Optimal Regional Water Network Management in Drought Conditions: the Catalonia Case Study

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Abstract: In the present work, Model Predictive Control (MPC) is applied to the regional water network of Catalonia, which consists of several dams in the Llobregat and Ter rivers, a desalination plant and a treated water recirculation system. The objective is to evaluate the impact of these two latter alternative sources to guarantee water supply for prolonged drought periods. The MPC formulation minimizes the multi-objective cost function, considering specific operational objectives, such as flow controls, tank levels and ecological flows, weighted according to their relative importance. Two cases are analyzed: with and without alternative sources. The simulation shows an improvement by using alternative sources, significantly delaying water depletion and allowing for greater network resilience in with limited supply.

Keywords: Urban water management, regional water network, model predictive control.

1. INTRODUCTION

The increasing water demand due to climate change and urban growth has led to an acceleration in its depletion, which is why many regions around the world face water scarcity (Ghernaout, 2018). Catalonia is among the regions threatened by this effect, hence an efficient water cycle management is sought, specifically drinking water supply (Merlos, 2022). As droughts become increasingly common and prolonged, access to water through sustainable and environmentally friendly practices must be ensured.

Pressure on conventional water sources may be reduced by resorting to alternative sources, such as reinjected treated water and desalinated water, contributing to a more sustainable use of water supply (Munné et al., 2023). This approach enables a flexible and effective response to fluctuations in water demand, while also contributing to a more sustainable use of existing water resources. The reuse of treated water falls within the principles of the Circular Economy (CE), but unfortunately this model has not yet been fully integrated into dynamic water resource optimization schemes (Delgado et al., 2024; Heiberg et al., 2022; Hoffmann et al., 2020). Furthermore, current water management policies continue to be based on rules and are still limited by changing environmental conditions.

The main objective of this paper is to optimize urban water supply by deciding the contributions from different sources, including water from reservoirs, treated water and desalinated water, which can mitigate the problem of water shortages, especially during periods of drought. This is achieved through the application of advanced control approaches—such as model predictive control (MPC)—to decide the optimal contribution of each water source depending on the availability of reservoirs (influenced by climatic conditions) and the costs associated with each option. MPC, which has been widely applied to water systems of diverse nature, e.g., reservoir systems (Cestari et al., 2025), canals (Segovia et al., 2024), water distribution networks (Wang et al., 2017), and urban drainage systems (Svensen et al., 2023), enables the system to respond to variations in water availability, demand, and climatic and seasonal inconsistencies. This results in more resilient and cost-effective system operation (Castelletti et al., 2023), while also reducing the dependence on a single supply source, ultimately contributing to the protection of reservoirs, especially in adverse conditions, e.g., droughts.

MPC is applied to Catalonia's Regional Network to assess the impact of recirculation and desalination on water availability and system resilience, using storage, demand coverage, and ecological flows as performance indicators.

The rest of the paper is organized as follows. Section 2 contains a description of the water supply system for Catalonia region. Section 3 formulates the problem to be solved. Section 4 describes the simulation setup and discusses the results obtained. Section 5 draws conclusions and discusses future research opportunities.

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2. SYSTEM DESCRIPTION

Catalonia, one of Europe's most populated regions, has faced major droughts in recent decades. The years 1990, 2005 and 2008 were particularly critical, with reservoirs reaching only 20.1% of their capacity in 2008. Crucially, this problem resurfaced between 2021 and 2024, when the area faced the longest droughts. A drought emergency was declared in mid-February 2024, affecting more than 6 million people (Euronews, 2024).

2.1 Hydraulic infrastructure in Catalonia

Catalonia is mainly supplied by the Ter and Llobregat rivers (Fig. 1a). Water from the Ter river is stored at the Pasteral reservoir and transported to the drinking water treatment plant (DWTP) in Cardedeu (located in the province of Barcelona, 37 km from the city and 7 km from Granollers). The DWTP in Cardedeu has a treatment capacity of 8 m^3/s and comprises four reservoirs with a total storage capacity of 557,664 m^3. Water from the Llobregat river is collected in Abrera, which has had a drinking water treatment plant since 1980, with a treatment capacity of 3.2 m^3/s and is equipped with two tanks with a total storage capacity of 213 m^3. Finally, the DWTP in Sant Joan Despí contributes with a daily treatment capacity of 550 million liters, being one of the largest in Europe (Agència Catalana de l'Aigua, 2025).

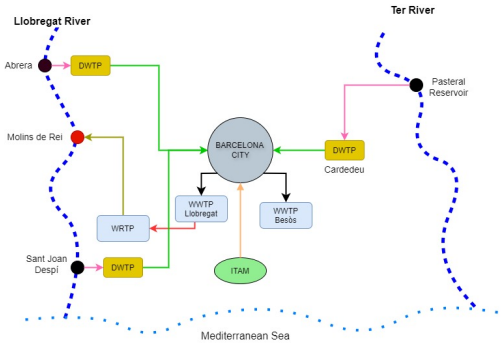
In addition, the region has a seawater catchment system at ITAM Llobregat (Fig. 1b) to supplement the region's drinking water demands, supplying 60 Hm^3/year of desalinated seawater, with a treatment capacity equal to 2 m^3/s. The seawater catchment is located 2.2 km from the coast, which is pumped 3 km parallel to the sea under the Llobregat River to reach the desalination plant (Agència Catalana de l'Aigua (ATL), 2025).

Catalonia has two main wastewater treatment plants (WWTP). The first, located in El Prat de Llobregat, has a treatment capacity of 420,000 m^3/day. This treated water is fed to a water reuse system (WRTP), which was developed to reduce the pressure on the fresh water supply, and thus improve water management. Regenerated water is reinjected at an upstream location in the Llobregat River, specifically at Molins de Rei (Ciudad FCC, 2025; ACCIONA, 2024). The other major wastewater treatment plant is the Besòs plant, which is one of the largest wastewater treatment plants in Europe, with a capacity of 525,000 m^3/day. This treatment plant treats a large part of the water from the municipalities of Badalona, Barcelona, Montgat, Sant Adrià de Besòs, Santa Coloma de Gramanet, Tiana and part of Montcada i Reixac. This treatment plant has been operating since 1977 with physical and chemical treatments, incorporating biological treatments in 2005 (Barcelona Sostenible, 2025).

2.2 Towards better water resources management practices

Catalonia's water system, still governed by rigid rules, struggles to adapt to droughts and changing demand. Applying MPC could improve resource management and system resilience, enabling real-time decisions that integrate multiple objectives and optimize network operation.

(a) Geographical location of the Ter and Llobregat river basins.



(b) Water catchment and distribution scheme.

Fig. 1. Water intake, treatment, and reuse system in Catalonia.

3. PROBLEM STATEMENT

The problem considered in this paper consists in fulfilling water demands in Catalonia's internal basins, including the metropolitan area of Barcelona, through the application of MPC. Its solution yields optimized contributions from surface water stored in reservoirs, recirculated treated water and desalinated water.

A model of the network is presented first. Then, physical and operational objectives are stated. With these elements, the MPC is finally formulated.

3.1 Network model

A suitable mathematical representation of the process is derived to be used as prediction model for the MPC. According to Figure 1, the system consists of four reservoirs along the Llobregat and Ter rivers, which store water that can be used to fulfill the requested demands.

Let $\boldsymbol{x}_k \in \mathbb{R}^{n_x}$ represent the states (water volumes stored in the reservoirs); $\boldsymbol{u}_k \in \mathbb{R}^{n_u}$, the control inputs (water released from each reservoir, recirculated treated water and desalinated water); and $\boldsymbol{d}_k \in \mathbb{R}^{n_d}$, the combination of water demands and external inflows at time step k.

The mass balances at the reservoirs are given by

$$\boldsymbol{x}_{k+1} = \boldsymbol{A}\boldsymbol{x}_k + \boldsymbol{B}\boldsymbol{u}_k + \boldsymbol{B}_d\boldsymbol{d}_k, \tag{1}$$

where $\boldsymbol{A} \in \mathbb{R}^{n_x \times n_x}$, $\boldsymbol{B} \in \mathbb{R}^{n_x \times n_u}$ and $\boldsymbol{B}_d \in \mathbb{R}^{n_x \times n_d}$ are system matrices. Note that all states $\boldsymbol{x}_k$ are measured, hence no observer is required.

Moreover, the mass balances at the nodes (network locations where water flows combine or separate) are given by

$$\boldsymbol{E}_u\, \boldsymbol{u}_k + \boldsymbol{E}_d\, \boldsymbol{d}_k + \boldsymbol{E}_q\, \boldsymbol{q}_k = \boldsymbol{0}, \tag{2}$$

where $\boldsymbol{q}_k$ represents internal flows between nodes or ecological discharges, and $\boldsymbol{E}_u$, $\boldsymbol{E}_d$ and $\boldsymbol{E}_q$ are matrices that define the inflows and outflows at each node.

3.2 Objectives and cost function

The multi-objective function to be minimized penalizes the control effort, the balance between basins, slack in the demands, slack in the nodes, required ecological flows, safety levels in the tanks and the use of energy for the activation or deactivation of the desalination plant and/or recirculation.

The cost function to be optimized at time k is given by

$$\begin{aligned} J_k = & J_k^{\text{control}} + J_k^{\text{smooth}} + J_k^{\text{balance}} + J_k^{\text{backlash}} + \\ & J_k^{\text{spillways}} + J_k^{\text{minflow}} + J_k^{\text{maxflow}} + J_k^{\text{tankmin}} + \\ & J_k^{\text{tankmax}} + J_k^{\text{reinjection}} + J_k^{\text{desalination}}. \end{aligned} \tag{3}$$

Each term in (3) is explained and defined next.

- Control effort minimization (J^{control}). This term aims to reduce the magnitude of control actions. From an energy point of view, minimizing the control effort promotes efficient operation by reducing mechanical stress on the actuators. The term for minimizing control effort is

$$J_k^{\text{control}} = \left(\frac{\boldsymbol{u}_k}{\boldsymbol{u}_{\max}}\right)^{\top} \boldsymbol{R} \left(\frac{\boldsymbol{u}_k}{\boldsymbol{u}_{\max}}\right), \tag{4}$$

  where $\boldsymbol{u}_{\max} \in \mathbb{R}^m$ is the vector of maximum allowable control actions for tank flows and the values for each control action (used for normalization) and $\boldsymbol{R} \in \mathbb{R}^{m \times m}$ is a positive definite diagonal matrix to penalize each control input.
- Smooth operation (J^{smooth}). This term is key to avoid oscillatory control behavior. Sudden changes in manipulated variables can cause mechanical wear, energy inefficiency and operational insecurity. Penalizing the squared difference between consecutive control actions ensures greater smoothness. The term for smoothing control actions is given by

$$J_k^{\text{smooth}} = \left(\frac{\Delta \boldsymbol{u}_k}{\Delta \boldsymbol{u}_{\max}}\right)^{\top} \boldsymbol{W}_s \left(\frac{\Delta \boldsymbol{u}_k}{\Delta \boldsymbol{u}_{\max}}\right) \tag{5}$$

  where $\Delta \boldsymbol{u}_k = \boldsymbol{u}_k - \boldsymbol{u}_{k-1}$ is the control input variation at time step k, $\Delta \boldsymbol{u}_{\max}$ is the maximum allowable control input variation, and $\boldsymbol{W}_s$ is the corresponding weight.
- Source balance (J^{balance}). This term aims to maintain the balance between the two basins from the Ter and Llobregat rivers, as an excessive dependence on either river would cause an imbalance in the sustainability of the resource. Therefore, this term penalizes the percentage difference between the reservoirs of each river associated with each source, promoting equitable use. The term is expressed as

$$J_k^{\text{balance}} = \boldsymbol{\delta}_k^{\top} \boldsymbol{W}_b\, \boldsymbol{\delta}_k, \tag{6}$$

  where $\boldsymbol{\delta}_k$ is the percentage difference between the basins. Basin 1, which is associated with the Llobregat river, is normalized according to the maximum storage volume of its two reservoirs. The same is done for basin 2, which is associated with the Ter river. Moreover, $\boldsymbol{W}_b$ is the weight that adjusts the relative importance of this objective.
- Slack in claims (J^{backlash}). In order to allow demand flexibility, either because demand may be variable or there are environmental constraints that prevent exact extraction from a source, small deviations between the requested demand and the actual supplied demand are allowed. This criterion, which is penalized so that this situation arises only used when necessary, is formulated as

$$J_k^{\text{backlash}} = \left(\frac{\boldsymbol{\alpha}_k}{\max\left(\boldsymbol{q}_\alpha^{\text{out}}\right)}\right)^{\top} \boldsymbol{W}_\alpha \left(\frac{\boldsymbol{\alpha}_k}{\max\left(\boldsymbol{q}_\alpha^{\text{out}}\right)}\right), \tag{7}$$

  where $\boldsymbol{\alpha}_k$ is a slack vector, which represents the difference between the required flow rate and the flow rate actually supplied at each node where there is demand at time step k, and $\max(\boldsymbol{q}_\alpha^{\text{out}})$ represents the expected maximum demand for each of these nodes, a term used to normalize the slack values.

  The goal of this term is to assign priority to fulfill the demands. However, the inclusion of this slack variable allows flexibility in situations where strict demand satisfaction is not possible.
- Spillways ($J^{\text{spillways}}$). There are certain parts of the network for which over-saturation must be avoided. When the flow entering the corresponding nodes exceeds an established maximum limit $\boldsymbol{\varepsilon}^{\max}$, the excess water is diverted to alternative routes, acting as hydraulic safety valves. To discourage the frequent use of these spillways, a penalty term is included in the objective function as

$$J_k^{\text{spillways}} = \left(\frac{\boldsymbol{\varepsilon}_k}{\boldsymbol{\varepsilon}^{\max}}\right)^{\top} \boldsymbol{\lambda} \left(\frac{\boldsymbol{\varepsilon}_k}{\boldsymbol{\varepsilon}^{\max}}\right), \tag{8}$$

  where $\boldsymbol{\varepsilon}_k$ represents the vector of excess flows diverted at instant k and lambda is the corresponding weight. This term enforces the system to remain within the normal hydraulic capacity limits, making use of spillways only when strictly necessary.
- Minimum ecological flows (J^{minflow}). This term penalizes unmet minimum ecological flows required at the outflow points to the Llobregat and Ter rivers using slack variables. Each slack variable is normalized with respect to the nominal value of the corresponding flow, and is penalized via an independent weight. In this way, compliance with the established flow rate is guaranteed, allowing small deviations only when strictly necessary. The term J^{minflow} reads as

$$J_k^{\text{minflow}} = \gamma_1 \left(\frac{\varepsilon_k^L}{\boldsymbol{q}_k^L}\right)^2 + \gamma_2 \left(\frac{\varepsilon_k^T}{\boldsymbol{q}_k^T}\right)^2, \tag{9}$$

  where ε_k^L and ε_k^T are the slack variables for the Llobregat and Ter rivers, respectively, and $\boldsymbol{q}_k^L$ and $\boldsymbol{q}_k^T$ are the maximum allowable values of these flows.
- Maximum ecological flow (J^{maxflow}). This term penalizes excess in the ecological outflows for Llobregat ($\boldsymbol{q}^L$) and Ter ($\boldsymbol{q}^T$) by means of slack variables $\boldsymbol{\zeta}_k^L$ and $\boldsymbol{\zeta}_k^T$, which allow a margin of excess to the ecological nominal flow. In this way, the solution is guaranteed

despite demanding operating conditions. However, this situation is undesirable, as they may represent an unsustainable use of water, and is therefore penalized with γ_3 and γ_4 as

$$J_k^{\text{maxflow}} = \boldsymbol{\gamma}_3 \left(\frac{\boldsymbol{\zeta}_k^L}{\boldsymbol{q}_k^L} \right)^2 + \boldsymbol{\gamma}_4 \left(\frac{\boldsymbol{\zeta}_k^T}{\boldsymbol{q}_k^T} \right)^2. \tag{10}$$

- Lower tank volumes (J^{tankmin}). This term penalizes non-compliance with the minimum admissible storage tank volumes. The slack variable $\boldsymbol{\beta}_k$ allows the tank level to fall below that threshold; its use is justified to avoid infeasibility in the optimization problem in emergency situations. However, from an operational point of view, this is not desirable, so a penalty is applied by means of $\boldsymbol{\gamma}_5$ to preserve water availability in the reservoirs as

$$J_k^{\text{tankmin}} = \left(\frac{\boldsymbol{\beta}_k}{\boldsymbol{x}_\beta^{\min}} \right)^\top \boldsymbol{\gamma}_5 \left(\frac{\boldsymbol{\beta}_k}{\boldsymbol{x}_\beta^{\min}} \right), \tag{11}$$

where $\boldsymbol{x}_\beta^{\min}$ are the minimum volumes of the tanks and are defined as $\boldsymbol{P}_1 \boldsymbol{x}^{\max}$, where $\boldsymbol{x}^{\max}$ denotes the physical capacity of the tanks and $\boldsymbol{P}_1$ is a diagonal matrix with entries taking values between 0 and 1 that is used to set the minimum volume.
- Maximum operating limit in tanks (J^{tankmax}). This term penalizes non-compliance with the maximum operating volumes of the tanks. Slack variable $\boldsymbol{\gamma}$ allows for tank volumes to be slightly above the upper threshold in extraordinary situations, such as in times of heavy rainfall, allowing to avoid infeasibility in the optimization problem. However, exceeding the limit is not desirable for safety reasons, so a weight $\boldsymbol{\gamma}_6$ is assigned to penalize their use as

$$J_k^{\text{tankmax}} = \left(\frac{\boldsymbol{\gamma}_k}{\boldsymbol{x}_{\max} - \boldsymbol{x}_{\max}^\gamma} \right)^\top \boldsymbol{\gamma}_6 \left(\frac{\boldsymbol{\gamma}_k}{\boldsymbol{x}_{\max} - \boldsymbol{x}_{\max}^\gamma} \right), \tag{12}$$

where $\boldsymbol{x}_{\max}$ is the vector of maximum tank capacities and $\boldsymbol{x}_{\max}^\gamma$ are the maximum adjusted operating volumes, defined as $\boldsymbol{P}_2 \boldsymbol{x}_{\max}$, where $\boldsymbol{P}_2$ is a diagonal matrix with entries taking values between 0 and 1 used to set the safety limit.
- Reinjection ($J^{\text{reinjection}}$). This term penalizes recirculation, which is activated only in the event that one of the basins falls below a threshold $\boldsymbol{P}$. Although the use of this additional resource allows for greater water availability, it entails an additional cost associated with upstream pumping. For this reason, this term is penalized as

$$J_k^{\text{reinjection}} = \boldsymbol{W}_r \left(\frac{\boldsymbol{q}_k^L}{\boldsymbol{q}_{\max}^L} \right)^2, \tag{13}$$

where $\boldsymbol{q}_k^L$ is the recirculation flow rate at time k, $\boldsymbol{q}_{\max}^L$ is the maximum amount allowed for recirculation and $\boldsymbol{W}_r$ is the weight that penalizes the use of recirculation.
- Desalination ($J^{\text{desalination}}$). This term penalizes the use of water from the desalination plant as an alternative source in critical conditions, its activation will occur when the level of any of the basins is below a minimum threshold $\boldsymbol{P}$, the integration of desalinated water implies a higher cost, but in turn, it is an alternative source that prolongs the availability of water for more days. The penalty is

$$J_k^{\text{desalination}} = \boldsymbol{R}_d \left(\frac{\boldsymbol{u}_k^{(d)}}{\boldsymbol{u}_{\max}} \right)^2, \tag{14}$$

where $\boldsymbol{u}_k^{(d)}$ is the flow provided by the desalination plant to fulfill the demand, $\boldsymbol{u}_{\max}$ is the maximum desalination plant flow and $\boldsymbol{R}_d$ is the corresponding weight.

3.3 MPC formulation

MPC is an advanced multivariable control technique that uses a model of the process to predict the future behavior of a system and determine the optimal control actions with respect to an objective function while observing the constraints (Maciejowski, 2002). An optimization problem is solved at each time step k to minimize a cost function over a prediction horizon of length H_p.

The prediction model presented in Section 3.1 and the operational objectives defined in Section 3.2 are used to formulate the MPC as

$$\min_{\left\{\boldsymbol{u}_{k+l|k}\right\}_{l=0}^{H_p-1}} J_k \tag{15}$$

subject to, $\forall l \in \{0, 1, \ldots, H_p - 1\}$:

$$\begin{aligned}
\boldsymbol{x}_{k+1+l|k} &= \boldsymbol{A}\boldsymbol{x}_{k+l|k} + \boldsymbol{B}\boldsymbol{u}_{k+l|k} + \boldsymbol{B_d}\boldsymbol{d}_{k+l|k}, \\
\boldsymbol{0} &= \boldsymbol{E}_u\, \boldsymbol{u}_{k+l|k} + \boldsymbol{E}_d\, \boldsymbol{d}_{k+l|k} + \boldsymbol{E}_q\, \boldsymbol{q}_{k+l|k}, \\
\boldsymbol{x}_{k+1+l|k} &\in \mathcal{X}, \\
\boldsymbol{u}_{k+l|k} &\in \mathcal{U}, \\
\boldsymbol{q}_{l|k} &\geq 0, \\
\boldsymbol{\varepsilon}_{l|k}, \boldsymbol{\alpha}_{l|k}, \boldsymbol{\varepsilon}_{L,l|k}, \boldsymbol{\varepsilon}_{T,l|k}, \boldsymbol{\zeta}_{L,l|k}, \boldsymbol{\zeta}_{T,l|k}, \boldsymbol{\beta}_{l|k}, \boldsymbol{\gamma}_{l|k} &\geq 0,
\end{aligned}$$

where $\boldsymbol{x}_k$, $\boldsymbol{u}_k$, and $\boldsymbol{d}_k$ represent the system states, control actions (reservoir outflows, treated recirculated water and desalinated water) and user demands, respectively. Moreover, J_k is defined as shown in (3), and $\mathcal{X}$ and $\mathcal{U}$ represent the sets of physical and operational constraints on the states and the inputs, respectively.

The constraint $\boldsymbol{q}_{l|k} \geq 0$ guarantees the non-negativity of the internal flow variables. In addition, the slack variables $\boldsymbol{\varepsilon}_{l|k}$, $\boldsymbol{\alpha}_{l|k}$, $\boldsymbol{\varepsilon}_{L,l|k}$, $\boldsymbol{\varepsilon}_{T,l|k}$, $\boldsymbol{\zeta}_{L,l|k}$, $\boldsymbol{\zeta}_{T,l|k}$, $\boldsymbol{\beta}_{l|k}$, and $\boldsymbol{\gamma}_{l|k}$ are used to ensure feasibility and penalize constraint violations, and are constrained to take only non-negative values.

Problem (15) is solved at each discrete time step k, ensuring that the system evolves within the defined constraints, while minimizing the cost function. As a result, the sequence of optimal inputs $\left\{\boldsymbol{u}_{k+l|k}\right\}_{l=0}^{H_p-1}$ is obtained. However, only the first component is applied to the system, and its effect is measured. The problem is solved again at the next time instant to exploit updated system information.

4. RESULTS AND DISCUSSION

This section presents the results obtained by implementing the proposed MPC-based control strategy on Catalonia's regional water distribution network. This study focuses on the operational benefits of integrating alternative sources such as treated water recirculation, desalinated water and

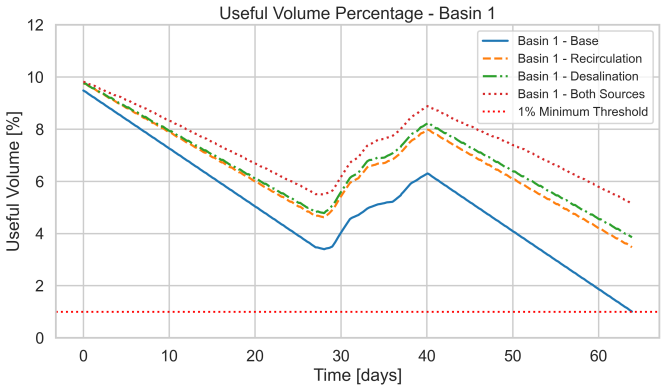


Fig. 2. Percentage of useful volume in the Llobregat basin in an evaluated period of 64 days under different operating conditions, using as a base case the single use of the reservoirs, comparing its evolution with the aggregate use of alternative sources.

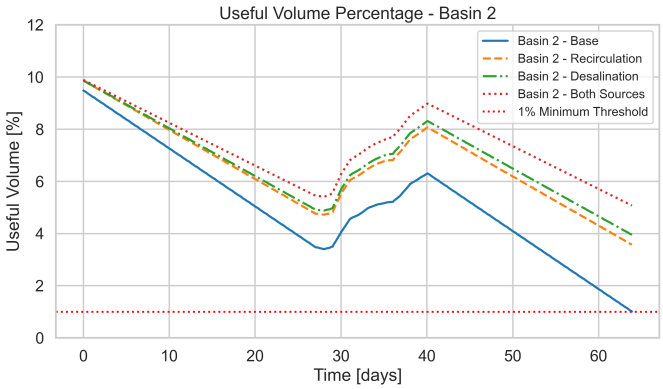


Fig. 3. Percentage of useful volume in the Ter basin with the same conditions as in Fig. 2. It shows the analogous behavior between the Ter and Llobregat basins, reflecting the balance between basins as an objective of the optimization strategy.

the impact on system resilience, availability for city demand and the balance between Llobregat and Ter basins.

4.1 Simulation setup and evaluation window

To evaluate performance under critical shortage conditions, four setups were considered: reservoirs only (Base), reservoirs plus recirculation (R), reservoirs plus desalination (D), and all three sources (RD). Each case started at 20% useful volume per basin and ended when any basin reached 1%. Table 1 shows that the Base case lasted 137 days, while R, D and RD extended availability to 151, 153 and 162 days, respectively, that is, up to 25 extra days under extreme drought.

Table 1. Water availability per scenario starting at 20% in each basin and decreasing to 1%.

Scenario	Days to 1% volume	Initial volume (%)	Duration increase (days)
Base	137	20%	–
Base + Recirculation (R)	151	20%	+14
Base + Desalination (D)	153	20%	+16
Base + RD	162	20%	+25

To ensure a fair comparison of cost and performance between the simulated scenarios, a standardized evaluation window of 64 days was established. This window starts when all scenarios are at 10% of useful volume and ends when the base case reaches a threshold of 1%. This 64-day window allows recording the critical phase where the strategies applied favor a more evident comparison.

4.2 Flow Performance in the Llobregat and Ter Basins

Figures 2 and 3 show the evolution of the usable volume in the Llobregat and Ter basins over 64 days. The base case shows a critical drop of 9%, while the incorporation of additional sources such as recirculation or desalination maintains the volume at around 3.7%. The best result is obtained with both sources (RD), which retain more than 5% at the end of the time horizon. The similar trajectories of both basins highlight inter-basin balance as one of the terms to be fulfilled in the objective function.

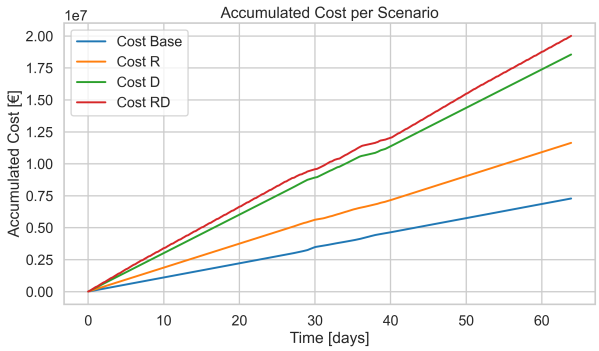


Fig. 4. Cumulative operating costs corresponding to each supply alternative for a period of 64 days. Cases where additional sources such as recirculation or desalinated water are used show higher cost but higher water availability, improving system resilience.

4.3 Accumulated Operational Costs

Figure 4 shows the cumulative costs over 64 days. As expected, the base case has the lowest cost but the lowest availability. Adding recirculation or desalination increases costs, especially the latter, while combining both sources (RD) offers the highest cost but also the best resilience. The strategy can be adapted depending on whether economic efficiency or resource security is prioritized.

4.4 Distribution of the percentage of useful volume

Figure 5 shows the proportion of days in which the average useful volume was at different levels, highlighting system resilience under different operating conditions.

Analyzing the base case, it is observed that approximately 44% of the days the useful volume was between 1 and 5%, while the remaining days were between 5 and 10%. This shows a critical condition during the 64-day analysis window. By adding additional sources such as recirculation (R) or desalination (D), a significant decrease can be observed in proportion to very low volumes (less than 5%), allowing more efficient water management. It should be

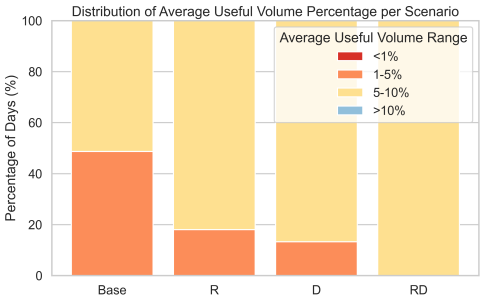


Fig. 5. Distribution of mean percent usable volume over the 64-day horizon for: reservoir use only (Base), reservoirs plus treated wastewater (R), reservoirs plus desalinated water (D), and reservoirs plus both sources (RD). Bars represent the fraction of days that the system was maintained within specific ranges.

noted that in the case where recirculation and desalination are used together, the accumulated volume is maintained between 5 and 10%, avoiding critical situations for this 64-day window analyzed. This reflects greater sustainability by maintaining a more stable useful volume over the analysis horizon. This figure complements Figures 2 and 3, comparing the effectiveness in the implementation of each strategy, demonstrating a more robust and balanced performance for a longer period of time.

4.5 Comparative analysis of operating scenarios

The incorporation of additional sources such as R and D have been shown to improve water availability for a longer period of time. The basins in the base case reach 1% in 137 days, while using the additional sources extends this period to 162 days. Fair comparison of scenarios motivated the consideration of a 64-day analysis window, starting when the basins are at 10% and ending when the first scenario drops to 1%. During this period, the cases with recirculation and desalination maintained a useful volume over 4%, demonstrating better operating performance. Although the scenarios that use additional sources present a higher cost, they also offer greater water availability for a longer period of time in cases of extreme drought.

5. CONCLUSION

This work demonstrated the efficiency of MPC in Catalonia's regional water network, showing that the integration of treated water and desalination increased availability by up to 25 days compared to the use of reservoirs alone. Future research could explore the use of more accurate climate forecasts and other non-conventional sources. On the other hand, data-driven predictive control strategies could be used to leverage the availability of data.

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