Coordinating Regional Supply and Urban Delivery Networks

C.C. Sun, G. Cembrano, V. Puig and C. Ocampo-Martínez

Abstract Complex water networks, which have been structurally organized into *Regional Supply* and *Urban Delivery* networks from a functional perspective, are facing more challenges in their real-time control because of the reduced water resources, intensive energy requirements and increased attention towards the environmental impact of water use. Optimal management of complex water networks involves more difficulties because of different dynamics and control requirements in the specific parts. This chapter proposes a multi-layer model predictive control (MPC) with temporal multi-level coordination for regional supply and urban delivery networks. Inside each network, an MPC based controller is used. Between the regional supply and urban delivery networks, a temporal multi-level coordination mechanism is used to generate control strategies which consider objectives and time scales in different networks. According to the real practices, regional supply network works in a daily scale in order to achieve the global management policies for the different reservoirs, while the urban delivery network works in a hourly scale and is in charge of manipulating the actuators (pumps and valves) set-point to satisfy the local objectives. Real-life pilot demonstration in Catalunya (Spain) will be used to prove the general applicability of the proposed solution and its effectiveness for improving efficiency of water use, energy consumption and reducing computing load for complex water systems.

C.C. Sun, G. Cembrano, V. Puig and C. Ocampo-Martínez
Advanced Control Systems Group at the Institut de Robòtica i Informàtica Industrial (CSIC-UPC). Llorens i Artigas, 4-6, 08028 Barcelona, (Spain).
email(csun,cembrano,vpuig,cocampo)@iri.upc.edu

G. Cembrano
CETaqua, Water Technology Centre at Esplugues 75, 08940, Cornellà de Llobregat, Barcelona.

1 Introduction

A complex water network normally operates to deliver water from natural sources to municipal, industrial and irrigation needs. Management of these systems from planning to operation is challenging since the problem deals with many complex modelling issues related to inflows, river delays, storage, urban, irrigation and industrial water demands as described in [1]. An effective management of complex water network requires a supervisory control system that takes optimal decisions regarding the operation of the whole network. Such decisions are implemented automatically or offered as a decision support to operators and managers. The decisions of the control systems are translated into set-points to individual, localized, lower distribution water systems that optimize the pressure profile to minimize losses by leakage and provide sufficient pressure. The whole control system responds to changes in network topology (ruptures), typical daily/weekly profiles, as well as major changes in demand.

Considering different dynamics and control objectives, complex water network can be divided into two functional parts: *Regional supply network* and *Urban delivery network*:

- Regional supply network, composed by rivers, natural aquifers and large reservoirs, which mainly conveys water from natural sources to the urban cities.
- Urban delivery network, which links water treatment and desalinization plants and transports water using pipes and tanks distributed in a city.

Both of the partitions in a complex water network must be modelled separately because of their different time scales, composition elements and specified objectives. This chapter presents separately the modelling and designing of MPC controllers for regional supply and urban delivery networks. In order to generate control strategies for the complex water network which includes both parts, a temporal multi-level coordination for regional supply and urban delivery networks are presented. The Catalunya Regional Water Network is applied to validate the proposed controlling and modelling schemes.

2 Problem Formulation

2.1 State Space Model for Regional Supply Network

In order to model the river in regional supply network, a single reach canal can be approximated by using the modelling approach proposed by [3] that leads to the following relation between the upstream (q_{ups}) and downstream (q_{dns}) flows:

$$q_{dns}(k+1) = a_1 q_{dns}(k) + b_0 q_{ups}(k-d) \tag{1}$$

where $d = \tau_d/T_s$, τ_d is the downstream transport delay, T_s is the sampling time, $b_0 = 1 - a_1$ and $a_1 = e^{-\frac{T_s}{T}}$.

Because of the existence of river delays, the state space model of regional supply network has two kinds of states and control variables. First kind of state variable represents reservoirs and the managed variable corresponds to actuator flows:

$$x(k+1) = Ax(k) + Bu(k) + B_p\,[d(k) - \varepsilon(k)], \quad k \in \mathbb{Z} \tag{2}$$

where

$$\begin{aligned}
x(k) &\in \mathbb{R}^{n_x} \text{ state variables represent volumes}\\
u(k) &\in \mathbb{R}^{n_u} \text{ control corresponds to actuator flows}\\
d(k) &\in \mathbb{R}^{n_d} \text{ disturbances correspond to demands}\\
\varepsilon(k) &\in \mathbb{R}^{n_d} \text{ slack variables for unsatisfied demands}
\end{aligned}$$

In normal operation, all demands in regional supply network are expected to be satisfied by the MPC control strategy with exceptional situations (e.g. drought) when some demands (especially irrigation demands) may be satisfied only partially. In (2), $\varepsilon(k)$ is introduced to control the amount of demand which is not satisfied.

The second kind of states and control variables represents river flows in a river reach model with delays. For simplicity and brevity of the explanation, the river reach model (1) is considered as a transport delay [2]:

$$q_{out_i} = q_{in_i}(k - \tau_d) \tag{3}$$

where τ_d represents the delay value. For time delays associated with flows within the network, the following auxiliary state equations are introduced:

$$x_{j,1}\,(k+1) = q_j(k) \tag{4}$$

$$x_{j,i+1}\,(k+1) = x_{j,i}\,(k), i = 1, \cdots, \tau_d \tag{5}$$

where

$$\begin{aligned}
x_{j,i}\,(k) &\in \mathbb{R}^{n'_x} \text{ state variables represent flows}\\
q_j(k) &\in \mathbb{R}^{n'_u} \text{ flows, part of control variables}\\
\tau_d &\in \mathbb{Z} \quad \text{delay}
\end{aligned}$$

More details on how this approach can be extended to the case that river reach model (1) is not just considered as a delay can be found in [2].

After combining (4) and (5) with (2), we have a new augmented state space representation

$$\widetilde{x}(k+1) = \widetilde{A}\widetilde{x}(k) + \widetilde{B}\widetilde{u}(k) + \widetilde{B}_p\,[d(k) - \varepsilon(k)], \quad k \in \mathbb{Z} \tag{6}$$

where

$$\widetilde{x}(k) = \begin{bmatrix} x(k) \\ x_{j,i}(k) \end{bmatrix}, \quad \widetilde{u}(k) = \begin{bmatrix} u(k) \\ q_j(k) \end{bmatrix}$$

and

$$\widetilde{x}(k) \in \mathbb{R}^{\widetilde{n}_x}$$
$$\widetilde{u}(k) \in \mathbb{R}^{\widetilde{n}_u}$$

All variables are subject to the following inequality constraints:

$$\widetilde{x}_{min} \leq \widetilde{x}(k) \leq \widetilde{x}_{max} \tag{7}$$

$$\widetilde{u}_{min} \leq \widetilde{u}(k) \leq \widetilde{u}_{max} \tag{8}$$

$$\varepsilon_{min} \leq \varepsilon(k) \leq \varepsilon_{max} \tag{9}$$

where $\widetilde{x}_{min}$ and $\widetilde{x}_{max}$ are physical limitations of the reservoirs, while $\widetilde{u}_{min}$ and $\widetilde{u}_{max}$ are physical limitations of the river flows. The range of ε_{min} lies between zero and the related demand.

Besides, the balance at every node should be satisfied, where E, E_d, $E_{\widetilde{x}}$ are matrices which parameters can be obtained from topology of the water network:

$$E\,\widetilde{u} + E_d\,d - E_d\,\varepsilon + E_{\widetilde{x}}\widetilde{x} = 0$$

During the consumption process, water storage of reservoir should be kept above a given level (named as water safety level) which is used as emergency supply for drought period or emergency situations. Any situation below the emergency level should be penalized using soft constraints:

$$\widetilde{x} \geq \widetilde{x}_r - \varepsilon_{\widetilde{x}} \tag{10}$$

$$\varepsilon_{\widetilde{x}} \geq 0 \tag{11}$$

where $\widetilde{x}_r$ is the water safety level and $\varepsilon_{\widetilde{x}}$ is the slack variable associated to $\widetilde{x}_r$.

2.2 Operational Goals for Regional Supply Networks

Considering the specific water dynamics, a regional supply network maybe operated with a 30-day horizon and daily time interval. The main operational goals to be achieved are:

- *Operational safety* (J_{safety}): To maintain appropriate water storage levels in dams or reservoirs for emergency-handling.
- *Demand management* (J_{demand}): To satisfy drinking demand and as much as possible irrigation demands with allowable slackness during drought seasons.
- *Balance management* ($J_{balance}$): To keep rivers or reservoirs exploited in a balanced way in order to escape water deficit problems.
- *Minimizing waste* (J_{waste}): To avoid unnecessary water release from reservoirs.
- *Environment conservation* ($J_{ecological}$): To maintain water levels and ecological flows. Because the river flow is modelled as one part of the state vector, this control objective is included in J_{safety}.

The above-mentioned goals lead to the following function:

$$
\begin{aligned}
J &= J_{safety} + J_{demand} + J_{waste} + J_{balance} \\
&= \varepsilon_{\widetilde{x}}(k)^{\top} W_{\widetilde{x}} \varepsilon_{\widetilde{x}}(k) + \varepsilon(k)^{\top} W_f \varepsilon(k) \\
&+ (\widetilde{u}_{i\ldots j}(k) - \widetilde{u}_s(k))^{\top} W_{\widetilde{w}} (\widetilde{u}_{i\ldots j}(k) - \widetilde{u}_s(k)) \\
&+ \left(\begin{pmatrix} 0 \ldots 0 & \frac{1}{xi'_{max}} & 0 \ldots 0 & \frac{-1}{xj'_{max}} & 0 \ldots 0 \end{pmatrix} \widetilde{x}(k) \right)^{\top} w_{\widetilde{m}} \\
&\times \left(\begin{pmatrix} 0 \ldots 0 & \frac{1}{xi'_{max}} & 0 \ldots 0 & \frac{-1}{xj'_{max}} & 0 \ldots 0 \end{pmatrix} \widetilde{x}(k) \right)
\end{aligned}
\tag{12}
$$

where

$$
\begin{aligned}
\varepsilon_{\widetilde{x}}(k) &= \widetilde{x}(k) - \widetilde{x}_r \\
\widetilde{u} &= \Theta \Delta \widetilde{u} + \Pi \widetilde{u}(k-1) \\
\Delta \widetilde{u}(k) &= \widetilde{u}(k) - \widetilde{u}(k-1)
\end{aligned}
$$

and:

$$
\Theta = \begin{pmatrix} I_{m_i} & 0 & \ldots & 0 \\ I_{m_i} & I_{m_i} & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ I_{m_i} & I_{m_i} & \ldots & I_{m_i} \end{pmatrix}, \quad \Pi = \begin{pmatrix} I_{m_i} \\ I_{m_i} \\ \vdots \\ I_{m_i} \end{pmatrix}.
$$

$W_{\widetilde{x}}$, W_f, $W_{\widetilde{w}}$, $W_{\widetilde{x}}$, $w_{\widetilde{m}}$ are weights related to priorities of objectives (established by the water network authorities) for all the terms in the objective function.

2.3 Water Supply to the Urban Delivery Network

A basic state space model is used to the urban delivery network where the states correspond to the tank volumes and the manipulated variables are the flows in pumps and valves, as described in Chapter 12.

The urban delivery network is operated with 24-hour horizon and hourly time interval. The main operational goals to be achieved are (as described in Chapter 12):

- *Cost reduction* (J_{cost}): To minimize economical cost during water transportation, which is affected by power tariffs varying during a day.
- *Operational safety* (J_{safety}): To maintaining appropriate water storage levels in tanks for emergency-handling.
- *Control actions smoothness* ($J_{smoothness}$): To smooth water flows in order to protect water assets during the operation process.

Above mentioned goals lead to the following function:

$$\begin{aligned} J &= J_{safety} + J_{smoothness} + J_{cost} \\ &= \varepsilon_{\widetilde{x}}(k)^\top W_{\widetilde{x}} \varepsilon_{\widetilde{x}}(k) + \Delta\widetilde{u}(k)^\top W_{\widetilde{u}} \Delta\widetilde{u}(k) \\ &+ W_a(a_1 + a_2(k))\widetilde{u}(k) \end{aligned} \tag{13}$$

where

$$\begin{aligned} \varepsilon_{\widetilde{x}}(k) &= \widetilde{x}(k) - \widetilde{x}_r \\ \widetilde{u} &= \Theta\Delta\widetilde{u} + \Pi\widetilde{u}(k-1) \\ \Delta\widetilde{u}(k) &= \widetilde{u}(k) - \widetilde{u}(k-1) \end{aligned}$$

and $W_{\widetilde{x}}$, $W_{\widetilde{u}}$, W_a are the related weights.

The vectors a_1 and a_2 contain the cost of water treatment and pumping, respectively, where vector a_2 is time varying.

3 Centralized MPC for Regional Supply and Urban Delivery Networks

In order to generate optimal strategies for the complete system including both regional supply and delivery networks, centralized MPC is an option. Considering their different dynamics and time scales, the control horizon in regional supply network, which is 30-day, and the time interval in the urban delivery network, which is hourly, are selected as the common time scales for the centralized MPC. The state space model of the complete water system includes volumes of dams and tanks, actuator flows and also river flows in a river reach model with delays as in (2).

The operational goals to be achieved in the complex water network is presented after combining control objectives using appropriate weights in both river and city network as explained in (12) and (13):

$$
\begin{aligned}
J &= J_{safety} + J_{demand} + J_{waste} + J_{balance} + J_{smoothness} + J_{cost} \\
&= \varepsilon_{\widetilde{x}}(k)^\top W_{\widetilde{x}} \varepsilon_{\widetilde{x}}(k) + \varepsilon(k)^\top W_f \varepsilon(k) \\
&+ (\widetilde{u}_{i\ldots j}(k) - \widetilde{u}_s(k))^\top W_{\widetilde{w}} (\widetilde{u}_{i\ldots j}(k) - \widetilde{u}_s(k)) \\
&+ \left(\begin{pmatrix} 0 \ldots 0 & \frac{1}{xi'_{max}} & 0 \ldots 0 & \frac{-1}{xj'_{max}} & 0 \ldots 0 \end{pmatrix} \widetilde{x}(k) \right)^\top w_{\widetilde{m}} \\
&\times \left(\begin{pmatrix} 0 \ldots 0 & \frac{1}{xi'_{max}} & 0 \ldots 0 & \frac{-1}{xj'_{max}} & 0 \ldots 0 \end{pmatrix} \widetilde{x}(k) \right) \\
&+ \varepsilon_{\widetilde{x}}(k)^\top W_{\widetilde{x}} \varepsilon_{\widetilde{x}}(k) + \Delta \widetilde{u}(k)^\top W_{\widetilde{u}} \Delta \widetilde{u}(k) \\
&+ W_a (a_1 + a_2(k)) \widetilde{u}(k)
\end{aligned}
\tag{14}
$$

The weight tuning method proposed in [7], based on computing the Pareto front of the multi-objective optimization problem presented in (14), is used in this chapter. The initial step of this tuning approach is to find what are known as the anchor points corresponding to the best possible value for each objective obtained by optimizing a single criterion at a time. Then, a normalization procedure is applied, a Management Point (MP) defined by establishing objective priorities is defined, and the optimal weights are determined by computing those that minimize the distance from the solutions of the Pareto front and the MP.

4 Coordination Scheme for Regional Supply and Urban Delivery Networks

A temporal multi-level coordination scheme is another option to optimize regional supply and urban delivery networks by organizing the separated MPC controllers in the river and urban city parts. The general policies for coordinating these MPC controllers are: to transfer the the long-term control decisions of regional supply network to urban delivery network by *Target constraints*. Besides, the short-term urban delivery network will update its daily demand information to regional supply network by *Measured disturbance*, where:

- Measured disturbance (M_s): handles the daily related aggregated demands at the urban delivery network as communication information to the regional supply network.
- Target constraint (T_d): expresses management policies at regional supply network to urban delivery network in the form of control constraints.

4.1 Measured Disturbance

In the topology of the regional supply network, the whole urban delivery network is simplified as one aggregated demand. Measured state in every optimization process for regional supply network should be sum of the related demand every prediction horizon (here is 24 hours)

$$M_s(k) = \sum_{m=1}^{24} d_t(k,m) \tag{15}$$

where $d_t(k,i)$ is demand vector at the urban delivery network corresponding to the k-th day.

Thus, $M_s(k)$ should be considered as the demand for the regional supply network

$$d_s(k) = M_s(k) \tag{16}$$

4.2 Target Constraints

The goal for the temporal coordination algorithm is transferring management policies from the regional supply network to the urban delivery network. In order to achieve this coordination, the following constraint is added to the the urban delivery MPC:

$$\sum_{m=1}^{24} u(k,m) \leq T_d(k) \tag{17}$$

where u is the shared control vector between regional supply and urban delivery network.

This constraint is introduced in order to enforce that the amount of water decided to be transferred from the regional supply to the urban delivery networks by the regional supply MPC is respected by the urban delivery MPC. Without such a constraint, the urban delivery MPC would decide the amount of water ignoring the regional supply MPC policy.

The coordination structure is shown at Figure 1:

Algorithm 1 shows how this constraint, that establishes a daily limitation, is generated and adapted at every time iteration of the urban delivery layer MPC that operates at a hourly scale. Algorithm 1 takes into account the following facts when generating the constraint (17).

- after the application of n hourly control actions $u_s(m)$ corresponding to the k-th day, the total remaining water for this day will be: $T_d(k) - \sum_{m=1}^{n} u(m)$
- when limiting the control actions in the prediction horizon L, there is a part of control actions $u(m)$ that corresponds to hours of the current day k that should be limited by $T_d(k)$, while the control actions correspond to hours of the next day $k+1$ that should be limited by $T_d(k) - \sum_{m=1}^{n} u(m)$.
- the generated constraints are added as additional constraints of the basic optimization problem (BOP) problem associated to the lower layer MPC.

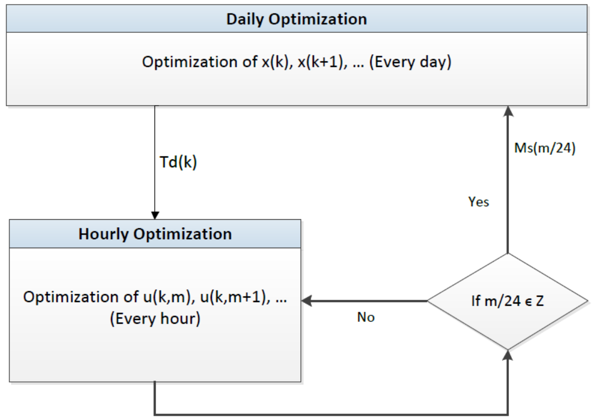


Fig. 1 Optimizations of multi-layer MPC

5 Case Study: the Catalunya Regional Water Network

The Catalunya Regional Water Network in Figure 2 lies within the Catalunya Inland Basins, from which the Metropolitan area of Barcelona is feed and where most of the population is concentrated. It composed by river *Llobregat*, *Ter* and the related components. According to functional partitions of supply and delivery networks, the two rivers *Llobregat*, *Ter* and all the connected elements compose the regional supply network while the urban delivery network lies inside the center part which represents topology of water network inside a city.

Results are produced after applying the proposed centralized MPC and the coordination scheme to the Catalunya Regional Water Network for validating and comparing.

6 Results

6.1 MPC Results for Regional Supply Network

According to environment conservation management for the regional supply network, ecological water levels should be maintained in both rivers.

Figure 3 is one example of river reach. This plot shows that, after MPC control, water flow at this reach could meet the ecological objective during the whole optimization process.

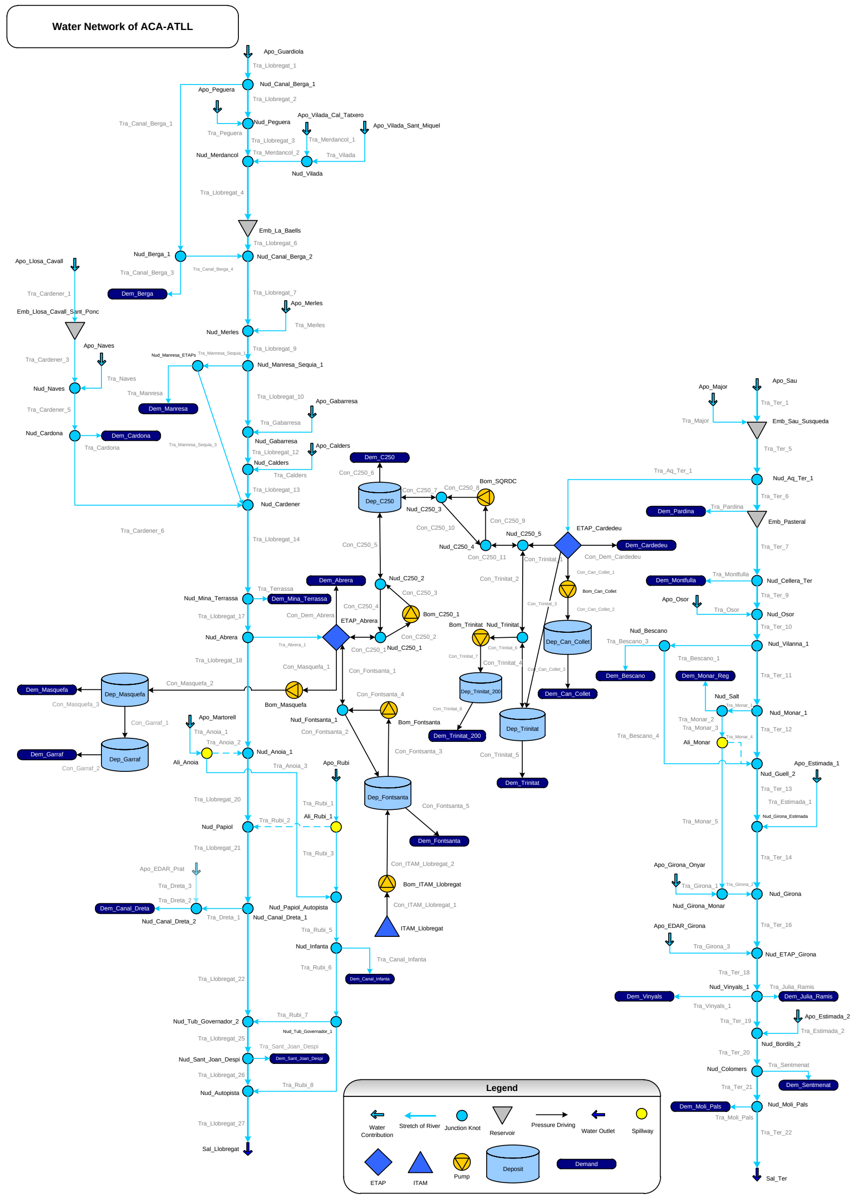


Fig. 2 Aggregate diagram of Catalunya Regional Water Network

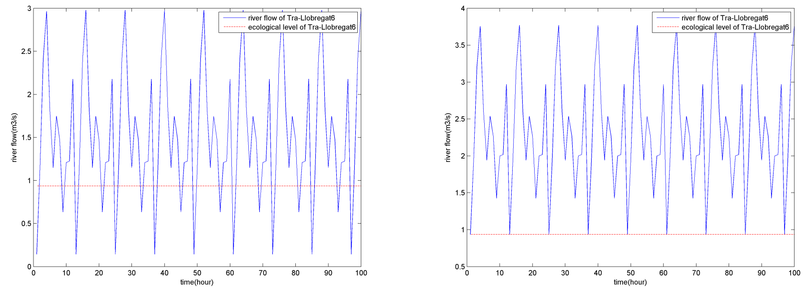
Algorithm 1 Temporal multi-level coordinator

$L := 24$ hours
$I := 24N$ hours
$T_s := 1$ hour
{start creating new constraints for urban delivery *BOP* }
for $i := 1$ to I **do**
  $d := floor(i/24)$
  $t := rem(i, 24)$
  if $t == 0$ **then**
    Update BOP by adding the following constraints:
    $u(1|k) \leq T_d(d) - \sum_{j=i-L+1}^{i-1} u_s(j|k);$
    $\sum_{j=2}^{L} u(j|k) \leq T_d(d+1);$
  end if
  if $t == 1$ **then**
    Update BOP by adding the following constraints:
    $\sum_{j=1}^{L} u(j|k) \leq T_d(d+1);$
  end if
  if $t == 2$ **then**
    Update BOP by adding the following constraints:
    $\sum_{j=1}^{L-1} u(j|k) \leq T_d(d+1);$
    $u(L|k) \leq T_d(d+2);$
  end if
  if $t \geq 3$ **then**
    Update BOP by adding the following constraints:
    $\sum_{j=1}^{L-t+1} u(j|k) \leq T_d(d+1) - \sum_{j=i-L+1}^{i-1} u_s(j|k);$
    $\sum_{j=L-t+2}^{L} u(j|k) \leq T_d(d+2);$
  end if
  Solve *BOP* to obtain $u(j|k), u(j+1|k), \ldots$ with the new constraints added
  $u_s(i|k) := u(1|k);$
end for
{end of $'i'$ loop}

6.2 MPC Results for Urban Delivery Network

In the urban delivery network, water transportation implies electrical costs when pumping water from lower elevation to the higher elevation. Figure 4 shows in the same plot the pump flow and the electricity tariff. From which, it can be noticed that pump sends more water to the reservoir at the lower price period and less or no water at the higher price period.

For the safety control objective in urban delivery network, Figure 5 shows water level of one tank $Dep\_Trinitat$ compared with its safety level before and after



(a) before (b) after

Fig. 3 River flow comparing with ecological level before and after ecological control in river Llobregat

the safety level control, which fits the safety objective of MPC in urban delivery network.

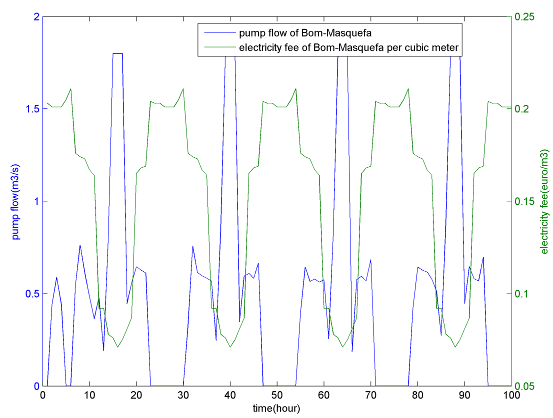
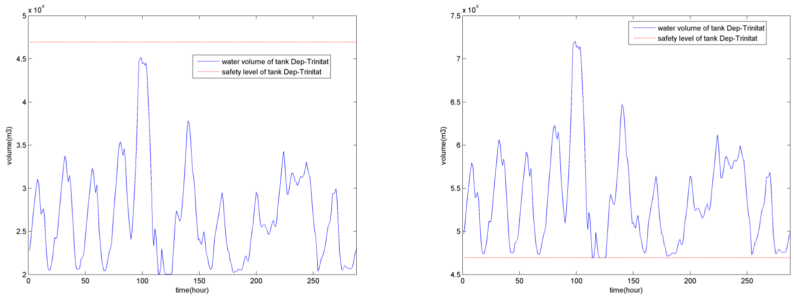


Fig. 4 Pump flow with electricity price

6.3 Results of Centralized MPC

The centralized MPC optimizes the complex water network as a whole, which can realize optimal strategies fit objectives in both supply and delivery parts.

Table 1 provides detailed results and also the improvement of water usages in the two rivers achieved by balance management in the proposed centralized MPC



(a) before (b) after

Fig. 5 Water level of tank Dep-Masquefa before and after safety control starts from the date of *01/08/2011*

scheme. In this table, *Source* means outside sources flow into rivers, *Fixed Demand* means fixed demands which can not choose water source while *Vary Demand* is the demand which can receive water from more than one river. *Bala. Demand*, is water volume that has been consumed from each of the reservoirs and *Bala. Prop.*, is the proportion of *Bala. Demand* for the two reservoirs. *Res. Prop.*, is the proportion of storage capacities of the two reservoirs. The similar values for *Bala. Prop.* and *Res. Prop.* is what the centralized MPC scheme wants to reach. And *Supply Abil.*, is a measure in days of how long the network might supply the demand needs, considering the case of no additional rainwater or other input. The comparisons prove that, after using this centralized MPC scheme, the proportion of water usage from two rivers (58.93%, which is ratio of Llobregat/Ter) is much closer with proportion of their storage capacities (53.48%). In this case, the Catalunya Regional Water Network can supply water 65 days longer than in the case without balance management, which represents an important benefit regarding the sustainable usage of water resource in the long term perspective.

Table 1 Balancing comparison of Complex Water Network

Sc.	**After Centralized MPC Control**						
Es.	Source	Fixed Demand	Vary Demand	Bala. Demand	Bala. Prop.	Res. Prop.	Supply Abil.
L.	3008	2981	724	697	58.93%	53.48%	242 Days
T.	3532	3518	1196	1182			
Sc.	**Before Centralized MPC Control**						
Es.	Source	Fixed Demand	Vary Demand	Bala. Demand	Bala. Prop.	Res. Prop.	Supply Abil.
L.	3008	2981	7.6	-19.4	-1.02%	53.48%	177 Days
T.	3532	3518	1914	1900			

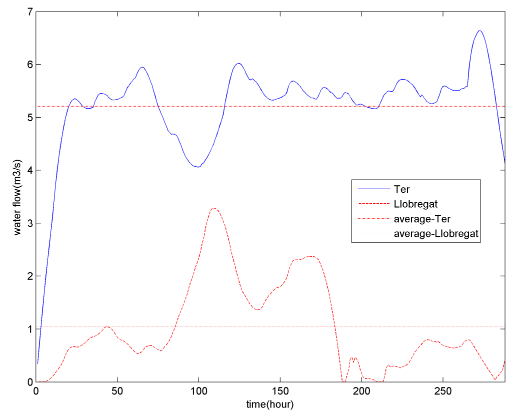


Fig. 6 Water consumed from two rivers by urban delivery network without coordination

6.4 Results of Temporal Multi-level Coordination Scheme

Without coordination, MPC controllers in the regional supply and urban delivery parts of complex water network are working separately in different time scale and control objectives. In order to manage the two controllers, the coordination scheme is applied.

In order to balance the regional supply network, water consumption in both of the rivers will be proportional to their supplying capacity. When coordination is used, this balance management goal will also be included in the urban delivery management problem.

Figure 6 and 7 show the amount of water consumed by the urban delivery network from different rivers with and without coordination, respectively. While both solutions meet the goals of the urban delivery network, the strategy using coordination achieves a good balance in the use of water of both rivers.

6.5 Comparisons between Centralized MPC and Coordination Scheme

In order to operate the regional supply and urban delivery networks, which have different time scales and control objectives, centralized MPC and coordination scheme have been presented. The centralized MPC can optimize complex water network by one controller. However, this implies using the shortest time interval and the longest horizon for both problems.

The coordination scheme, in contrast, allows each system to be optimized separately with its appropriate time interval and horizon, but sharing more information.

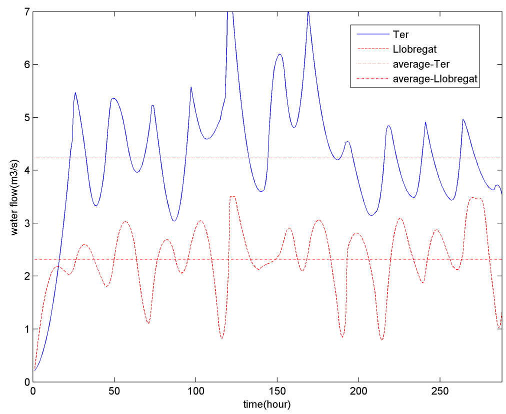


Fig. 7 Water consumed from two rivers by urban delivery network with coordination

The advantage of using coordination with MPC in these networks is apparent when considering that, for a small suboptimality in the urban delivery management problem, a more convenient long-term strategy may be achieved.

7 Conclusions and Future Research

In this chapter, two functional parts have been divided in a complex water network and MPC has been presented to operate each of them. The need of partitioning definition of water network derives from the fact that different functional parts in the water network are modelled and designed separately according to different composition dynamics and operational goals. In order to optimize water network completely, a centralized MPC scheme and a temporal multi-layer coordination scheme have been proposed to the complex water network which includes regional supply and urban delivery networks. The use of the centralized MPC techniques and coordination scheme makes it possible to manage the water network as a complete part in order to let individual operational goals affect to each other and finally, obtain control strategies which can effectively consider objectives in both functional parts as well. Results of different operational goals show the feasibility of MPC for managing water network in the requirement of reality. Comparisons between centralized MPC and coordination scheme provide the usage of them in different situations. Improvements and limitations of MPC application have been discussed after comparing with the current control using human experiences.

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