# Real-time Reservoir Optimization for Long-term Operation Considering Seasonal Ensemble Precipitation Forecast: A case study of the Sirikit Dam in 2019

Thatkiat Meema[1,2]*, Suppatana Wichakul[1] and Yasuto Tachikawa[2]

[1]TEAM Consulting Engineering and Management Public Company Limited, Bangkok, Thailand

[2]Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto, Japan

*E-mail: thatkiat.meema@gmail.com*

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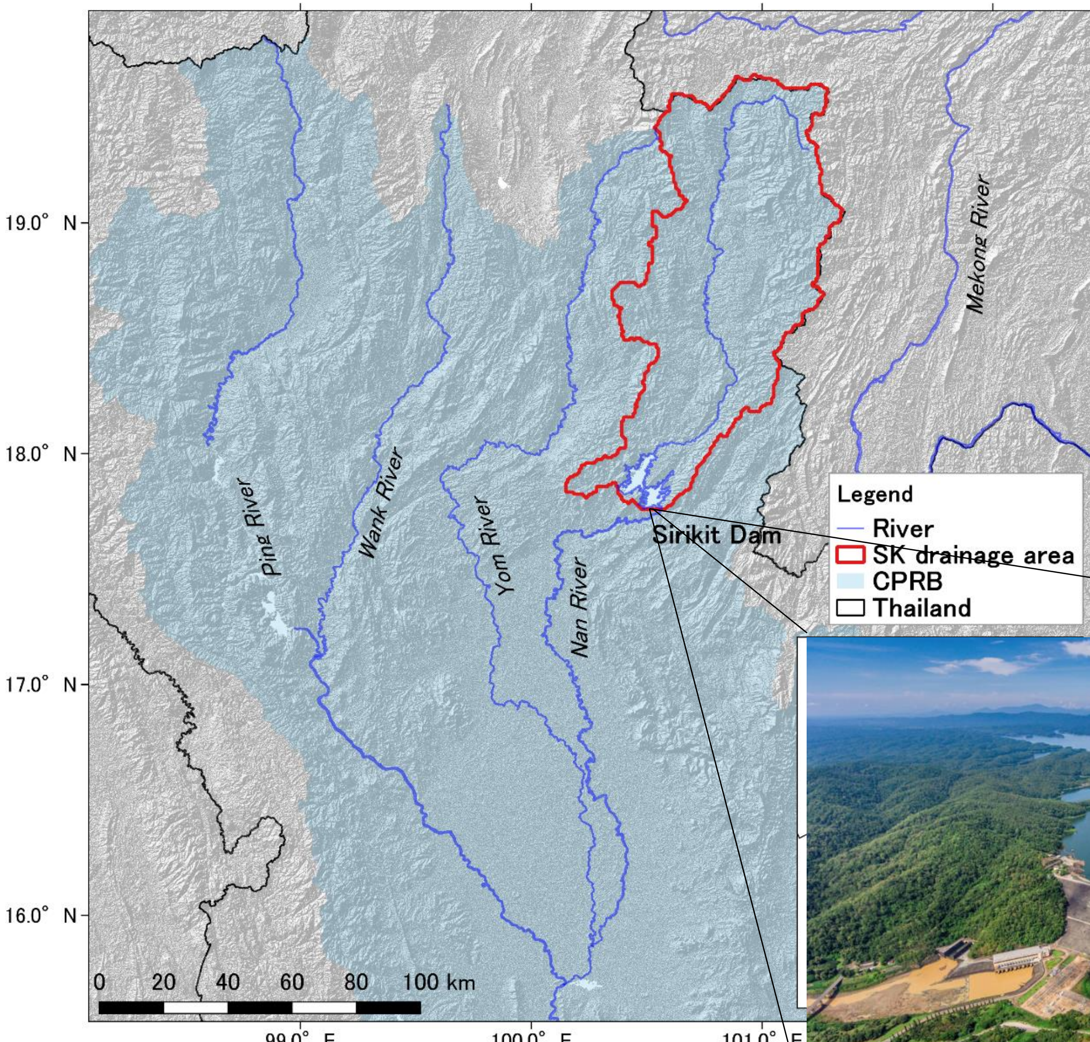
# Background of study

- The uncertainty regarding the basin's hydrological condition in a tropical climate **have a primary effect on reservoir operation**, increasing the risk of water shortages.
- Incorporating **weather forecast data** may improve the efficiency of decision making.
- For more robustness in reservoir operation using Dynamic Programming (DP), **seasonal forecast may be considered** *(Meema et al., 2021).*

Meema, T., Tachikawa, Y., Ichikawa, Y., Yorozu, K., 2021. Real-time optimization of a large-scale reservoir operation in Thailand using adaptive inflow prediction with medium-range ensemble precipitation forecasts. J. Hydrol. Reg. Stud. 38, 100939. 10.1016/j.ejrh.2021.100939.

# A case study; Sirikit Dam

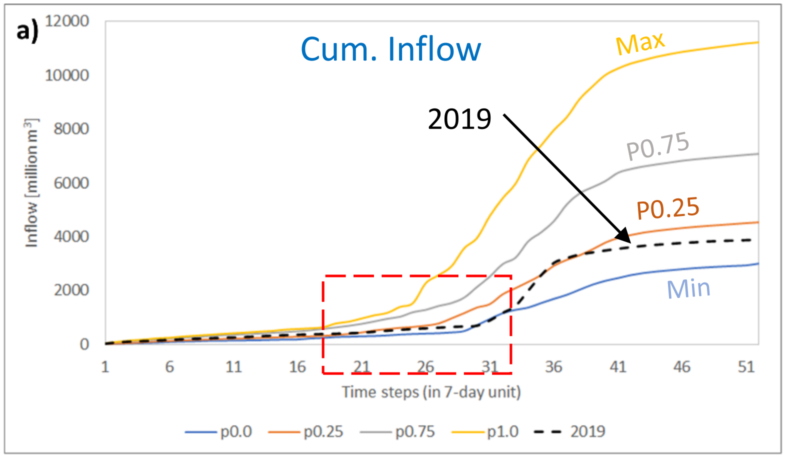


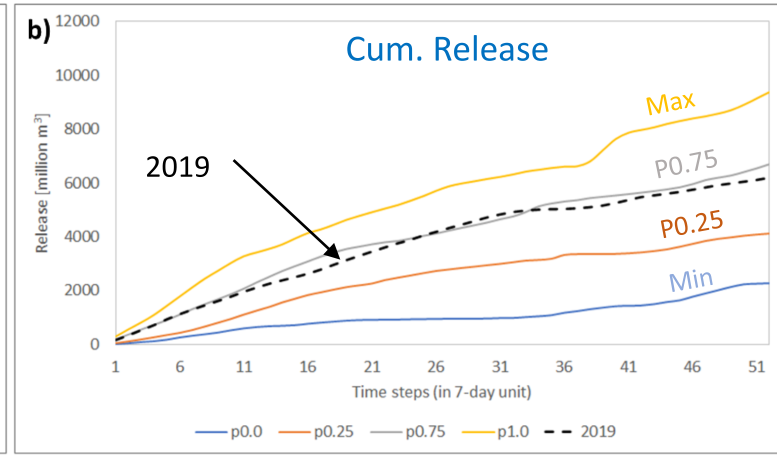


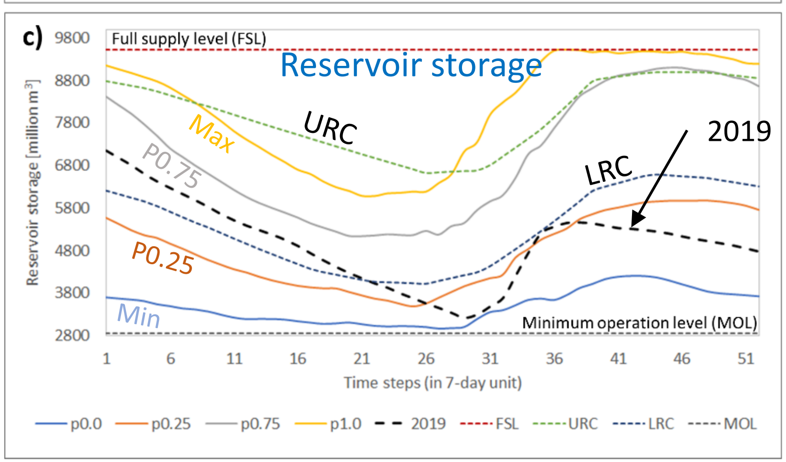
- River: **Nan River**
- Type: **Earth dam with clay core**
- Height: ***113.6*** m
- Catchment area: ***13,229*** km$^2$
- Total storage: ***9,510*** mcm
- Active storage: ***6,666*** mcm
- Power capacity: ***500*** MW

# The Sirikit Reservoir situation in 2019

Operation record in 2019 compared with 30-year historical data



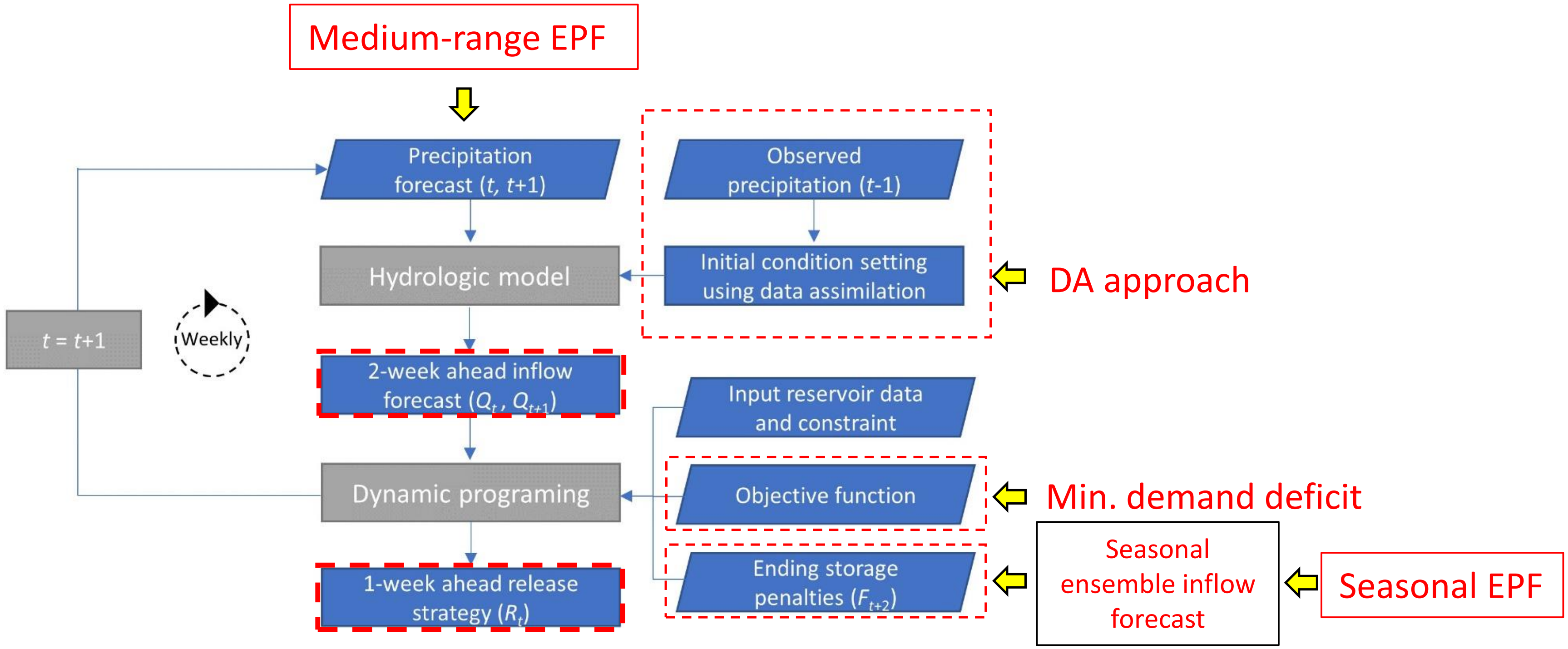




- The reservoir storage could be considered to be at a high level at the beginning of the year.
- The low inflow volume from the beginning to the middle of the wet season **was unexpected**. This event **presented difficulties** for reservoir operation.
- The water storage gradually decreased to low storage levels as a result of the imbalance between reservoir inflows and outflows.

# Real-time reservoir optimization flowchart

- This study aim to **introduce forecast information** **(medium-range and seasonal)** to the real-time reservoir operation **for determining release policy 1 week in advance**.



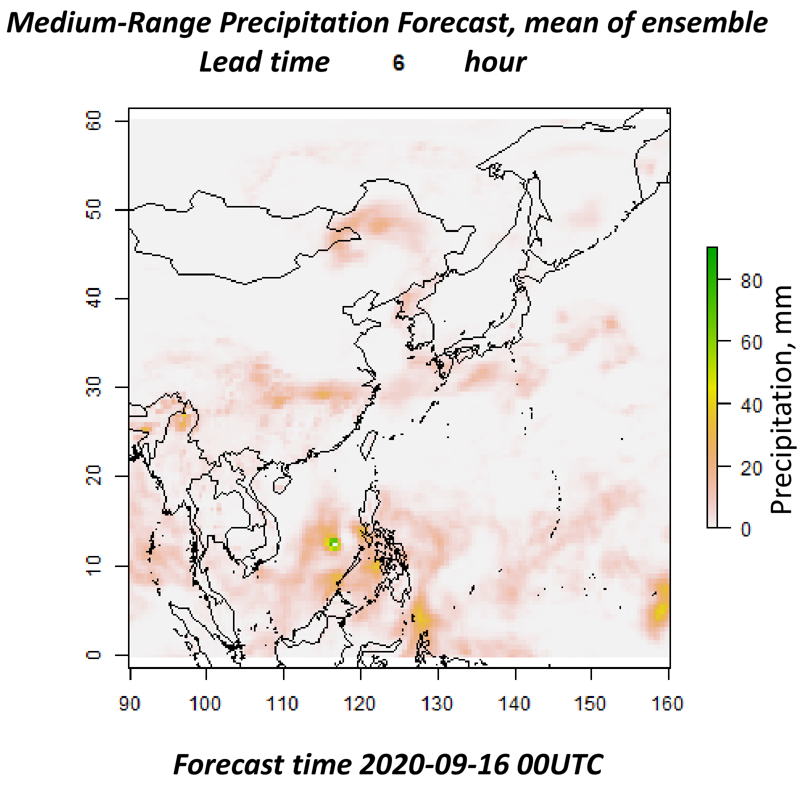

**Real-time optimization flowchart**

# Ensemble Precipitation Forecast data (EPF)

- **Medium-range precipitation forecast**

***ECMWF (European Centre for Medium-Range Weather Forecasts)***

- **51** members
- Approximately **0.5** degree resolution
- Forecast of **15** days
- **6** hours of temporal resolution

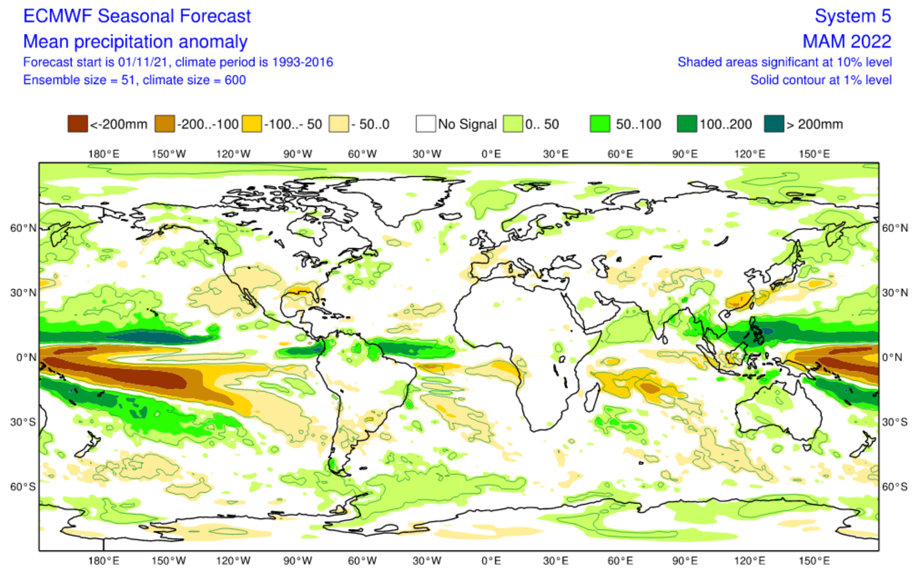


# Ensemble Precipitation Forecast data (EPF)

## • Seasonal precipitation forecast

### *ECMWF seasonal forecast*

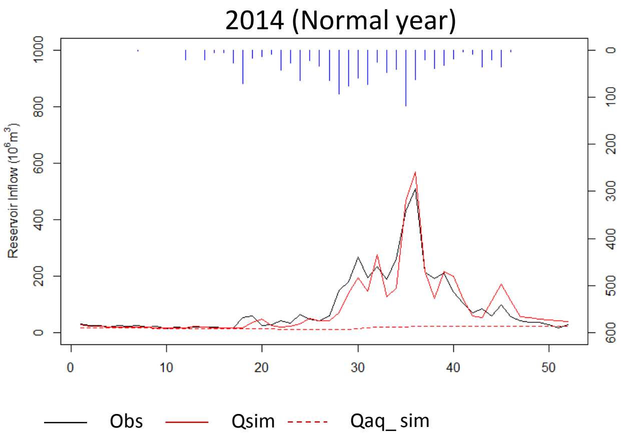
- **51** members
- Approximately **1.0** degree resolution
- Forecast of **215** days (7 months)
- **24** hours of temporal resolution
- Released every month



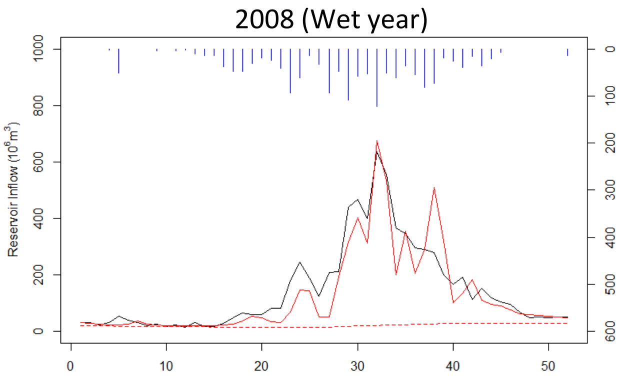

*Source : apps.ecmwf.int*

# Prediction model

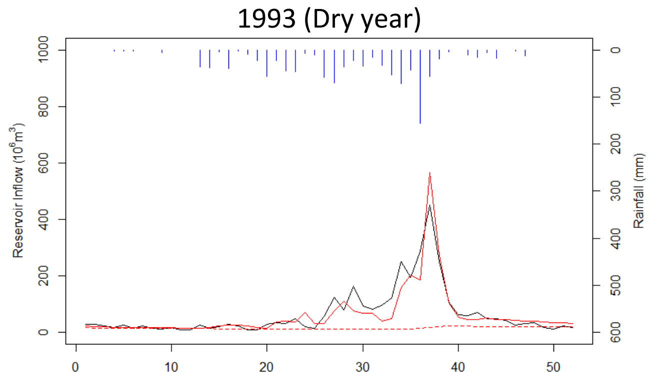
**Calibration period**



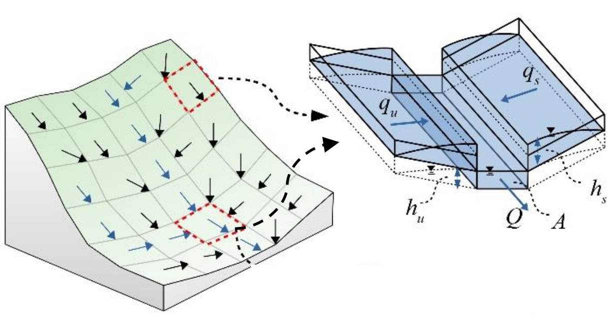

**Validation period 1**




**Validation period 2**




**Improved 1K-DHM** *(Meema and Tachikawa, 2020)* was applied for this study.




**Calibrated parameters**

| **Parameter (Units)** | **Value** |
|---|---|
| $n_s$ (m-1/3/s) | 0.975 |
| $k_a$ (m/s) | 0.000114 |
| $d_a$ (m) | 3.179 |
| $d_m$ (m) | 2.984 |
| *Beta* (-) | 19.906 |
| $k_u$ (m/s) | 8.460E-05 |
| $d_u$ (m) | 0.323 |
| $k_v$ (m/s) | 1.084E-07 |

**Model performances**

| **Period** | **Calibration** | **Validation 1** | **Validation 2** |
|---|---|---|---|
| NSE | 0.89 | 0.82 | 0.84 |
| RMSE (mcm) | 35.0 | 63.6 | 33.9 |
| PBIAS (%) | -3.7 | -13.3 | -6.6 |

The model performs well in both calibration and validation periods.

# Real-time state update of hydrological model

- We adopted **empirical data assimilation procedure** (*Collischonn et al.*, 2005) to incorporate with the distributed hydrologic model **to determine the initial state** of the basin (at $t0$).

The **updating correction factor** (*FCA*) is calculated at the gauge station $k$ using the equation as follow;

$$FCA_k = \frac{Q_{obs,k}}{Q_{cal,k}}$$

where $Q_{obs,\,k}$ and $Q_{cal,\,k}$ are observed and calculated river discharge at gauge station $k$.

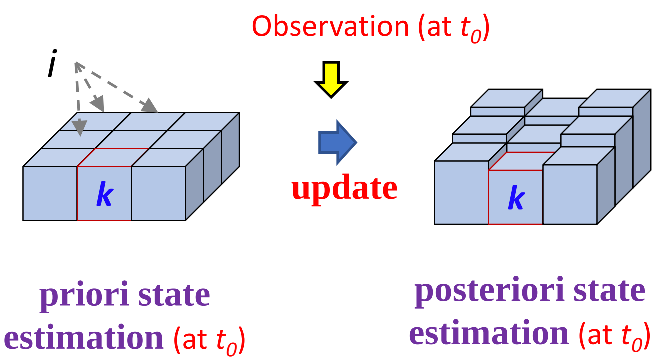
## Upstream grids state update

- **Stages update**

$$S_{up,i,k} = FCA_k \cdot S_{cal,i} \cdot \left(\frac{A_i}{A_k}\right) + S_{cal,i} \cdot \left(1 - \frac{A_i}{A_k}\right)$$

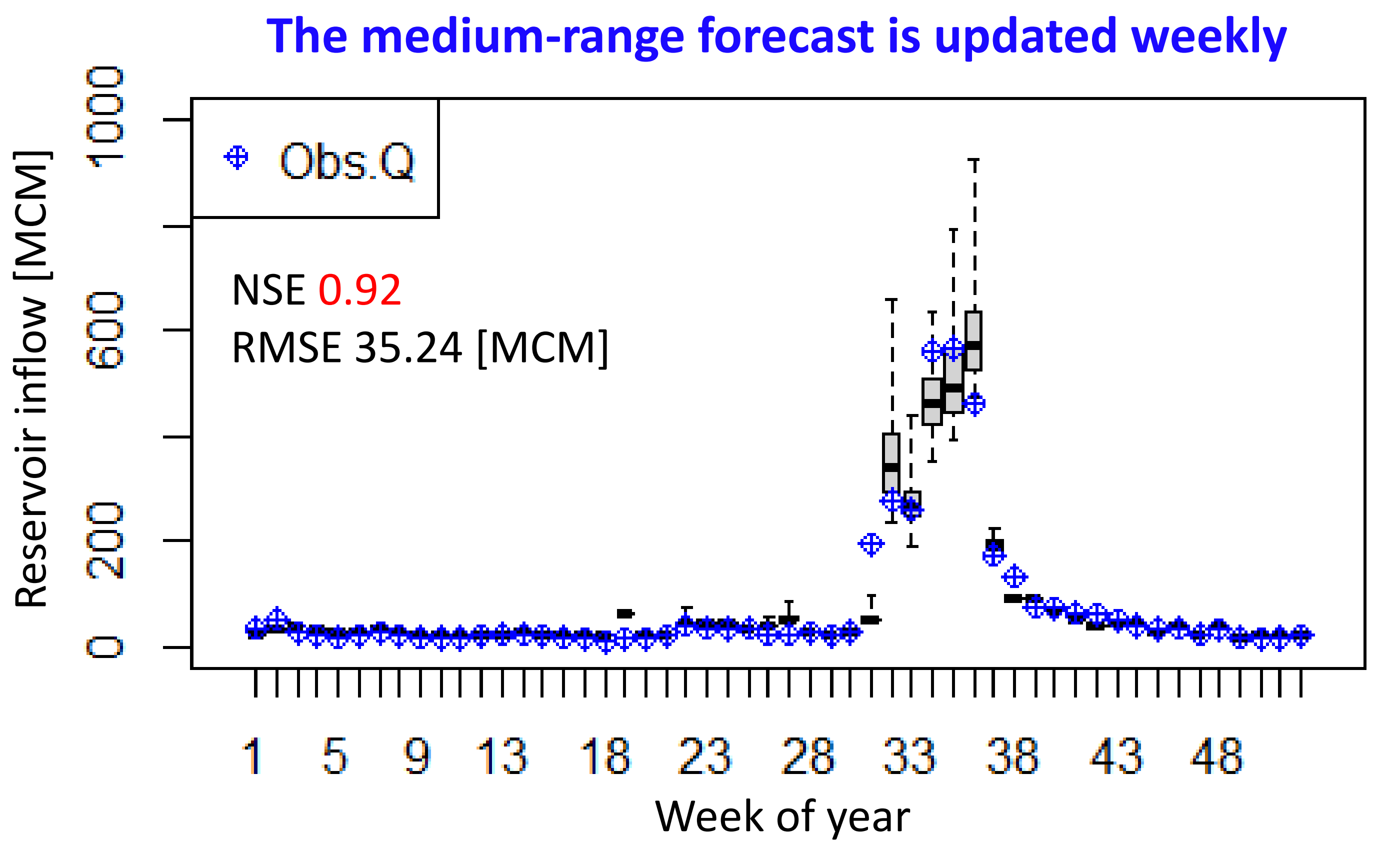
where $S_{up,\,i,\,k}$ is the updated model state variables at cell $i$ located upstream of gauge station $k$ in which it is river discharge ($Q$), lateral discharge from the surface soil layer ($q_s$) and the bedrock aquifer layer ($q_u$) of the hydrologic model for this study, $A_i$ and $A_k$ are the drainage areas upstream of cell $i$ and gauging station $k$.

**State update conceptual drawing in a distributed model**



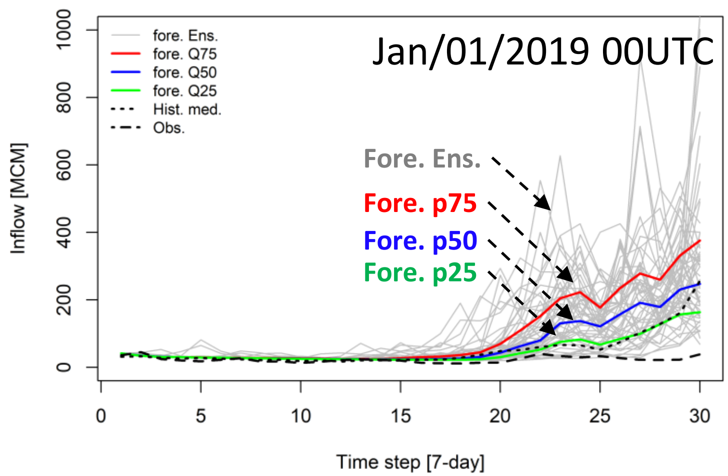

$t_0$ is initial forecast time

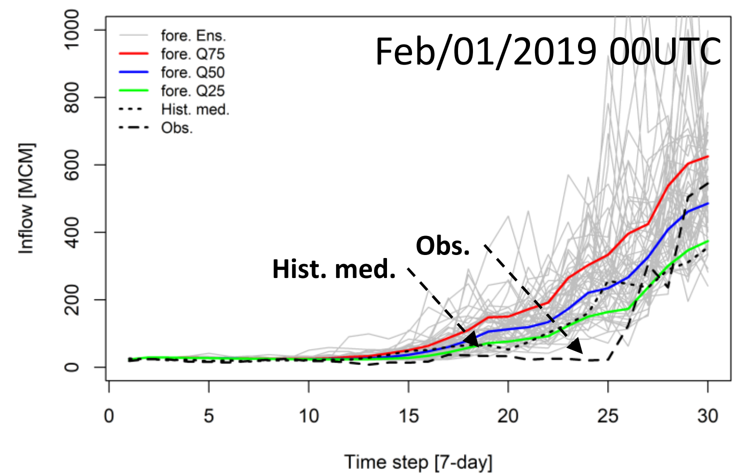
# Reservoir inflow forecast using Medium-Range EPF (weekly update)

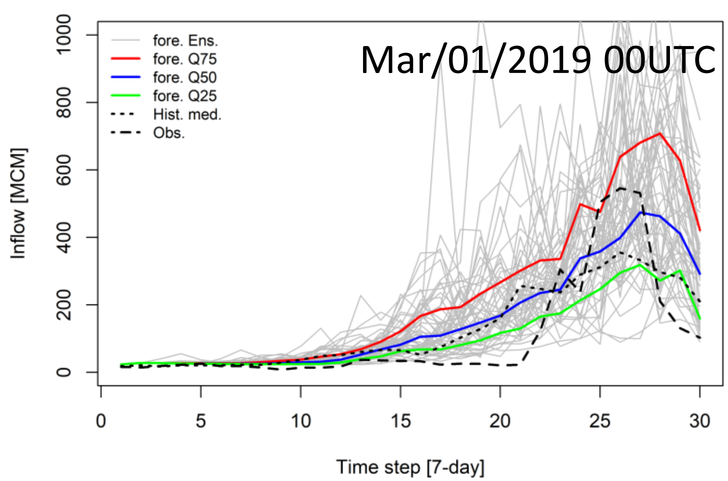


# Results of seasonal ensemble inflow forecast

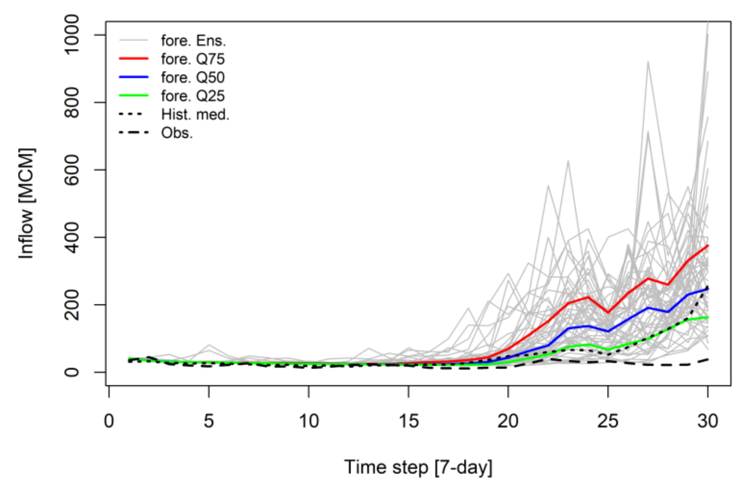
## *For different initial forecast time (update once a month)*



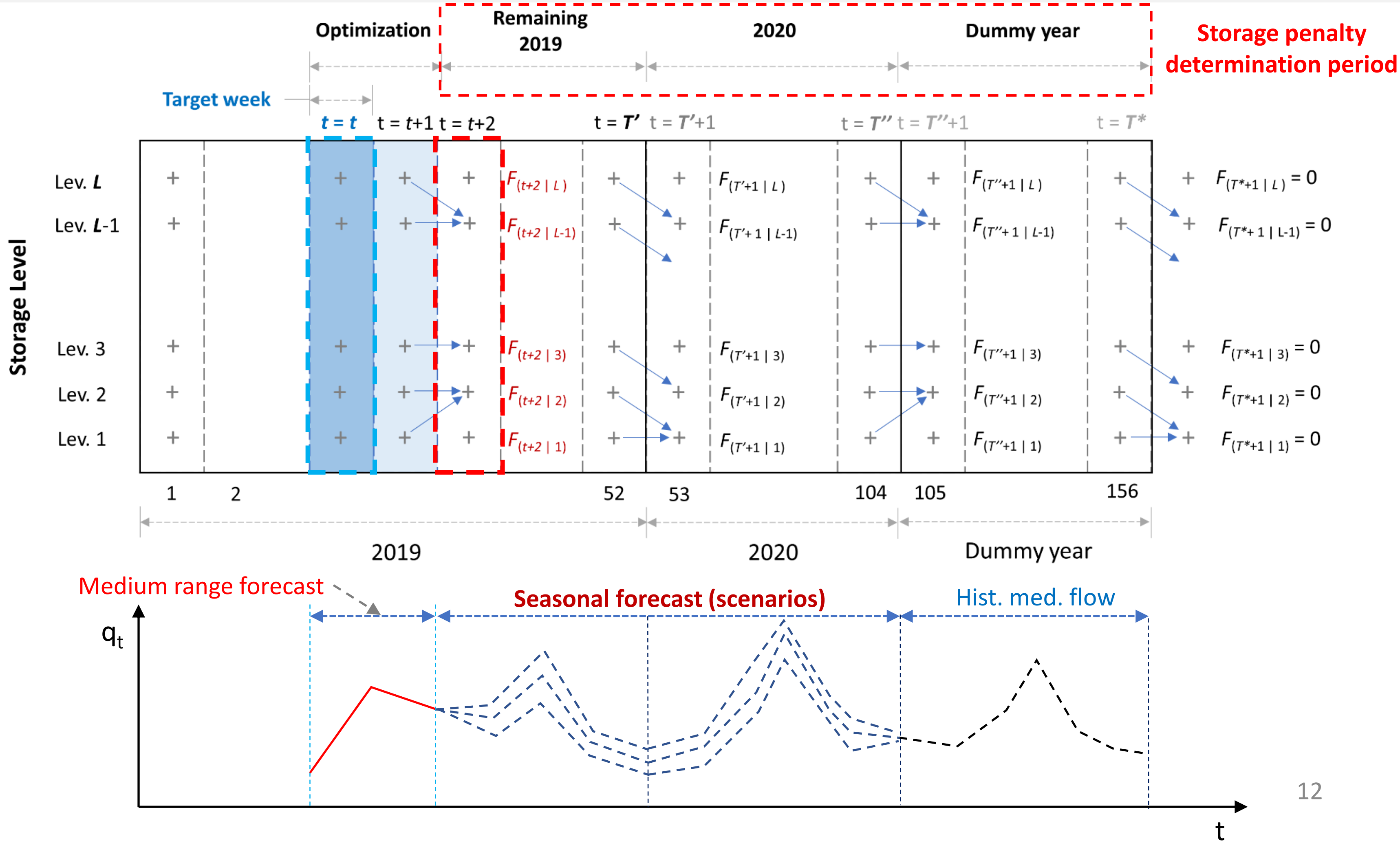




**The seasonal forecast is updated monthly**



# Real-time optimization scheme

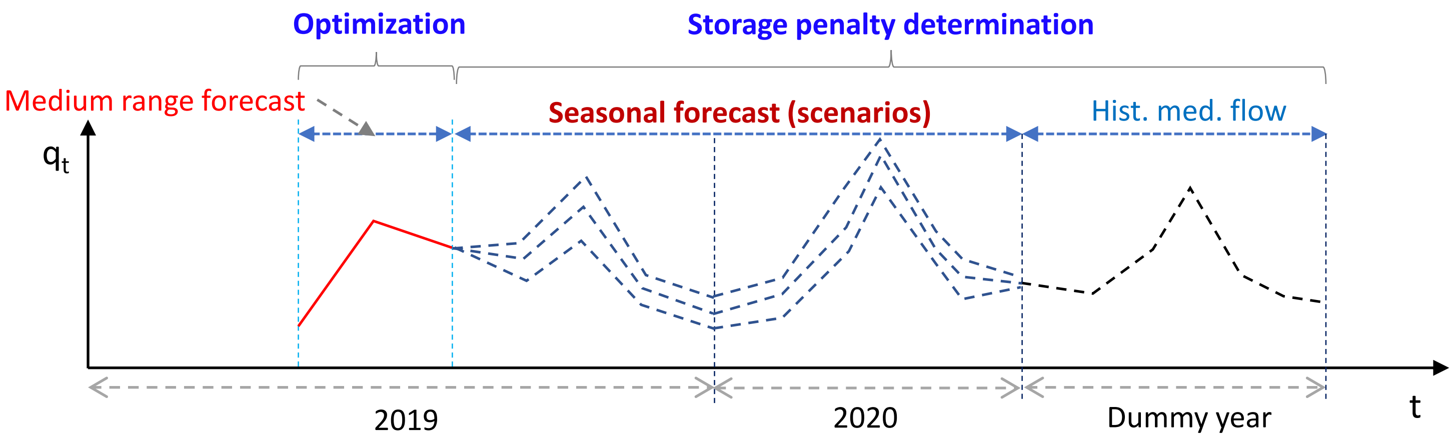
- To adopt **DP**, the ***penalties*** ($F_{(\cdot)}$) must be accounted into the lower storage levels. **This to ensure that the reservoir will not draw down to low storage levels** (by releasing excess water to generate benefits).
- The ***dummy year*** was proposed to make the penalties at the end of 2020 ($F_{(T'+1)}$) independent of the assumption that the operation will end somewhere.



# Real-time optimization inflow scenarios

***Real-time optimization inflow scenarios* with *different inflow assumptions* for penalty calculation.**

| Scenarios | | Periods | | | |
|---|---|---|---|---|---|
| | | Optimization | Storage penalty determination | | |
| | | | Seasonal forecast | until the end of 2020 | Dummy year |
| Scenario 0 | | baseline scenario (actual operation) | | | |
| Scenario 1 | | perfect forecast (obs. inflow) | | | Hist. med. Inflow |
| Scenario 2 | | Hist. med. Inflow | | | |
| Scenario 3 | 3.1 | Medium-range fore. mean | Seasonal fore. p75 | Hist. med. Inflow | |
| | 3.2 | | Seasonal fore. p50 | | |
| | 3.3 | | Seasonal fore. p25 | | |



# Objective function

For this study, ***drought damage function*** was considered which is the function of the reservoir release and water demand.

***The objective function*** for this problem can be expressed as

$$min \sum_{t=1}^{T} H_t$$

***T*** is the number of optimization stage
***$H_t$*** is the total damage at stage ***t***

***Drought damage function*** (Ikebuchi et al., 1990)

$$H_t(R_t) = \frac{[max(D_t - R_t, 0)]^2}{D_t}$$

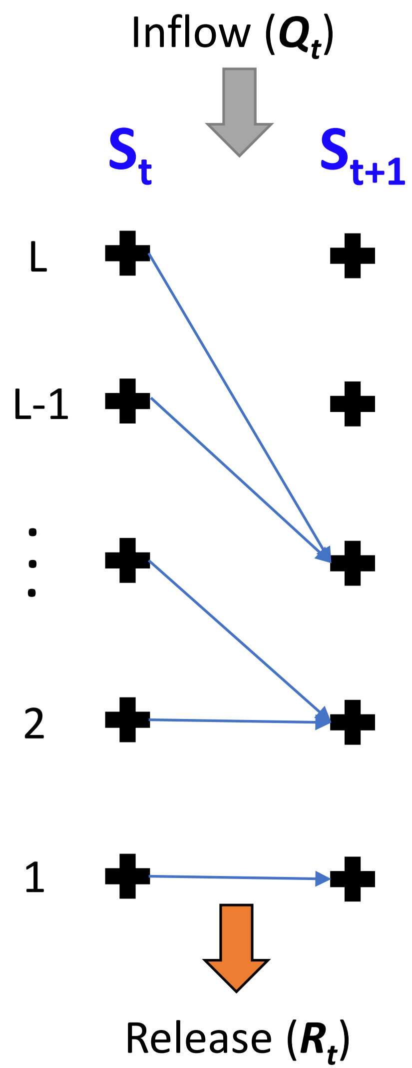
where ***$R_t$*** and ***$D_t$*** are reservoir release and downstream demand at stage ***t*** respectively

*For water demand (**$D_t$**) in this study, we assumed that the actual release during 2019 could supply the downstream demand.*

# Scheme output and implementation

**Output release strategy**

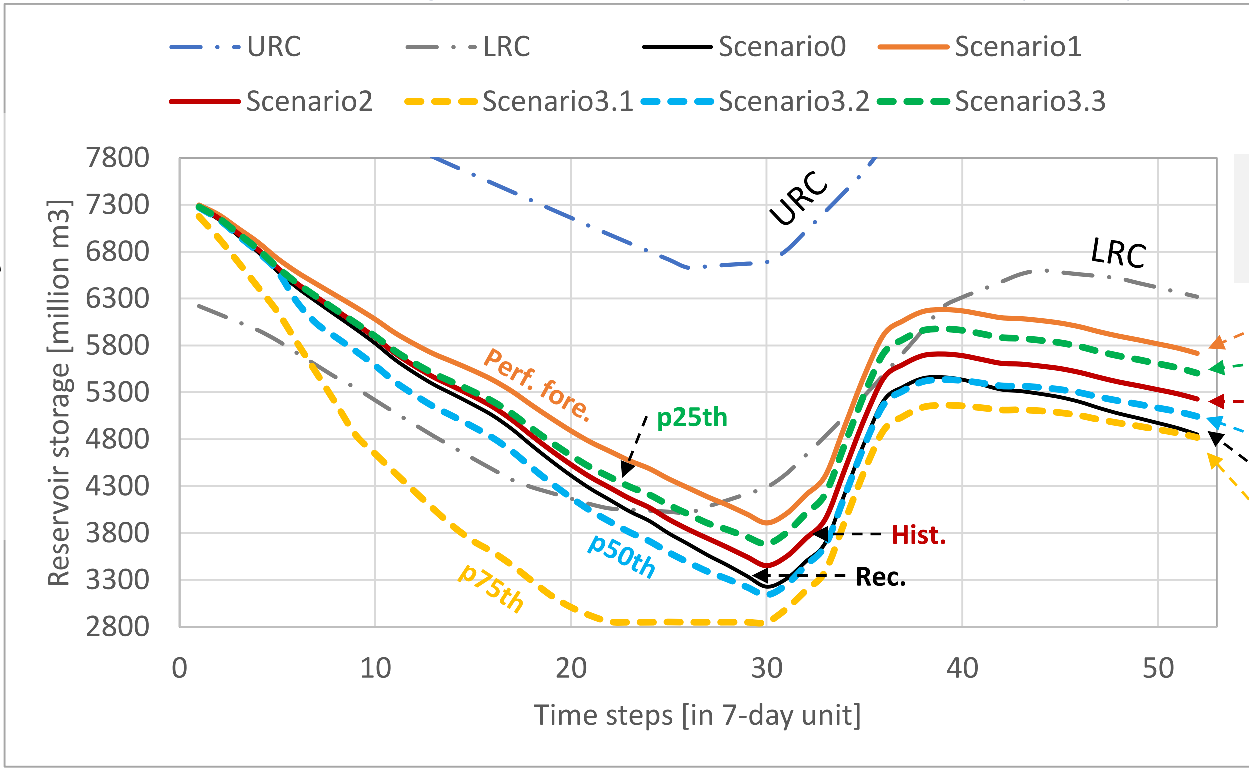
| Current Storage ($S_t$) | Release strategy ($R_t$) |
|---|---|
| 7803.6 | 214.1 |
| 7732.5 | 167.6 |
| 7661.4 | 161.1 |
| 7590.3 | 157.9 |
| 7519.2 | 158.0 |
| 7448.1 | 154.8 |
| 7377.0 | 155.0 |
| 7305.9 | 151.8 |
| 7234.8 | 148.6 |
| 7163.7 | 145.4 |
| 7092.6 | 145.6 |
| 7021.5 | 142.4 |
| 6950.4 | 139.2 |
| 6879.3 | 132.7 |
| 6808.2 | 112.8 |
| 6737.1 | 86.3 |
| 6666.0 | 43.2 |




- The **one-week advanced release strategy** ($R_t$) obtained from the optimization scheme **can be implemented for any initial reservoir storage level** ($S_t$) at the target time ($t$).
- This **strategy can be implemented under different flow patterns** using linear interpolation among the release tables.

# Result (reservoir simulation using 1 week in advance release policy)

Although more releases provided lower damage, the remaining **water budget** for the future operation is different.




| | Scenarios | | Total release [million m$^3$] | End year storage [million m$^3$] | End year storage penalties* [million m$^3$] | Acc. drought damage [million m$^3$] within 2019 | Acc. drought damage [million m$^3$] including penalties* | Hydropower production [GWh] within 2019 | Hydropower production [GWh] including future potential** |
|---|---|---|---|---|---|---|---|---|---|
| Actual operation | Scenario 0 | | 6175.9 | 4851.0 | 624.6 | 0.0 | 624.6 | 1023.4 | 2618.4 |
| **Perfect forecast** | Scenario 1 | | 5294.3 | 5715.5 | 218.0 | 132.0 | **350.0** | 908.6 | **2661.7** |
| Historical information | Scenario 2 | | 5791.7 | 5228.5 | 399.9 | 37.8 | 437.7 | 972.0 | 2634.9 |
| **Forecast information** | Scenario 3 | 3.1 | 6229.2 | 4819.3 | 647.0 | 901.7 | 1548.7 | 1011.2 | 2606.8 |
| | | 3.2 | 5984.9 | 5043.6 | 500.0 | 88.0 | 588.0 | 989.7 | 2622.0 |
| | | 3.3 | 5511.7 | 5504.3 | 285.4 | 104.7 | **390.1** | 936.4 | **2646.0** |

* possible min. drought damage at the end year storage level based on actual inflow in 2020 and Hist. p50 in dummy year

** potential of power generation at the end year storage level based on actual inflow in 2020 and Hist. p50 in dummy year

Considering **p25 of long fore.** during drought condition resulted in a similar tendency with **Perf. fore.**

# Conclusions

- Even though the **seasonal forecast** **has high uncertainty**,
- there are ***advantages*** in the use of **seasonal EPF** for long-term reservoir operation when **appropriately considering the probability of results** among the forecast members **compared to** without taking predictions into account.
- An accurately **long-term forecast is required** for more robustness in reservoir operation.
- For more robustness, **real-time actual d/s water demand** may need to consider.
- The evaluation of the real-time scheme should be **followed up with the further years**.

Thank you for your kind attention..