SWAT Conference 2025

An Improved Aggregation-Decomposition Optimization Approach for Ecological Flow Supply in Parallel Reservoir Systems

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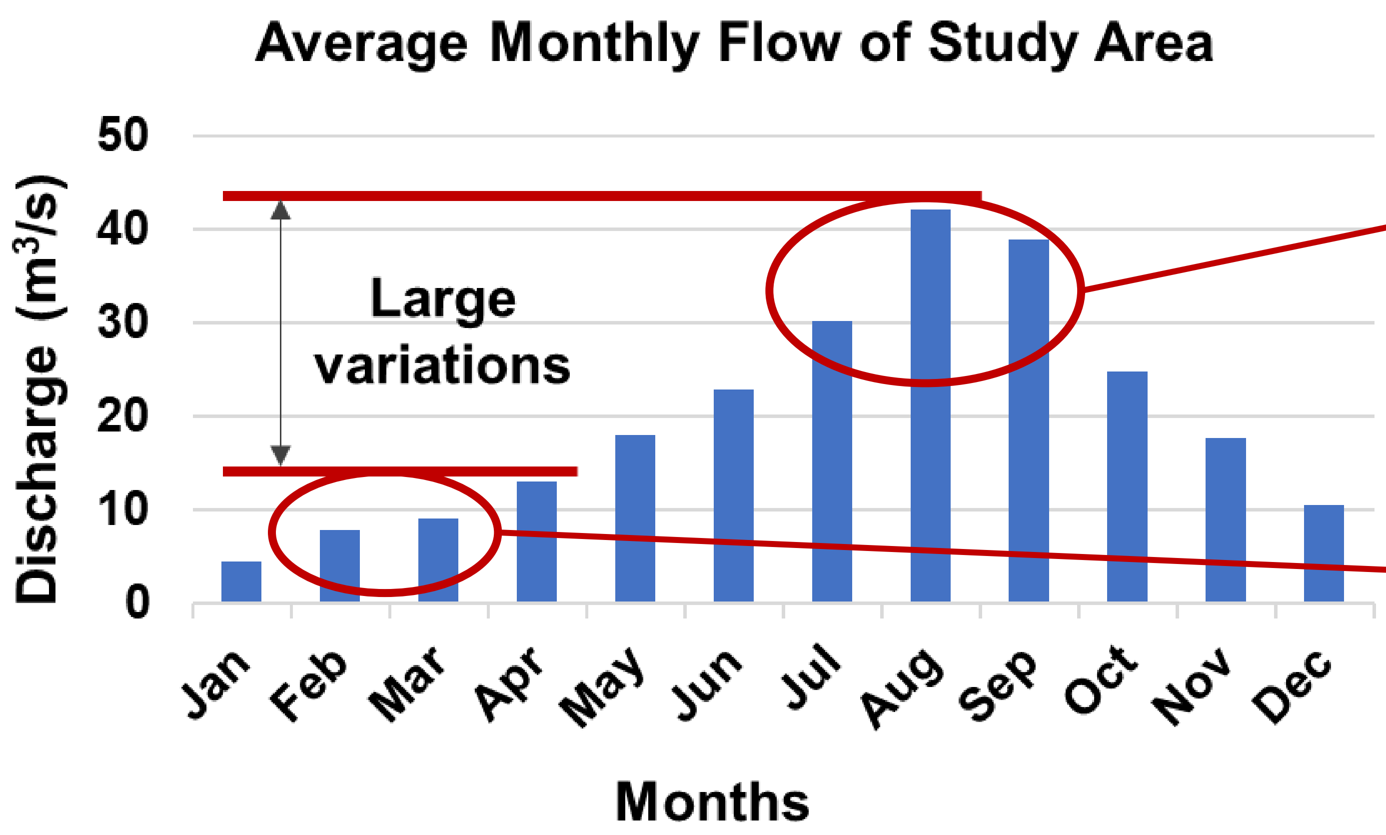
Contents

01| Introduction

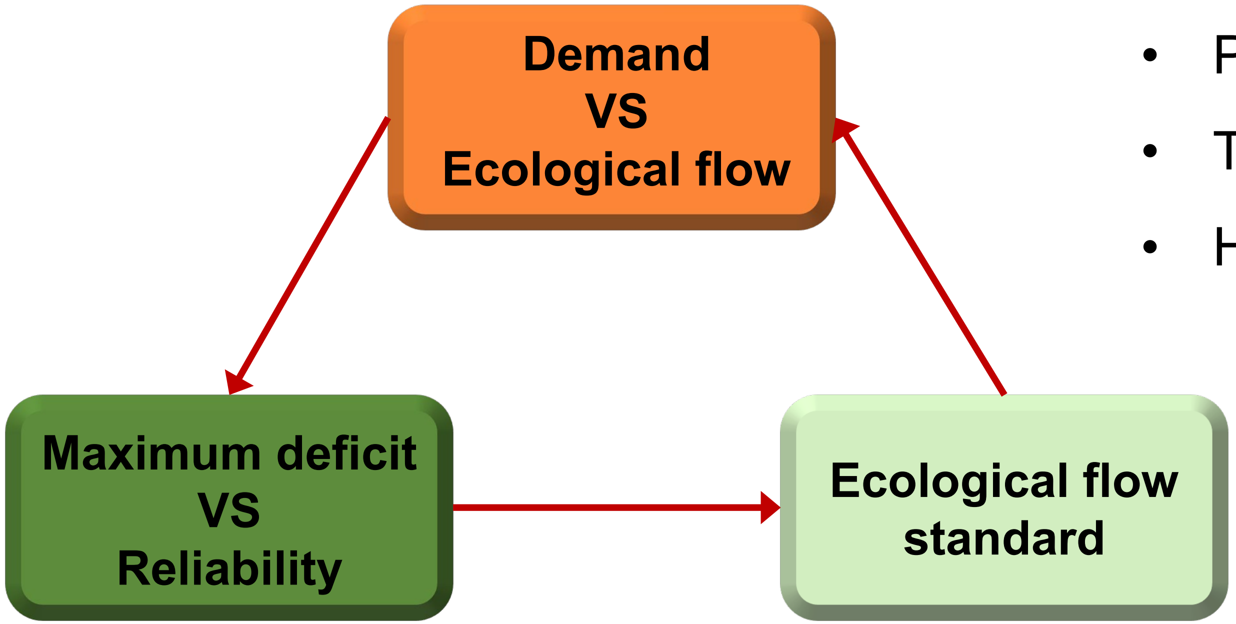
Study Background

- Recurring droughts due to inter-annual fluctuations in streamflow
- highlighting the importance of managing water resources more efficiently



| Study Background

Ecological Flow : Minimum quantity, quality, and timing of water required to sustain freshwater ecosystems

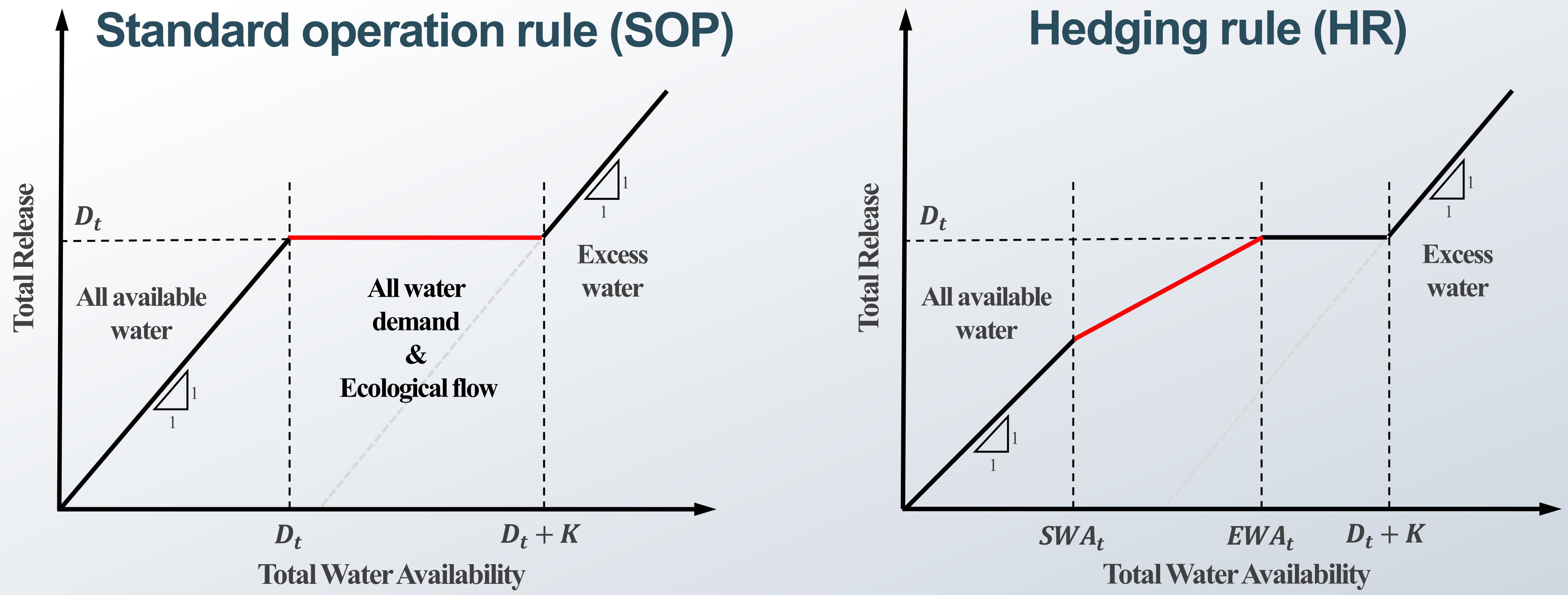


- Prioritized water demand, or ecological flow
- Trade-off between maximum deficit and reliability
- How to set the ecological flow standard

➡ Optimization of multi-reservoir operation for securing ecological flow

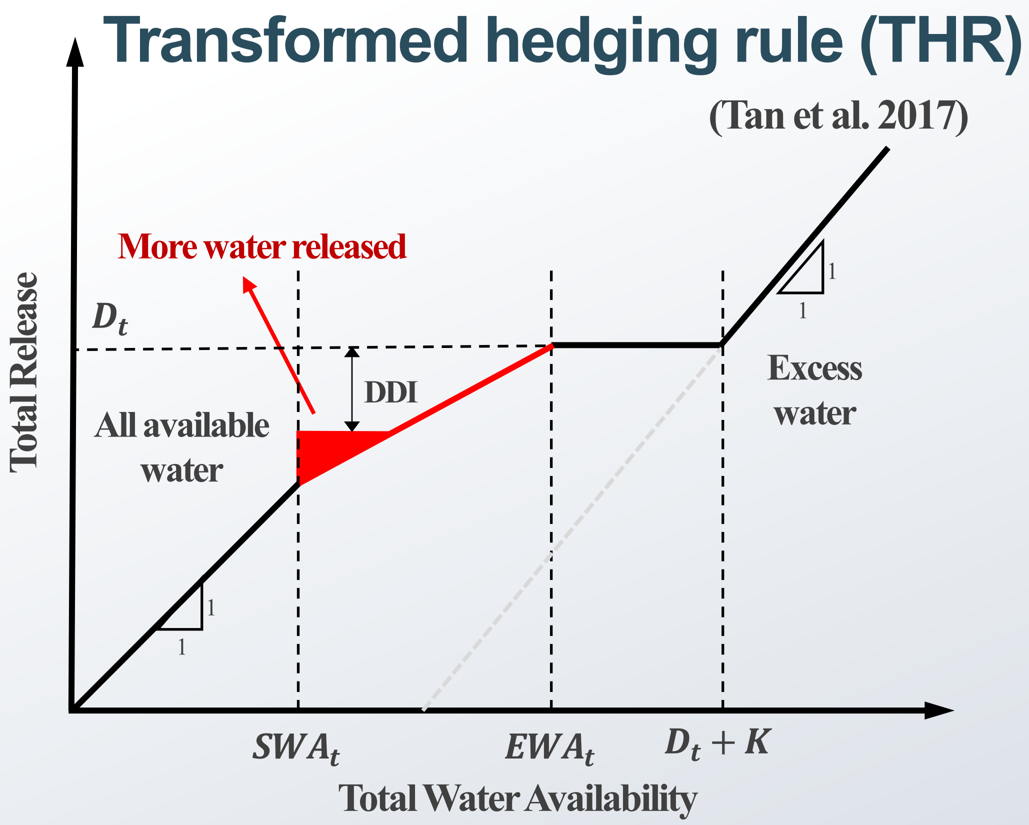
Problem Statement

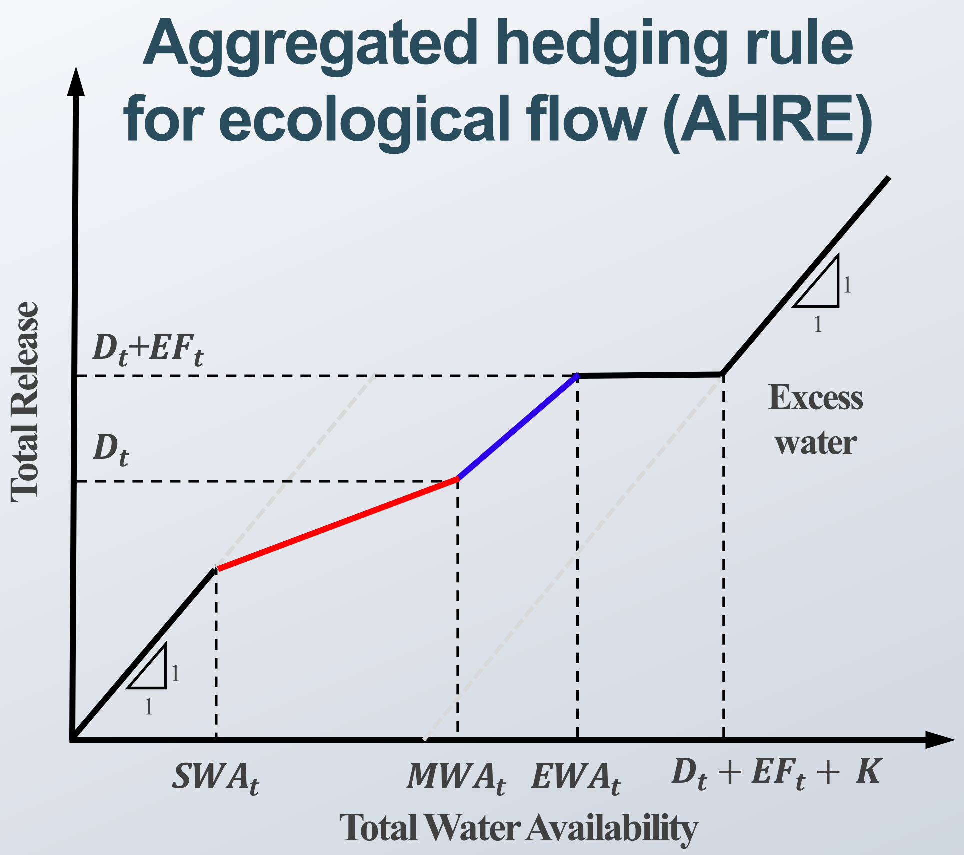
Reservoir Operation Rule



Problem Statement

Reservoir Operation Rule





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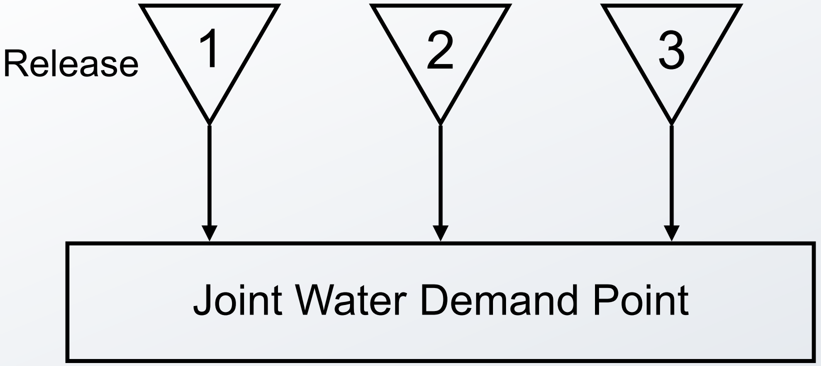
Problem Statement

Distribution Method

Separated operation of multi-reservoir

Determination of each reservoir's release based on the rule



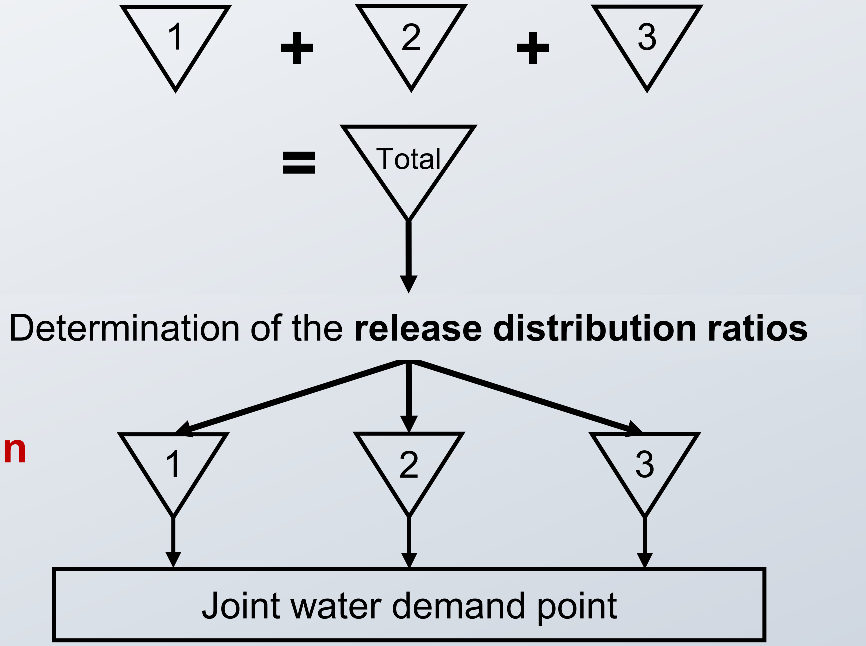
Separate optimization of each reservoir's operation variable **is required**

Coordinated operation of multi-reservoirs

Determination of total release based on the rule

Aggregation

Decomposition



Problem Statement

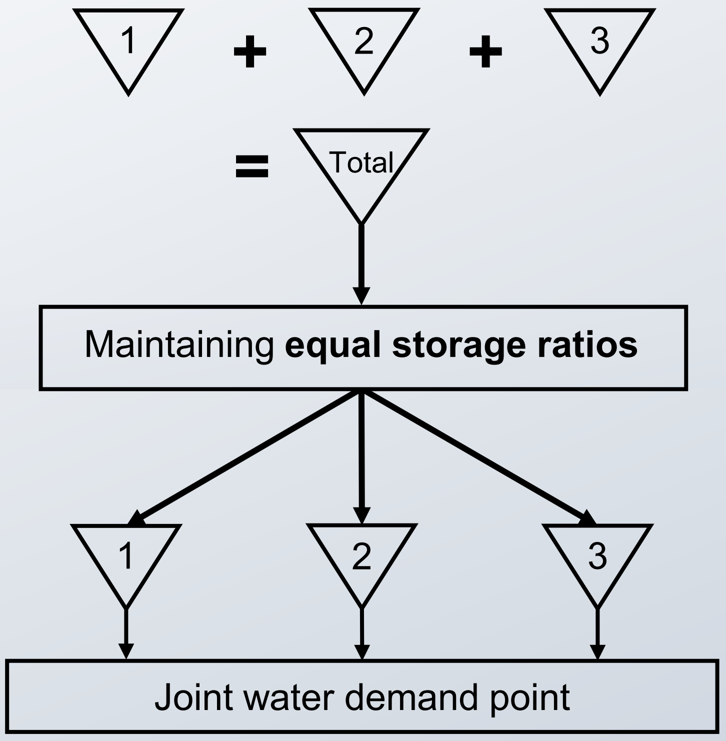
Distribution Method

How can we distribute the total release?

- Synchronous consideration of multiple indices (e.g., Storage, inflow)
- Minimization of **reaching the dead level** or **causing overflow**

Optimization of release distribution ratios

to maintain **similar storage ratios** across all reservoirs at each time step



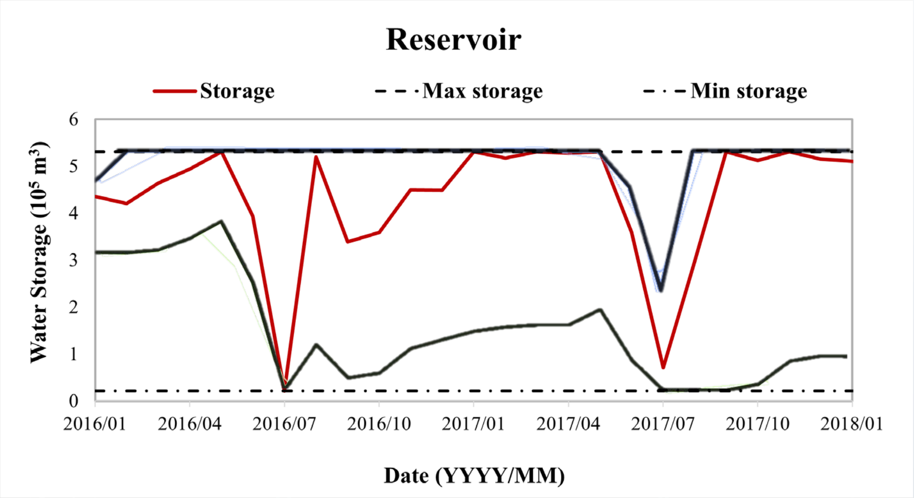
01. Introduction

Problem Statement

Distribution Method

Conventional approach

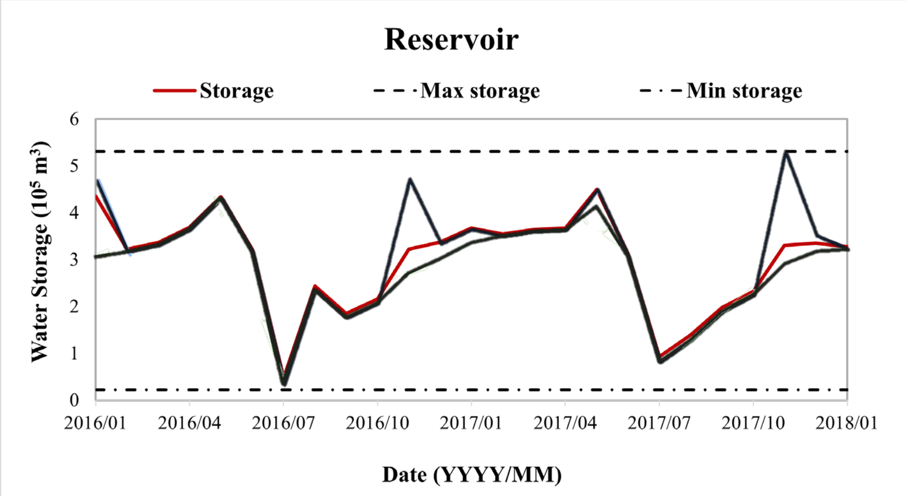
Distribution based on **inflow ratios** across reservoirs



Some reservoirs face shortages while others overflow

Spatial imbalance in water distribution

Proposed method



Co-occurrence of deficit and overflow during most of the period

Efficient Reservoir Operation

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| Objectives

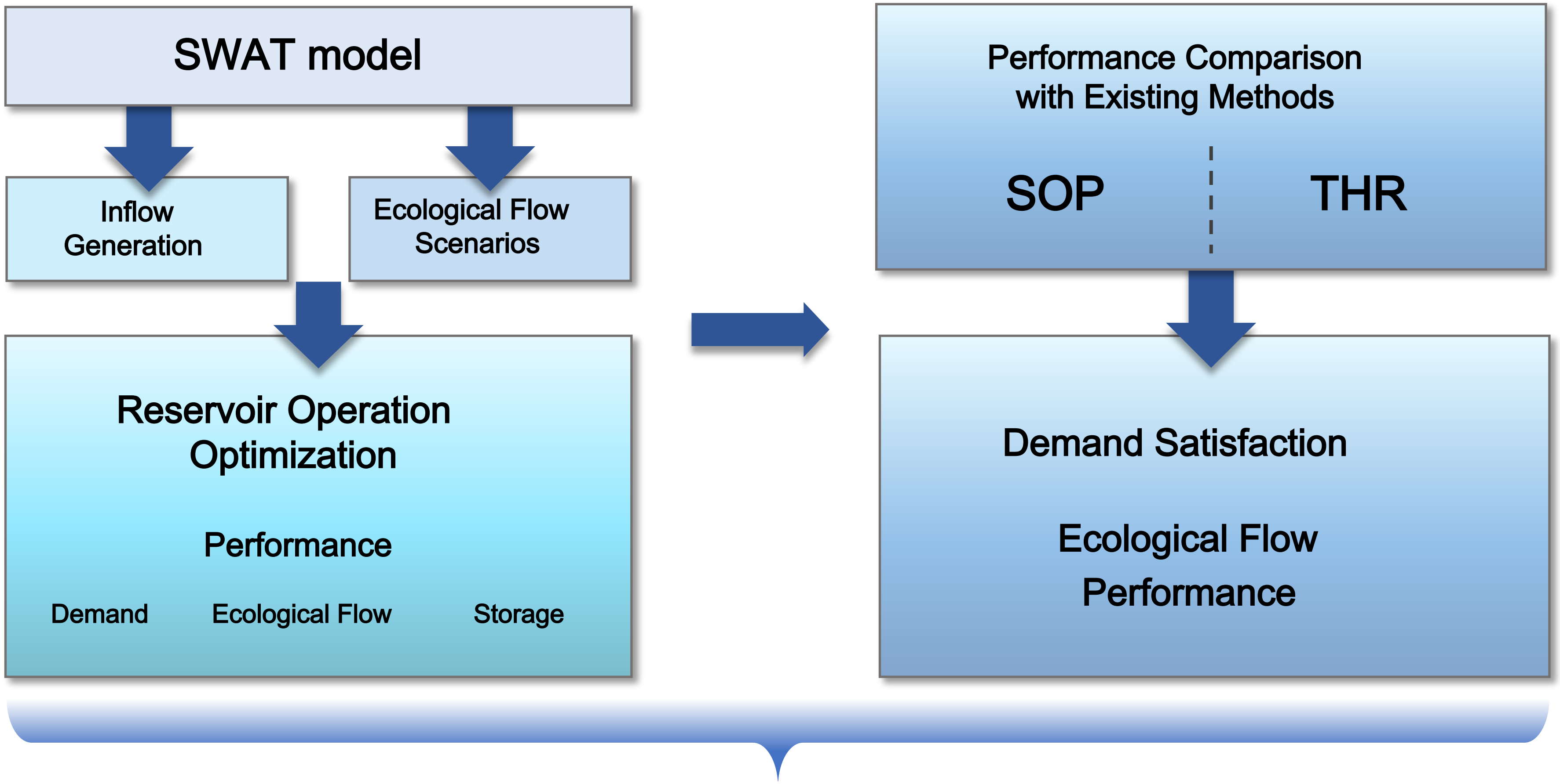
- Enhancement of **hedging rules** to directly consider ecological flow in reservoir operation
- Improvement of **aggregation-decomposition optimization** method to enable efficient operation of parallel reservoirs
- Evaluation of the operation performance through **comparison with existing two methods (SOP, THR)**

➡ **Assessing the capability of operation rule to secure ecological flow**

02| Method

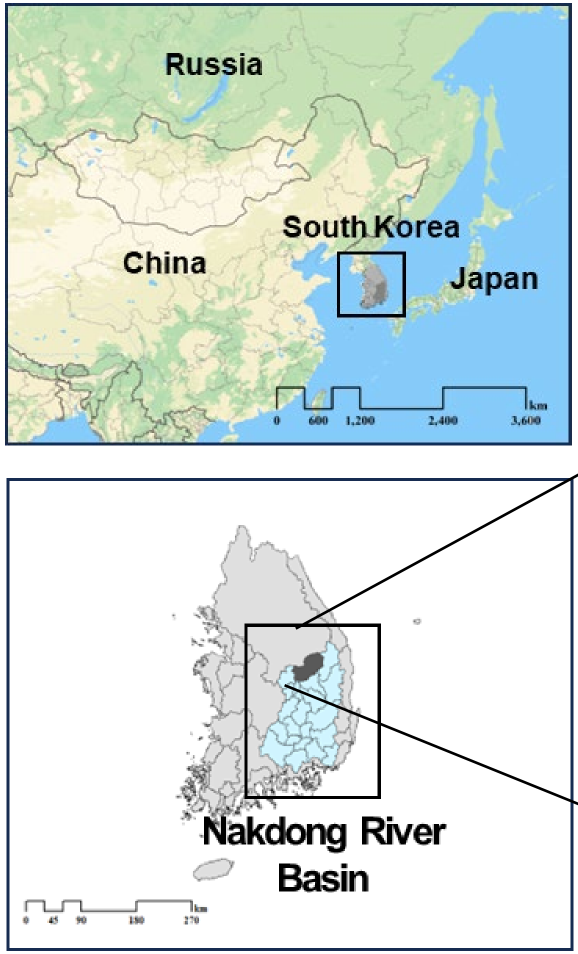
02. Method

Study Process

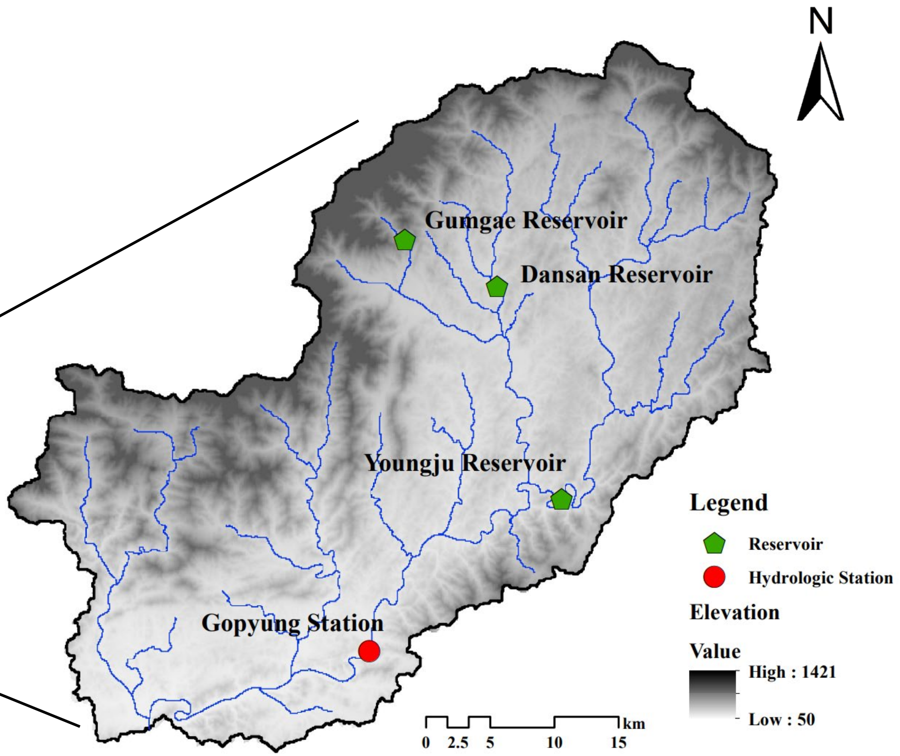


Flexible and implementable tool for balancing supply and ecological objectives

Study Area



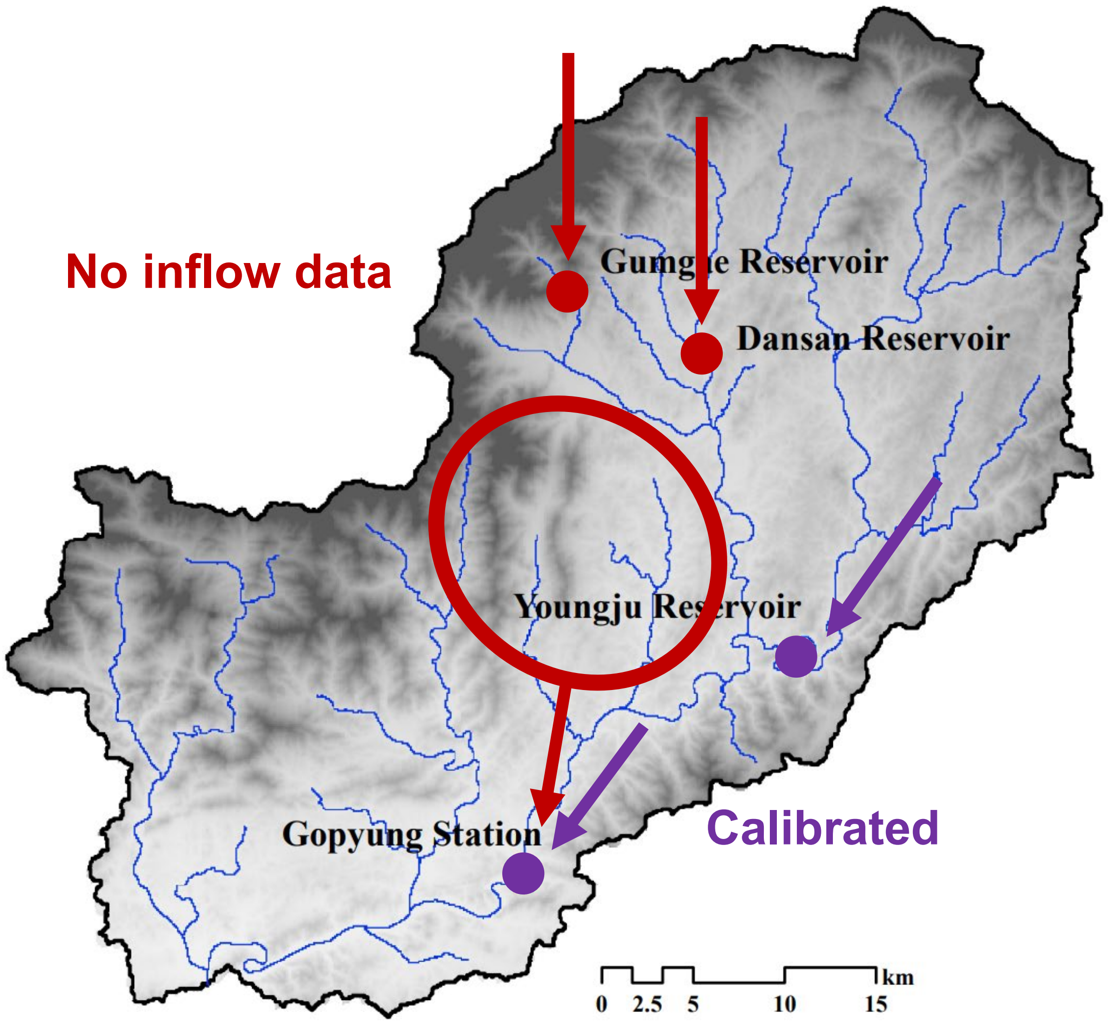
Three parallel reservoirs in **Naesung stream watershed,** South Korea



- Watershed area of 1,815 km^2
- Land cover composition
  - **Forest area** : 62%
  - **Agricultural area** : 24%
- Three reservoir in study area
  - **GG(Gumgye)**
  - **DS(Dansan)**
  - **YJ(Youngju)**

02. Method

| SWAT Model – Inflow Generation

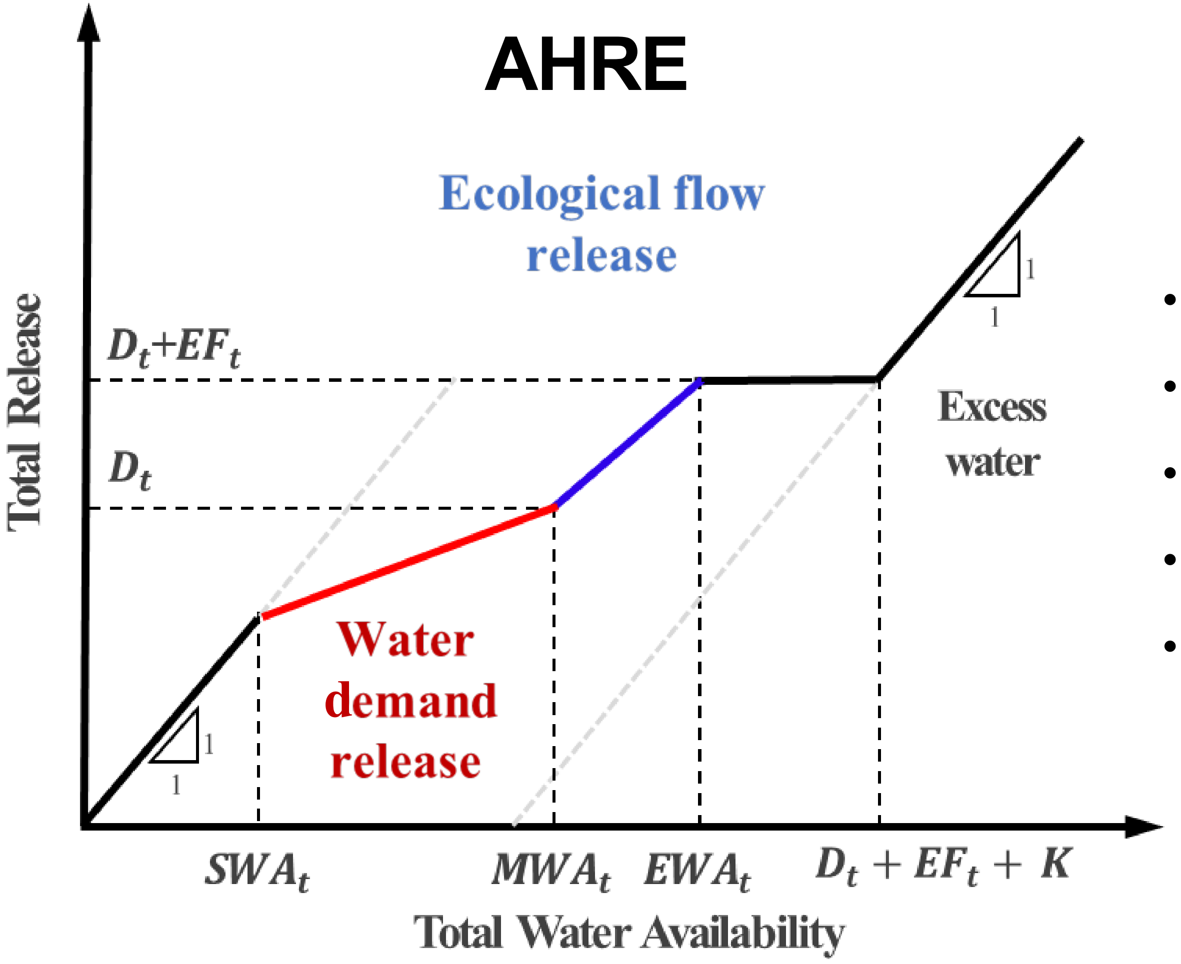


| SWAT Model – Ecological Flow Scenarios

- No official **ecological flow standard** in this area
- Using various **flow analysis methods** to estimate ecological flow thresholds

Ecological flow estimation method			
Flow Duration Curve Shifting	**Tennant (Yearly/Monthly)**	**Tessman**	**Q95 / 7Q10**
Reduces the original flow duration curve while preserving flow patterns	Sets ecological flow as 30% or 50% of the Mean Annual Flow (MAF) or Mean monthly Flow (MMF)	Divides the year into three periods based on the ratio of MAF to MMF	Low flow exceeded 95% of the time 7-day low flow that occurs once every 10 years

Reservoir Operation Rule

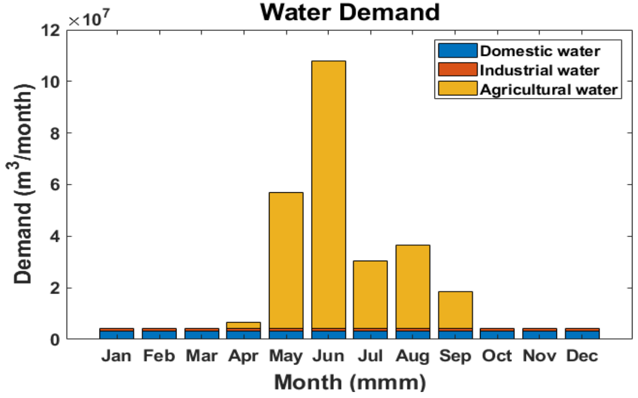


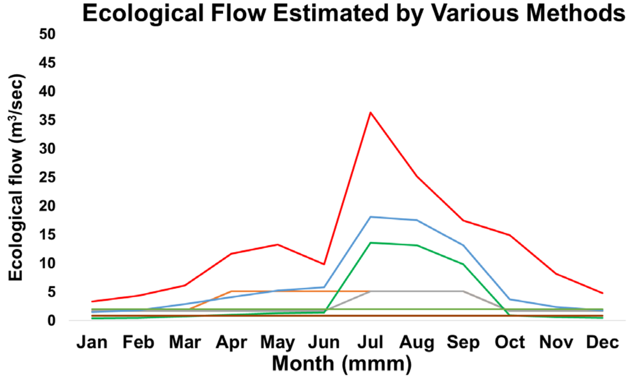
- 0–SWA : All available water
- SWA–MWA : A portion of water demand
- MWA–EWA: Full water demand and partial ecological flow
- EWA–Overflow : Full water demand and ecological flow
- Overflow

| Reservoir Operation Rule

➔ Annual domestic and industrial water demand is evenly distributed monthly

➔ Annual agricultural water demand is converted to monthly data using average distribution patterns





Prioritized use of release to meet water demand
(Domestic, Industrial, Agricultural)

⬇

Only the remaining flow after meeting water demands is released into the river for ecological flow

Optimization Algorithm

1) Outer optimization for total release

F1 = minimize (DDV + EFV)

F2 = minimize (DDV + MED)

1) **Water demand deficit rate** (%), DDV $\frac{\sum_{t=1}^{T} D_t - R_t^*}{\sum_{t=1}^{T} D_t}$ * 100 (%)

2) Ecological flow deficit rate (%), EFV $\frac{\sum_{t=1}^{T} EF_t - Q_t}{\sum_{t=1}^{T} EF_t}$ * 100 (%)

3) Maximum monthly deficit rate of ecological flow (%), MED $\frac{Max\ (EF_1 - Q_1, EF_2 - Q_2, \ldots, EF_T - Q_T)}{Max\ (EF_1, EF_2, \ldots, EF_T)}$ * 100 (%)

2) Internal optimization for distribution

: Minimizing the standard deviation of each reservoir's storage rate after the release

$$\sum_{t=1}^{T} std\left(\frac{S_{1,t} + I_{1,t} - R_{1,t}}{C_1}, \frac{S_{2,t} + I_{2,t} - R_{2,t}}{C_2}, \ldots, \frac{S_{N,t} + I_{N,t} - R_{N,t}}{C_N}\right)$$

| Optimization Algorithm

Constraints

1) Water balance $S_{n,t+1} = S_{n,t} + I_{n,t} - R_{n,t}$

2) Min / Max storage $S_n^{min} \le S_{n,t} \le S_n^{max}$

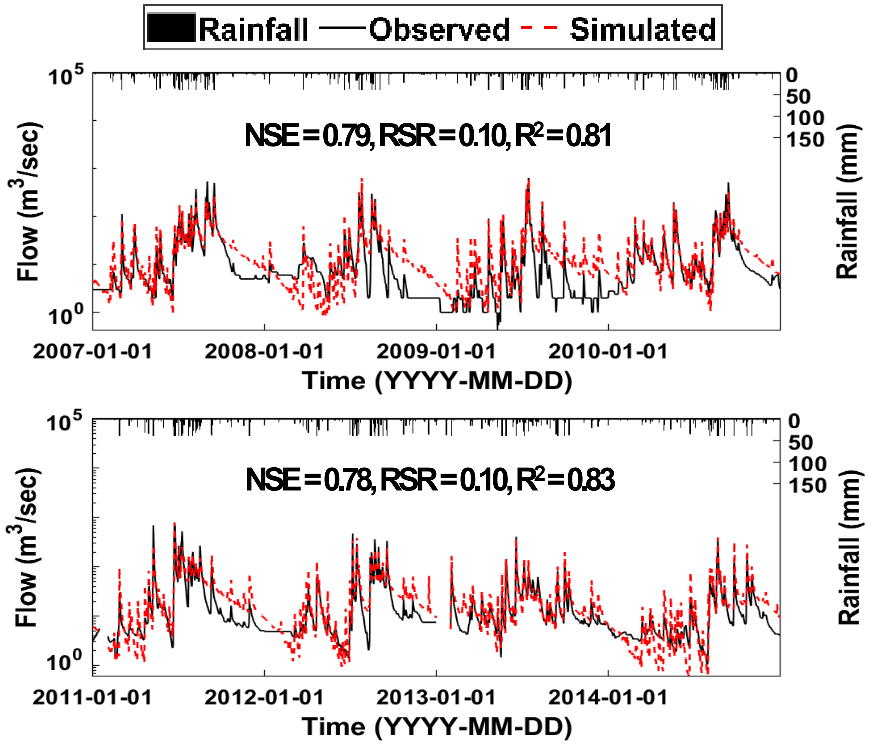
3) Min / Max release $R_n^{min} \le R_{n,t} \le R_n^{max}$

4) Hedging parameters $0 < SWA_t < D_t \ , \ SWA_t < MWA_t < EWA_t \ , \ MWA_t < EWA_t < D_t + EF_t + C^*$

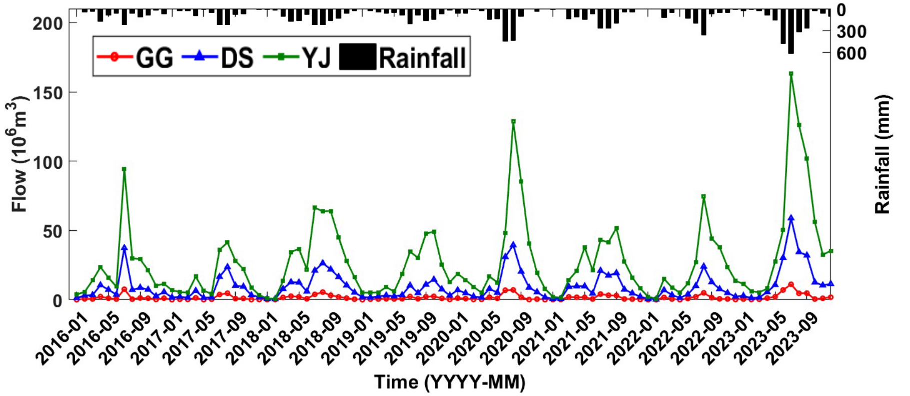
03| Result

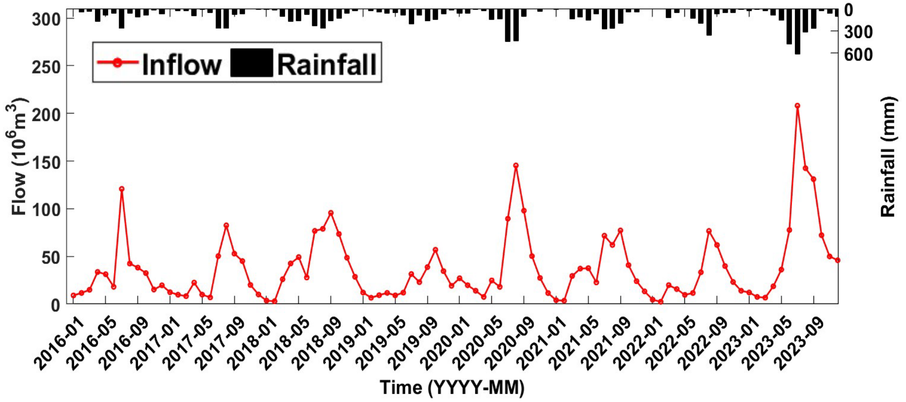
SWAT Model – Estimation of Inflow

Calibration and validation result of the SWAT model at Gopyung station (2007 – 2014)



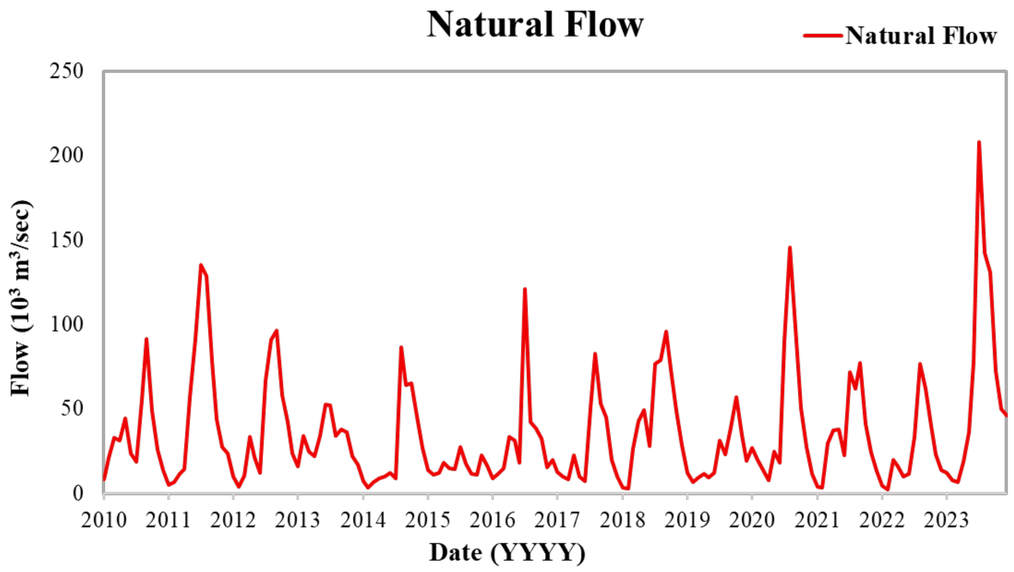
Inflow for each reservoir and the downstream watershed



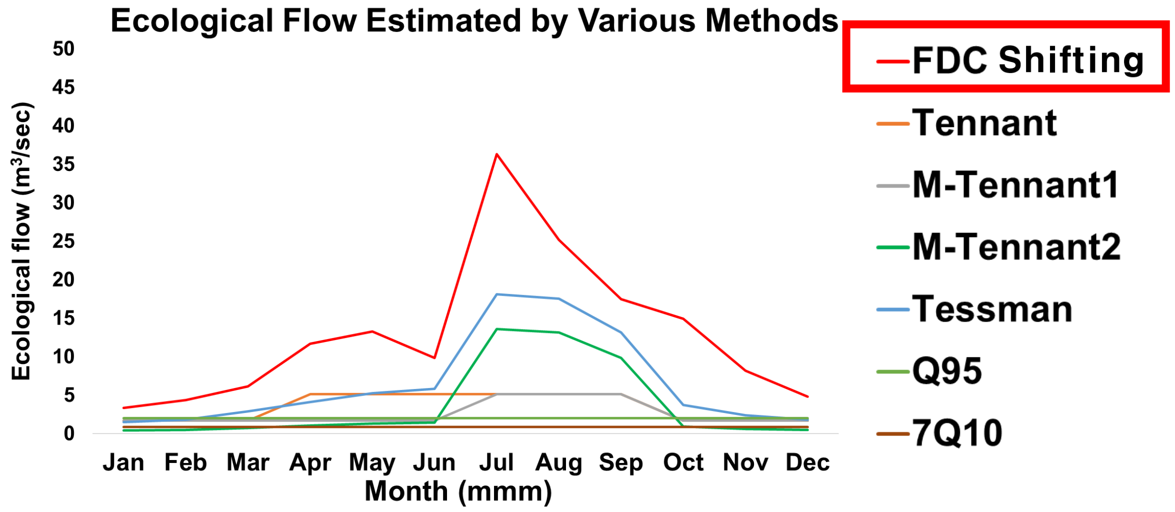


| SWAT Model – Ecological Flow Scenarios

Estimated natural flow



The highest ecological flow → FDC Shifting

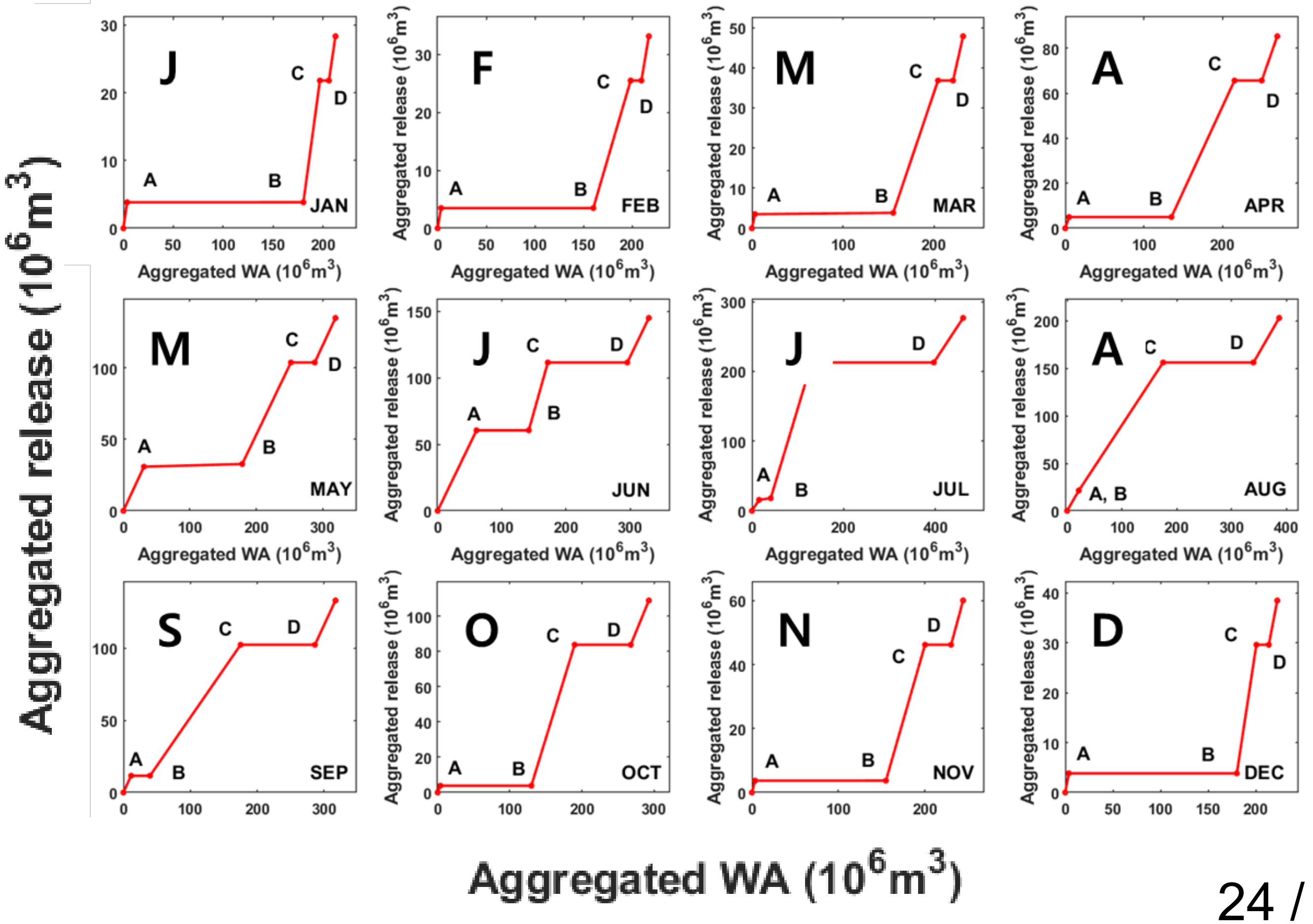


Optimization of Parallel Reservoir Operation

Optimization of hedging rules

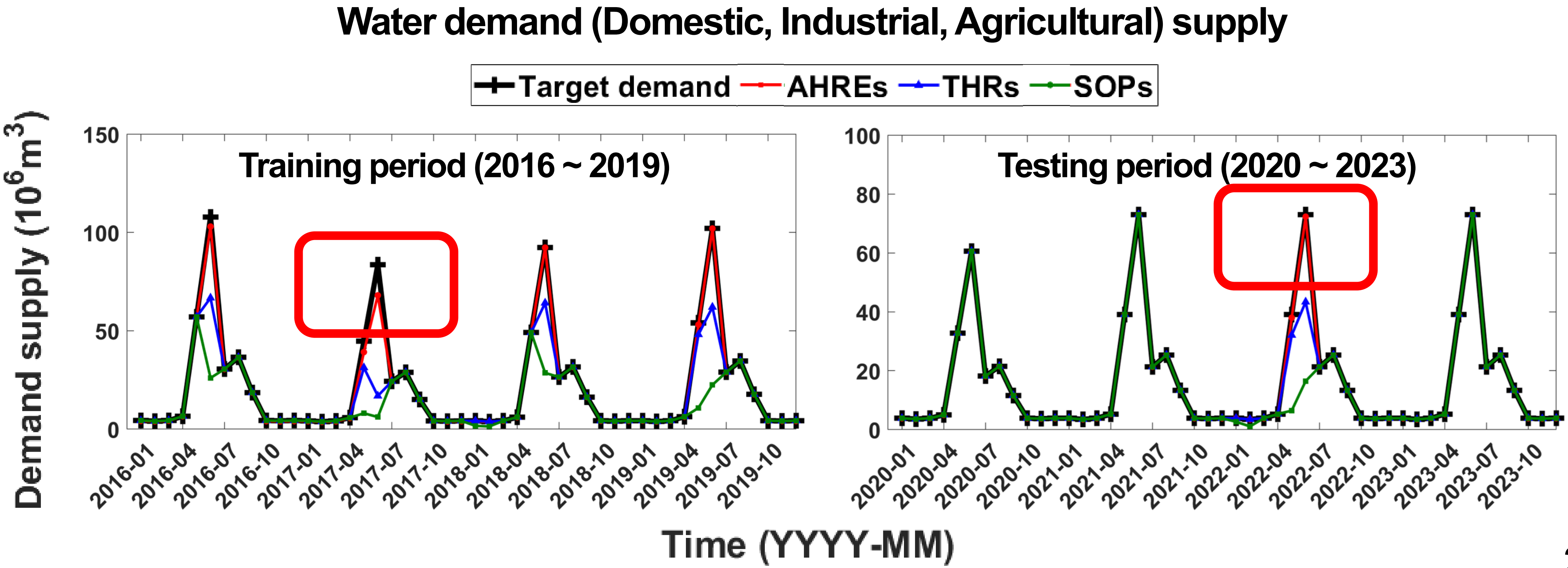
- Training period : 2016 ~ 2019 (4 years)
- Testing period : 2020 ~ 2023 (4 years)
- Operation step : Monthly

Final optimized hedging rules



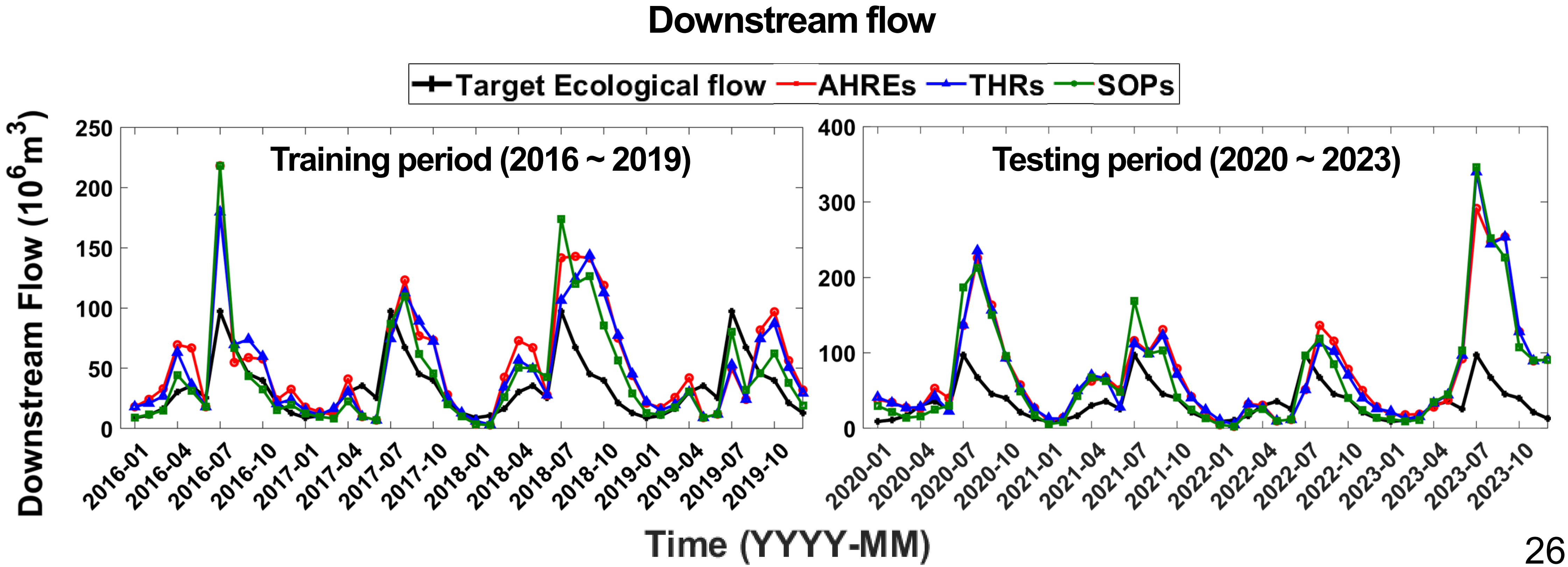
Optimization of Parallel Reservoir Operation

- AHRE has a 97, 99% water demand satisfaction rate during training and testing periods.
- AHRE maintained high performance, outperforming SOP and THR.



Optimization of Parallel Reservoir Operation

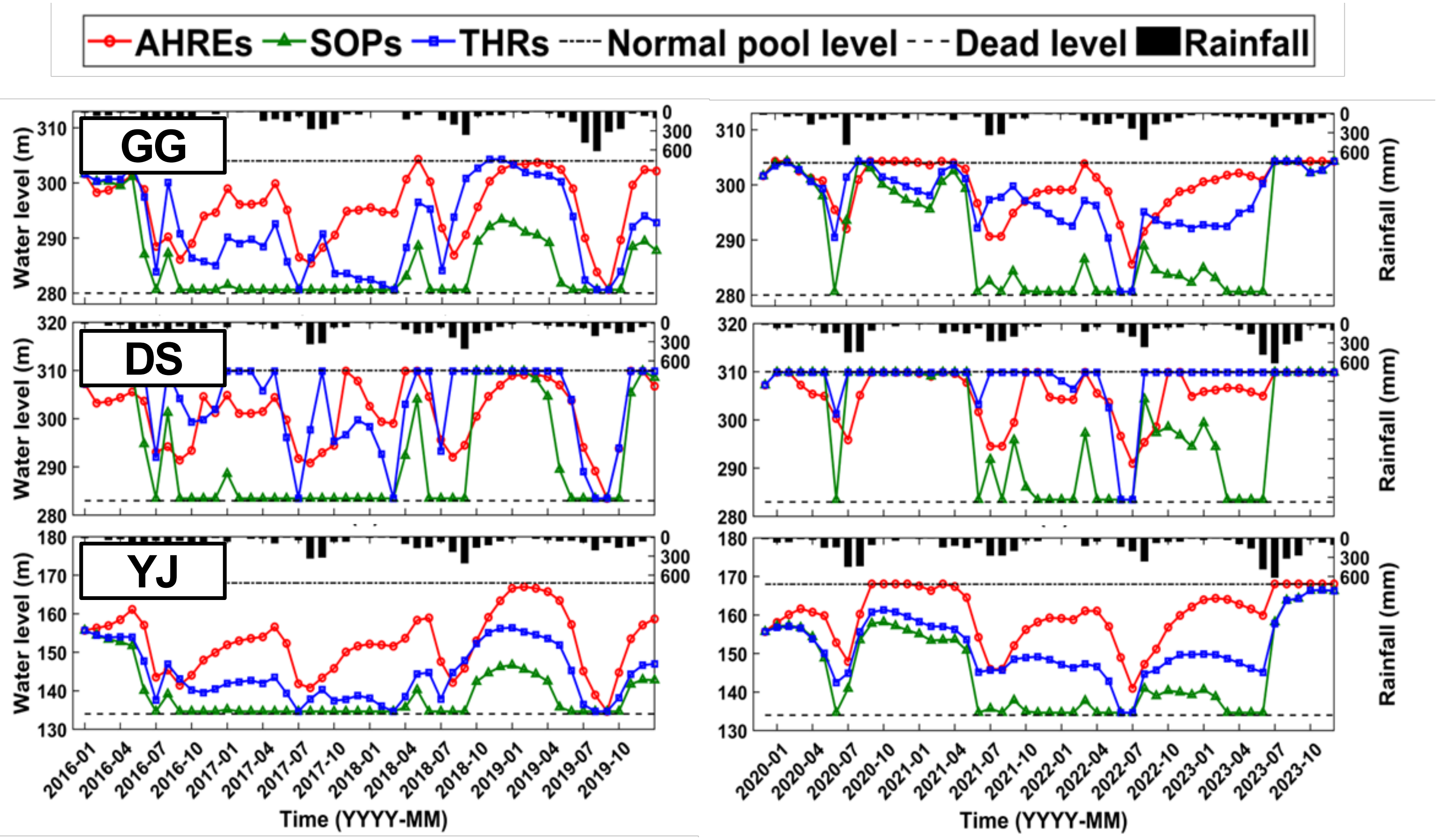
- AHRE has a 11, 5% ecological flow deficit rate during training and testing periods.
- AHRE maintained high performance, outperforming SOP and THR.



| Evaluation of the Operation Performance

- AHRE demonstrated the most stable and consistent operation.
- THR frequent exceed the normal pool level - indicate less effective water use.
- During the testing period, the same stable pattern appeared.

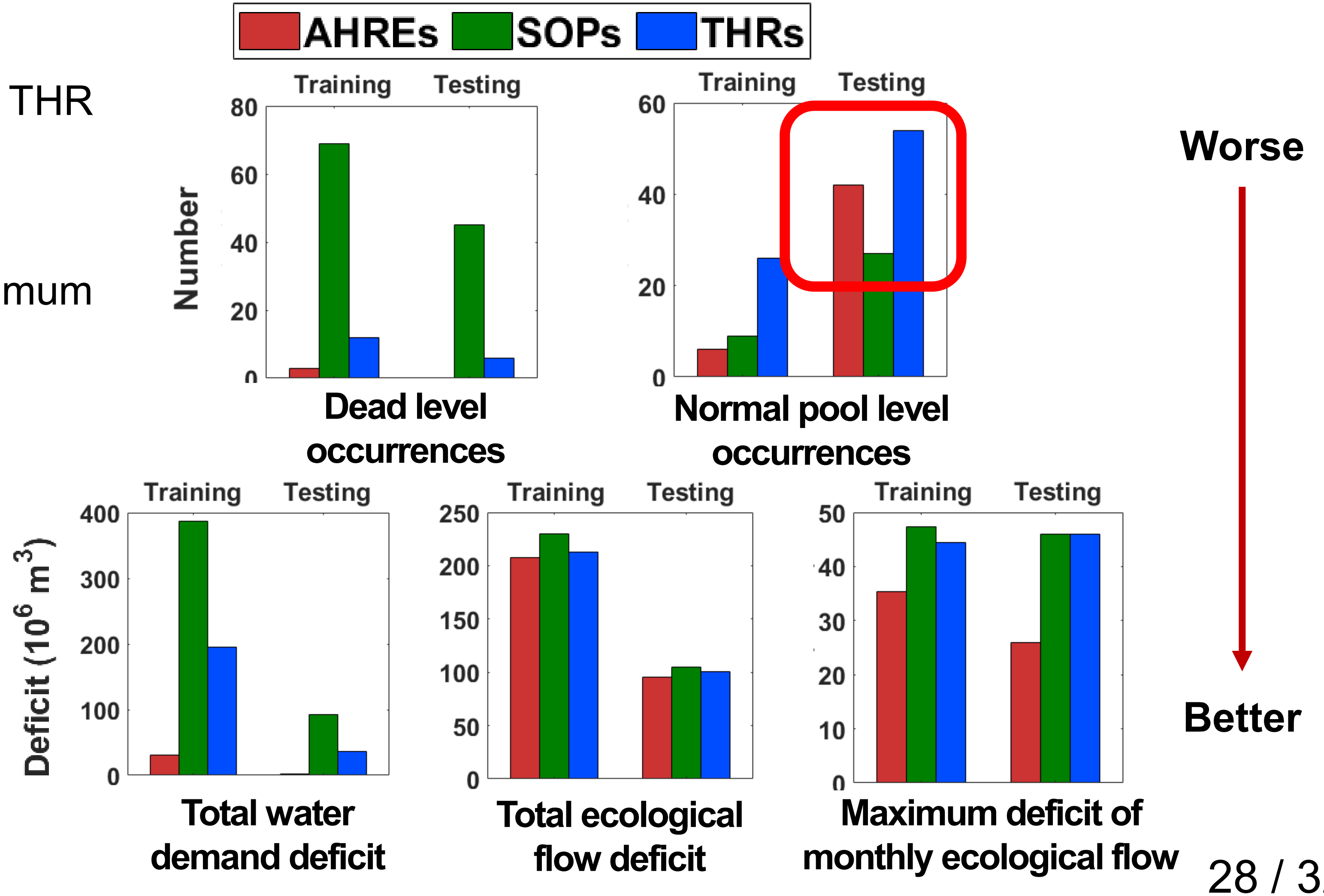
Water level of each reservoir



Training period (2016 ~ 2019) Testing period (2020 ~ 2023)

| Evaluation of the Operation Performance

- AHRE outperformed both SOP and THR across almost performance metrics.
- AHRE significantly reduced the maximum deficit of monthly ecological flow



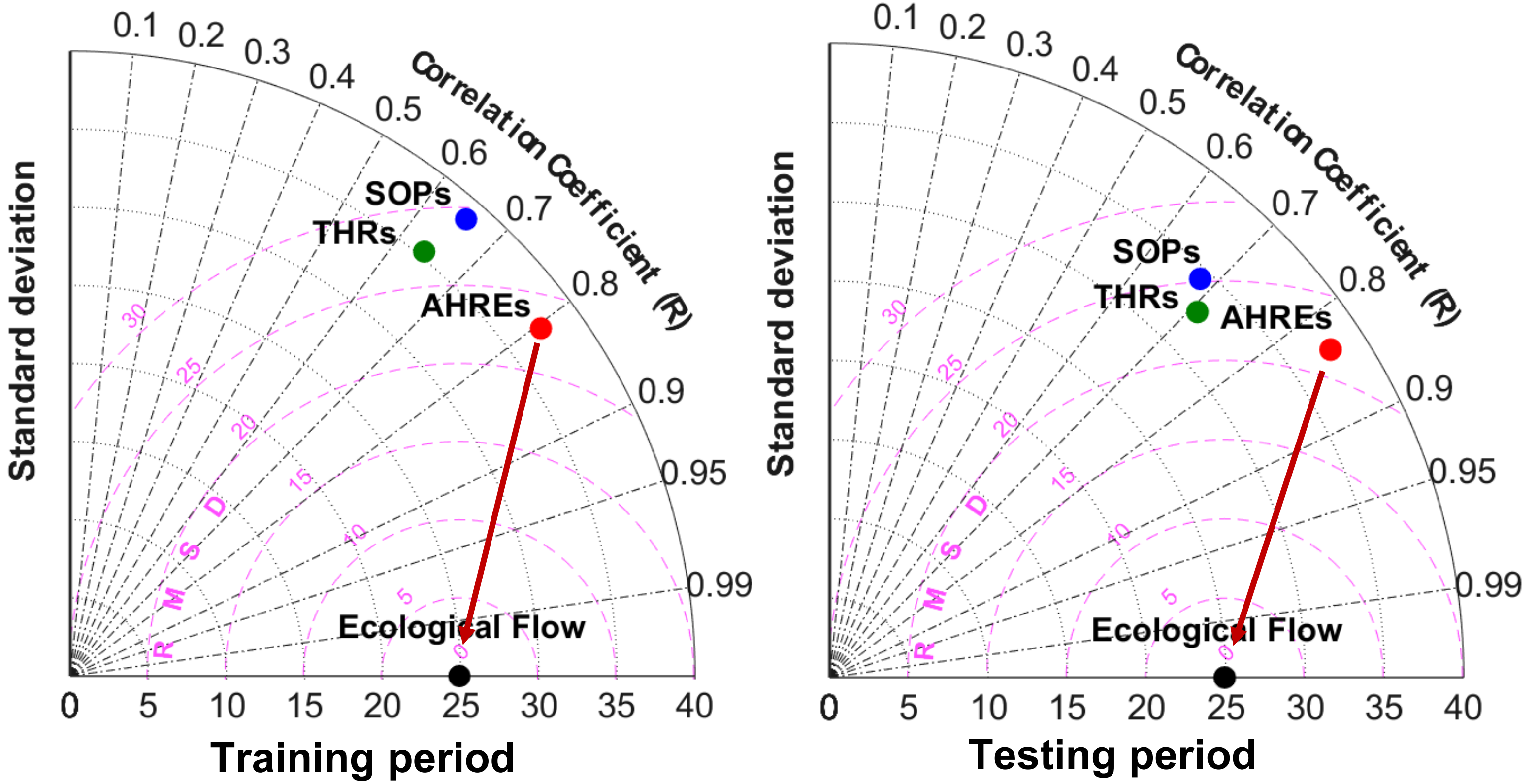
| Evaluation of the Operation Performance

- Radial distance from the center
  → **Standard deviation**
- Azimuthal angle within the quadrant
  → **Correlation coefficient** between the ecological and downstream flows
- Spatial distance between circles
  → **Root-mean-square deviation, RMSD**

Downstream flow of **AHREs**
is **most similar to ecological flow**
among the three methods

➔ **Efficient reservoir operation**

Taylor diagrams



04| Conclusion

04. Conclusion

During the operation period 2016 – 2023

- The water demand deficit rate was the smallest for AHREs, followed by THRs, and then SOPs.
- The ecological flow deficit rate was the smallest for AHREs, followed by THRs, and then SOPs.
- The **maximum monthly ecological deficit** was the smallest for AHREs, followed by THRs, and then SOPs.
  → Ensured **stable ecological flow** throughout the operational period
- AHREs minimized water level fluctuations and reaching the dead and normal pool level in parallel reservoirs.
  → **Better drought response** capabilities

➔ **AHRE method can operate the parallel reservoirs more efficient rather than SOP and THR.**

THANK YOU FOR LISTENING

QUESTIONS ?

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Acknowledgments

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02. Methods

Study Process

Input data generation

- Inflow Estimation
- Monthly Demand Conversion
- Ecological flow calculation

→

Optimization of Reservoir operation

Aggregation

Aggregated Hedging Rule for Ecological flow

Vs

Existing two method

Decomposition

Internal optimization

Minimize the standard deviation of each reservoir's storage rate after release

→

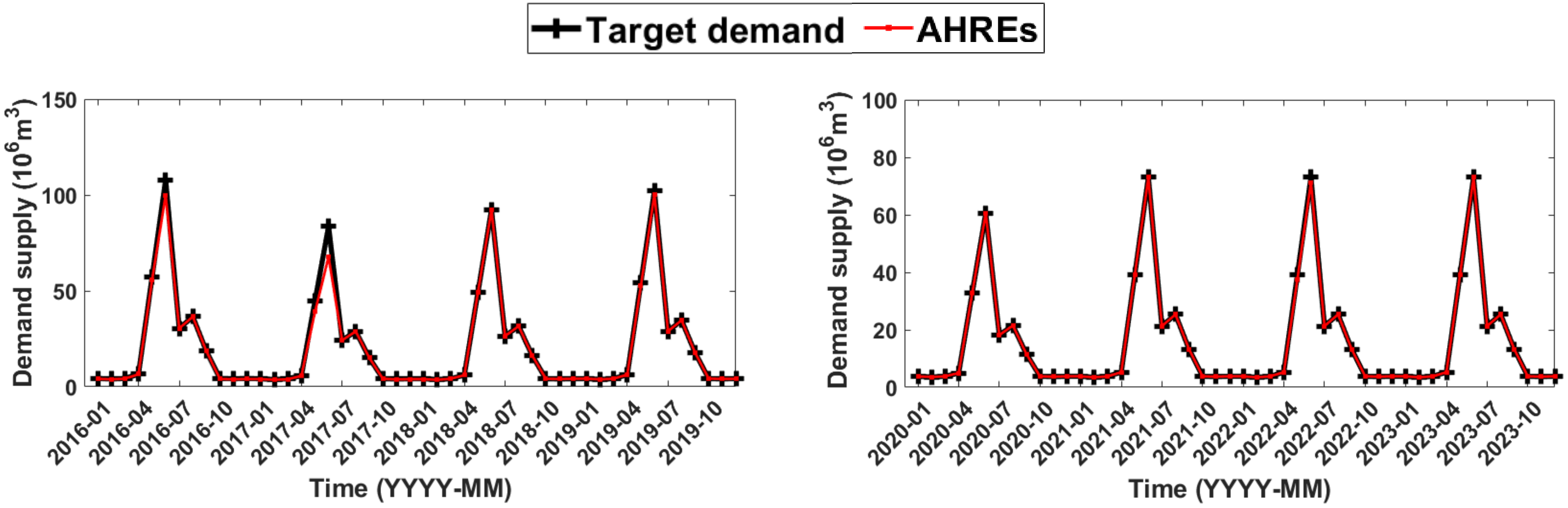
Evaluation of operation performance

- Demand deficit rate
- Ecological flow deficit rate
- Maximum ecological flow deficit rate
- Reservoir water level fluctuation

03. Results

Optimization of Parallel Reservoir Operation

Demand Supply



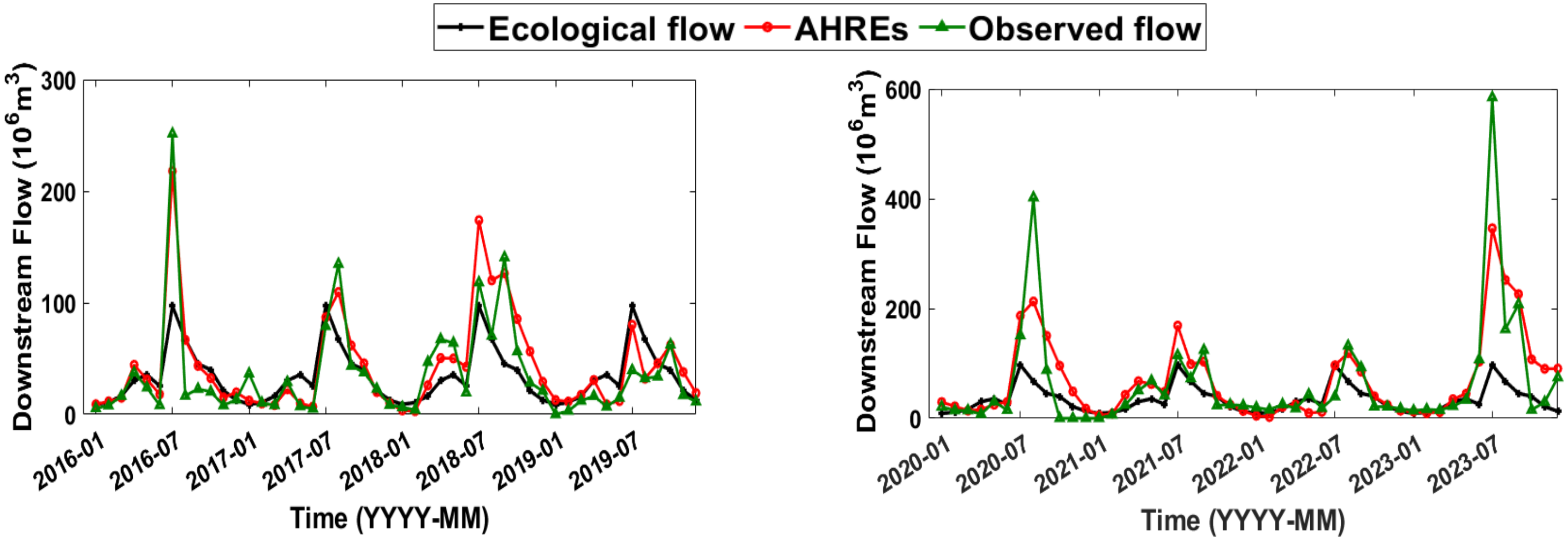
Training period (2016 ~ 2019) **Testing period (2020 ~ 2023)**

AHREs have a **95%** demand satisfaction rate

03. Results

Optimization of Parallel Reservoir Operation

Downstream flow



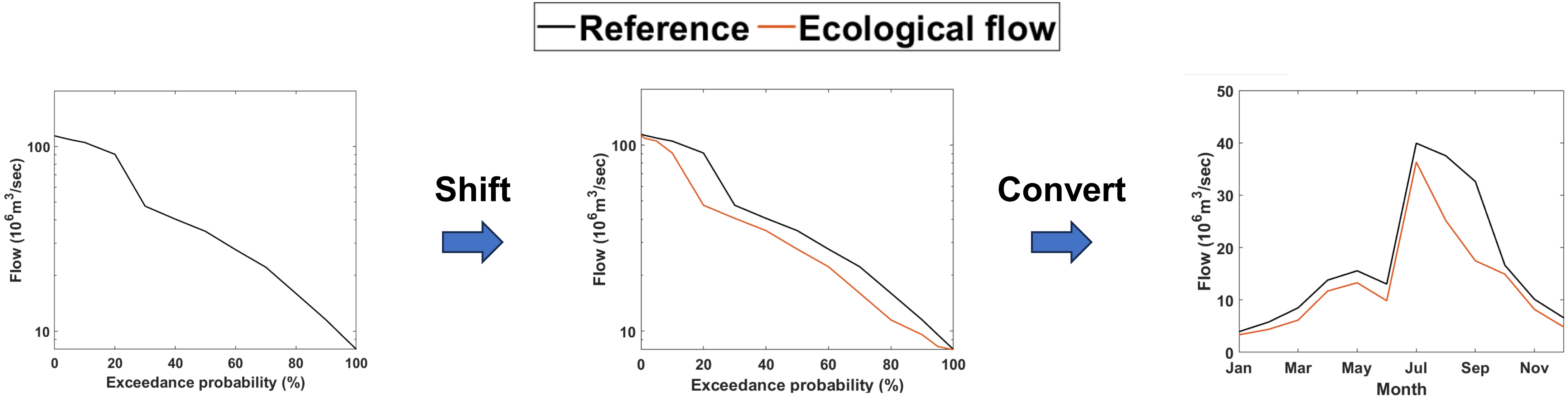
Training period (2016 ~ 2019) **Testing period (2020 ~ 2023)**

The **total ecological flow satisfaction rate** was approximately **87.5%**

→ The ecological flow was supplied in a stable

SWAT Model – Ecological Flow

Flow duration curve (FDC) shifting method



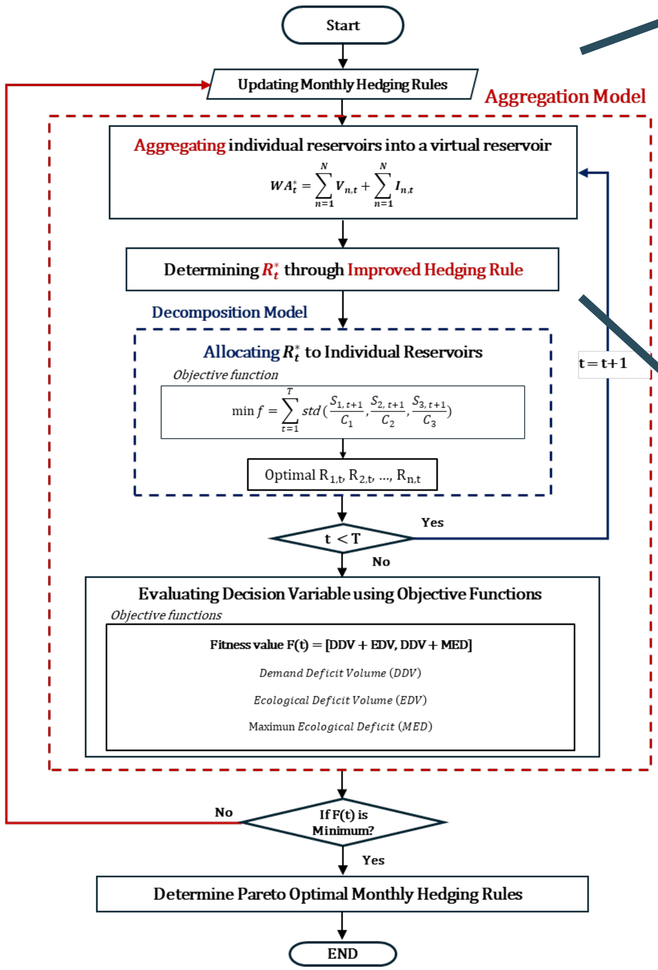
Reference FDC

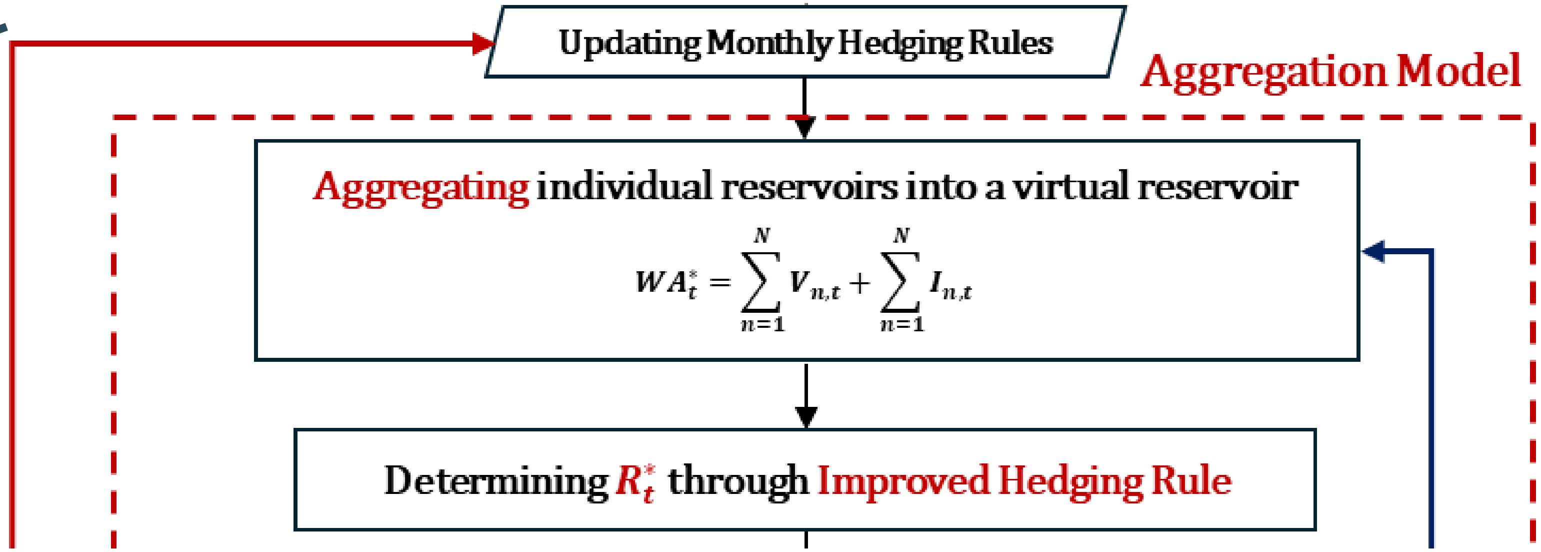
Ecological FDC

Time series of ecological flow

02. Methods

| Optimization Algorithm



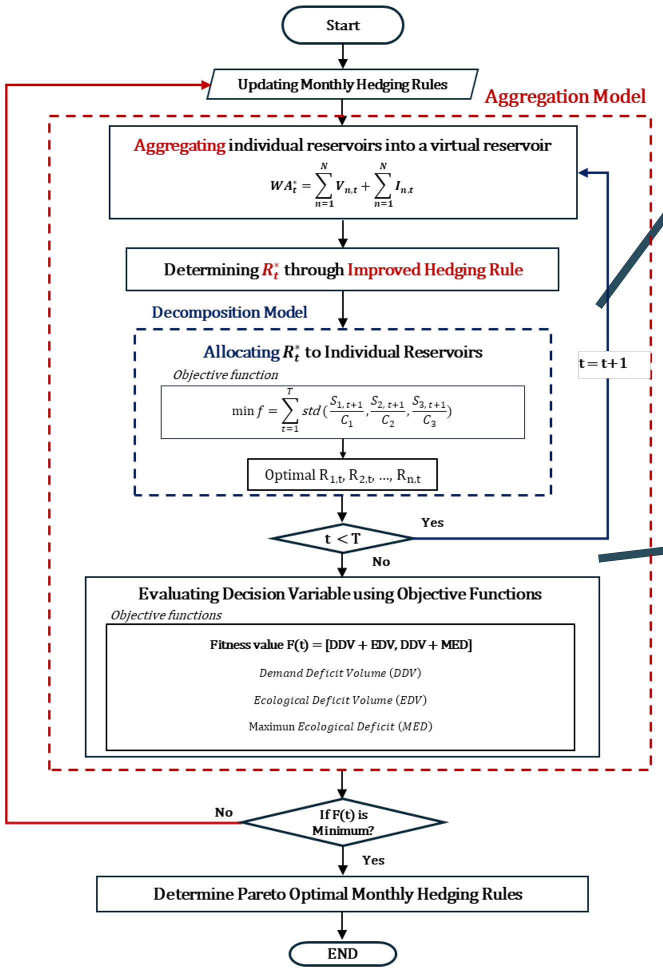


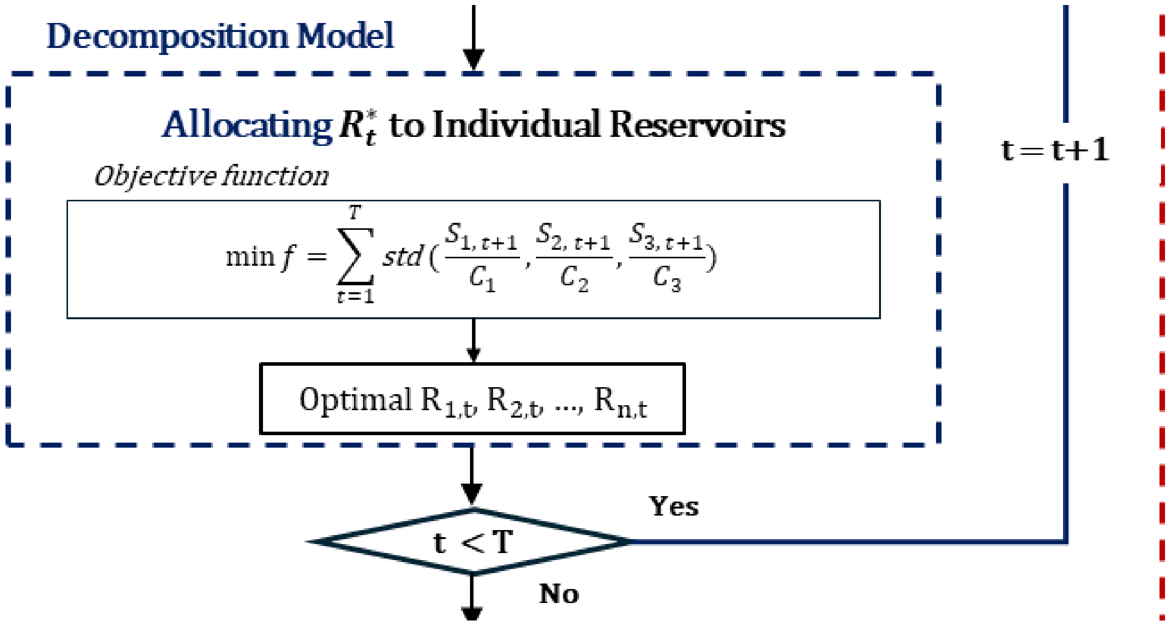
➔ Aggregating individual reservoirs

➔ Determining total release of Aggregated reservoir using hedging rule with initial hedging rule parameters

02. Methods

| Optimization Algorithm





➔ Distributing the total release of aggregated reservoir by **inner optimization**

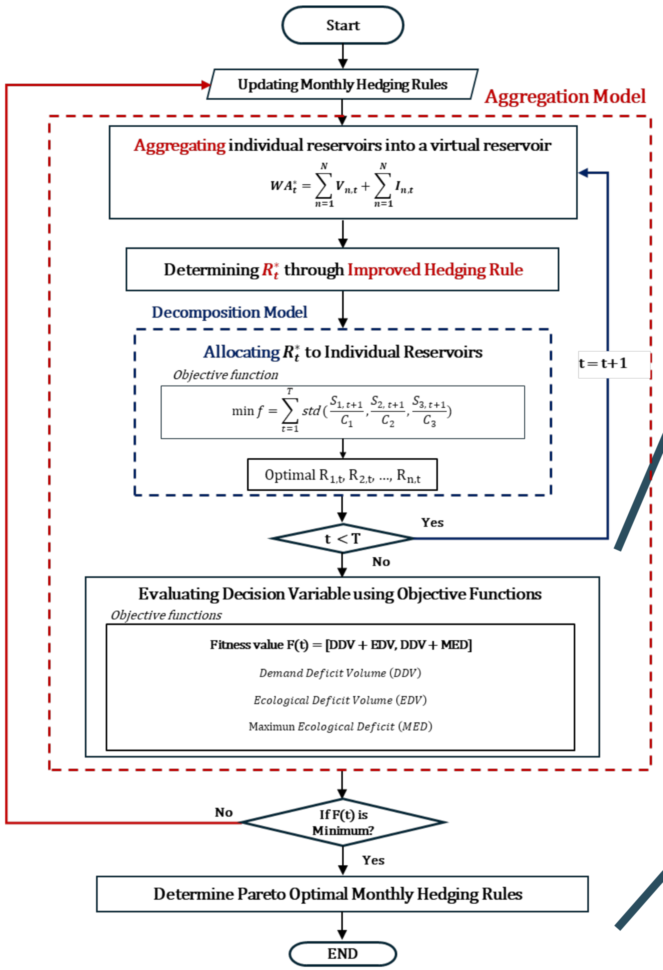
Objective function : minimize the STD of each reservoirs' storage rate

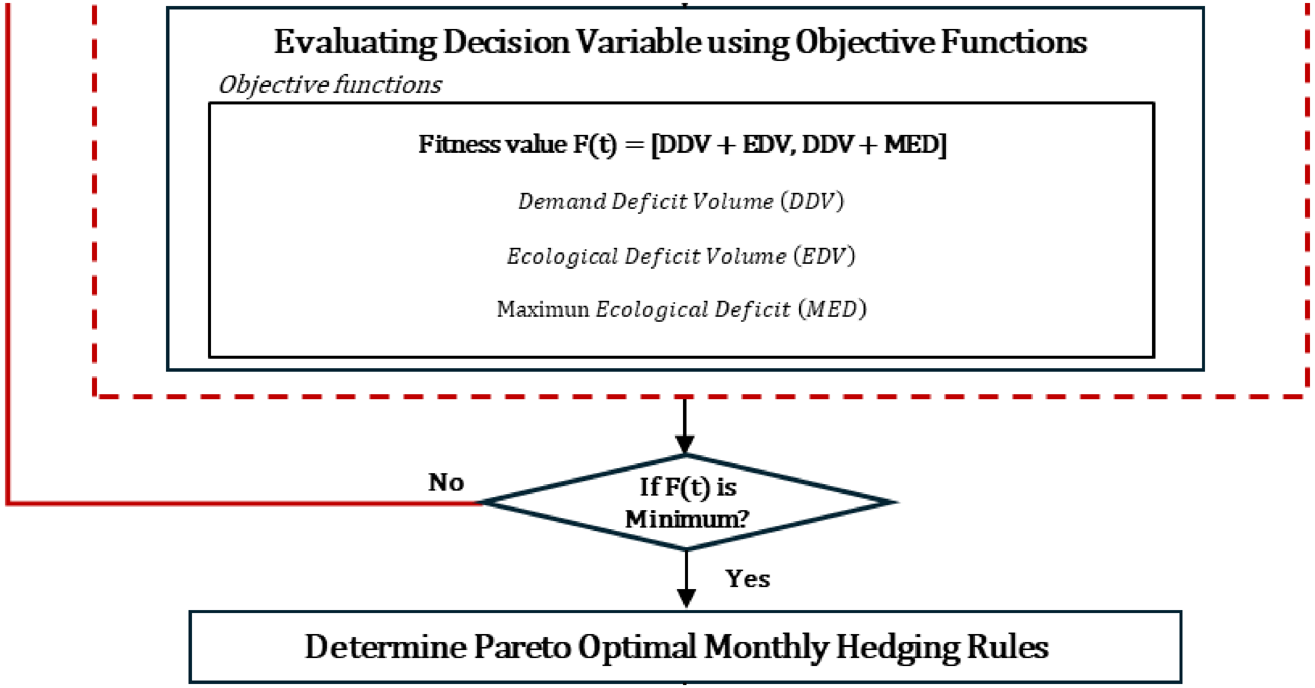
➔ Calculating reservoirs' storage of next time-step

➔ Repeating this process until the operation period ends

02. Methods

| Optimization Algorithm





➔ Calculate the Objective function of **outer optimization**

Objective function : minimize the water demand & ecological flow deficit

➔ Repeating the total process until the optimal hedging parameters is selected

Evaluation of the Operation Performance

Comparison with existing methods

➔ Comparison with **standard operating policy (SOP)** and **transformed hedging rule (THR)**

➔ Performance evaluation of the proposed method

Testing the practical applicability of optimal operation rules

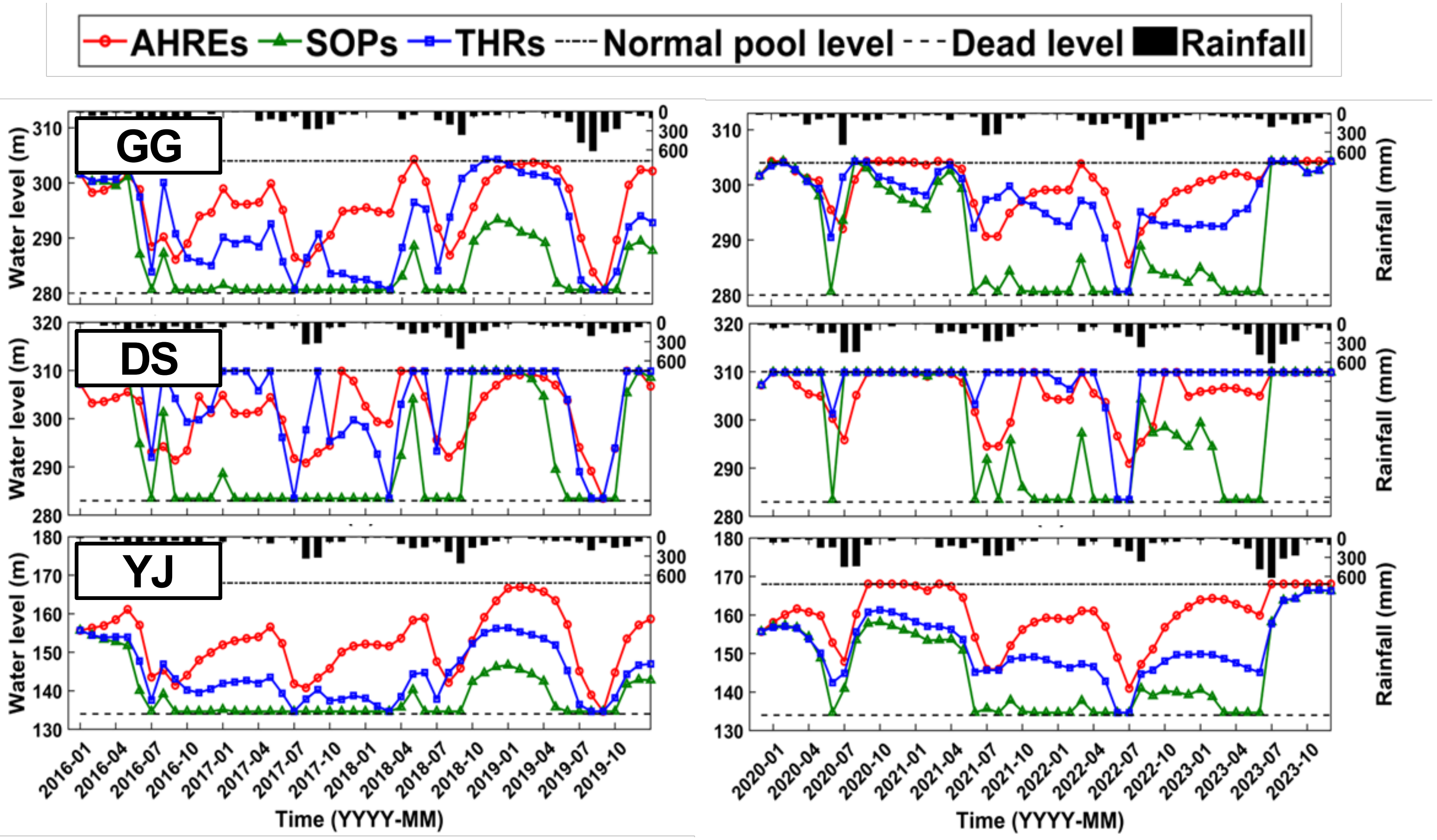
➔ Testing the operation rules to check the ability to respond to uncertainties such as inflows

➔ Applying the rules **without knowing the input variables** during the testing period (2020-2023)

Evaluation of the Operation Performance

- AHRE demonstrated the most stable and consistent operation.
- THR frequent exceed the normal pool level - indicate less effective water use.
- During the testing period, the same stable pattern appeared.

Water level of each reservoir



Training period (2016 ~ 2019) Testing period (2020 ~ 2023)