Conflict, Coordination & Control: How can we discover the real risks and resilience of Land-Energy-Water Systems?

Patrick Reed, Cornell University

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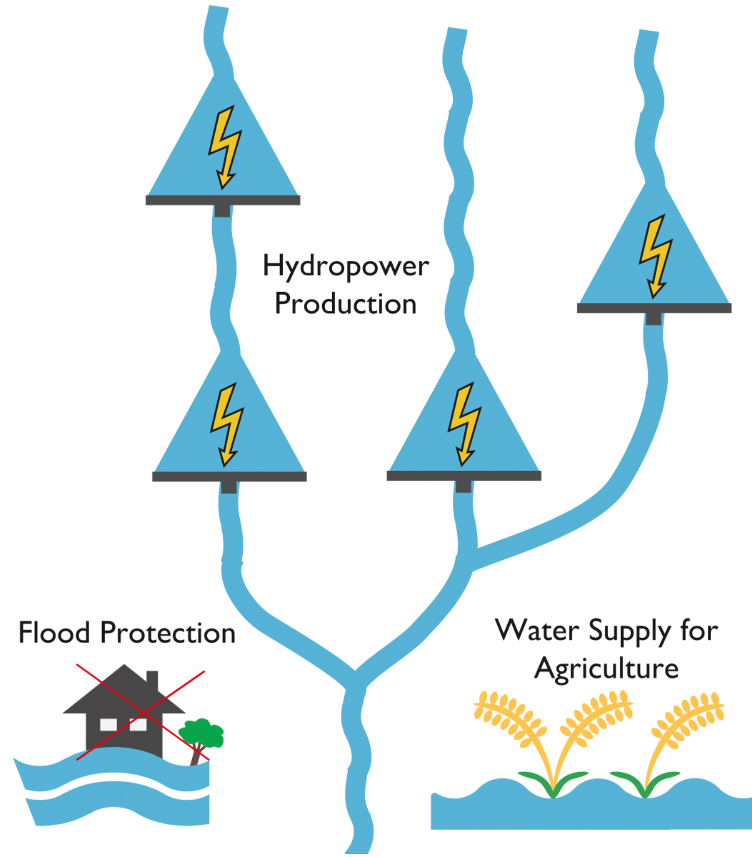

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10 May 2018

Key Points

Model-based understanding of the complex evolution of land-energy-water systems as well as their "risks" and "resilience"

1. Must be able to capture extremes and real failure modes.

2. Is heavily influenced by human preferences, tradeoffs in conflicting demands, and high fidelity representations of candidate actions

3. Should create a platform for understanding *state-action-consequence feedbacks* as a function of the information available to the actual humans managing the systems

Red River Basin

Second largest river basin in Vietnam

Capital city of Hanoi sits in delta, threatened by floods

In 2002, UNDP estimated annual damages of 130M USD in the delta, 50M USD in Hanoi[1]

[1]Hansson, K., and Ekenberg, L. (2002). Flood Mitigation Strategies for the Red River Delta, in: International Conference on Environmental Engineering, An International Perspective on Environmental Engineering, Canada.

Red River Basin

To provide flood protection to Hanoi and the delta, the Vietnamese government has started constructing reservoirs

But how should they be coordinated to meet multi-sector demands?

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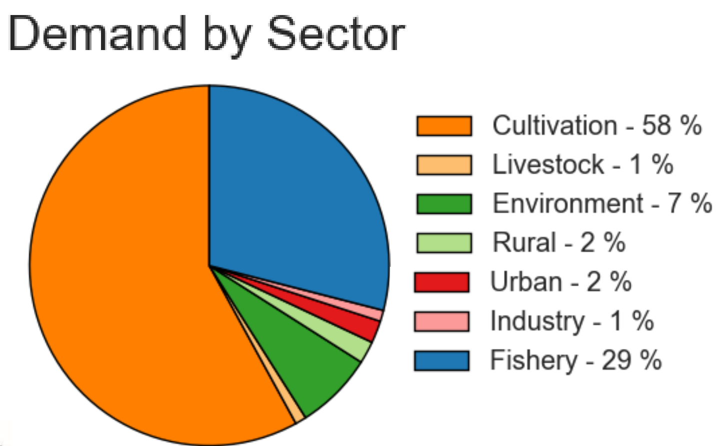
Multi-sector reservoir demands

Dams provide hydropower

Hydropower currently represents 46% of Vietnam's total installed electric power capacity

Reservoirs provide reliable water supply

70% of Vietnamese population employed in agriculture,
76% of Vietnamese agriculture is irrigated



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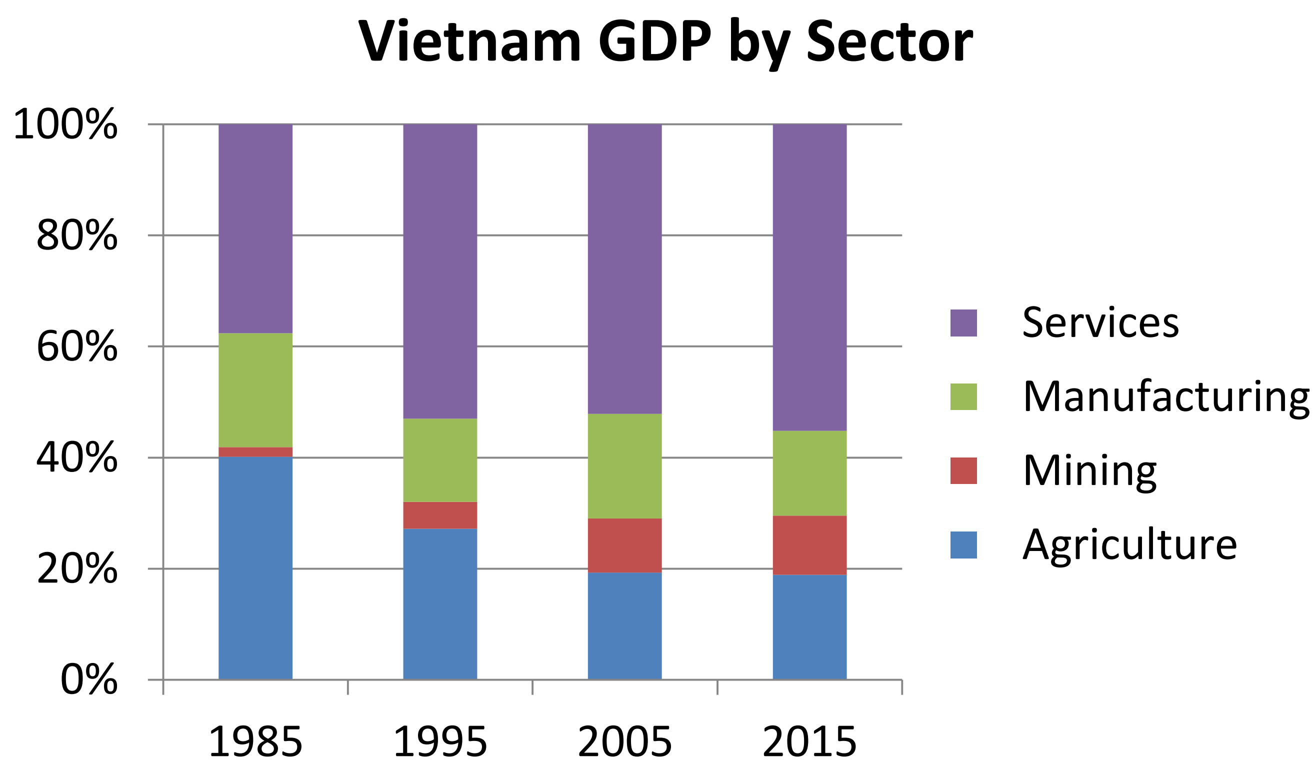
But will these demands change? How?



Population growth in Hanoi could increase water demands

Or urbanization could reduce water demands

Will the climate change? How?

Vietnam Feels the Heat of a 100-Year Drought

TIME

By Martha Ann Overland / Hanoi | Thursday, Mar. 04, 2010

Like 4 | Tweet | G+1 2 | Share | Read Later

Every year, even at the peak of Vietnam's dry season, when the Red River is at its lowest, Hanoi's skilled captains manage to negotiate their flat-bottomed boats through its shallow waters. But this year, with a drought gripping the entire country and water levels at record lows, the river is eerily quiet. What is normally a bustling waterway is becoming a winding river of sand, and farmers who depend upon the river for irrigation are watching the expanding sandbars as nervously as the boat captains. "If there is no water in the coming days," says 59-year-old farmer Vu Thi La, who just put in her spring rice seedlings, "it will all die."

Nguyen Huy Kham / Reuters

The dried-up bed of the Red River, near Long Bien Bridge in Hanoi on Dec. 1, 2009

ASIA PACIFIC

The New York Times

Drought and 'Rice First' Policy Imperil Vietnamese Farmers

By JANE PERLEZ MAY 28, 2016

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Red River rising

The water level of the Red River has been rising sharply in I discharge from the Hoa Binh Hydropower Plant reservoir.

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Red River System Goals

How should we translate and evaluate these narrative goals in our models?

Find operations for four largest reservoirs that

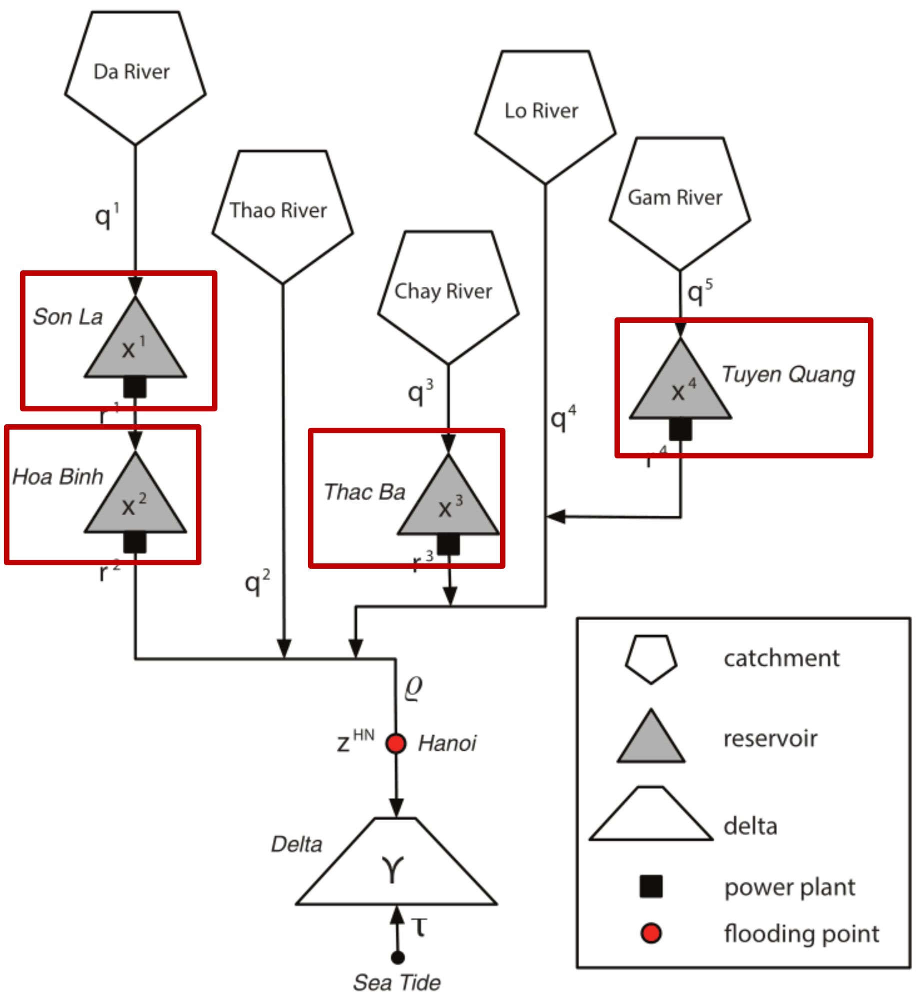
1) Maximize Hydropower Production

2) Minimize Water Supply Deficit

3) Minimize Flooding at Hanoi

and are robust to deep uncertainties

Red River System



Official Guidelines

Flood Season | **Dry Season** | **Between Seasons**

Determine SL release → If/then/else statements that depend on: t, s^{SL}, s^{HB}, s^{TQ}, $z^{HN, fcst}$

Determine HB release → If/then/else statements that depend on: t, r^{SL}, s^{HB}, s^{TQ}, $z^{HN, fcst}$

Determine TQ release → If/then/else statements that depend on: t, r^{HB}, s^{HB}, s^{TQ}, $z^{HN, fcst}$

Determine TB release → Unregulated. Use release from one of our optimized policies.

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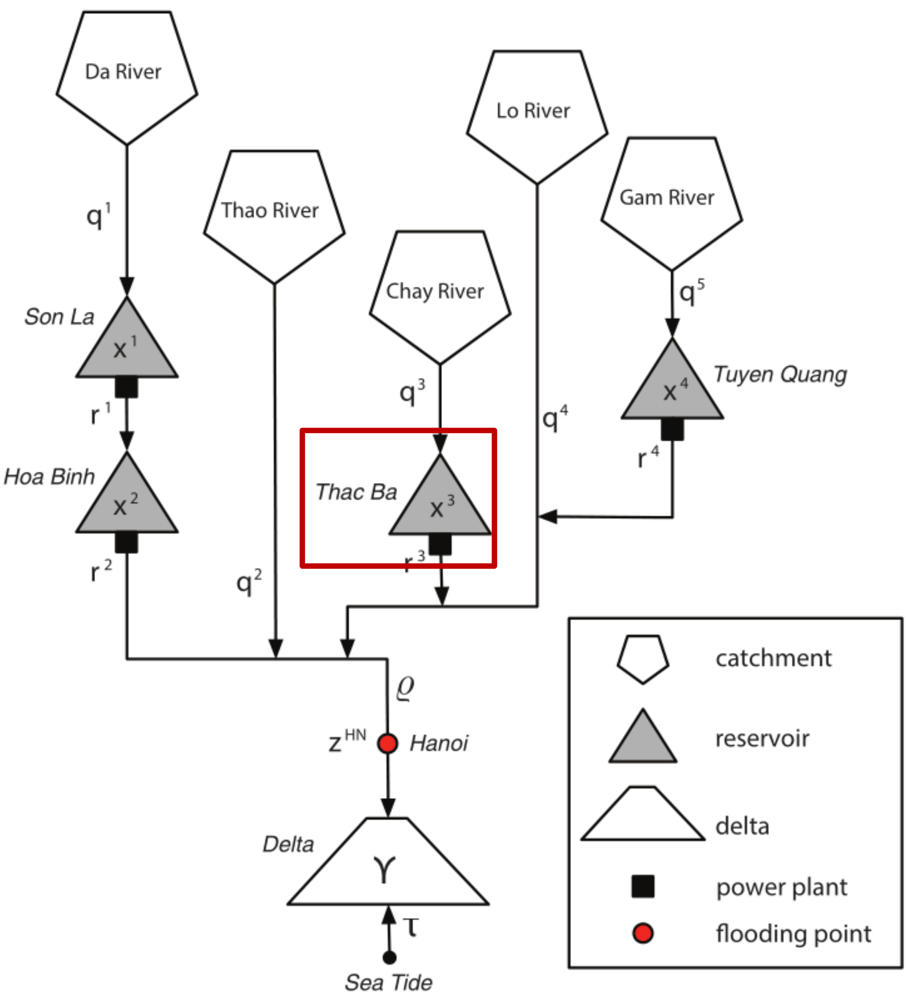
Red River System

Official Guidelines



Flood Season

↓

Determine SL release

↓

Determine HB release

↓

Determine TQ release

↓

Determine TB release

Dry Season

↓

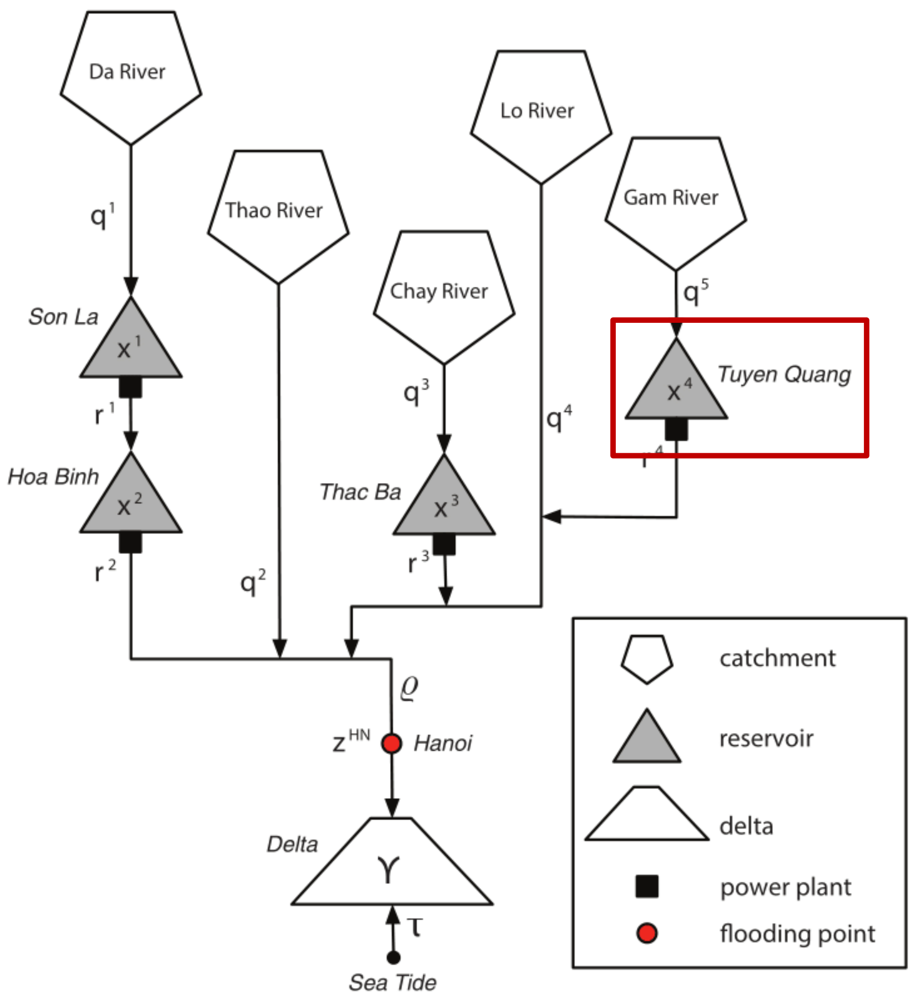
Determine TB release

If $s^{TB} < s^{TB, lower\ target}$ → $u^{TB} = 0$

Else → $u^{TB} = u^{TB, min}$

Between Seasons

Red River System



Official Guidelines

Flood Season

Determine SL release → Determine HB release → Determine TQ release → Determine TB release

Dry Season

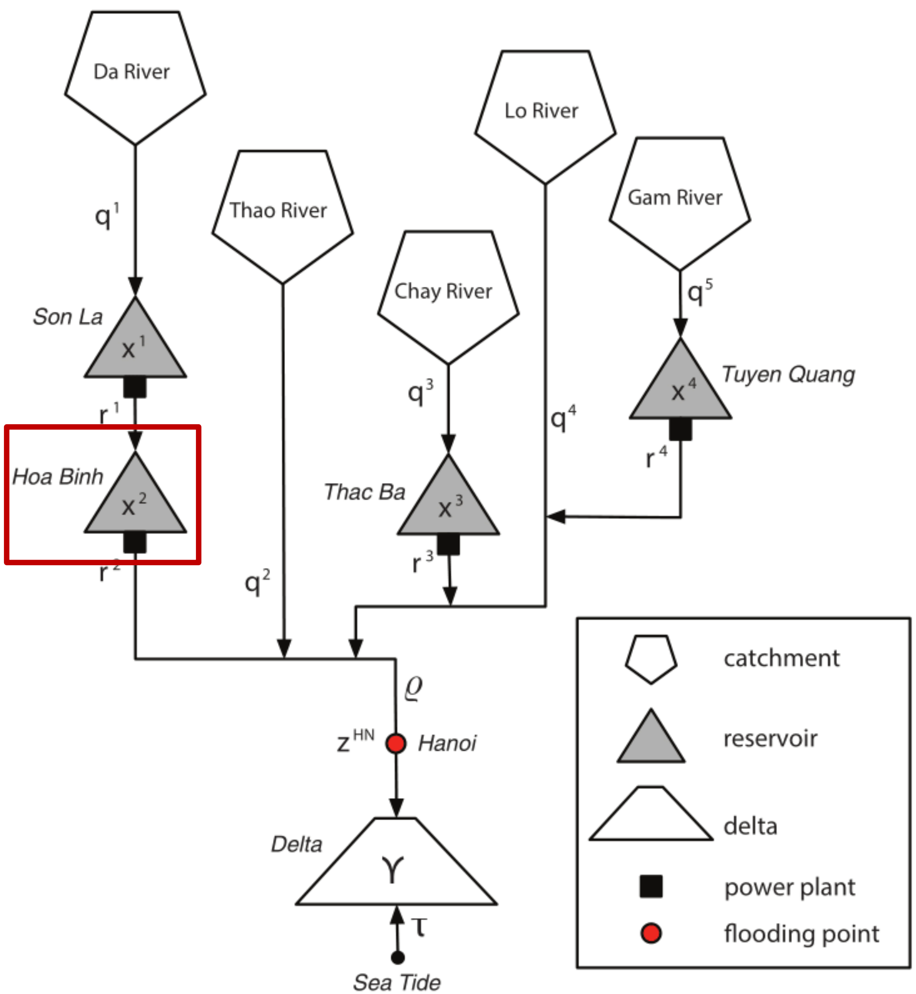
Determine TB release → Determine TQ release

If $s^{TQ} < s^{TQ,\text{ lower target}}$ → $u^{TQ} = 0$

Else → $u^{TQ} = u^{TQ,\text{ min}}$

Between Seasons

Red River System



Official Guidelines

Flood Season

↓

Determine SL release

↓

Determine HB release

↓

Determine TQ release

↓

Determine TB release

Dry Season

↓

Determine TB release

↓

Determine TQ release

↓

Determine Preliminary HB release

If t!=(27,28,41,42,55,56)

If $s^{HB} < s^{HB,\ lower\ target}$ → $u^{HB} = 0$

Else → $u^{HB} = u^{HB,\ min}$

Between Seasons

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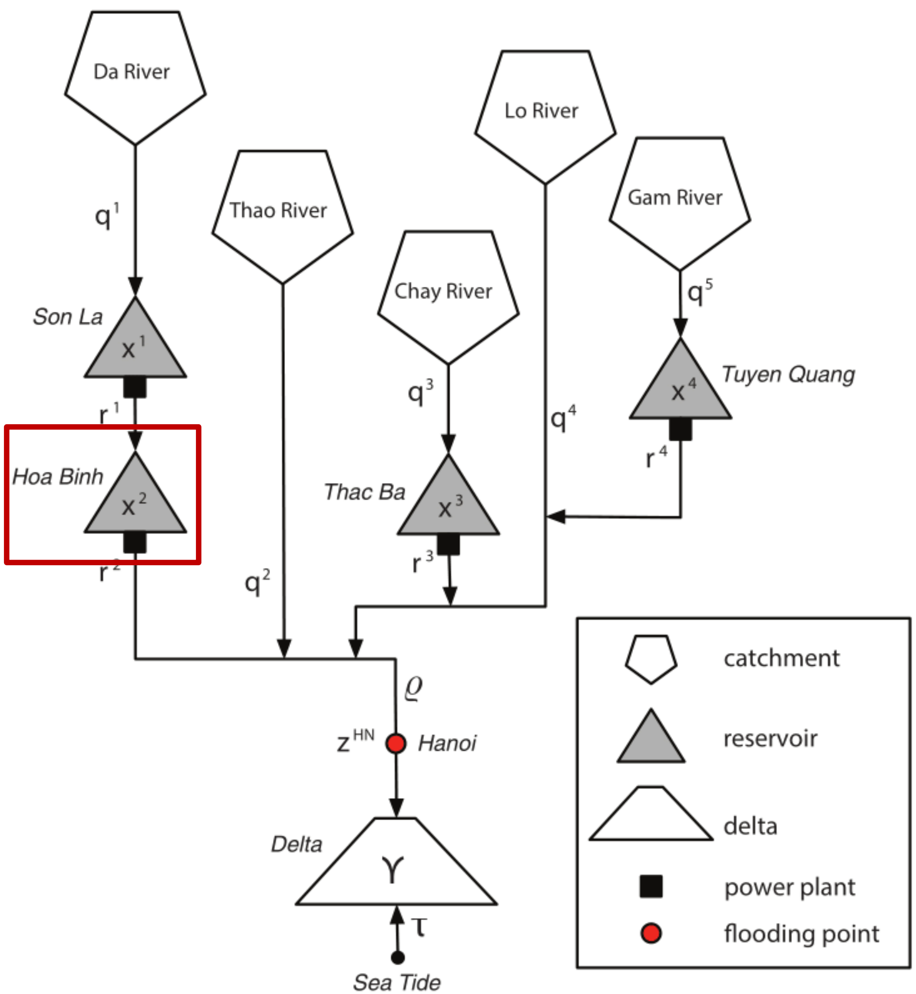
Red River System



Official Guidelines

Flood Season

↓

Determine SL release

↓

Determine HB release

↓

Determine TQ release

↓

Determine TB release

Dry Season

↓

Determine TB release

↓

Determine TQ release

↓

Determine Preliminary HB release

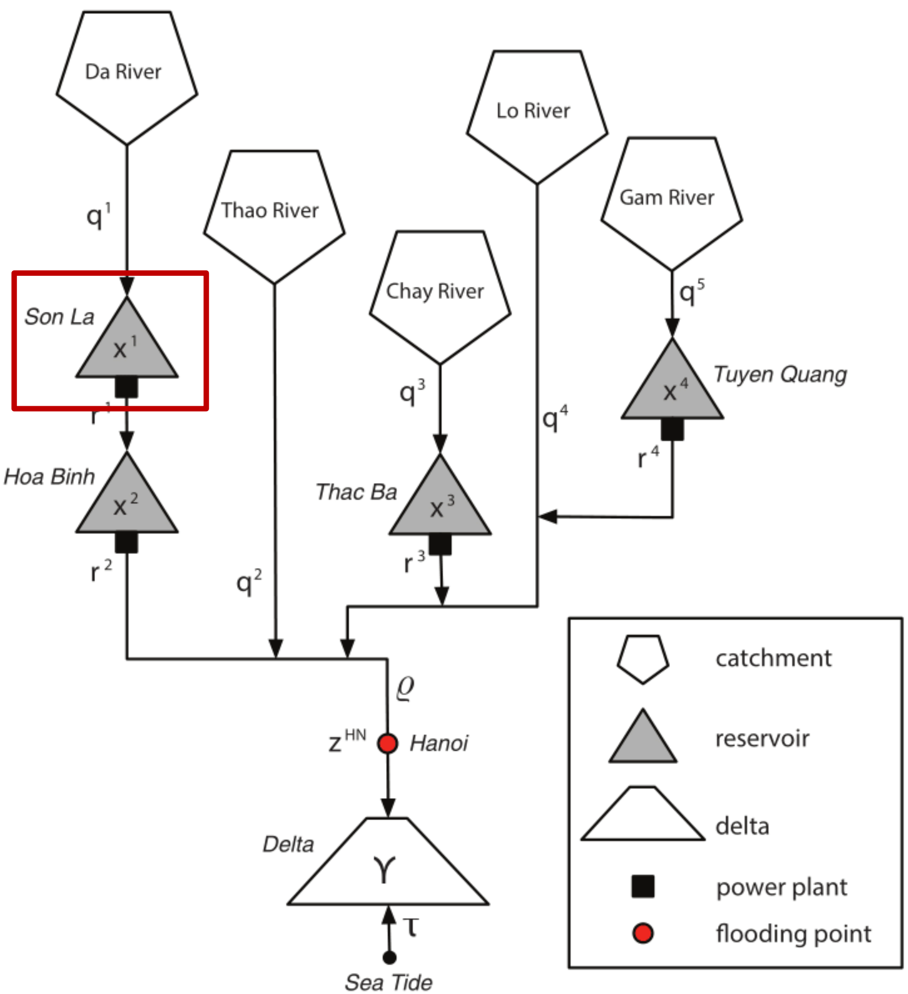
If $t=(27,28,41,42,55,56)$

If $Q^{dry,lim}-q^{TOT}<0$ → $u^{HB} = 0$

Else → $u^{HB} = Q^{dry,lim}-q^{TOT}$

Between Seasons

Red River System



Official Guidelines

Flood Season

↓

Determine SL release

↓

Determine HB release

↓

Determine TQ release

↓

Determine TB release

Dry Season

↓

Determine TB release

↓

Determine TQ release

↓

Determine Preliminary HB release

↓

Determine SL release

u^{SL} = max(0,q needed to raise s^{HB} to $s^{HB,\ lower\ target}$)

Between Seasons

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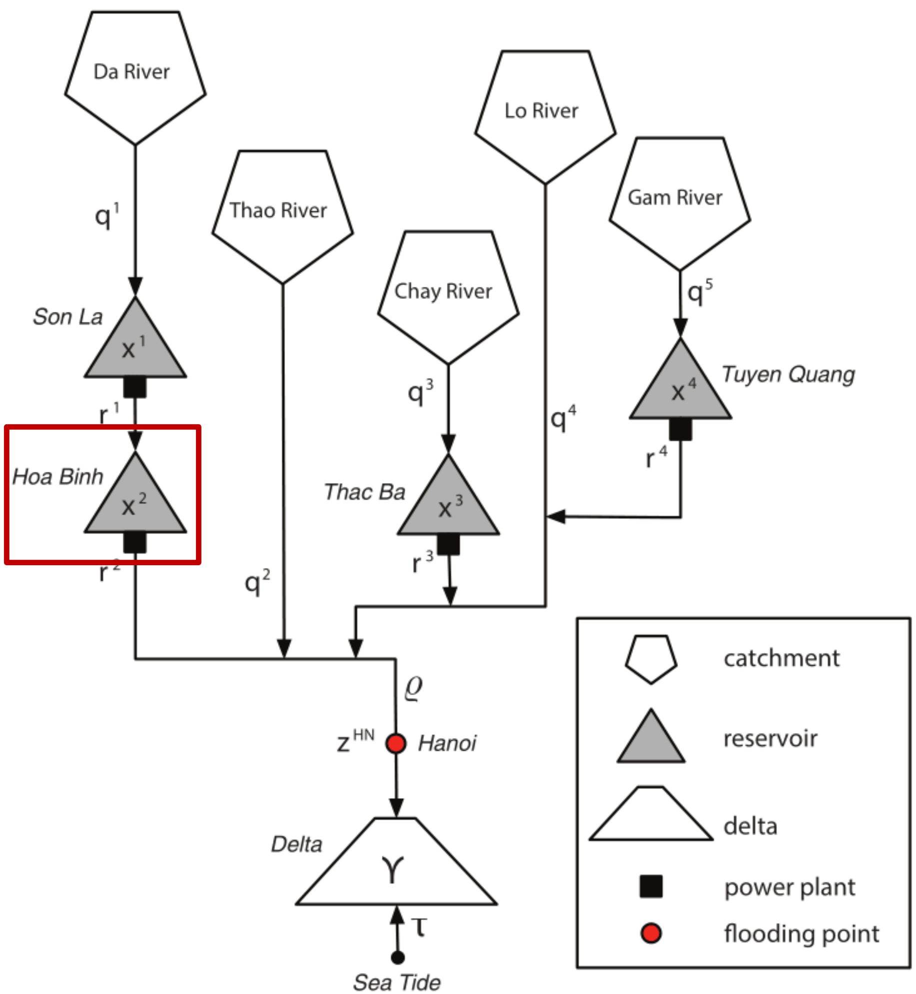
Red River System



Official Guidelines

Flood Season

↓

Determine SL release

↓

Determine HB release

↓

Determine TQ release

↓

Determine TB release

Dry Season

↓

Determine TB release

↓

Determine TQ release

↓

Determine True HB release

↓

Determine SL release

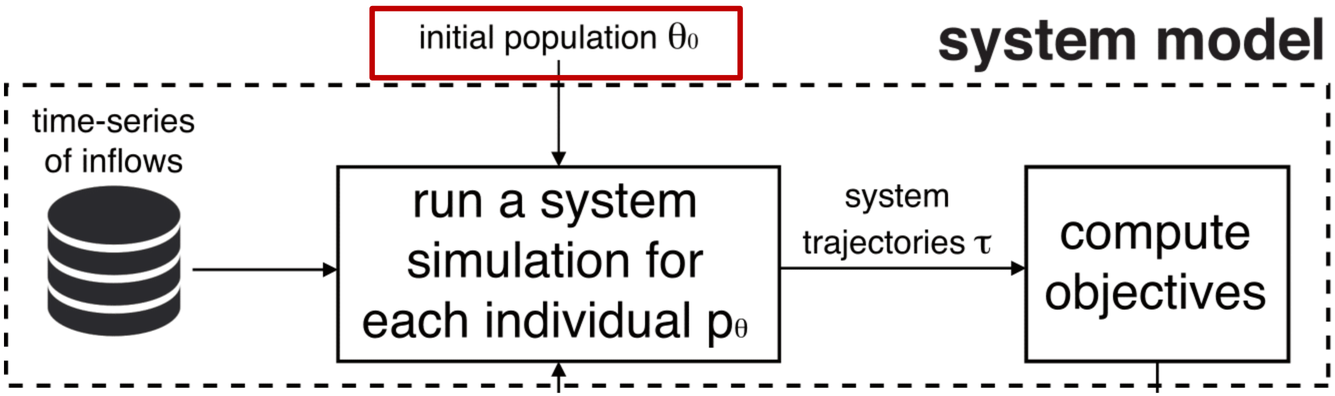
Between Seasons

↓

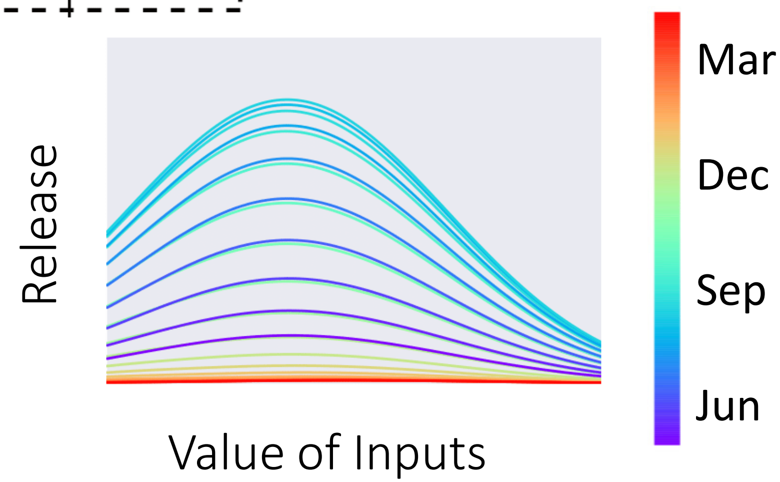
Unregulated. Use release from one of our optimized policies.

Evolutionary Multi-Objective Direct Policy Search (EMODPS)

Computationally efficient method for solving high-dimensional, multi-objective control problems

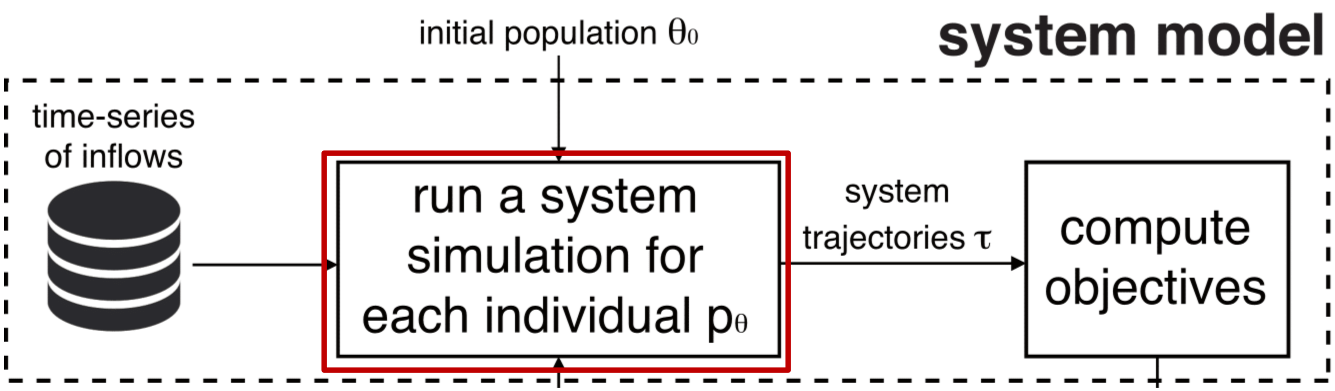


Step 1:
Parameterization

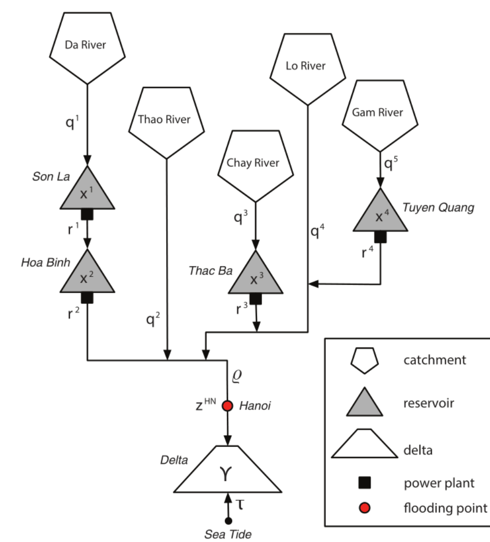


Evolutionary Multi-Objective Direct Policy Search (EMODPS)

Computationally efficient method for solving high-dimensional, multi-objective control problems



Step 2: Simulation



Evolutionary Multi-Objective Direct Policy Search (EMODPS)

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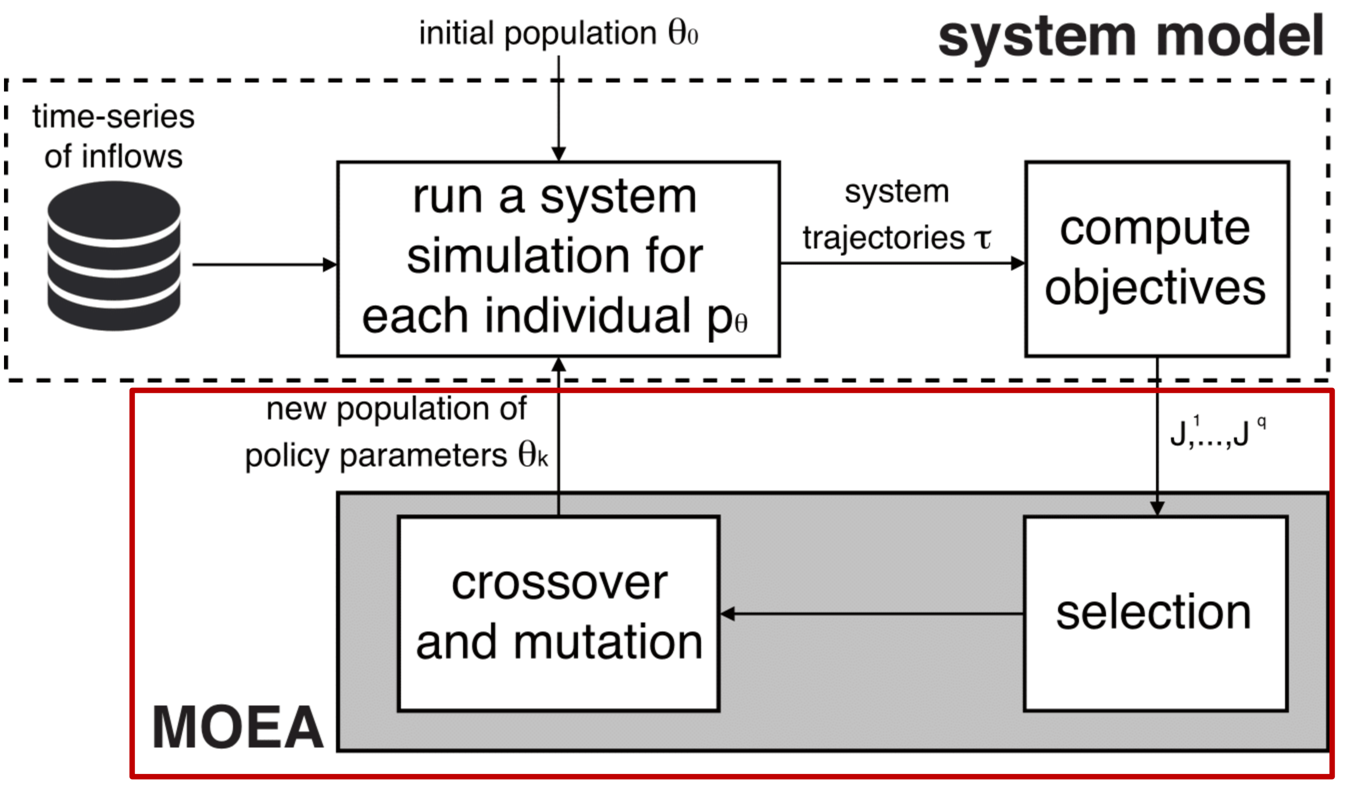
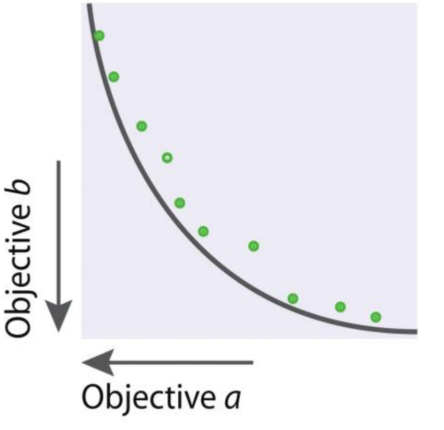
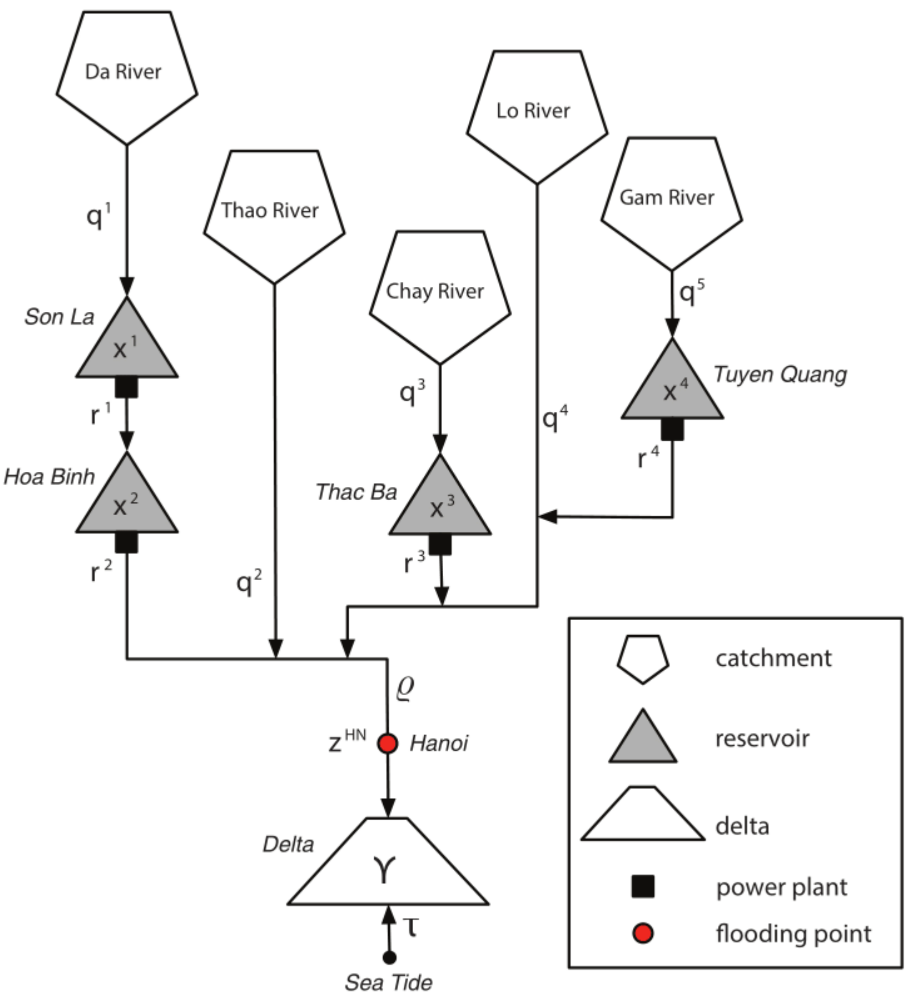


Step 3: Optimization



Red River System



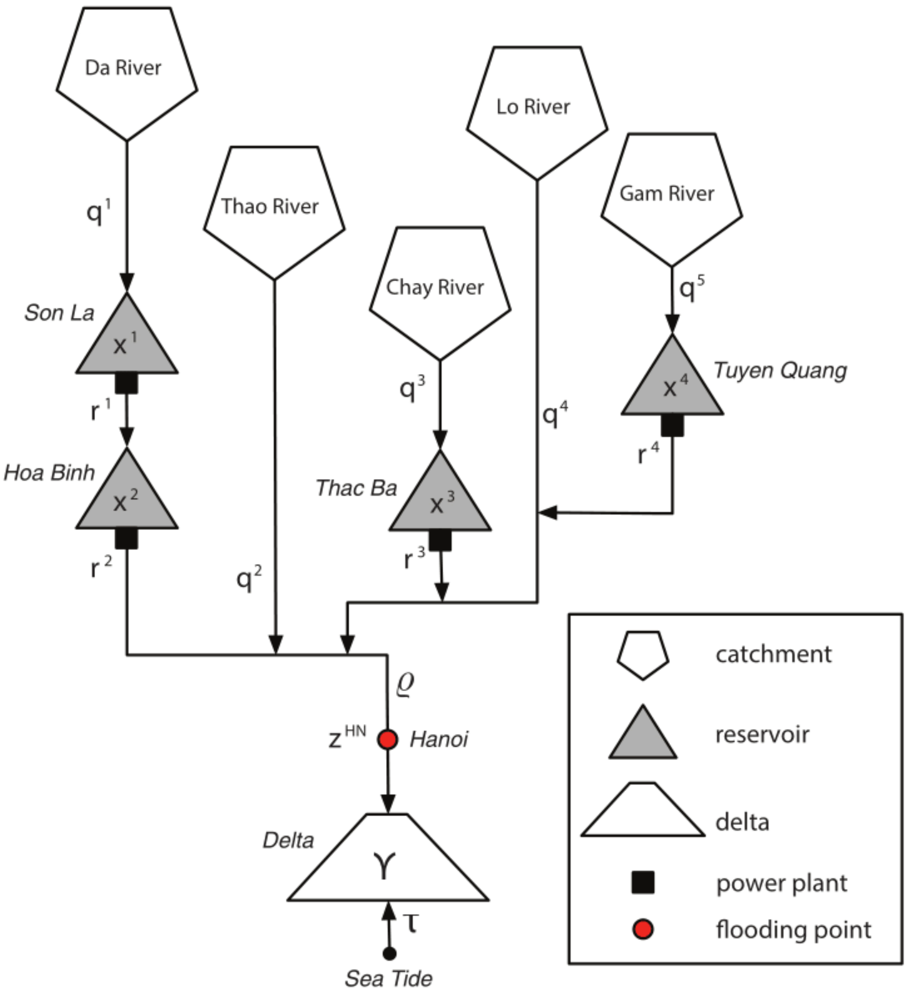
EMODPS Policies

$$u_t^k = \sum_{i=1}^{n} w_i^k \exp\left(-\sum_{j=1}^{M}\left(\frac{(x_t)_j - c_{i,j}}{r_{i,j}}\right)^2\right)$$

u_t = outputs = $\{u_t^{SL}, u_t^{HB}, u_t^{TQ}, u_t^{TB}\}$

Red River System

EMODPS Policies

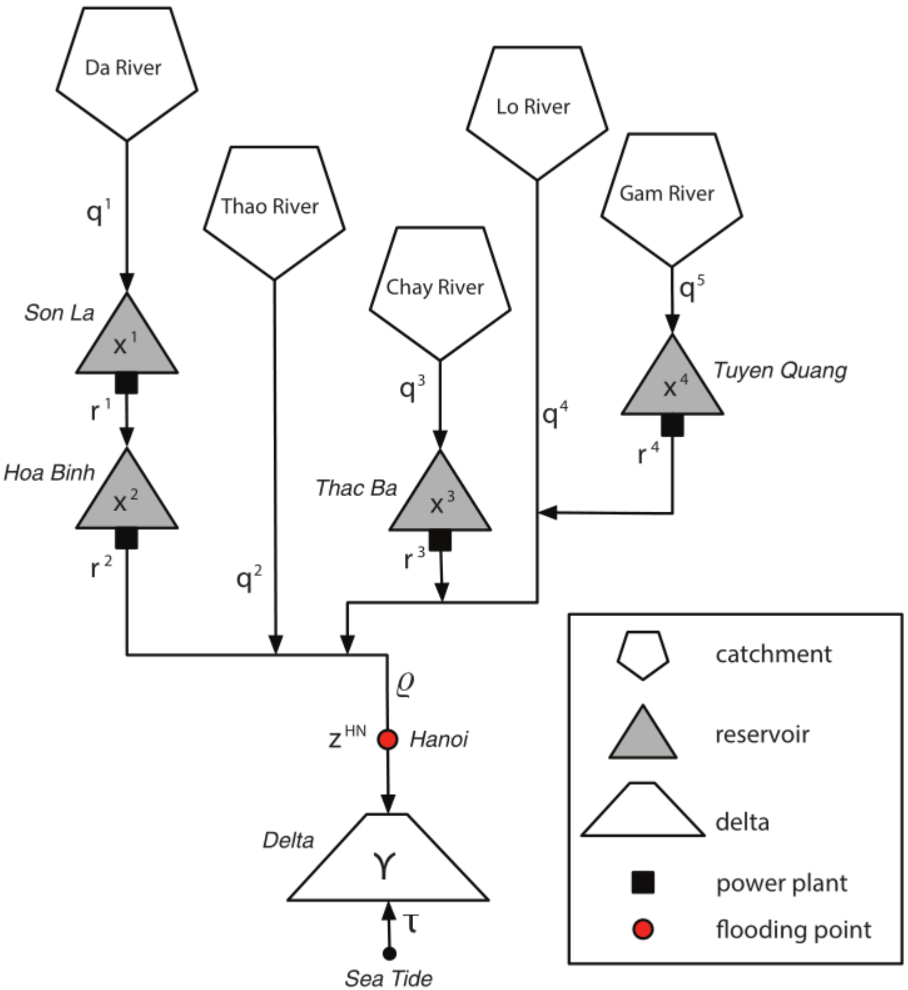


$$u_t^k = \sum_{i=1}^{n} w_i^k \exp\left(-\sum_{j=1}^{M}\left(\frac{(x_t)_j - c_{i,j}}{r_{i,j}}\right)^2\right)$$

u_t = outputs = $\{u_t^{SL}, u_t^{HB}, u_t^{TQ}, u_t^{TB}\}$

x_t = inputs = $\left\{ \begin{array}{c} s_t^{SL}, s_t^{HB}, s_t^{TQ}, s_t^{TB}, z_{t+1}^{HN,fcst}, \\ \sin\left(\frac{2\pi t}{365} - \varphi_1\right), \cos\left(\frac{2\pi t}{365} - \varphi_2\right) \end{array} \right\}$

Red River System



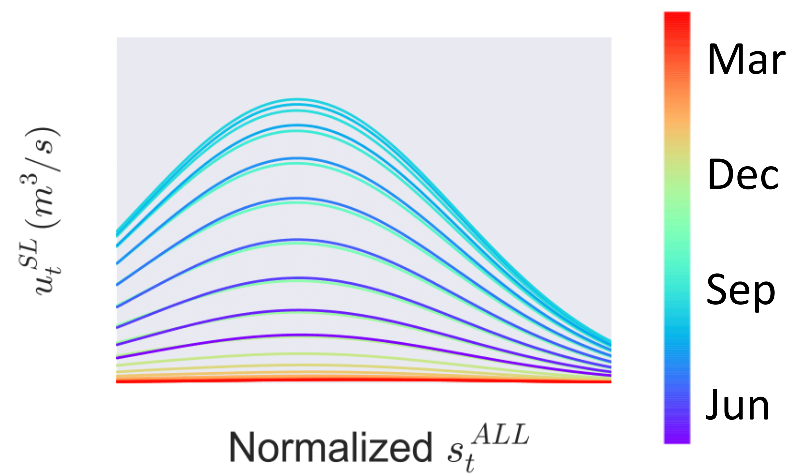
EMODPS Policies

$$u_t^k = \sum_{i=1}^{n} w_i^k \exp\left(-\sum_{j=1}^{M}\left(\frac{(x_t)_j - c_{i,j}}{b_{i,j}}\right)^2\right)$$

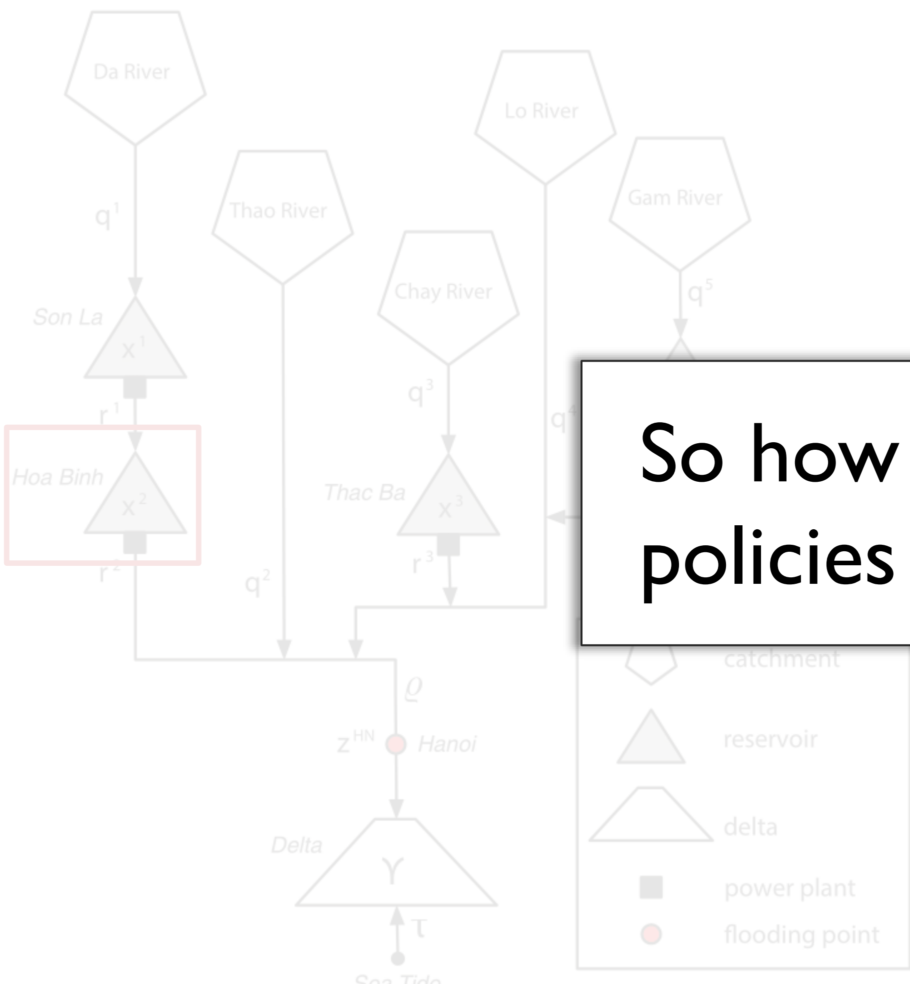
u_t = outputs = $\{u_t^{SL}, u_t^{HB}, u_t^{TQ}, u_t^{TB}\}$

x_t= inputs = $\left\{\begin{matrix} s_t^{SL}, s_t^{HB}, s_t^{TQ}, s_t^{TB}, z_{t+1}^{HN,fcst}, \\ \sin\left(\frac{2\pi t}{365} - \varphi_1\right), \cos\left(\frac{2\pi t}{365} - \varphi_2\right) \end{matrix}\right\}$

$w_i^k, c_{i,j}, b_{i,j}, \varphi_1, \varphi_2$ = decision variables



Red River System Official vs EMODPS



Flood Season	Dry Season	Between Seasons
Determine SL release	Determine TB release	Unregulated. Use release from one of our optimized policies.
Determine TQ release	...termine TQ ...ease	
Determine TB release	Determine True HB release	
	Determine SL release	

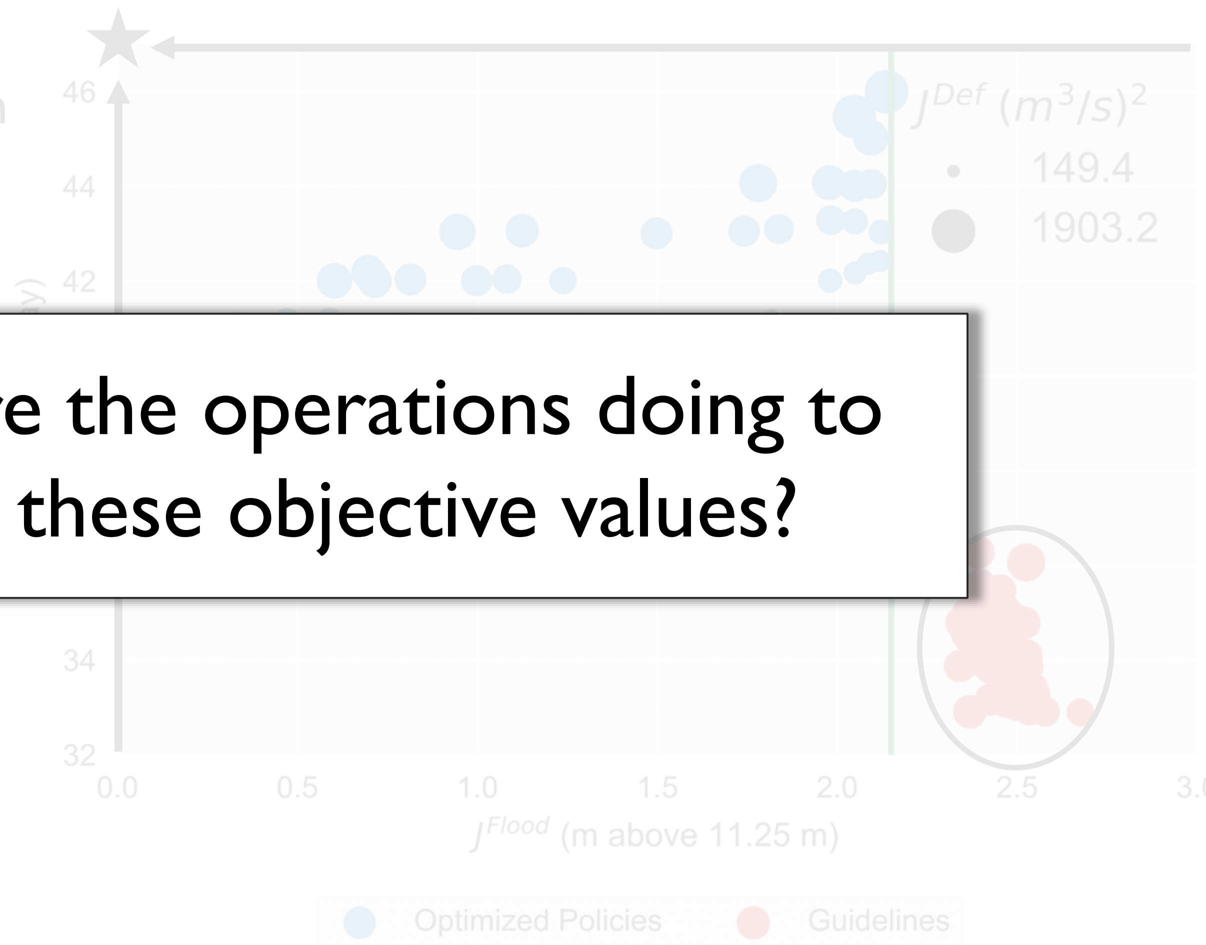
So how do the policies compare?

Objective Comparison

Guidelines are fully dominated, and domination should increase with # of reservoirs

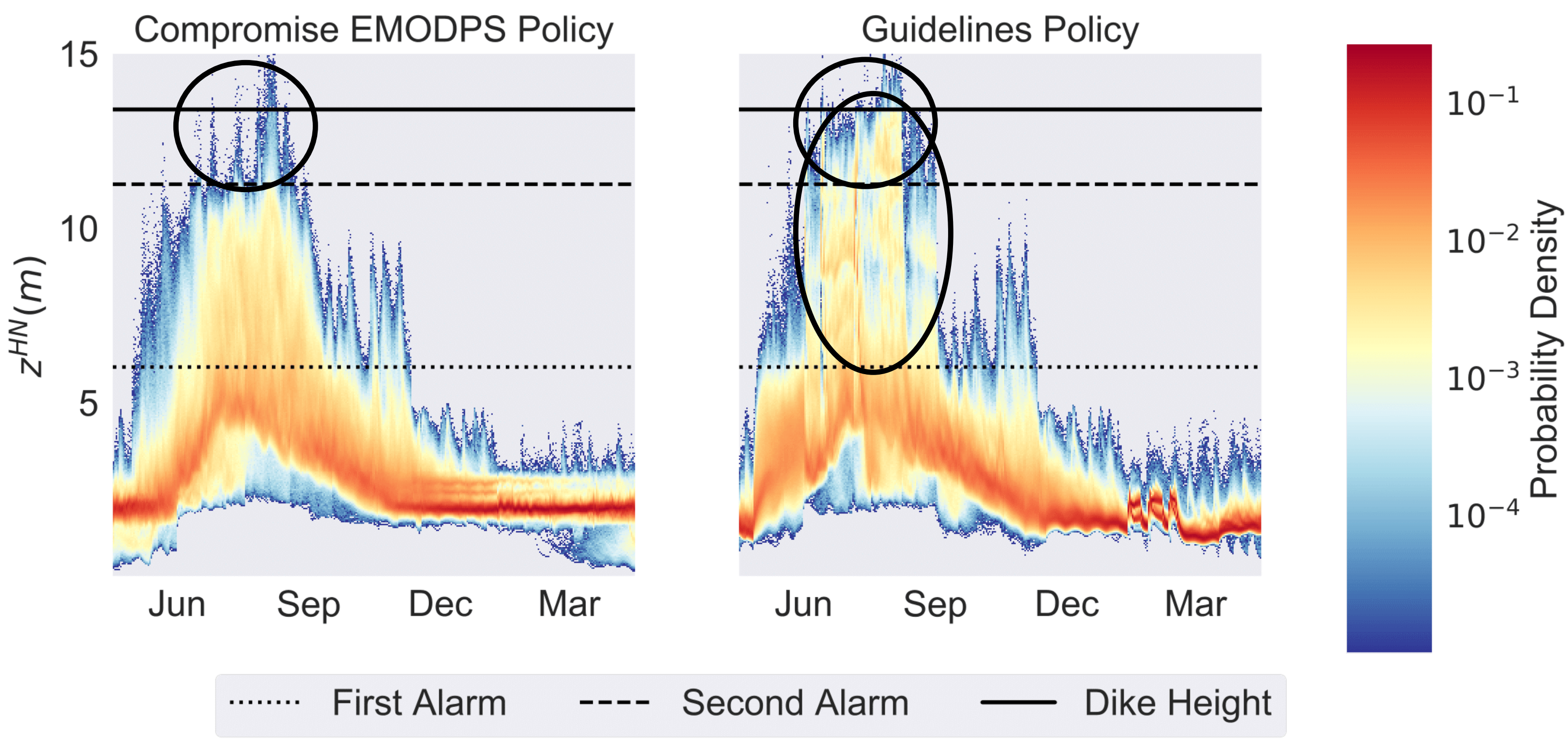
Do not prov
to the 100-y

Range of ob
indicates operations between seasons matter; objectives are not time-separable



What are the operations doing to result in these objective values?

Probabilistic Flood Behavior



Guidelines have much greater probability of high water levels
If/then/else rules result in poorly coordinated, discontinuous behavior

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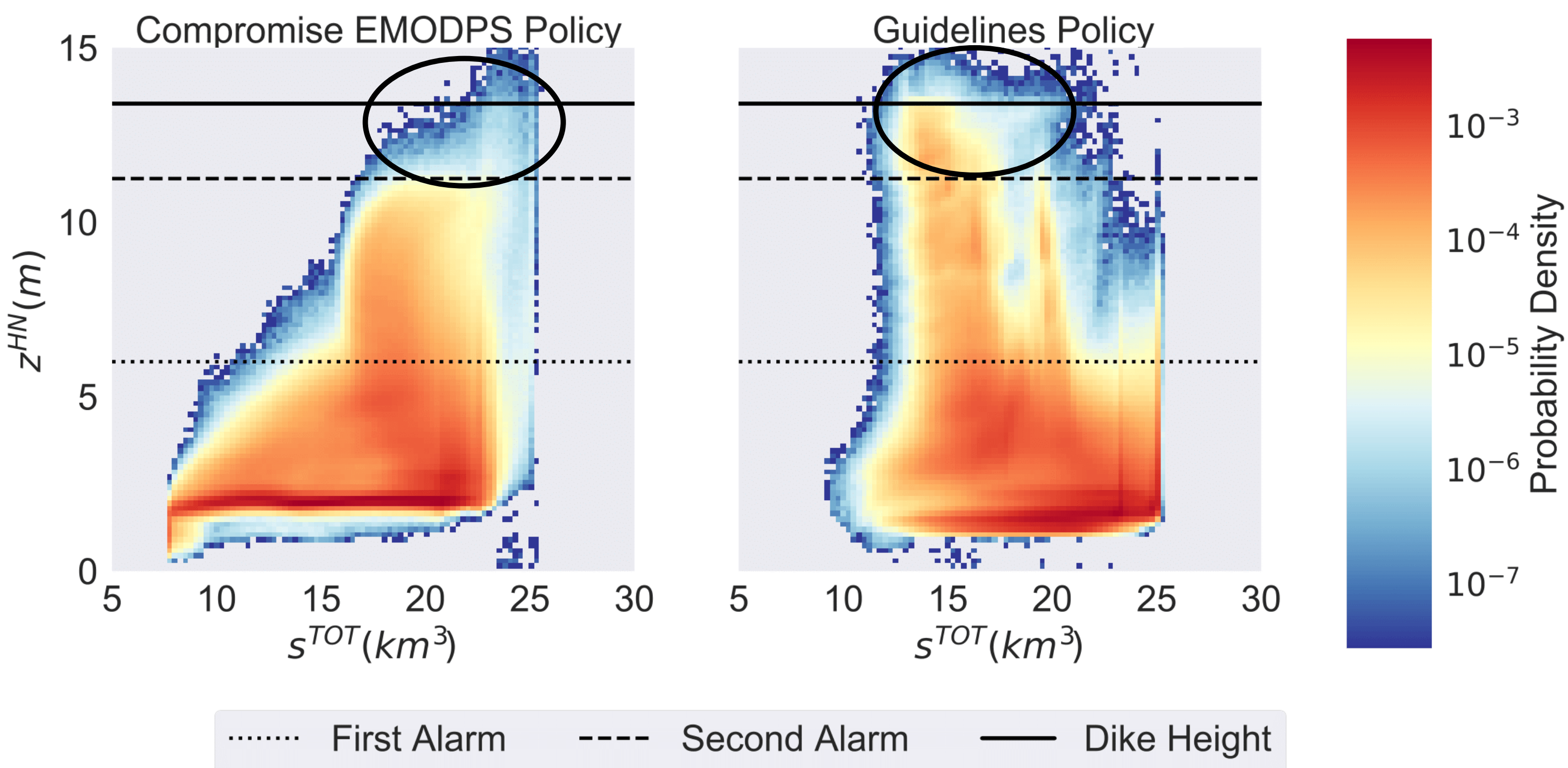
Probabilistic Flood Behavior



Guidelines do not effectively coordinate operations to make use of reservoir storage for flood protection

Guidelines are not coordinating operations well

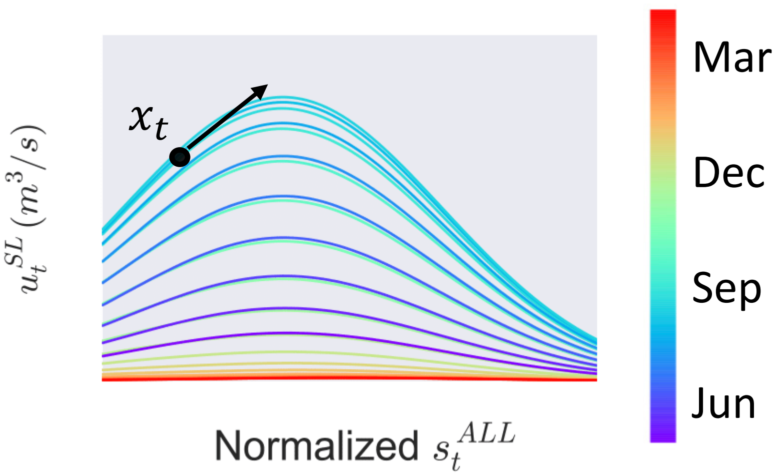
But why? They use all the same information as the EMODPS policies. How are they using this information differently?

Adaptivity and information feedbacks are key, let's play with a time-varying uncertainty analysis to reveal how

Time-Varying Uncertainty Analysis

Simulate policies for 1000 years and at each day t, calculate 1st order Taylor Series approximation of variance in prescribed release at each time step, u_t^k:

$$Var(u_t^k) \approx \sum_{a=1}^{A}\sum_{b=1}^{B} \frac{\delta u_t^k}{\delta (x_t)_a}\frac{\delta u_t^k}{\delta (x_t)_b} Cov((x_t)_a, (x_t)_b)$$



EMODPS Policy:

$$u_t^k = \sum_{i=1}^{n} w_i^k \exp\left(-\sum_{j=1}^{M}\left(\frac{(x_t)_j - c_{i,j}}{b_{i,j}}\right)^2\right)$$

$$\frac{\delta u_t^k}{\delta (x_t)_a} = \sum_{i=1}^{n} -\frac{2(x_t)_a}{{b_{i,a}}^2} w_i \exp\left(-\sum_{j=1}^{m}\left(\frac{(x_t)_j - c_{i,j}}{b_{i,j}}\right)^2\right)$$

Use central differencing for guidelines

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Time-Varying Uncertainty Analysis

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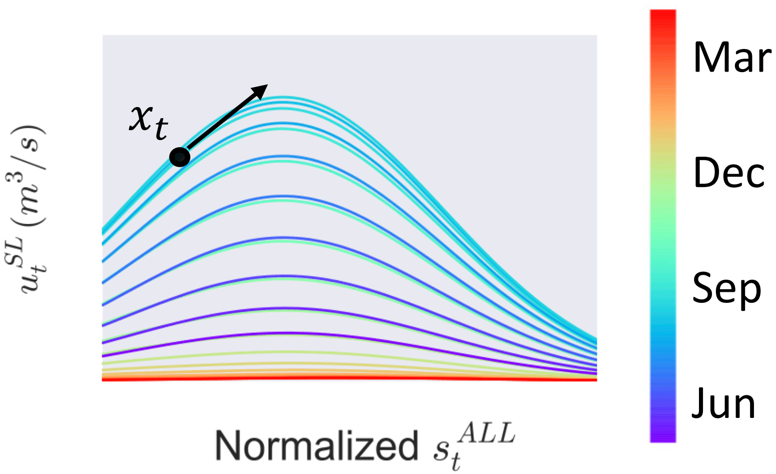

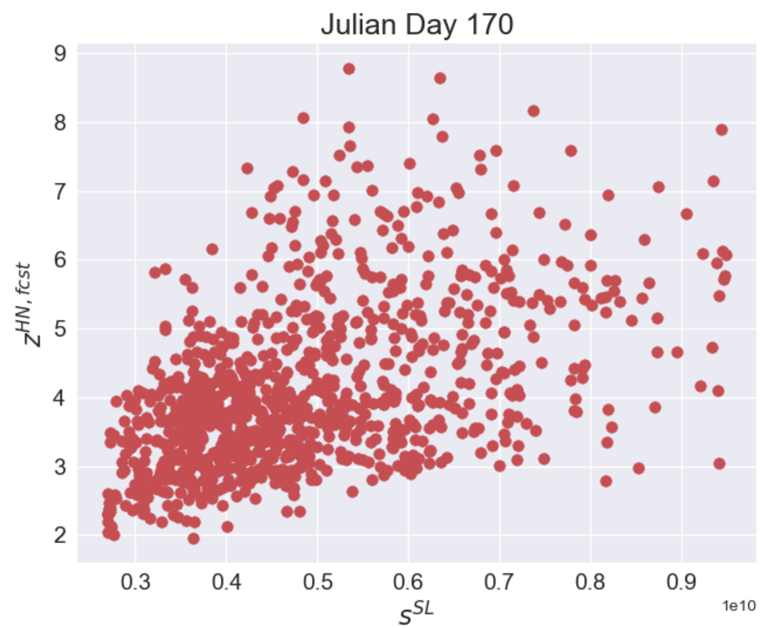

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Time-Varying Uncertainty Analysis

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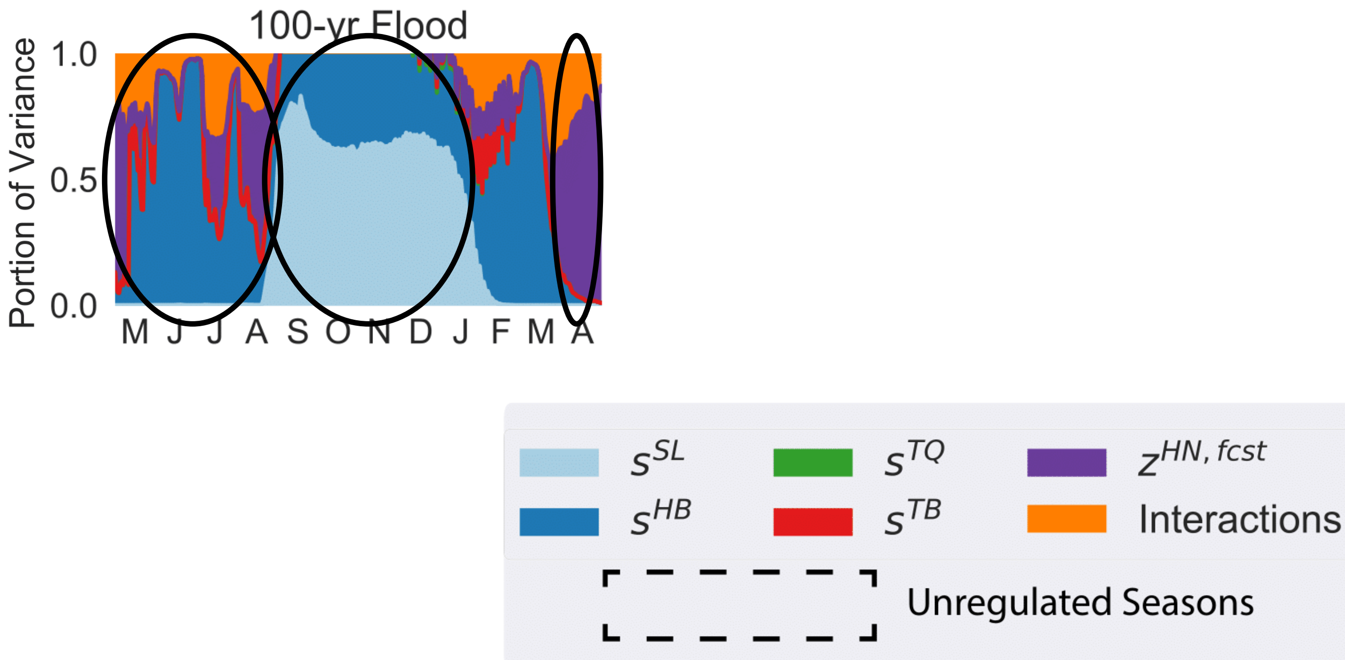
1st order effects of $(x_t)_a$: $\left(\frac{\delta u_t^k}{\delta (x_t)_a}\right)^2 Var((x_t)_a)$

2nd order effects of $(x_t)_a$ and $(x_t)_b$: $\frac{\delta u_t^k}{\delta (x_t)_a} \frac{\delta u_t^k}{\delta (x_t)_b} Cov((x_t)_a, (x_t)_b)$

Assume higher order effects are negligible

Sensitivity of u^{HB} with Best Flood Solution



s^{HB} explains most of variance in u^{HB} during flood season of wet years
s^{SL} becomes important when transitioning to dry season
$z^{HN,fcst}$ becomes important when transitioning back to flood season

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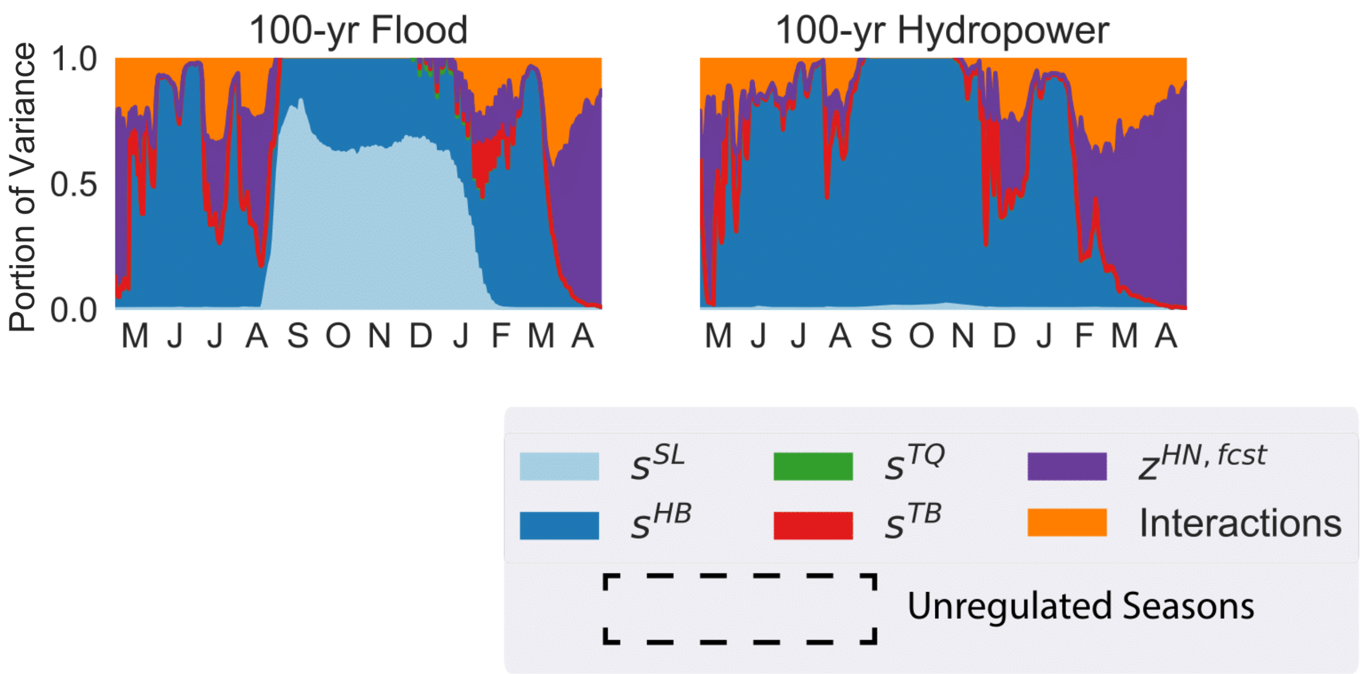
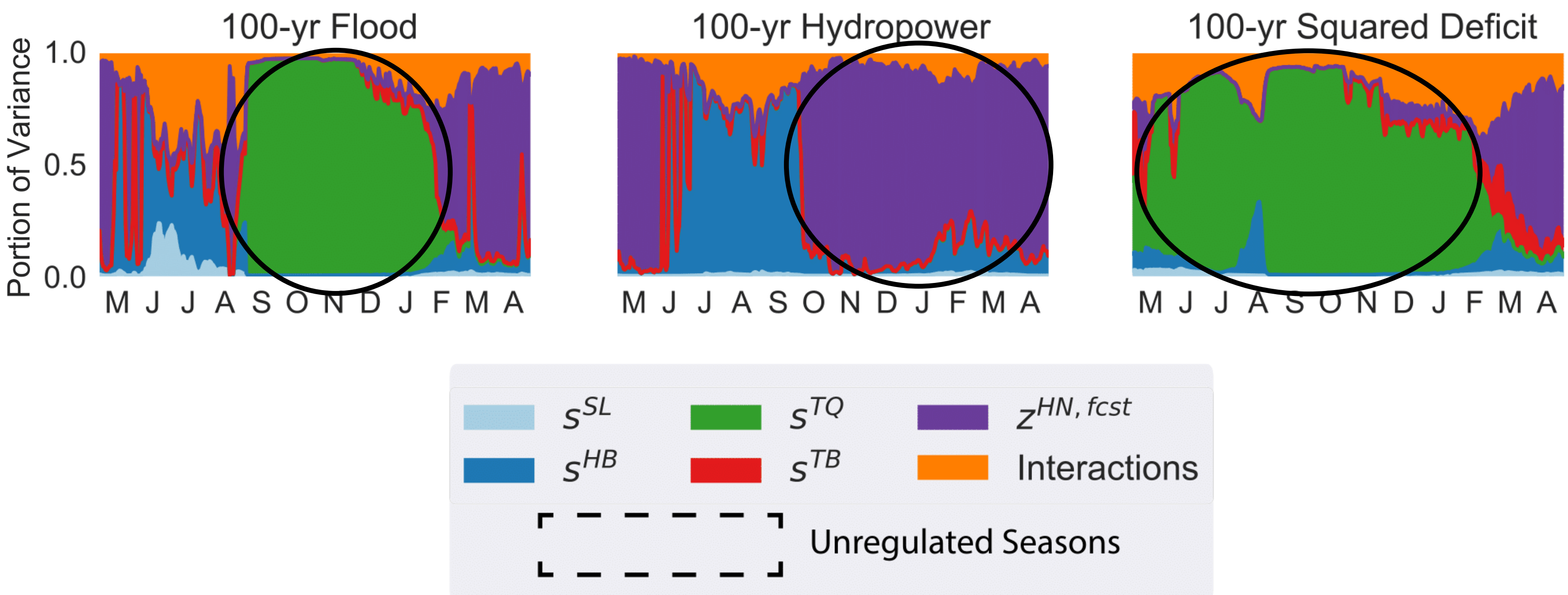
Sensitivity of u^{HB} with Best Flood Solution



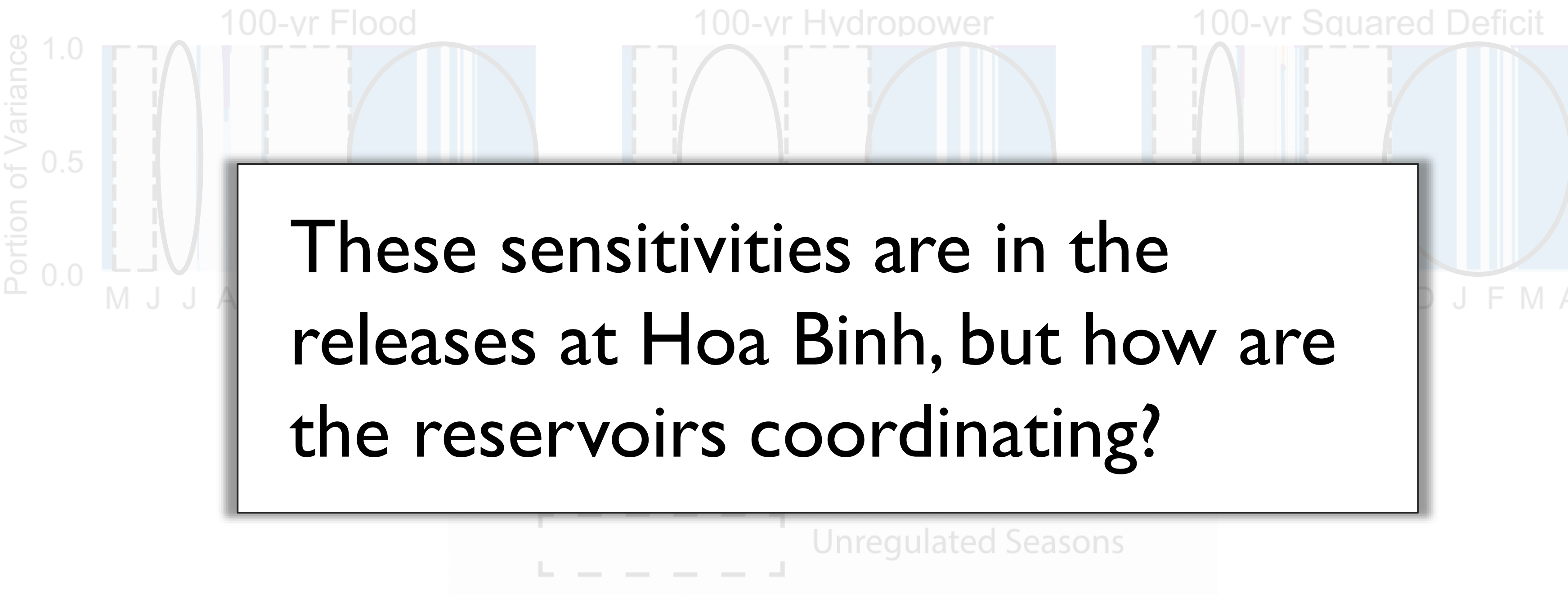
In dry years with low hydropower production, the influence of s^{SL} on u^{HB} disappears
But reappears in years with particularly dry dry seasons
State dynamics could reveal why, but clearly policies are adapting to changing state

Sensitivity of u^{HB} with Best Hydropower Solution



- More sensitive to s^{TQ} than best flood solution; it fills the largest reservoirs regardless and only responds to changes in smaller reservoir storages
- During dry years, forecasted hydrologic conditions become more important

Sensitivity of u^{HB} with Official Guidelines



These sensitivities are in the releases at Hoa Binh, but how are the reservoirs coordinating?

Sensitivity of guidelines much less dynamic
Long periods of no variance due to if/then/else conditions not changing
When policies vary, u^{HB} almost entirely explained by s^{HB} or occassionally s^{SL}

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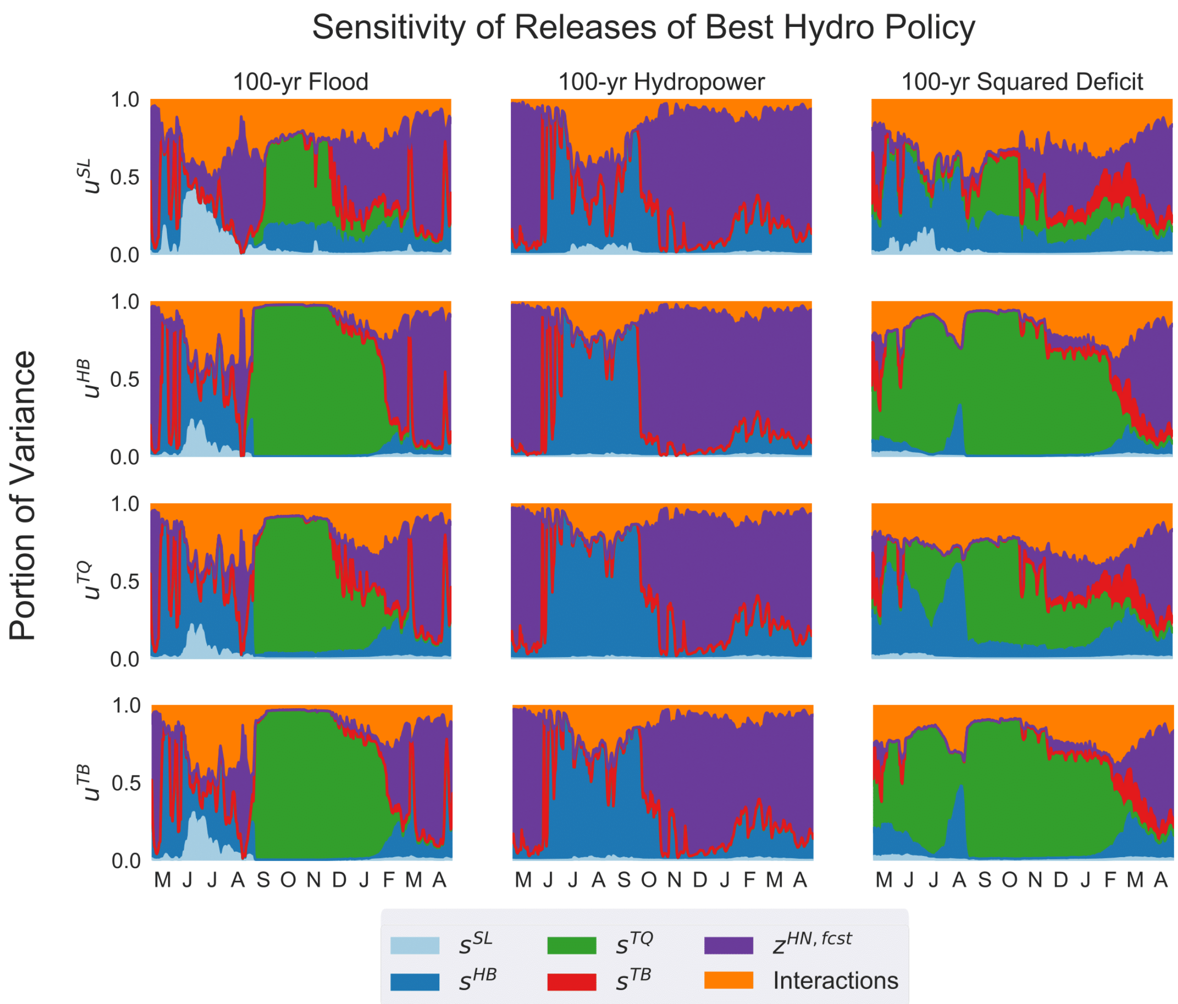
Coordination of Best Hydropower Solution

Structure of sensitivity is very similar across reservoirs, highlighting coordination

All reservoirs taking in same information and reacting as a system

Interactions are significant



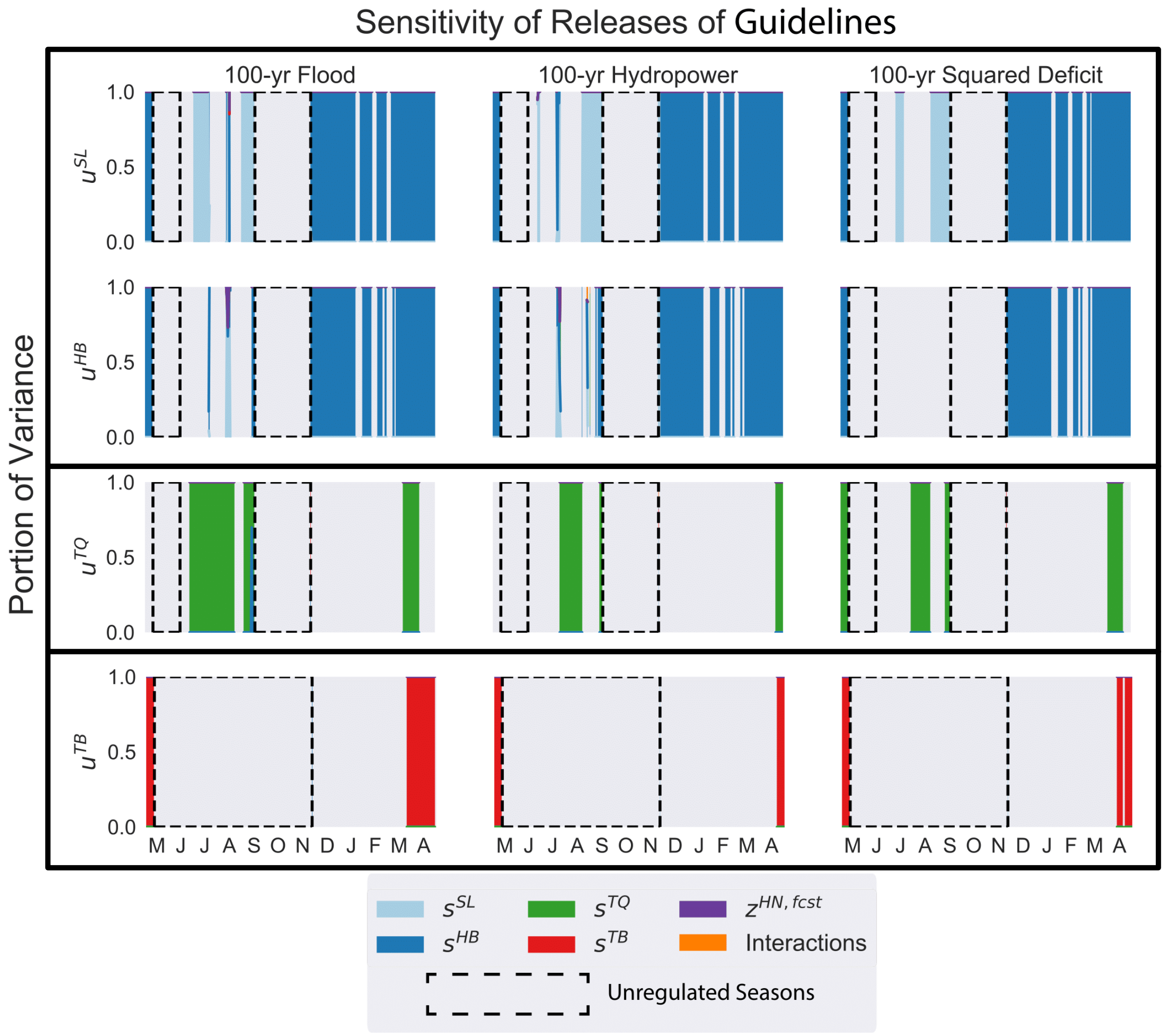
Coordination (or lack thereof) of Guidelines

Variability in releases from guidelines only coordinated for reservoirs in series, *SL* and *HB*

u^{TQ} depends solely on s^{TQ}

u^{TB} depends solely on s^{TB}

Interactions insignificant



Frequently Ignored Issues for Complex Systems

1. Simple discrete if/then/else-based human systems abstractions lack fidelity and likely to inadvertently ignore major failures modes

2. Deterministic "fits" to historical observations do not reflect rare events or the extrapolation of how they are changing. This is not a regression problem…it's an extrapolation problem

3. Poor abstractions of sequential decision-making, coordination failures, sectoral conflicts, and poor use of information will cause severe errors in projecting candidate future pathways

4. Human institutions, land rights/competition, economic and technology transitions, infrastructure investments, etc. all can have huge landscape effects with small changes ("lack strong causality mapping" & "high hysteresis in time/preference effects")

Thanks! Any questions?

Acknowledgements

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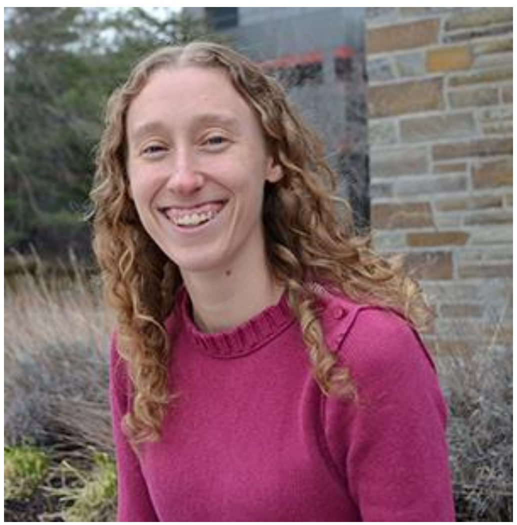
TEXAS ADVANCED COMPUTING CENTER

SCRiM

an NSF-sponsored research network for
Sustainable Climate Risk Management



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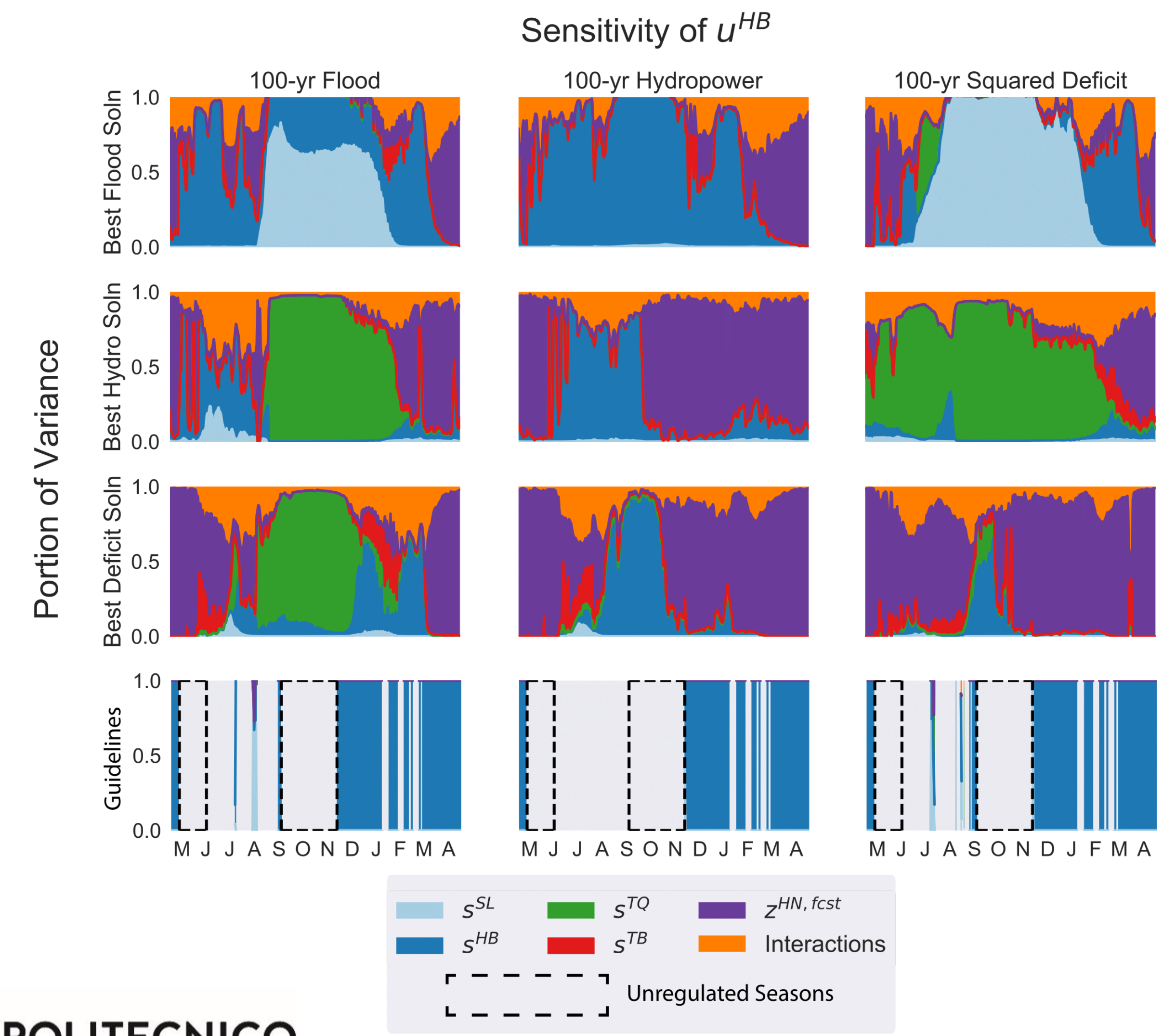
Appendix

Sensitivity of u^{HB} with Different Policies



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