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The sensitivity of the performance of a water resource system to forcing and model related choices

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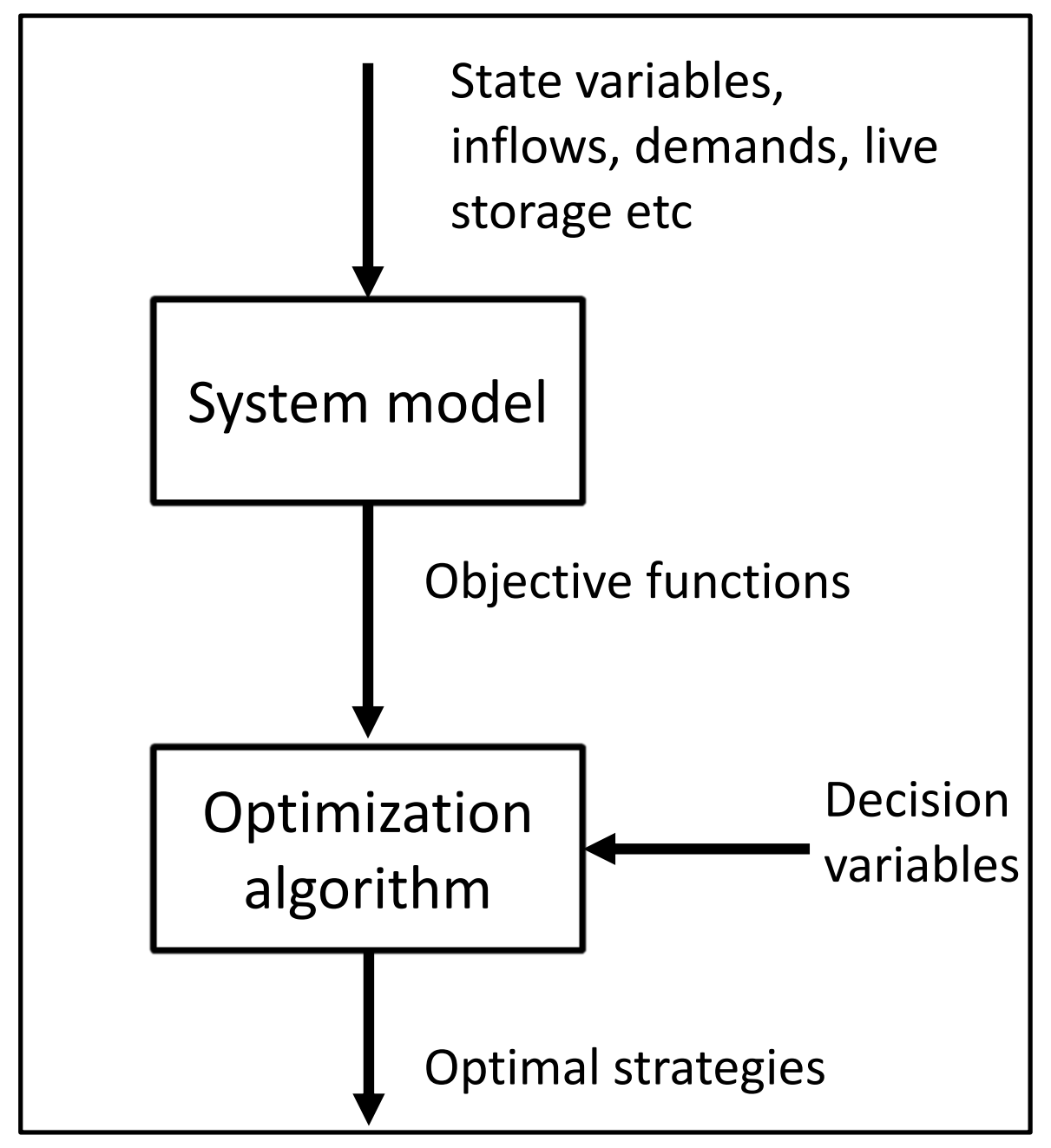
1. Introduction

Why sensitivity analysis in water resources management?

Water resource management strategies are often identified and evaluated using performance metrics within a simulation-optimization framework. These metrics are likely to have varying levels of sensitivity to input variables such as inflows, model-related choices, and errors from the implementation of the strategies. Quantifying the sensitivity of the performance metrics to the aforementioned uncertain factors may therefore be useful for decision-makers in understanding the relative importance of these factors and their interactions. Furthermore, the total variation in the performance measures, arising as a consequence of the uncertain factors, may be useful to quantify the stability of the performance measures. We propose a framework to calculate sensitivity and stability of the metrics following [1].

Typical reservoir optimization setup



State variables, inflows, demands, live storage etc

System model

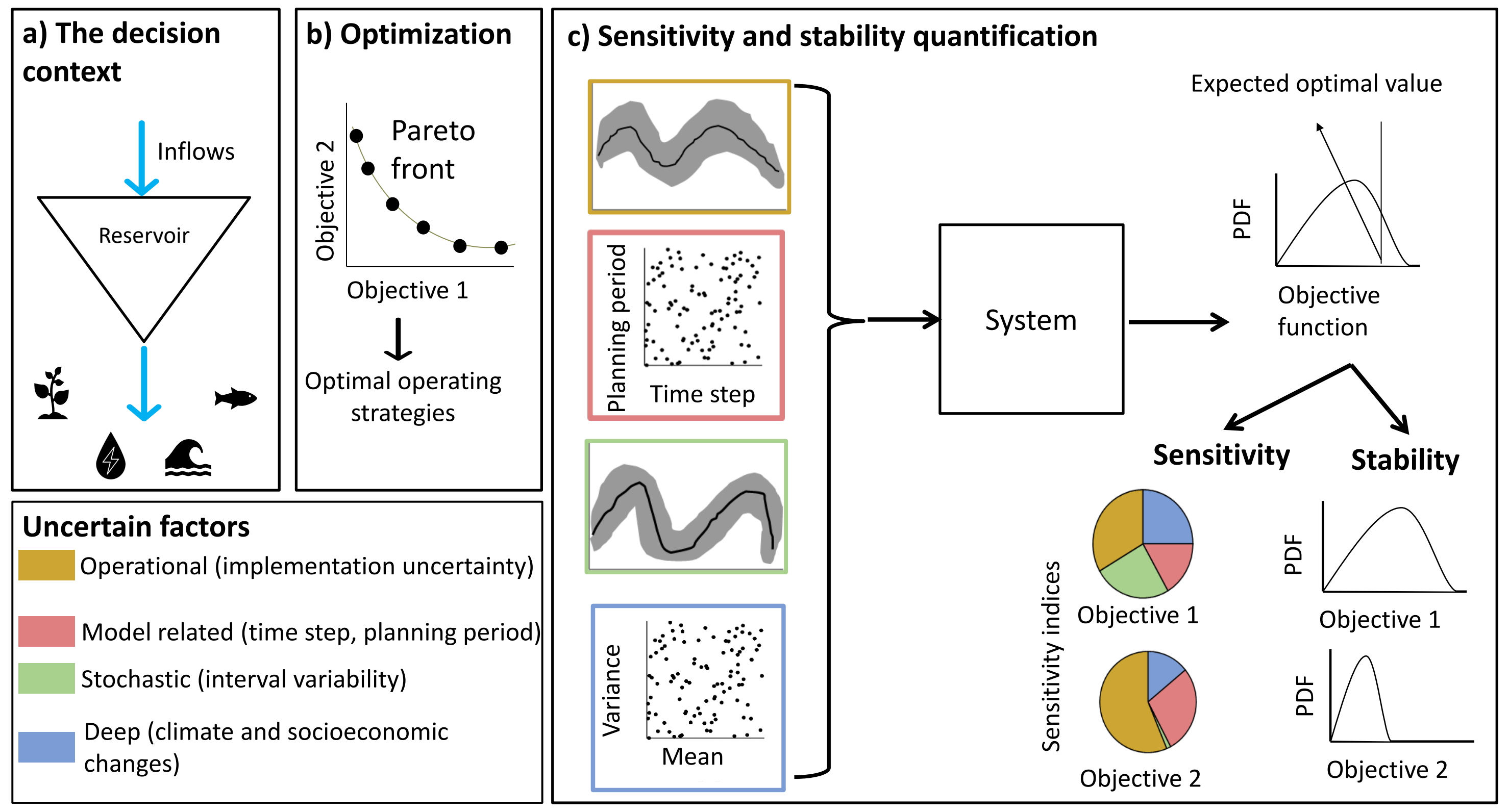
Objective functions

Optimization algorithm

Decision variables

Optimal strategies

2. A framework to evaluate sensitivity and stability of water resource system performance



The framework proposed in this study to quantify sensitivity and stability of objective functions

Methodology

Step 1: (a) Develop system model for reservoir operation, identify objective functions, relevant uncertainties

Step 2: (b) Identify optimal operating strategies via optimization

Step 3: (c) Evaluate the stability and sensitivity of objective functions across selected strategies

Sensitivity and stability

Y: performance metric, index *k*

X: uncertain factors, indices *i, j*

Sobol's variance-based sensitivity analysis (VBSA)

First order: $S_i^k = \left(\frac{V(E(Y_k|X_i))}{V(Y_k)}\right)$

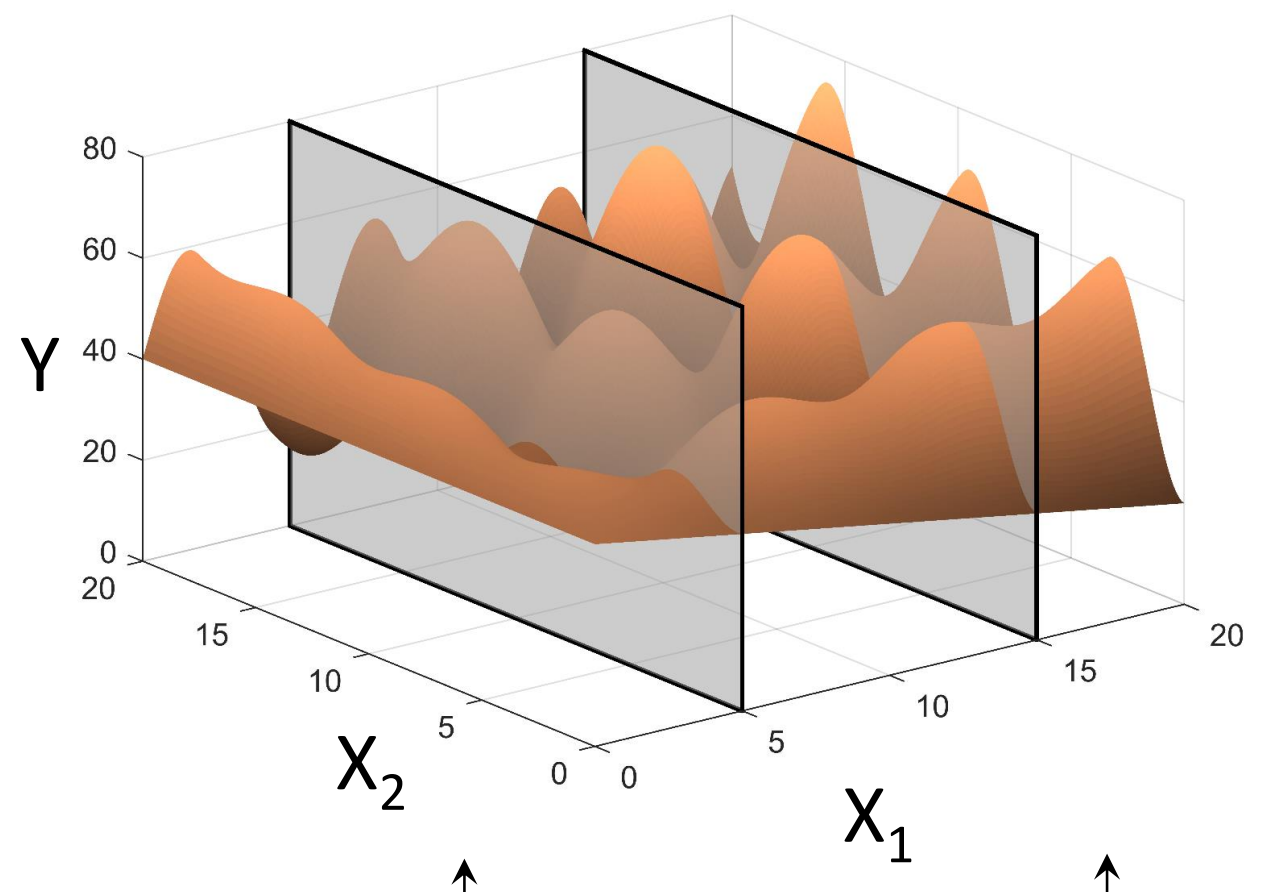
Second order: $S_{ij}^k = \left(\frac{V\left(E\left(Y_k|X_i,X_j\right)\right) - V\left(E\left(Y_k|X_i\right)\right) - V\left(E\left(Y_k|X_j\right)\right)}{V(Y_k)}\right)$

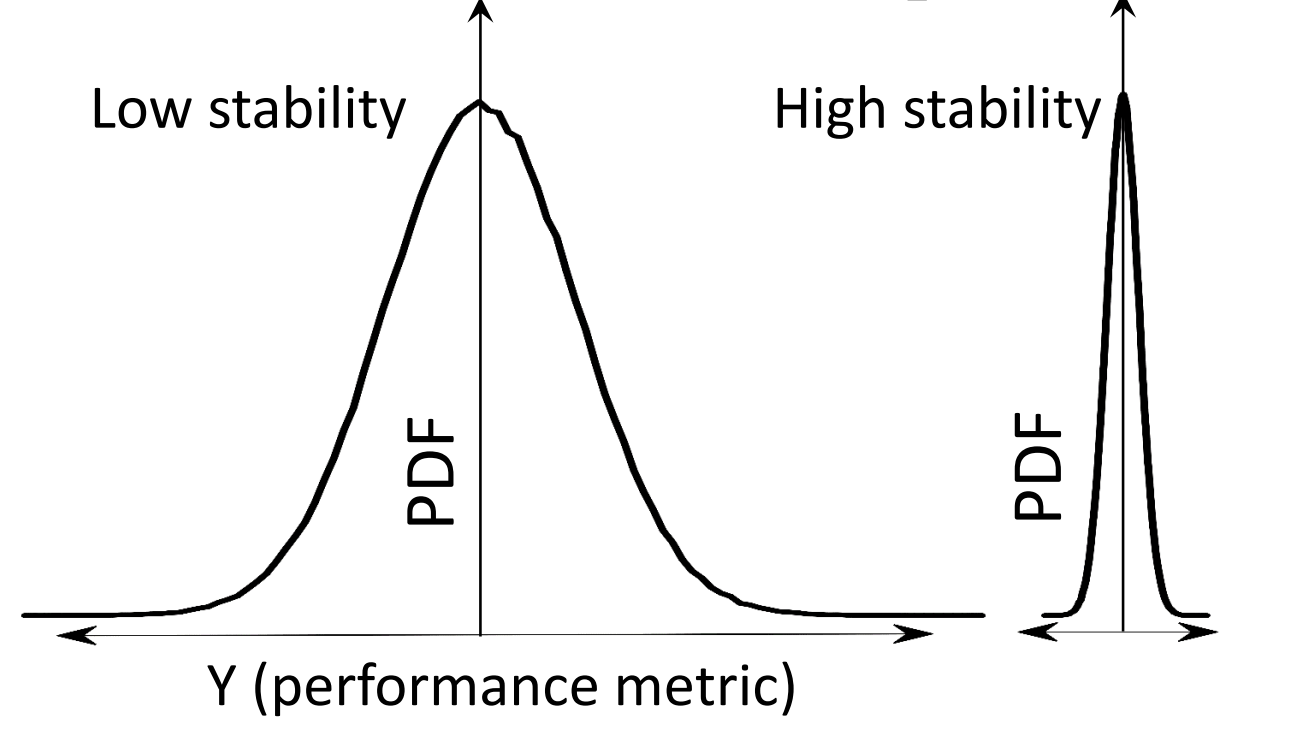
Total order: $S_{Ti}^k = \left(1 - \frac{V(E(Y_k|X_{\sim i}))}{V(Y)}\right)$

Stability of an objective function is quantified via the coefficient of variation (CoV)

$$\text{CoV} = \frac{SD\ of\ the\ metric\ across\ all\ uncertain\ realitzations}{mean\ of\ the\ metric\ across\ all\ uncertain\ realizations}$$

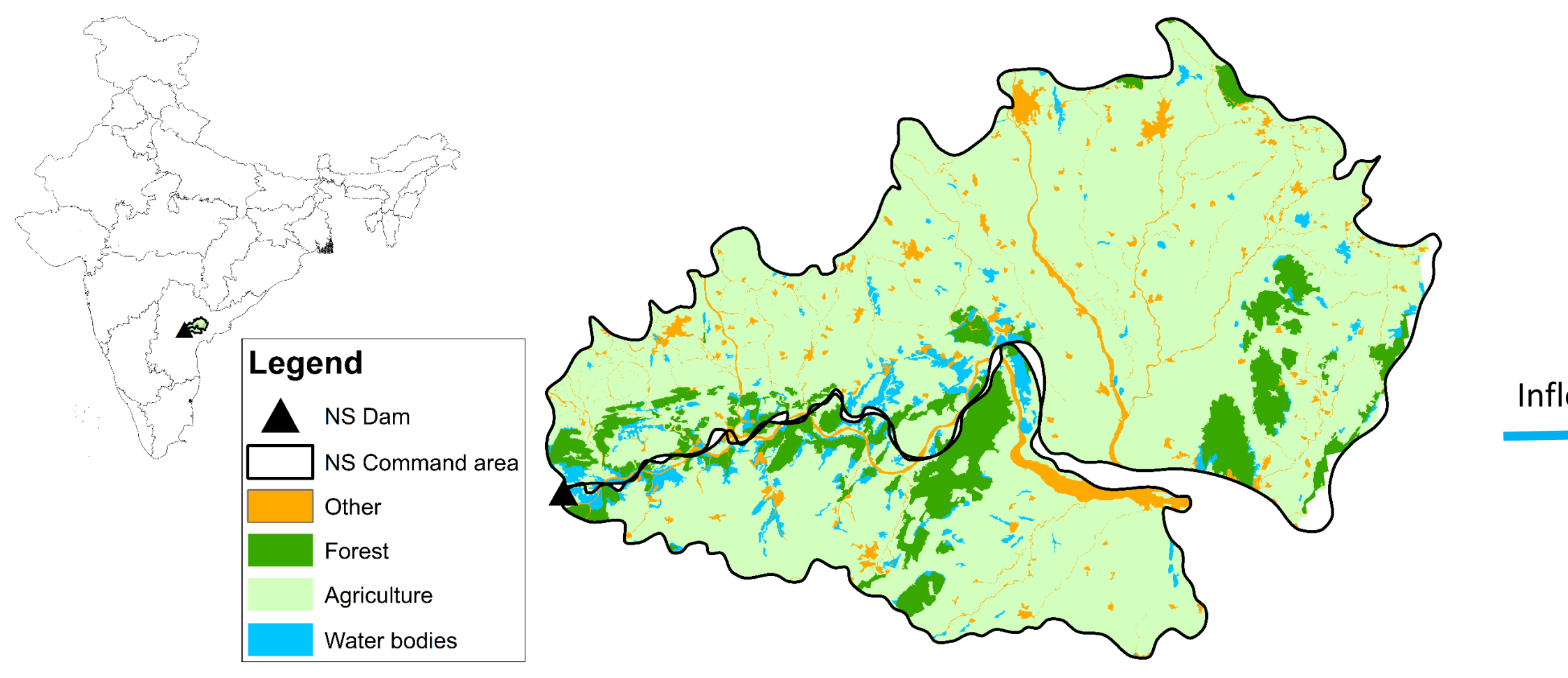
Example: first order sensitivity index calculation



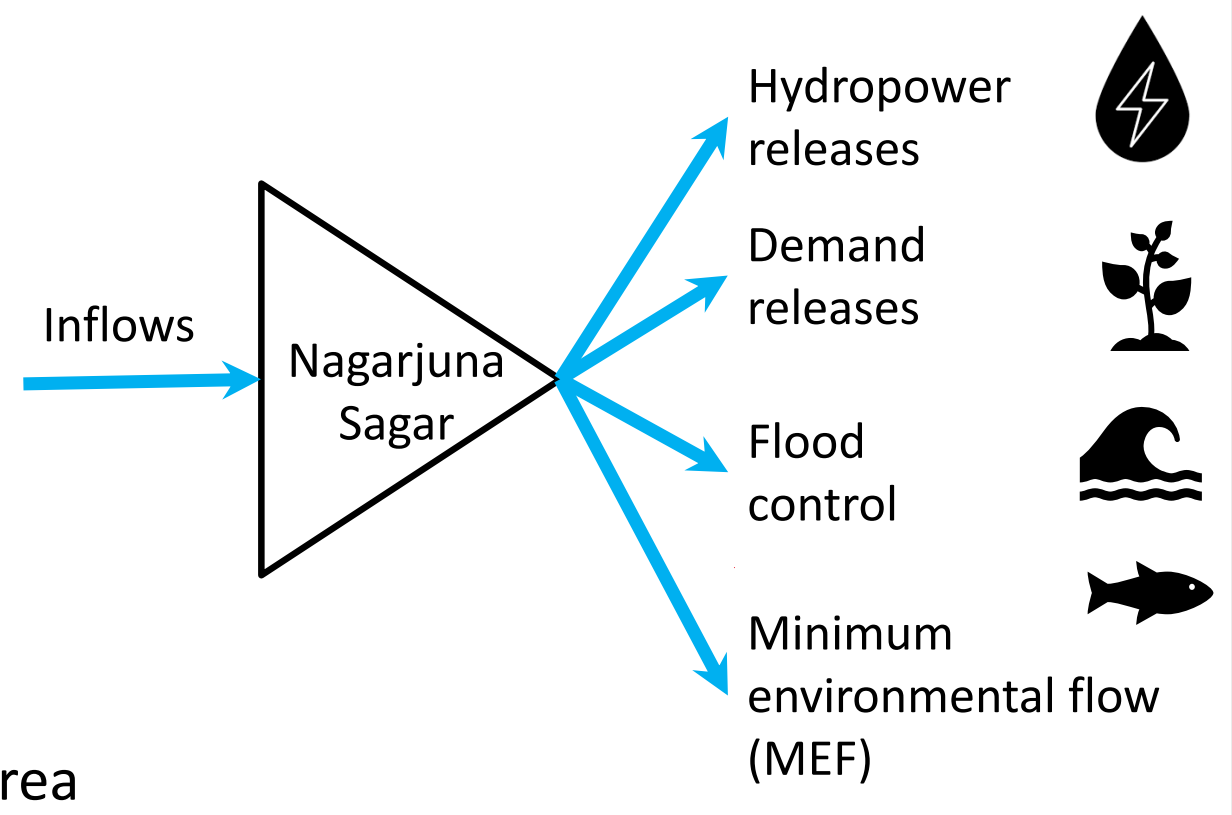


3. Application: The Nagarjuna Sagar (NS) reservoir in Southern India

System's model and performance measures



The location of the Nagarjuna Sagar in India and a land cover map of its command area



Identification of Pareto optimal strategies via Evolutionary Multi-Objective Direct Policy Search (EMODPS) [3]

Objectives (Y)

Annual hydropower generated [GWh] = $\sum_{t=1}^{T} \rho g\, r_t Hnet_t$

Annual demand deficits [Mm³] = $\frac{\sum_{t=1}^{T} demand\_deficit_t}{no. of\ years}$

MEF reliability [%] = $\frac{\sum n(ds\_release_t > MEF\_threshold_t)}{no. of\ time\ steps}$

High flow non exceedance reliability [%] = $\frac{\sum n(ds\_release_t < high\_flow\_threshold_t)}{no. of\ time\ steps}$

$$r_t = \exp\left(-\frac{(x_t - c)^2}{b^2}\right)$$

$$\theta = [b, c] = argmin_\theta Y$$

r_t: Downstream releases at timestep t

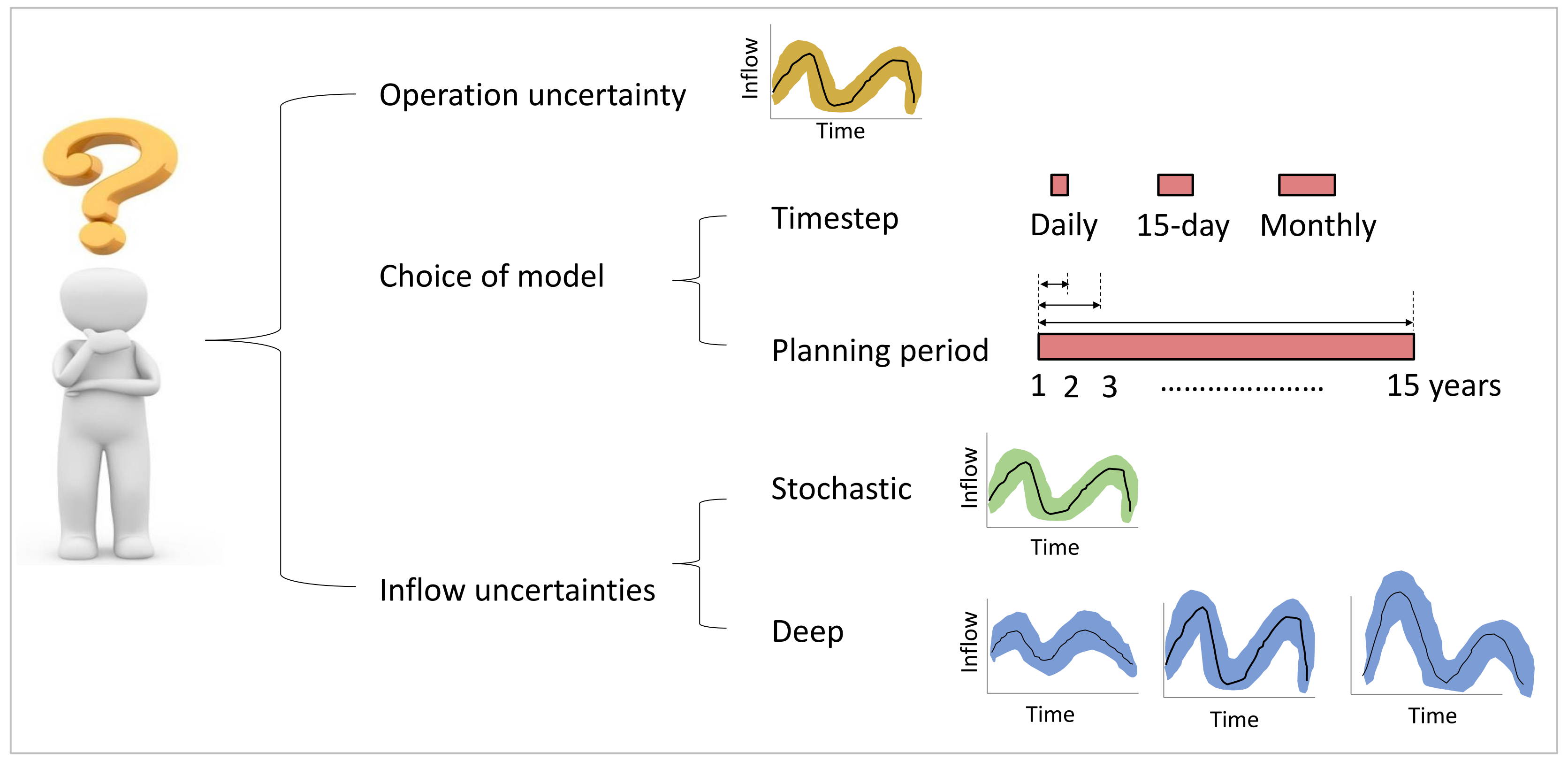
x_t: Normalised storage at time step t

b, c: RBF parameters

Y: Objectives

ds: downstream

Understanding controls on performance of the Nagarjuna Sagar reservoir in Southern India



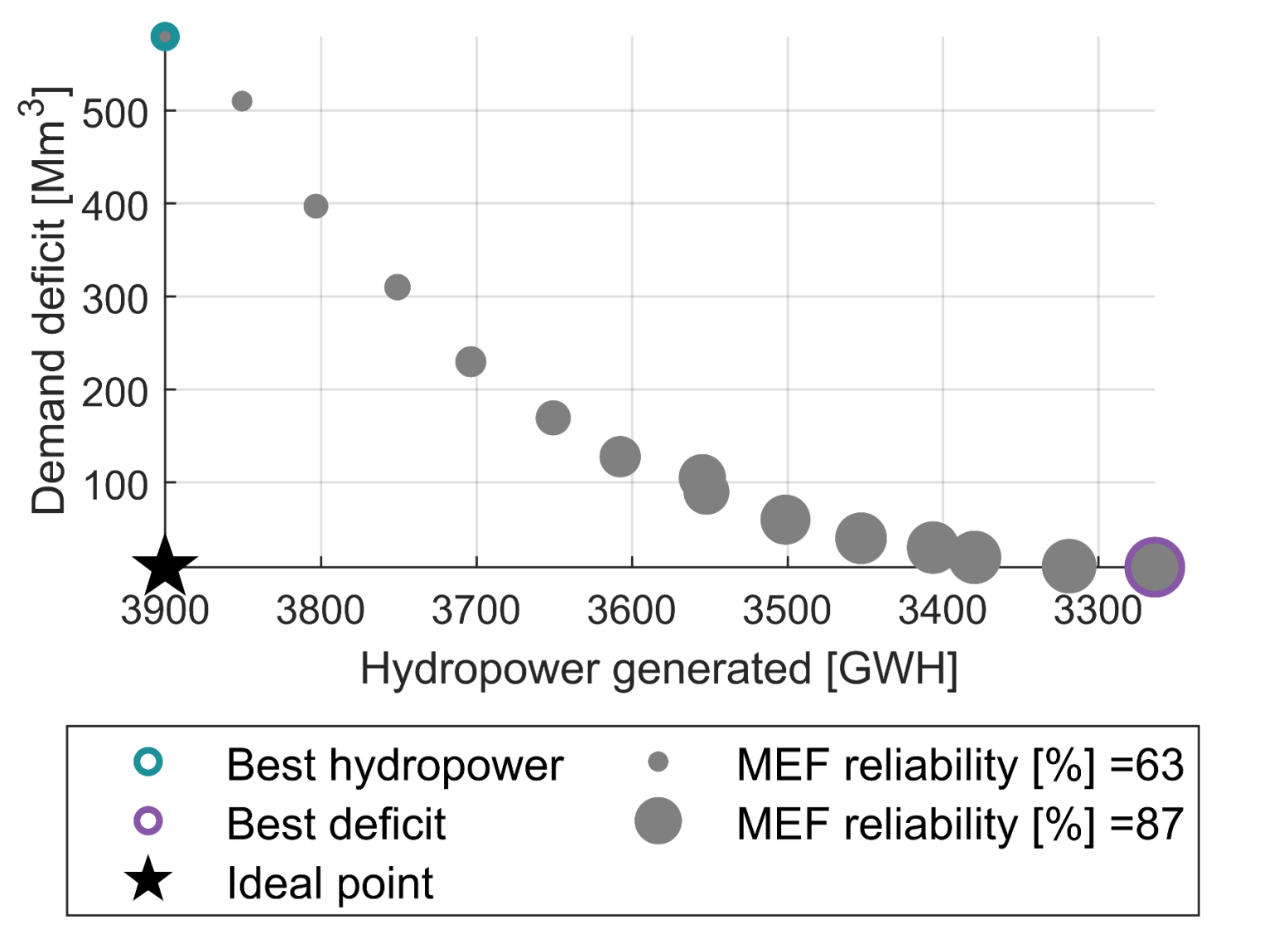
Schematic representation of the uncertain factors considered in this study

	Details of factors	Range of factors		Distribution function	Sampling strategy	Factor groups
		Min	Max			
Operation uncertainty (O)	Standard deviation from the baseline strategy	0	30%	Uniform	LHS	Group 1
Model uncertainty (M)	Daily, Fortnightly, monthly	1	3	Discrete uniform		Group 2
	Planning period(years)	1	15	Discrete uniform		
Stochastic uncertainty (S)	Number of stochastic inflow samples	1	10,000	Discrete uniform		Group 3
Deep uncertainty (D)	Mean inflow multiplier	0.80	2.56	Uniform		
	Standard deviation multiplier	0.38	7.14	Uniform		Group 4

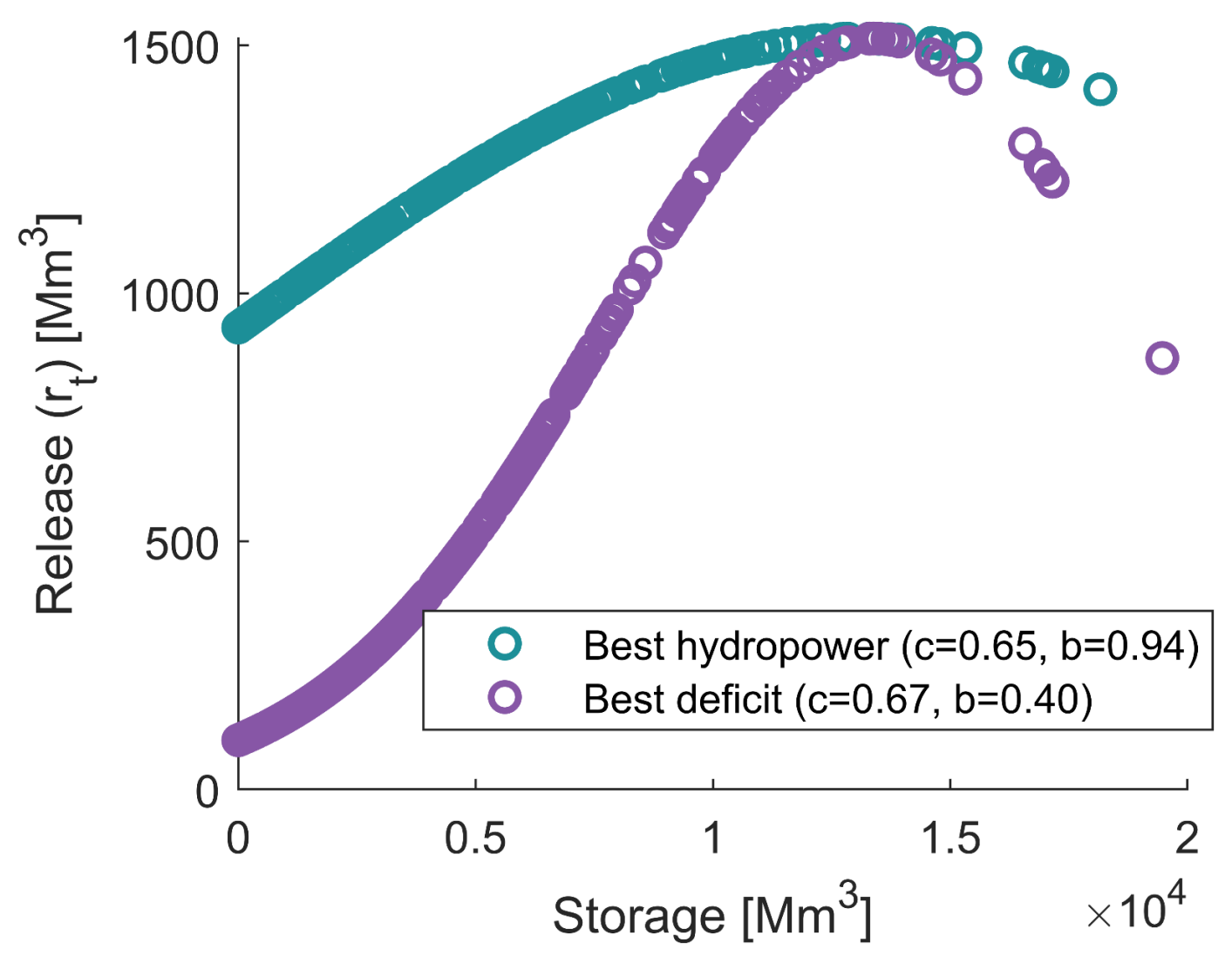
Details of the uncertain factors used in the study

- We use SAFE toolbox [2] to perform Sobol's variance based sensitivity analysis to calculate sensitivity indices
- The results are of the sensitivity analysis obtained for 30,000 samples are presented
- We applied convergence analysis to arrive at the number of samples

4. Results

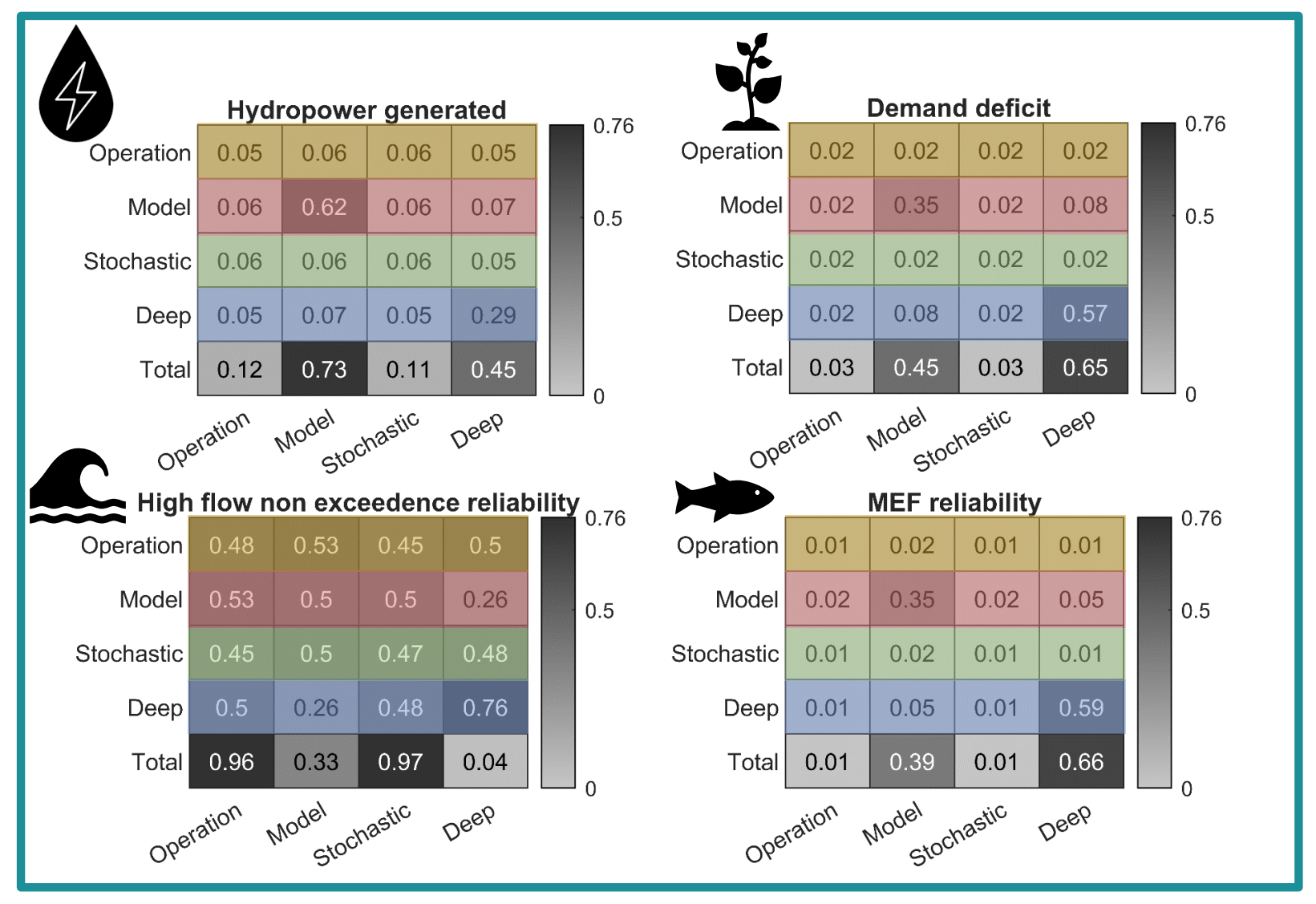


The Pareto optimal strategies identified using the Borg MOEA



Two example rule curves derived using EMODPS

- Significant trade-offs between demand deficits and hydropower [4-5]
- EMODPS identifies operating rules for a range of compromises
- Sensitivity and stability are quantified for the strategies best in hydropower generation and demand deficits



Hydropower generated

	Operation	Model	Stochastic	Deep
Operation	0.05	0.06	0.06	0.05
Model	0.06	0.62	0.06	0.07
Stochastic	0.06	0.06	0.06	0.05
Deep	0.05	0.07	0.05	0.29
Total	0.12	0.73	0.11	0.45

Demand deficit

	Operation	Model	Stochastic	Deep
Operation	0.02	0.02	0.02	0.02
Model	0.02	0.35	0.02	0.08
Stochastic	0.02	0.02	0.02	0.02
Deep	0.02	0.08	0.02	0.57
Total	0.03	0.45	0.03	0.65

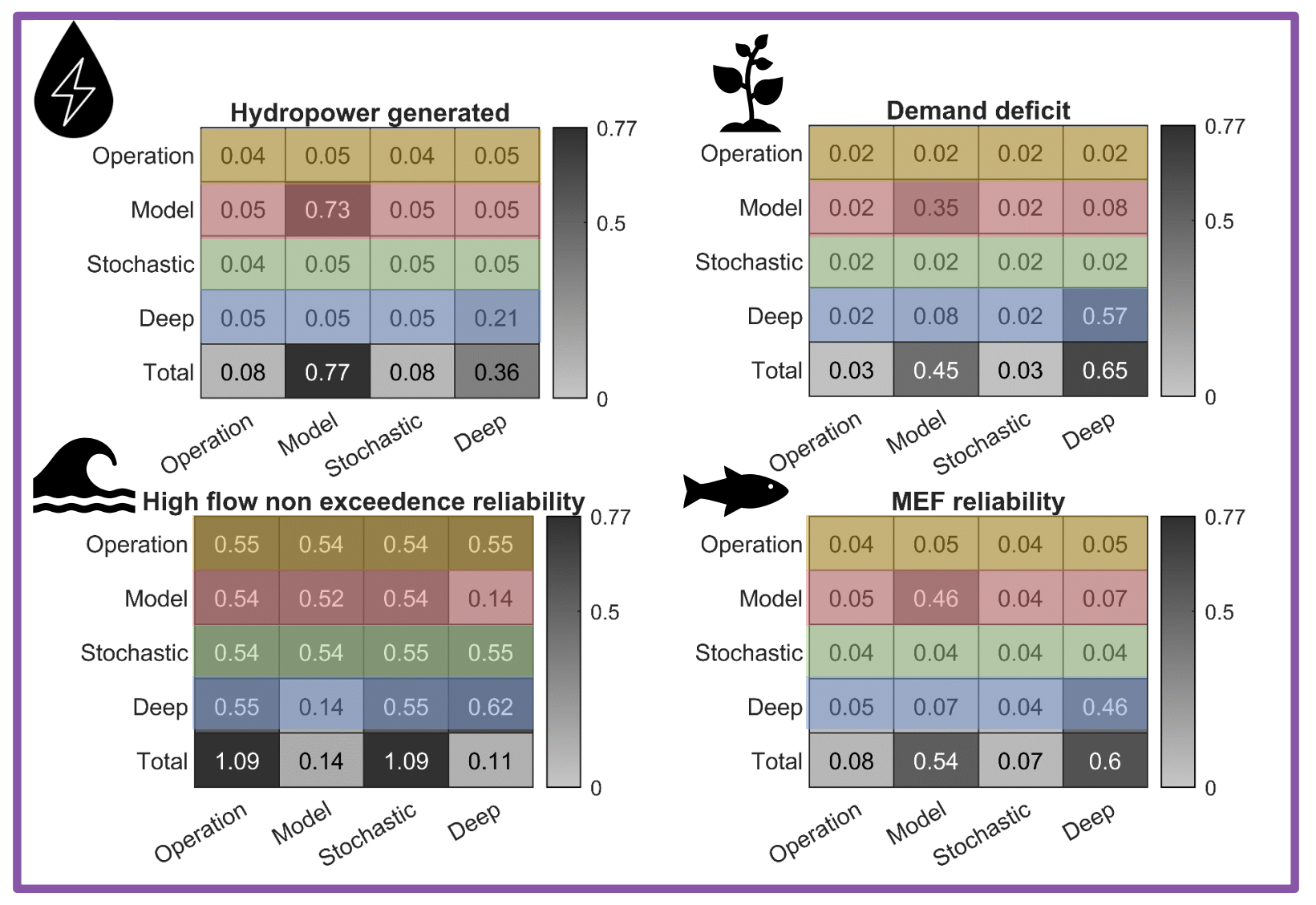
High flow non exceedence reliability

	Operation	Model	Stochastic	Deep
Operation	0.48	0.53	0.45	0.5
Model	0.53	0.5	0.5	0.26
Stochastic	0.45	0.5	0.47	0.48
Deep	0.5	0.26	0.48	0.76
Total	0.96	0.33	0.97	0.04

MEF reliability

	Operation	Model	Stochastic	Deep
Operation	0.01	0.02	0.01	0.01
Model	0.02	0.35	0.02	0.05
Stochastic	0.01	0.02	0.01	0.01
Deep	0.01	0.05	0.01	0.59
Total	0.01	0.39	0.01	0.66

Best hydropower strategy



Hydropower generated

	Operation	Model	Stochastic	Deep
Operation	0.04	0.05	0.04	0.05
Model	0.05	0.73	0.05	0.05
Stochastic	0.04	0.05	0.05	0.05
Deep	0.05	0.05	0.05	0.21
Total	0.08	0.77	0.08	0.36

Demand deficit

	Operation	Model	Stochastic	Deep
Operation	0.02	0.02	0.02	0.02
Model	0.02	0.35	0.02	0.08
Stochastic	0.02	0.02	0.02	0.02
Deep	0.02	0.08	0.02	0.57
Total	0.03	0.45	0.03	0.65

High flow non exceedence reliability

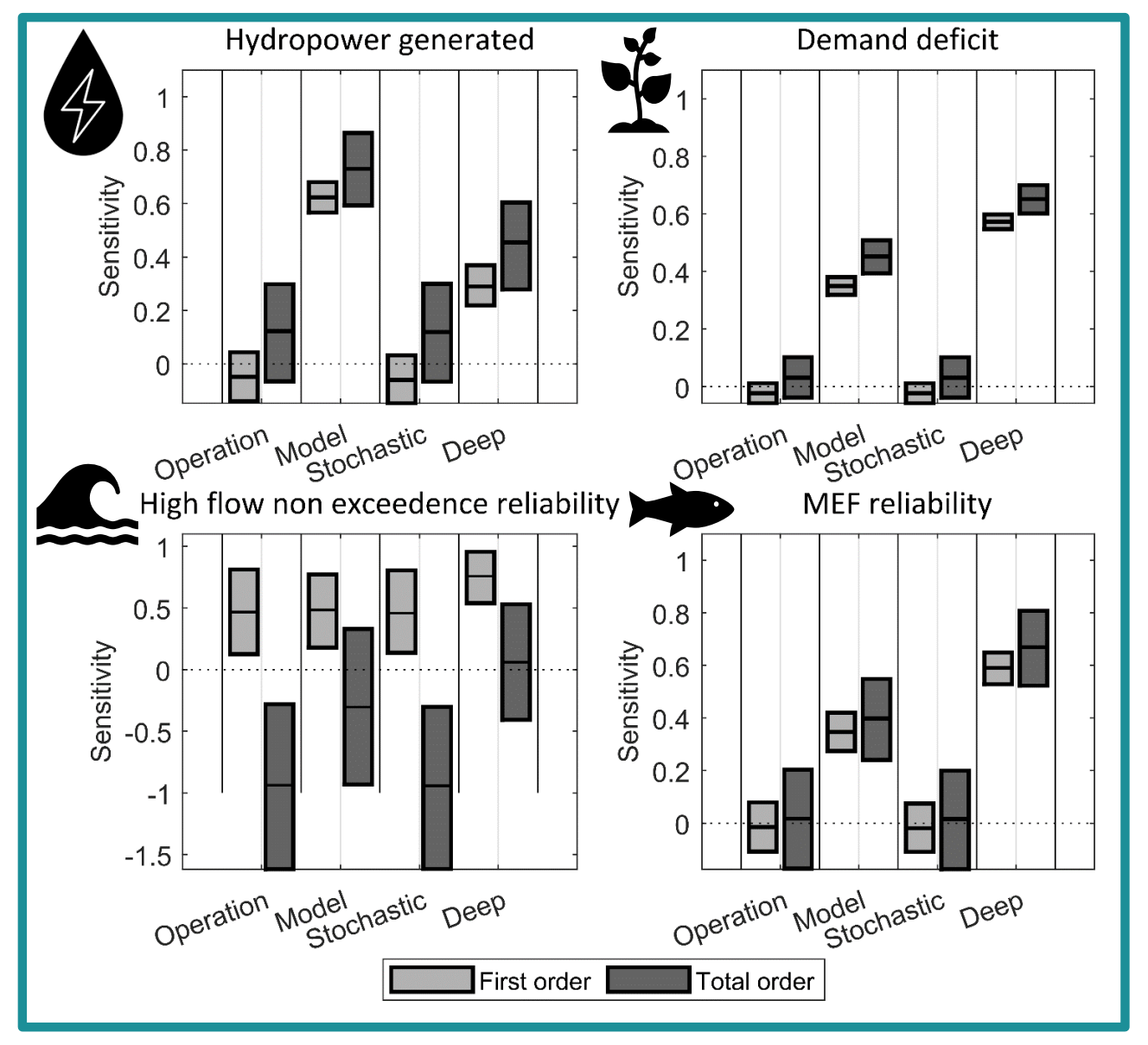
	Operation	Model	Stochastic	Deep
Operation	0.55	0.54	0.54	0.55
Model	0.54	0.52	0.54	0.14
Stochastic	0.54	0.54	0.55	0.55
Deep	0.55	0.14	0.55	0.62
Total	1.09	0.14	1.09	0.11

MEF reliability

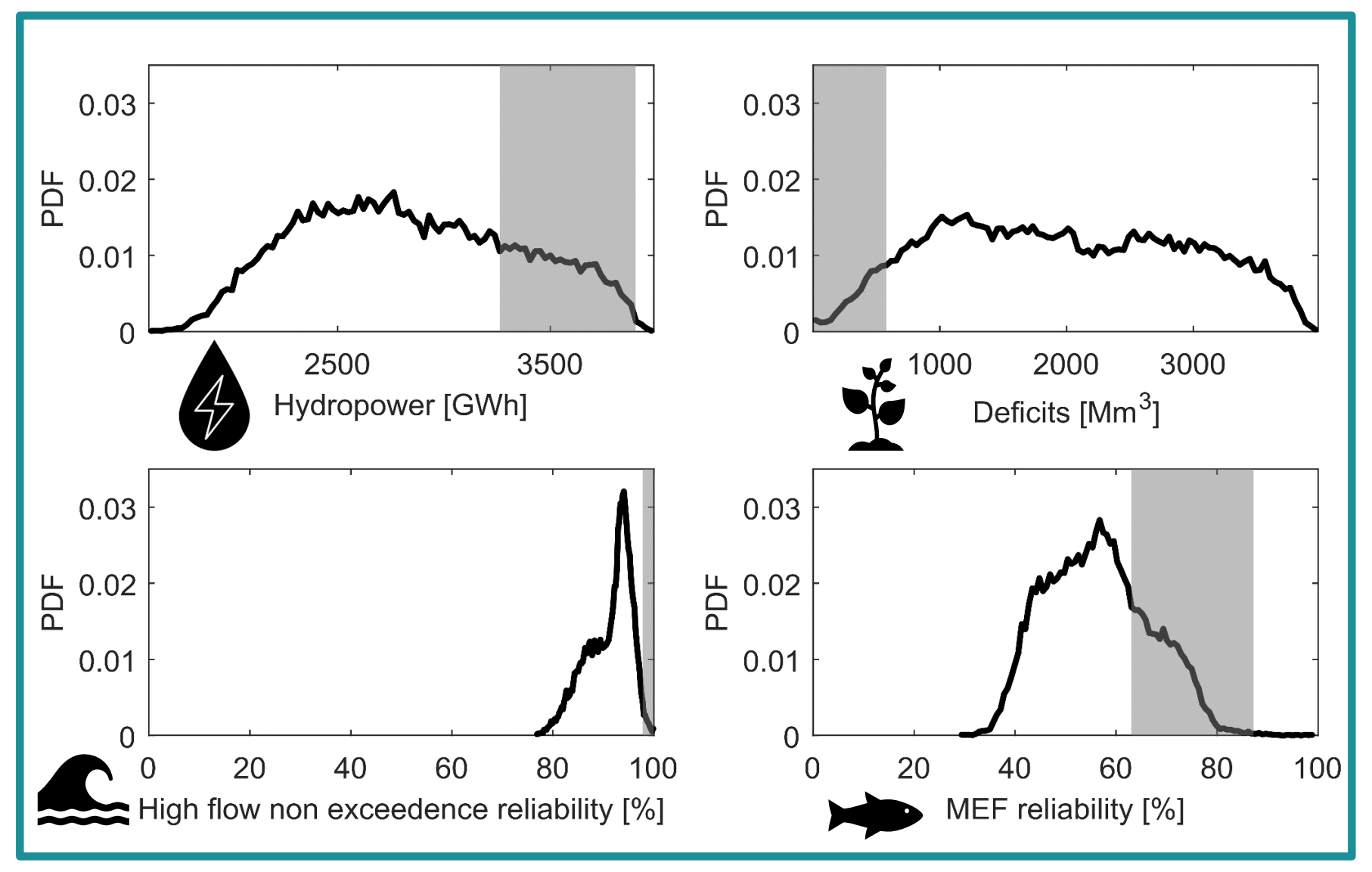
	Operation	Model	Stochastic	Deep
Operation	0.04	0.05	0.04	0.05
Model	0.05	0.46	0.04	0.07
Stochastic	0.04	0.04	0.04	0.04
Deep	0.05	0.07	0.04	0.46
Total	0.08	0.54	0.07	0.6

Best deficit strategy

Result: First total and second order sensitivity indices calculated for the best hydropower and best deficit strategies



90% confidence bounds of the sensitivity indices calculated for 500 bootstrap samples



PDF of objective function values across the sampled factors. Shaded gray region shows the range across the Pareto-optimal strategies

- Hydropower objective is most sensitive to model choices
- Deficits and MEF reliability are the most sensitive to deep uncertain factors
- Interactions between the uncertain factors are seen in high flow non-exceedance reliability objective
- The confidence bounds of the total order sensitivity indices are greater than the first order indices
- High flow non-exceedance reliability is the most stable and demands deficits is the least stable objective

5. Conclusions

- The proposed framework can be used to applied to any water management problem involving multiple sources of uncertainties.
- This framework enables an understanding of the relative importance of the uncertainties.
- This gives an opportunity to focus on the most important uncertain factor while identifying the best operating strategies

References

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