Policy trees and threshold-based adaptation of water resources systems under climate change

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DMDU – Nov. 15, 2018

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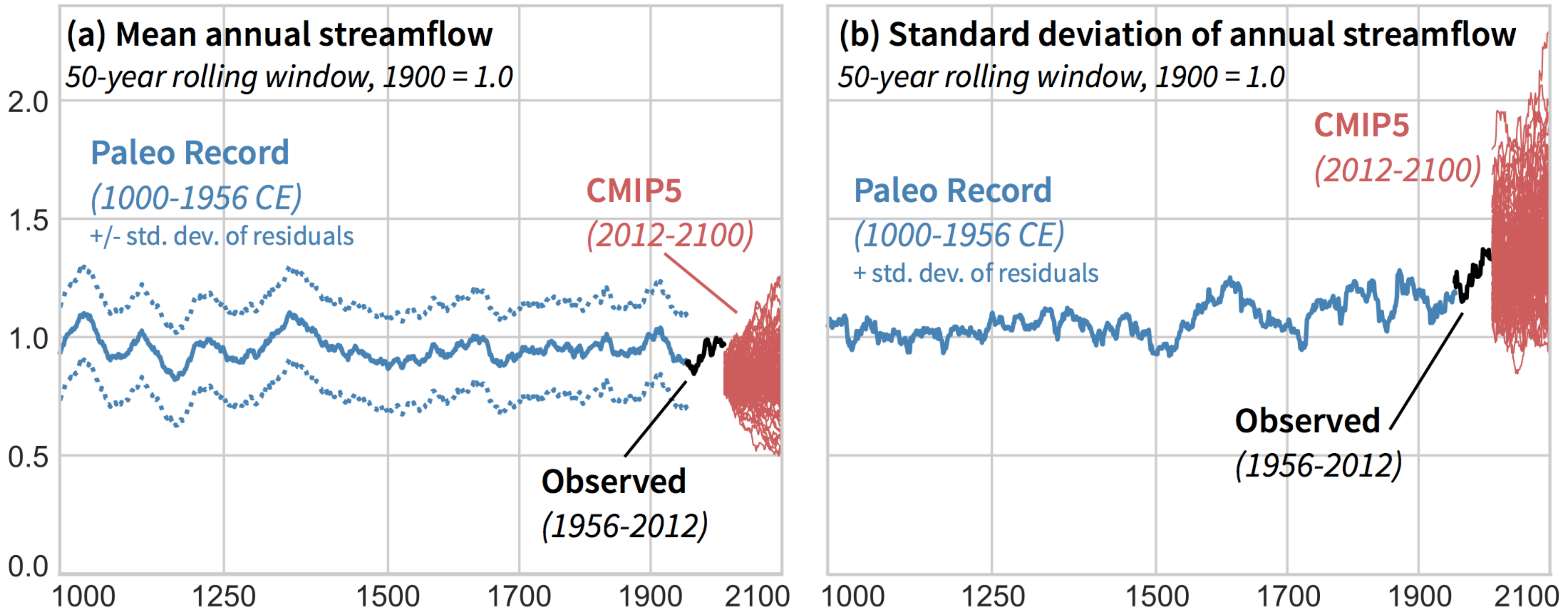
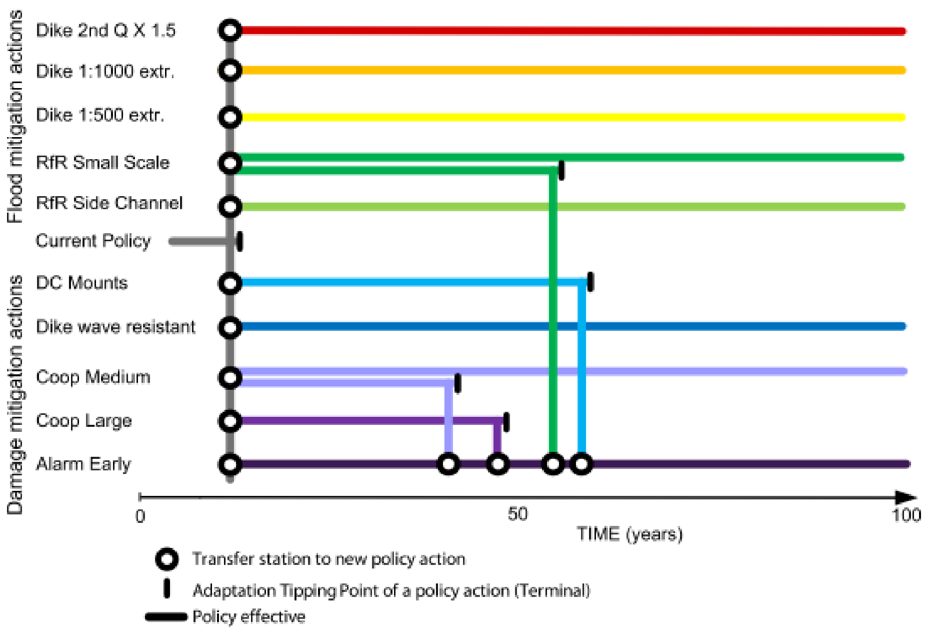
Uncertainty in water resources systems



Example: Sacramento River at Bend Bridge (California)

[Data sources: TreeFlow, USBR CMIP5 simulations]

Policies that respond to observed conditions: climate adaptation as a control problem



[Kwakkel et al. 2015]

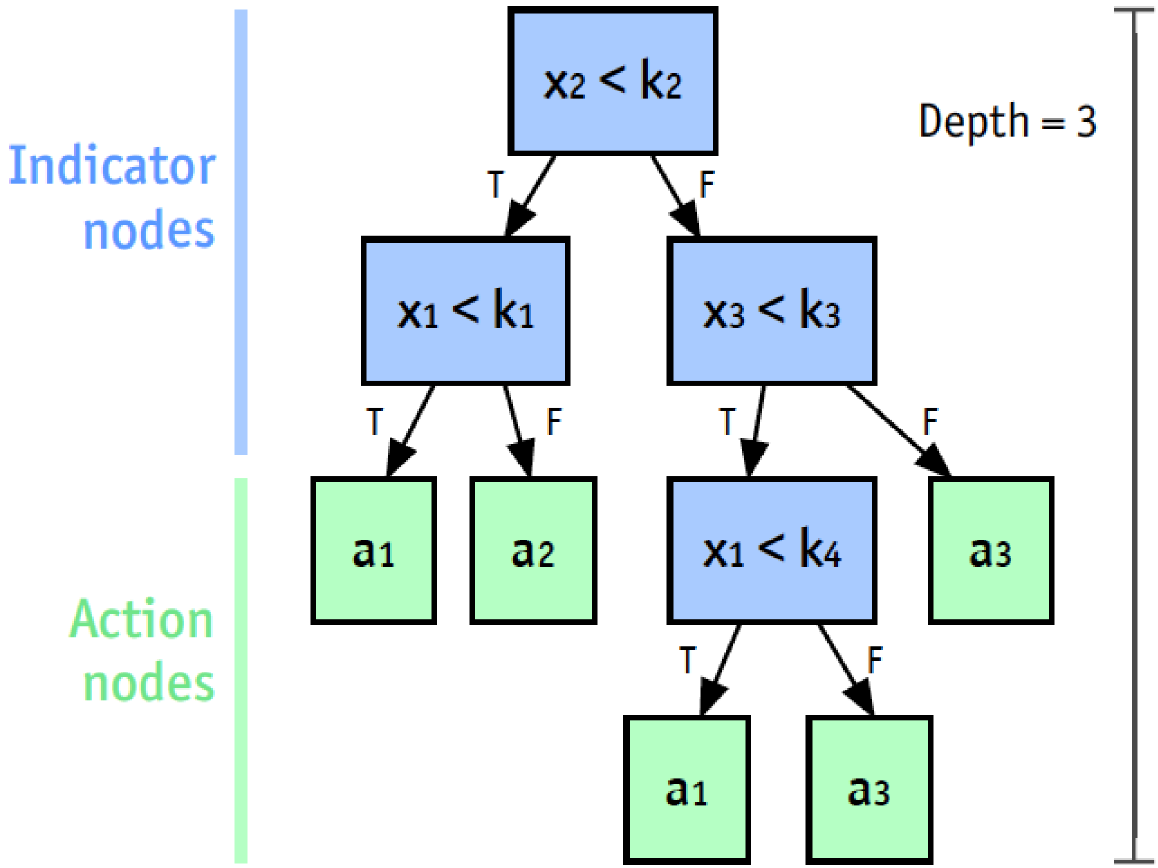
Discrete actions, continuous costs

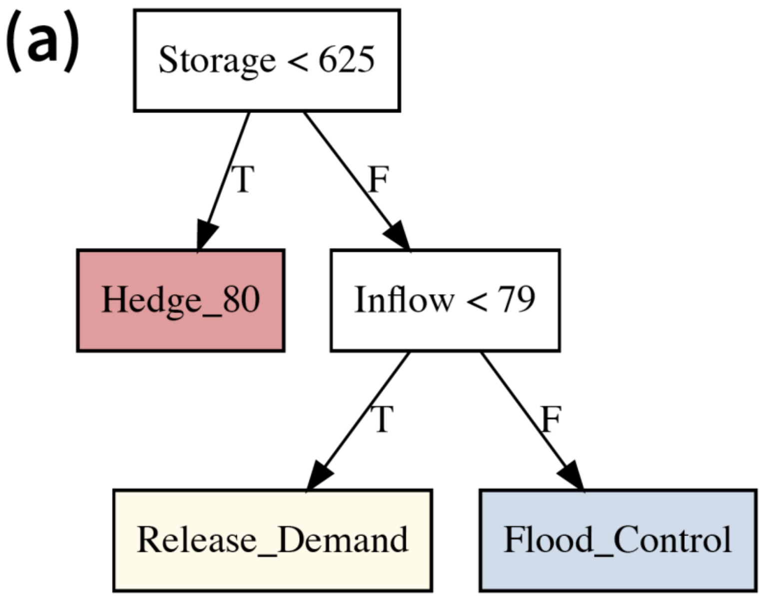
$$\min_{\pi} \mathbb{E}_{\mathbf{e}_t}\left[\sum_{t=0}^{N} J(\mathbf{x}_t, a_t) + J_{N+1}(\mathbf{x}_{N+1})\right]$$

$$\text{subject to: } \mathbf{x}_{t+1} = f(\mathbf{x}_t, a_t, \mathrm{e}_{t+1}), \; a_t = \pi(\tau_t)$$

- The policy is a function mapping observations to actions

How to structure a policy?
One idea: a tree mapping observations (**x**) to actions (**a**) based on the values of thresholds (**k**)

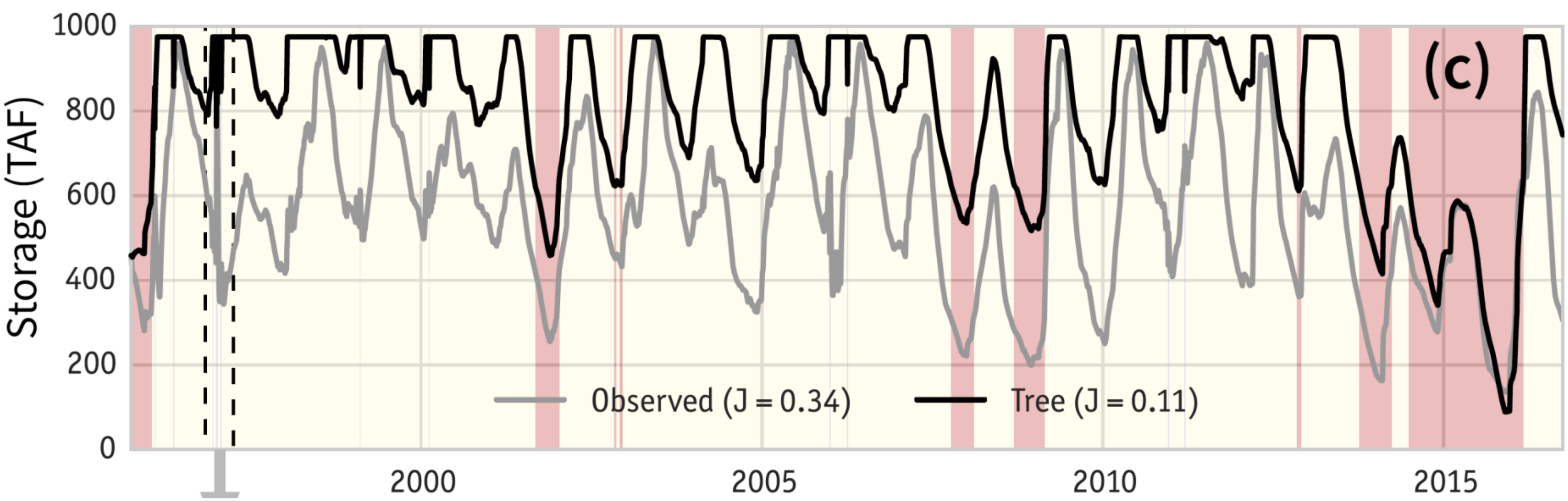




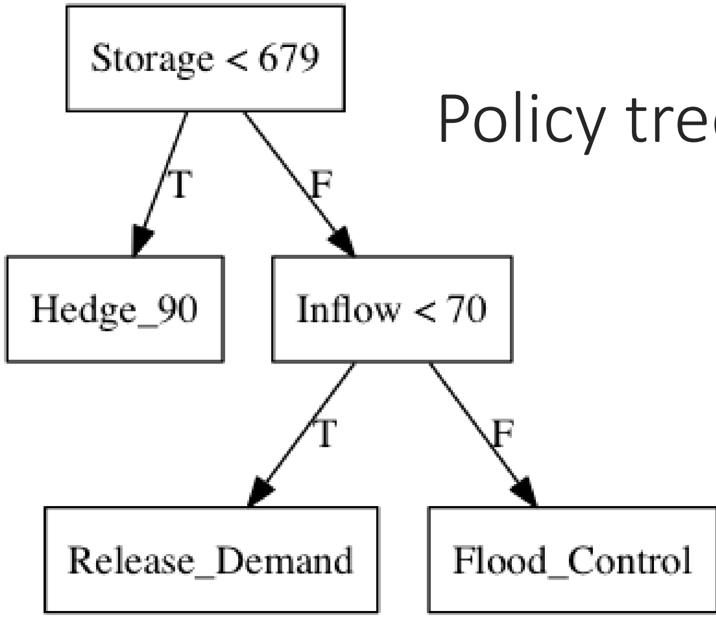
Example: short-term control rules for reservoir operations in California

[*Herman and Giuliani, 2018*]

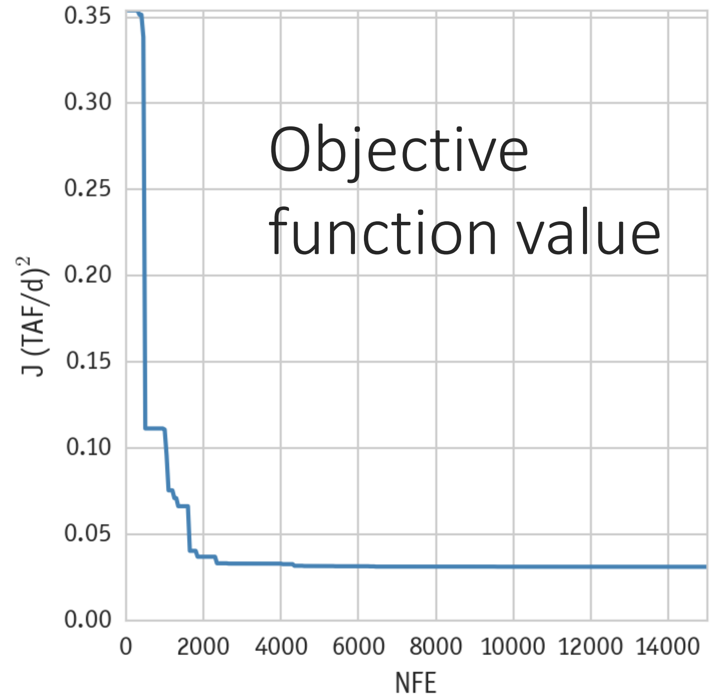
jdherman/ptreeopt



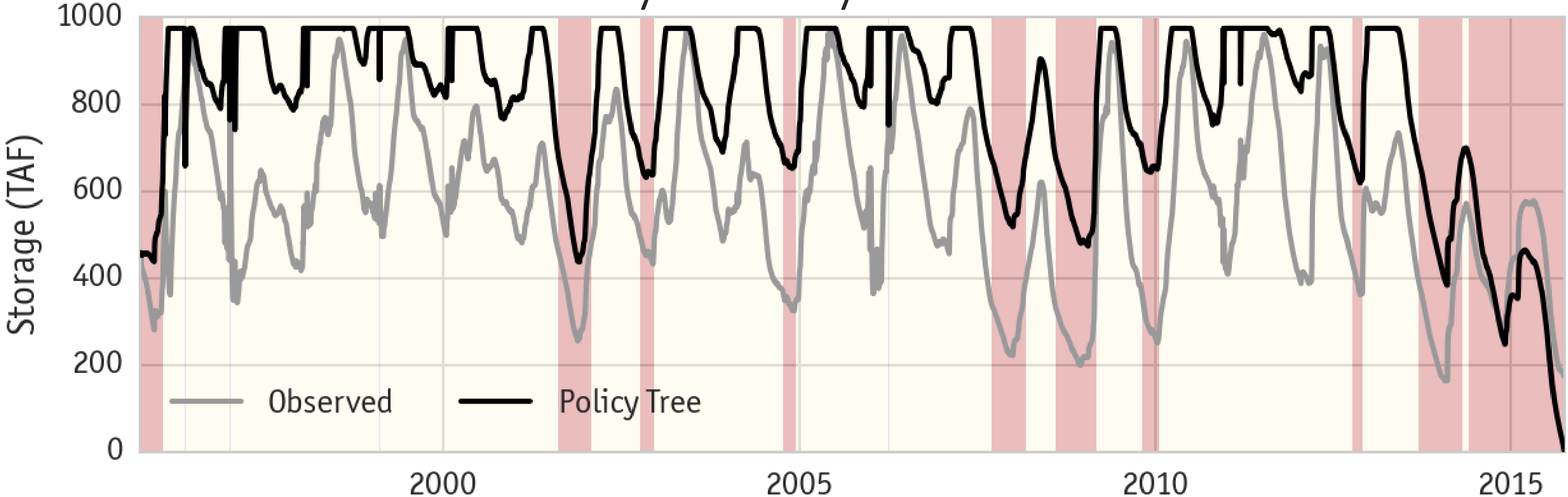
Policy tree



Objective function value



System dynamics



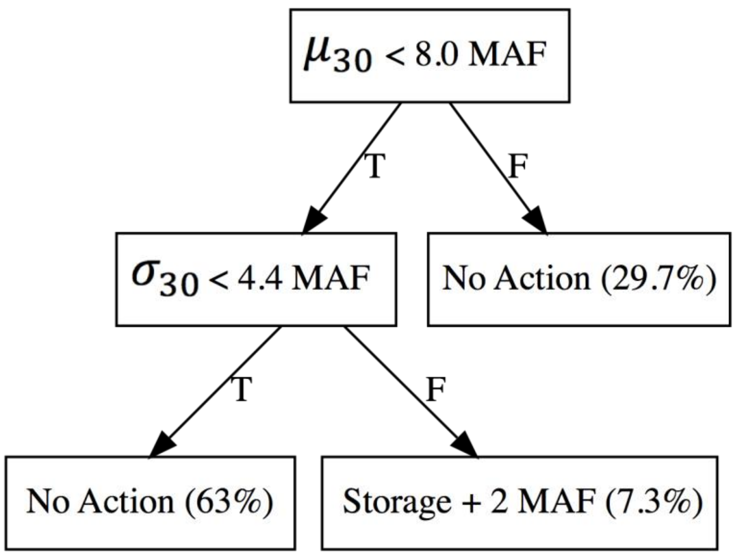
Can trees be used to represent long-term adaptation policies? An illustrative case study

- Sacramento River CMIP5 projection ensemble, annual timestep 2000-2100
- One reservoir with fixed annual water demand
- ***Indicators:*** 30-year mean and std. deviation of reservoir inflow (μ_{30}, σ_{30})
- ***Actions:*** Do nothing, or increase reservoir storage by a set amount ΔS
- ***Objective function:*** Minimize NPC (water shortage plus construction costs)

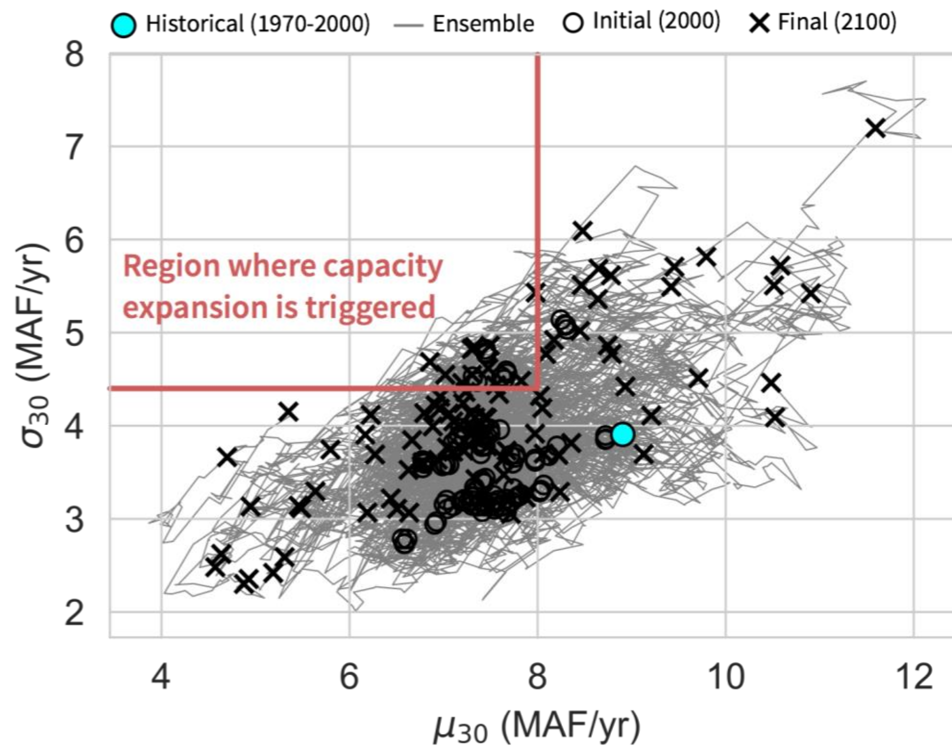
Illustrative case study: policy result optimized to the ensemble mean NPC

(a) Policy tree with minimum NPC

(50,000 NFE, 30 random seeds)



(c) Indicator variable space



- It works! But, raises some other questions…

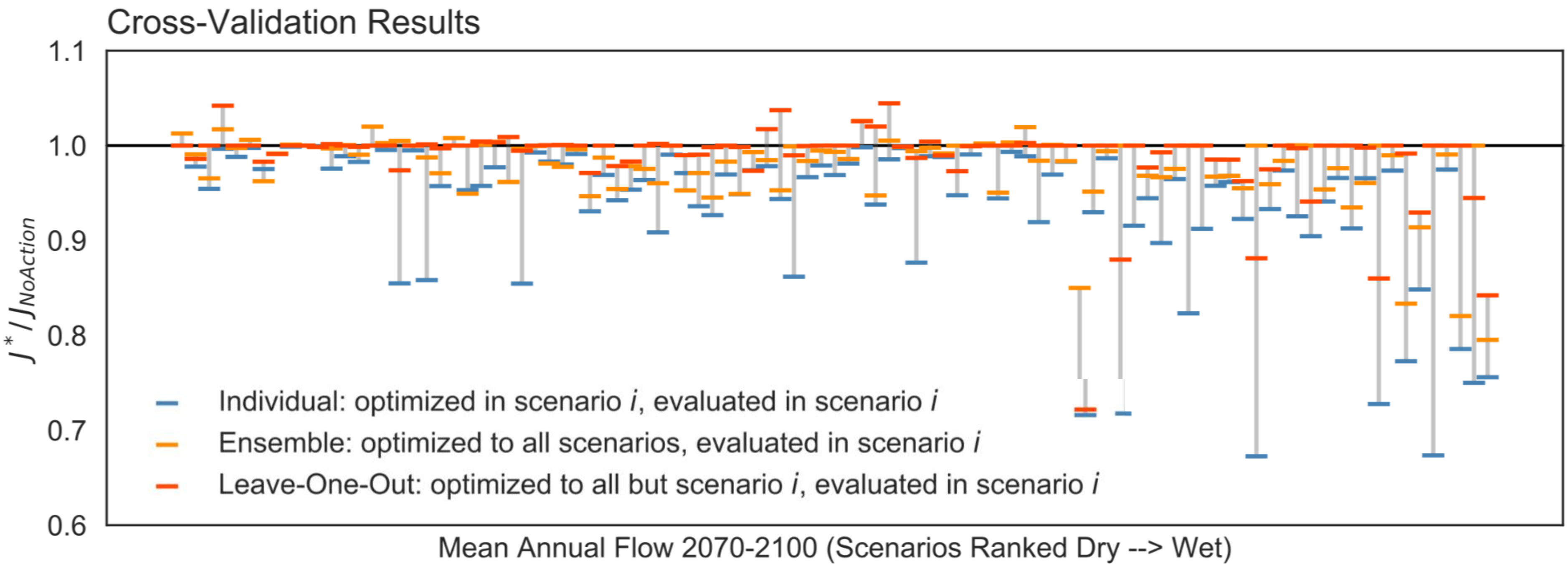
Questions/challenges with optimized policies

① Cross-validation: how well does the policy perform in scenarios it hasn't seen before?

② Irreversible actions: how well can we classify vulnerable scenarios in advance?

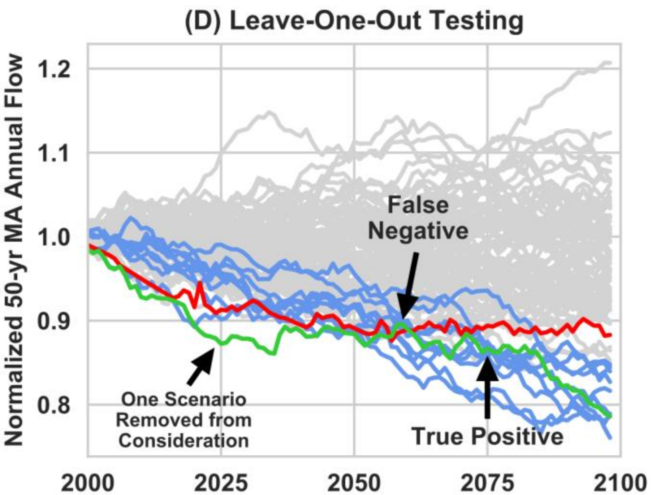
③ Input variable selection: what other indicators would be informative?

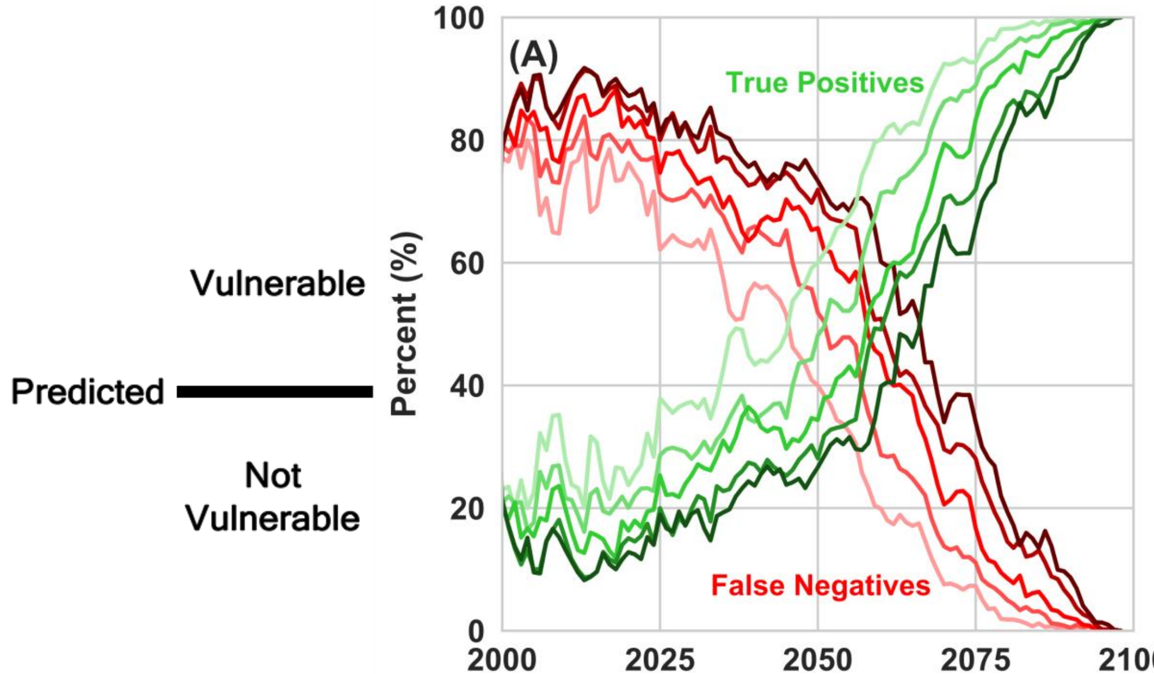
(1) Cross-validation (example)



- In this case, leave-one-out costs are equal or greater in most scenarios than the "do nothing" policy

(2) Vulnerability classifications and irreversible infrastructure decisions *[Robinson and Herman, in review]*





- Predict a “not vulnerable” scenario when it should be: will incur costs by waiting too long to adapt
- Predict a “vulnerable” scenario when it should not be: will over-invest in adaptation measures

(3) Input variable selection: what other long-term observations could be informative?

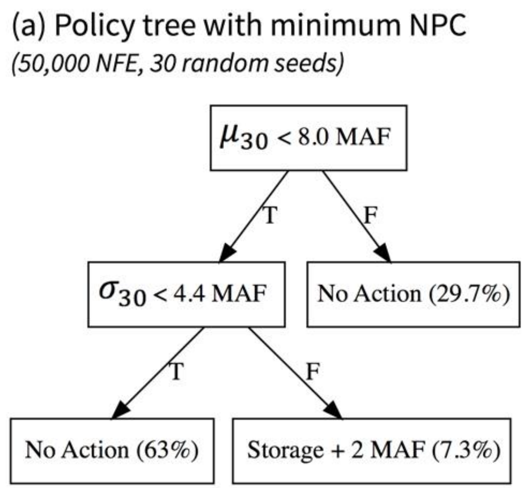
- **Variables:** temperature, precipitation, land use
- **Timescales and quantiles:** e.g. daily 99% flow (floods), or annual average flow (water supply)
- **Aggregation windows:** 5-yr, 10-yr, 30-yr (tradeoff between adapting quickly vs. correctly)
- **Lead time:** could CMIP5 scenarios serve as a long-term "forecast" input to the policy?

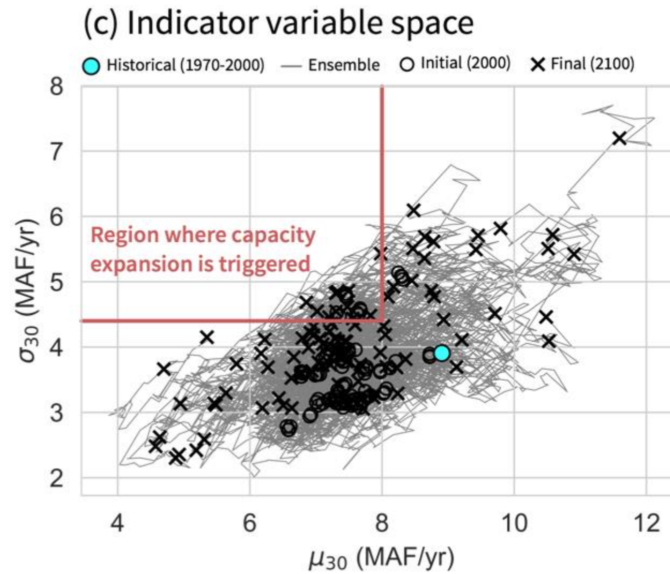
General strategy: run optimization with many of these (ideally not too correlated) and see how costs improve

Key points

1. We can optimize threshold-based adaptation policies structured as binary trees
2. All such policies (tree or not) would benefit from cross-validation against other scenarios
3. Open-source tool available; many interesting and challenging research questions remain.

Thanks!





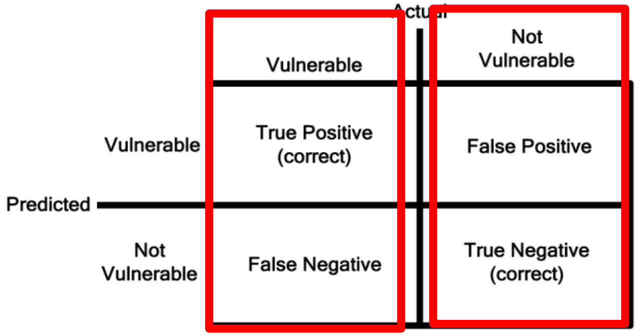
References

Robinson and Herman, Testing threshold-based identification of future water supply vulnerabilities in the Western U.S., in review.

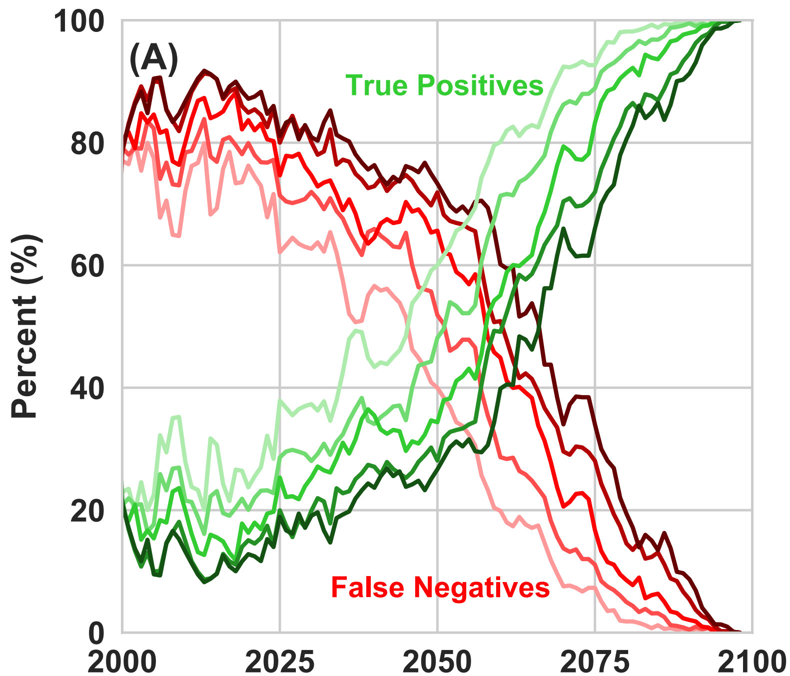
Herman and Giuliani (2018) Policy tree optimization for adaptive management of water resources systems. Environmental Modelling & Software, 99.

Zeff et al. (2016) Cooperative drought adaptation: Integrating infrastructure development, conservation, and water transfers into adaptive policy pathways. WRR.

Herman et al. (2015) How should robustness be defined for water systems planning under change? JWRPM.

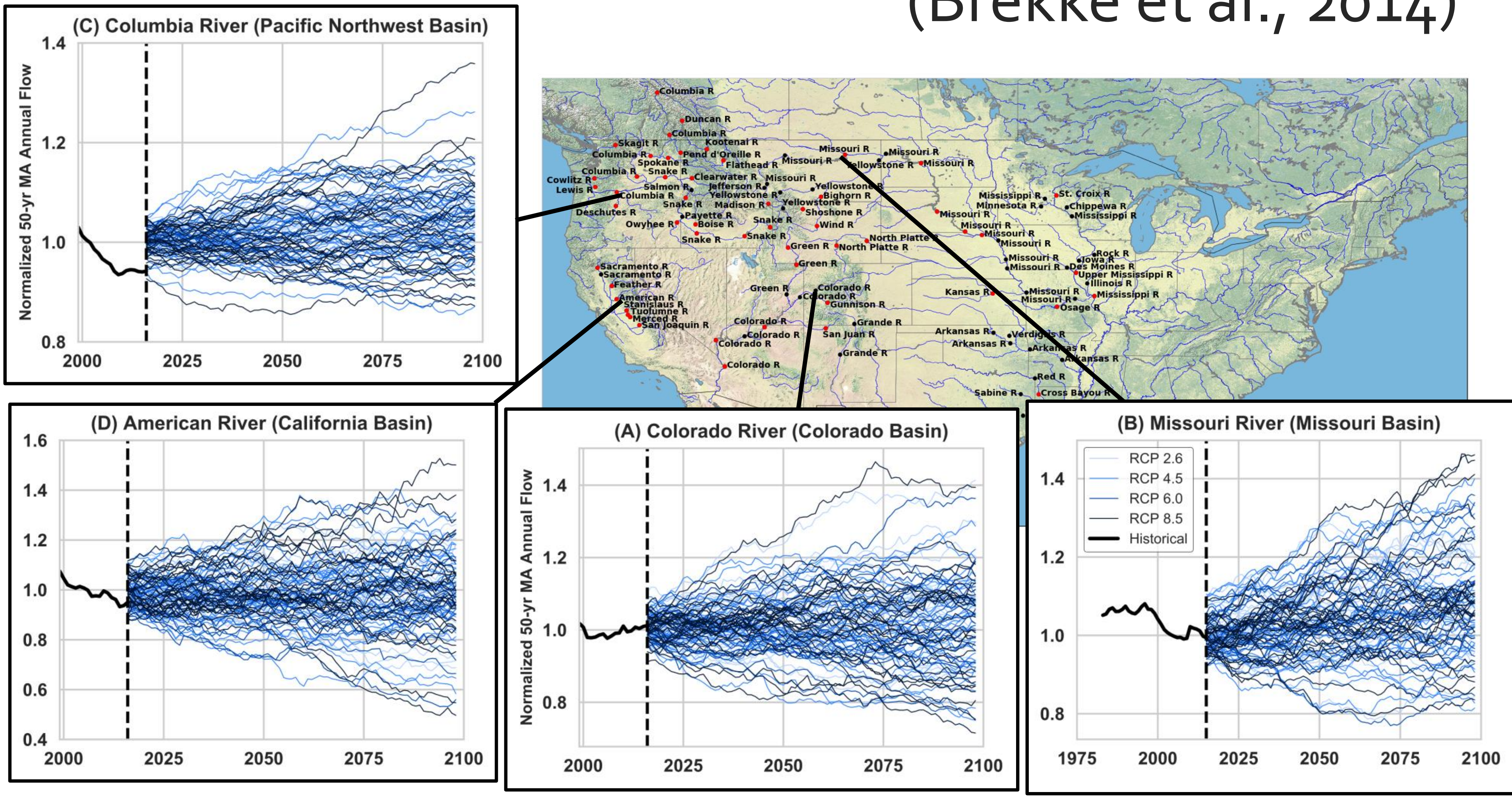


Classification error rates decrease over time



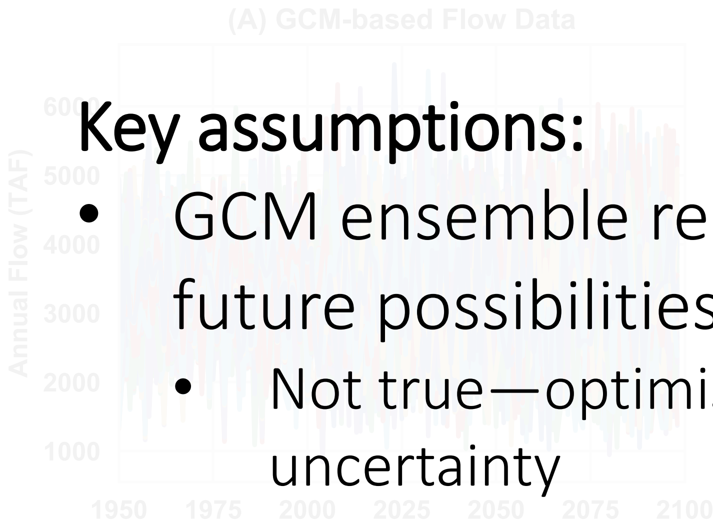
- FP% generally low; FN% remains high until much later
- Model agreement controls FP-FN tradeoff

GCM reservoir inflow projections through 2100 (Brekke et al., 2014)



50-year moving average (1950-2000 = 1.0)

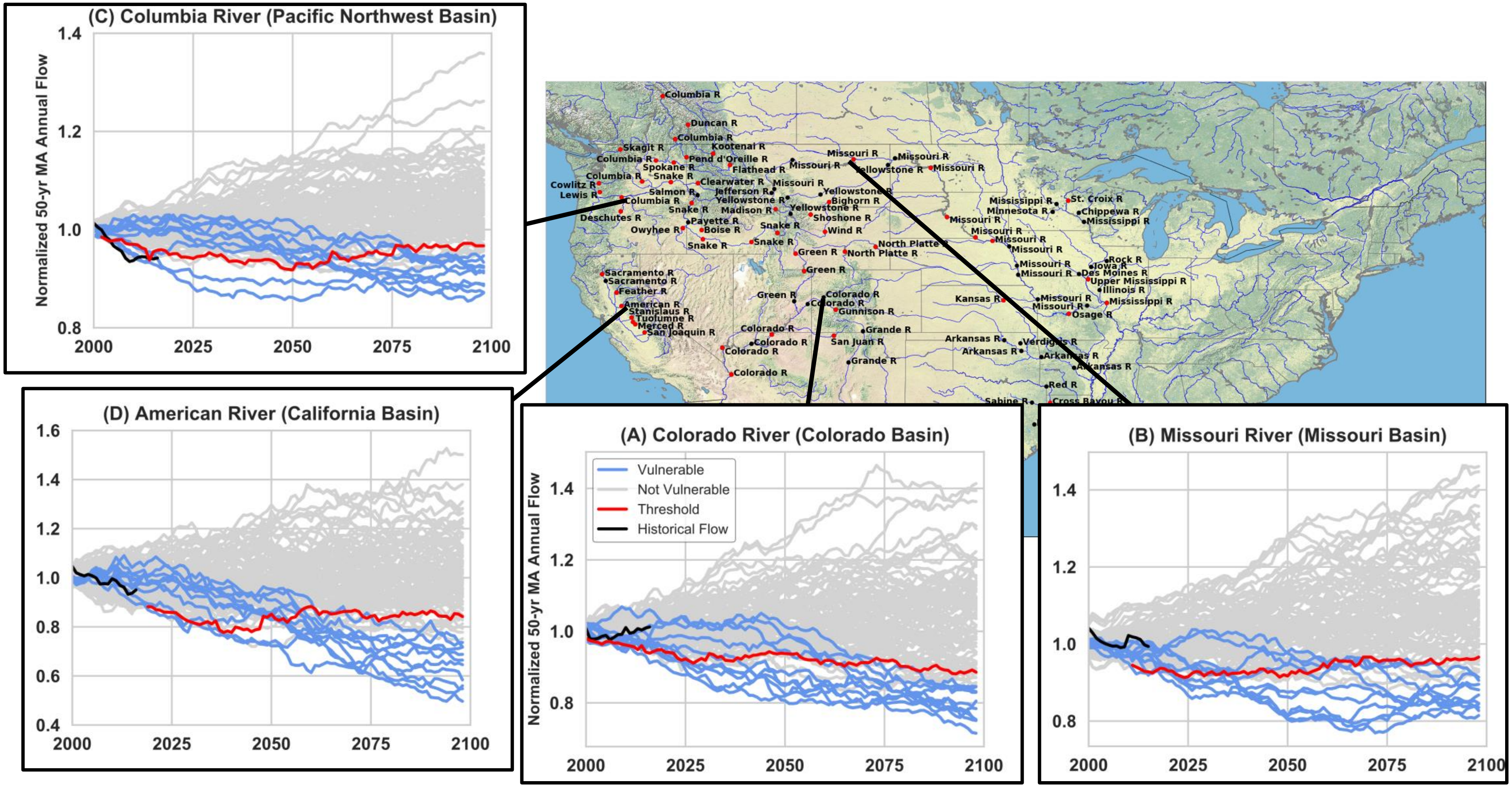
Experiment design: focus on decrease in μ_Q



Key assumptions:

- GCM ensemble represents full range of future possibilities
  - Not true—optimistic lower-bound uncertainty
- Only concerned with average annual flow
  - Could use variance, drought frequency, flood risk, sea level rise (etc.)
- Vulnerable scenarios are the lowest 10% of average flows—illustrative case study

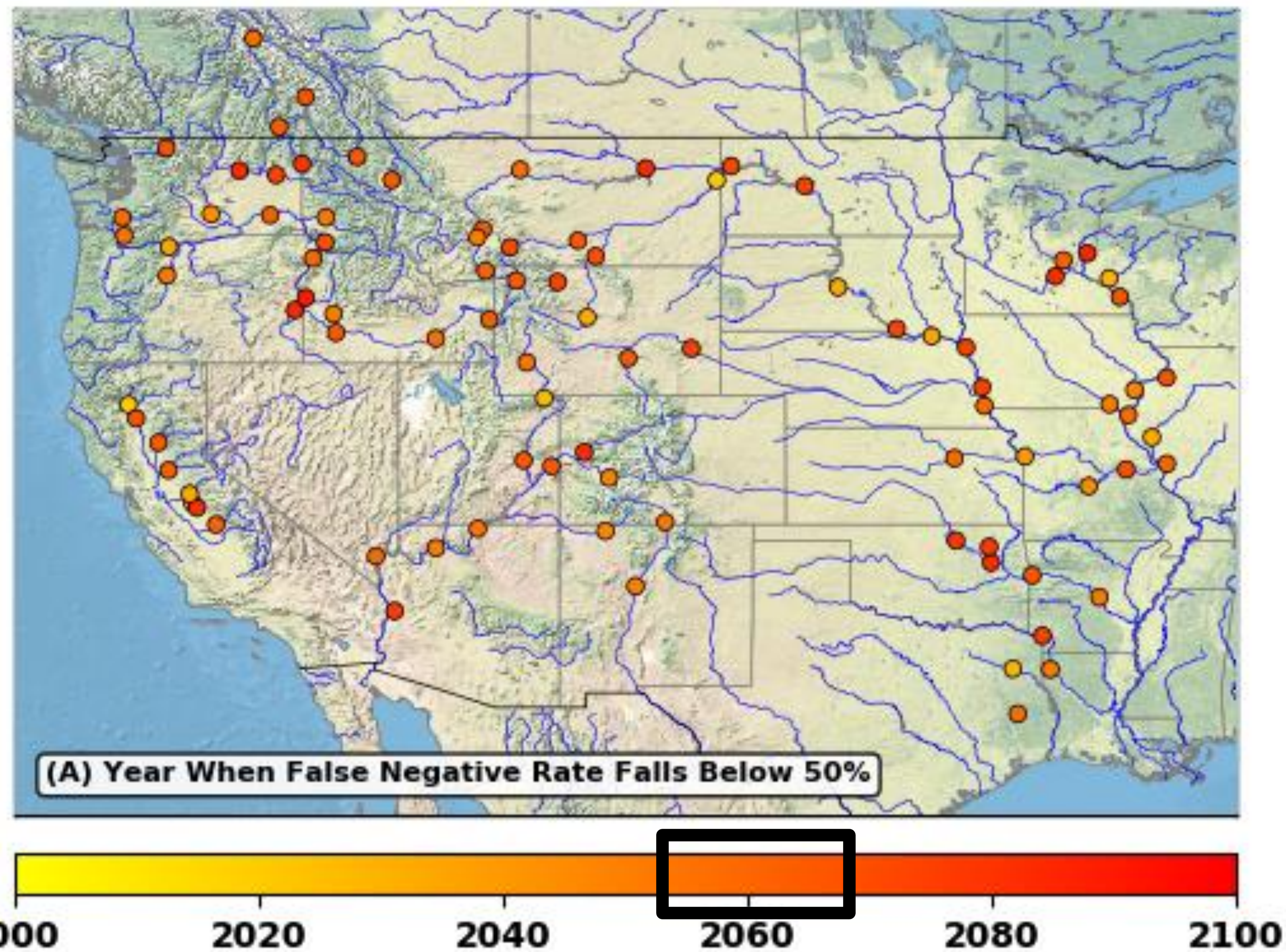
Dynamic thresholds for selected rivers



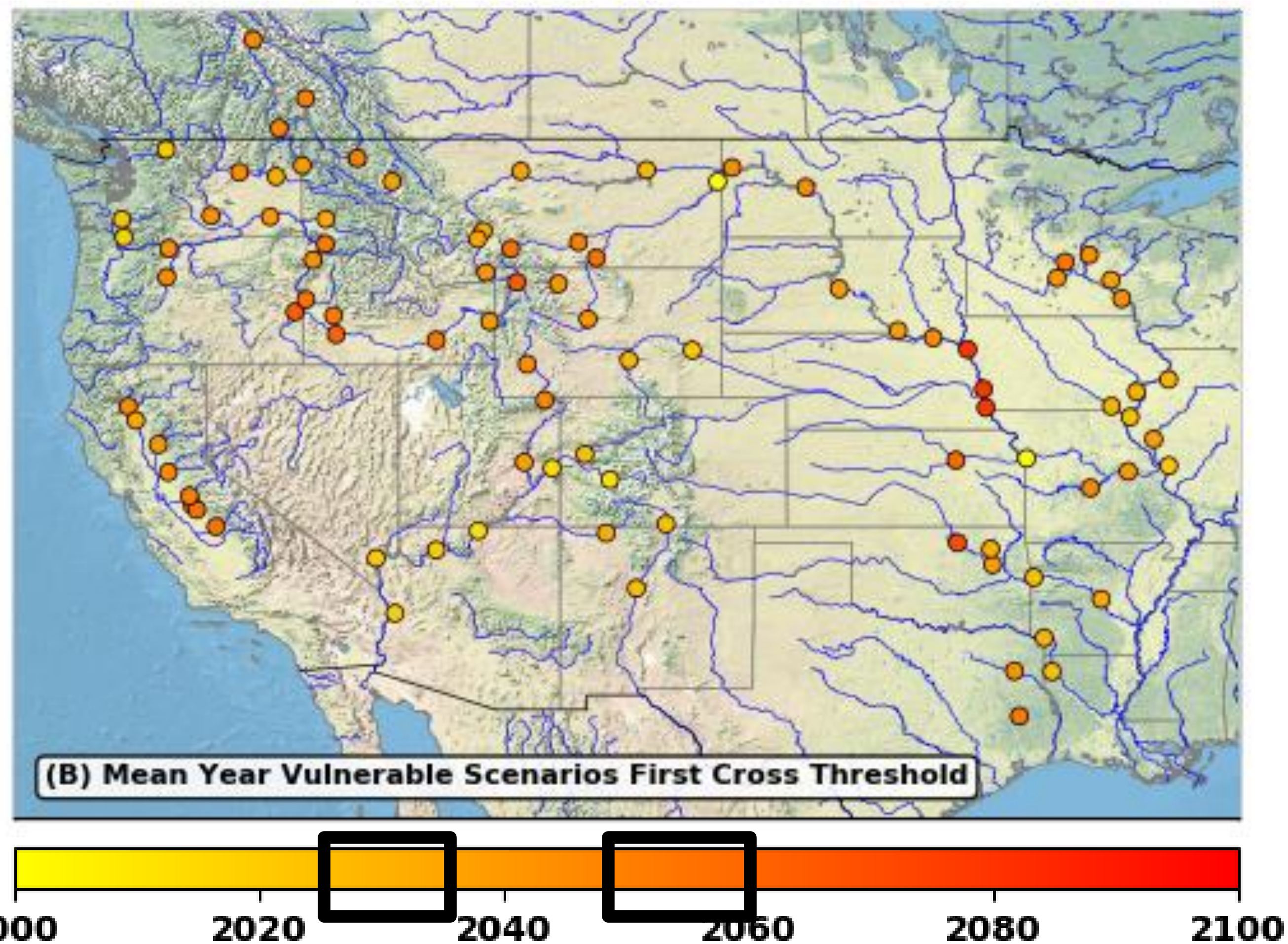
Thresholds represent if-then rules (observation → action)

Year when false negative rate falls below 50%

(i.e., when a negative classification becomes better than random)



Average year when "vulnerable" scenarios are first identified (basin-specific patterns)



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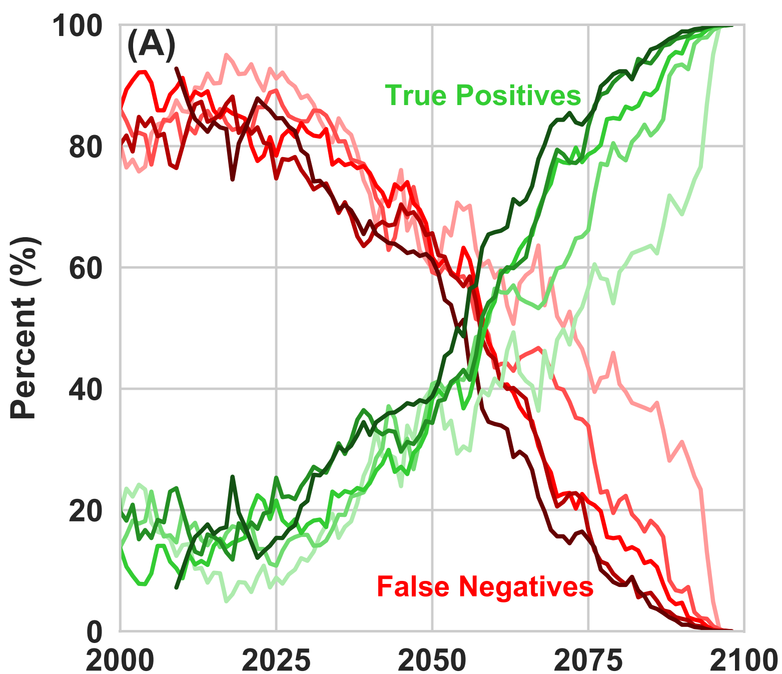
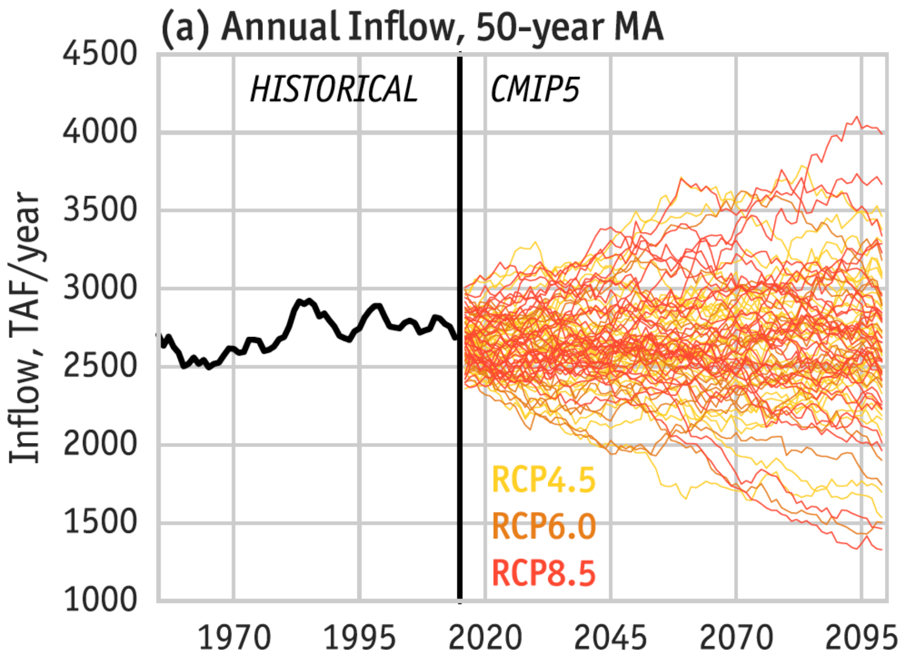
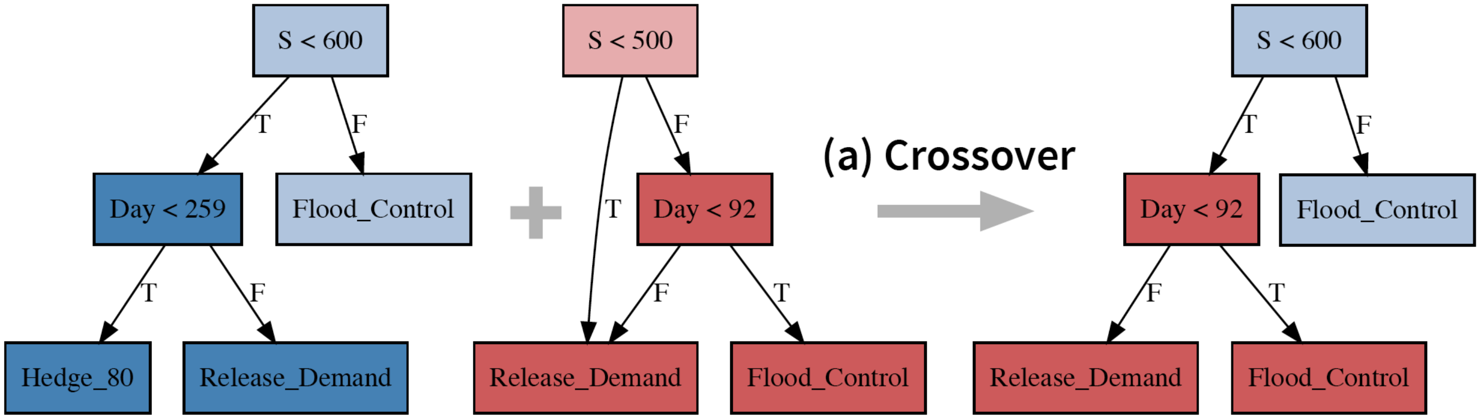
Sensitivity of results to moving window length

Predicted \ Actual	Vulnerable	Not Vulnerable
Vulnerable	True Positive (correct)	False Positive
Not Vulnerable	False Negative	True Negative (correct)



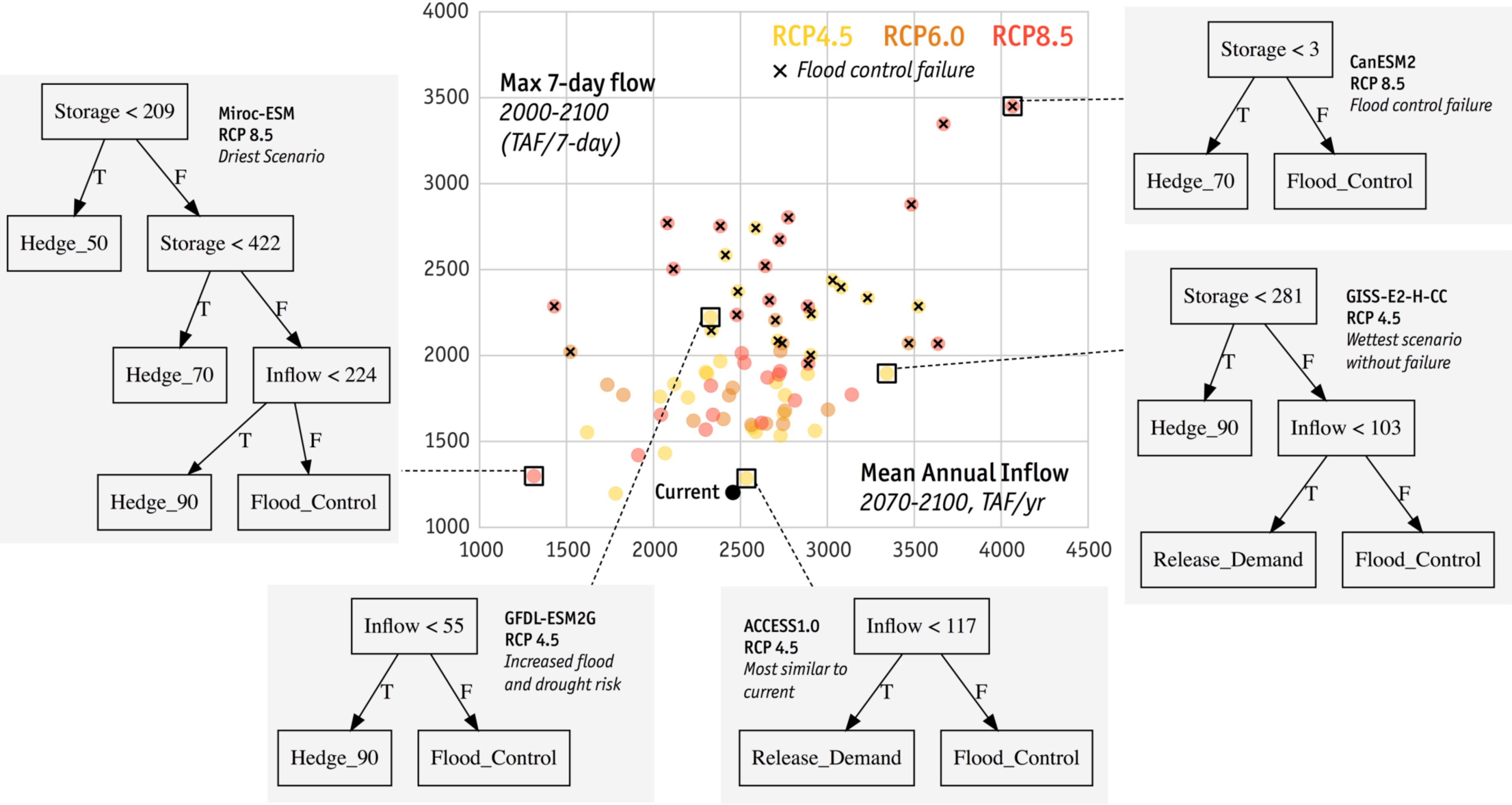
- Short moving window: respond quickly to changes
- Long moving window: wait-and-see, lower error rates


(a) Annual Inflow, 50-year MA
Inflow, TAF/year
4500
4000
3500
3000
2500
2000
1500
1000
HISTORICAL
CMIP5
RCP4.5
RCP6.0
RCP8.5
1970
1995
2020
2045
2070
2095



Genetic programming customized for binary trees

(2) Policies trained on CMIP5 scenarios



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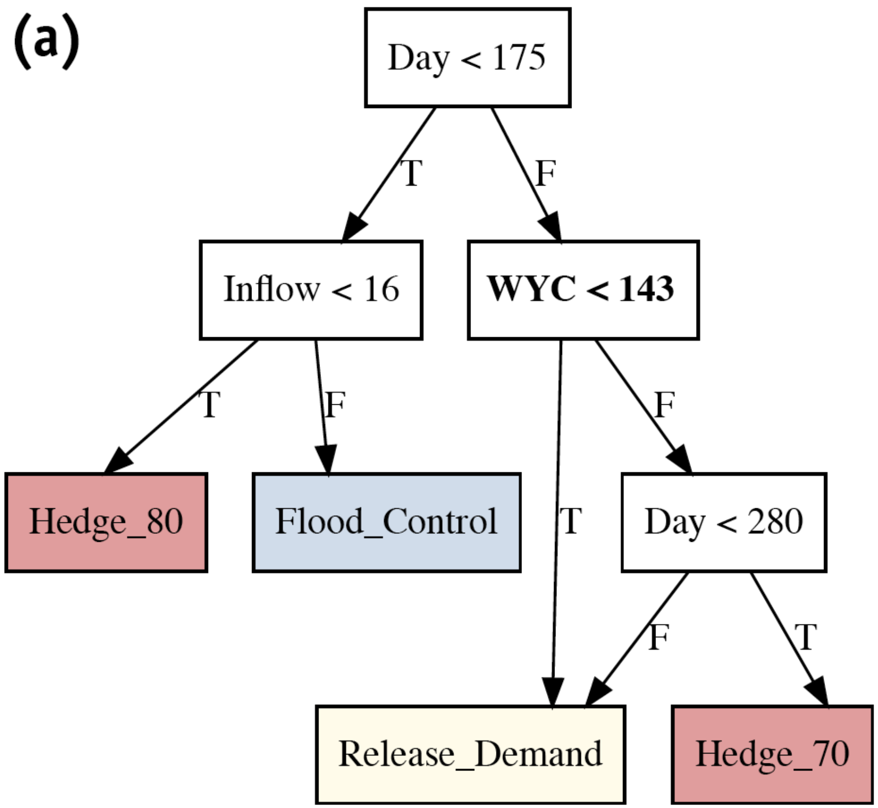
(3) Policy trained on all CMIP5 scenarios



Long-term indicator variables: MA Inflow, flood risk, WY centroid

Problem: Validation