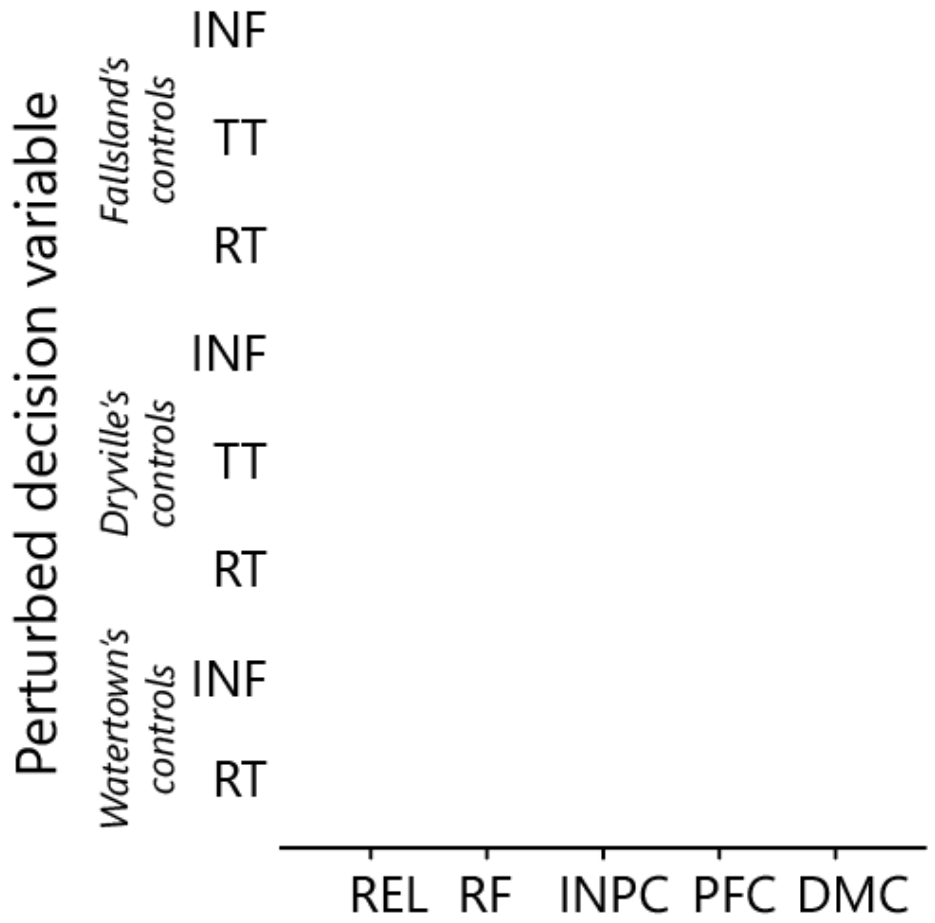


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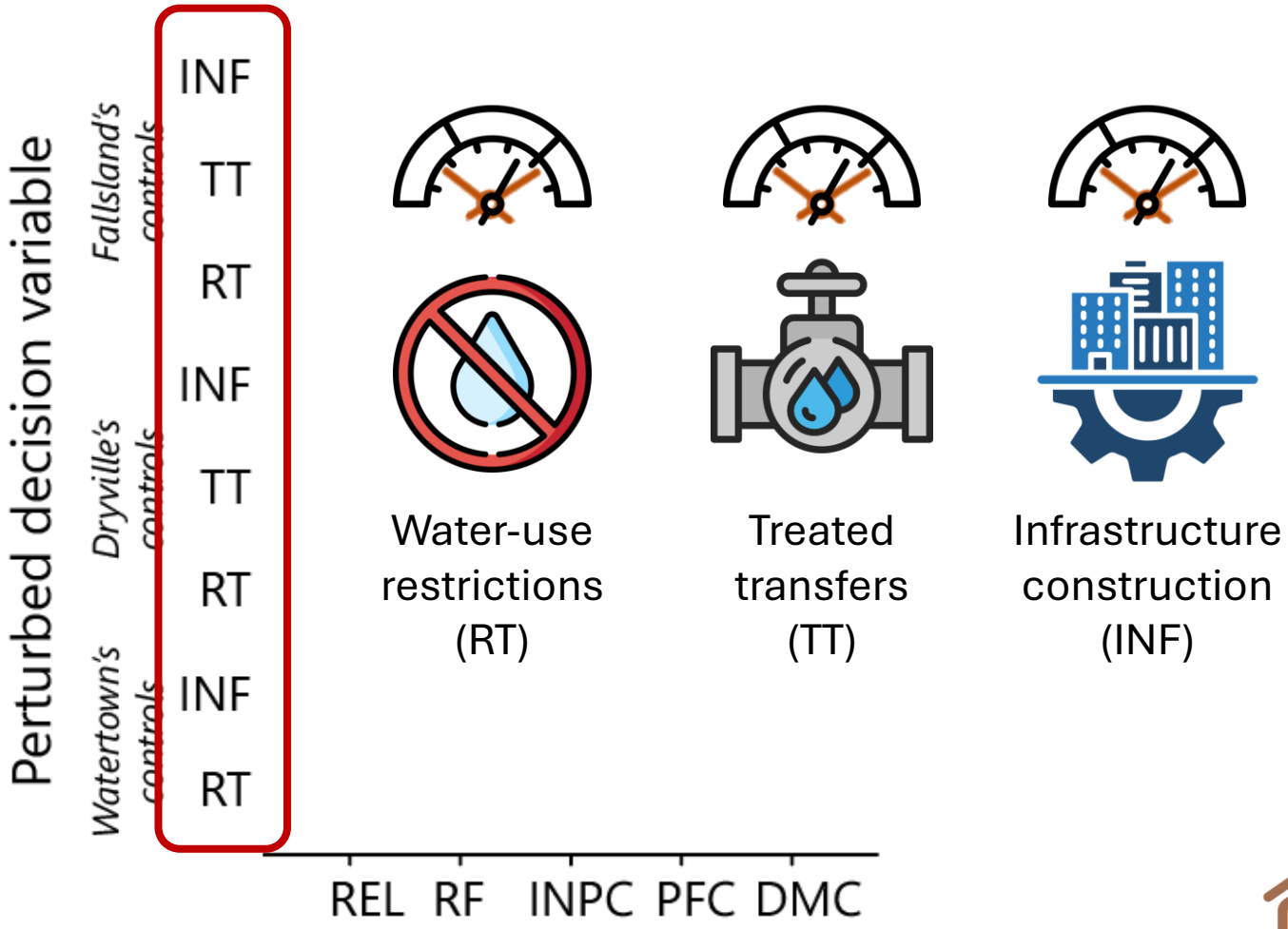


Back to Tour

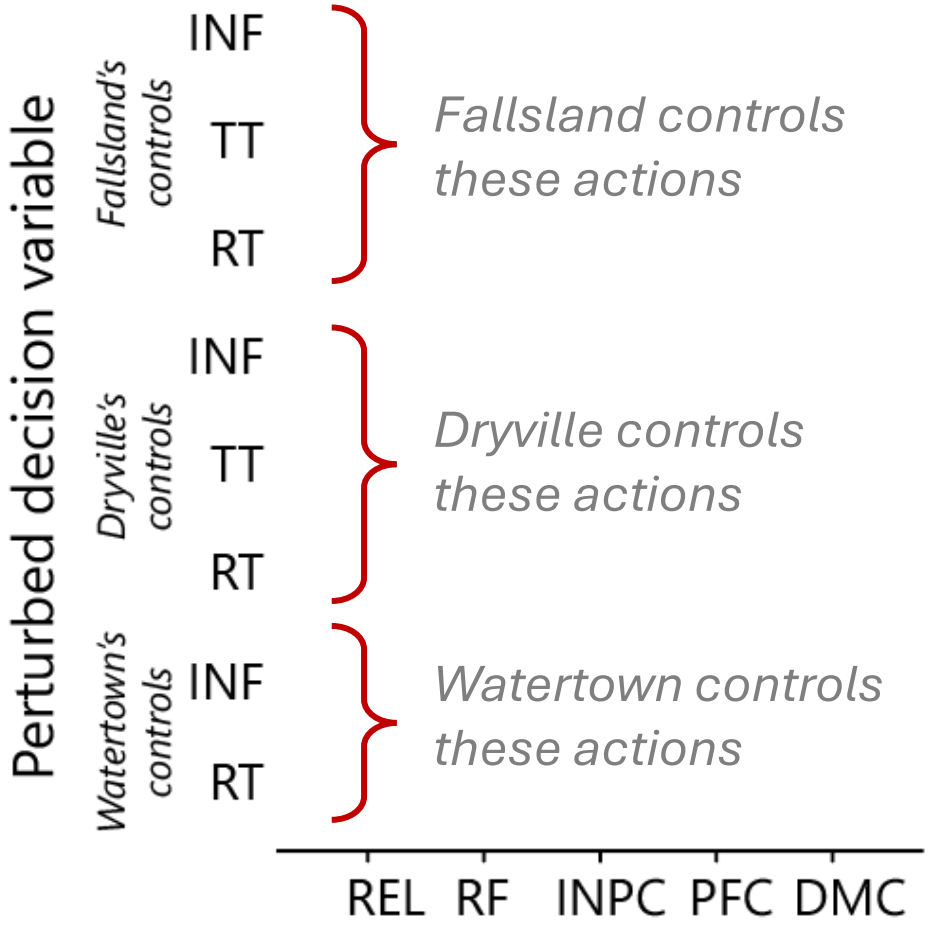
Delta Moment-Independent sensitivity analysis reveals differences in how vulnerabilities to imperfect implementation manifest across utilities



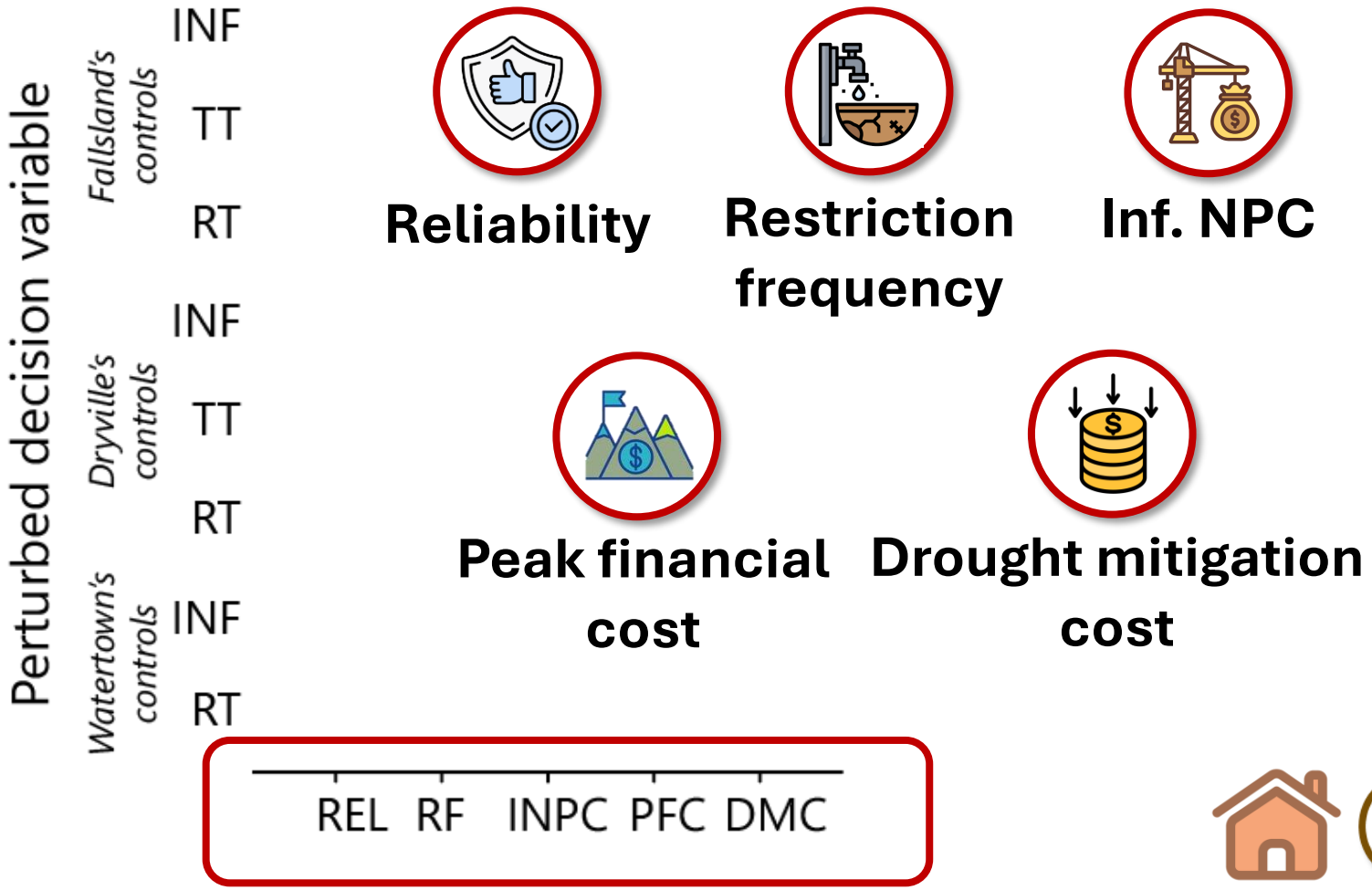
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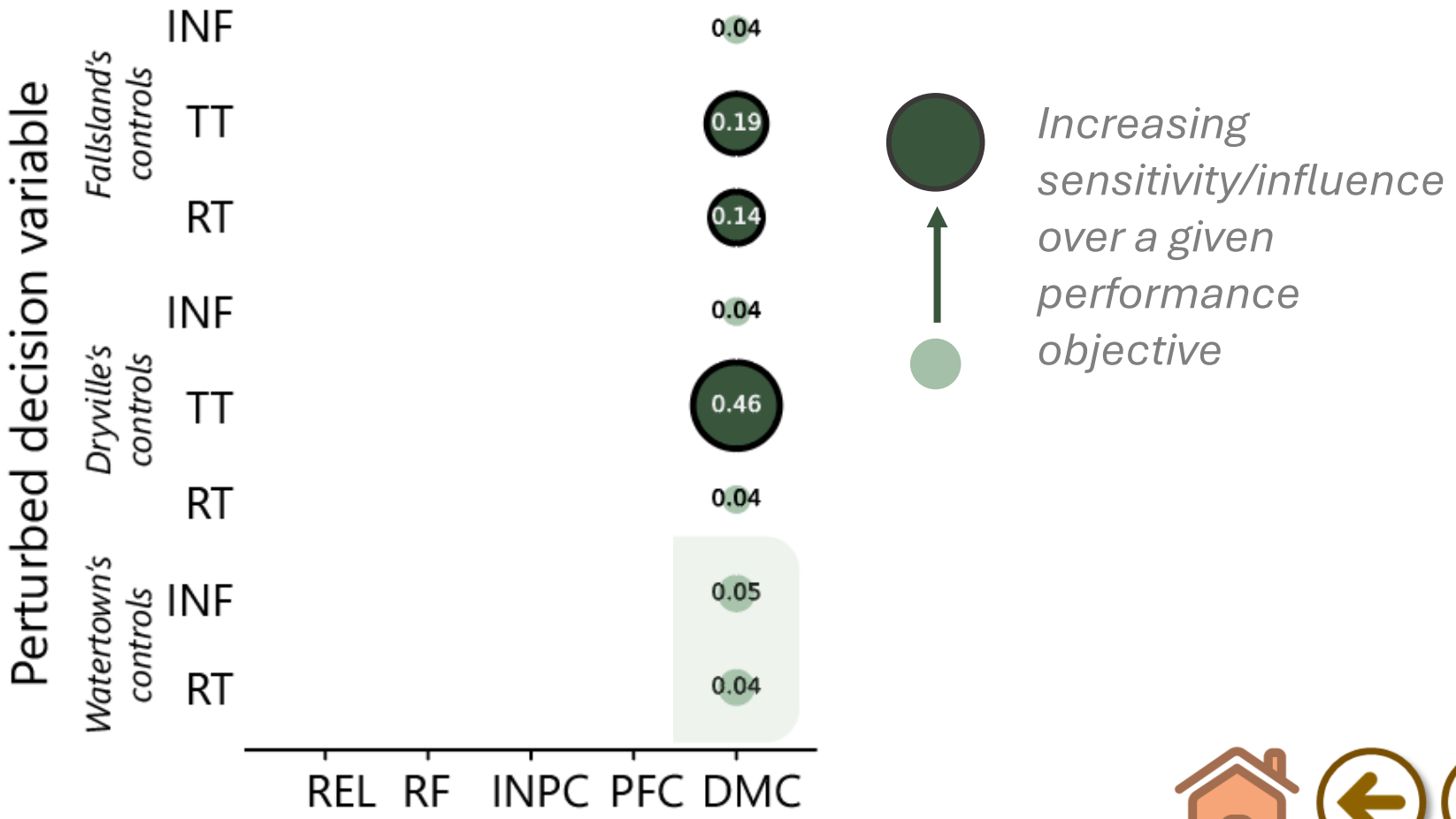
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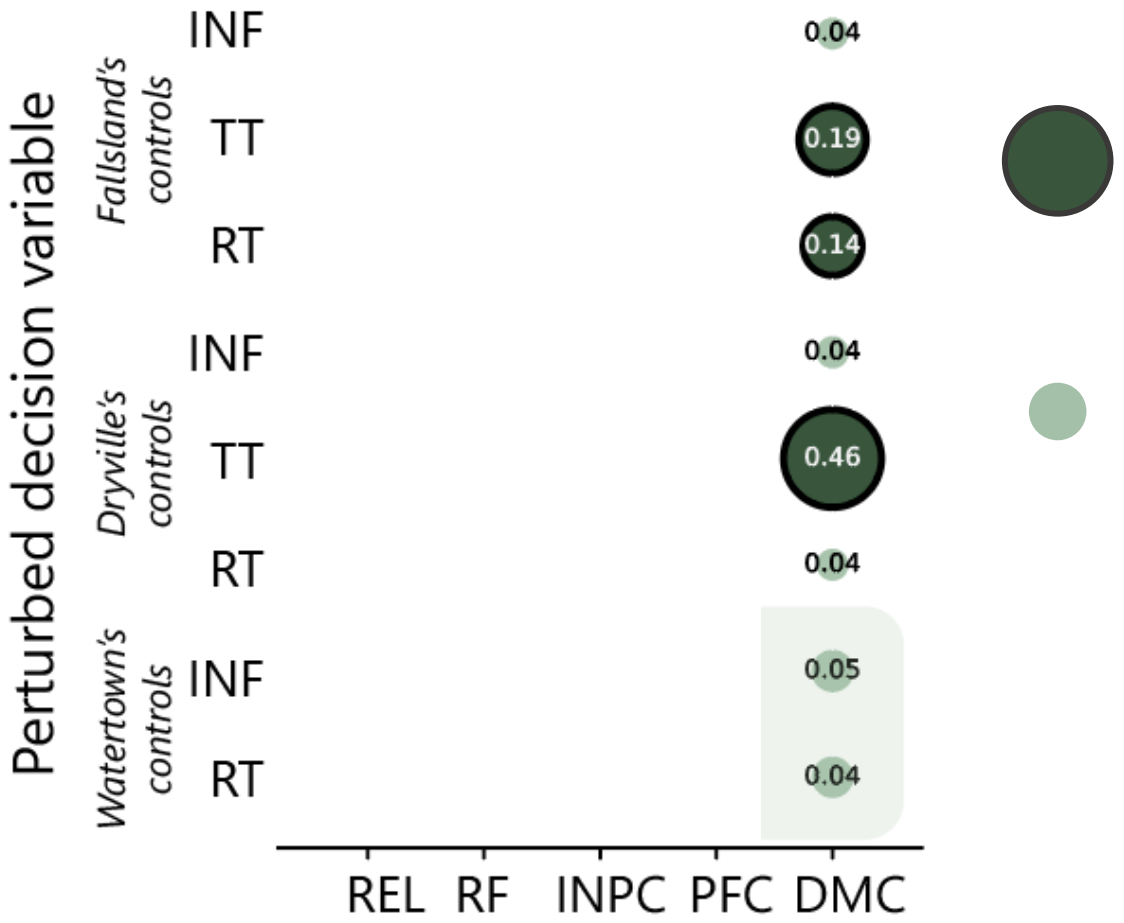
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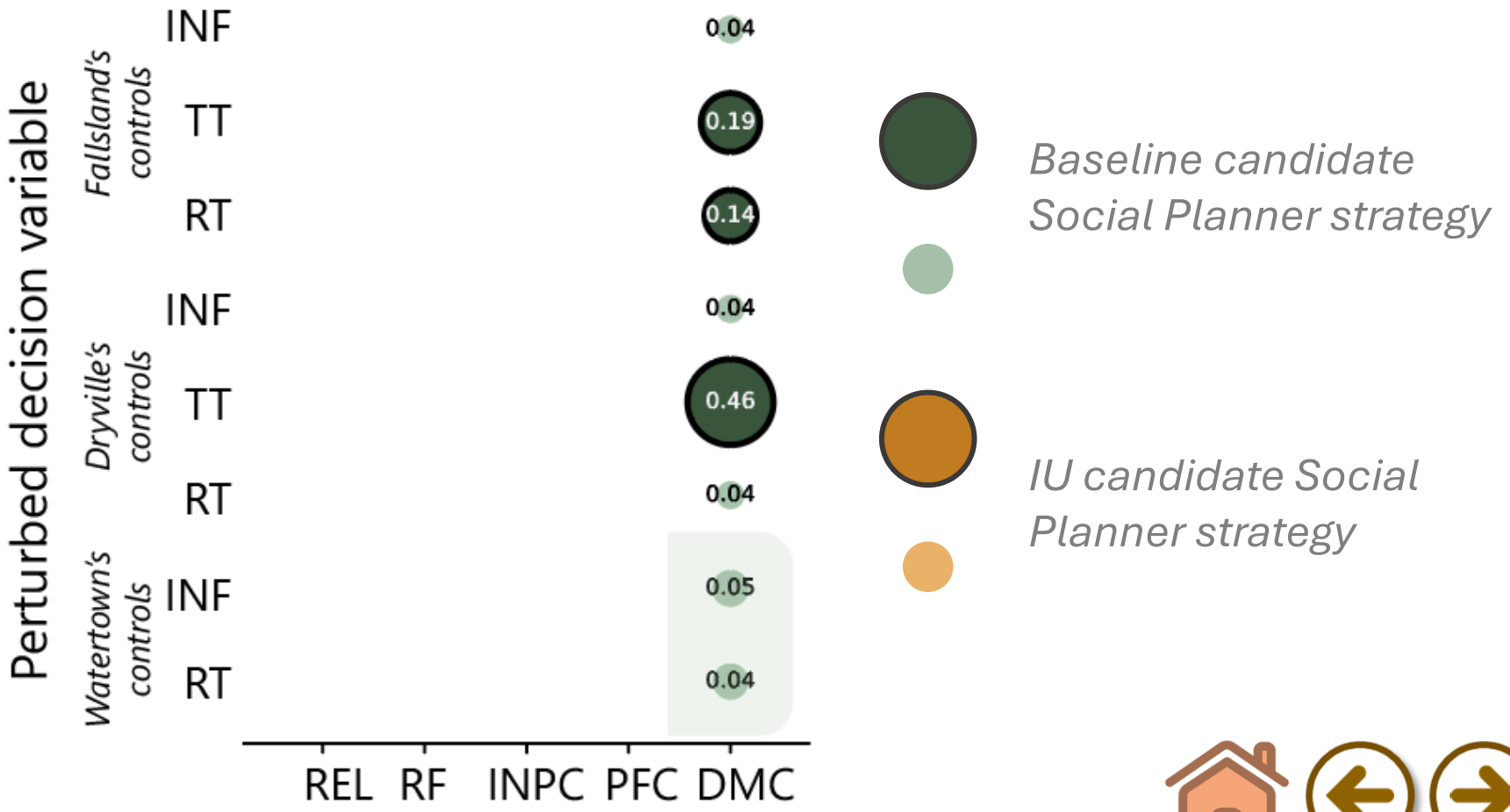
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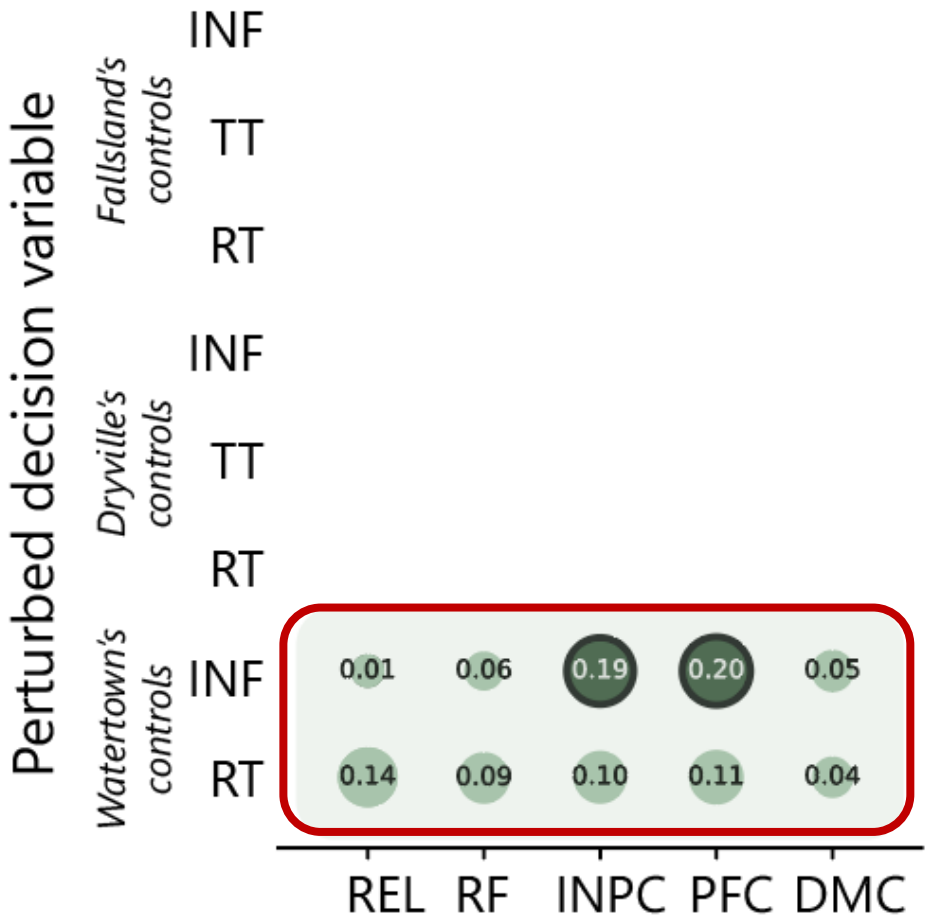
Top 3 most influential decision variables on performance

Sensitivity of performance to all other decision variables

Delta Moment-Independent sensitivity analysis reveals differences in how vulnerabilities to imperfect implementation manifest across utilities



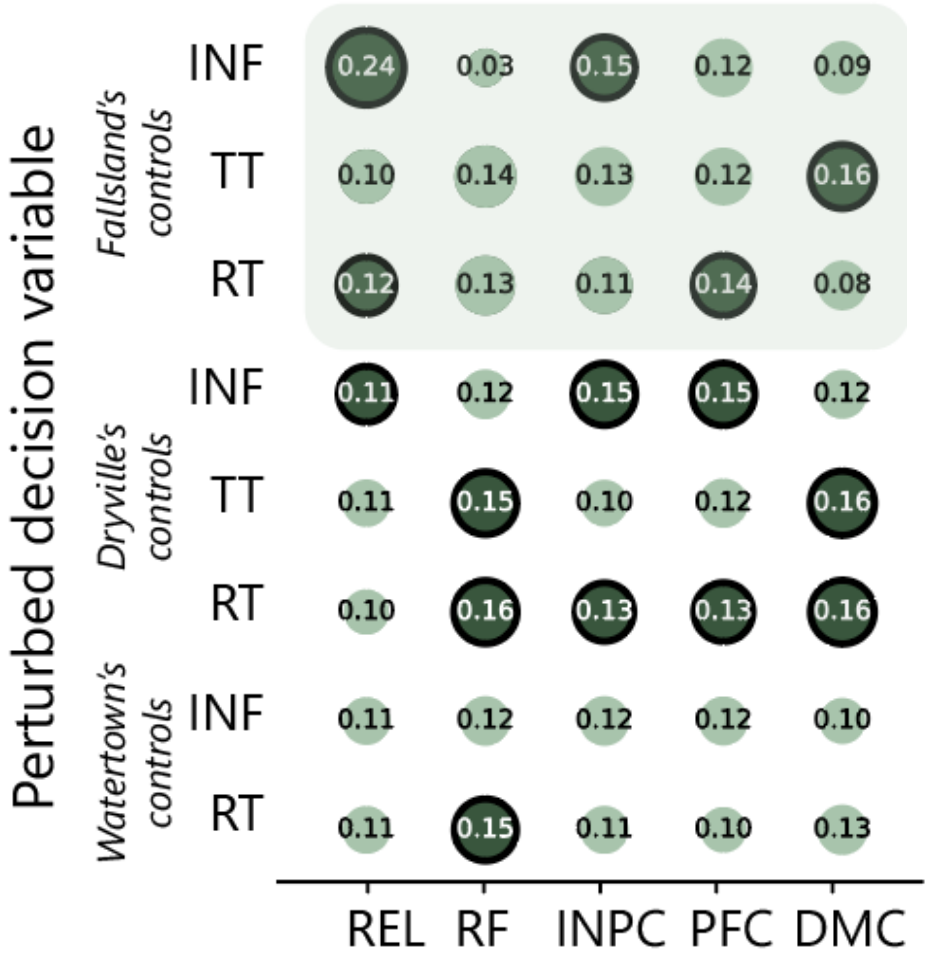
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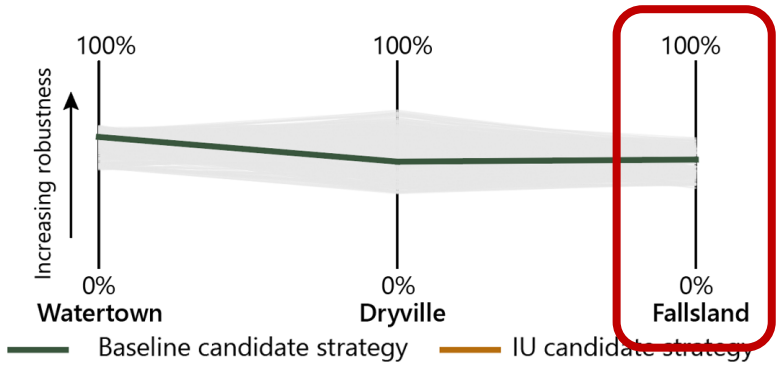


Region of control

Individual utilities' **baseline strategy** performance is **highly dependent on their partners' precise implementation** of cooperative actions

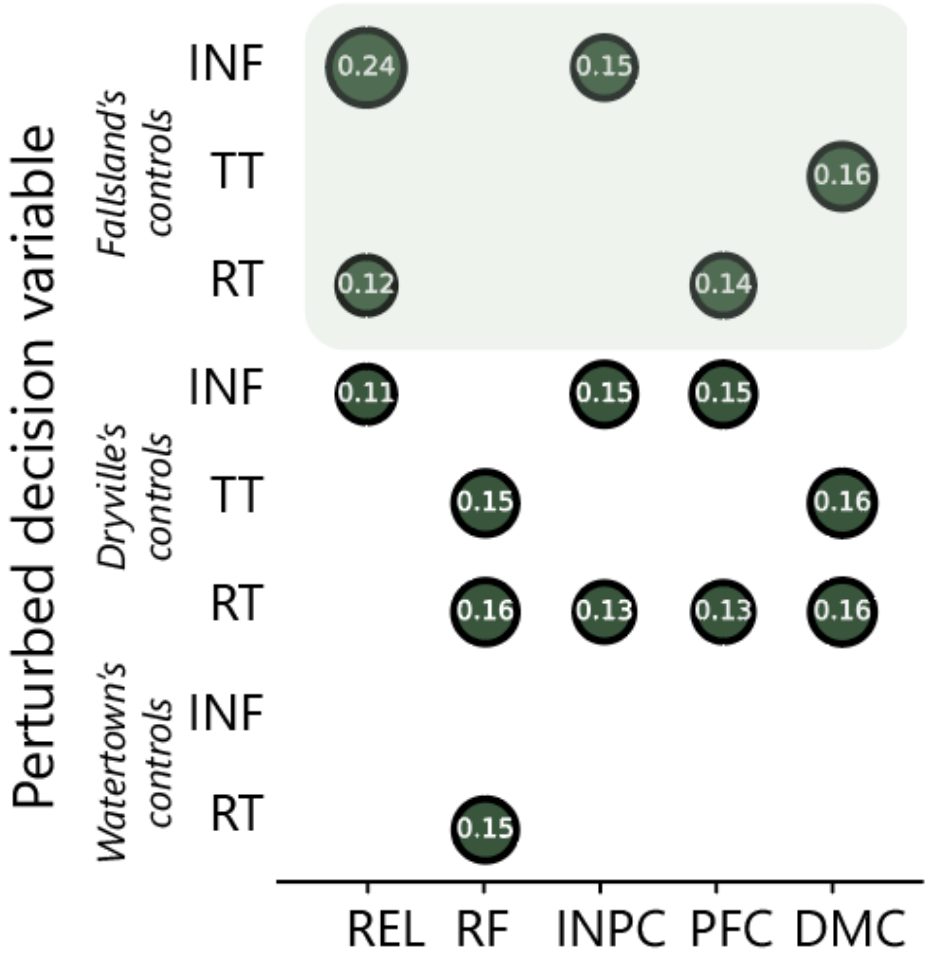
Fallsland

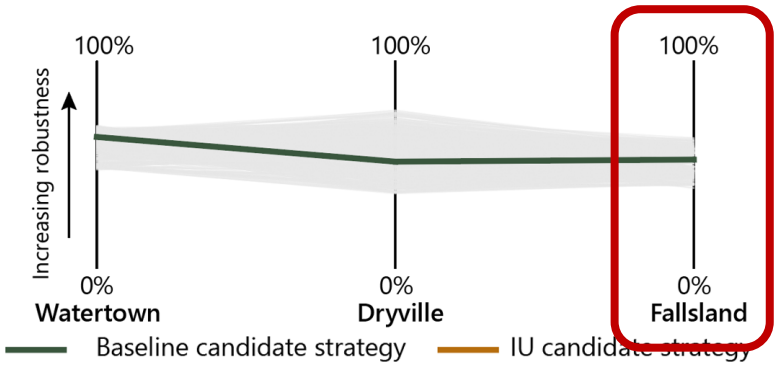




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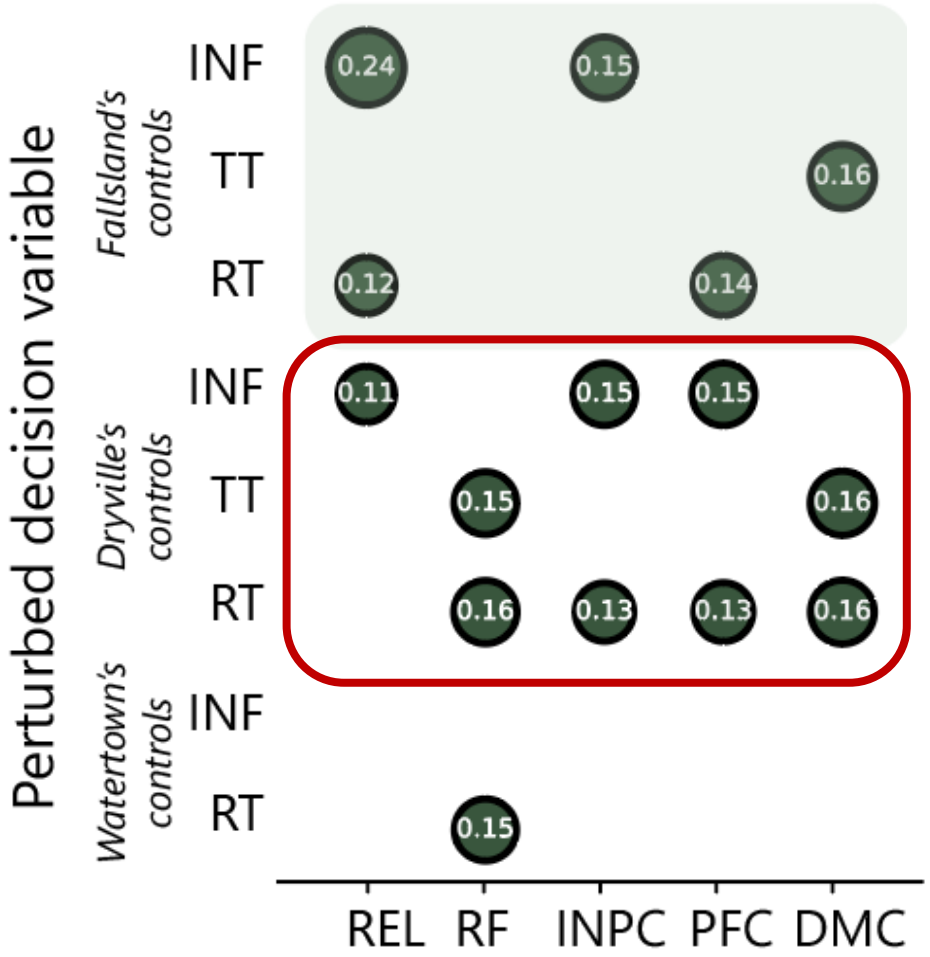
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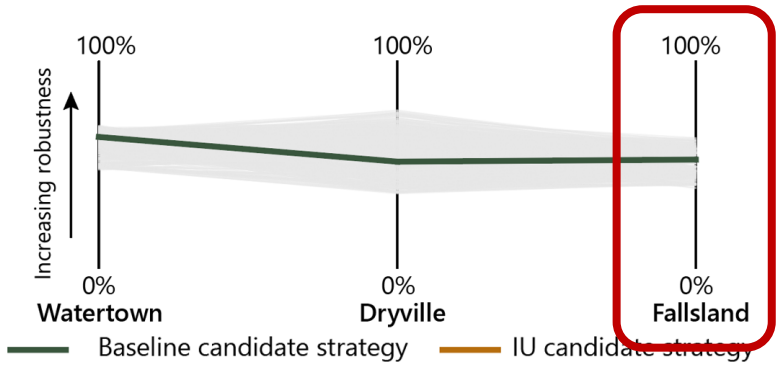


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Fallsland

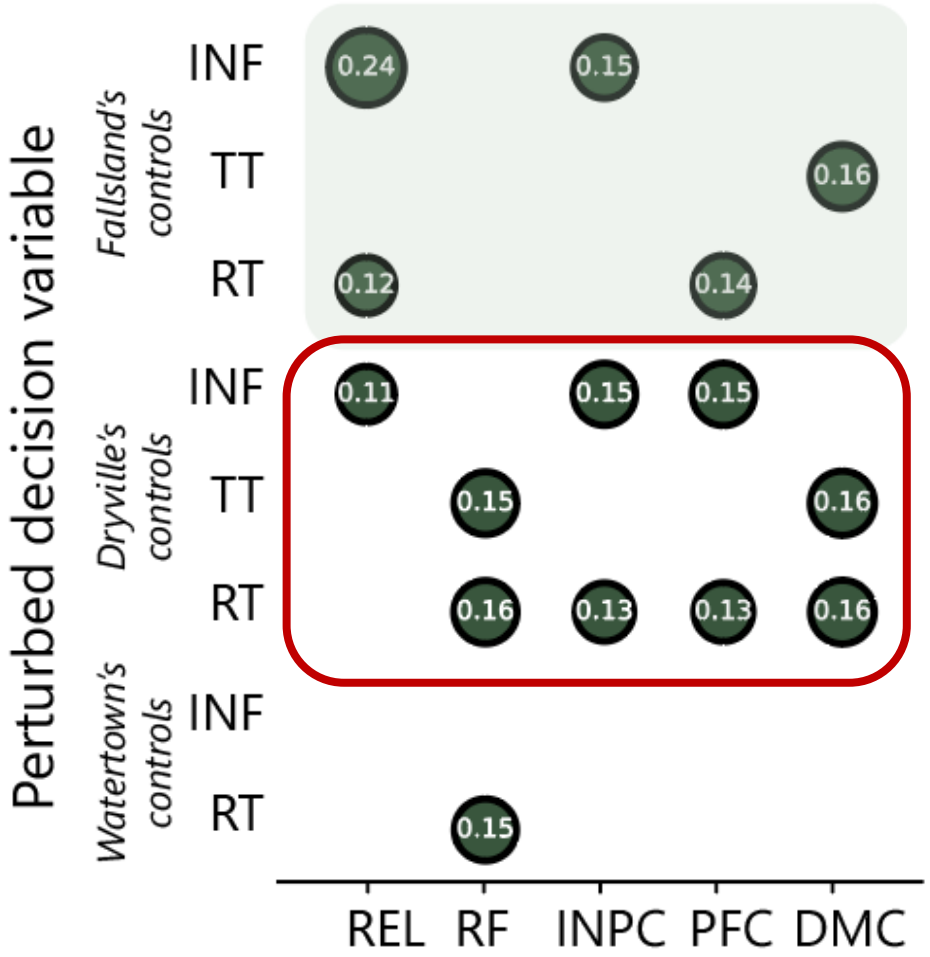


With the **smallest supply-to-demand ratio**, Fallsland is **most dependent** on its counterparts' precise implementation of cooperative actions

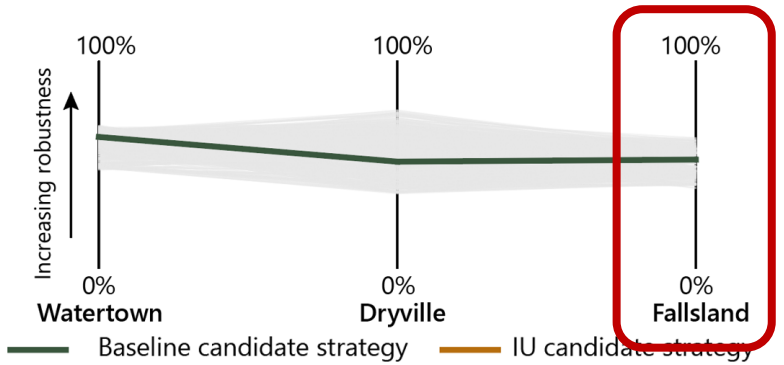


Individual utilities' **baseline strategy** performance is **highly dependent on their partners' precise implementation** of cooperative actions

Fallsland

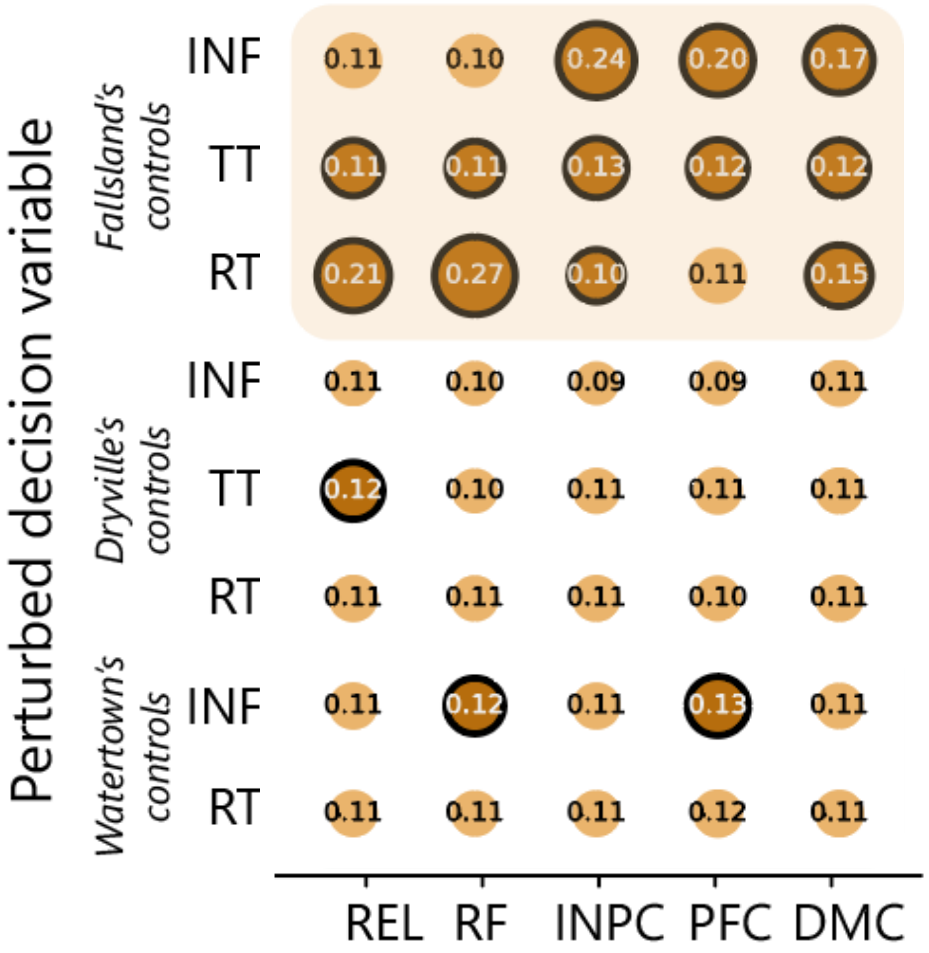


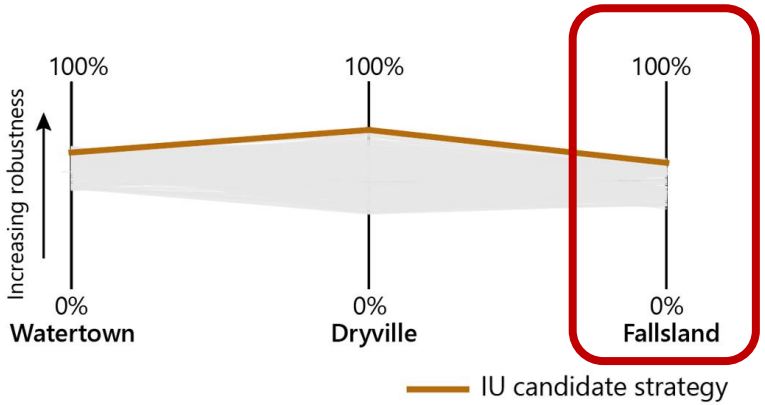
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The **IU strategy** affords utilities **better control** over their individual performance, **reducing vulnerability to implementation uncertainty**

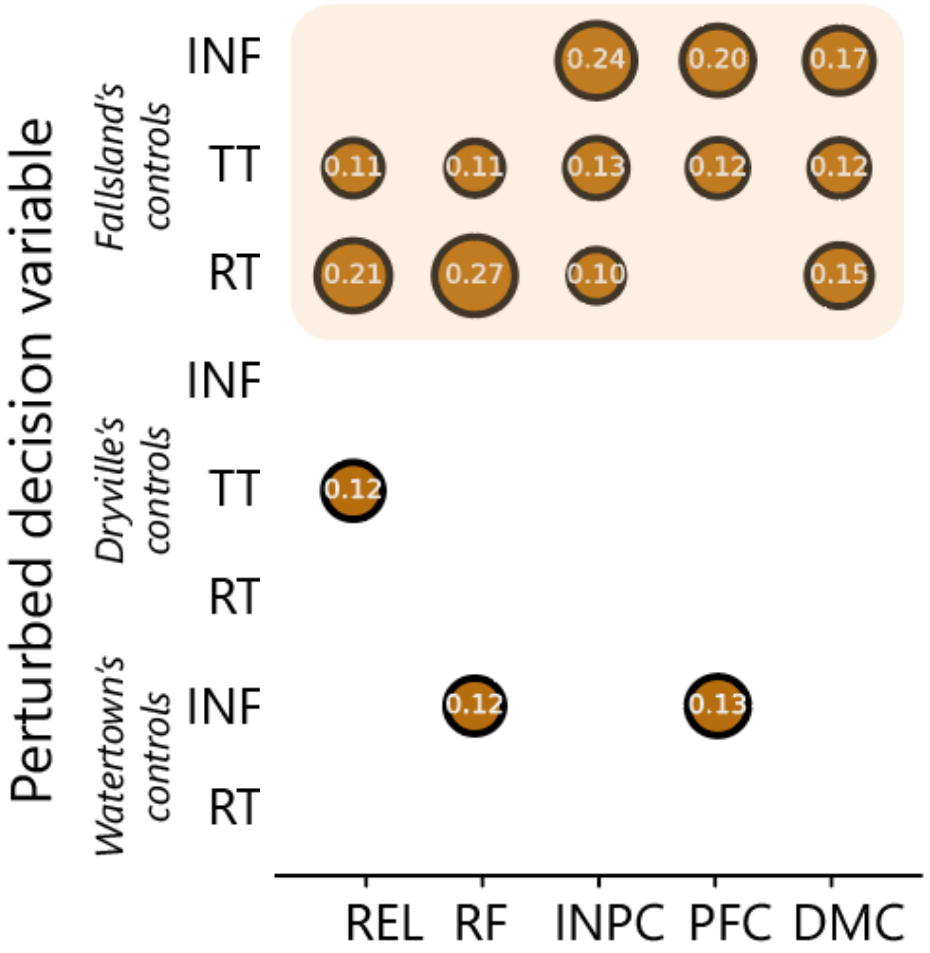
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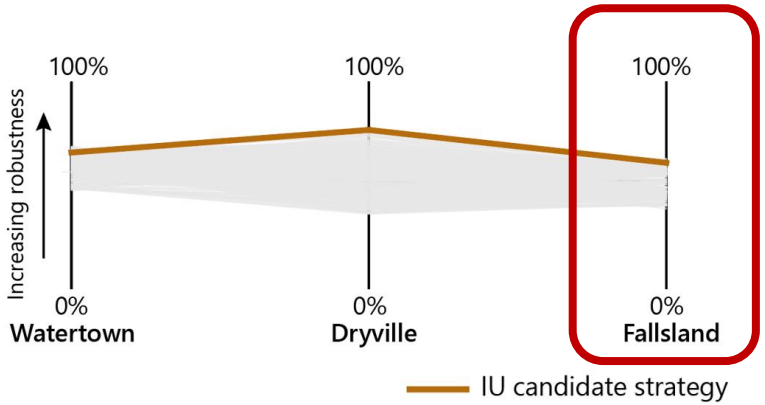




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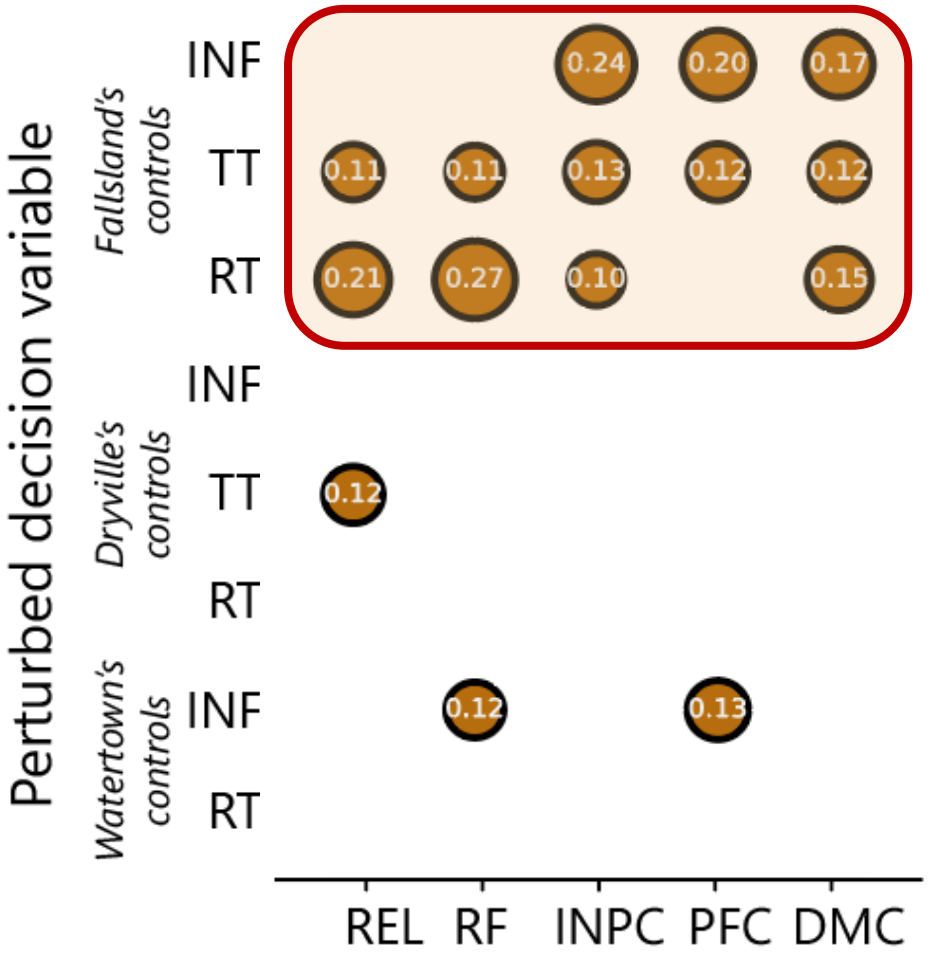
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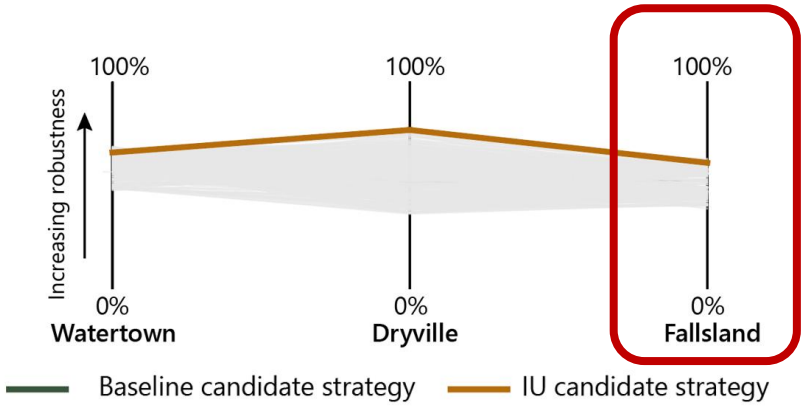


The **IU strategy** affords utilities **better control** over their individual performance, **reducing vulnerability to implementation uncertainty**

Fallsland



Fallsland **benefits both from regional cooperation and an improved ability to maintain high performance** when implementation uncertainty is considered



Back to Tour

Summary

Key Takeaways



DU Pathways (IU) facilitates the discovery of a **more diverse set of highly cooperative pathway strategies** that **generalize well** under both expected and challenging conditions



Such policies are also **more robust** and **maintain high performance under deviations** from the original strategy, affording utilities **more agency** over their decisions



This **improves transparency** into how human-driven **implementation uncertainty drives potential future conflicts**, facilitating acknowledgement and joint mitigation.

Thank you! Questions?



@lillianlau97



lbl59@cornell.edu



WaterProgramming Blog