

# Synthetic ensemble forecasting: Background, verification, and performance against extremes

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(CWEMF) Annual Meeting 2026

**Acknowledgements:** Rob Hartman, Brett Whitin, Jon Herman, Chris Delaney, Will Taylor

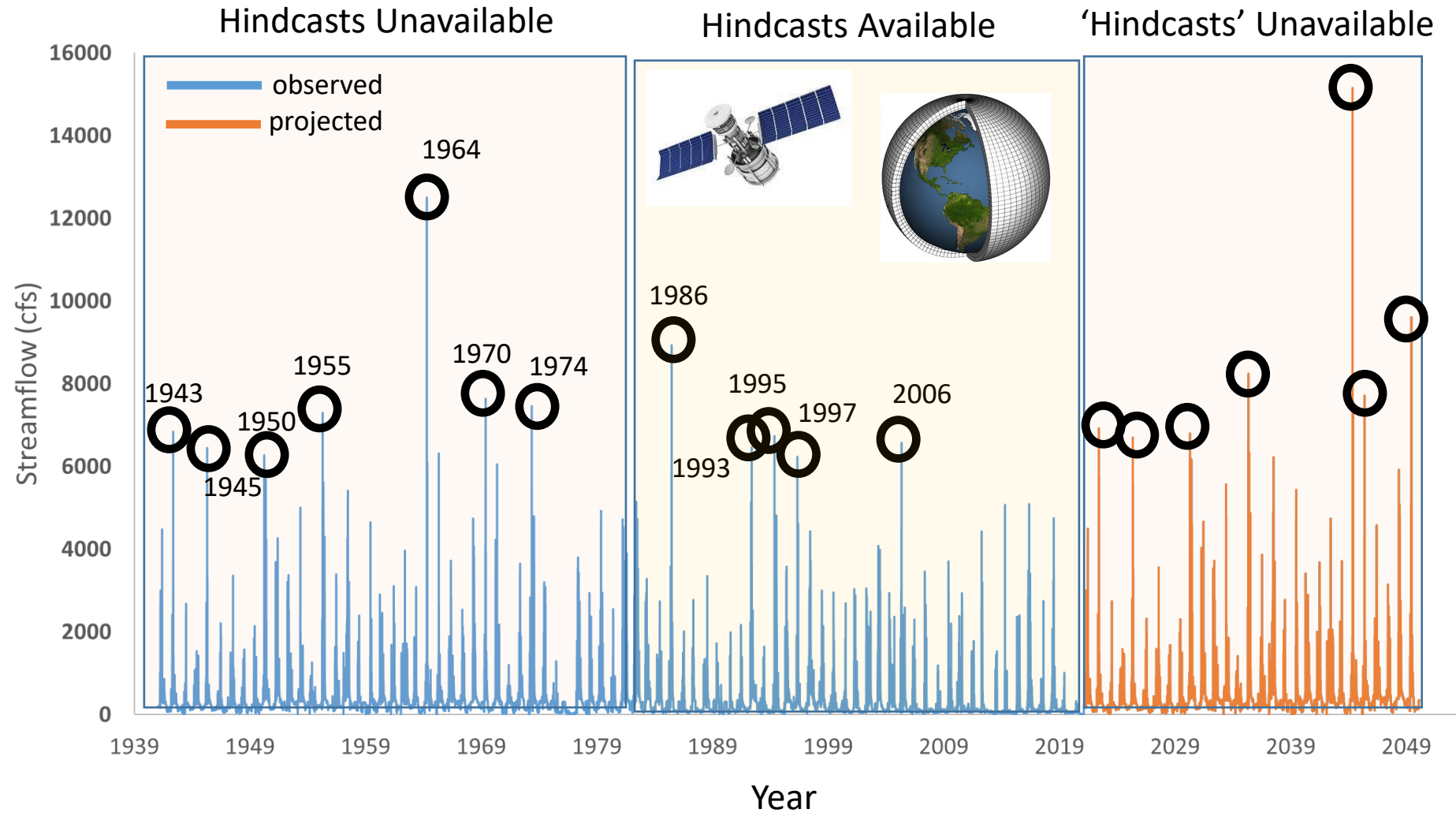


Sonoma  
Water

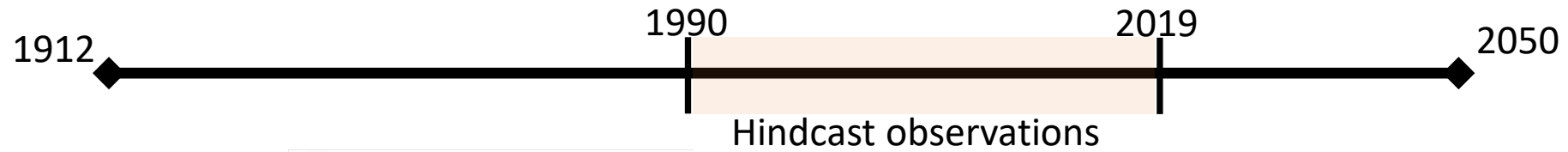


# Background

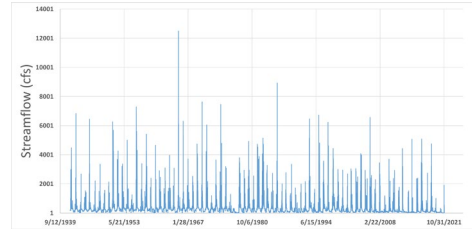
# Hindcast challenges



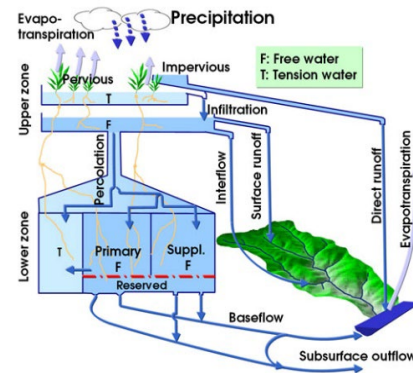
# Synthetic forecasts: enhancing the forecast dataset



Observations



GEFS/HEFS



Hindcast Period  
Fit synthetic forecast model

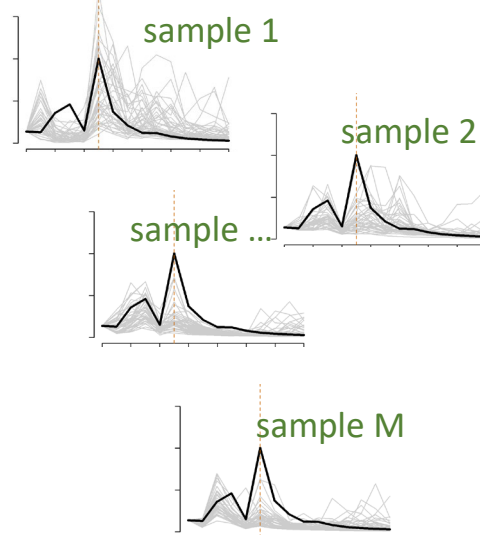
'Observation' dependent model  
 $F^* = f(Q_{\text{hindcast}})$

# Synthetic forecasts: enhancing the forecast dataset



Synthetic  
Ensemble  
Forecasting  
Algorithm

Synthetic forecast samples



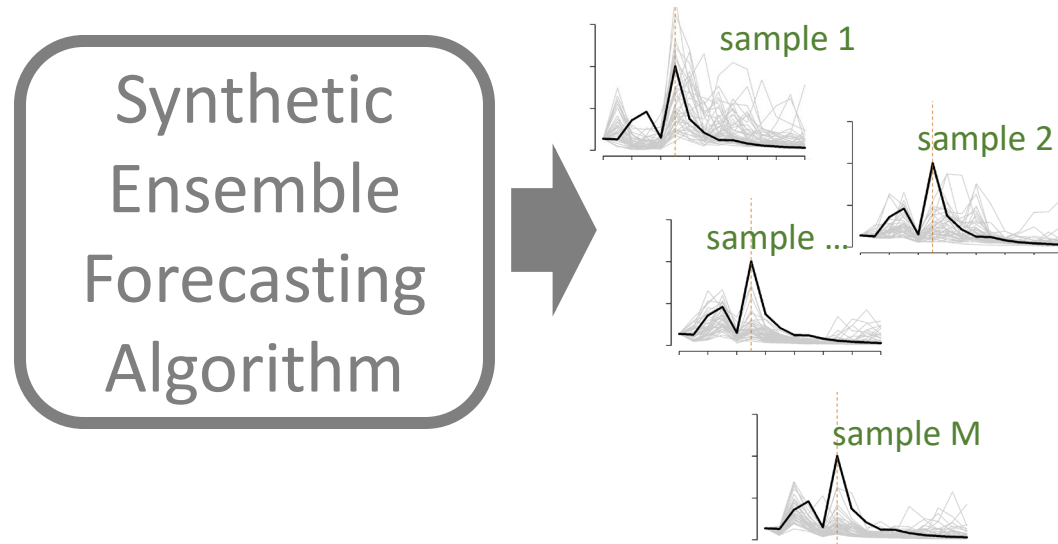
Hindcast Period  
Fit synthetic forecast model

'Observation' dependent model  
 $F^* = f(Q_{\text{hindcast}})$

Non-Hindcast Period  
Synthetic Forecasts =  $f(Q_{\text{hist}})$  or  $f(Q^*_{\text{proj}})$

# Synthetic ensemble forecasting research

A lineage of research work to get to here:



## **A Multivariate Approach to Generate Synthetic Short-To-Medium Range Hydro-Meteorological Forecasts Across Locations, Variables, and Lead Times**

Zachary P. Brodeur<sup>1</sup>  and Scott Steinschneider<sup>1</sup> 

*Brodeur & Steinschneider, 2021*



## **Synthetic Forecast Ensembles for Evaluating Forecast Informed Reservoir Operations**

Zachary P. Brodeur<sup>1</sup> , Chris Delaney<sup>2</sup> , Brett Whitin<sup>3</sup> , and Scott Steinschneider<sup>1</sup> 

*Brodeur et al., 2024*

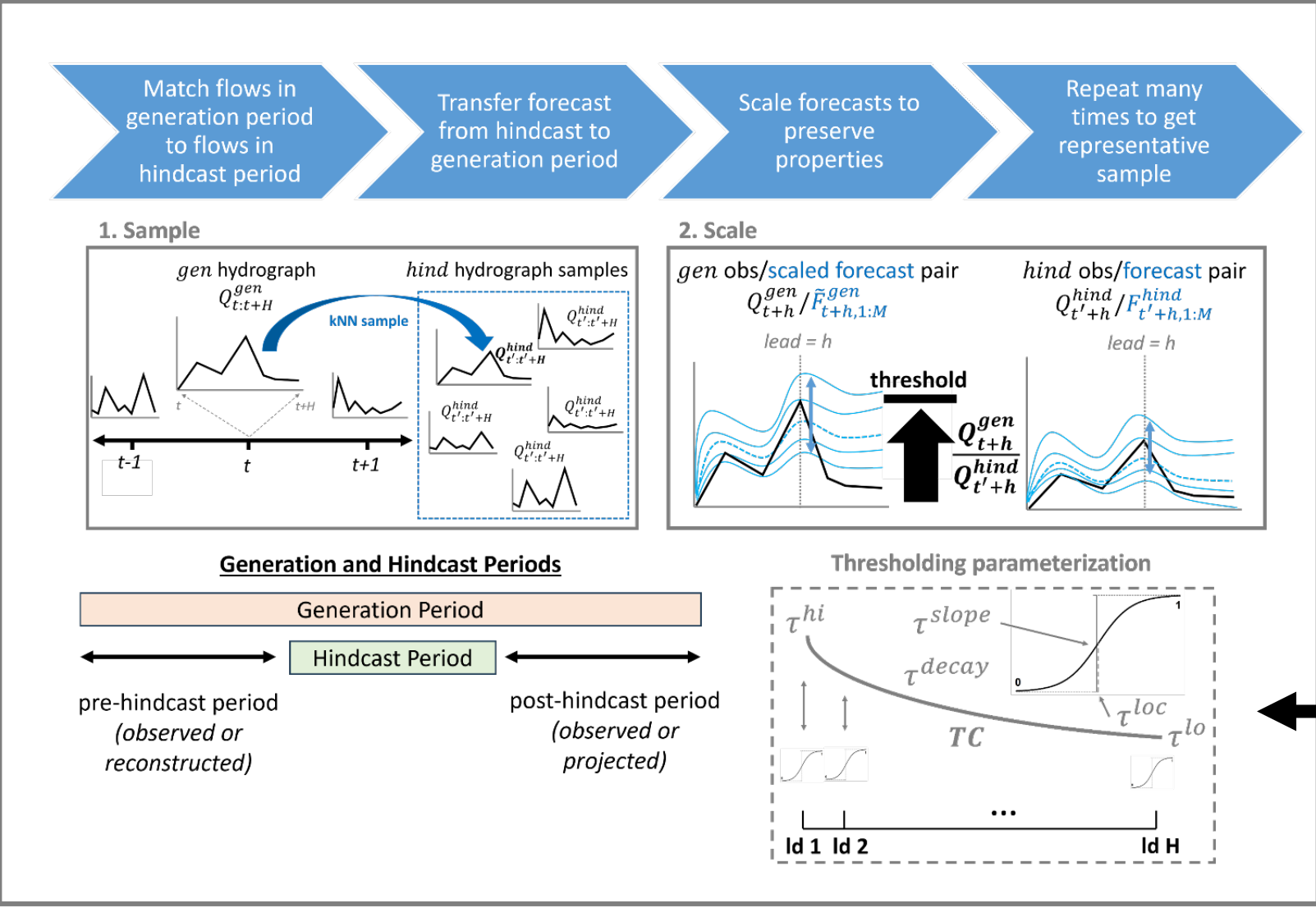


## **Synthetic Ensemble Forecasts: Operations-Based Evaluation and Inter-Model Comparison for Reservoir Systems Across California**

Zachary P. Brodeur<sup>1</sup> , William Taylor<sup>2</sup> , Jonathan D. Herman<sup>2</sup> , and Scott Steinschneider<sup>1</sup> 

*Brodeur et al., 2025*

# Synthetic forecasting algorithm overview



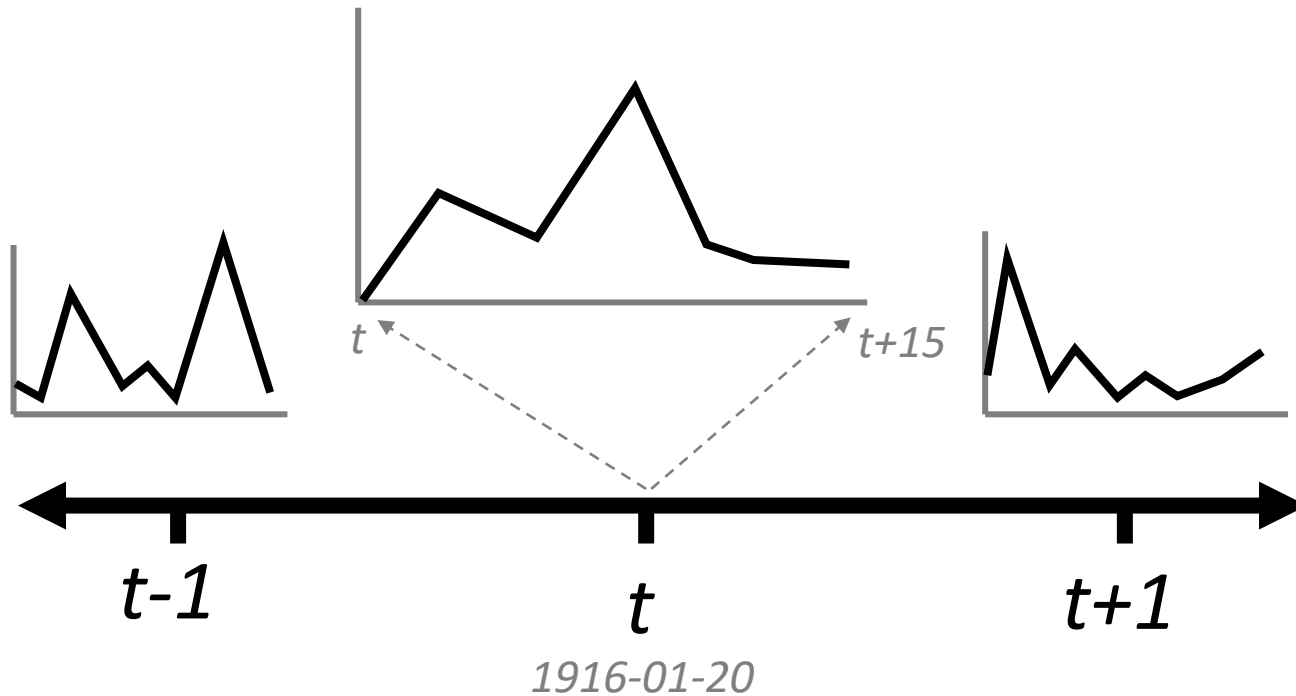
Methodology developed in Brodeur et al. (2025)

- Optimizable procedure:**
- Preserve skill across lead times
  - Ensure stability

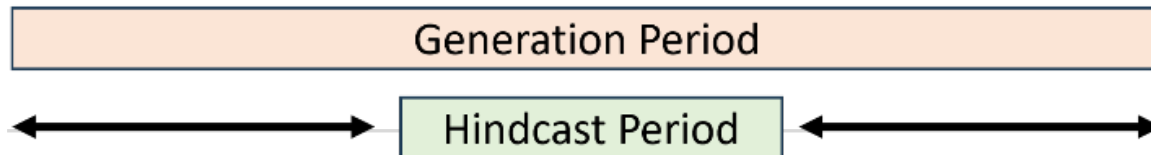
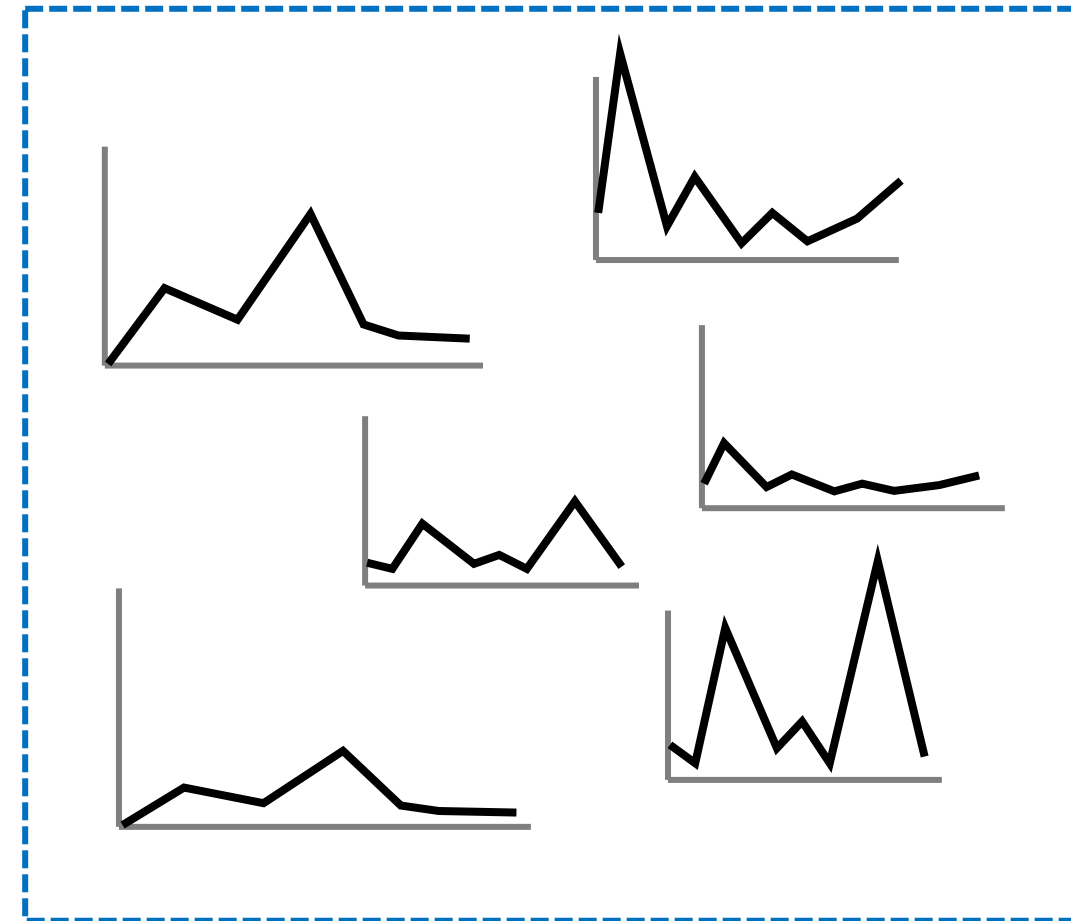


# Synthetic forecasting algorithm implementation

GEN period 'obs-fwd',  
time =  $t$   
(e.g.  $t = 1916-01-20$ ; SOD example)



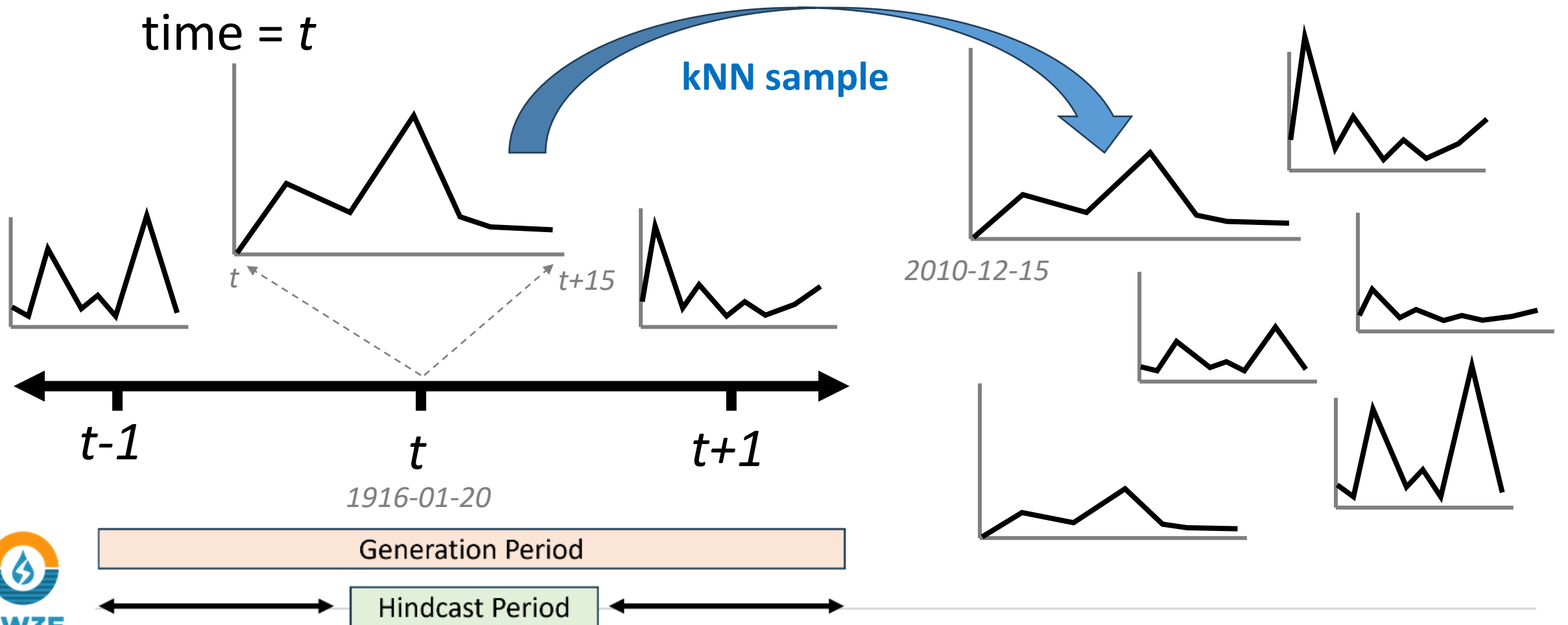
HIND period (e.g. 1989-2019)  
'obs-fwd' samples



# Synthetic forecasting algorithm implementation

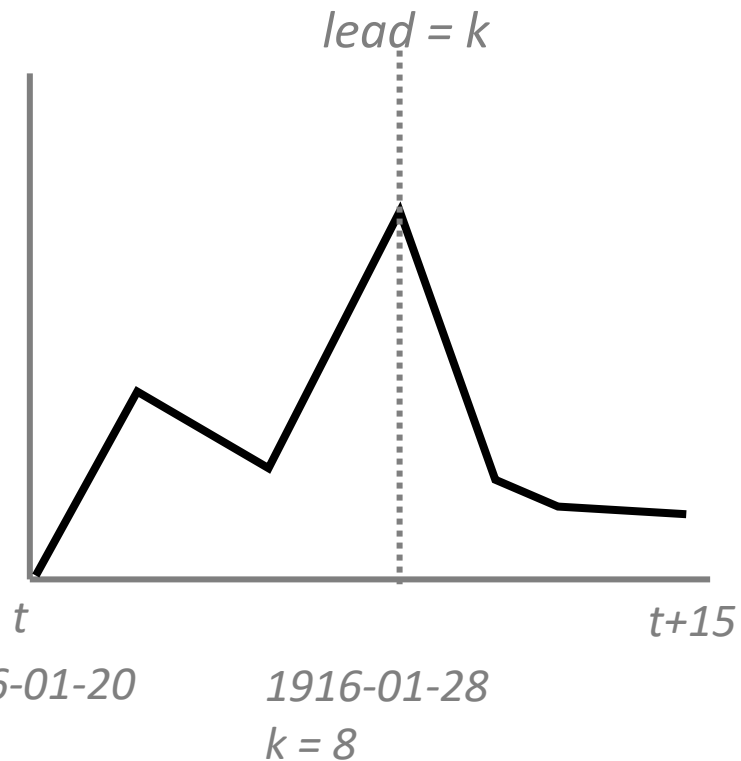
GEN period 'obs-fwd',  
time =  $t$

HIND period 'obs-fwd' samples

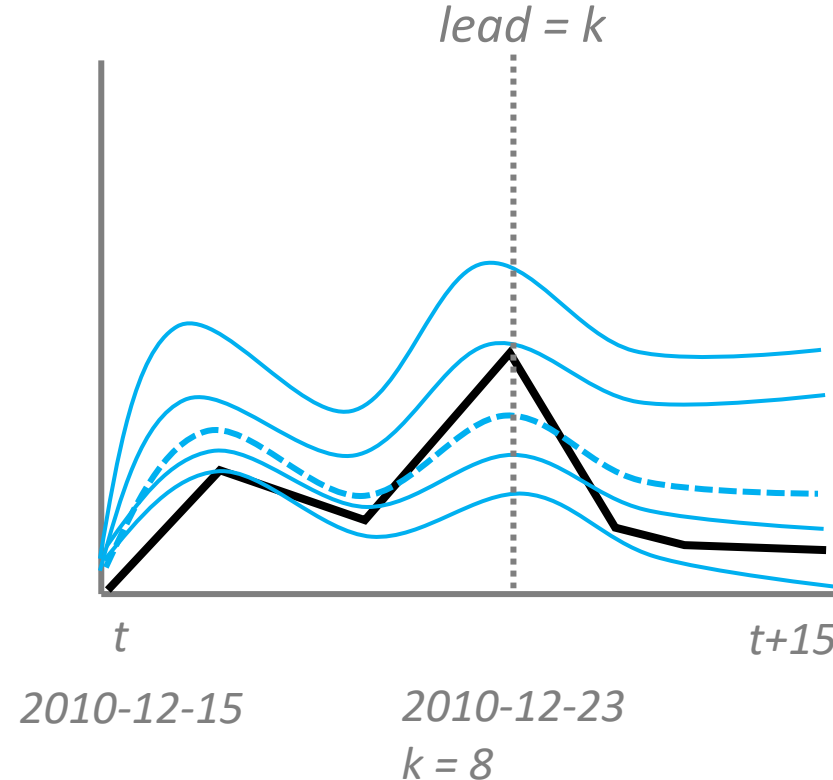


# Synthetic forecasting algorithm implementation

## GEN period obs sample

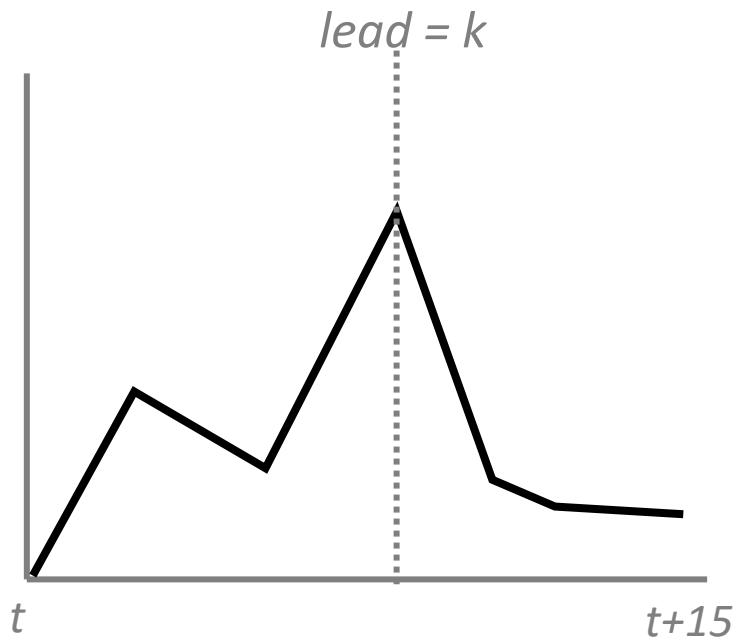


## HIND period obs and forecast pair



# Synthetic forecasting algorithm implementation

## GEN period obs sample

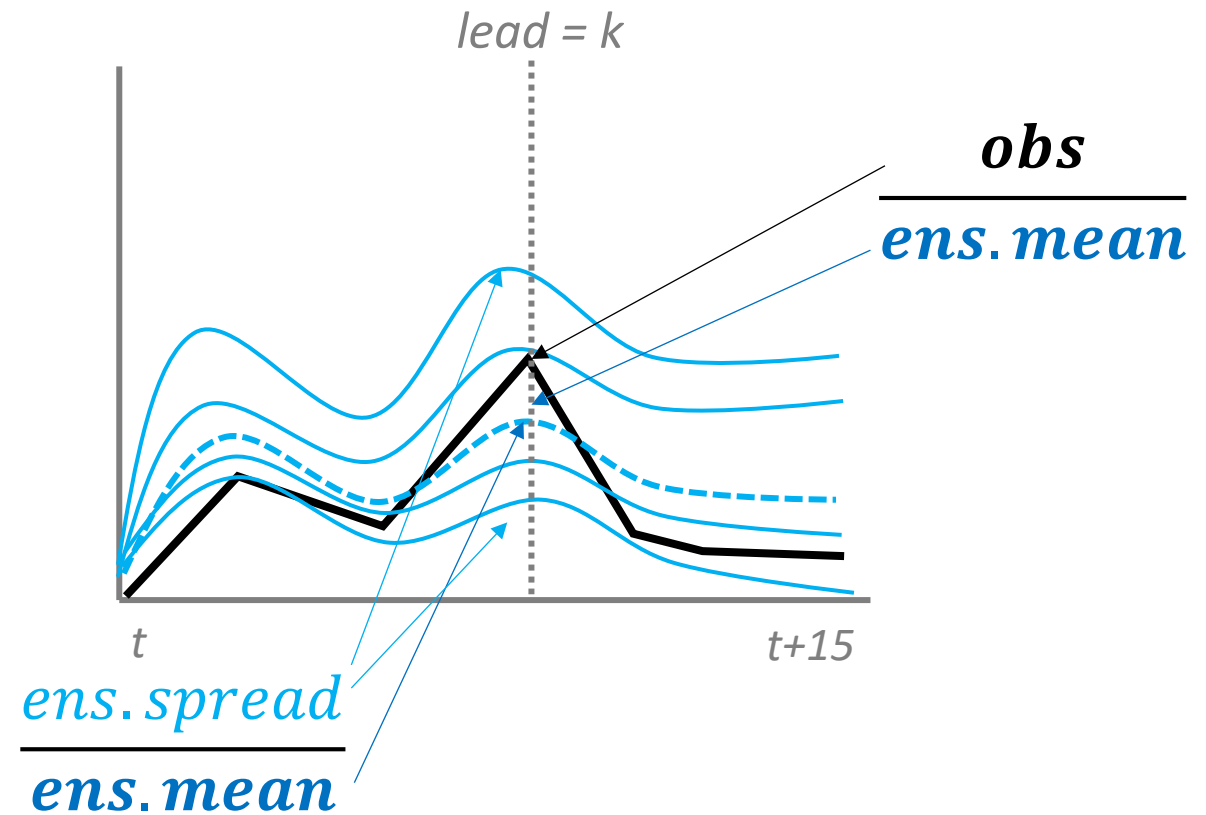


1916-01-20

1916-01-28

$k = 8$

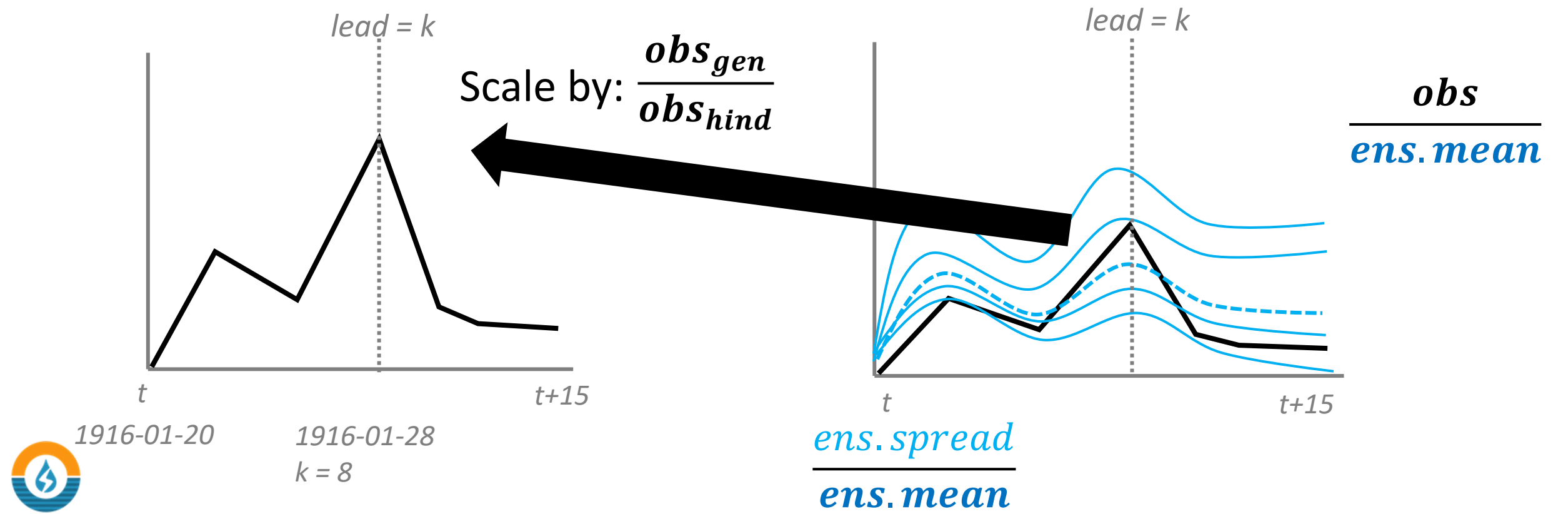
## HIND period obs and forecast pair



# Synthetic forecasting algorithm implementation

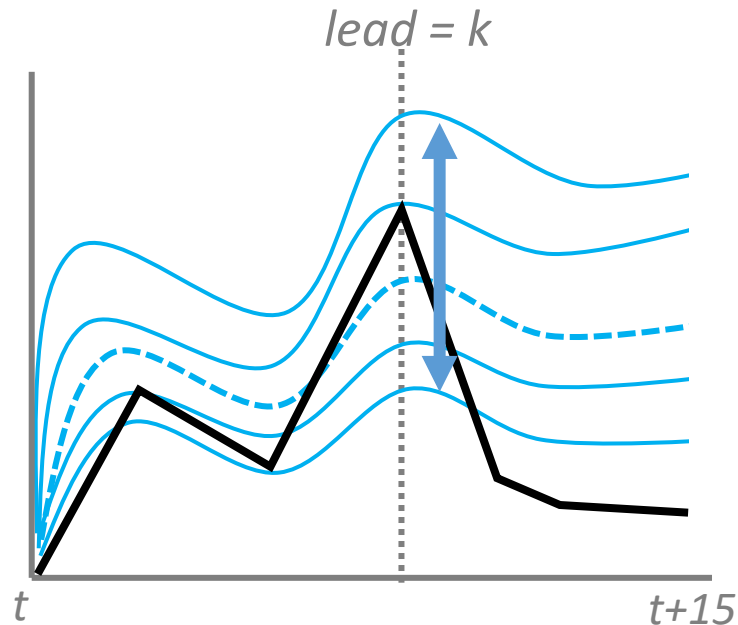
GEN period obs sample

HIND period obs and forecast pair



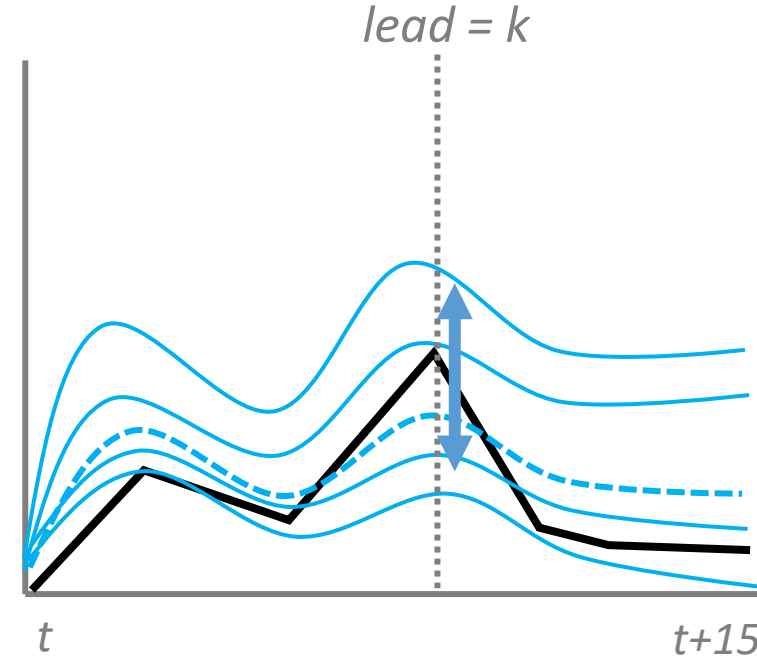
# Synthetic forecasting algorithm implementation

GEN period obs sample



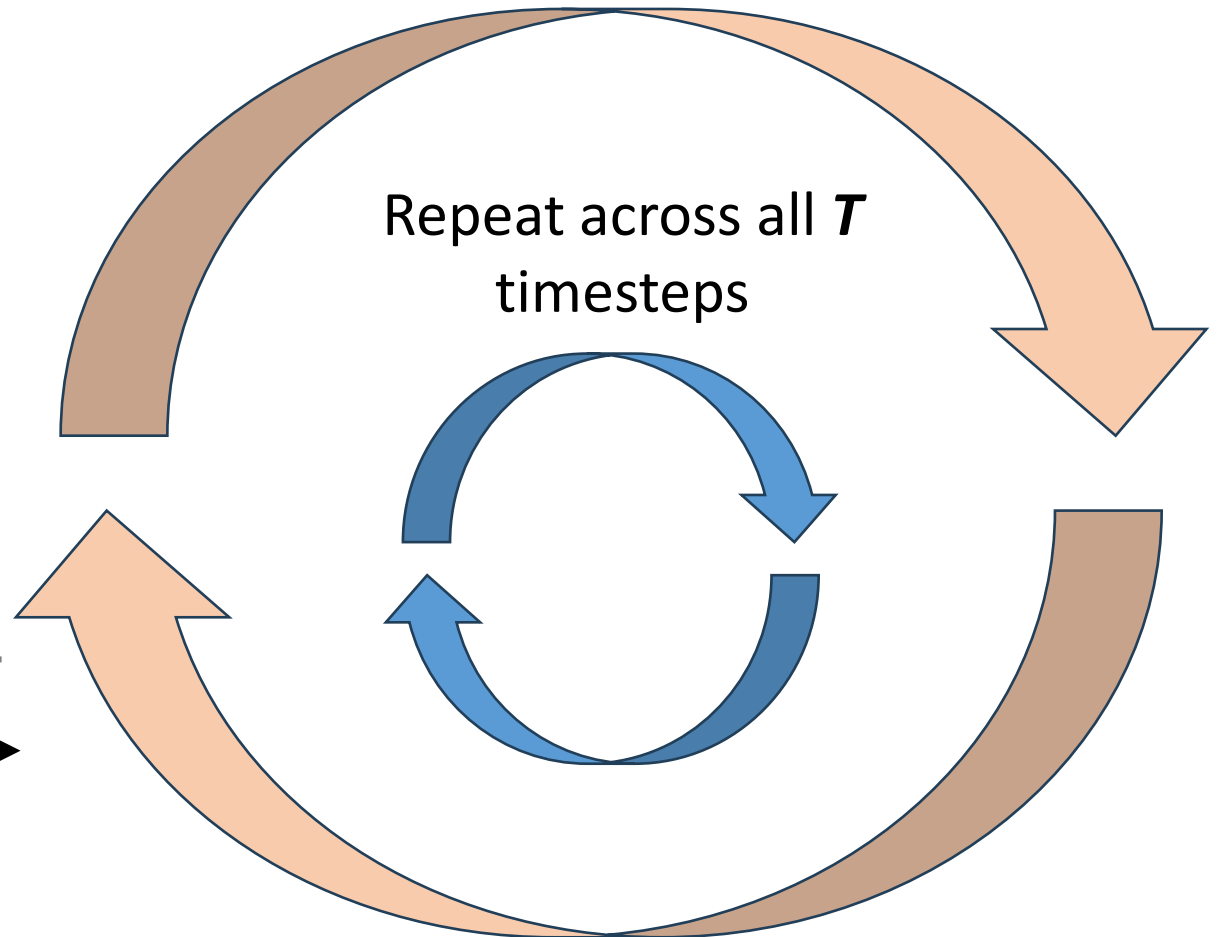
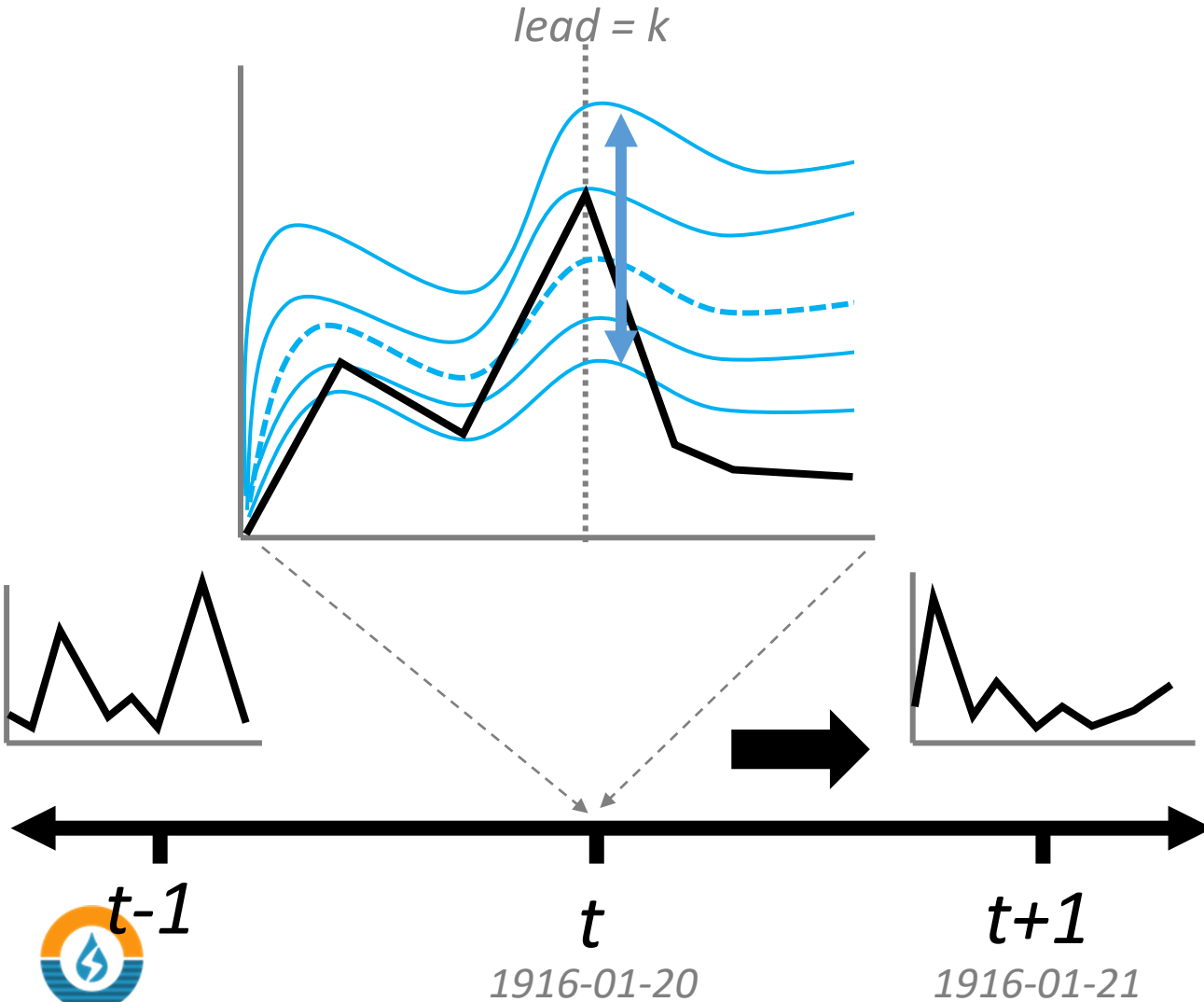
Scaled synthetic forecast

HIND period obs and forecast pair



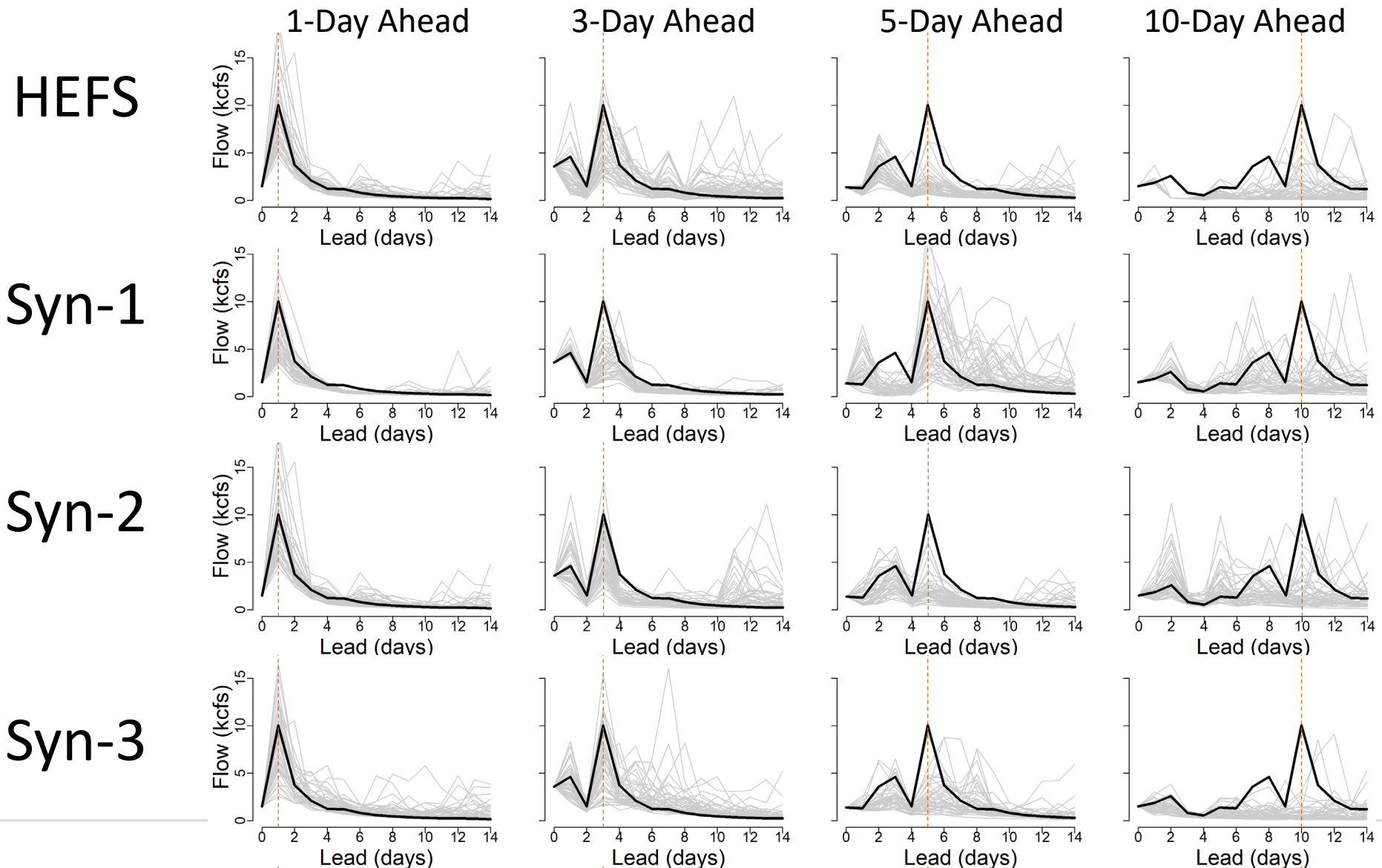
# Synthetic forecasting algorithm implementation

Repeat *entire* process  $M$  times to produce  $M$  syn-forecast samples

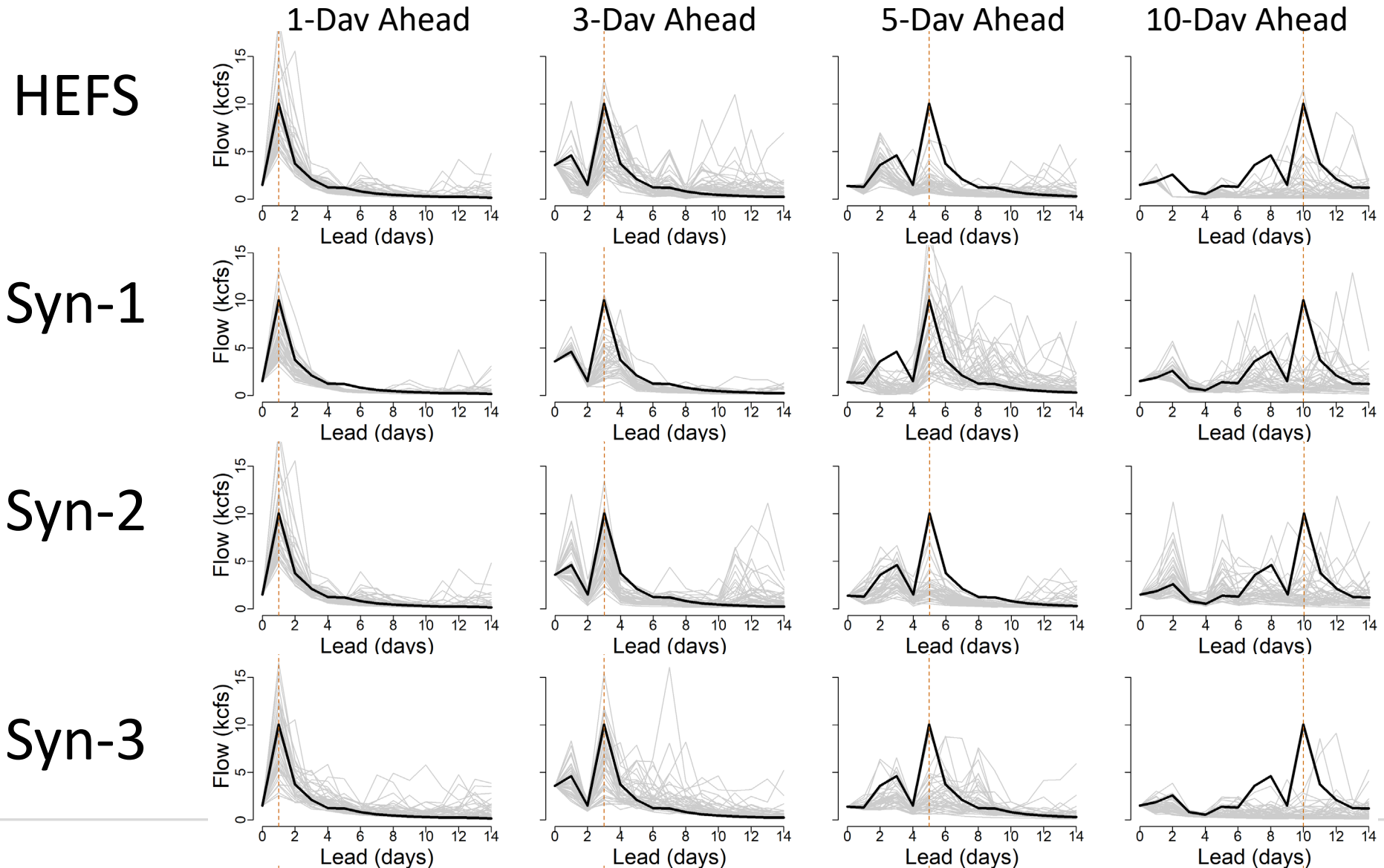


# Verification in hindcast period: Seven Oaks dam example

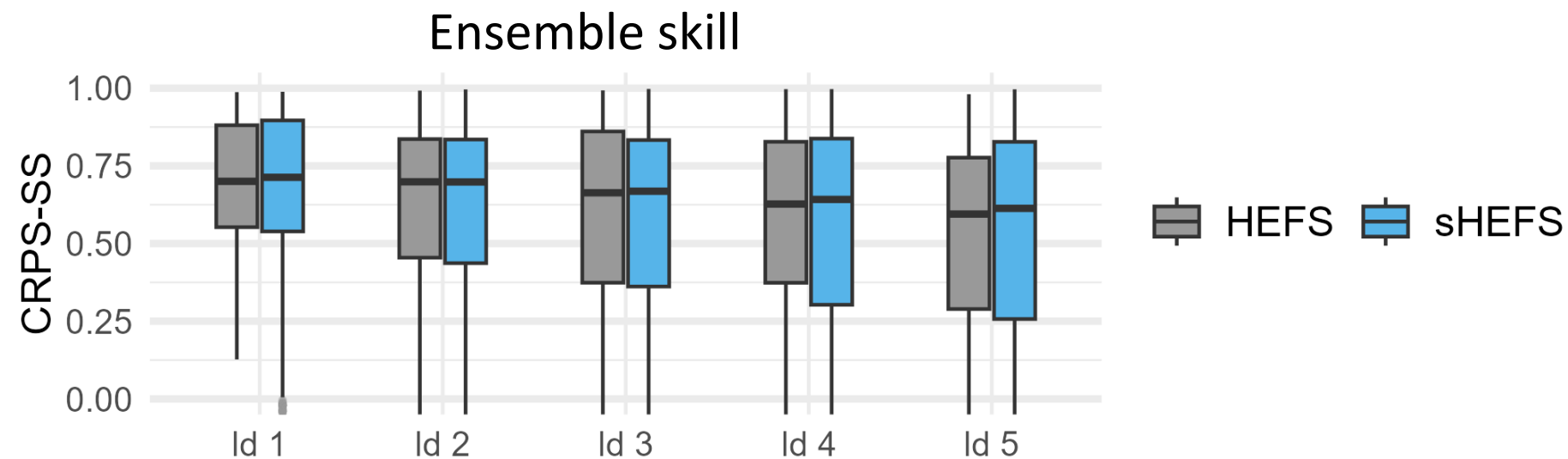
# Ensemble verification: 'Statistically indistinguishable'



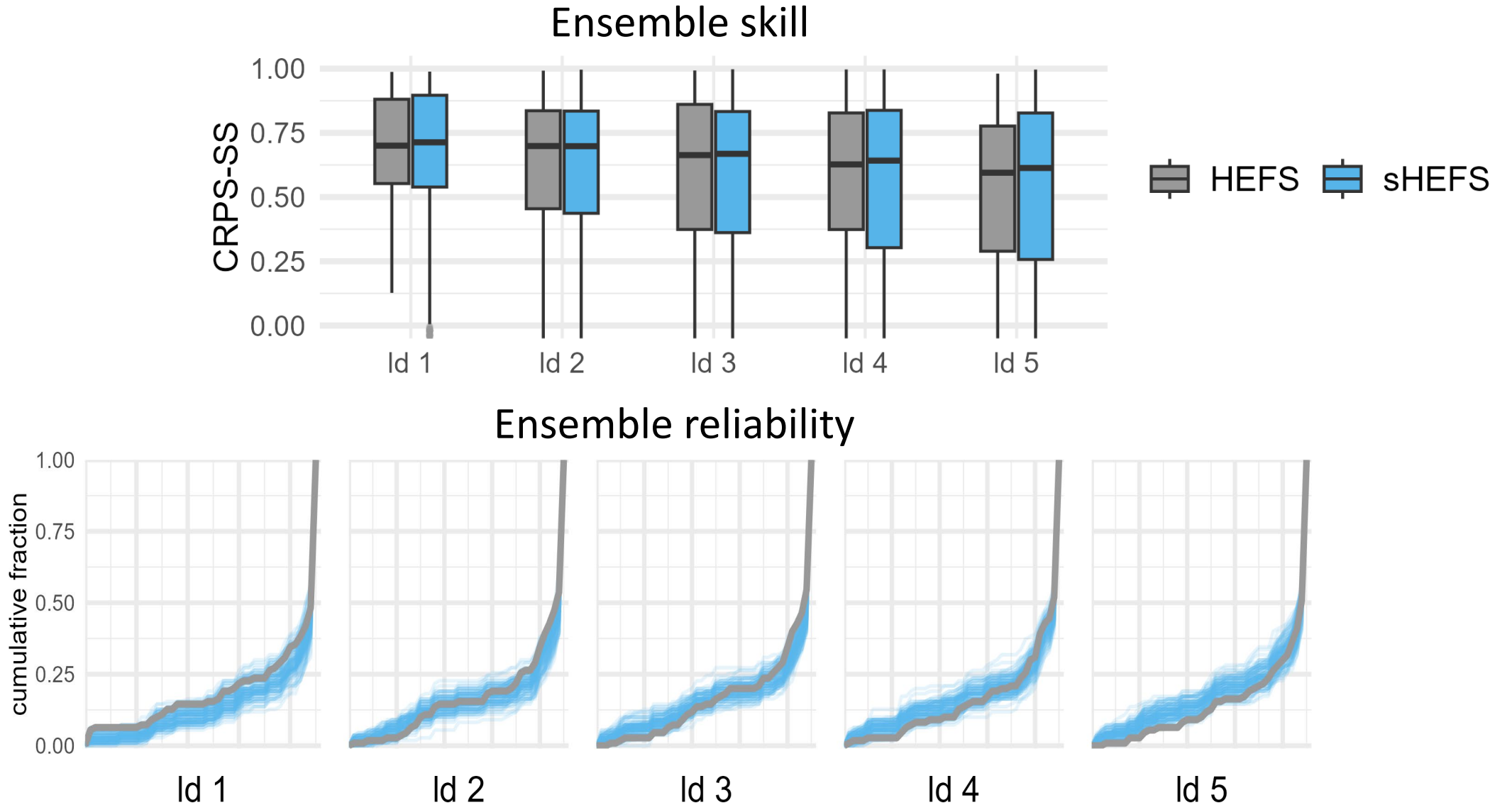
# Ensemble verification: 'Statistically indistinguishable'



# Seven Oaks Dam: Aggregate ensemble verification



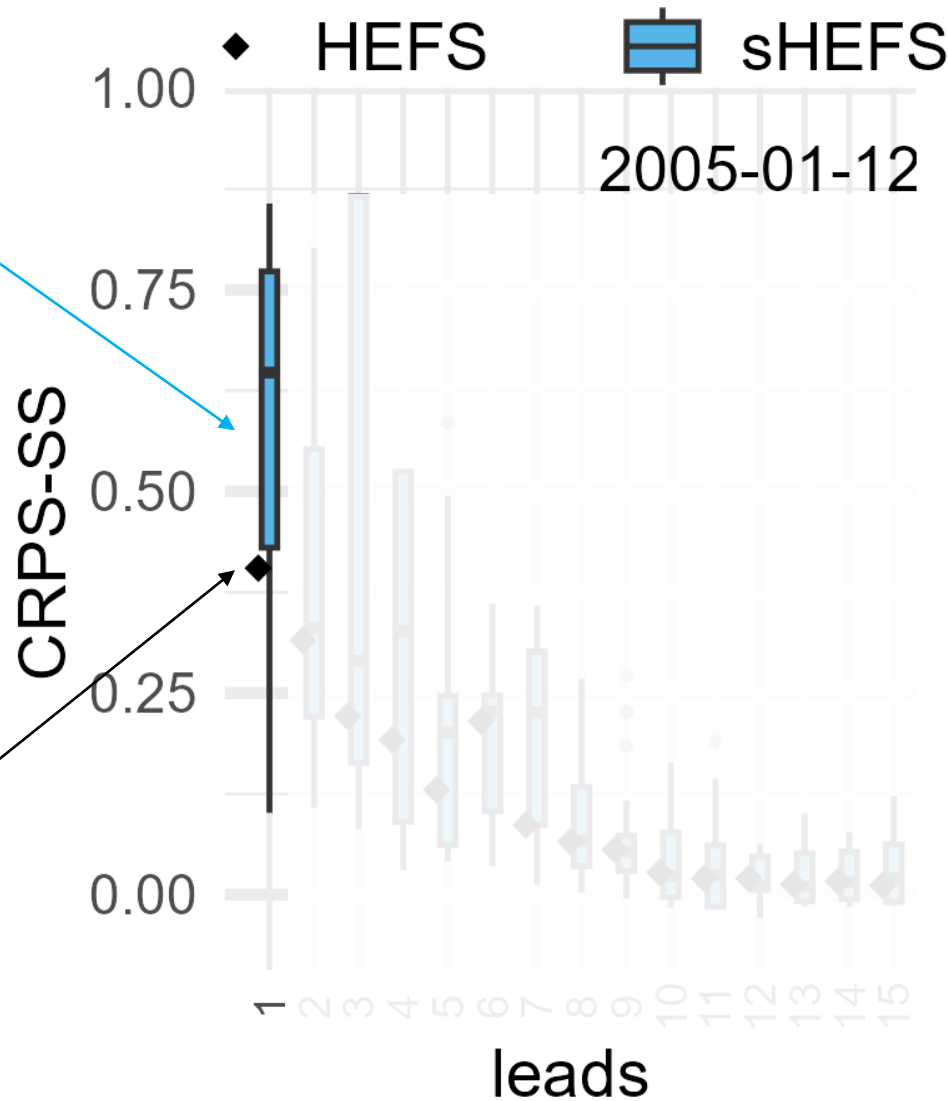
# Seven Oaks Dam: Aggregate ensemble verification



# Seven Oaks Dam: Event based verification

Distribution of **100X** samples of sHEFS CRPS-SS scores at lead 1 for 2005-01-12 peak flow

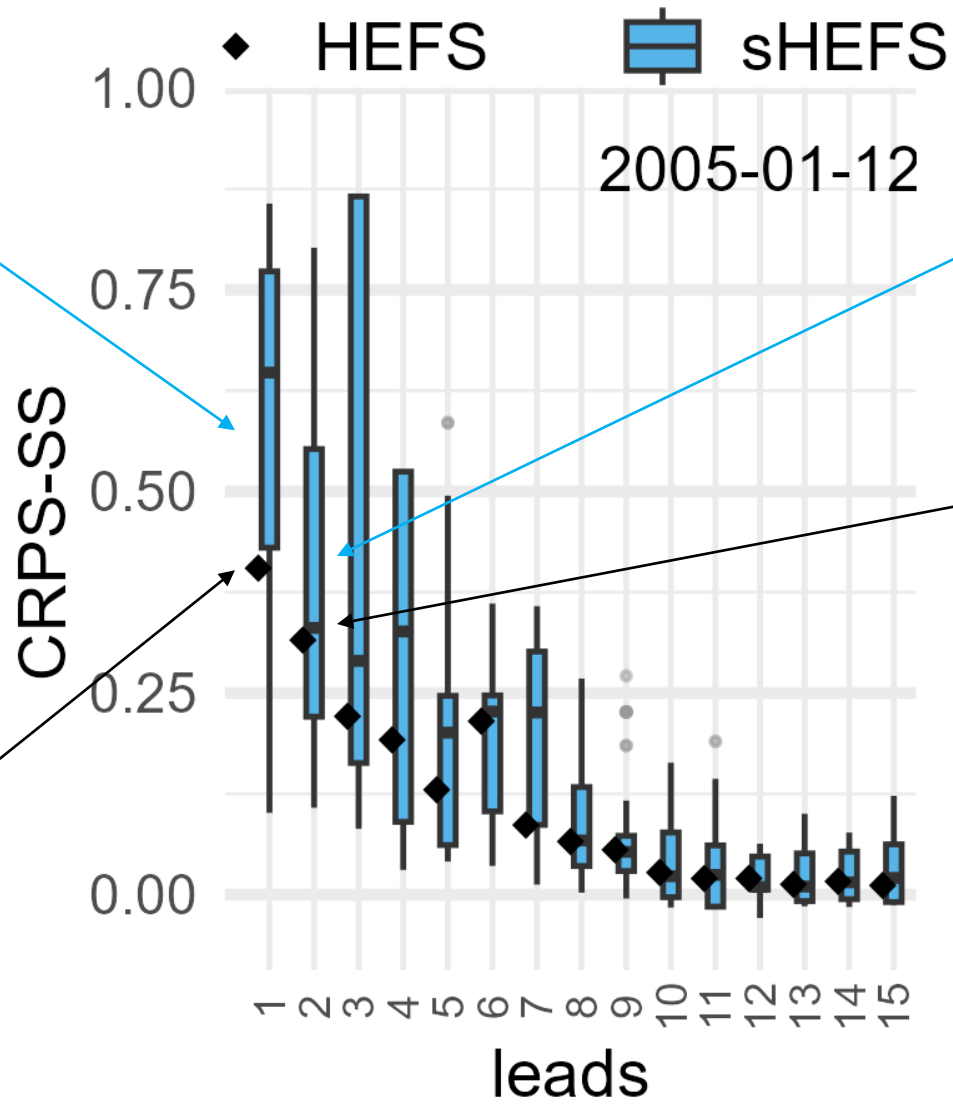
**HEFS** CRPS-SS score at lead 1 for 2005-01-12 peak flow



# Seven Oaks Dam: Event based verification

Distribution of **100X** samples of sHEFS CRPS-SS scores at lead 1 for 2005-01-12 peak flow

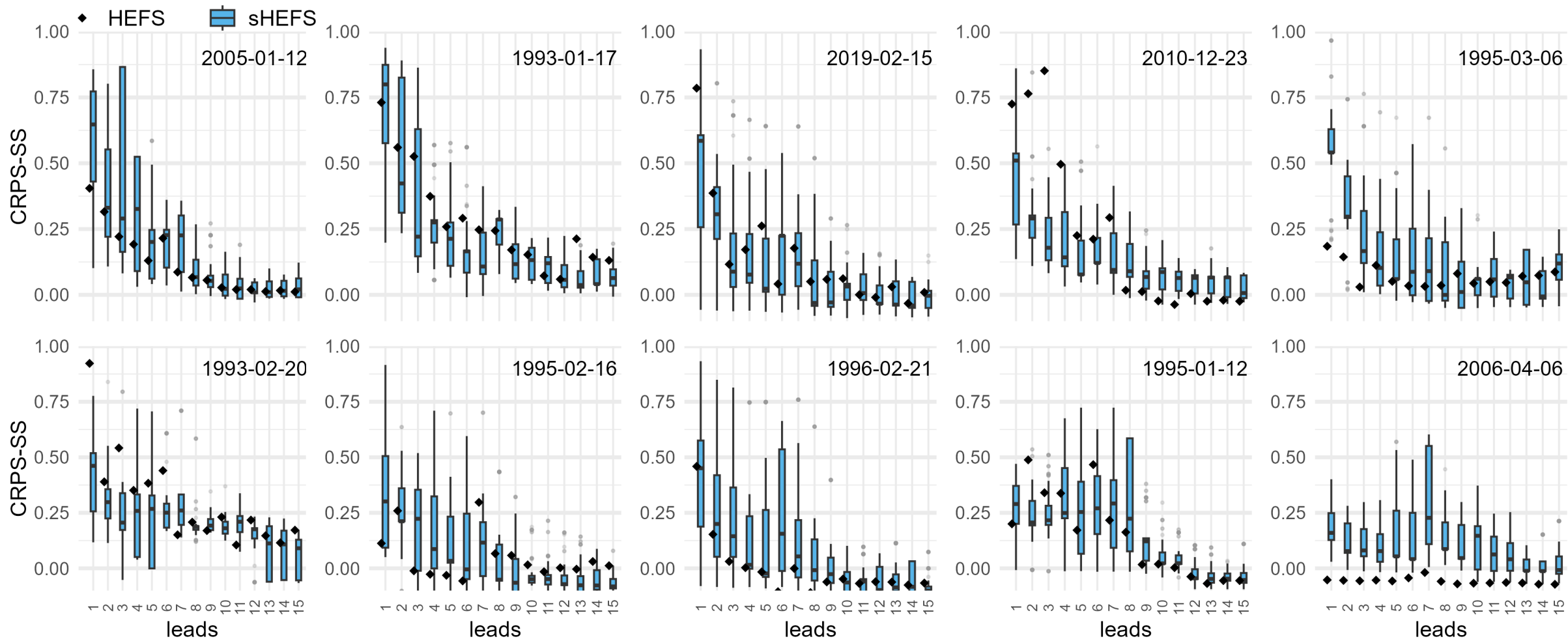
**HEFS** CRPS-SS score at lead 1 for 2005-01-12 peak flow



Distribution of **sHEFS** ... lead 2 ...

**HEFS** ... lead 2 ...

# Seven Oaks Dam: Event based verification

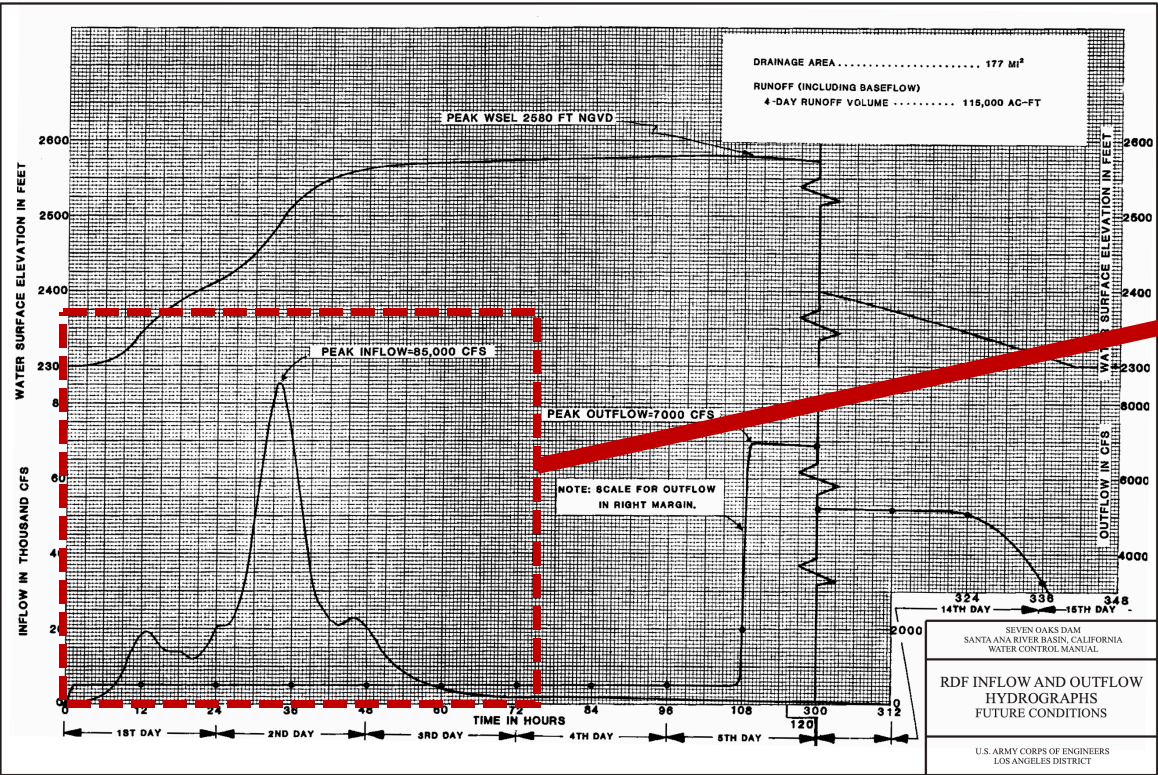


10 largest floods in Hindcast Period (1989-2019)

Performance against extremes  
unseen in the hindcast period:  
Seven Oaks Dam example

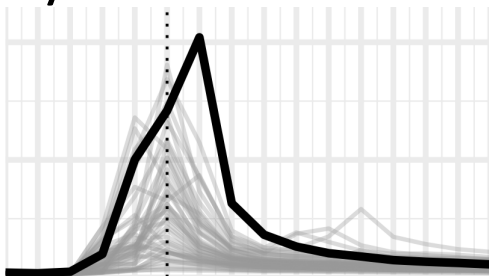
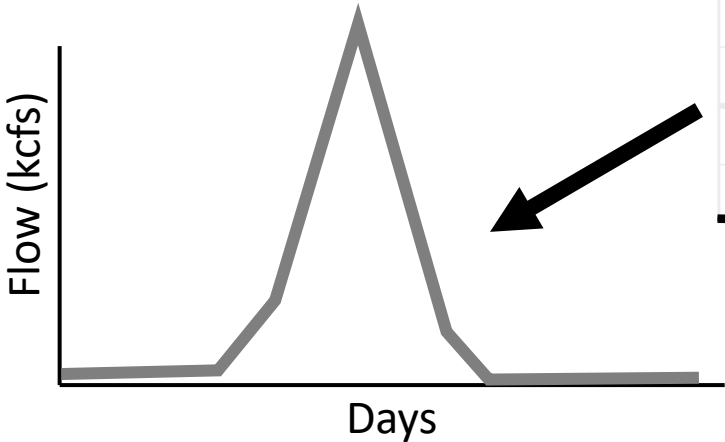
# Synthetic forecasts against Reservoir Design Flood

Reservoir Design Flood (RDF) from WCM

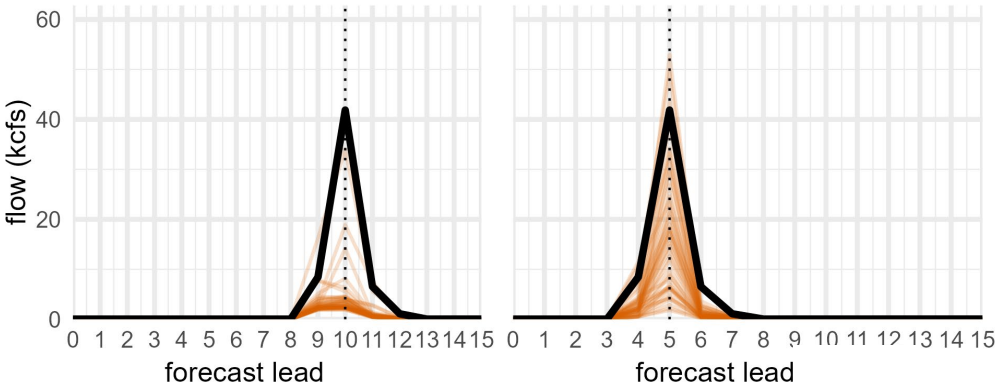


Daily inflow series

Synthetic forecasts

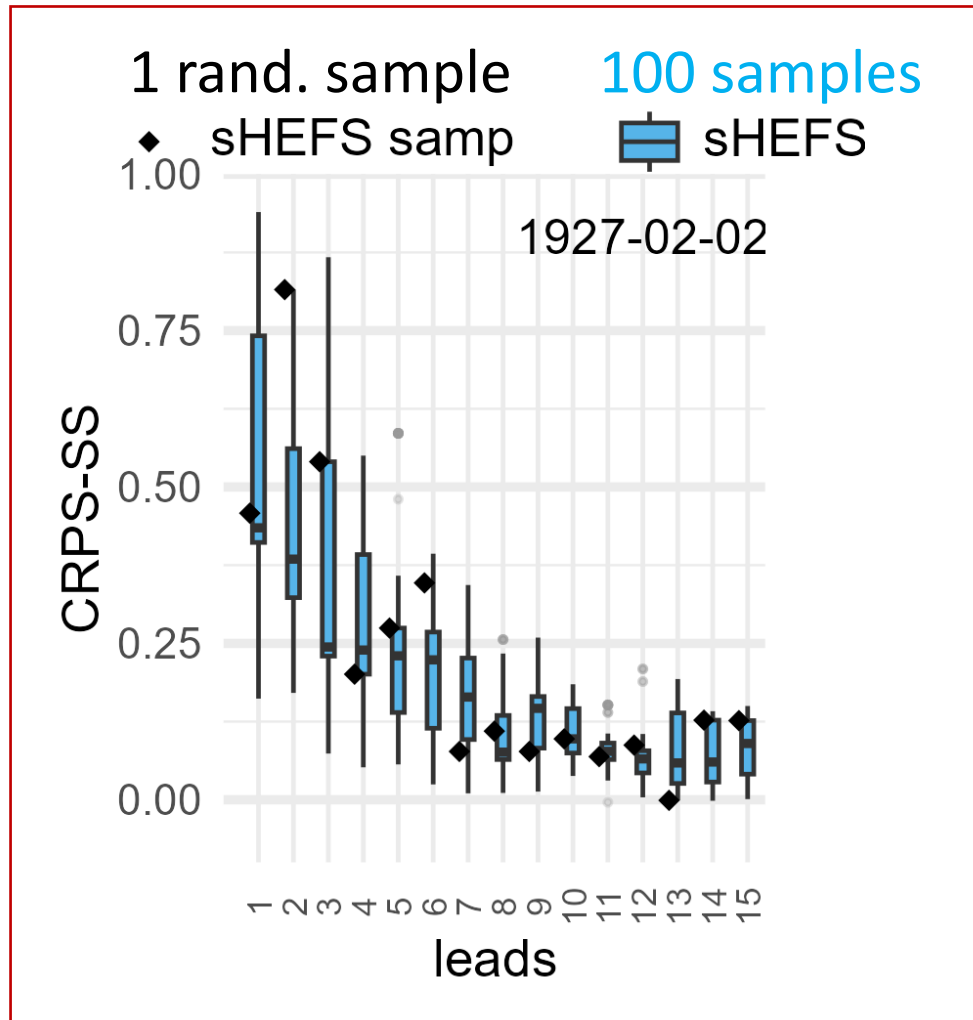


RDF synthetic ensemble forecast sequences

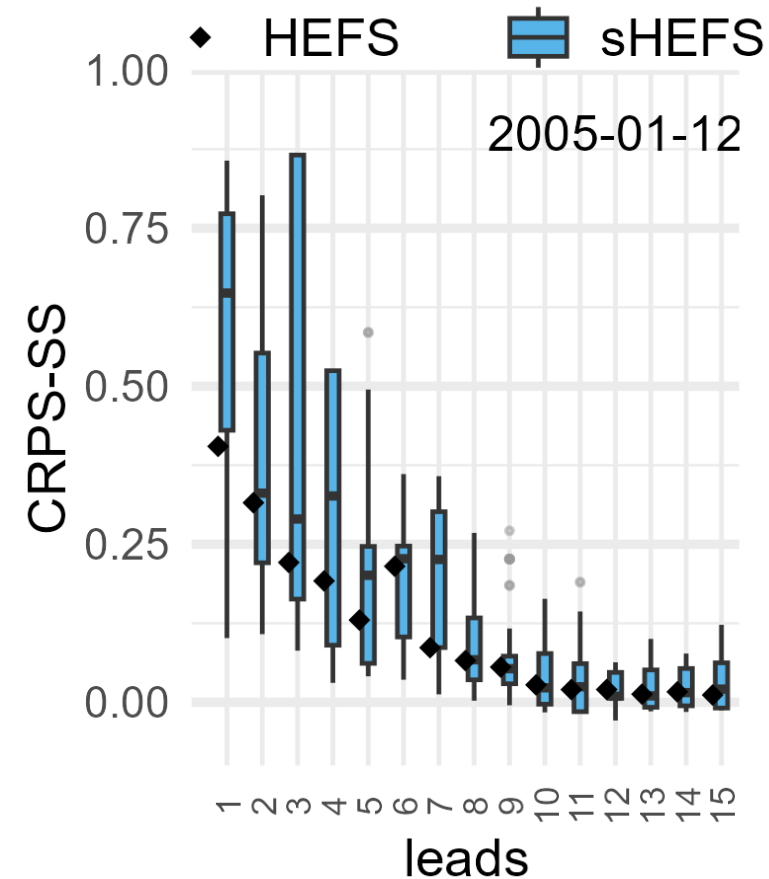


# RDF synthetic forecast analysis

## RDF + Syn-Forecasts



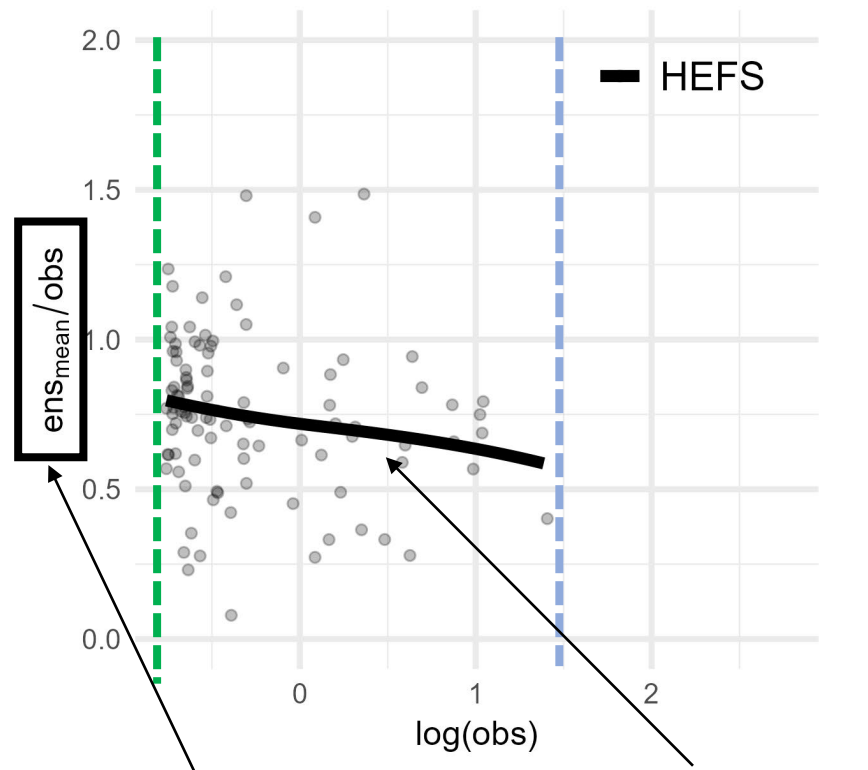
## Syn-Forecasts vs largest Hindcast Event



# Consistency of extrapolated forecast behaviors

Top-100  
hindcast events  
(Lead 1)

Hindcast  
thresholds:  
! hcst-lower  
! hcst-upper

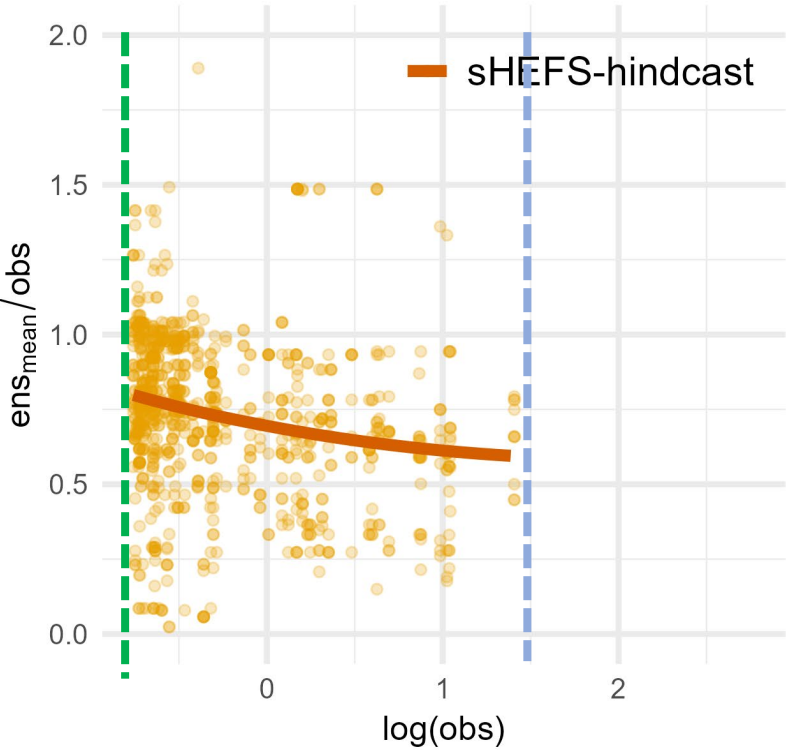
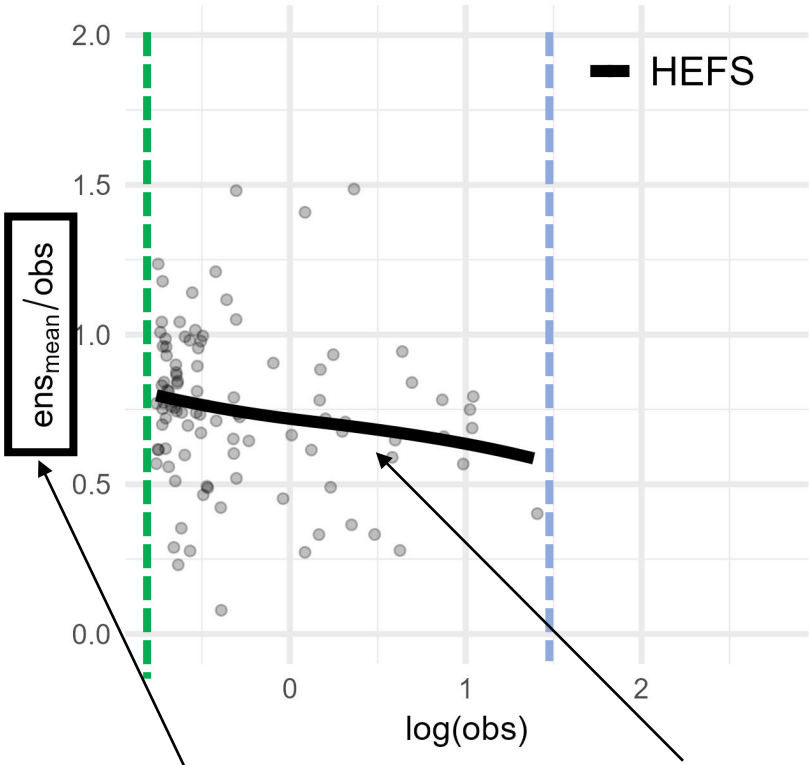


# Consistency of extrapolated forecast behaviors

Top-100  
hindcast events  
(Lead 1)

Hindcast

thresholds: 10 sHEFS samples against  
top-100 hindcast events  
(Lead 1)



# Consistency of extrapolated forecast behaviors

Top-100  
hindcast events  
(Lead 1)

Hindcast

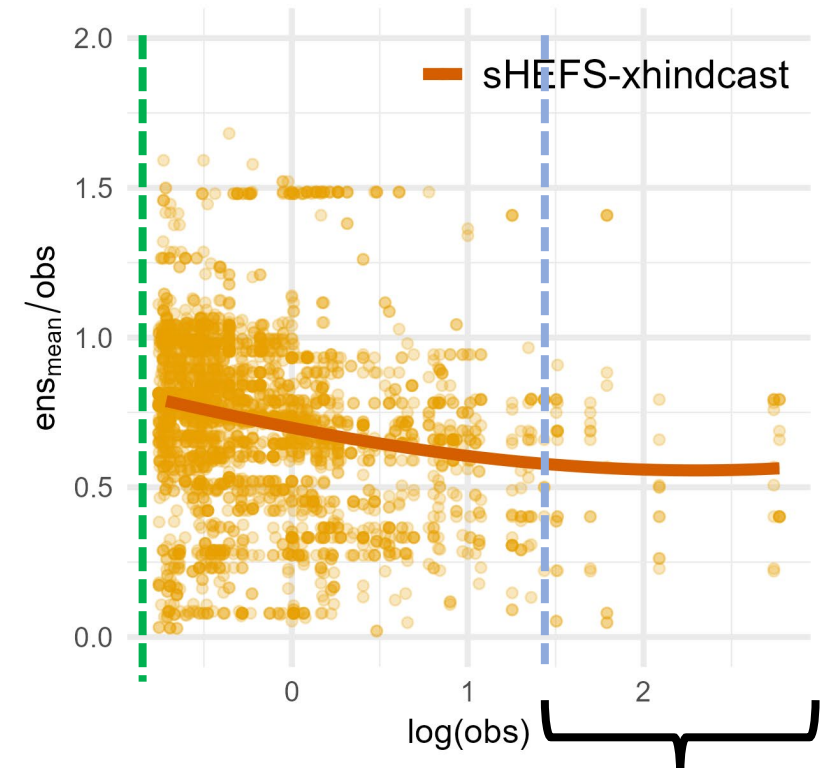
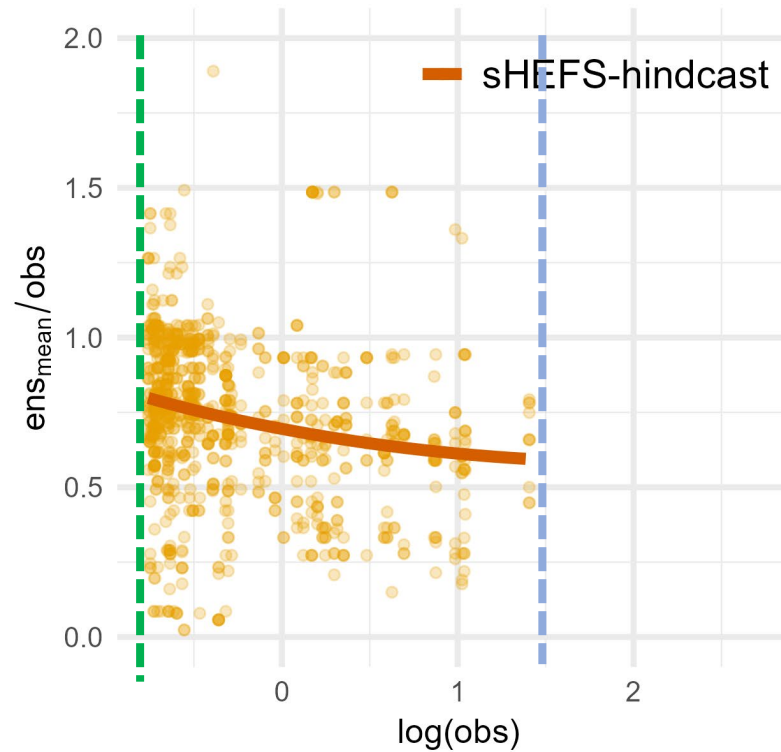
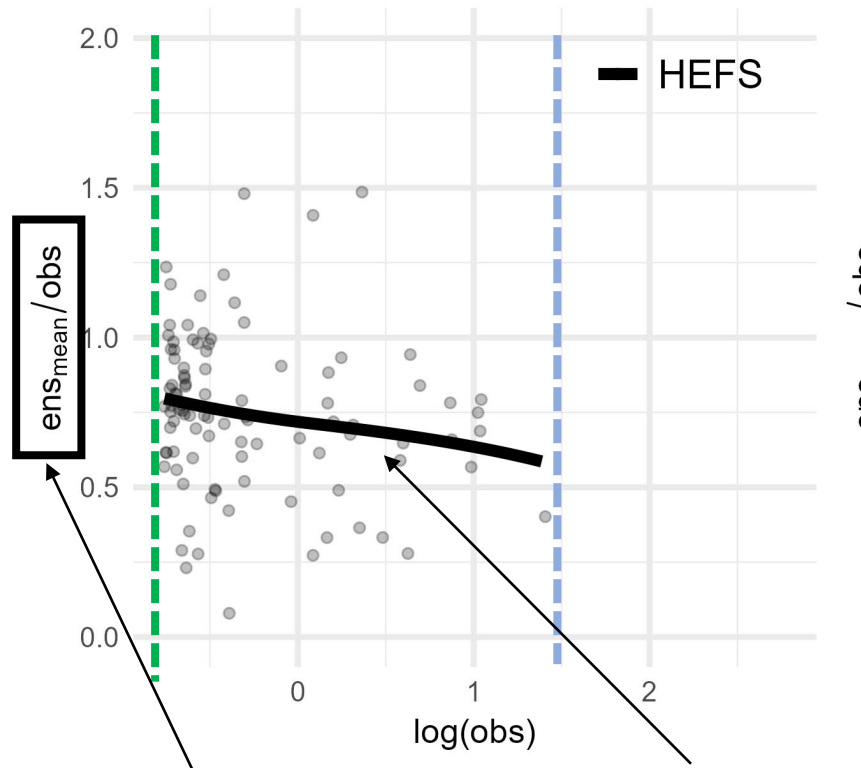
thresholds:

! hcst-lower

! hcst-upper

10 sHEFS samples against  
top-100 hindcast events  
(Lead 1)

10 sHEFS samples against  
all events > hcst-lower  
(Lead 1)



# Questions

## Reference

Brodeur, Z., & Steinschneider, S. (2021). A Multivariate Approach to Generate Synthetic Short-To-Medium Range Hydro-Meteorological Forecasts Across Locations, Variables, and Lead Times. *Water Resources Research*, 57(6). <https://doi.org/10.1029/2020WR029453>

Brodeur, Z., Delaney, C., Whitin, B., & Steinschneider, S. (2024). Synthetic Forecast Ensembles for Evaluating Forecast Informed Reservoir Operations. *Water Resources Research*, 60(2), e2023WR034898. <https://doi.org/10.1029/2023WR034898>

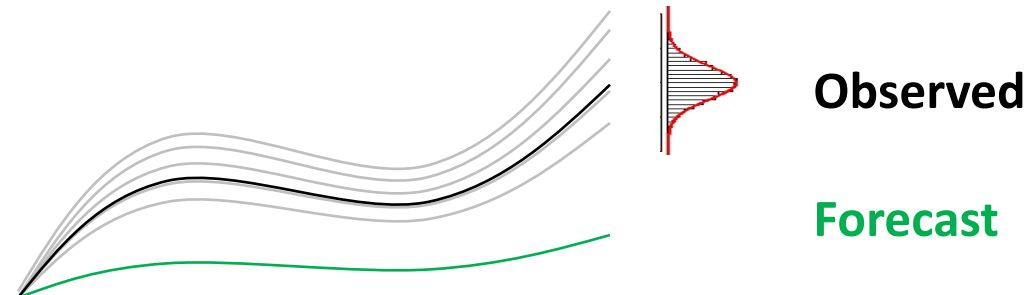
Brodeur, Z. P., Taylor, W., Herman, J. D., & Steinschneider, S. (2025). Synthetic Ensemble Forecasts: Operations-Based Evaluation and Inter-Model Comparison for Reservoir Systems Across California. *Water Resources Research*, 61(e2024WR039324). <https://doi.org/10.1029/2024WR039324>

# Additional Slides

# Synthetic ensemble forecasting theory

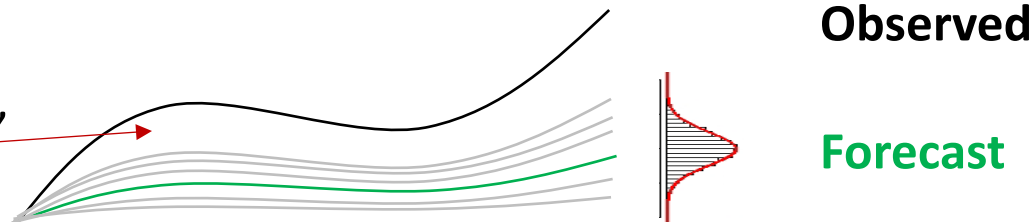
Model output statistics:  $P(\text{Obs}|\text{Forecast})$

Synthetic  
Ensemble  
Forecasting  
Algorithm

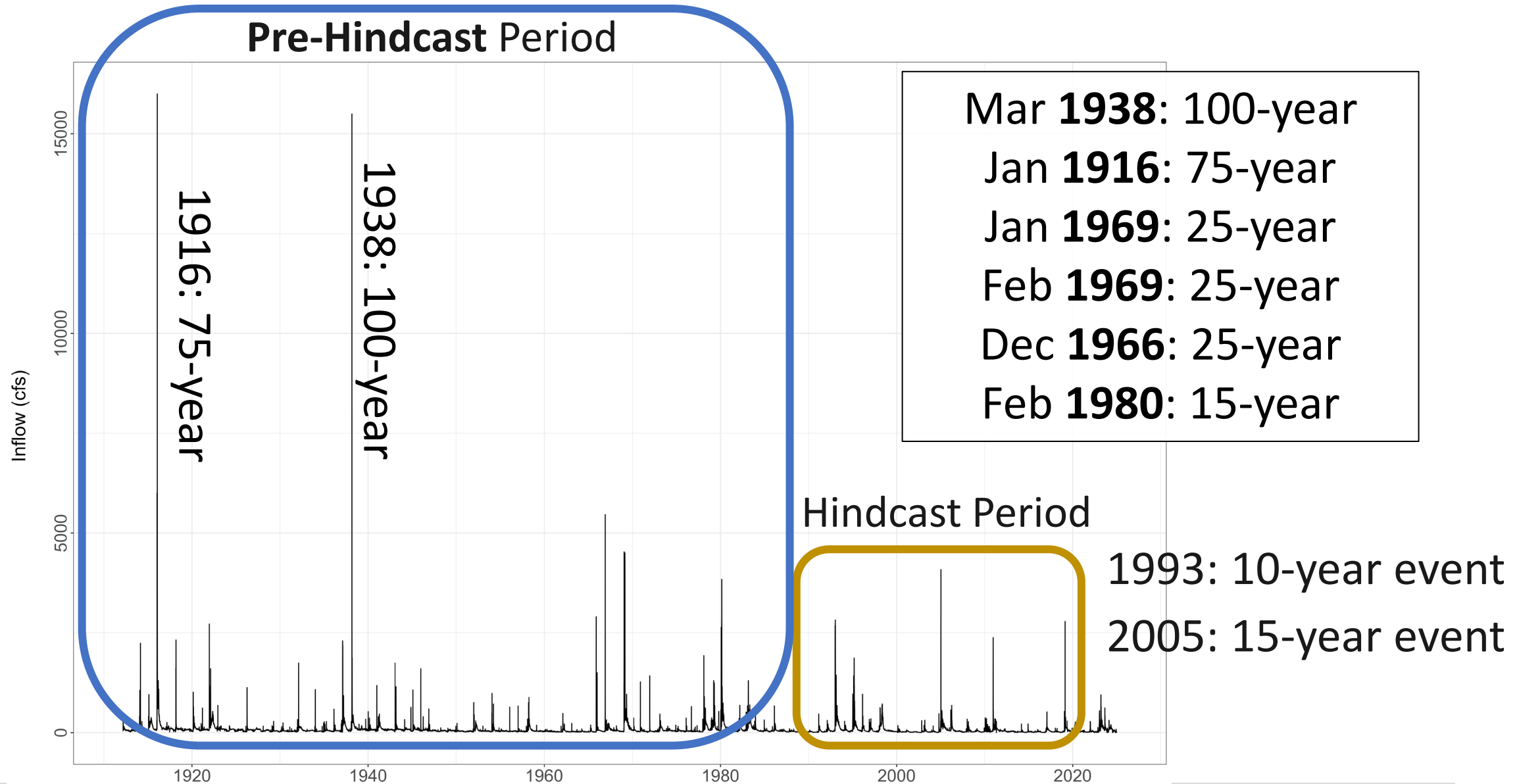


Synthetic ensemble forecasts:  $P(\text{Forecast}|\text{Obs})$

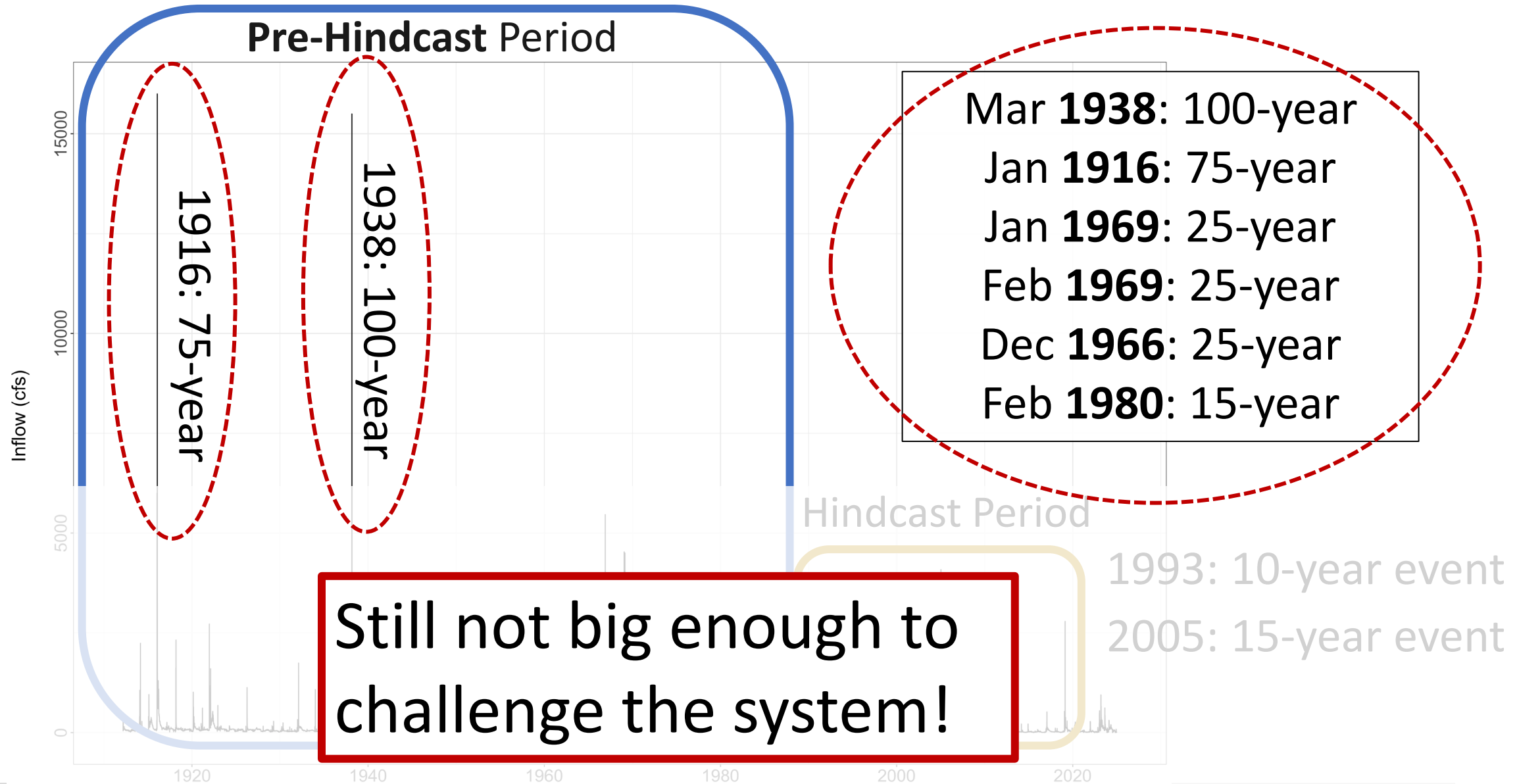
Preserve hindcast *deficiencies*,  
e.g. **biases**



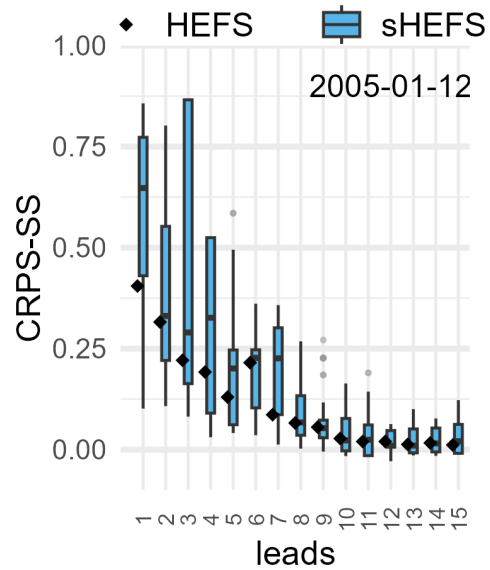
# Seven Oaks dam hindcast vs pre-hindcast



# Seven Oaks dam hindcast vs pre-hindcast



# Seven Oaks Dam: Event based verification

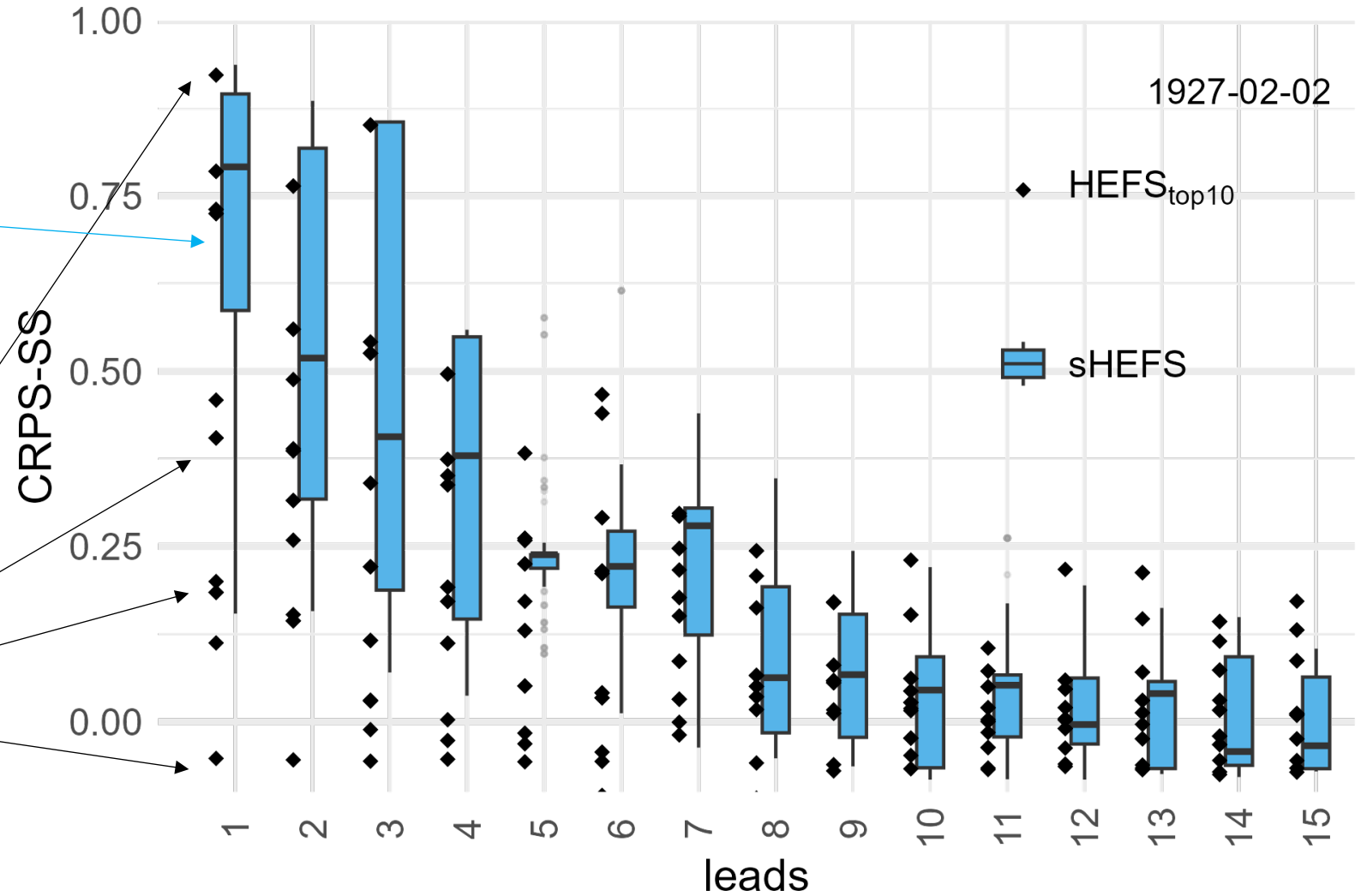


**10 largest floods in Hindcast Period (1989-2019)**

# RDF synthetic forecast analysis

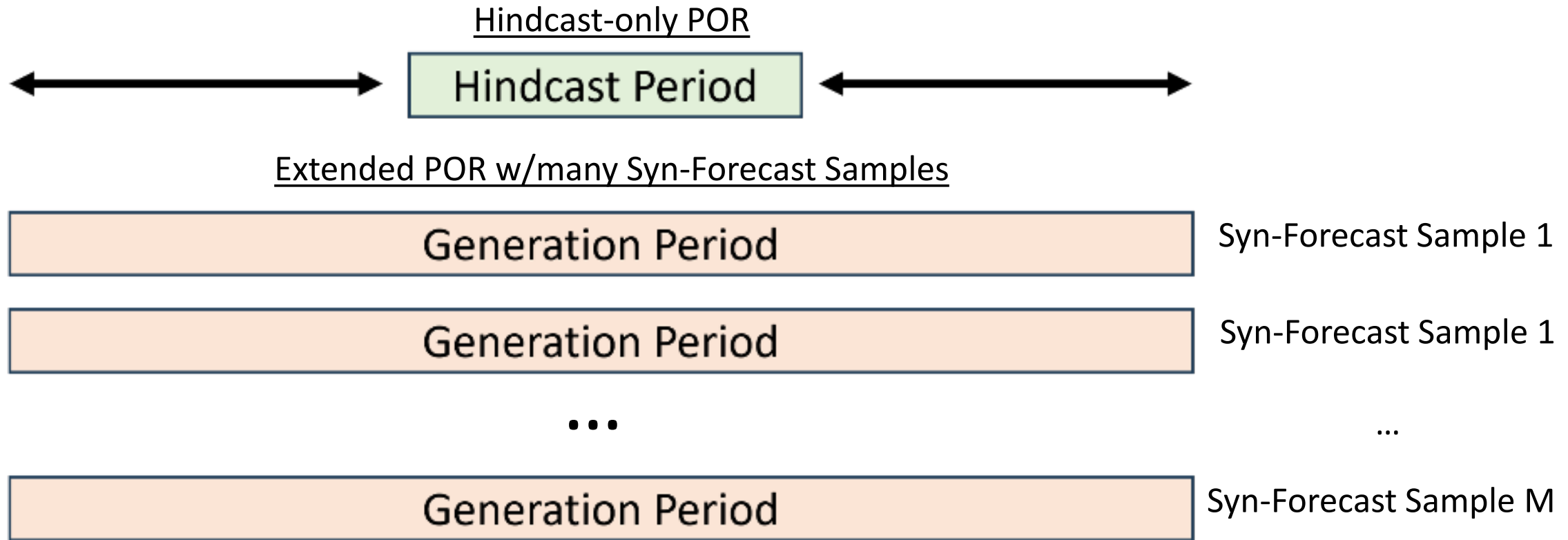
CRPS-SS distribution  
for 100X sHEFS  
samples at lead 1 for  
1927 RDF event

CRPS-SS score at lead  
1 for top-10 HEFS  
hindcast events



# Two key thrusts

1. Extended POR, *probabilistic* analysis of FIRO water supply, flood control, environmental, etc., benefits



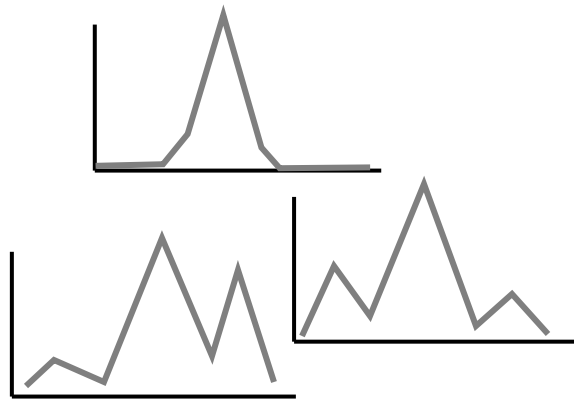
# Two key thrusts

1. Extended POR, *probabilistic* analysis of FIRO water supply, flood control, environmental, etc., benefits
  - Ability to assess a *greater range* of hydrologic variability
  - *Probabilistic* assessment of risk and benefits

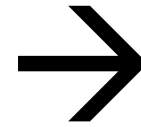
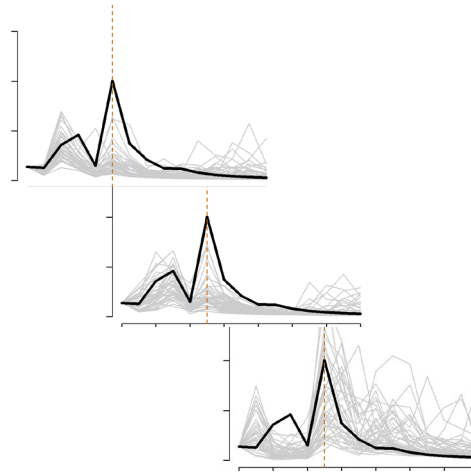
# Two key thrusts

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2. Event-based simulations to explore Flood Risk Management (FRM) outcomes

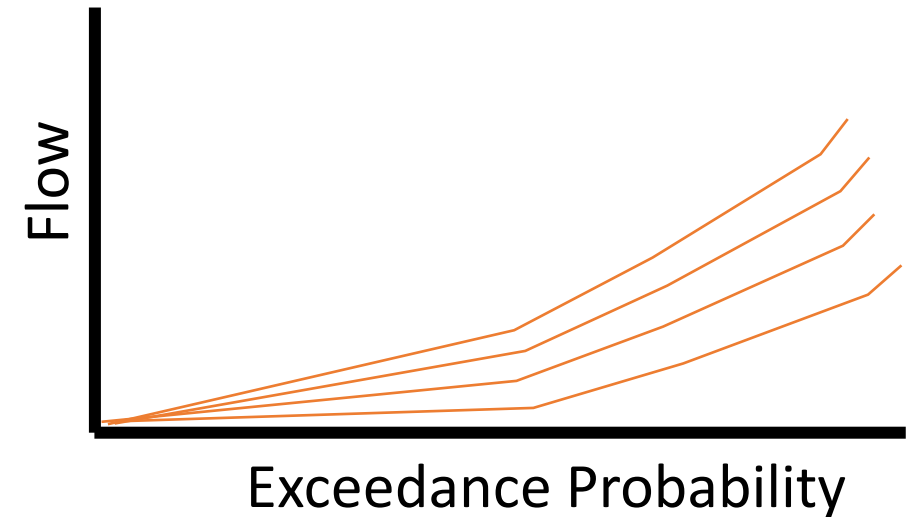
Synthetic hydrologic events



Synthetic ensemble forecasts



FRM outcomes



# Two key thrusts

1. Extended POR, *probabilistic* analysis of FIRO water supply, flood control, environmental, etc., benefits
  - Ability to assess a *greater range* of hydrologic variability
  - *Probabilistic* assessment of risk and benefits
2. Event-based simulations to explore Flood Risk Management (FRM) outcomes
  - Multiple methods for synthetic event generation including:
    - Simple scaling of POR extremes
    - HEC-WAT Hydrologic Sampler (this section)
    - Synthetic hydrology generation (last section, Research)

# Two key thrusts

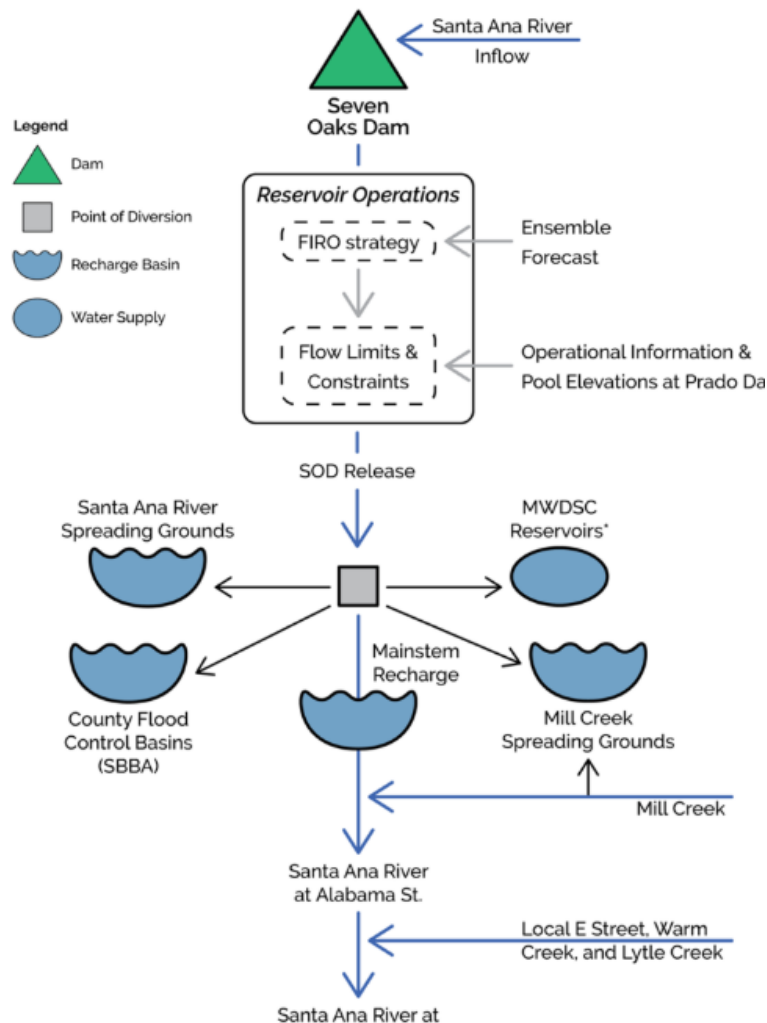
1. Extended POR, *probabilistic* analysis of FIRO water supply, flood control, environmental, etc., benefits
  - Ability to assess a *greater range* of hydrologic variability
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2. Event-based simulations to explore Flood Risk Management (FRM) outcomes
  - Multiple methods for synthetic event generation including:
    - Simple scaling of POR extremes
    - HEC-WAT Hydrologic Sampler (this section)

Research and development of synthetic ensemble forecasts through RAOPs will create new use cases

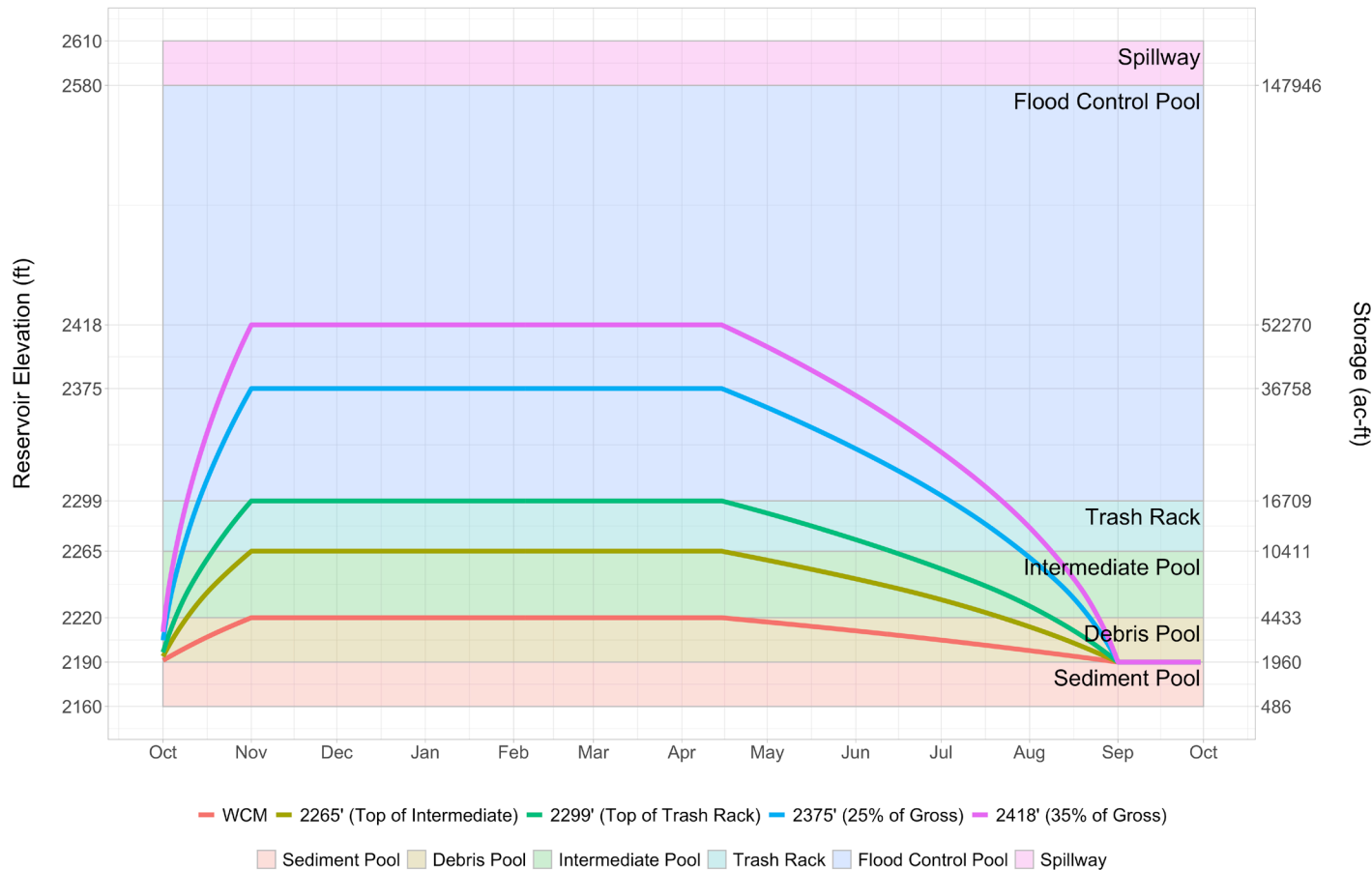
- E.g, stochastic hydrology + synthetic forecasts, last section (Research efforts)

# Single-site FIRO risk analysis: Seven Oaks dam (SOD)

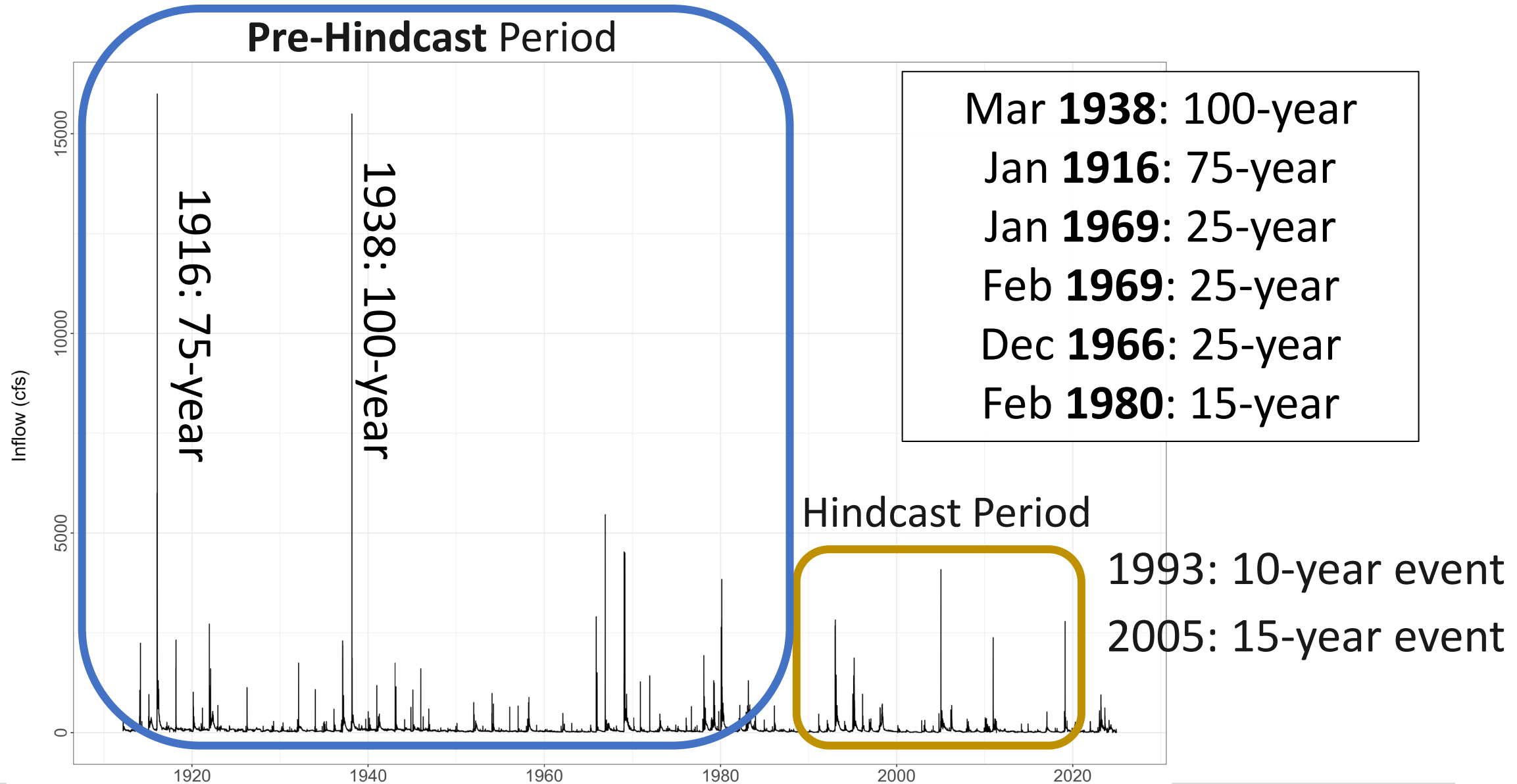
SOD System



PVA assessed FIRO pools

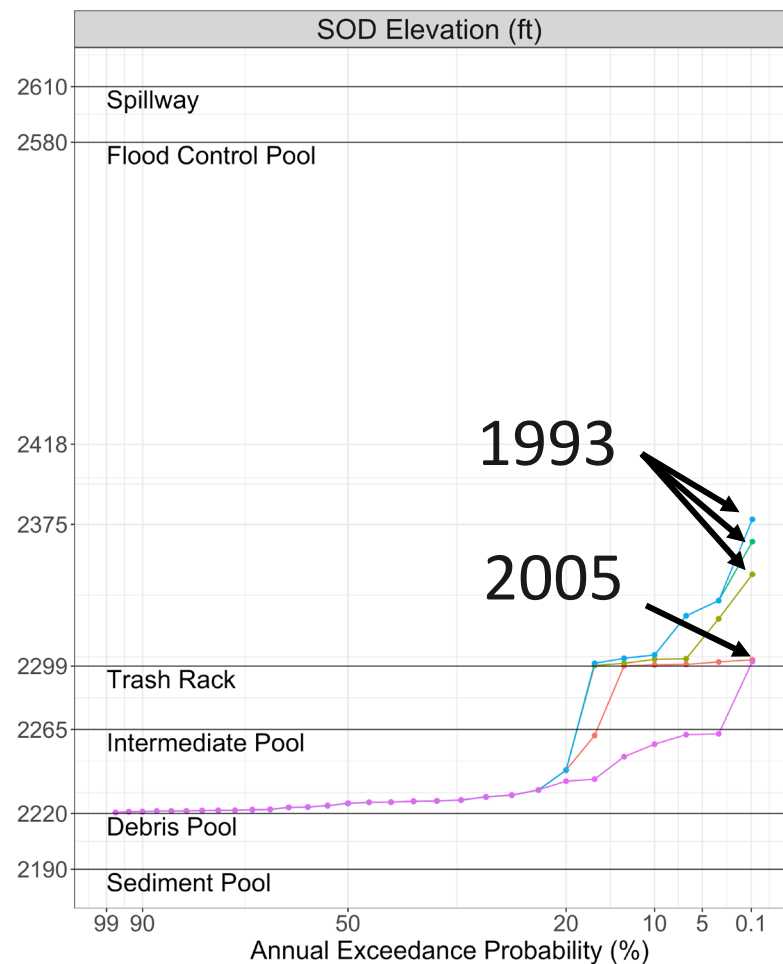


# Seven Oaks dam hindcast vs pre-hindcast

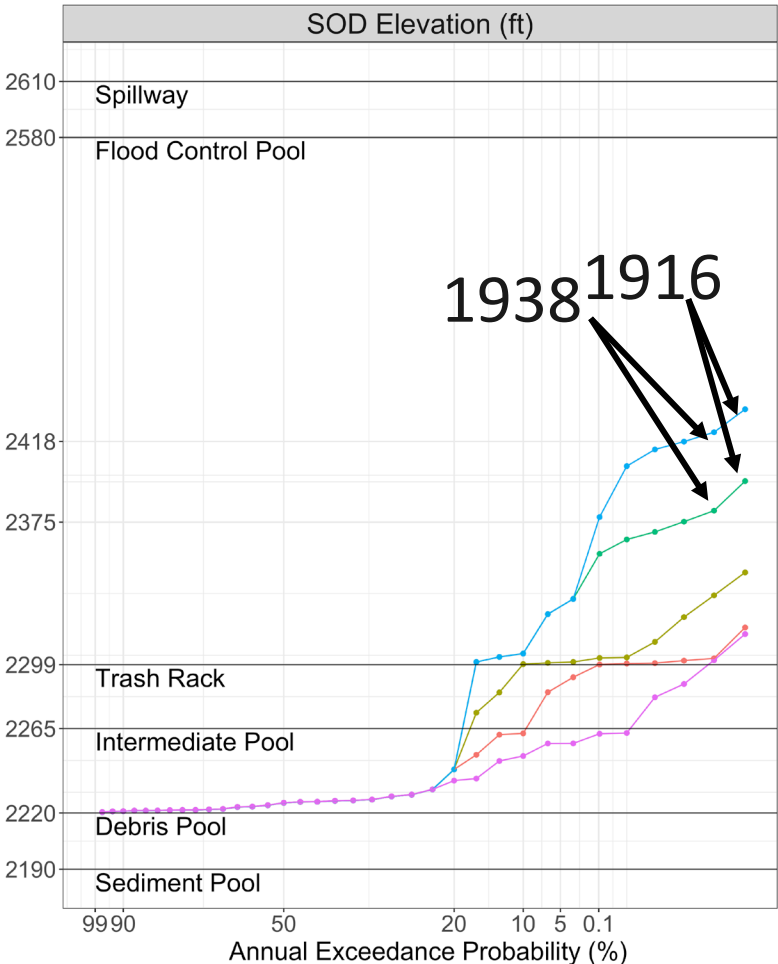


# Challenge: Lack of impactful floods in record

POR (1989 - 2019)



POR + (1912 - 1989)

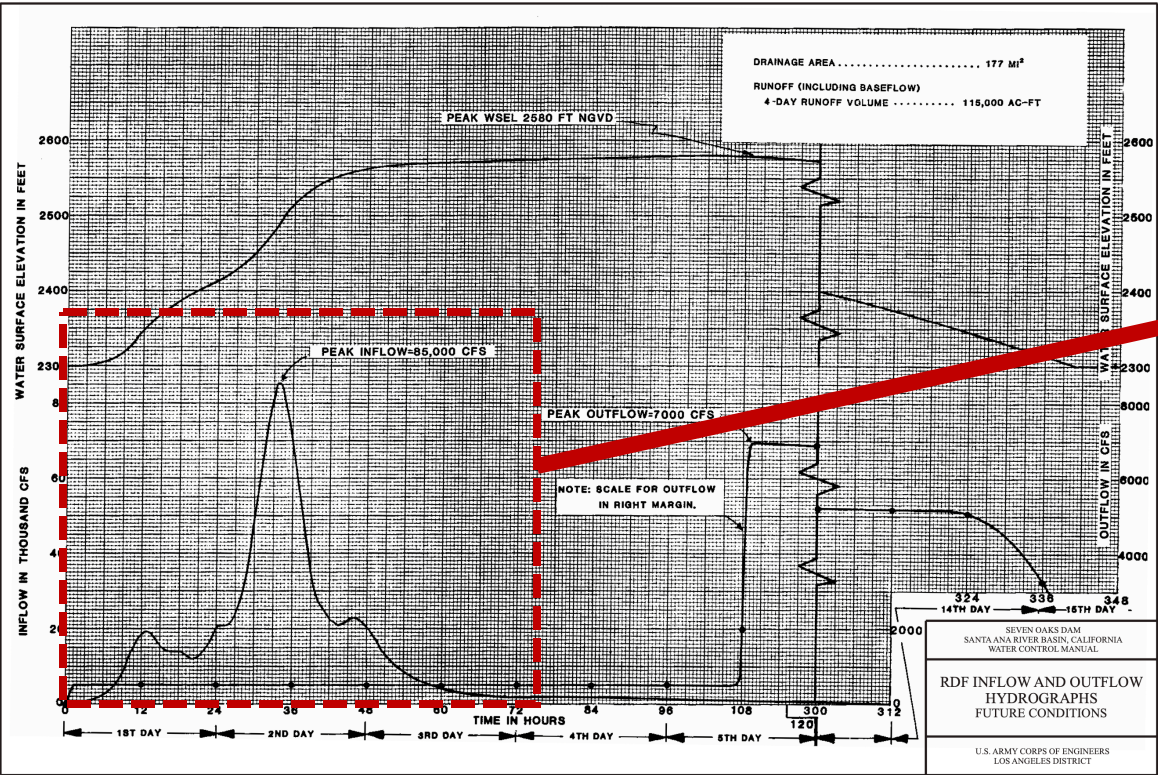


No spillway releases in POR or in pre-hindcast events

— WCM — 2265' — 2299' — 2375' — 2418'

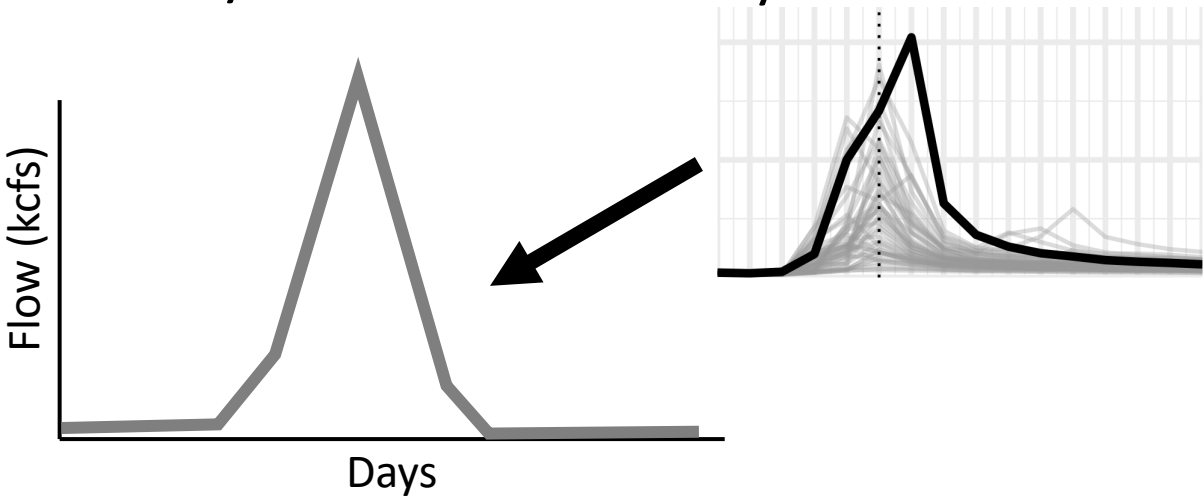
# A solution: Digitize the RDF + synthetic forecasting

Reservoir Design Flood (RDF) from WCM

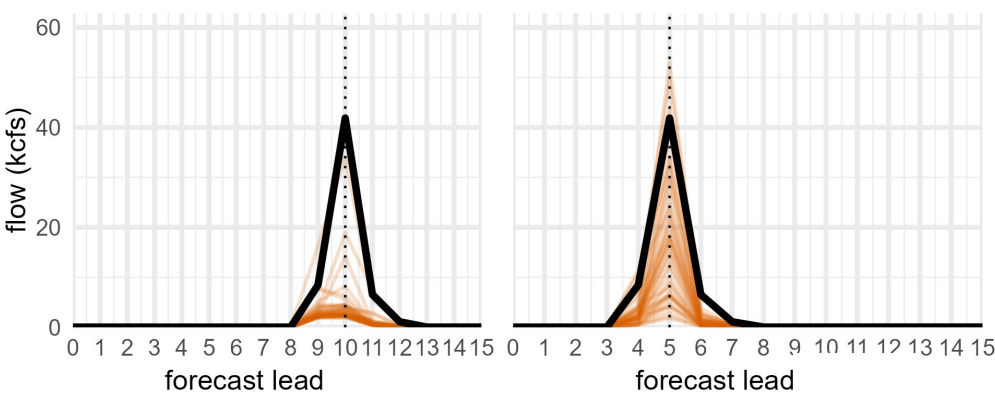


Daily inflow series

Synthetic forecasts

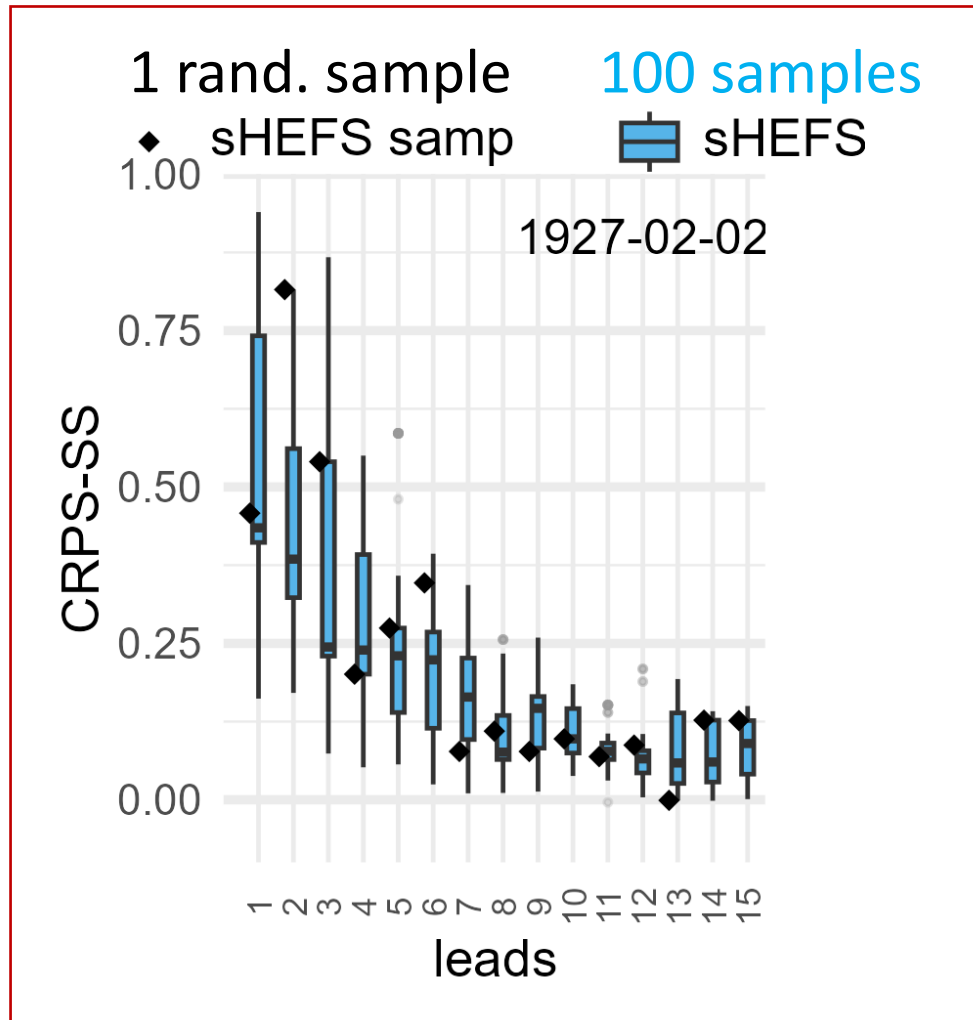


RDF synthetic ensemble forecast sequences

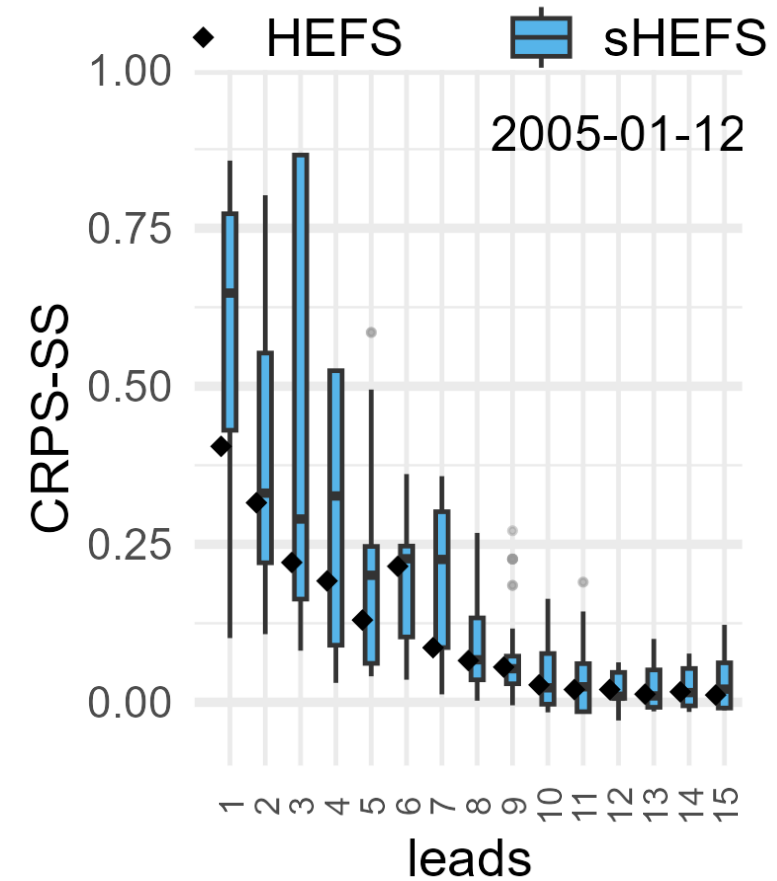


# RDF synthetic forecast analysis

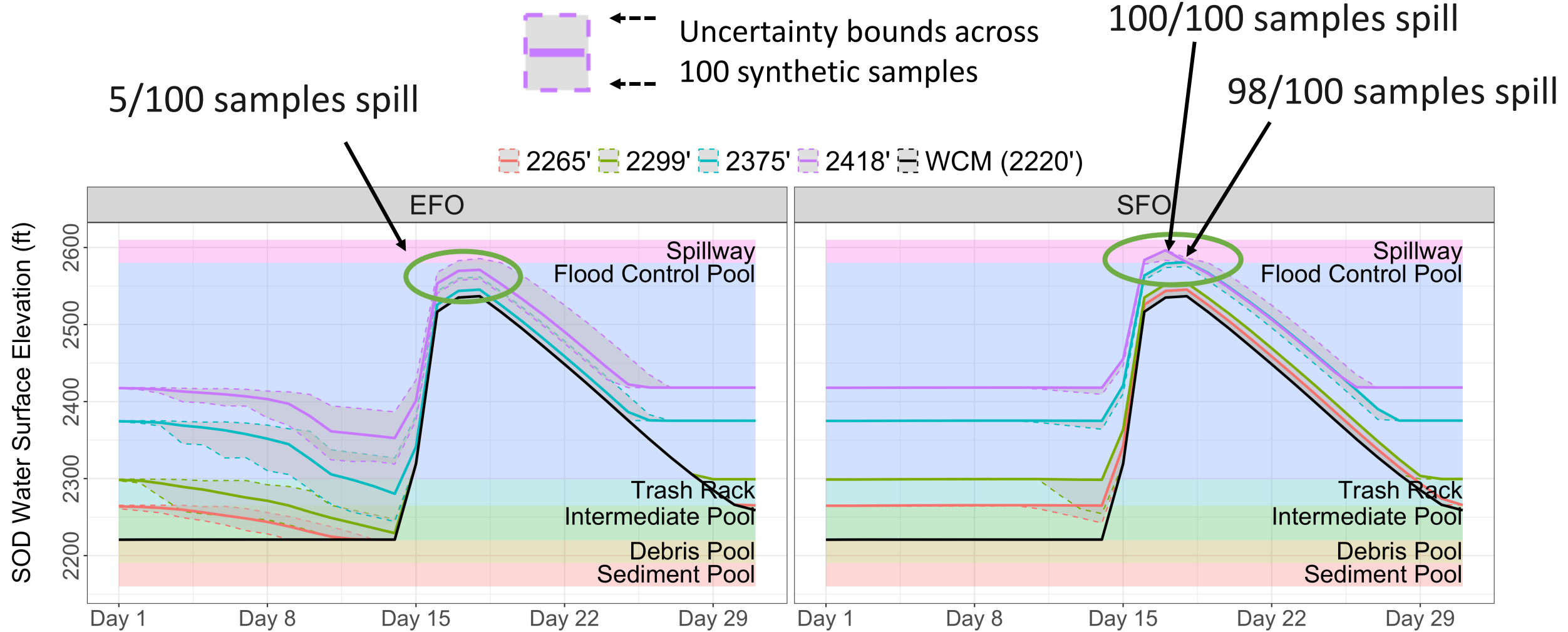
RDF + Syn-Forecasts



Syn-Forecasts vs #1  
Hindcast Event



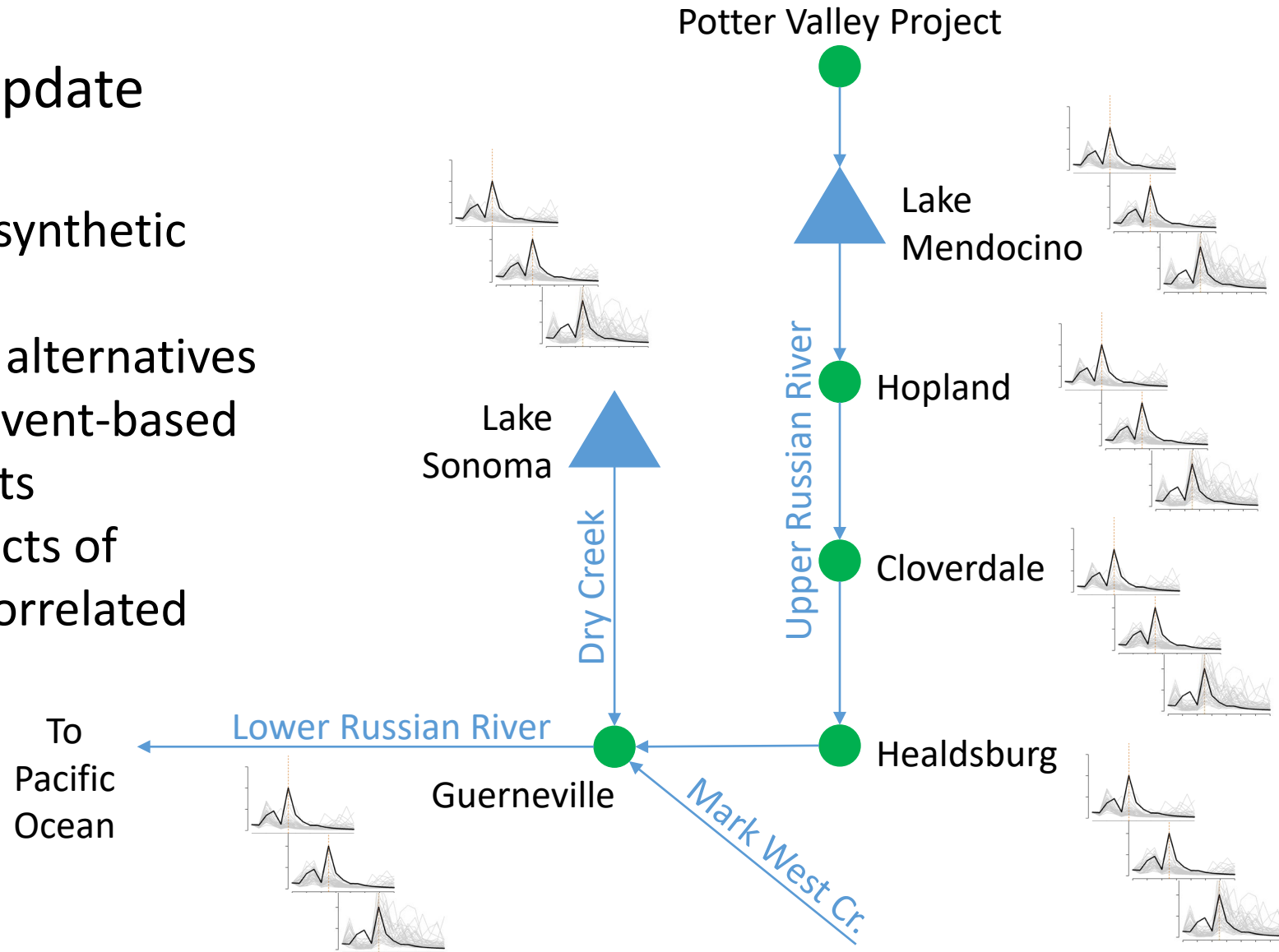
# RDF simulation results



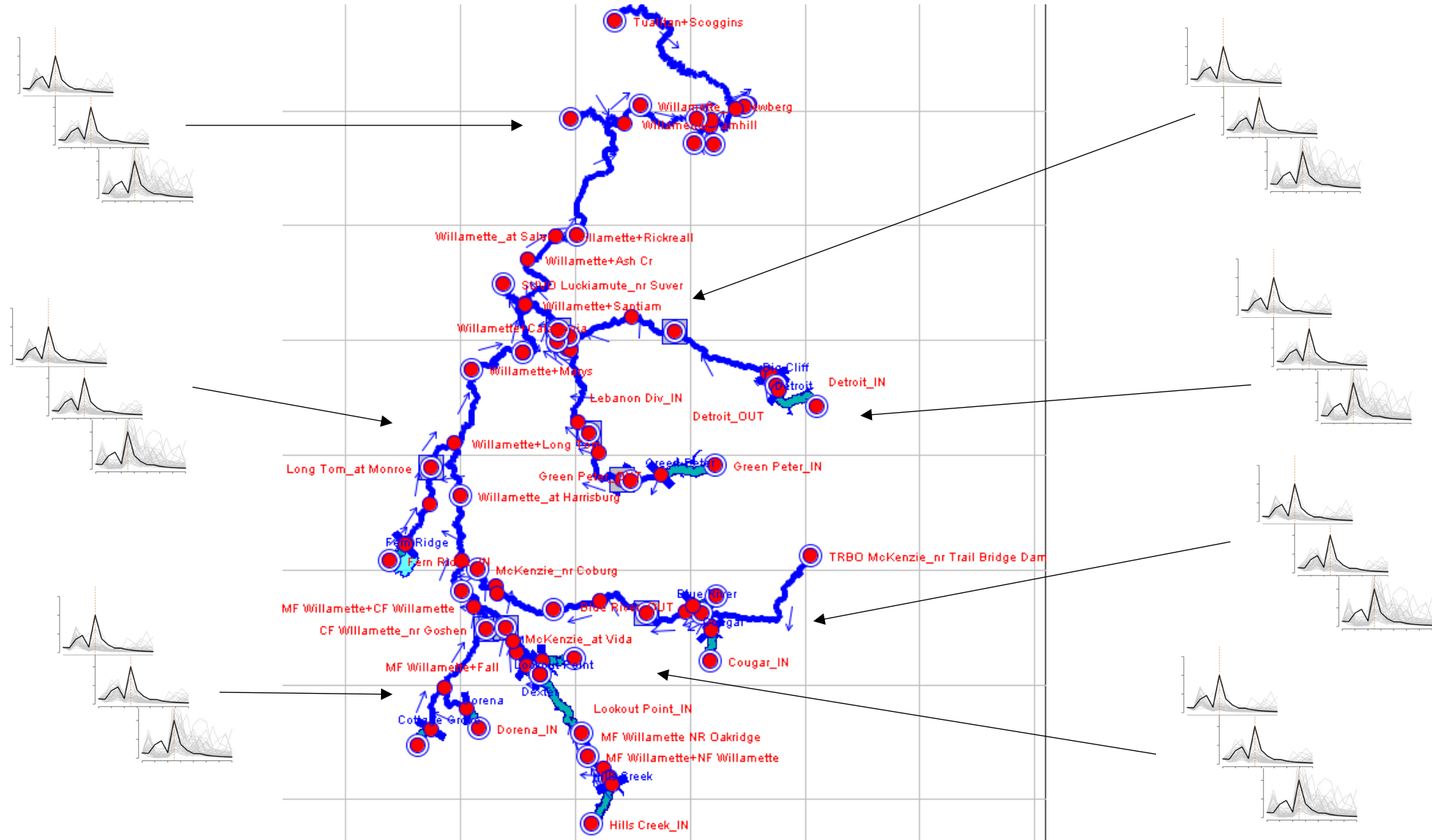
# FIRO risk analysis for a multisite system: Lake Sonoma

## Viability assessment/WCM update integration

- Generate multisite, correlated synthetic ensemble forecasts
- Test final set of candidate FIRO alternatives against extended POR and/or event-based analyses with synthetic forecasts
- Evaluate FIRO system-level effects of downstream uncertainty and correlated operations



# Upcoming multisite: Willamette River basin



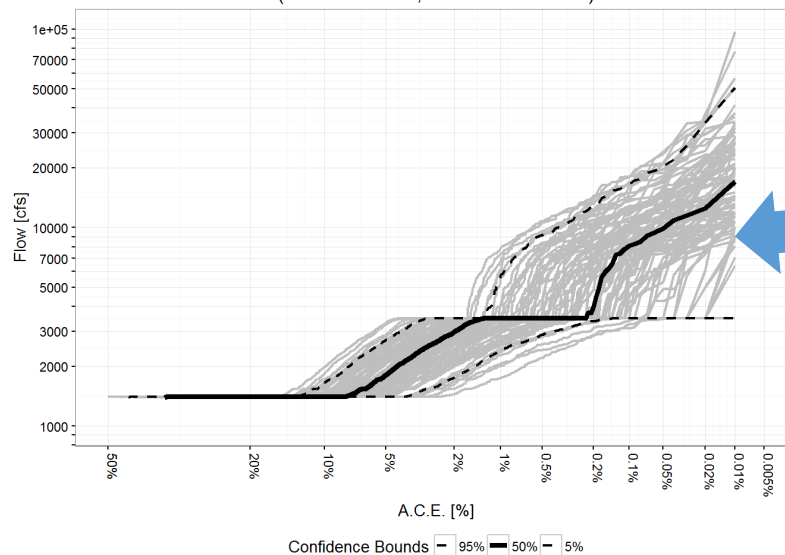
# FRA with HEC-WAT: Recall Evan's presentation

1 outer loop B =  
a realization

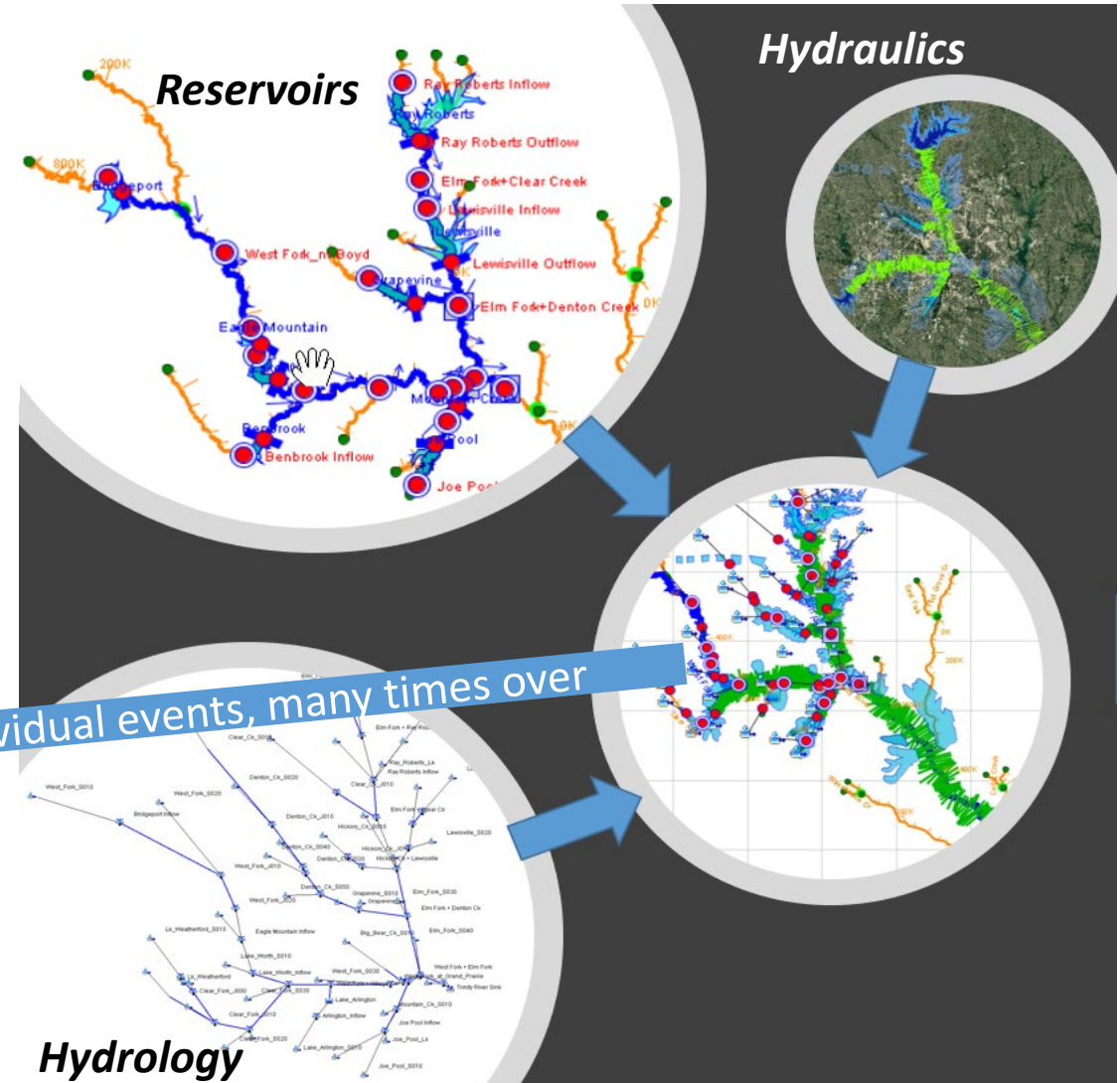


inner loop A varies natural  
variability, computes Stage  
Frequency;

outer loop B varies  
knowledge uncertainty,  
computes distribution of  
Stage Frequency

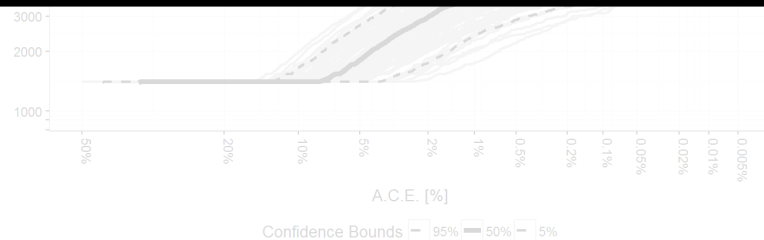


Individual events, many times over



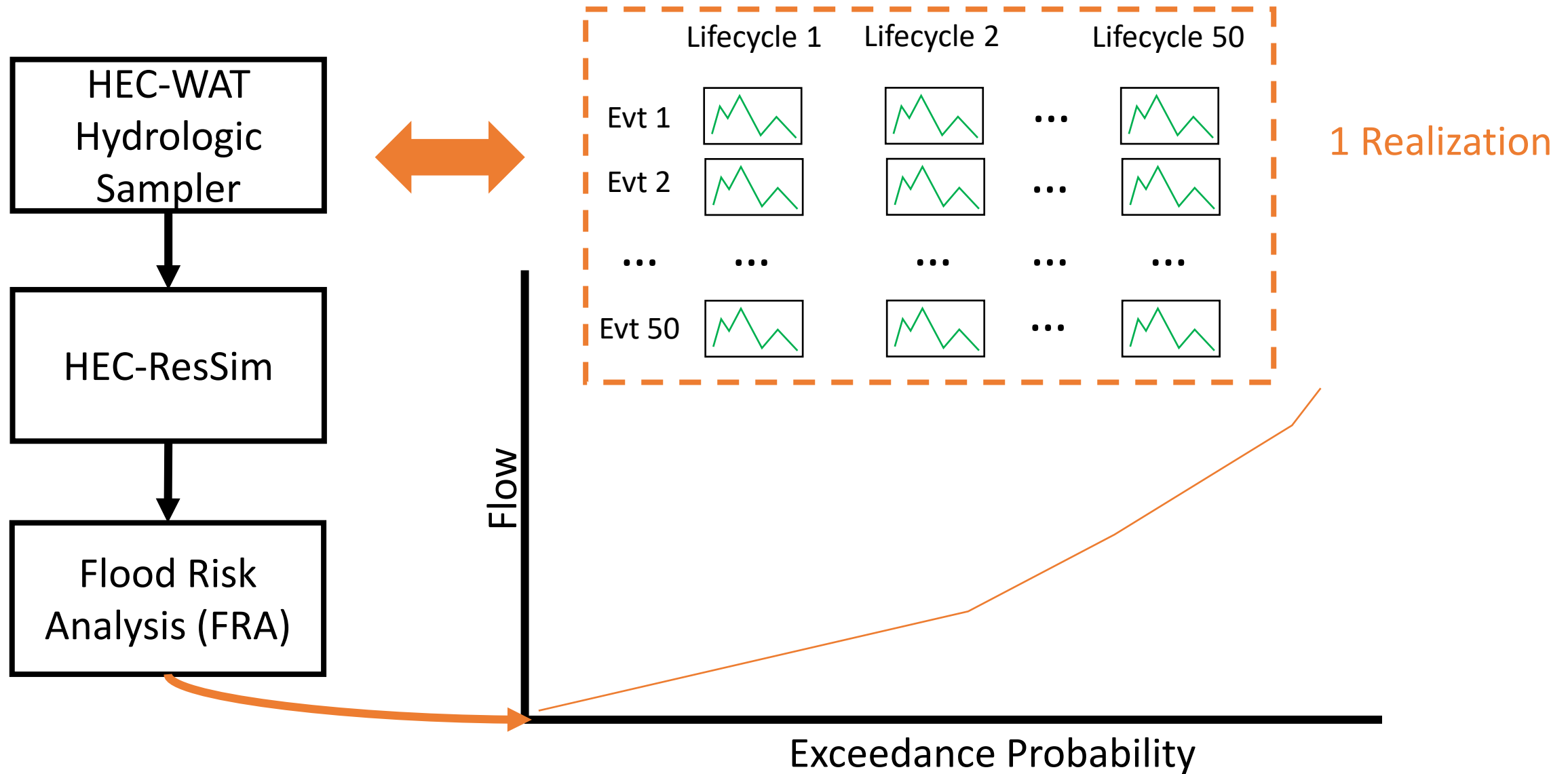
# FRA with HEC-WAT: Recall Evan's presentation

USACE flood risk management (FRM) policy requires that USACE analytical processes include methods and tools that employ *integrated, comprehensive, systems and life-cycle based* approaches and risk-based concepts in planning, design, construction, operations and major maintenance. These USACE methods need to incorporate the *system response of projects* when considering load distribution and failure possibilities

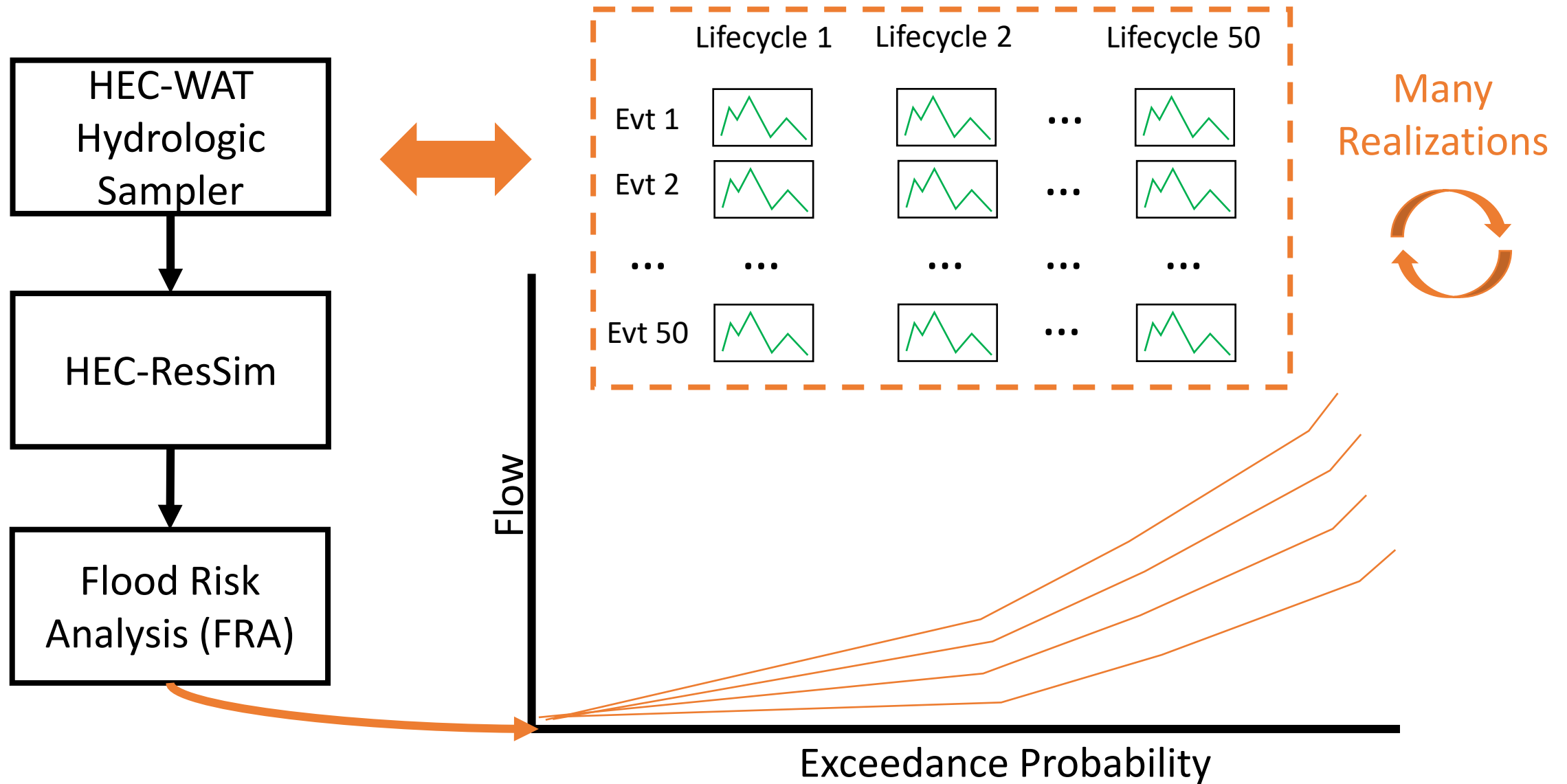


Hydrology

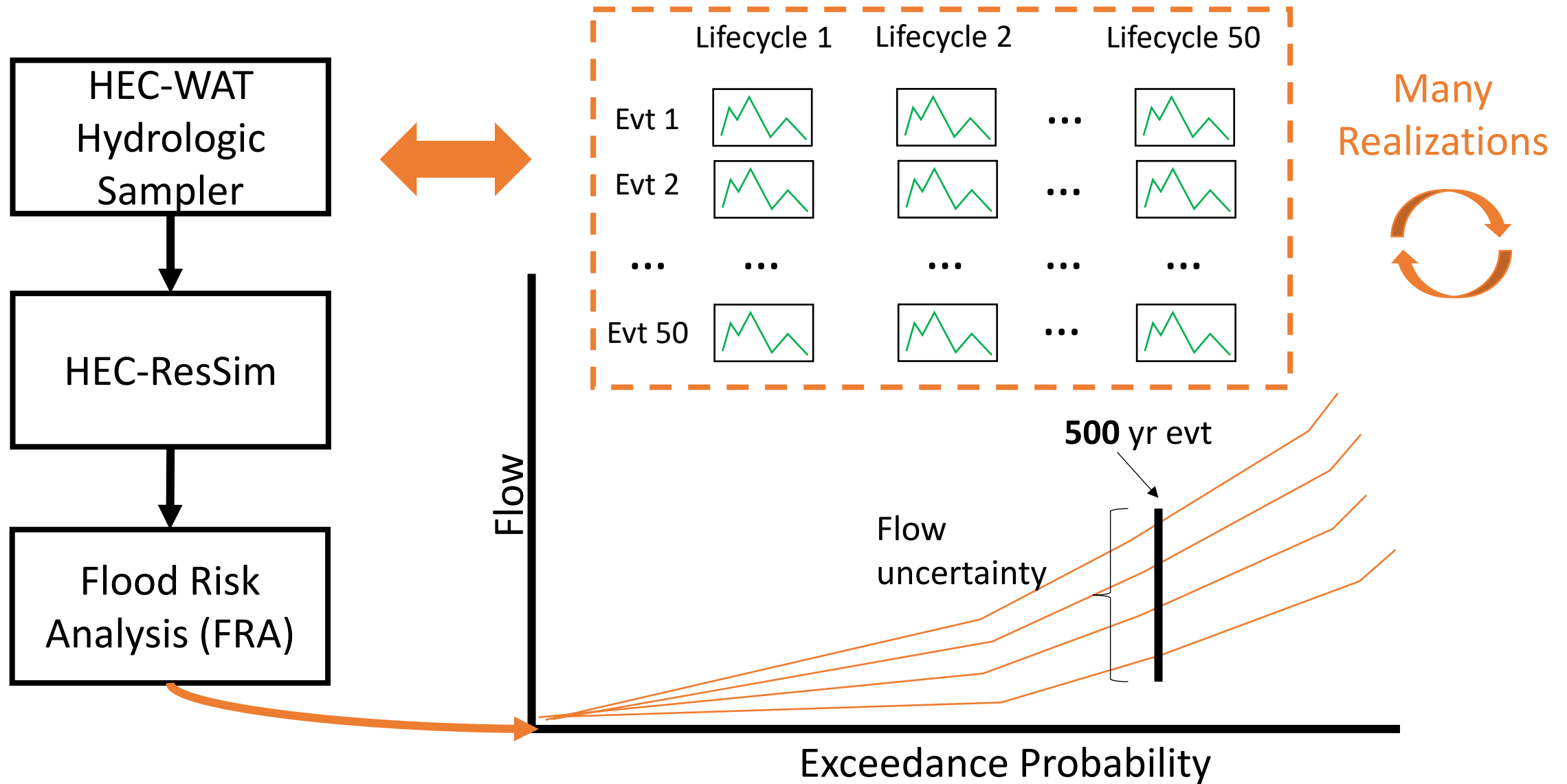
# HEC-WAT FRA basic procedure



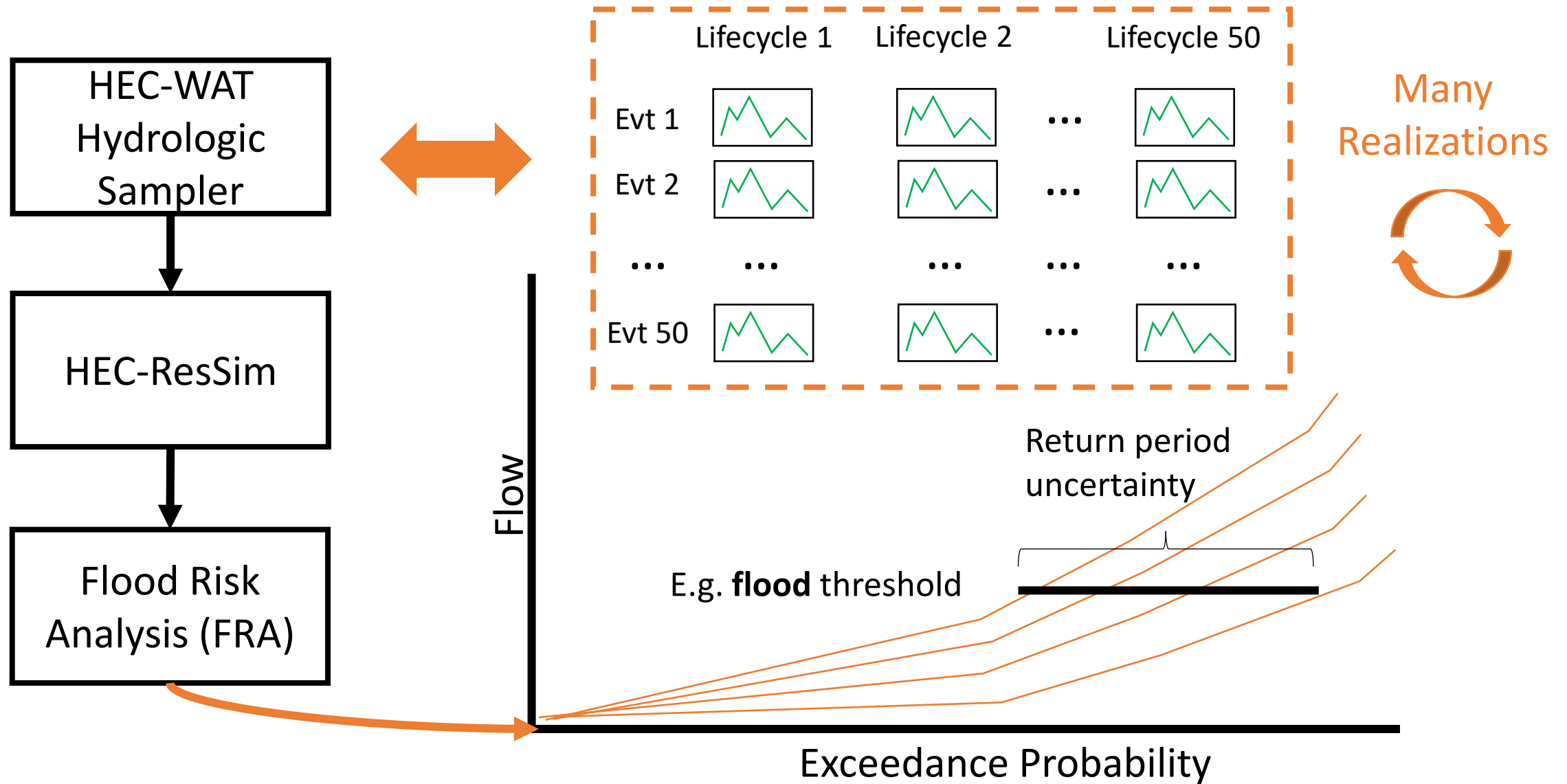
# HEC-WAT FRA basic procedure



# HEC-WAT FRA basic procedure

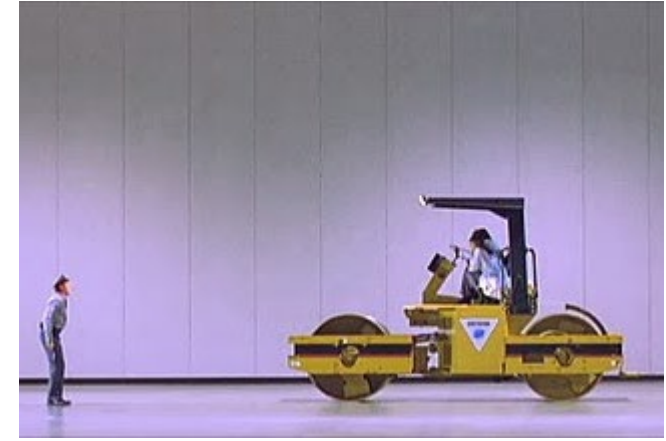
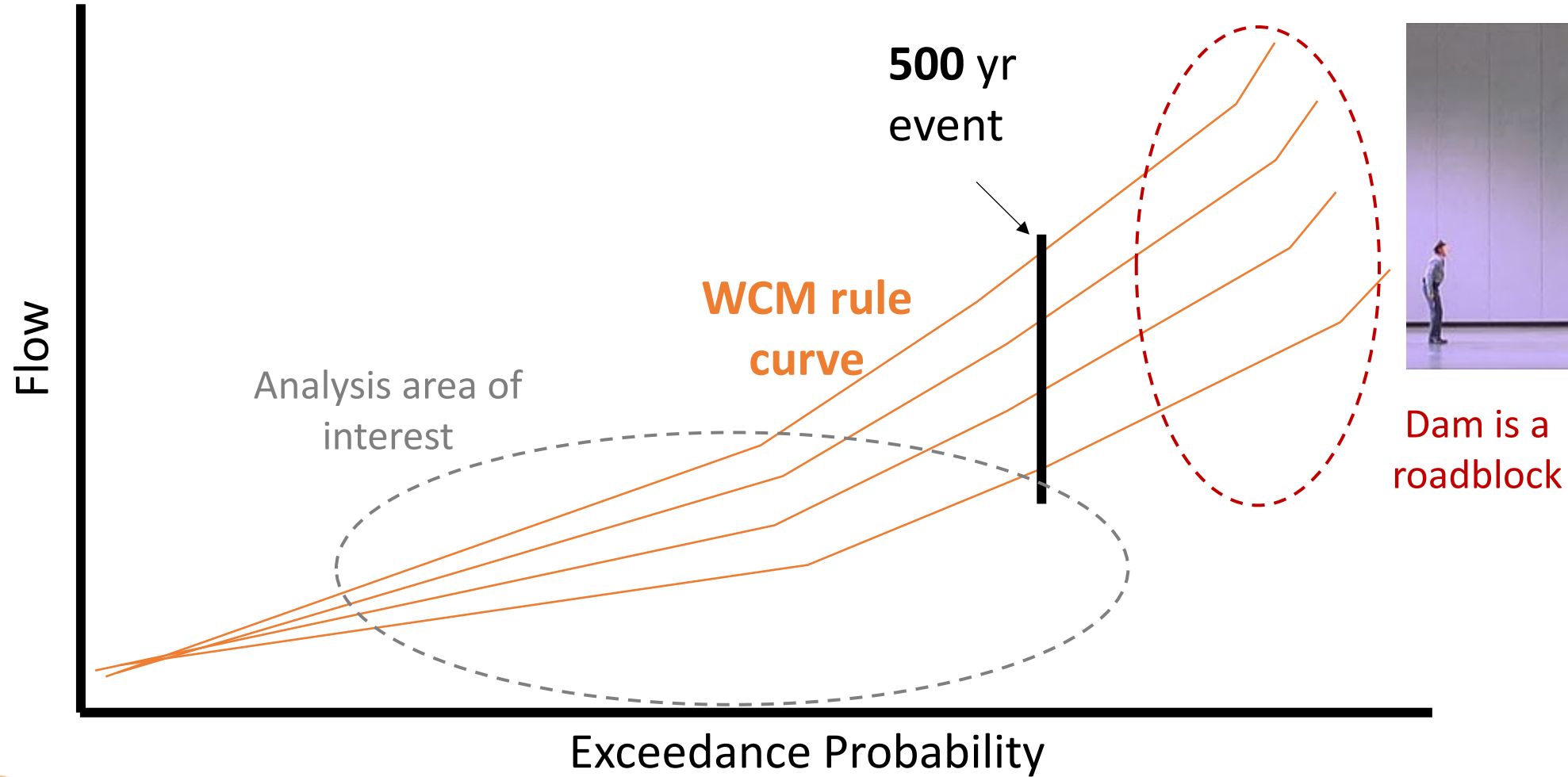


# HEC-WAT FRA basic procedure

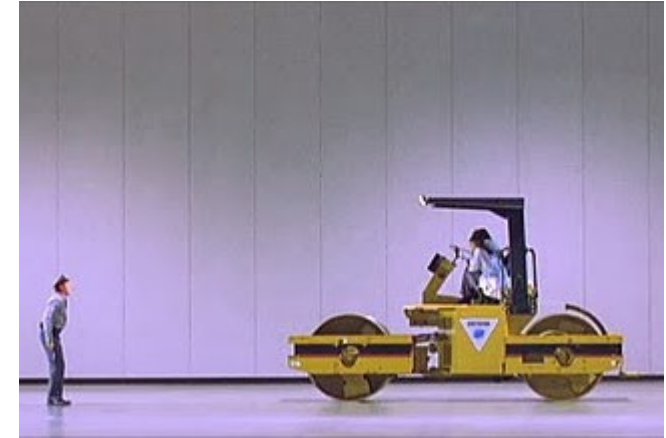
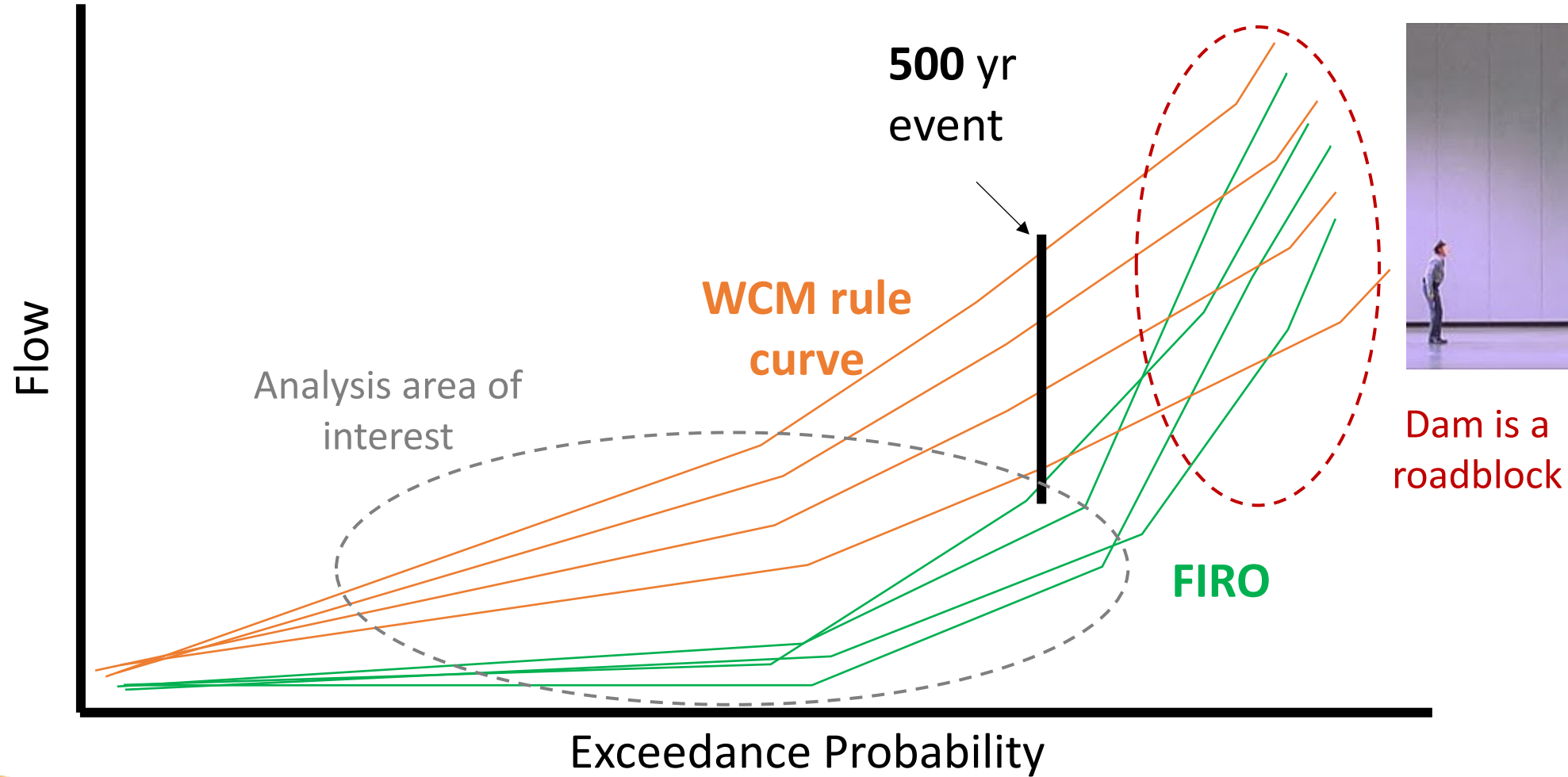




# FIRO FRA with HEC-WAT + Synthetic Forecasts



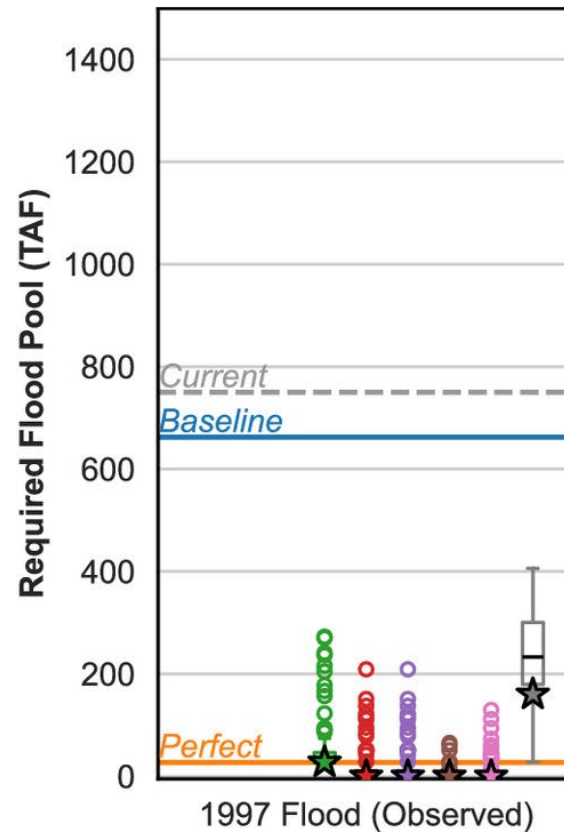
# FIRO FRA with HEC-WAT + Synthetic Forecasts



Dam is a roadblock

# Synthetic ensemble forecasting to support FIRO research

# FIRO strategy robustness

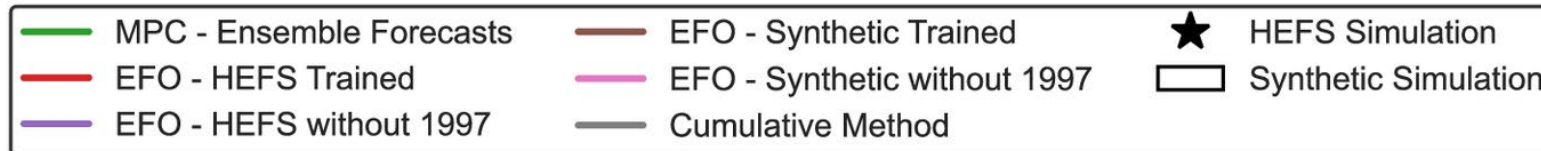


Current Lake Oroville Flood Pool

Flood pool required for WCM policy approximation

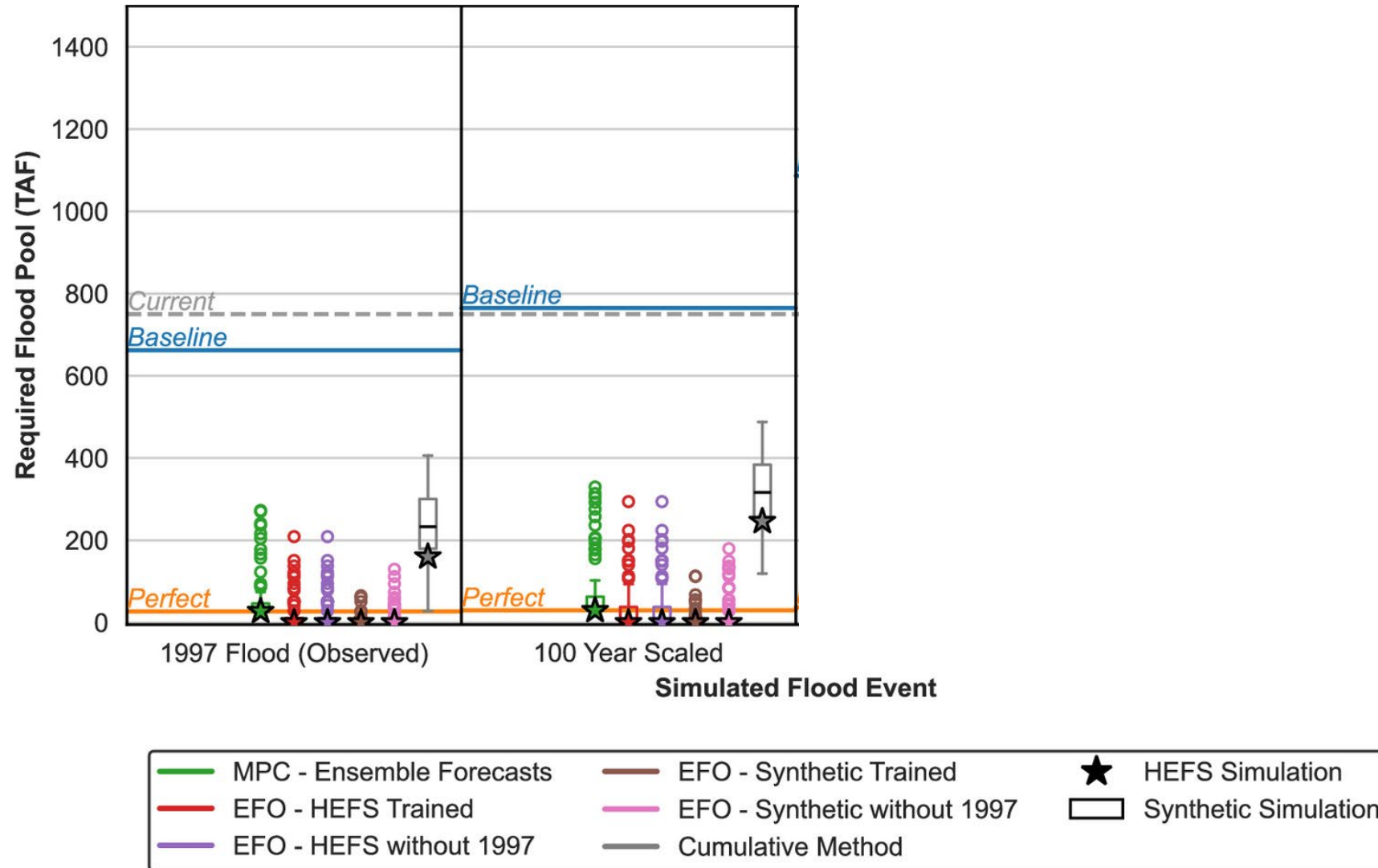
Flood pool required for FIRO policies + synthetic forecast uncertainty

Flood pool required for a Perfect Forecast FIRO policy



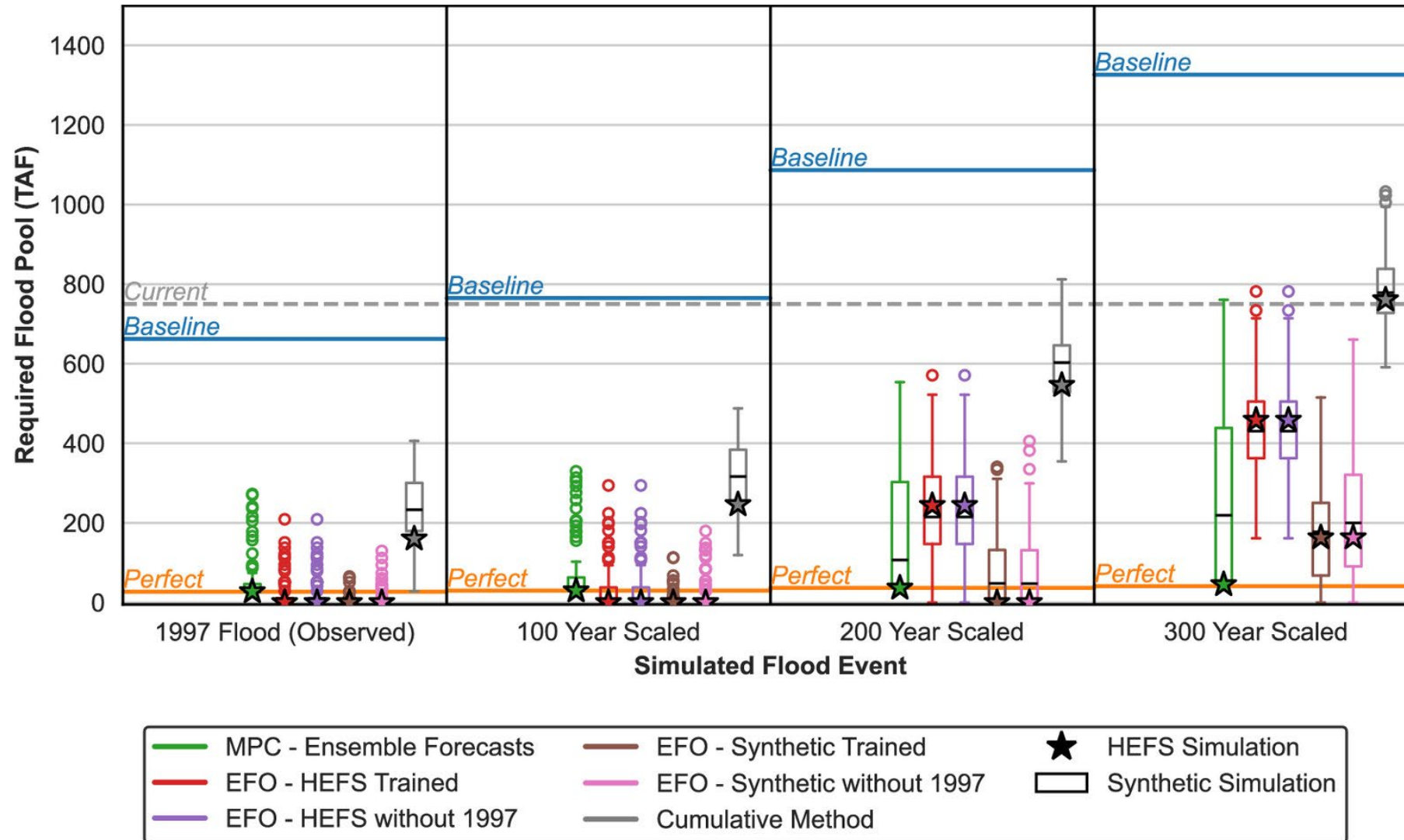
*Taylor et al., 2026*

# FIRO strategy robustness



*Taylor et al., 2026*

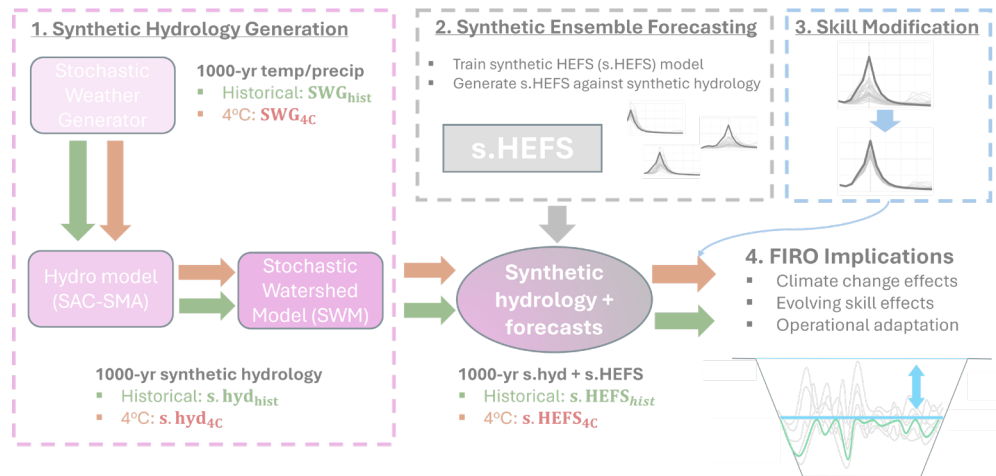
# FIRO strategy robustness



Taylor et al., 2026

# Evaluating FIRO under changing conditions

## Large-sample synthetic hydrology and forecasting generator



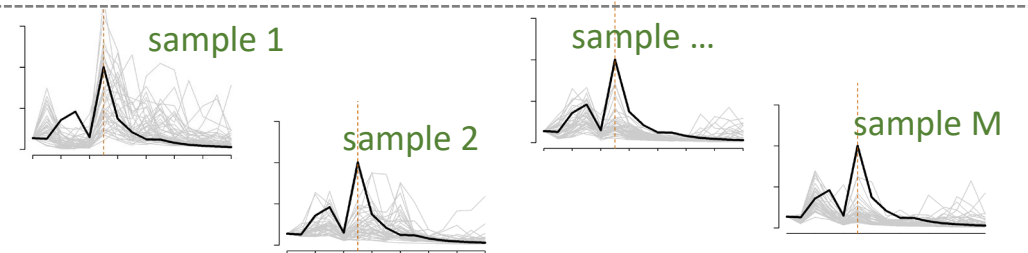
Brodeur et al., In Preparation

1000-yr  
synthetic  
hydrology



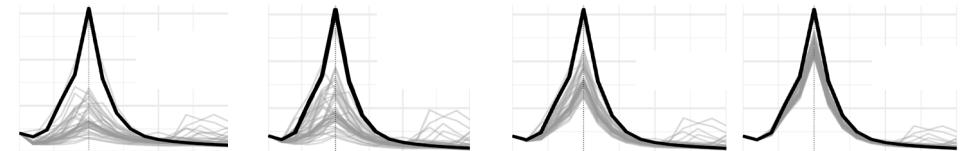
+

Synthetic  
ensemble  
forecasts



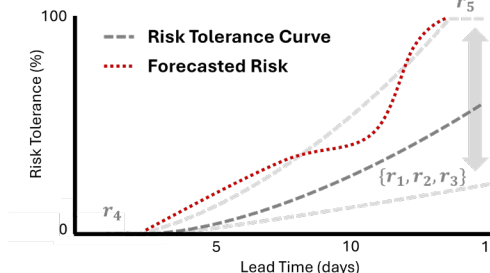
+

Forecast skill  
modification

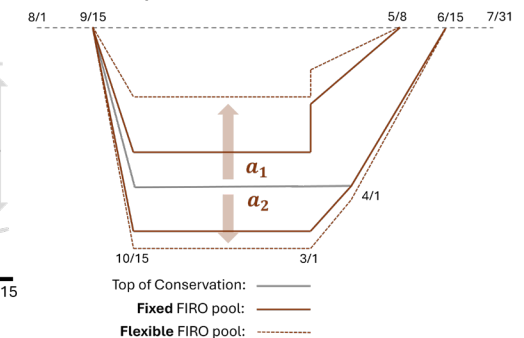


FIRO analysis  
under  
changing skill

a. EFO policy

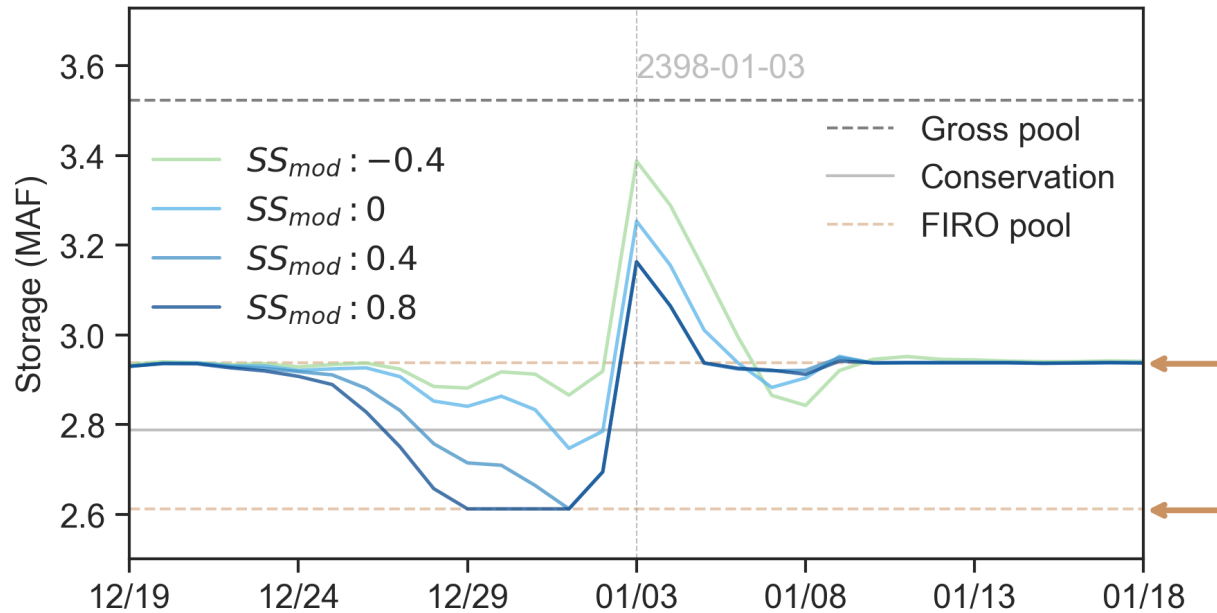


b. FIRO pool



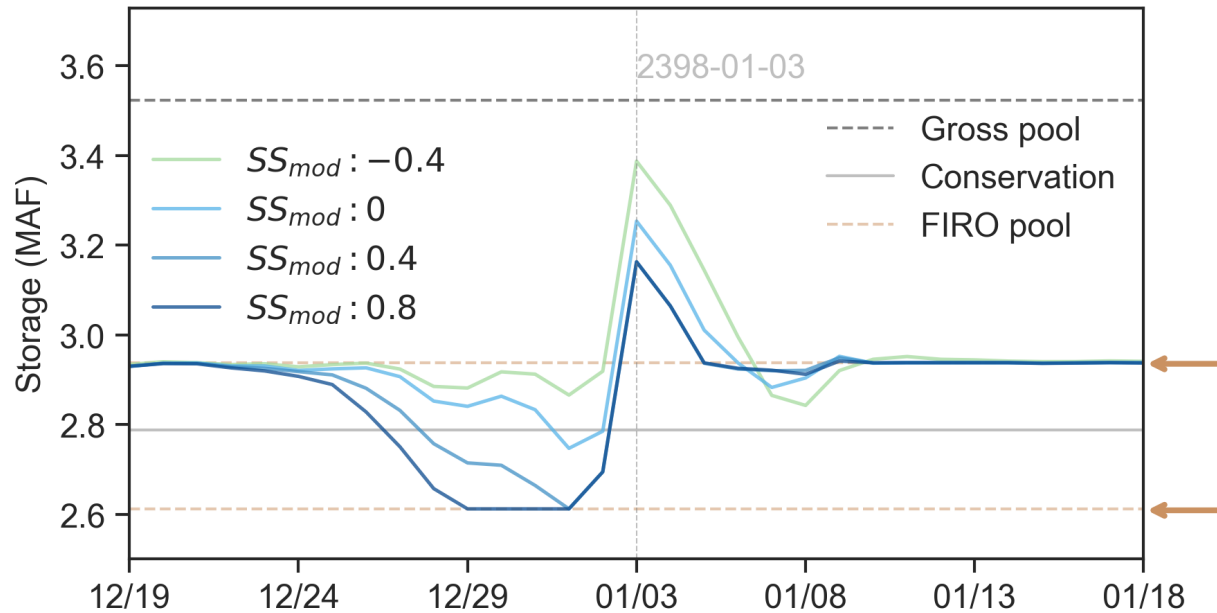
# Implications of evolving forecast skill

FIRO flood risk implications of  
evolving skill

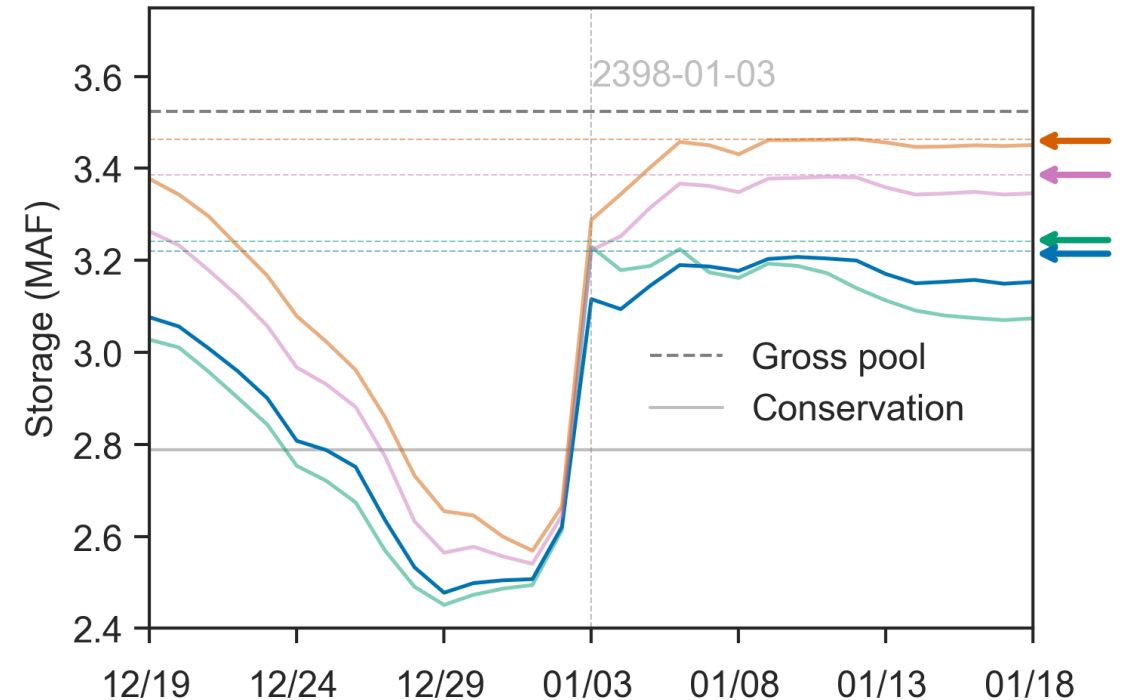


# Implications of evolving forecast skill

## FIRO flood risk implications of evolving skill



## Potential FIRO pool implications of evolving skill



# Synthetic forecasting development and operational applications to support robust FIRO risk analysis - Summary

## Key Topics

- Overview of synthetic ensemble forecasting
- Verification of synthetic ensemble forecasts
- Synthetic forecasts to support ongoing FIRO implementation efforts:
  - Single-site cases (e.g. Seven Oaks Dam)
  - Multisite cases (e.g. Lake Sonoma)
  - Integration w/HEC-WAT for Flood Risk Analysis
- Synthetic forecasts to support FIRO research
  - FIRO strategy robustness (Taylor et al., 2026)
  - FIRO performance under changing skill (Brodeur et al., *In preparation*)

## Key Takeaways

- Verification of synthetic forecasts supports operational trust in FIRO outcomes assessment
- Synthetic forecasting opens many doors for robust FIRO analysis:
  - Extended POR analysis of water supply, flood risk, environmental outcomes
  - Enhanced flood risk analysis through integration with USACE tools like HEC-WAT
- Synthetic forecasting can support a wide range of novel FIRO research:
  - Detailed testing of FIRO strategy robustness
  - Analysis of FIRO outcomes under changing forecast skill