# Revised Min-Max (RMM) Approach for Two-Objective Reservoir Operation

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## INTRODUCTION

Owing to the changing climate, rapid development, and population growth, the current management of water resources is expected to be critically affected. Several reservoirs are multi-objective and often involve competing interests, including water supply, flood control, and hydropower production. Most reservoir management practices are ineffective, outdated, and subjective. Therefore, it is necessary to re-evaluate the current management rules to optimize objectives, reduce water stress, and mitigate climate change impacts. This research mainly focused on optimizing two conflicting objectives: the satisfaction of agricultural demand and upstream flood regulation in the city of Como. Como Lake is a regulated lake in Northern Italy and the third largest lake, receiving water from the upper Adda River and controlled downstream by the "Olginate" regulation dam (Fig. 1).

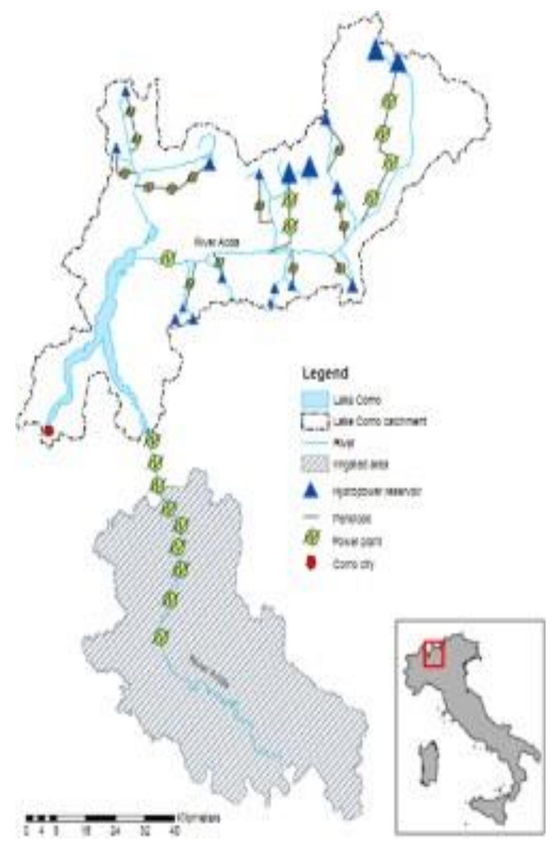


Figure 1. Lake Como and River Adda basin (source: [1])

## DATASET AND METHOD

The **RMM** approach (see Figure 6) aims to determine the optimal water levels ($h_{min}$ and $h_{max}$) for irrigation demand satisfaction and flood prevention for a specified value of α(satisfaction factor) and β(flood indicator). It simulates the water balance equation for 71 years of historical inflow data (see Figure 3) from 1946 (the operation of the Olginate dam began) to 2016 [4]. In particular, the historical outflow time series is used to simulate the current management policy and historical efficiency of the system in terms of α and β.

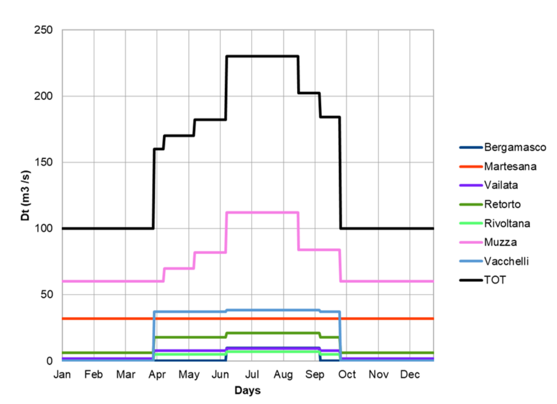


Figure 2. Daily irrigation water demand of the of seven canals and total daily demand (Black line)

I. **Objective-I**: Agricultural demand satisfaction: parameterized by α (the ratio between the actual release ($R_t$) and the agricultural demand ($D_t$) as shown Fig. 2.

II. **Objective-II**: Flood protection in the city of Como: parameterized by β (the ratio between the actual active storage ($S_t$) and the reference storage ($S_{max}$), given as 1.2 m above the null point at Malgrate hydrometer.

The two objectives were solved independently for different values of α (0<α<1) and β (β<1) in accordance with the reservoir characteristics [2], respecting the constraints and within the control range ($H_{min}$ = -0.5m, $H_{max}$ = +1.2m).

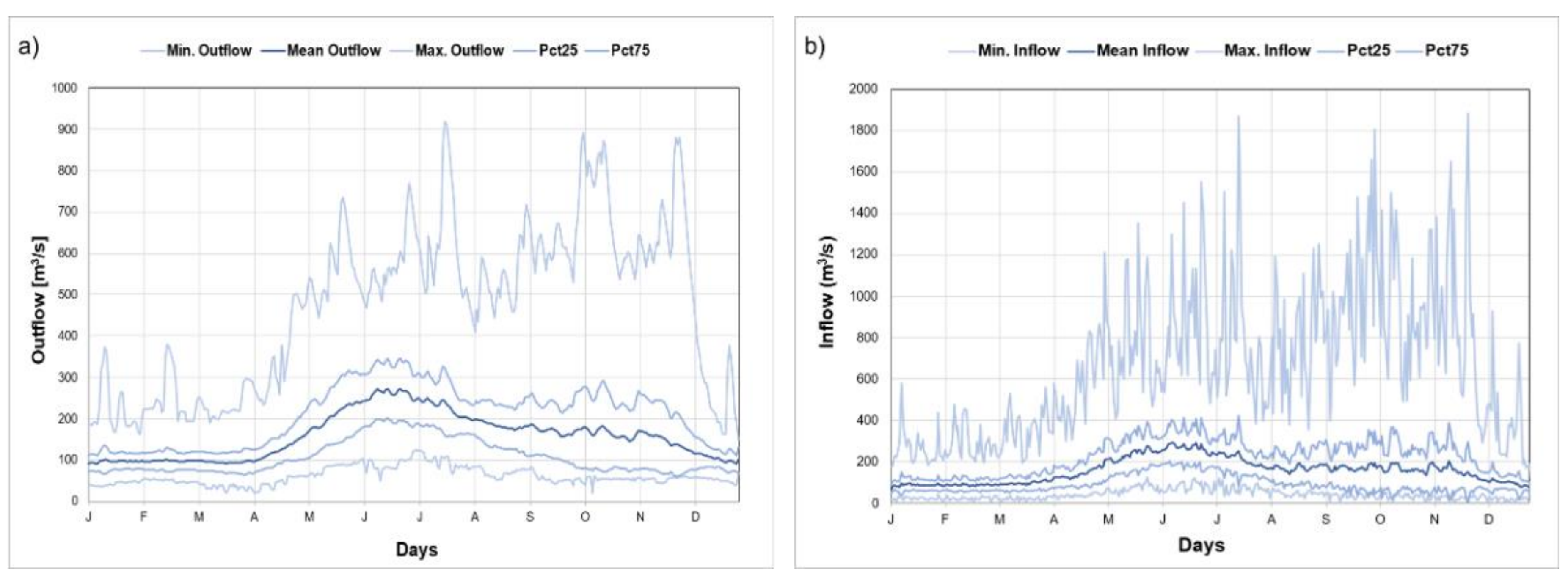



Figure 3. Presents the daily minimum, mean, maximum, 75th percentile, and 25th percentile values for both outflow (a) and inflow (b), in the post-regulation period (1946-2016).

## RESULTS

### i. Release Strategies

Feasible solutions (see Figure 4) are obtained by combining the solutions of each problem, it shows the set of possible releases depending on the storage level in the lake within the control range (i.e., between $S_{min} \equiv h_{min}$ and $S_{max} \equiv h_{max}$ expressed in m³).

The daily releases to satisfy objective-1 and objective-2 on a specific day t are represented by $R^{\alpha}_{t}$ and $R^{\beta}_{t}$ for given values of α and β, respectively.

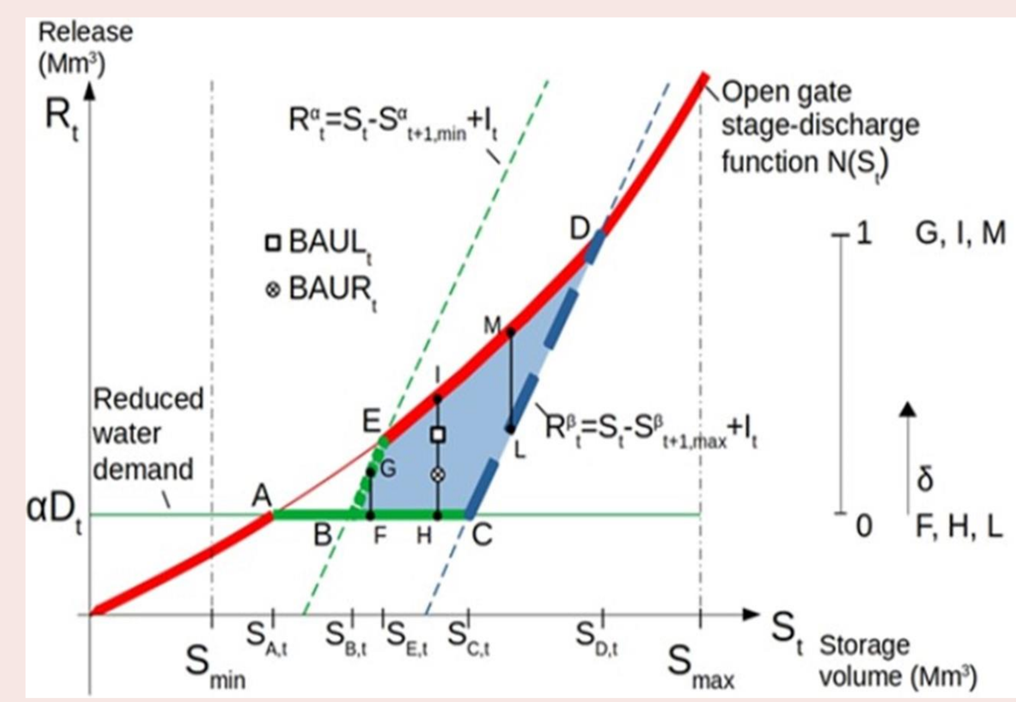
Proposed release strategies:

I. **Business as Usual Level** (**BAUL**): aims to reach the historical average water level.

II. **Business as Usual Release** (**BAUR**): aims to reach the historical average release.

III. **δ–solution**: allows the manager to modulate the release with δ, where δ is between 0 (irrigation demand satisfaction oriented: see F, H, and L) and 1 (flood control-oriented: see G, I, and M).

Figure 4. Feasible release volumes $R_t$ expressed as storage volume, constrained between the minimum release needed to satisfy the reference irrigation demand (BC), the minimum release needed to meet the flood safety target β (CD), the maximum release with fully opened gates (DE), and the maximum feasible release compatible with the irrigation deficit target α (EB). BAUL and BAUR values are also represented.




### ii. Efficient Solutions

- Simulating the system dynamics over the given dataset, an iterative procedure was used to find the initial storage that satisfies the irrigation demand (or flood protection objective) every following day for a given value of α (or β) see Figure 6.
- The system efficiency ($\eta_\alpha$ and $\eta_\beta$), represented as the percentage of a valid solution, varies with α and β because some years do not meet the given values of α and/or β.
- Efficient solutions (see Figure 5a, segment BC) were found iteratively by fixing α (satisfaction factor) and searching for a corresponding β (flood indicator) that satisfies $S^{\alpha}_{t,min} \leq S^{\beta}_{t,max}$ [3].

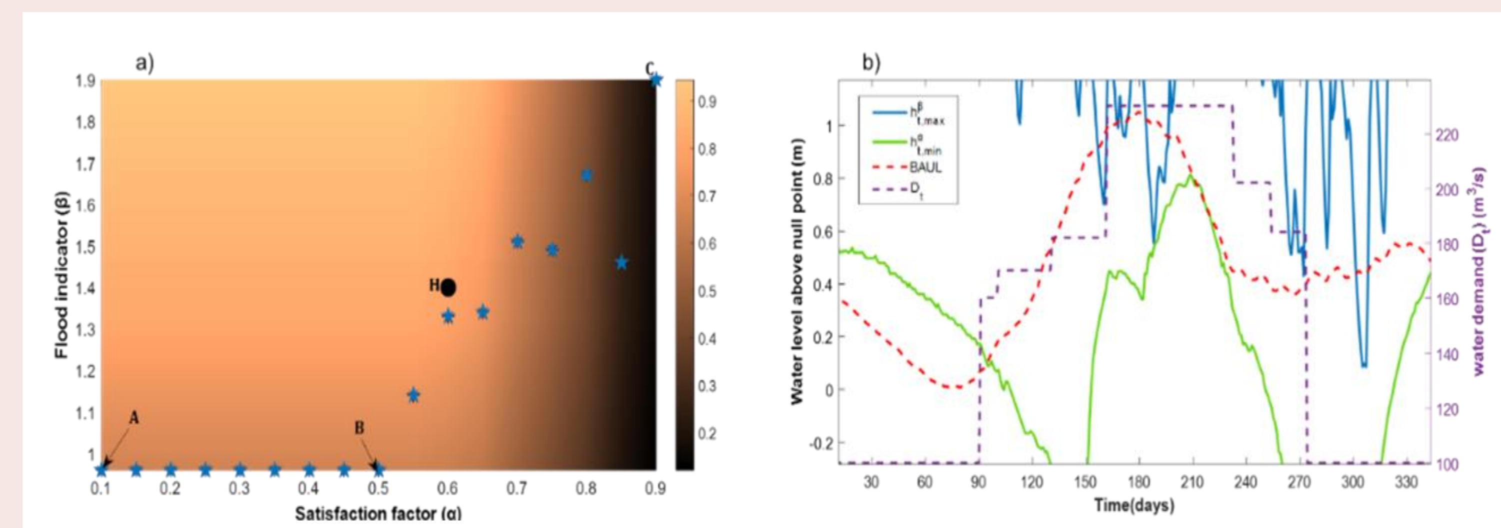



Figure 5. **a)** Pareto frontier in the α-β plane, the historical solution is reported as the black circle (H) and the background heatmap represents the overall efficiency η. **b)** The feasible efficient solution, historical average water level (BAUL), daily water demand ($D_t$), maximum allowed water level $h^{\beta}_{t,max}$ for β = 1.33, and minimum water level $h^{\alpha}_{t,min}$ for α = 0.6.

### iii. Performance Evaluation

- Two statistical performance indices, the flood index (FI) and deficit index (DI), were utilized to evaluate the performance of historical and efficient solutions (can be seen in segment BC of Fig. 5a).
- FI measures the ratio of flooding days in a year, whereas DI measures the ratio of total annual deficit to the total annual demand.
- These indices determine how effectively the release policy operates within a specified operating rule and time period [1].
- The combined performance was calculated by adding the results in Table-1 and Table-2.

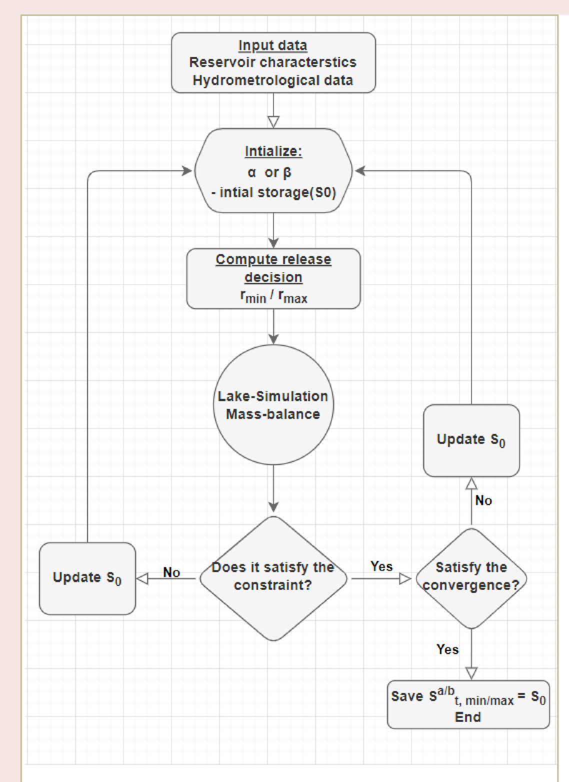



Figure 6. Revised Min-Max approach

Table 1: Flood index

| $\eta_\alpha$ | $\eta_\beta$ | α | β | BAUL | BAUR | δ=0.00 | δ=0.15 | δ=0.25 | δ=0.5 | δ=0.75 | δ=1 | Historical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100% | 82% | 0.56 | 1.36 | 5.4% | 1.8% | 44.0% | 2.92% | 2.6% | 2.0% | 1.7% | 1.4% | 6.1% |
| 97% | 82% | 0.60 | 1.33 | 5.4% | 1.7% | 34.8% | 2.66% | 2.3% | 1.9% | 1.6% | 1.3% | 6.1% |
| 92% | 82% | 0.65 | 1.34 | 5.4% | 1.7% | 31.3% | 2.60% | 2.3% | 1.9% | 1.6% | 1.3% | 6.1% |
| 77% | 85% | 0.70 | 1.51 | 5.4% | 1.8% | 37.2% | 2.94% | 2.6% | 2.1% | 1.7% | 1.5% | 6.1% |
| 65% | 85% | 0.75 | 1.49 | 5.4% | 1.8% | 30.2% | 2.72% | 2.4% | 2.0% | 1.6% | 1.4% | 6.1% |
| 51% | 89% | 0.80 | 1.67 | 5.3% | 2.0% | 30.2% | 2.79% | 2.5% | 2.1% | 1.8% | 1.6% | 6.1% |
| 31% | 85% | 0.85 | 1.46 | 5.2% | 1.8% | 18.8% | 2.30% | 2.1% | 1.8% | 1.6% | 1.4% | 6.1% |
| 18% | 94% | 0.90 | 1.90 | 5.1% | 1.8% | 16.7% | 2.70% | 2.1% | 1.8% | 1.6% | 1.4% | 6.1% |

Table 2: Deficit index

| $\eta_\alpha$ | $\eta_\beta$ | α | β | BAUL | BAUR | δ=0.00 | δ=0.15 | δ=0.25 | δ=0.5 | δ=0.75 | δ=1 | Historical |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100% | 82% | 0.56 | 1.36 | 14.4% | 21.9% | 23.9% | 18.29% | 16.8% | 16.7% | 17.8% | 18.8% | 16.1% |
| 97% | 82% | 0.60 | 1.33 | 14.4% | 22.0% | 23.4% | 17.54% | 16.0% | 15.3% | 16.3% | 17.2% | 16.1% |
| 92% | 82% | 0.65 | 1.34 | 14.4% | 22.0% | 21.9% | 16.51% | 15.5% | 15.6% | 16.4% | 17.3% | 16.1% |
| 77% | 85% | 0.70 | 1.51 | 14.3% | 20.5% | 19.3% | 15.17% | 14.5% | 15.6% | 16.6% | 17.3% | 16.1% |
| 65% | 85% | 0.75 | 1.49 | 14.3% | 21.1% | 18.0% | 14.28% | 13.8% | 14.8% | 15.6% | 16.3% | 16.1% |
| 51% | 89% | 0.80 | 1.67 | 14.2% | 21.2% | 15.7% | 13.13% | 13.3% | 14.3% | 14.9% | 15.4% | 16.1% |
| 31% | 85% | 0.85 | 1.46 | 14.0% | 21.7% | 15.1% | 12.96% | 13.2% | 13.9% | 14.4% | 14.8% | 16.1% |
| 18% | 94% | 0.90 | 1.90 | 13.6% | 22.2% | 13.5% | 12.69% | 13.1% | 13.7% | 14.1% | 14.4% | 16.1% |

Table 1 (Flooding indices) and Table 2 (Deficit indices) of historical, BAUL, BAUR, and δ-release policies for different efficient solution with different values of α and β. $\eta_\alpha$ and $\eta_\beta$ represent the percentage of years when the solution is achieved.

## CONCLUSION

- According to the results, flood regulation improvement was more significant than irrigation deficit reduction.
- The δ-solution with α=0.85 and β=1.46, reduces the total annual deficit by 19% and flooding days by 15 days (69%).
- BAUL, BAUR, and Historical solutions show lower overall performance for the selected optimal solution.
- **Outlook**: this can serve as a model for creating a tool and/or software to solve water management issues.

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