



*Quatrième workshop du réseau thématique NuTS
Data assimilation
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Optimization under uncertainty for the definition of aquifer sustainable yield under climate change

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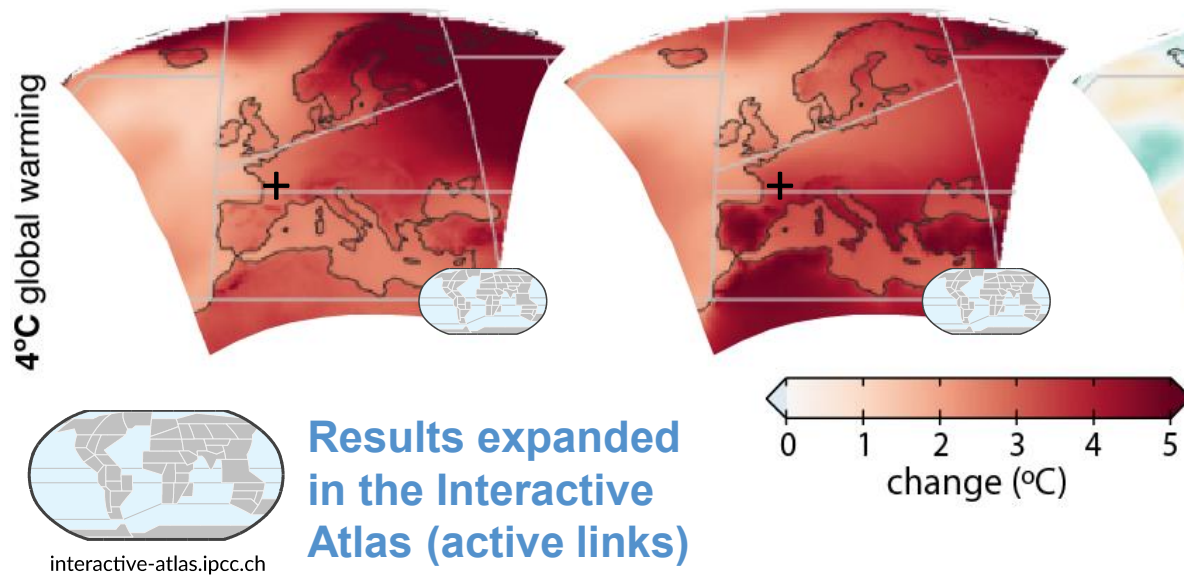


Climate projections for Western Europe (2080-2100)

Projected temperature change

Winter

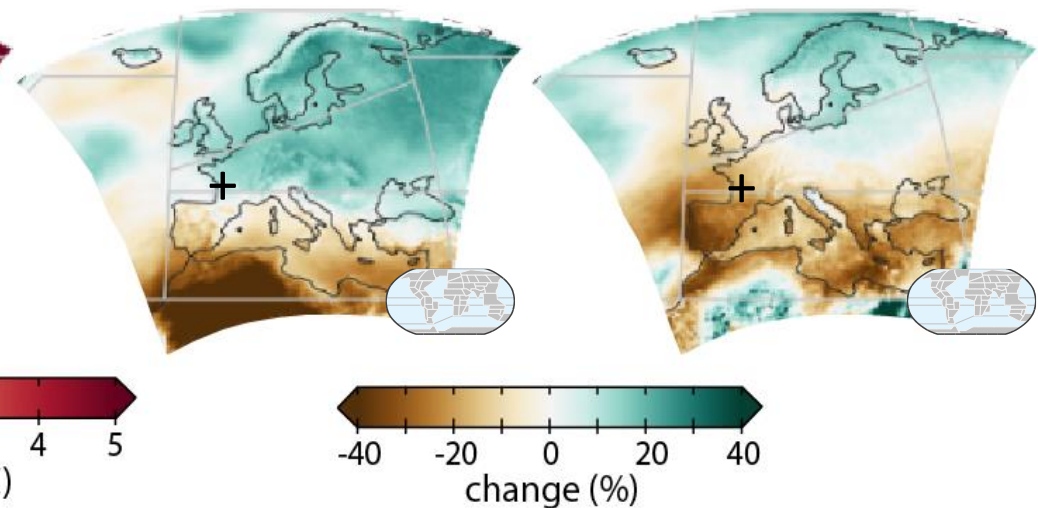
Summer



Projected precipitation change

Winter

Summer



- Rising temperature

- Undetermined change in winter precipitation
- Reduction of summer precipitation

+4°C Global warming scenario (2080-2100) with respect to 1995-2005.

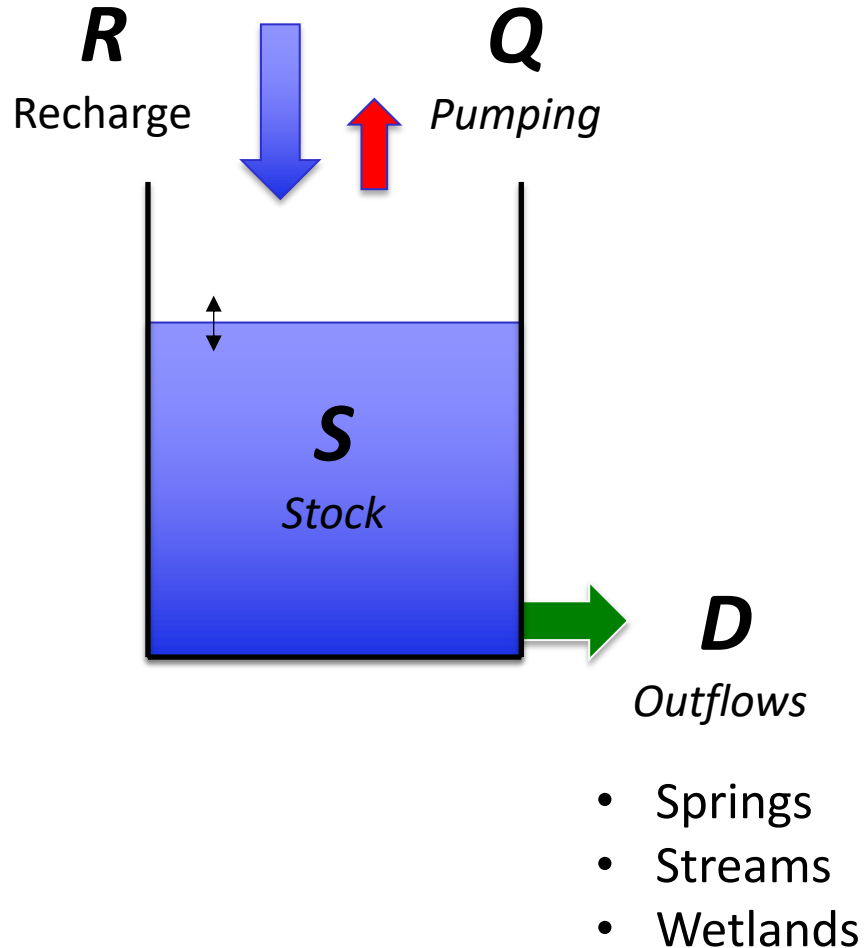
From EURO CORDEX (40 models) / RCP 8.5. – IPCC, Regional fact sheet, 6th assessment report, 2022



GREENPEACE



What is an “acceptable” pumping rate ?



“Safe” yield, Q_s

$\Delta S = 0$, no long-term depletion

$$\Rightarrow Q_s < R$$

“Sustainable” yield, Q_a :

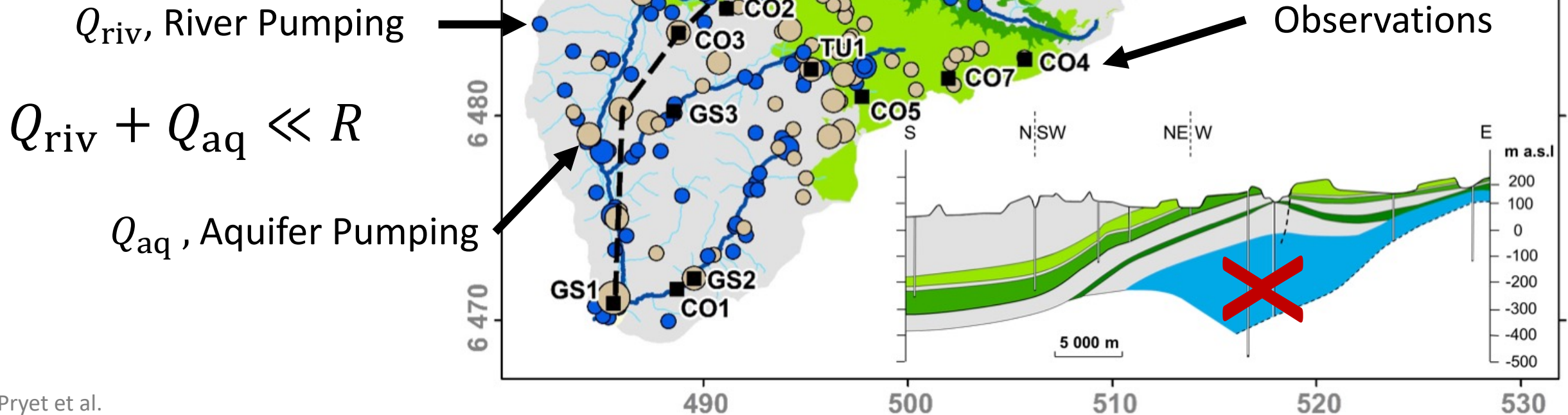
$\Delta D < \Delta D_a$, acceptable impacts on any other users

$$\Rightarrow Q_a < R - (D_0 + \Delta D_a) + \Delta S$$

$$\Rightarrow Q_a < -\Delta D_a$$

Elshall et al, (2020), Gleeson et al. (2020) ; Zhou et al (2009)

A « real world » problem...

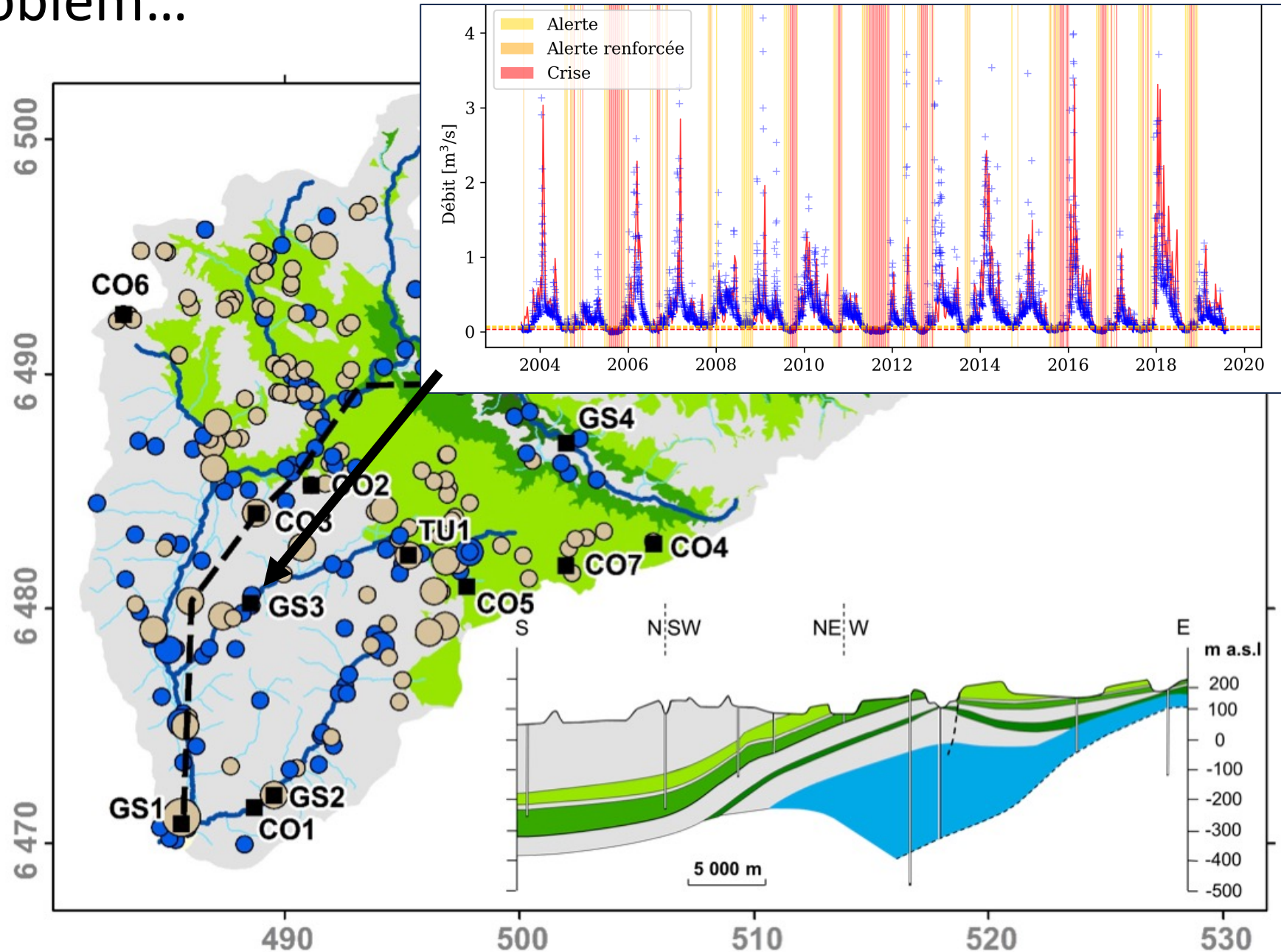


A « real world » problem...



$$Q_{\text{riv}} + Q_{\text{aq}} \ll R$$

But summer
river low flows...



MARTHE, a simple surface-subsurface flow model

Distributed Reservoir model

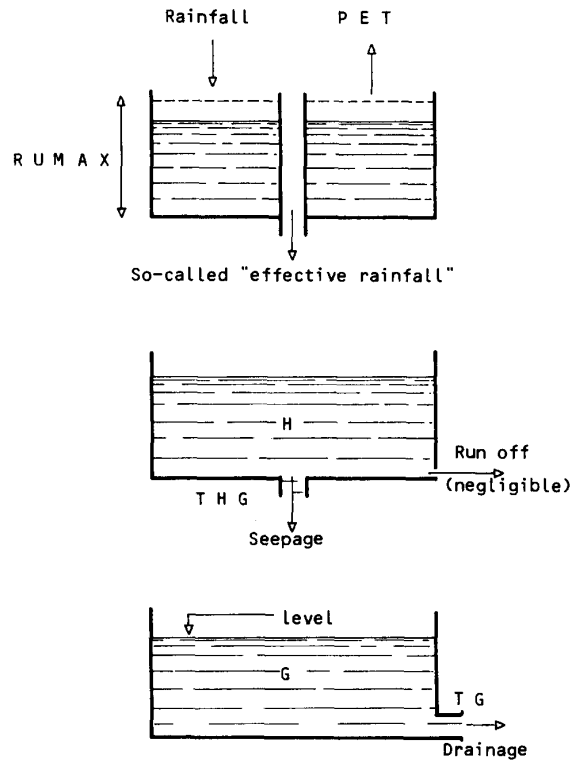
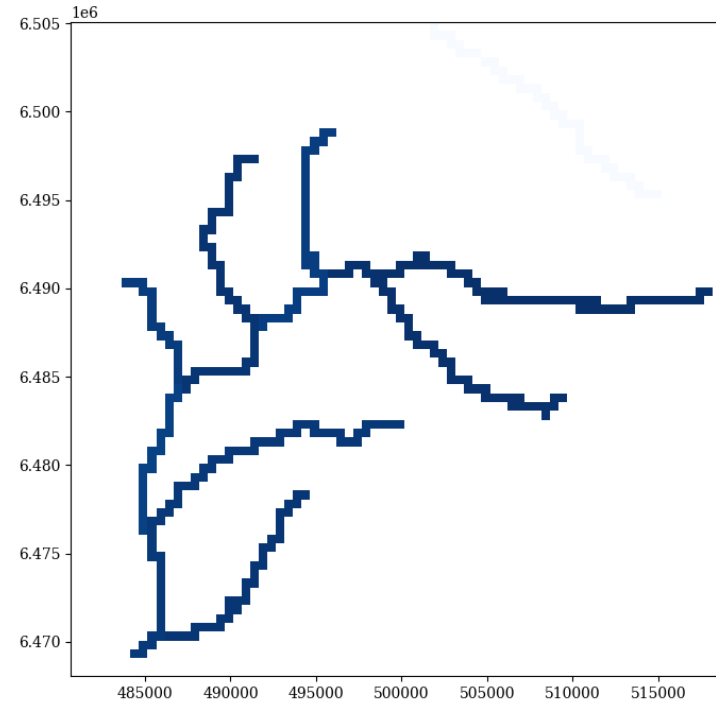
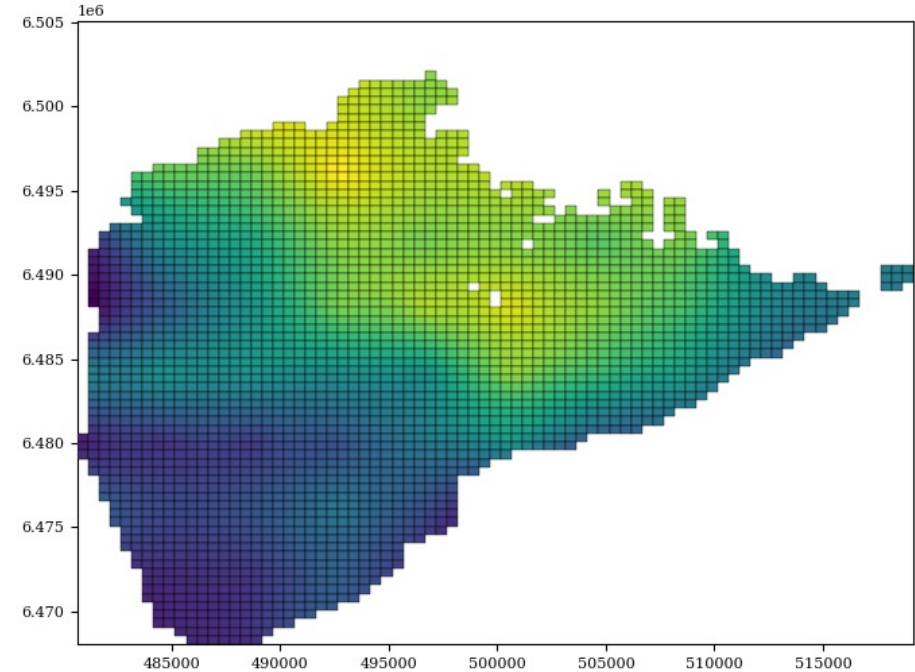


Fig. 1. Flow chart of BRGM simulation model GARDENIA.

Basic river flow routing



3D FD solution saturated flow



Coupled with



through



PyMarthe

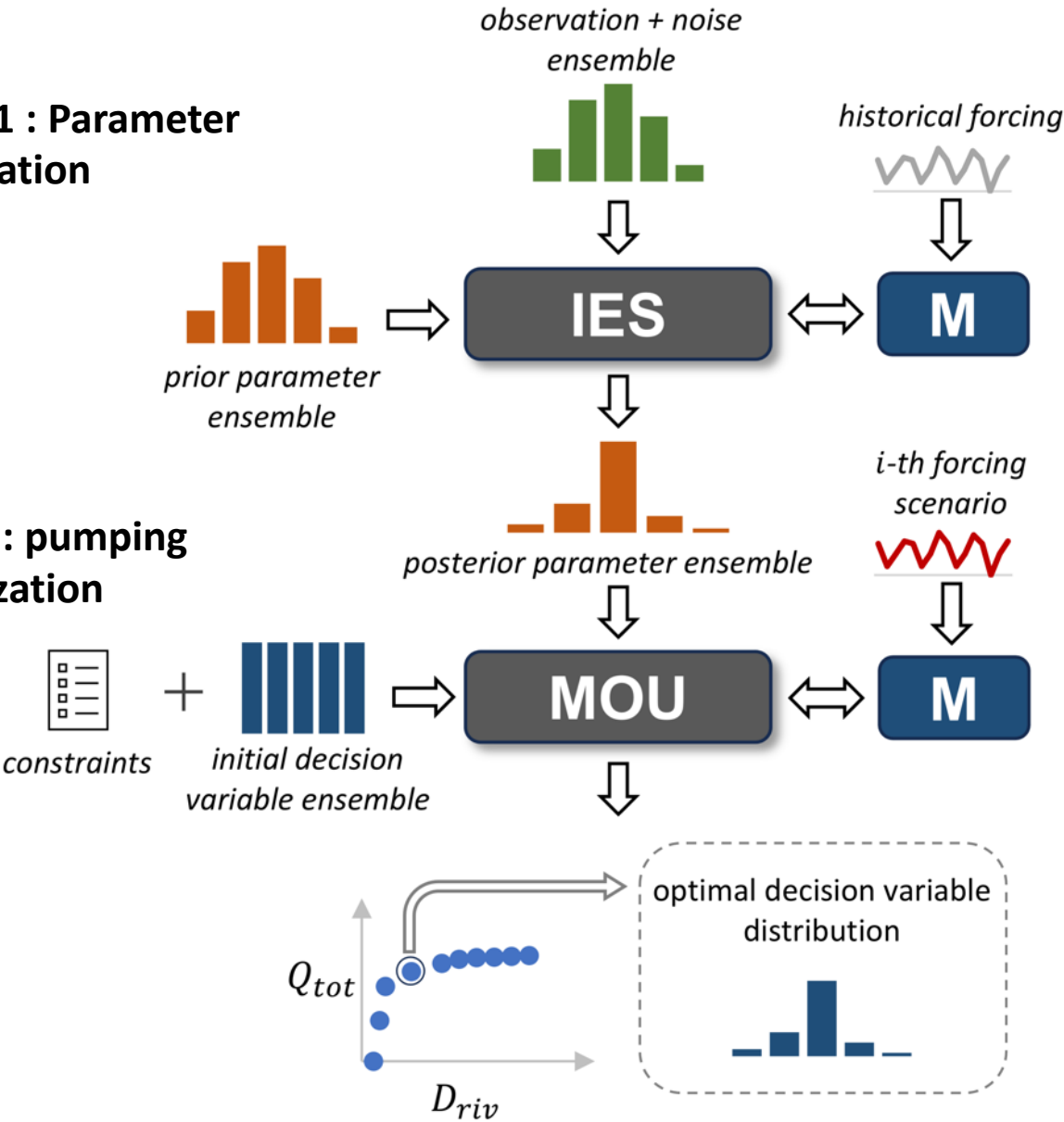
<https://github.com/pymartheproject/pymarthe>

A 3-step workflow

STEP 1 : Parameter estimation

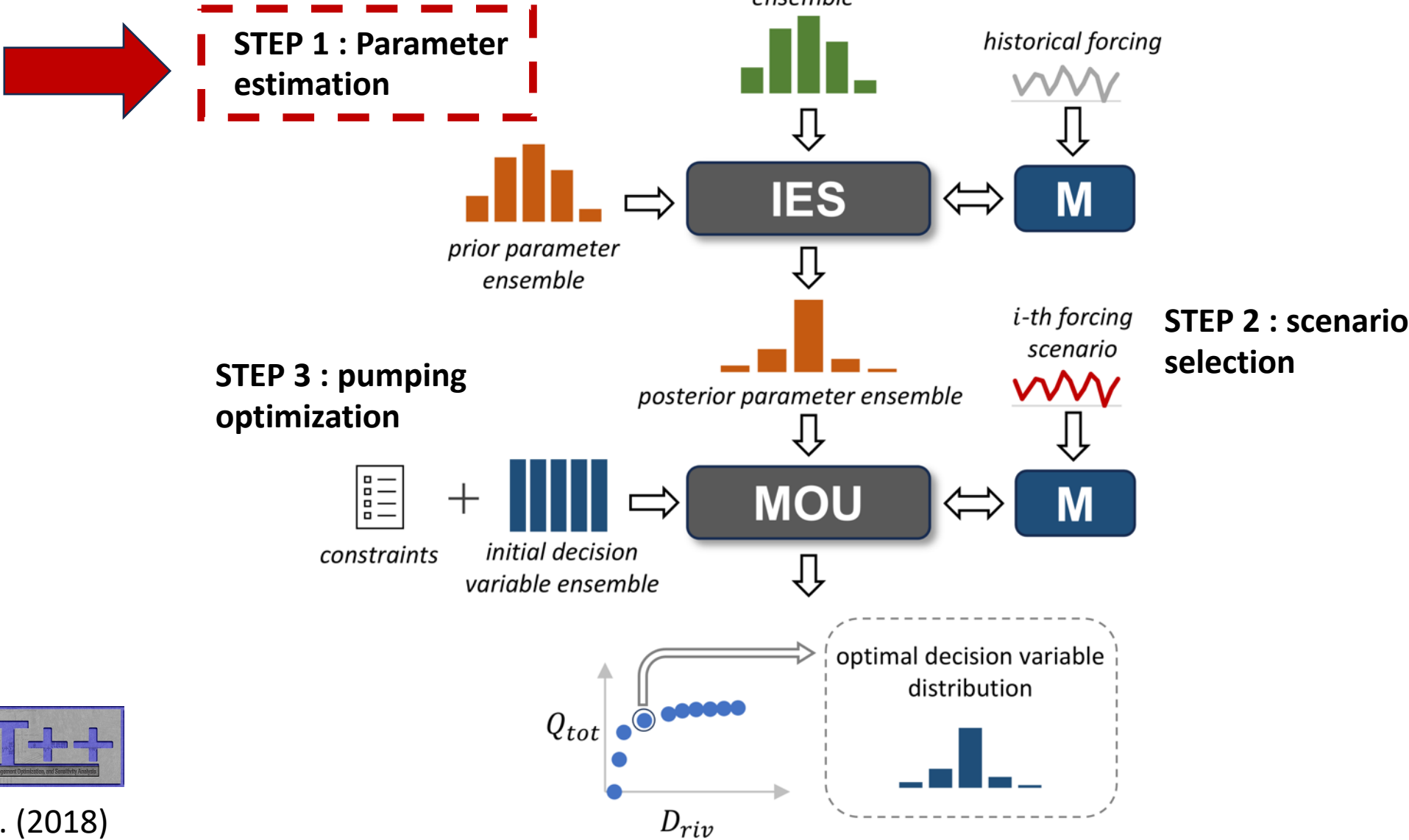
STEP 3 : pumping optimization

STEP 2 : scenario selection



White et al. (2018)

A 3-step workflow



White et al. (2018)

STEP 1:

ensemble-based history-matching

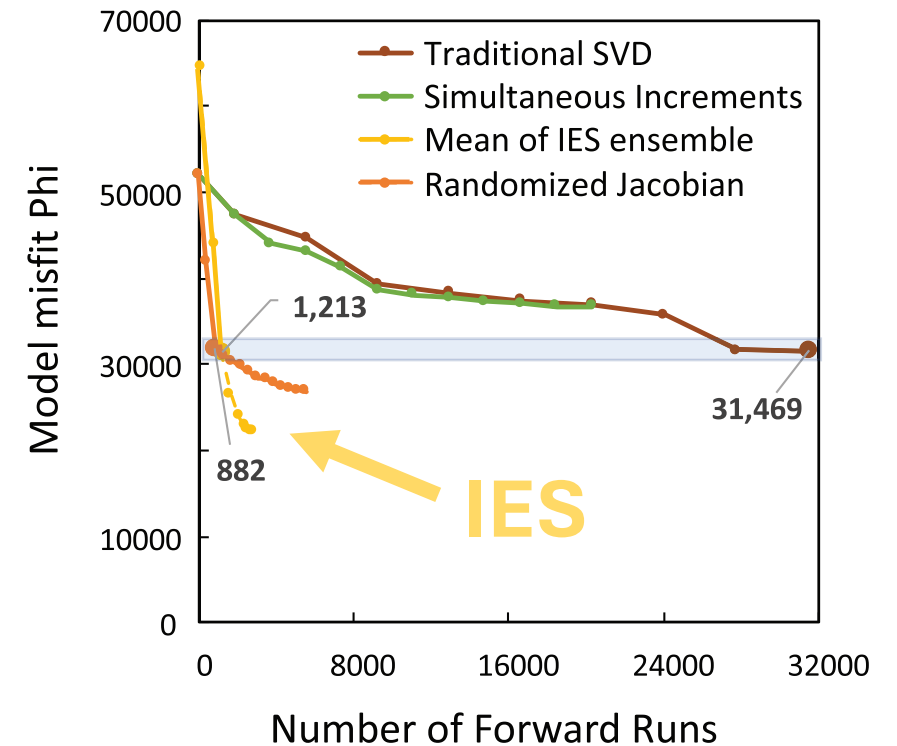
Iterative Ensemble Smoother => Levenberg-Marquardt – Ensemble Randomized Maximum Likelihood (LM-EnRML)

Parameter ensemble update (Chen & Oliver, 2013)

$$\Delta \mathbf{P}_i = \left((\hat{\mathbf{J}}^T \mathbf{C}_\varepsilon^{-1} \hat{\mathbf{J}}) + (1 + \lambda) \mathbf{C}_p^{-1} \right)^{-1} \left(\mathbf{C}_p^{-1} (\mathbf{P}_0 - \mathbf{P}_i) + \hat{\mathbf{J}} (\mathbf{D} - \hat{\mathbf{D}}_i) \right)$$

where $\hat{\mathbf{J}}$ is an ensemble-estimate of the Jacobian matrix

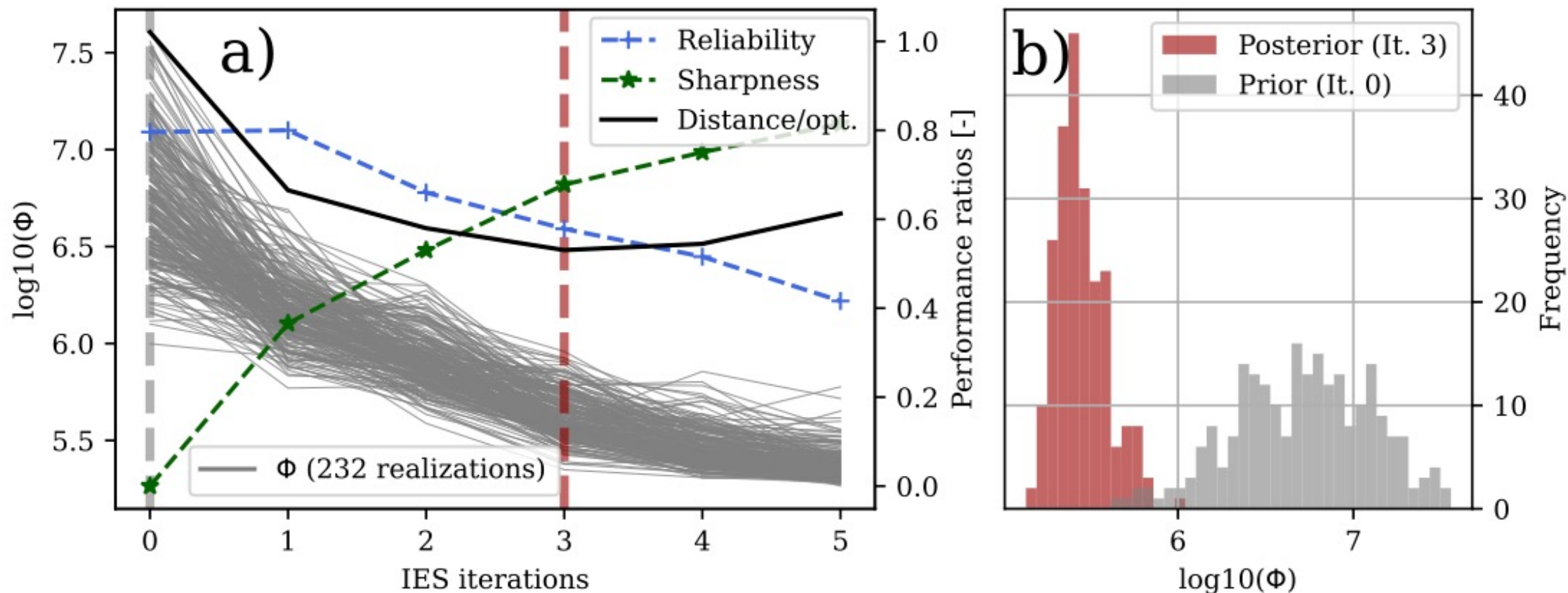
IES is implemented in the open-source PEST++ suite (White et al., 2018)



(Hunt et al., 2021)

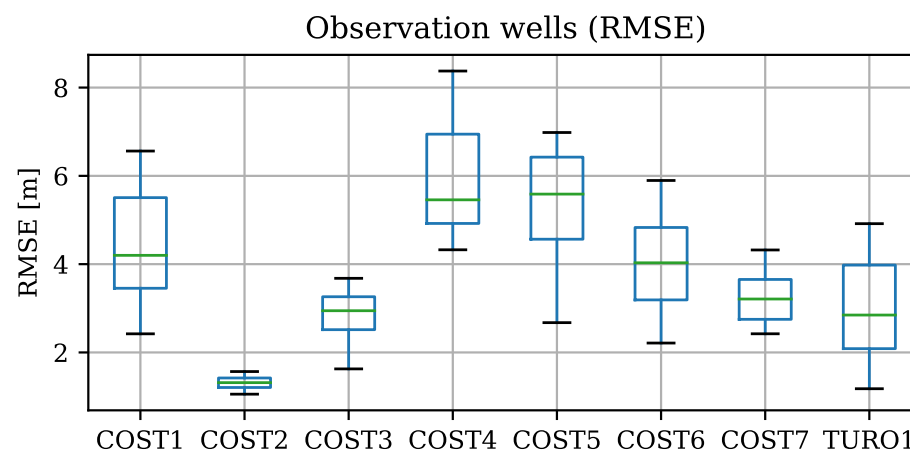
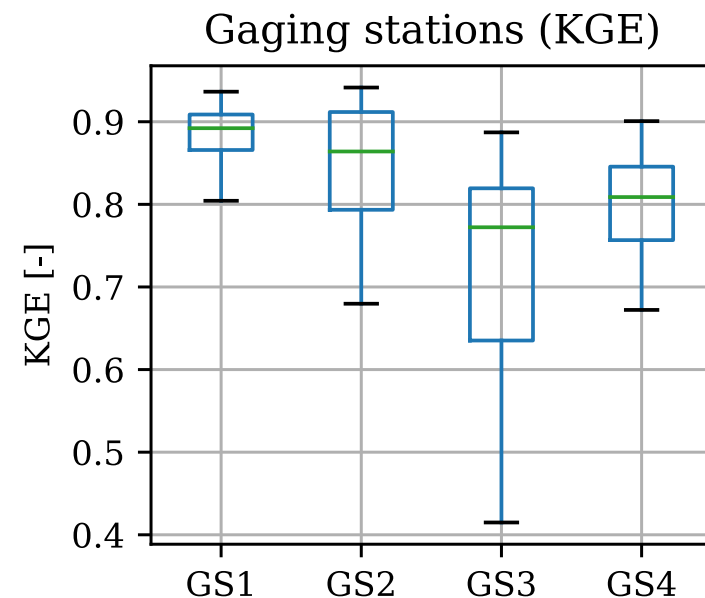
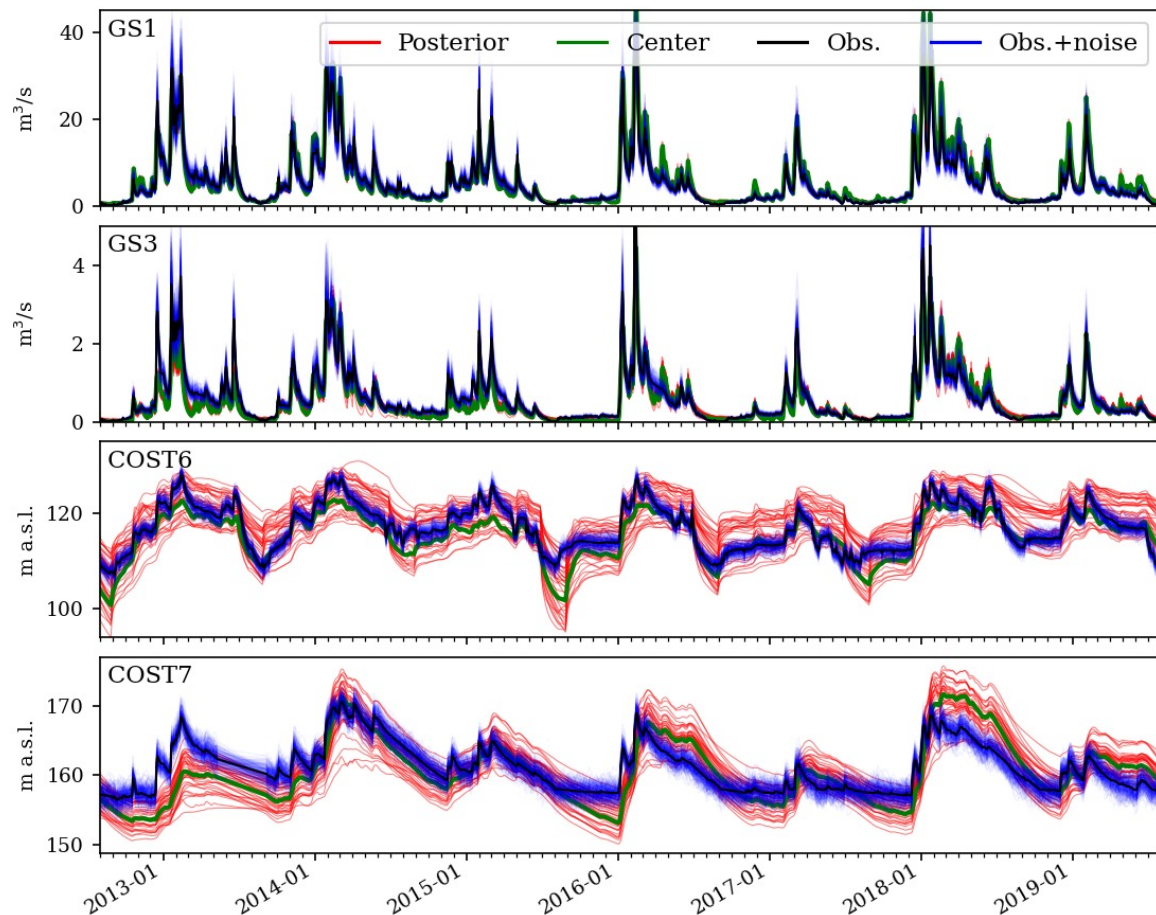
STEP 1: ensemble-based history-matching

Measurement Objective Function throughout IES Iterations



STEP 1: ensemble-based history-matching

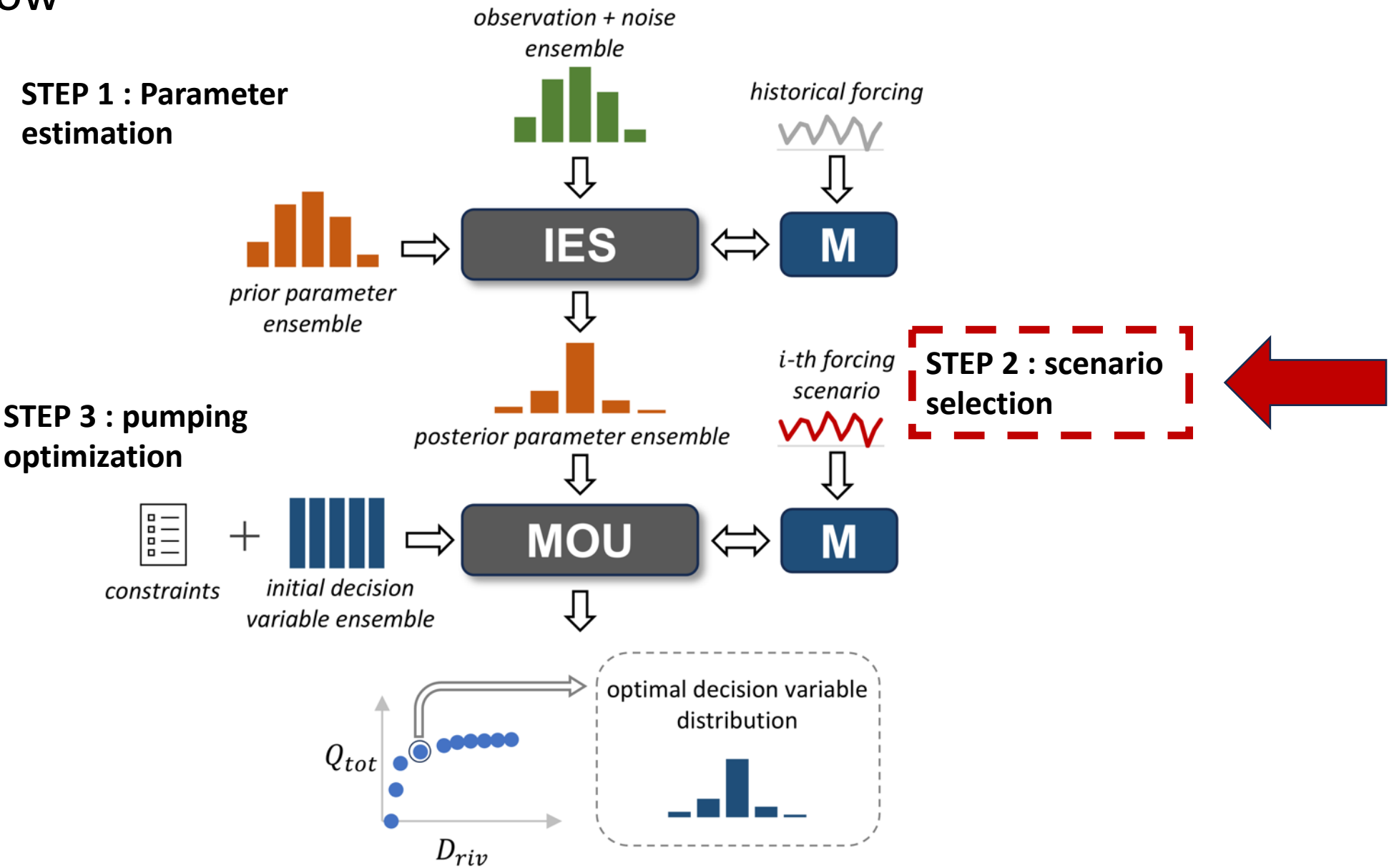
Calibration performance



A 3-step workflow

STEP 1 : Parameter estimation

STEP 3 : pumping optimization



White et al. (2018)

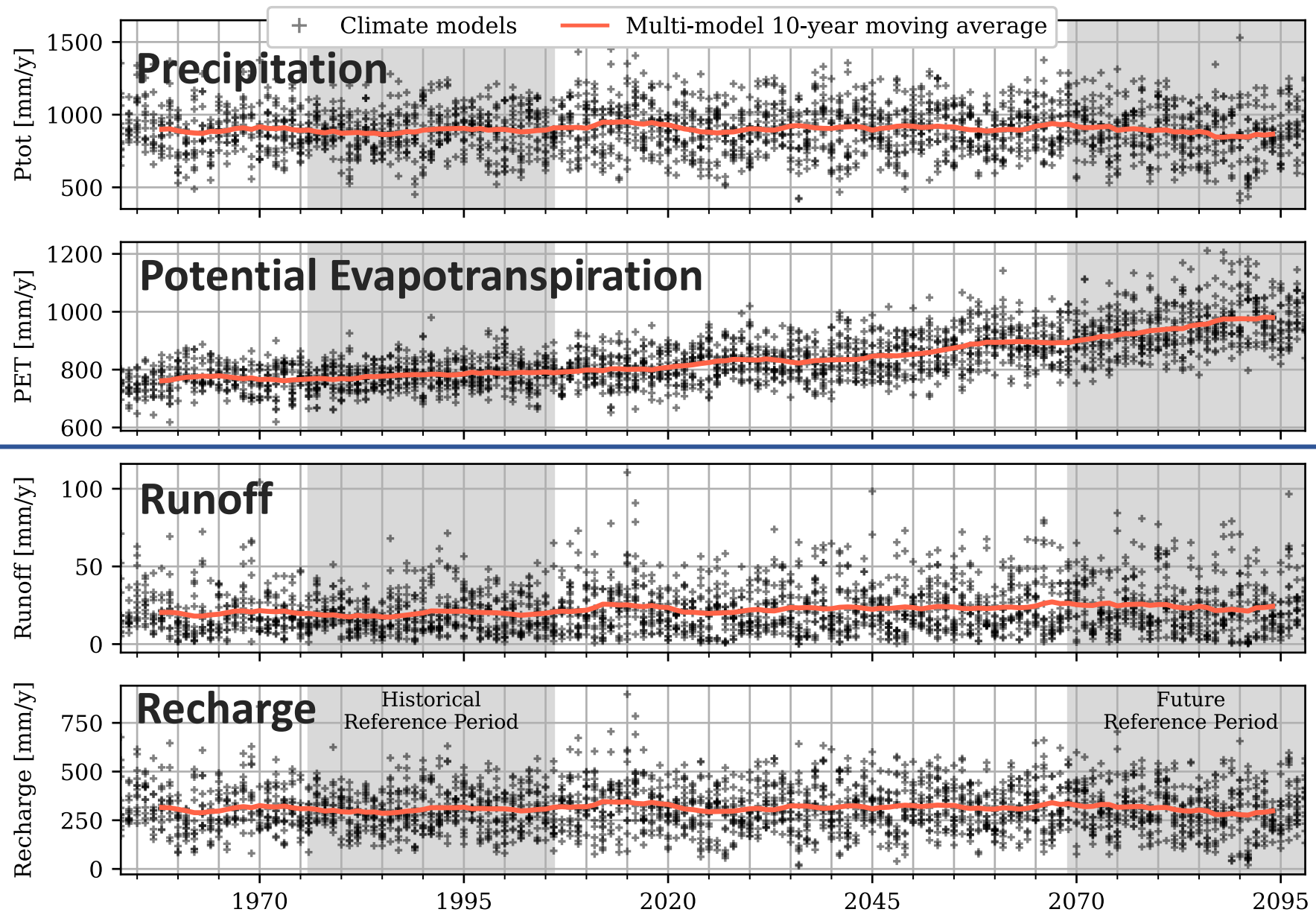
STEP 2: scenario selection

Forcings

17 GCM-RCMs from
the Explore² dataset
(Marson et al., 2024)

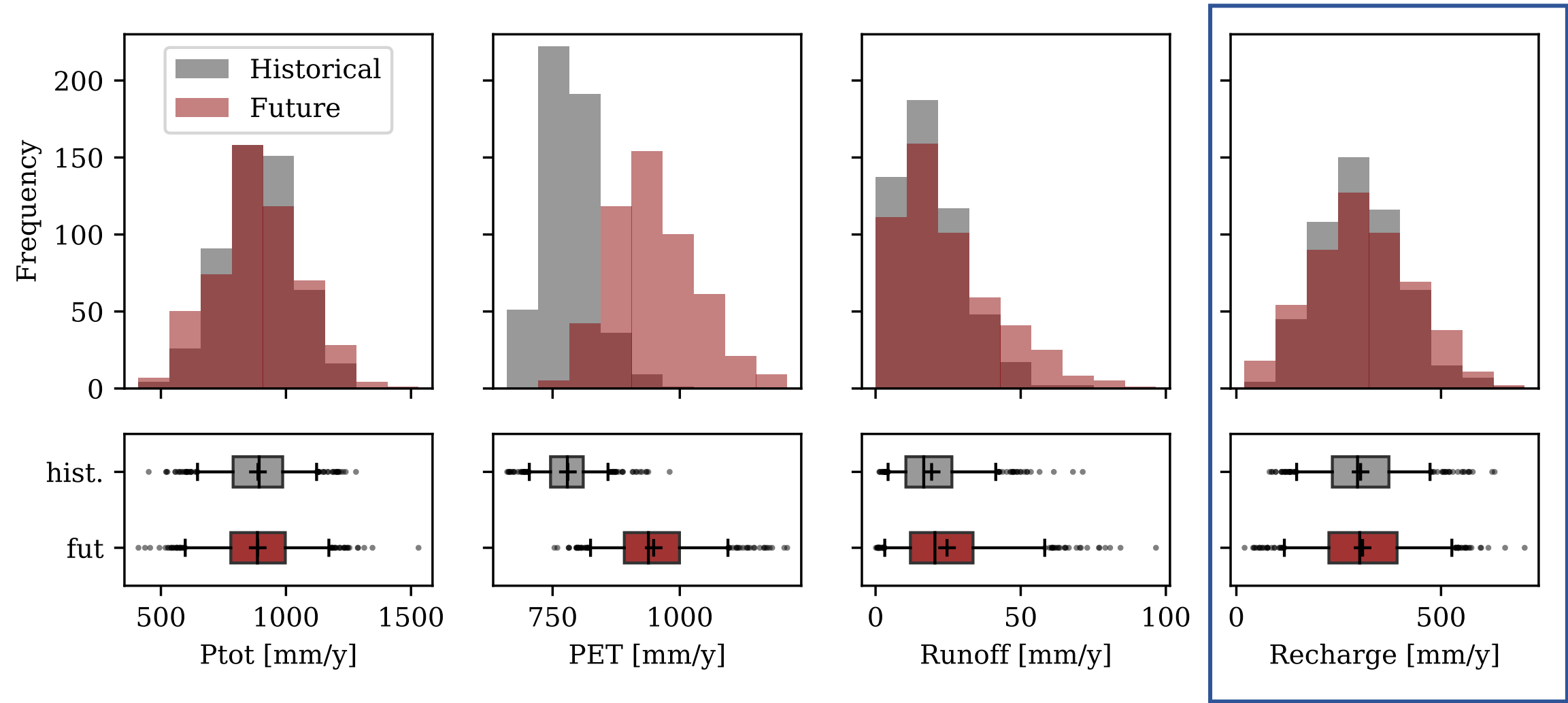
Simulated variables

Long term simulation with multiple (17) climate models (GCMs-RCMs)



STEP 2: scenario selection

Comparison of Hydrologic Variables over Historical and Future Periods



STEP 2: scenario selection

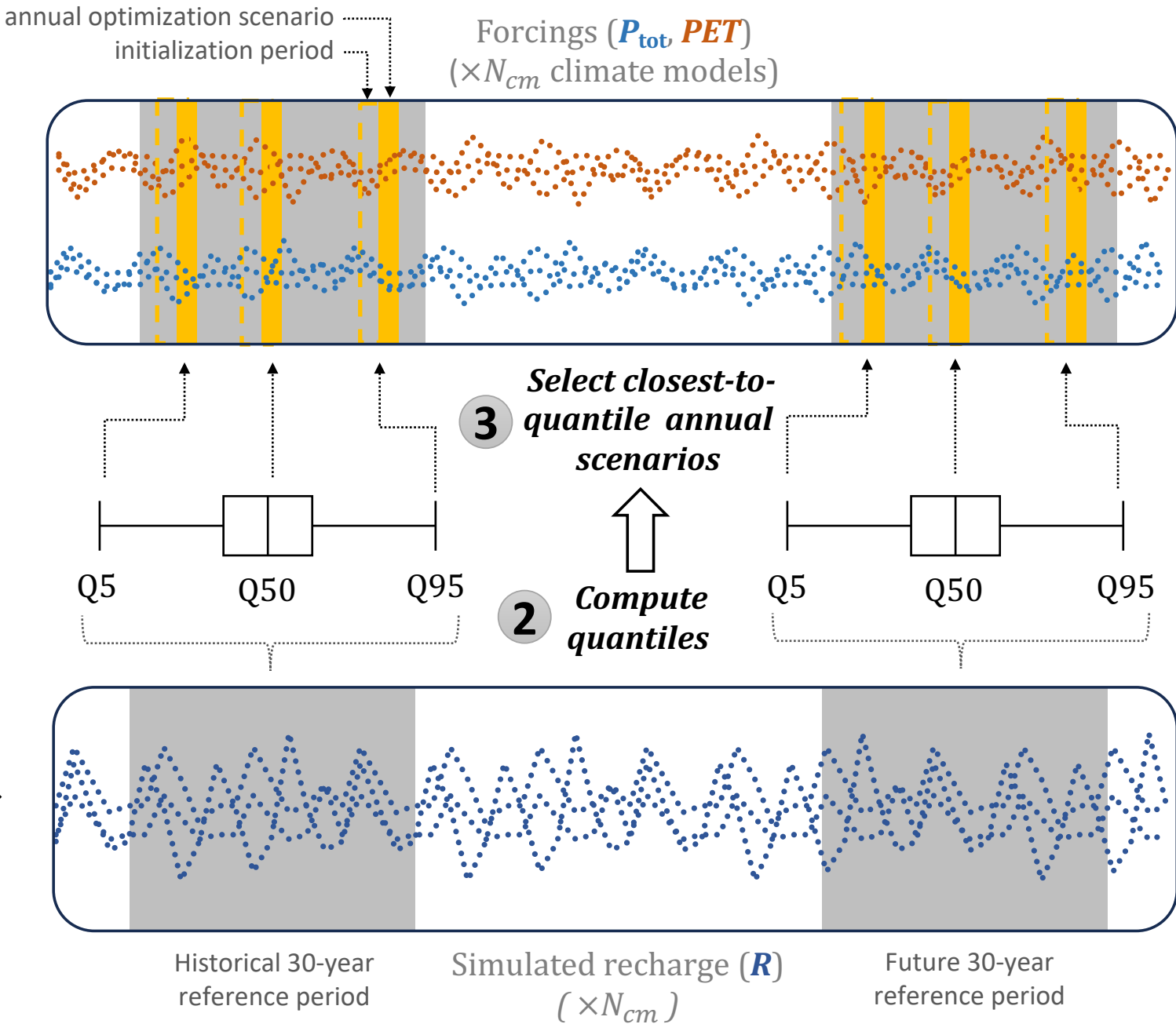
1 Run model ($\times N_{cm}$)

Forcings from climate models

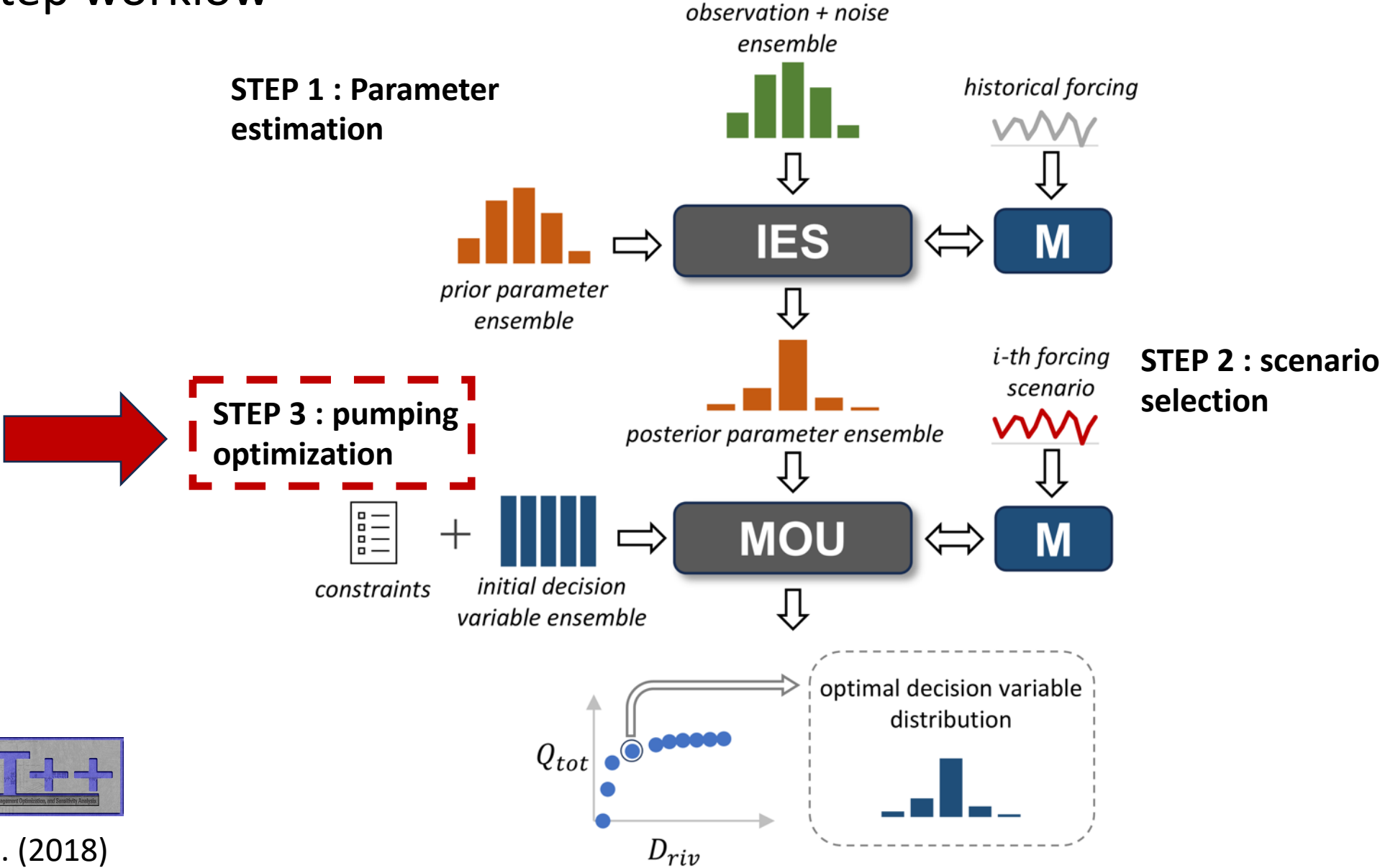


surface-subsurface flow model with posterior base parameter set

Simulated groundwater recharge



A 3-step workflow



White et al. (2018)

STEP 3: Constrained, multi-objective optimization

Management Variables

Objective #1 : max. **total pumping**

$$\max_{Q_{PAQ,(j,n)}; Q_{PRIV,(k,n)}} V = \sum_n \left(\underbrace{\sum_j \left(Q_{PAQ,(j,n)} \cdot \Delta t \right)}_{\text{Aquifer pumping}} + \underbrace{\sum_k \left(Q_{PRIV,(k,n)} \cdot \Delta t \right)}_{\text{River pumping}} \right)$$



STEP 3: Constrained, multi-objective optimization

Management Variables

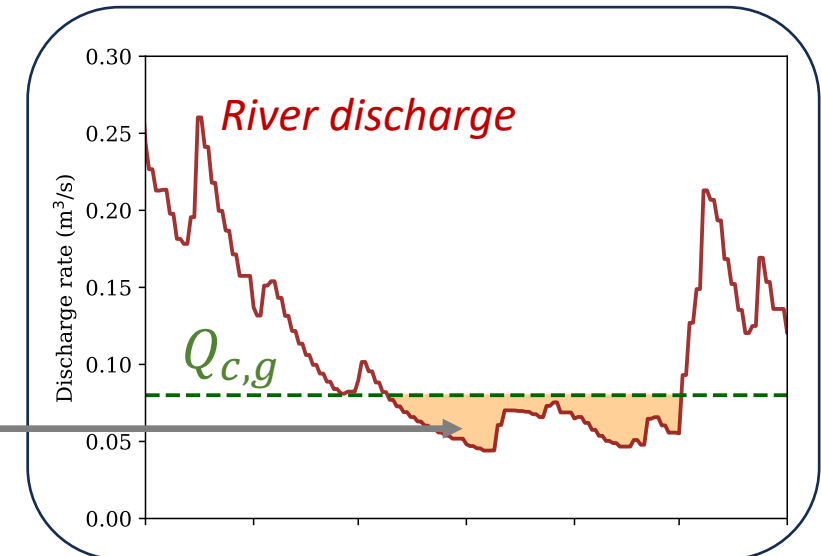
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Objective #2 : min. river flow deficit :

$$\min_{Q_{PAQ,(j,n)}; Q_{PRIV,(k,n)}} D = \sum_{g,n} \underbrace{\left(\min(Q_{c,g} - Q_{riv,(g,n)}, 0) \cdot \Delta t \right)}_{\text{Deficit}}$$



STEP 3: Constrained, multi-objective optimization

Management Variables

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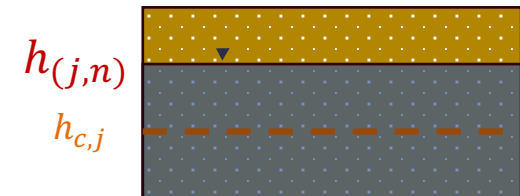
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With constraints on gw levels :

subject to $h_{(j,n)} > h_{c,j}$



STEP 3: Constrained, multi-objective optimization

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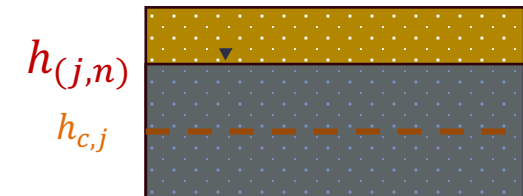
$$\min_{Q_{PAQ,(j,n)}; Q_{PRIV,(k,n)}} D = \sum_{g,n} \left(\min(Q_{c,g} - Q_{riv,(g,n)}, 0) \cdot \Delta t \right)$$



Model outputs (uncertain!)

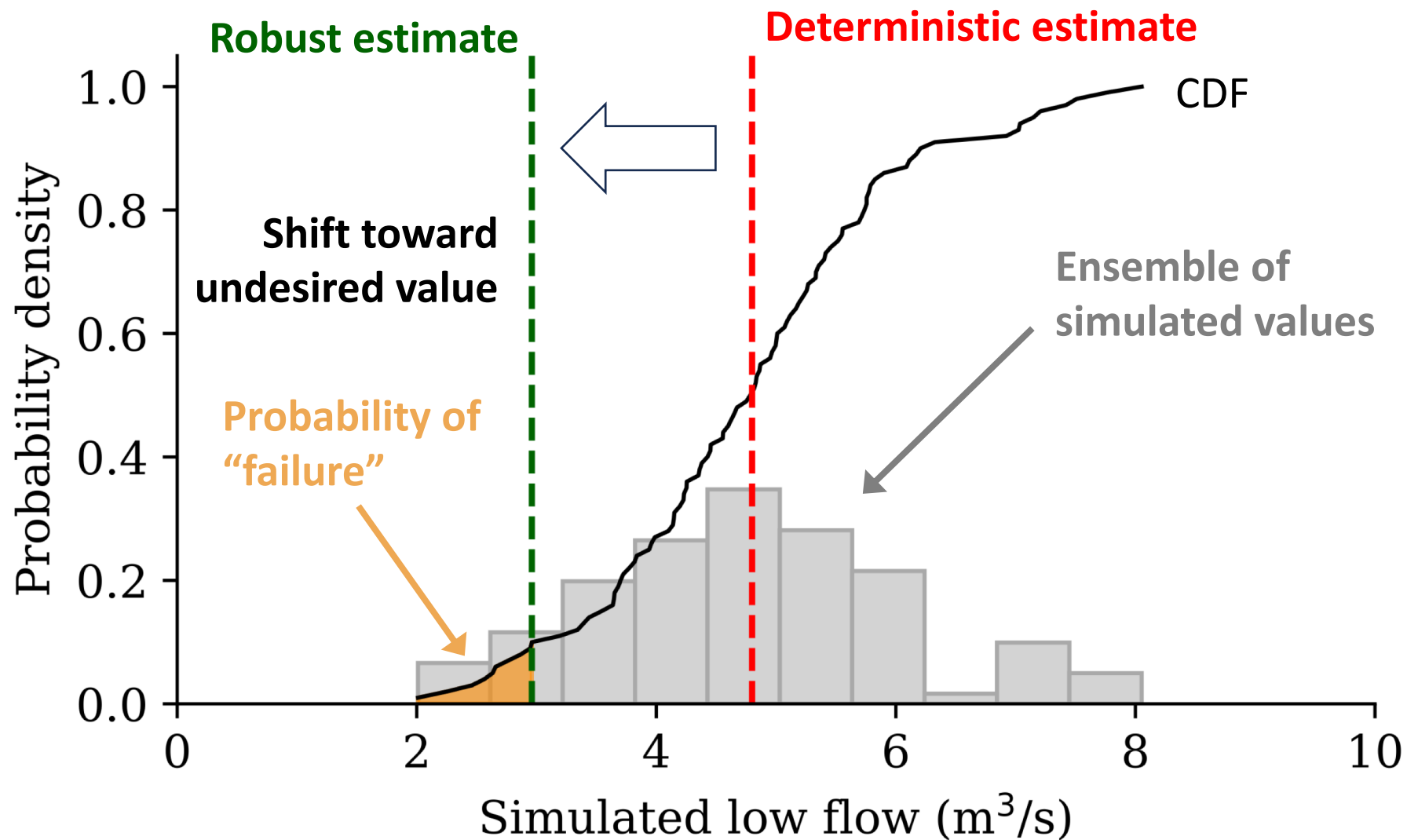
With constraints on **gw levels** :

subject to $h_{(j,n)} > h_{c,j}$



STEP 3 : optimization

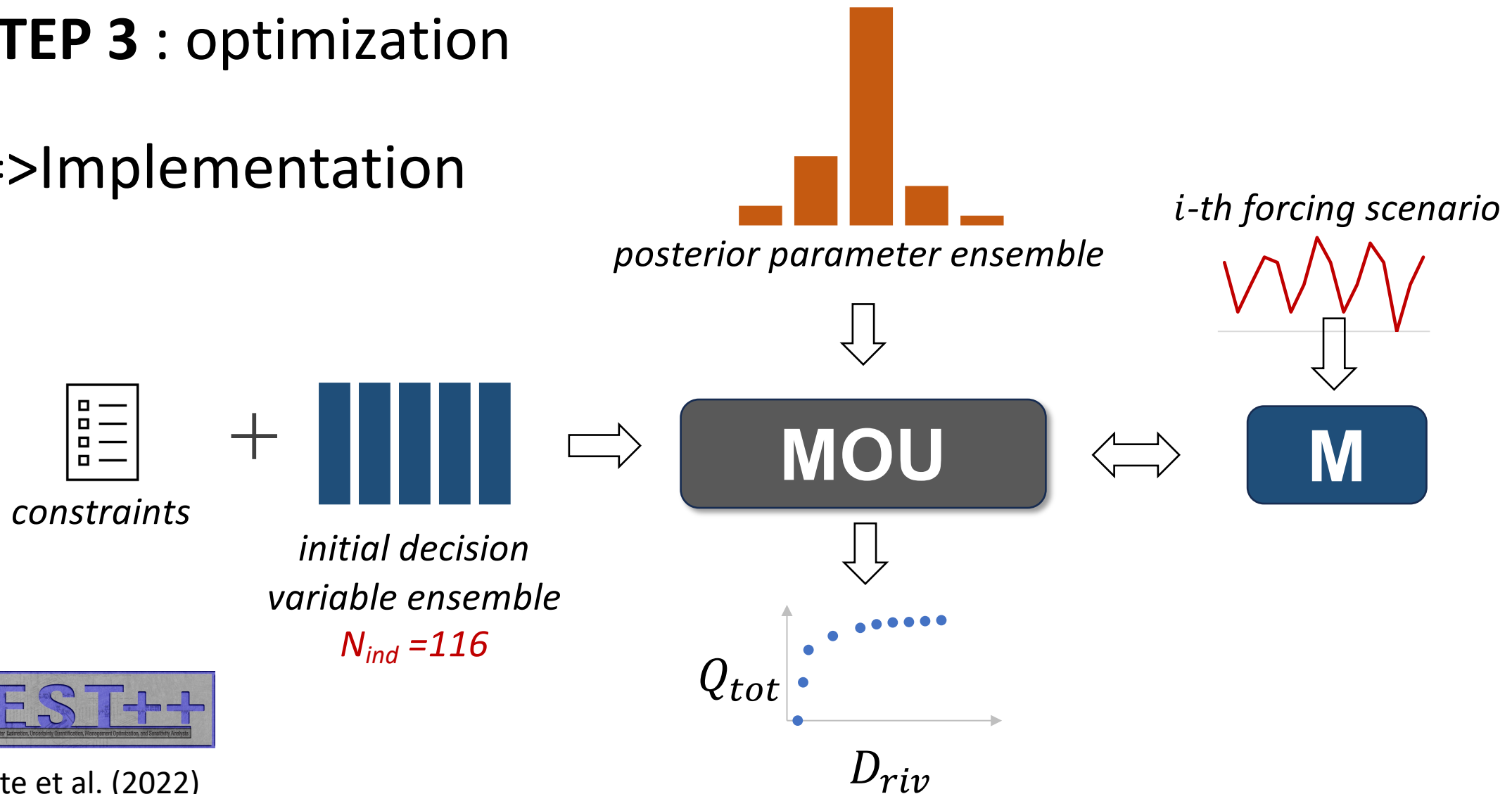
⇒ Chance
constrained
optimization



Synthetic data, illustrative purpose only

STEP 3 : optimization

=>Implementation

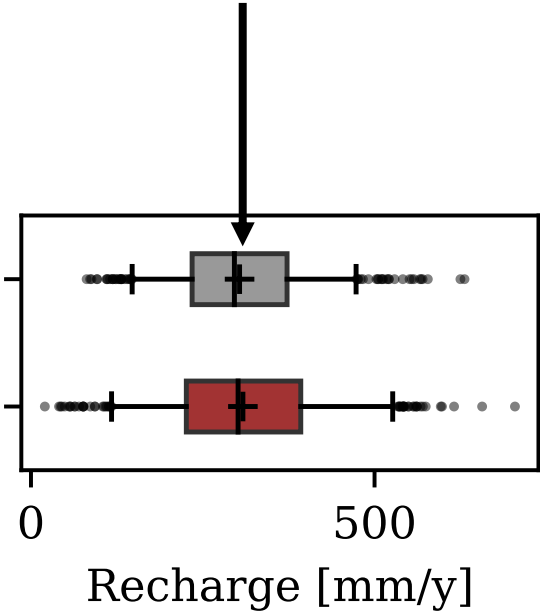


White et al. (2022)

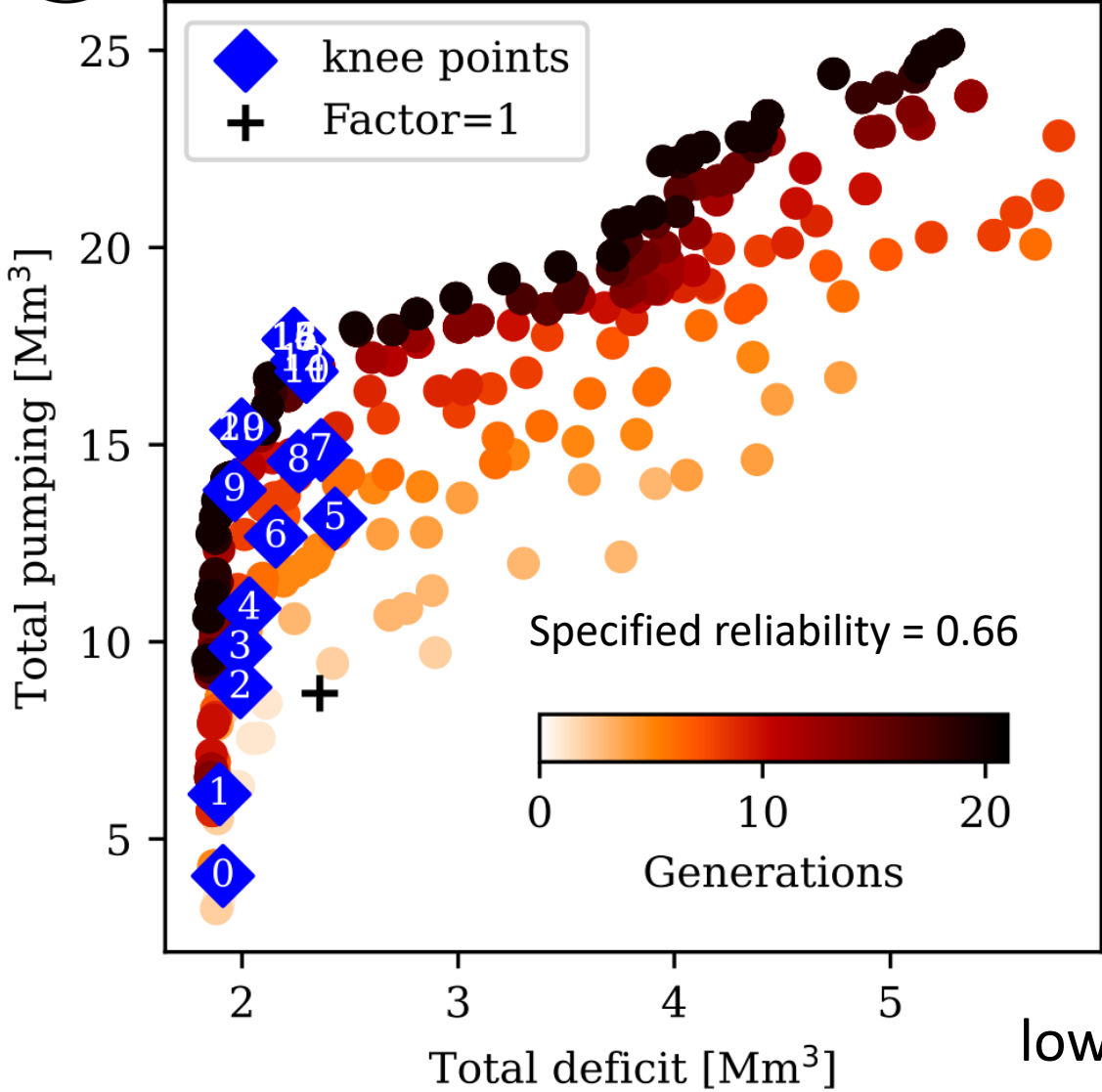
- **Particle swarm** for the generation of the offsprings (Eberhart & Kennedy, 1995; Siade et al., 2019)
- **Nondominated, Sorting-based Genetic Algorithm (NSGA-II)** as the constrained environmental selector (Deb et al., 2002)

STEP 3 : optimization

historical median scenario



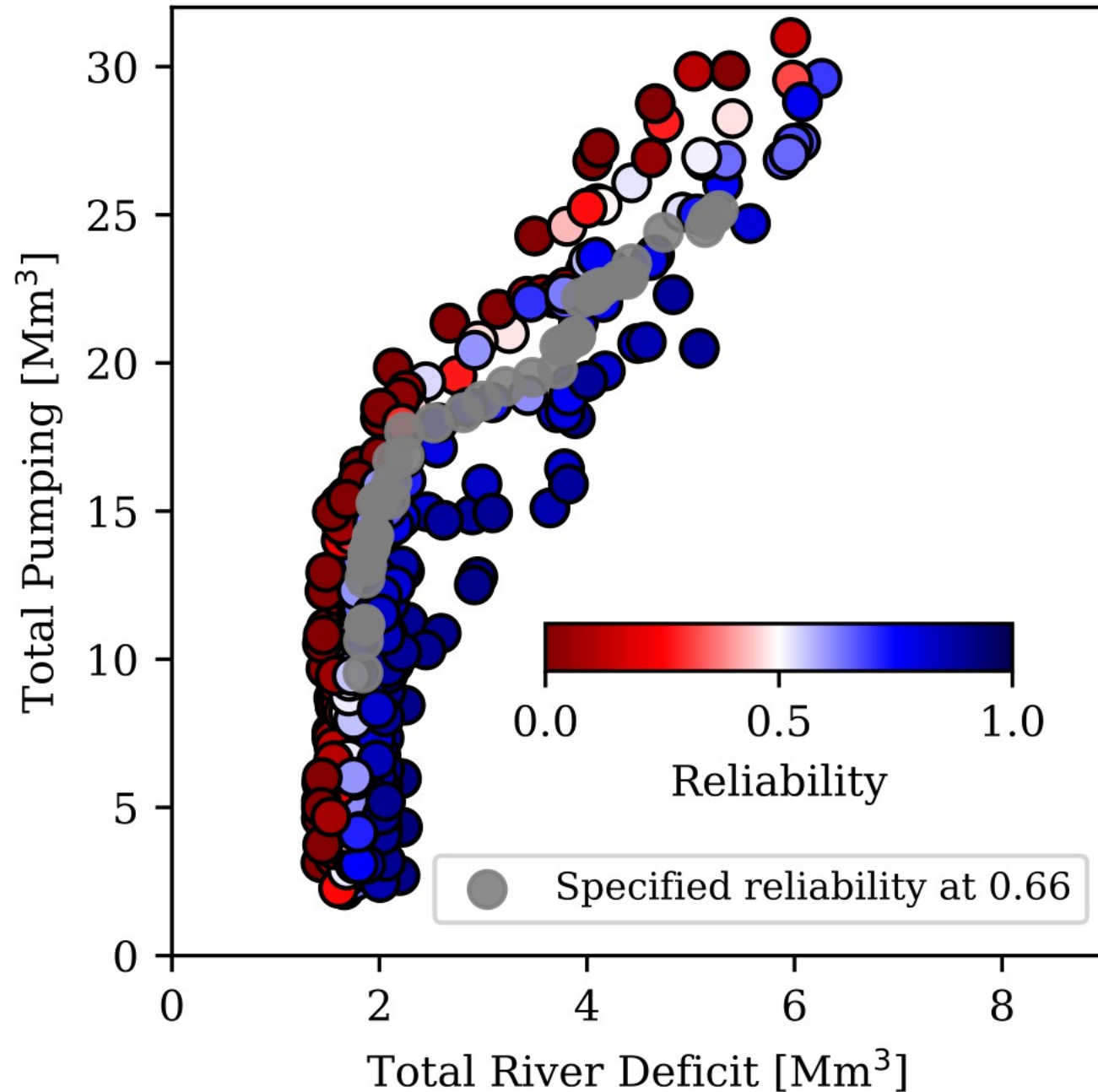
high pumping, low deficit



low pumping,
high deficit

STEP 3 : optimization

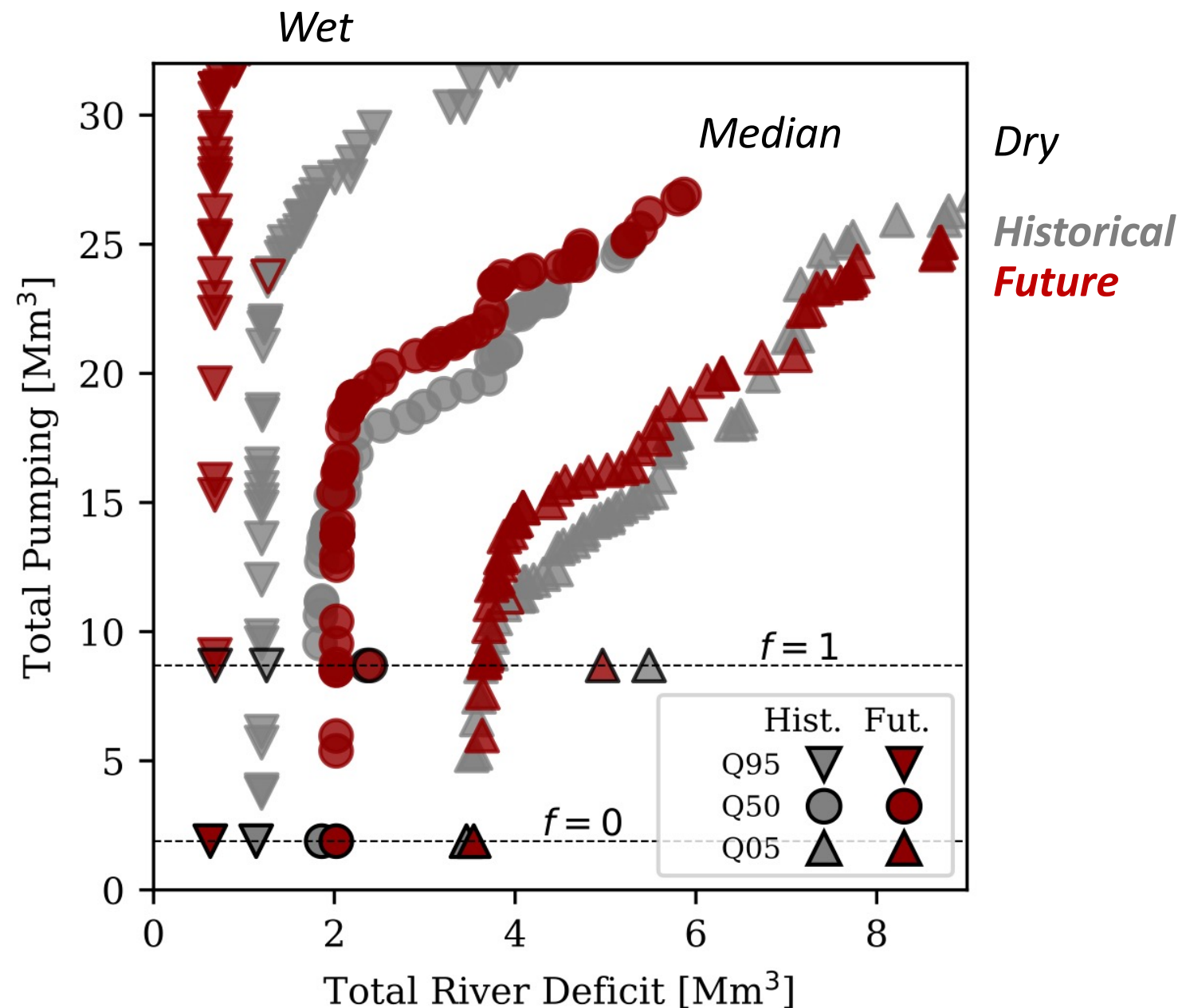
Reliability as the 3rd objective



STEP 3 : optimization

⇒ Scenario comparison

Specified reliability = 0.66





Change in Agricultural
Practices ?

Winter Water Storage ?

Thank you for your attention !

Optimization under uncertainty for the definition of aquifer sustainable yield under climate change.

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