SEVENTH FRAMEWORK PROGRAMME
THEME – ICT
[Information and Communication Technologies]

Contract Number:	223854
Project Title:	Hierarchical and Distributed Model Predictive Control of Large-Scale Systems
Project Acronym:	HD-MPC

Deliverable Number:	D7.3.3
Deliverable Type:	Report
Contractual Date of Delivery:	September 1, 2011
Actual Date of Delivery:	**September 1, 2011**
Title of Deliverable:	**Report on optimization of distribution of water**
Dissemination level:	Public
Workpackage contributing to the Deliverable:	WP7
WP Leader:	Damien Faille
Partners:	EDF, INOCSA, SUPELEC, POLIMI, USE, TUD
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Executive Summary

This report summarizes the results obtained during the project HD-MPC regarding the optimization of Water Distribution Systems (Irrigation Canals) using hierarchical and distributed model predictive control.
First of all, previous results are shown in Chapter 2.
In Chapter 3, information on how to model and control an Irrigation Canal (IC) can be found.
In Chapters 4 and 5, there is a description of some control tests performed using the benchmark defined during the HD-MPC project regarding IC.
The conclusions can be found in Chapter 6, and references in Chapter 7.

1 SYNOPSIS

This report presents the results obtained during the execution of the project HD-MPC regarding the modeling and control of Irrigation Canals (IC). In relation with control of IC, different kinds of controllers have been tested and analyzed:

- Decentralized controllers: Classical approaches based on PI and feedforward controllers.
- Distributed and hierarchical model predictive controllers.

In Chapter 2, the software tool chosen for modeling IC and also the benchmark selected are described. Regarding the simulation software, we decided to use SIC (Simulation of Irrigation Canals). The main advantage of SIC is that it is focused on control problems and has the advantage of having an interface with MATLAB, which has been used during the project to develop the different controllers.

A benchmark has been defined to perform tests with hierarchical and distributed controllers developed during the execution of HD-MPC project.

This benchmark is a section of the “postrasvase Tajo-Segura” in the South-East of Spain. The “postrasvase Tajo-Segura” is a set of canals which distribute water coming from the Tajo River in the basin of the Segura River. The selected section is a Y-shape canal.

In Chapter 3, information on how to model an IC can be found. Elements located in the canals, like the control structures (gates) and other (like syphons and off-takes) are detailed too.

Regarding control, canal operation concepts and the control objectives are described, taking into account that an Irrigation Canal (IC) is considered a large-scale system where hierarchical and distributed MPC can be used, especially if we take into account the interconnectivity among the geographically distributed parts of the system.

In Chapters 4 and 5, there is a description of five control tests performed using the benchmark defined during the HD-MPC project regarding IC.

In Chapter 4, tests with PI controllers are shown first. Then, one experiment with a downstream feedforward controller is presented. The objective is to compare downstream and upstream control in different scenarios.

In the first four tests we have used local controllers (PI controllers) in four different scenarios. In the last test, we have used PI controllers with feed-forward (decentralized control).

In section 5, a hierarchical and distributed MPC approach and the application to the IC benchmark are described.

Two levels of hierarchy are defined: In the upper level, risk management is used to optimize the Irrigation Canal operation in order to consider the process uncertainties. A centralized MPC is used in the optimization, and it determines the optimal water levels of reaches taking into account the benefits and costs associated to IC. In the lower level, a DMPC based on game theory drives the IC to the given set points.

2 PREVIOUS RESULTS

2.1 Objective

In this chapter some previous results obtained during the execution of HD-MPC project regarding Irrigation canals are summarized.

Previous results are described in D.7.3.1 and D.7.3.1.

2.2 Software tools for modeling Irrigation Canals

In deliverable D7.3.2 information about existing hydraulic models of IC and software tools was included. In that document, it was concluded that software tools SIC (Simulation of Irrigation Canals) [16] and HEC-RAS [13,14,15] were the ones selected for modeling IC, both based on Saint-Venant equations and using the Implicit finite differences method.

These equations are [1]:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\frac{\beta Q^2}{A} \right)}{\partial x} + gA\left(\frac{\partial h}{\partial x} + S_f - S_0 \right) - \beta q v_x + w_f B = 0 \qquad (2)$$

Both software tools, SIC and HEC-RAS, perform a one-dimensional unsteady flow simulation.

2.3 SIC

Due to the problems with the integration between HEC-RAS and platform FEWS, described in deliverable D7.3.2 (in chapter 5.1. Integration of HEC-RAS and MATLAB with the FEWS platform), that finally were not solved, we have focused on SIC.

SIC has the advantage of having an interface with MATLAB, which has been used during the project to develop predictive controllers.

2.4 IC BENCHMARK

Regarding IC, we defined a benchmark to perform some tests with hierarchical and distributed controllers developed during the execution of HD-MPC project.

This benchmark is a section of the "postrasvase Tajo-Segura" in the South-East of Spain. The “postrasvase Tajo-Segura” is a set of canals which distribute water coming from the Tajo River in the basin of the Segura River. The selected section is a Y-shape canal (see Figure 1), a main canal that splits into two canals with a gate placed at the input of each one of them.

- “Canal de la Pedrera”, 6,68 km long.
- “Canal de Cartagena”, with a length of 17,44 km

The total length of the canals is approximately of 24 km and there are 7 main gates (in pink in Figure 1) and 17 off-take gates in the section selected (in yellow). At the end of the whole “Canal de Cartagena” there is a reservoir with limited capacity.

Figure 1. Irrigation Channel benchmark

In Table 1 a list of the off-takes and gates, and detailed data regarding them can be seen there:

Data of Cartagena-La Pedrera irrigation canal.

Code	Type	P/G	Description	km
Canal del Campo de Cartagena				
Start of the Campo de Cartagena canal				0.000
CCMICAR-01	Gate	G	Initial Gate	0.200
MICAR-01	Off-take	G	Off-take 5 – Fuensanta and Estafeta	1.170
MICAR-02	Off-take	G	Off-take 5′ – Palacete	2.540
MICAR-03	Off-take	P	Off-take 6 – Santo Domingo	2.840
CCMICAR-04	Gate		Gate Canal Pedrera	4.485
MICAR-04	Off-take	P	Off-take 7 – Campo Salinas	5.970
MICAR-05	Off-take	G	Off-take 8 – San Miguel	6.550
MICAR-06	Off-take	G	Off-take 9 – Las Cañadas	8.050
MICAR-07	Off-take	G	Off-take 10 – San Miguel	9.390
MICAR-08	Off-take	P	Off-take 11 – Campo Salinas	9.590
CCMICAR-05	Gate		Gate Tunel San Miguel	10.480
MICAR-09	Off-take	G	Off-take 12 – San Miguel	12.630
MICAR-10	Off-take	P	Off-take 13 – Campo Salinas	12.780
CCMICAR-06	Gate		Gate La Rambla La Fayona (start)	14.433
CCMICAR-07	Gate		Gate La Rambla La Fayona (end)	14.579
MICAR-11	Off-take	P	Off take 14 – Villamartin	16.540
CCMICAR-08	Gate		Gate Cañada La Estacada	17.444
Canal de la Pedrera				
CCMIPED-01	Gate		Starting of the canal La Pedrera	0.000
MIPED-01	Off-take	G	Off-take 1P – Santo Domingo	0.770
MIPED-02	Off-take	G	Off-take 2P – Santo Domingo y Mengoloma	3.740
MIPED-03	Off-take	P	Off-take 3P – Santo Domingo	4.260
MIPED-04	Off-take	G	Off-take Riegos Levante 1	5.260
MIPED-05	Off-take	G	Off-take 4P – Santo Domingo	6.440
MIPED-06	Off-take	G	Off-take Riegos Levante 2 and 3	6.680

Table 1

3 IRRIGATION CANALS: MODELING AND CONTROL

3.1 Introduction and objectives

Model Predictive Control (MPC) is an optimal control strategy based on the explicit use of a model to predict the process output at future time instants. However, MPC is a technique with strong computational requirements which hinder its application to large-scale systems such as transportation systems including traffic, water or power networks. In these systems, the computational requirements or the impossibility of obtaining a centralized model are major problems that MPC cannot overcome.

For this reason, most large-scale and networked control systems are based on a decentralized control architecture where the system is divided into several subsystems, each controlled by a different control agent, which may or not share information with the rest.

Each of the agents implements an MPC based on a reduced model of the system and on partial state information which, in general, results in an optimization problem with lower computational burden. In the case where agents communicate to obtain a cooperative solution, we speak of distributed MPC (DMPC).

When we also have two or more levels of decision (two or more levels of control), we are speaking of hierarchical MPC (HDMPC).

We consider Irrigation Canals (IC) a large-scale system where hierarchical and distributed MPC can be used, especially if we take into account the interconnectivity between the geographically distributed parts of the system. Regarding control, this can be understood in two ways:

- Sometimes, due to existing communications, one branch (gate) can only communicate with near gates.
- Other times, there are several control centers, each of one controlling some gates and only having information about these gates.

IC can be considered also hierarchical from the control point of view:

- Set points to be used in the distributed MPC level can be decided in a higher control level optimizing for example costs or risks impacts (see Chapter 5 of this deliverable).

In Chapter 3, a description of IC is performed. After that, it is explained how to model IC, the basic canal operation concepts, and the control objectives.

3.2 Description of the scenario

An irrigation canal (IC) is composed of several branches or reaches separated by gates. It can have also one or more reservoirs in order to store and supply water. Inside the branches, normally we find offtakes, usually used by farmers to take water for irrigation. We can see a schema of an IC in Figure 2.

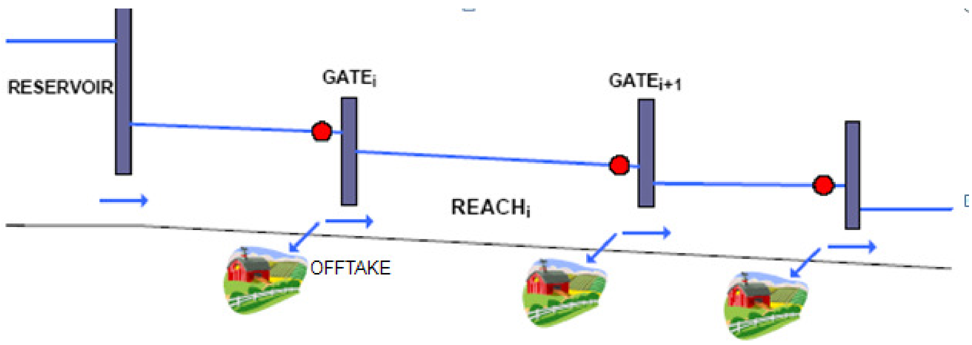


Figure 2

We can find other elements in an IC, like syphons and wastewaters. These elements will be described in chapters 3.3 and 3.4.

The benchmark detailed in chapter 2.4 (see Figure 1) is adapted to this description.

3.3 Control structures: Gates

In an IC we can find the following kinds of gates acting as control structures:

<u>Taintor (radial) gates</u>

Radial gates are designed normally for wide and unobstructed waterways, like irrigation canals, where a light-weight economical gate with minimal hoist effort to open and close is required. A radial gate consists of a curved gate leaf, rubber seals, support arms, seal rubbing embedments and embedded pivot points (see Figure 3). The gate leaf is of a welded construction varying in width and height as required by the size of the opening.

Later pressure applied against the curved gate leaf is transmitted through the support arms into the pivot points, which are embedded in the concrete wall. A smaller hoist is generally required to operate a radial gate as compared to other types of gates. Radial gates are used primarily for upstream level control in open-canal installations. Flow is always one-way, against the face of the gate. Low lifting forces are required for radial gate operation, which is normally by cable hoists.

Figure 3. Taintor gate

Sluice gates

As it is shown in Figure 4, a sluice gate is traditionally a metal plate that slides in grooves in the sides of the canal. Sluice gates are commonly used to control water levels and flow rates in rivers and canals.

The term ‘sluice gate’ refers to any gate that operates by allowing water to flow under it, sliding in the vertical direction. When a sluice gate is fully lowered, water sometimes spills over the top, in which case the gate operates as a weir.

Usually, a mechanism drives the sluice gate up or down. Normally, this may be electrically or hydraulically powered.

Higher lifting forces than in radial gates are needed to operate sluice gates.

Figure 4. Sluice gate

Side weirs

Side weirs provide a means of maintaining a reasonable constant water level by discharging excess water.

Figure 5. Side weirs

Figure 6. Two taintor gates with side weirs

3.4 Canal elements

In IC we can find other elements, like:

<u>Offtake</u>

It is a kind of vertical rising sluice gate that operates by allowing water to flow under it. It is allocated on the sides of the canal, and it is used by farmers to take water for irrigation.

Usually, a mechanism drives the sluice gate up or down. Normally, this is a simple, hand-operated, or in some cases it may be electrically powered.

There are two kinds of offtakes: those which use pumping stations to elevate water and bring it to the farmers, and gravity offtakes (see Figure 7).

The main canal is at the back part of Figure 7, and on one side of it we find the gravity offtake.

Figure 7. Gravity offtake

Waste weir

A waste weir provides a means of removing excess water from the canal and also allows draining a section of the canal for repairs, for winter, or in anticipation of flooding.

Because rising canal waters could overflow the banks, eroding them and causing a break in the canal, water weirs were and important safety feature.

Figure 8. Waste weir

Syphon

Siphon tubes are a basic implement used in irrigation canals to transfer water over a barrier (roads, rivers, other canals) using the syphon principle.

At the simplest they consist of a pipe with no working parts. To work they rely on the water level upstream being at a higher level than the water level downstream.

Figure 9. Syphon

Canal head

In Figure 10 the starting of the 'Canal del Bajo Guadalquivir' in the South of Spain (Seville) is shown. The water is taken from the Guadalquivir River.

Figure 10. Canal head

3.5 Modeling reaches

In order to model a canal, which is a set of reaches, we use the partial differential Saint-Venant equations (see section 2.2), that express a mass and momentum balance.

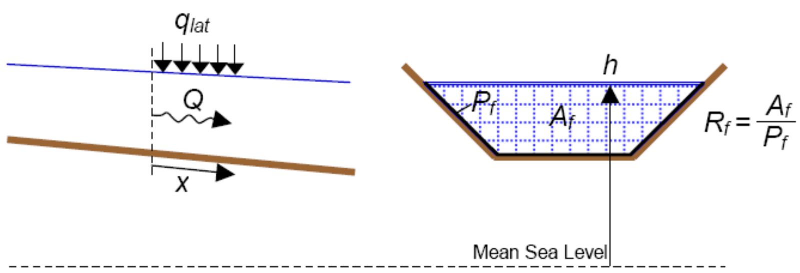
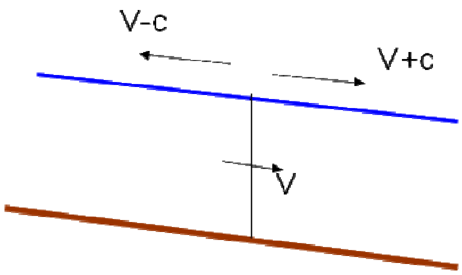


Figure 11

A disturbance, created in a reach, results in two wave movements., one wave travels with velocity V+ c and one travels with velocity V - c.



$$c = \sqrt{\frac{gA_f}{B}}$$

B Top width of wetted crosssection

A_f Wetted cross section surface

Figure 12

Flow Regimes:

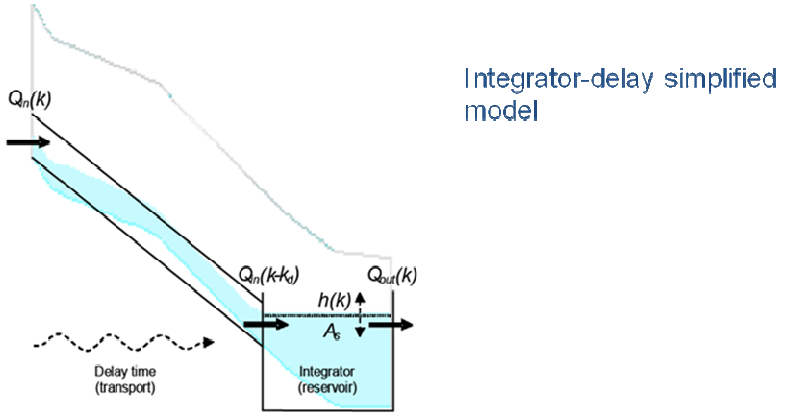
- If c>V, **subcritical flow**, a change in flow results in two waves in opposite directions
- If c=V, **critical flow**, a change in flow results in only one wave travelling downstream
- If c<V, **supercritical flow**, a change in flow results in two waves travelling downstream

Subcritical flow is presented in most real irrigation canals.

We can find in bibliography some approaches to simplify the partial differential Saint-Venant equations:

- Based on mathematical models
  - Integrator-delay model [19]
  - Linearization of Saint-Venant equations [8,9]
- Identification models
  - Weyer et al. [5,6]
  - Rivas Pérez
  - Rodellar, Sepúlveda [3]

One of them is the Integrator-delay (ID) simplified model [2,19]:



$$A_s(h(k+1)-h(k)) = T_d(Q_{in}(k-k_d)+q_{in}(k)-Q_{out}(k)-q_{out}(k))$$

T_d *Sampling time*

$q_{in}(k)$ *Lateral input: rainfall,...*

$q_{out}(k)$ *Offtakes*

Figure 13

3.6 Structure models: overshot gates

An overshot gate is a structure that backs up water; as the water has to flow over the crest of the gate (see Figures 14 and 15).

Figure 14

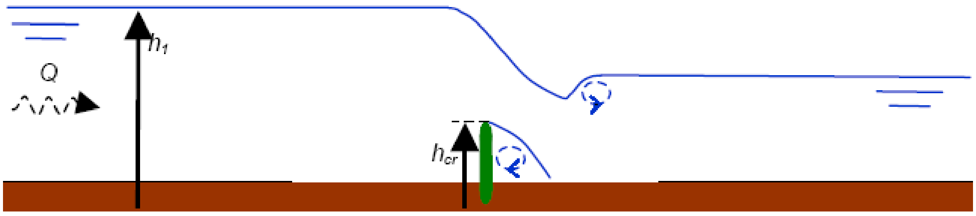


Figure 15

Many theoretical or empirical formulas have been proposed to model overshot gates. One of the most important is the following [11]:

$$Q = C_d L \sqrt{\frac{2}{3} g} (h_1 - h_{cr})^{3/2}$$

L: With of gate

C_d : Discharge coeficient

The flow can be decreased by raising the gate and vice versa. The upstream water level can be easily controlled by an overshot gate.

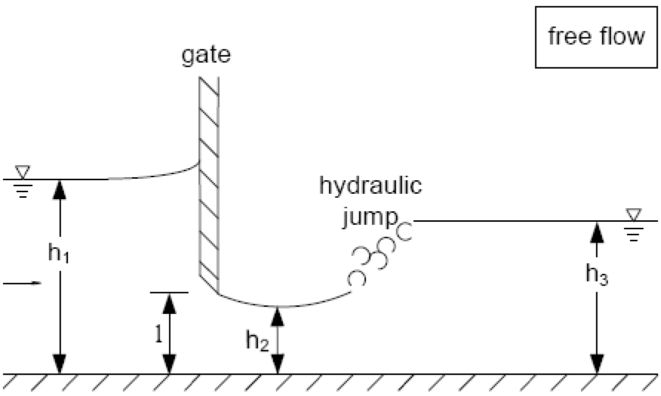
A disadvantage of the overshot gate is that sediment will accumulate at the bottom just in front of the structure as the velocity of water decreases there.

3.7 Structure models: undershot gates

Undershot gates have a gate that is put into the water from the top down. The water flows under the gate. The stream lines of the upper part of the flow, just before the gate, bend down to pass, causing the actual flow opening to be contracted.

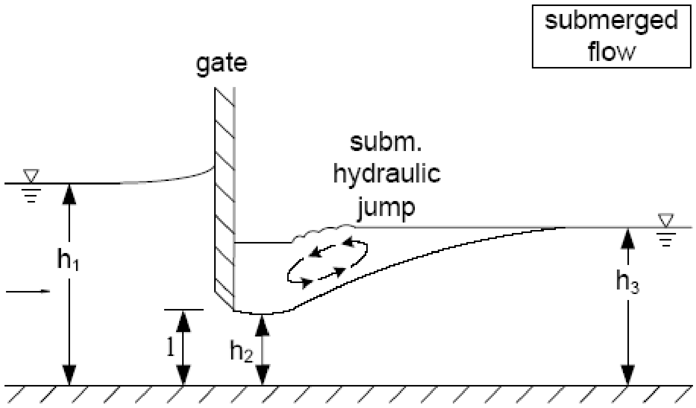
Figure 16

The flow through the undershot gate can be free or submerged. Both types are shown in Figures 17 and 18, together with the formulas that have been proposed to model overshot gates [2,3]:



$$Q = C_d \cdot L \cdot u \sqrt{2g(h_1 - h_3)}$$

Figure 17



$$Q = C_d \cdot L \cdot u\sqrt{2gh_1}$$

u : Gate opening

Figure 18

3.8 Canal operation concepts

When we operate a canal, we can make it through a ***demand oriented operation***, or using a ***supply oriented operation***.

<u>Supply oriented operation</u>

In this kind of operation:

- Upstream water supply source or inflow determines the canal system flow schedule.
- Used when the inflow is fixed by a different organization than the canal manager.

<u>Demand oriented operation</u>

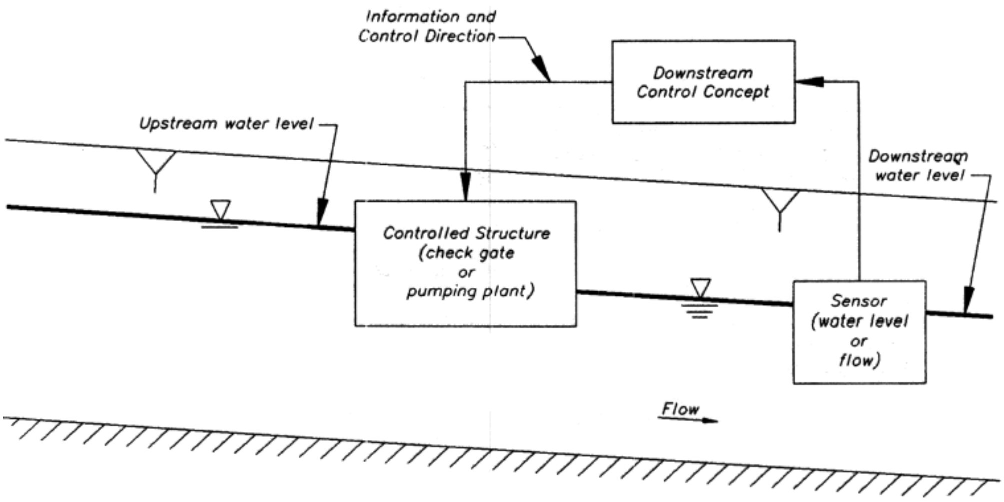
In this kind of operation:

- Downstream water demand (offtakes) determines the canal system flow schedule.
- The inflow is determined by the canal manager accordingly with the demand.

3.9 Control concepts: upstream and downstream control

Depending if we have a demand oriented operation or supply oriented operation, we can use respectively downstream or upstream control [10].

Downstream control



(a) Downstream control concept

Figure 19

As it can be seen from Figure 19, the main characteristics of downstream control are:

- Control structure adjustments (gates) are based upon information from downstream (usually levels).
- Downstream control transfers the downstream offtake demand to the upstream water supply source (flow at the head).
- Compatible with demand oriented operation.
- Impossible with supply oriented operation: flow at the head can't be fixed previously, because it is a consequence of the transference of the downstream demand to the head of the canal.

Upstream control

Looking at Figure 20, we can see that in upstream control:

- Control structure adjustments (gates) are based upon information from upstream (usually levels).
- Upstream control transfers the upstream water supply (or inflow) downstream to points of diversion or to the end of the canal, so it is compatible with a flow fixed at the head (supply oriented operation).
- Inefficient with demand oriented operation, because here we can´t adapt the flow at the head to the demands in the off-takes.

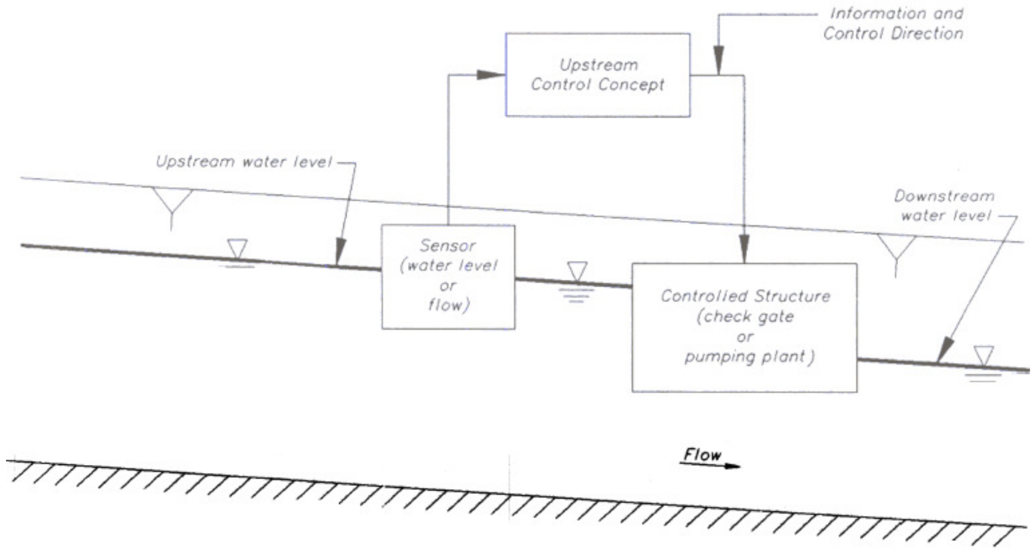


Figure 20

3.10 IC control: general ideas

In IC control, the controlled variables can be the ***water level*** (most common), the water volume or the discharge.

There are two global control strategies regarding the control of a IC:

- Directly ***manipulate gate openings*** in order to ***control levels***, or
- The 'two levels control' strategy, that consists of executing two steps:
  - The first one, consisting of computing the required gate discharges in order to ***control water levels (discharge as manipulated variable)***, and

- ***The second one, in which we manipulate gate openings*** to obtain the ***requested gate discharges***. This can be performed in two ways:
  - With a Local Controller (Cascade control).
  - Inverting the gate discharge equation.

In Figure 21 we can see an example of a ***two levels downstream*** controller: the first level is a predictive controller and the lower level is a PID.

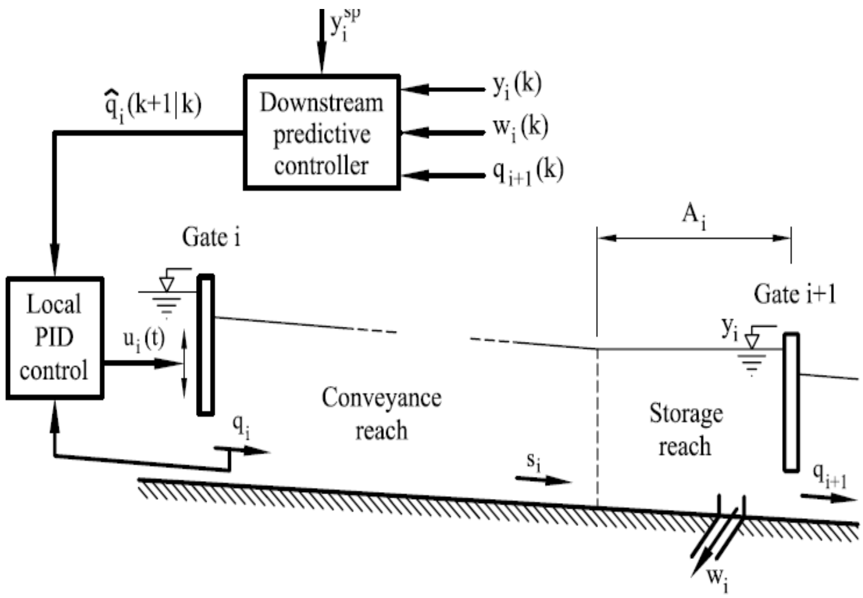


Figure 21

3.11 IC Control objectives

Regarding Irrigation Canals (IC) inside HD-MPC project, based on the analysis performed, we have to take into account the following issues:

The main objective of the control is to guarantee flows requested by users. It is necessary to maintain the level of the canal over the off-take gate.

The controlled variables can be:

- Levels upstream or downstream the gates.
- Flows through gates, mainly at the head of the canal and secondary canals.
- Water volume

The manipulated variables can be:

- Gate openings
- Flow is considered as a manipulated variable to control levels when a two level controller is used.

The disturbances are:

- Offtake flows: measured, aggregated values or predicted
- Rainfall: Measured or predicted

The constraints are:

- Maximum and minimum levels along the canal
- Maximum and minimum flows
- Operating levels on reservoir at the tail of the canal

4 SOME TESTS WITH LOCAL CONTROLLERS

We have performed some tests with the benchmark mentioned in chapter 2.4. We will describe them in the following chapters.

In the first 4 tests we have used local controllers (PI controllers) in 4 different scenarios.

In the last test, we have used PI controllers with feedforward (decentralized control).

The objective is to compare downstream and upstream control in different situations/scenarios.

4.1 TEST 1

Table 2 contains the description of the test, including the initial value of the flow at the head, the initial value of the flow at the off-takes, the controlled variables in downstream and upstream control, and also the errors. The duration of the tests is 4 days.

In this test, there is a variation in the level set point in km 4.275 (Canal de Cartagena I). An increase of +0.2 meters happens at that point in day 2 at 0:00. This is controlled by gate CCMICAR-01 (km 4.27) in the upstream scenario, and controlled by flow at the head in the downstream scenario.

Units in the table are meters (m) for levels, cubic meters per second (m3/s) for flows, and the errors are quadratic.

					DOWMSTREAM		UPSTREAM	
Code	Type	p.k.	Initial value opening	Initial value flow	CONTROLLED VARIABLE	ERRORS	CONTROLLED VARIABLE	ERRORS
CARTAGENA I								
	Head	4.465		12.00	4.275 level	2.5475		
CCMICAR-01	Gate	4.270	1.00		0.0 level	0.9478	4.275 level	0.0390
MICAR-01	Off-take	1.625		-0.50				
MICAR-02	Off-take			-2.54				
CARTAGENA II								
	Off-take	12.979		0.00				
CCMICAR-04	Gate	12.964	0.50		6.972 level	0.1927	12.968 level	4.8095
MICAR	Off-take	10.889		-0.50				
MICAR	Off-take	7.849		-2.00				
CCMICAR-05	Gate	6.969	0.50		3.021 level	0.0672	6.972 level	3.9998
MICAR	Off-take	4.659		-1.00				
CCMICAR-06	Gate	3.016	0.50		2.875 level	14.5809		
CCMICAR-07	Gate	2.870	0.50			0.2616	2.875 level	9.4703
MICAR	Off-take	0.889		-1.00				
END		0.000		-1.94				
PEDRERA								
"MIPED-01"	Off-take	6.675		-0.50				
CCMIPED-01	Gate	6.672	0.50		6.672 flow	1.4370	6.672 flow	1.6313
MIPED-02	Off-take	2.935		-1.00				
END PEDRERA				-3.56				

Table 2

Conclusions:

- Errors in controlled variables are low in both cases, so the control has a good behavior.
- Flow at the tail remains around the demanded value in both cases.

4.2 TEST 2

In this test, we try to compare downstream and upstream control. We have identified two kinds of downstream control: we can control the flow at the end of Cartagena II or not. Results are shown in Table 3.

Description: There is a variation of flow in the off-take located at the km 1.625 (Canal de Cartagena I) in day 2 at 0:00: from -0.5 to -1.5 m3/sec. Duration of the test: 4 days.

A more detailed description of data and results can be found in the following Table 3, where levels are expressed in meters (m), flows in cubic meters per second (m3/s), and the errors are quadratic:

					DOWNTREAM: controlling flow at the end		DOWMSTREAM 2: without controlling flow at the end		UPSTREAM	
Code	Type	p.k.	Initial value opening	Initial value flow	CONTROLLED VARIABLE	ERRORS	CONTROLLED VARIABLE	ERRORS	CONTROLLED VARIABLE	ERRORS
CARTAGENA I										
	Head	4.465		12.00	4.275 level	1.9826	4.275 level	1.9204		
CCMICAR-01	Gate	4.270	1.00		0.0 level	41.9608	0.0 level	41.1088	4.275 level	1.7045
MICAR-01	Off-take	1.625		from -0.5 to -1.5						
MICAR-02	Off-take			-2.54						
CARTAGENA II										
	Off-take	12.979		0.00						
CCMICAR-04	Gate	12.964	0.50		6.972 level	51.1920	6.972 level	48.5560	12.968 level	0.4411
MICAR	Off-take	10.889		-0.50						
MICAR	Off-take	7.849		-2.00						
CCMICAR-05	Gate	6.969	0.50		3.021 level	46.4750	3.021 level	42.1814	6.972 level	0.2972
MICAR	Off-take	4.659		-1.00						
CCMICAR-06	Gate	3.016	0.50		2.875 level	37.4641	2.875 level	32.8073		
CCMICAR-07	Gate	2.870	0.50		2.870 flow	149.6605			2.875 level	0.7099
MICAR	Off-take	0.889		-1.00						
END		0.000		-1.94						
PEDRERA										
"MIPED-01"	Off-take	6.675		-0.50						
CCMIPED-01	Gate	6.672	0.50		6.672 flow	36.4048	6.672 flow	36.1443	6.672 flow	0.2216
MIPED-02	Off-take	2.935		-1.00						
END PEDRERA				-3.56						
GLOBAL INDICATORS										
VOLUMEN HEAD						4332633.0000		4333583.0000		4147200.0000
VOLUMEN TAIL						1914542.3750		1912979.0000		1900693.6250
DIFFERENCE						2418090.6250		2420604.0000		2246506.3750

Table 3

Conclusions:

- Control shows a better performance when there are perturbations at the off-takes, because flow at the tail gets to remain around the initial value (expected demanded flow value), although flow at the tail is not a controlled variable (case DOWNSTREAM2).
- In upstream control, the flow at the tail decreases with perturbations in off-takes, because flow at the head is fixed.
- On the other hand, errors in controlled variables are lower with UPSTREAM control.

4.3 TEST 3

In this test, we try to compare downstream and upstream control. We have identified two kinds of downstream control: we can control the flow at the end of Cartagena II or not. Results are shown in Table 4.

Description: There is a variation in the set point (flow) at the km 6.672 (Canal de la Pedrera) in day 2 at 0:00:. An increase of +1.5 m3/sec happens. Duration of the test: 4 days.

A more detail description of data and results can be found in Table 4.

Units in the table are meters (m) for levels, cubic meters per second (m3/s) for flows, and the errors are quadratic.

					DOWNTREAM: controlling flow at the end		DOWMSTREAM 2: without controlling flow at the end		UPSTREAM	
Code	**Type**	**p.k.**	**Initial value opening**	**Initial value flow**	**CONTROLLED VARIABLE**	**ERRORS**	**CONTROLLED VARIABLE**	**ERRORS**	**CONTROLLED VARIABLE**	**ERRORS**
CARTAGENA I										
	Head	4.465		12.00	4.275 level	2.3834	4.275 level	2.3837		
CCMICAR-01	Gate	4.270	1.00		0.0 level	104.4774	0.0 level	104.5400	4.275 level	0.5800
MICAR-01	Off-take	1.625		-0.5						
MICAR-02	Off-take			-2.54						
CARTAGENA II										
	Off-take	12.979		0.00						
CCMICAR-04	Gate	12.964	0.50		6.972 level	60.9279	6.972 level	60.9844	12.968 level	8.7229
MICAR	Off-take	10.889		-0.50						
MICAR	Off-take	7.849		-2.00						
CCMICAR-05	Gate	6.969	0.50		3.021 level	53.7025	3.021 level	53.7212	6.972 level	4.7497
MICAR	Off-take	4.659		-1.00						
CCMICAR-06	Gate	3.016	0.50		2.875 level	41.6230	2.875 level	41.6362		
CCMICAR-07	Gate	2.870	0.50		2.870 flow	201.1726			2.875 level	12.0908
MICAR	Off-take	0.889		-1.00						
END		0.000		-1.94						
PEDRERA										
"MIPED-01"	Off-take	6.675		-0.50						
CCMIPED-01	Gate	6.672	0.50		6.672 flow	168.2404	6.672 flow	168.2818	6.672 flow	10.6436
MIPED-02	Off-take	2.935		-1.00						
END PEDRERA				-3.56						
GLOBAL INDICATORS										
VOLUMEN HEAD						4410116.0000		4410488.0000		4147200.0000
VOLUMEN TAIL						2153342.0000		2153717.0000		1907562.0000
DIFFERENCE						2256774.0000		2256771.0000		2239638.0000

Table 4

Conclusions:

- Upstream control is not able to supply water to the last off-take of Cartagena II, because flow is fixed at the head and also at La Pedrera, so the rest of flow goes into Cartagena II, but it is not enough to satisfy the off-takes demand.
- Downstream control when flow is controlled at the tail manages to supply flow to the whole Canal de Cartagena II, because flow at the head increases to get this.
- Downstream control with flow not controlled at the tail manages also to supply flow to the whole Canal de Cartagena II, because flow at the head is increased to get this.
- On the other hand, errors in controlled variables are lower with UPSTREAM control.

4.4 TEST 4

In this test, we try to compare downstream and upstream control. We have identified two kinds of downstream control: we can control the flow at the end of Cartagena II or not. Results are shown in Table 4.

In this test we have two variations:

- Perturbation in km 10.889 Cartagena II (off-take): from -0.5 to -1.5 m3/sec
- Perturbation in km 6.675, La Pedrera (off-take): from -0.5 to -1.5 m3/sec.

A more detailed description of data and results can be found in Table 4:

					DOWNTREAM: controlling flow at the end		DOWMSTREAM 2: without controlling flow at the end		UPSTREAM	
Code	**Type**	**p.k.**	**Initial value opening**	**Initial value flow**	**CONTROLLED VARIABLE**	**ERRORS**	**CONTROLLED VARIABLE**	**ERRORS**	**CONTROLLED VARIABLE**	**ERRORS**
CARTAGENA I										
	Head	4.465		12.00	4.275 level	2.5927	4.275 level			
CCMICAR-01	Gate	4.270	1.00		0.0 level	315.5319	0.0 level		4.275 level	0.3972
MICAR-01	Off-take	1.625		-0.5						
MICAR-02	Off-take			-2.54						
CARTAGENA II										
	Off-take	12.979		0.00						
CCMICAR-04	Gate	12.964	0.50		6.972 level	225.4774	6.972 level		12.968 level	5.2657
MICAR	Off-take	10.889		from -0.5 to -1.5						
MICAR	Off-take	7.849		-2.00						
CCMICAR-05	Gate	6.969	0.50		3.021 level	142.6056	3.021 level		6.972 level	4.9114
MICAR	Off-take	4.659		-1.00						
CCMICAR-06	Gate	3.016	0.50		2.875 level	123.1172	2.875 level			
CCMICAR-07	Gate	2.870	0.50		2.870 flow	348.6838			2.875 level	38.1397
MICAR	Off-take	0.889		-1.00						
END		0.000		-1.94						
PEDRERA										
"MIPED-01"	Off-take	6.675		from -0.5 to -1.5						
CCMIPED-01	Gate	6.672	0.50		6.672 flow	79.4276	6.672 flow		6.672 flow	1.9241
MIPED-02	Off-take	2.935		-1.00						
END PEDRERA				-3.56						
GLOBAL INDICATORS										
VOLUMEN HEAD						4443033.0000				4147200.0000
VOLUMEN TAIL						1683291.0000				1572886.0000
DIFFERENCE						2759742.0000				2574314.0000

Table 5

Conclusions:

- Upstream control is not able to supply water to all off-takes of Cartagena II, because flow is fixed at the head and also at La Pedrera, so the rest of flow goes into Cartagena II, but it is not enough to satisfy the off-takes demand.
- Downstream control when flow is controlled at the tail manages to supply flow to the whole Canal de Cartagena II despite of the two perturbations, because flow at the head is incremented to get this.

- On the other hand, errors in controlled variables are lower with UPSTREAM control.

4.5 TEST 5: feedforward controllers

The objective of this test is to show the behavior of downstream control using a PI with feedforward. In Table 6, errors with and without feedforward are compared.

Controlled variables are downstream levels; ***manipulated variables*** are flows, transformed into gate openings by inverting the discharge equation.

Duration of the test: 4 days.

Three variations:

- Set point change in km 6.972 Cartagena II (level): day 1 at 0:00, an increase of +0.2 m
- Set point change in km 3.021 Cartagena II (level): day 2 at 0:00, an increase of +0.2 m
- Perturbation in km 10.889 Cartagena II (off-take): day 3 at 0:00, from -0.5 to -1.0 m3/sec

In Table 6, a description of the test and errors obtained is performed:

					DOWNTREAM: without feedforward		DOWNTREAM: with feedforward	
Code	Type	p.k.	Initial value opening	Initial value flow	CONTROLLED VARIABLE	ERRORS	CONTROLLED VARIABLE	ERRORS
CARTAGENA I								
	Head	4.465		12.00	4.275 level	14.8393	4.275 level	8.6524
CCMICAR-01	Gate	4.270	1.00		0.0 level	20.2707	0.0 level	22.9599
MICAR-01	Off-take	1.625		-0.5				
MICAR-02	Off-take			-2.54				
CARTAGENA II								
	Off-take	12.979		0.00				
CCMICAR-04	Gate	12.964	0.50		6.972 level	27.1900	6.972 level	29.7763
MICAR	Off-take	10.889		from -0.5 to -1.5				
MICAR	Off-take	7.849		-2.00				
CCMICAR-05	Gate	6.969	0.50		3.021 level	32.5044	3.021 level	13.5682
MICAR	Off-take	4.659		-1.00				
CCMICAR-06	Gate	3.016	0.50		2.875 level	13.1010	2.875 level	12.3956
CCMICAR-07	Gate	2.870	0.50		2.870 flow	14.2945	2.870 flow	14.2982
MICAR	Off-take	0.889		-1.00				
END		0.000		-1.94				
PEDRERA								
"MIPED-01"	Off-take	6.675		-0.50				
CCMIPED-01	Gate	6.672	0.50		6.672 flow	1.9991	6.672 flow	1.7940
MIPED-02	Off-take	2.935		-1.00				
END PEDRERA				-3.56				
						124.1990		103.4446

Table 6

Conclusions:

1) It can be seen that the sum of errors is higher without feedforward.
2) The level in km 6.972 is better-controlled with feedforward (see Figures 21 and 22).

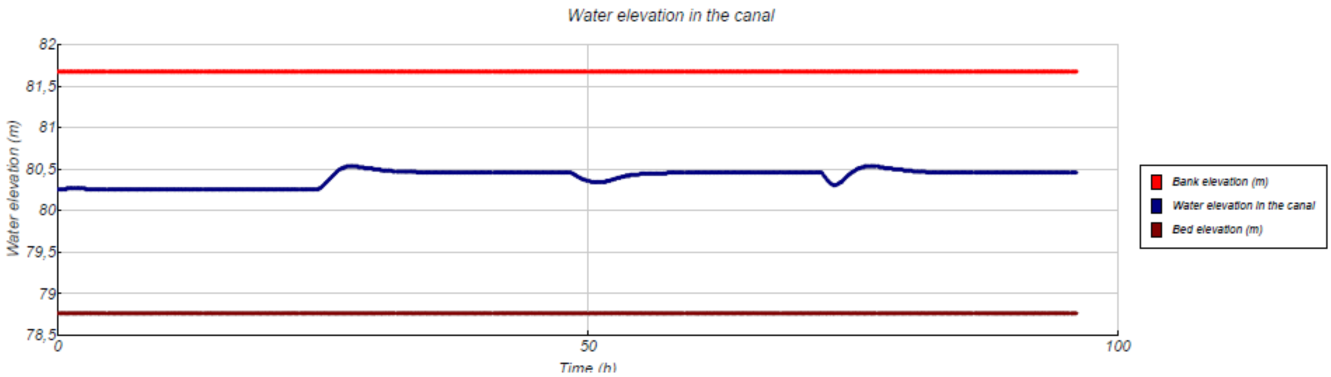


Figure 21. PI without feedforward

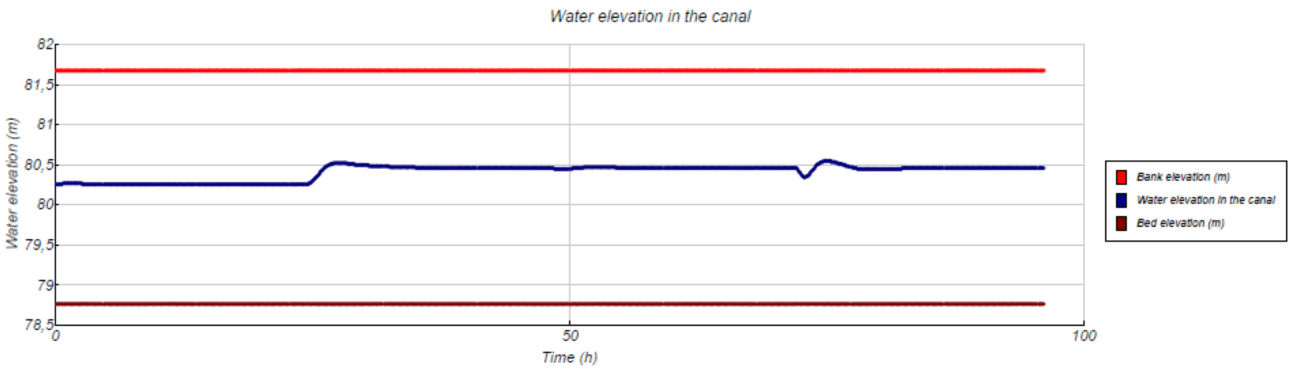


Figure 22. PI with feedforward

3) In the Figures 23-32, the evolution of flow (manipulated variable) and downstream level (controlled variable) at some reaches of Cartagena I and Cartagena II using PI with feedforward are shown.
    - Cartagena I: Reach 1 and Reach 2
    - Cartagena II. Reaches 3, 4 and 5

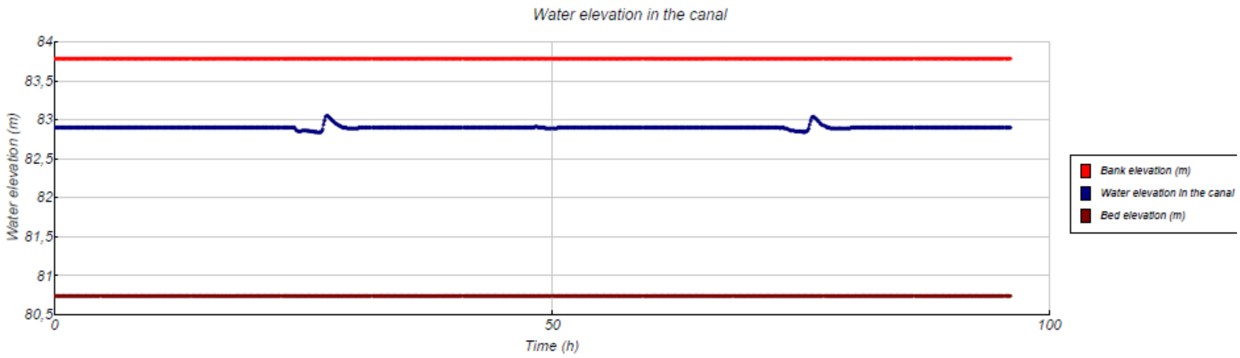


Figure 23. Reach 1: downstream level

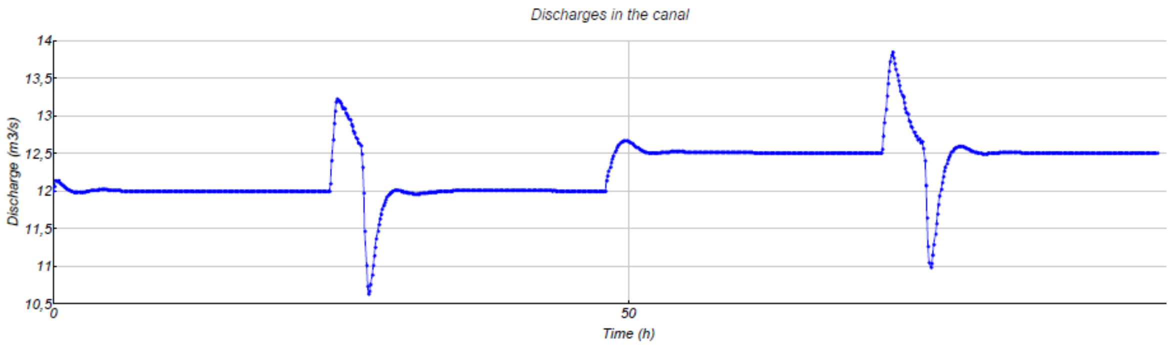


Figure 24. Reach 1: flow (manipulated variable) at the gate

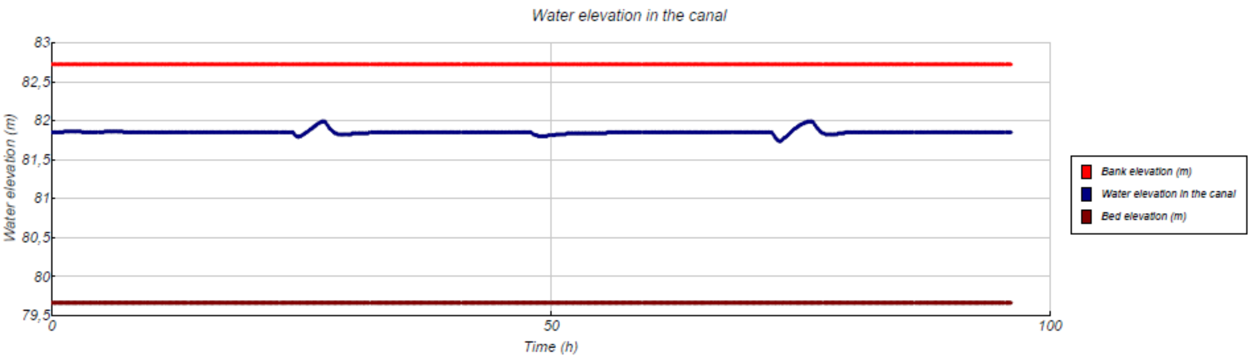


Figure 25. Reach 2: downstream level

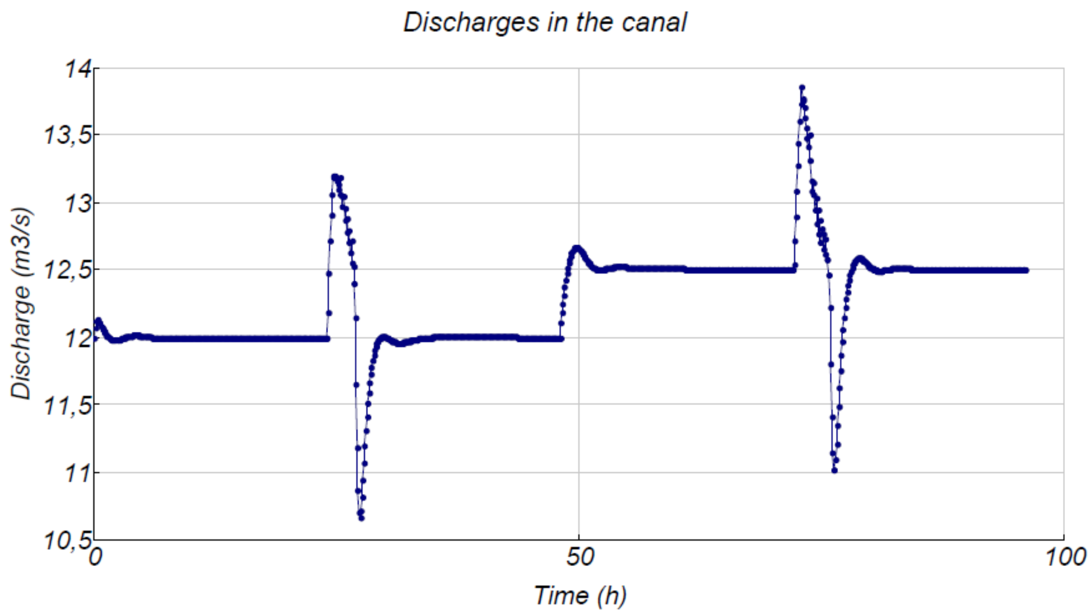


Figure 26. Reach 2: flow (manipulated variable) at the gate

Conclusions of Reach 1 and Reach 2: the 3 variations are located in gates and off-takes that are located downstream of these reaches. Their effects are well controlled in Reach 1 and 2, with a bit of delay respecting the time in which the variations happen.

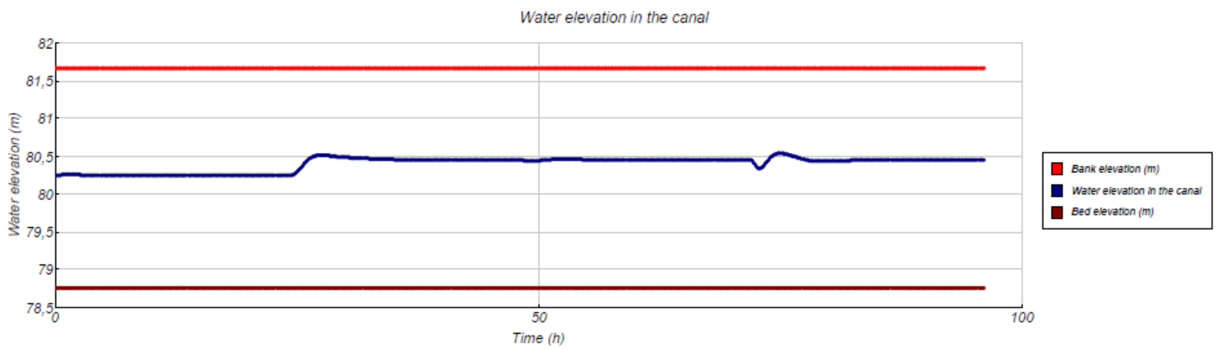


Figure 27. Reach 3: downstream level

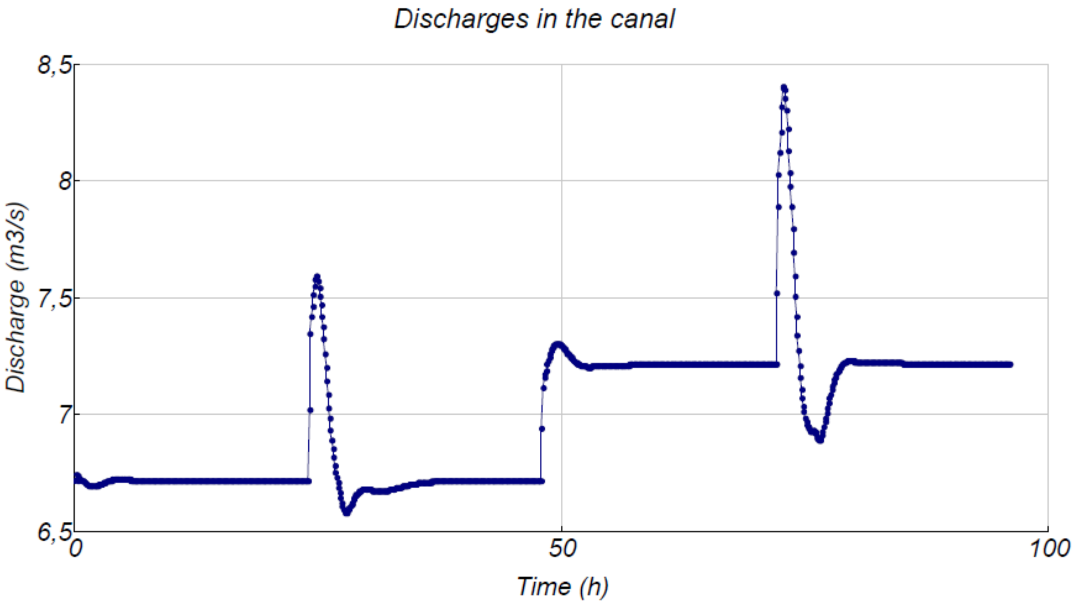


Figure 28. Reach 3: flow (manipulated variable) at the gate

<u>Conclusions of Reach 3</u>: km 6.972 of Cartagena II is located in this reach. The variation of the set point in day 1 at 0:00 (an increase of +0.2 m in level) is well accepted and controlled by the system. The other 2 variations are located downstream of this reach. Their effects are well controlled in Reach 3.

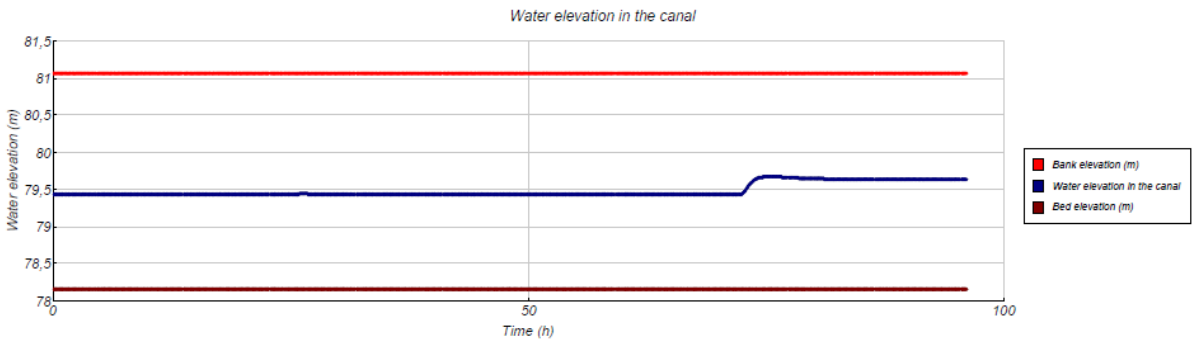


Figure 29. Reach 4: downstream level

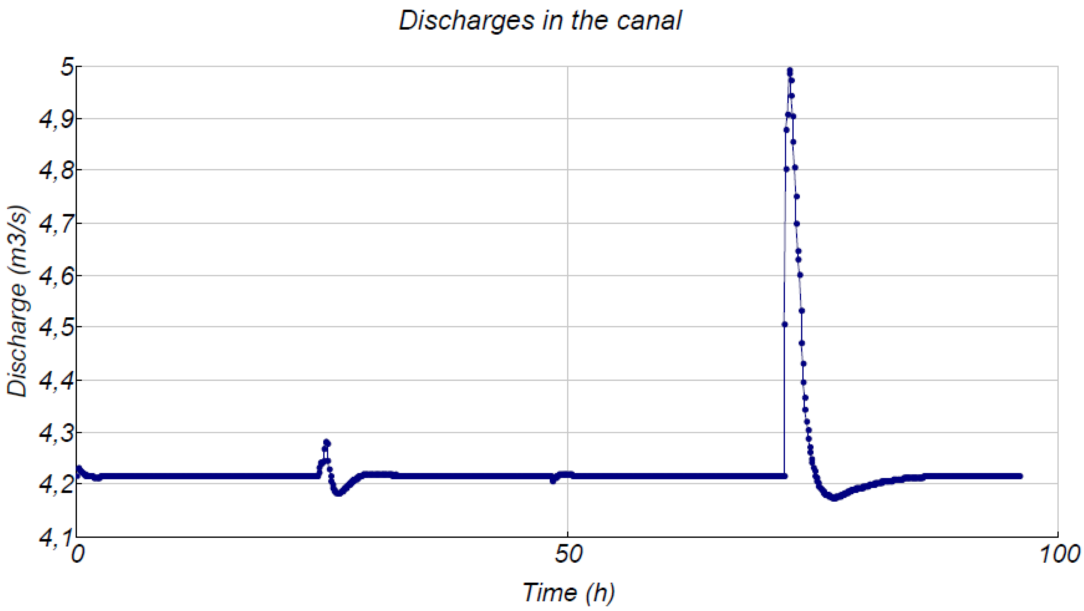


Figure 30. Reach 4: flow (manipulated variable) at the gate

Conclusions of Reach 4: km 3.021 of Cartagena II is located in this reach. The variation of the set point in day 2 at 0:00 (an increase of +0.2 m in level) is well accepted and controlled by the system. The variation of flow in the off-take is located downstream of this reach. Its effect and the effect of the increase of level at km 6.972, are well controlled in Reach 4.

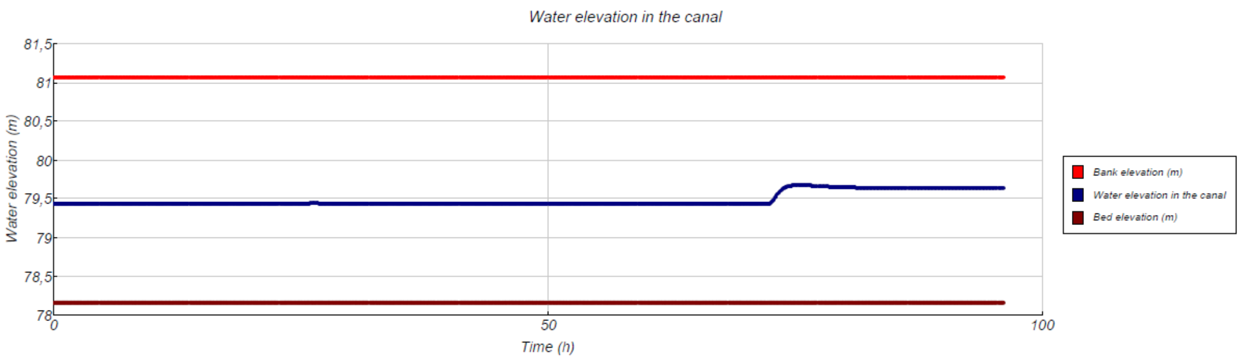


Figure 31. Reach 5: downstream level

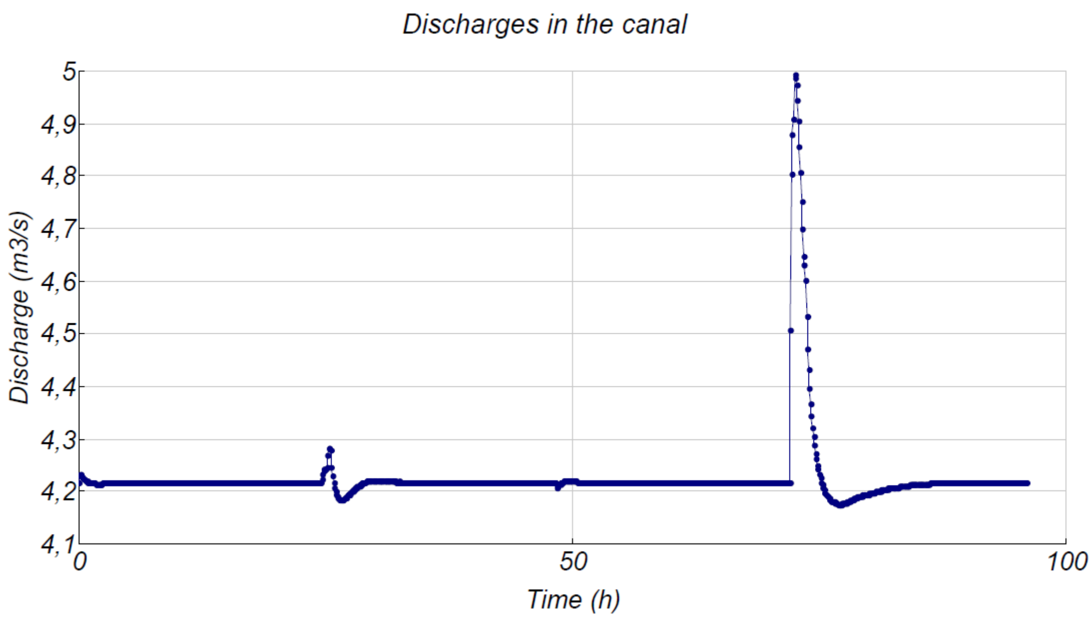


Figure 32. Reach 5: flow (manipulated variable) at the gate

<u>Conclusions of Reach 5</u>: the 3 variations are located in gates and off-takes that are located upstream of this reach. Their effects are well controlled in Reach 5.

5 HIERARCHICAL AND DISTRIBUTED MODEL PREDICTIVE CONTROLLER APPROACH

5.1 Description of the algorithm

In this section we explain the results of testing some **hierarchical and distributed MPC algorithms** with data from a real case, the benchmark explained in section 2.4.

Two levels of hierarchy are defined in this algorithm:

- Inside the upper level, **risk management** is used to optimize the Irrigation Canal operation in order to consider the process uncertainties. The method used in this level, for the use of risk metrics, forecasts the water level of reaches, taking into account the benefits and costs associated to IC. A centralized MPC is used in the optimization.
- At the lower level, a distributed model predictive controller optimizes the operation by manipulating flows / gate openings in order to follow the water level set-points.

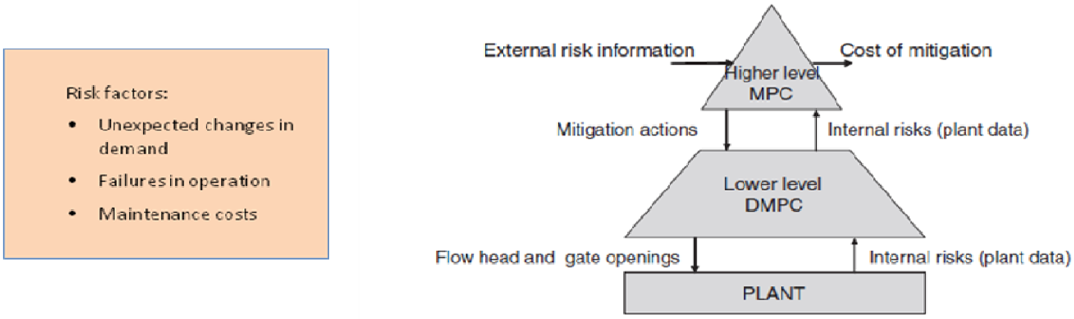


Figure 33

This approach has been published in [18, 21].

5.2 Hierarchical (upper level)

The **higher level** implements a risk management strategy based on the execution of mitigation actions if risk occurrences are expected. Cost is optimized using an MPC controller that can modify parameters at the lower level as a consequence of mitigation actions (e.g. level references).

The steps to undertake risk management are:

1) Identify those risks that can occur in any element of the plant: $R=\{R_1 \ldots R_m\}$.
2) Characterize risks and evaluate consequences if risks occur (impacts).
3) Select mitigation actions to reduce impacts: $A=\{A_1 \ldots A_p\}$.

We can define a Risk-Based Structure as follows (see Figure 34):

- The power system is composed of several units
- Units may have some associated risks.
- A risk can be mitigated by different actions
- One action may mitigate different risks.

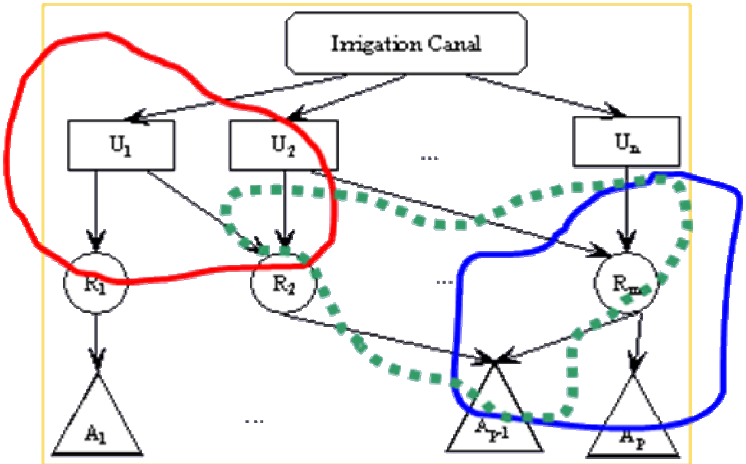


Figure 34

We define Risk (Rr) as an event that can take place when operating IC and may cause consequences, i.e., it has an impact (Impact: IIrc). We consider two kinds of risks:

- External risks: for example, changing weather or financial data.
- Internal risks: for example, failure in the gates or seepage losses.

The mitigation actions (Aa) are defined as a set of actions that can mitigate one or more risks.

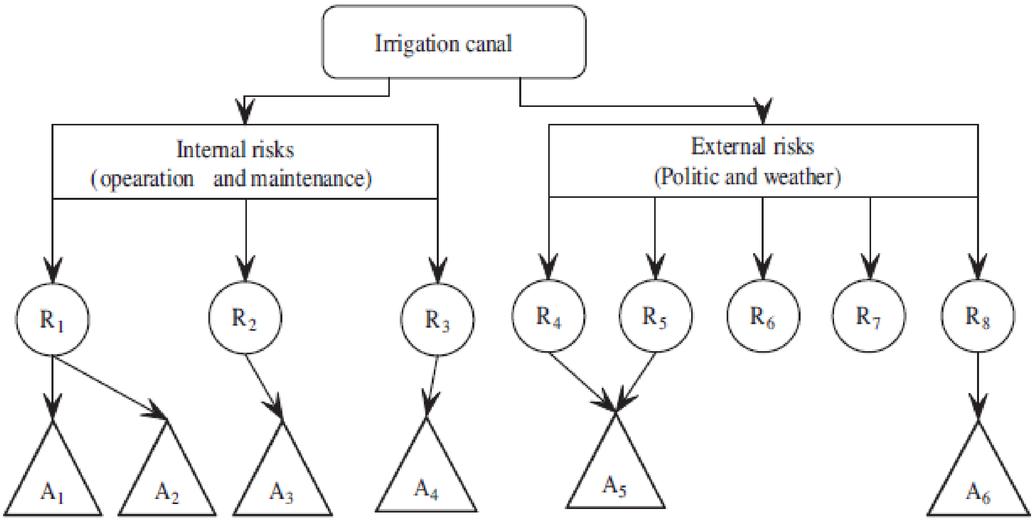


Figure 35

Each **mitigation action** is described by a set of three elements:

$$A_i = \{u_{M_i}, F_i, G_i\} \quad i = 1, \ldots, p$$

, where:

- p is the number of mitigation actions.
- u_{Mi} is the decision variable for action A_i ⇒ $\boldsymbol{u=\{u_{M1},\ldots,u_{Mp}\}}$ vector of control variables in mitigation.
- $F_i = \{f_{ji}: \mathbb{R} \rightarrow \mathbb{R}\}$, with j={1,…,$c$} being the set of functions that determine the risk impact reduction as a function of u_{Mi} at each time.
- $G_i=\{g_{ji}: \mathbb{R} \rightarrow \mathbb{R}\}$ describes the extra values to be added if action A_i is also carried out as a function of the corresponding decision variable u_{Mi}.

The decision concerning a mitigation action is usually not an execute/do not execute decision. In most cases, the **intensity** of the action and the time instant in which to execute it have to be determined. Therefore, control actions can take real or integer values ($u_{Mi} \in \mathbb{R}$ or $u_{Mi} \in \mathbb{N}$). An example of a discrete action may be the decision of repairing the canal floor. An example of a continuous action may be changing the water level.

Risk exposure is defined as:

$$RE_{rc}(u_M,t) = P_r(t)\Big(II_{rc} - \sum_{a=1}^{p} RA_{ra} f_{ca}(u_{M_a})\Big) + \sum_{a=1}^{p} RA_{ra} g_{ca}(u_{M_a})$$

where

- Pr(t) is the probability of risk Rr at instant t.
- IIrc denotes the initial impact of Risk Rr affecting parameter Zc.
- Function fca depends on decision variable uMa and it means the reduction of the impact by taking action Aa.
- RAra=1 if risk Rr is mitigated by action Aa, otherwise is 0. These values are obtained from the RBS.
- m is the number of risks.
- RErc means the exposure of risk Rr affecting parameter Zc.
- gca(uMa) is the extra value of mitigation action Aa on parameter Zc.

Regarding optimization, we use the following objective function:

$$\min_{u_M,t} J = \beta_1 J_{int}(u_M,t) + \beta_2 J_{ext}(u_M,t) + \beta_3 J_3(u_M,t)$$

where

$$J_3 = \sum_{k=1}^{N} \triangle u_M(t+k-1)^2$$

where J_{int} represents the optimization of the cost associated to internal risks such as operational risks or maintenance risks, and J_{ext} represents the optimization of the cost associated to external risks such as changes in reference levels due to rainfalls, financial opportunities or market issues. These terms are expressed as the standard term in MPC.

At this level, the decision variables are the mitigation actions to be executed U_M. These actions optimize the cost of the canal operation and may change parameters of the lower controller, if necessary. The index performance optimizes a multi-criteria weighted function where internal and external risks are involved. This optimization problem is solved by MPC.

Because decision variables of mitigation actions may be boolean, the resulting optimization problem is a mixed integer quadratic problem (MIQP). This belongs to the class of NP-complete problems. The complexity of the problem depends on the number of real and integer variables (mitigation actions) and the number of constraints. The computation time required to solve the problem is worst-case exponentially with the problem size. If the problem has *ni* binary inputs, the complexity is 2^{ni} (2^{ni} QP problems to be solved). The number of QP problems to be solved is finite and, therefore, the algorithm finds a feasible solution (if there is one) at a finite time. The sampling time should be sufficiently broad to satisfy that.

5.3 Lower level: DMPC

A distributed algorithm based on the DMPC scheme presented in [20] has been used in the lower level. This algorithm provides a reasonable trade-off between performance and the number of communications needed to reach a cooperative solution, which is a convenient characteristic for the type of physical system considered. It assumes that for each subsystem, there is an agent that has access to the model and the state of that subsystem. The agents do not have any knowledge of the dynamics of any of their neighbors, but can communicate freely among them in order to reach an agreement. The proposed strategy is based on negotiation between agents. At each sampling time, agents make proposals to improve an initial feasible solution on behalf of their local cost function, state and model, following a given protocol. The neighbors affected by the changes of a proposal evaluate the proposal when they receive it and answer with the cost increment (or decrement) implied by the proposal. Next, the agent that made the proposal computes a neighborhood cost as the sum of the corresponding neighbor cost increments plus its own increment (or decrement). If this sum results in a cost decrement, then the proposal is accepted and all the neighbors are notified so that they can update their information.

The procedure we propose is valid if, and only if, a given agent is not evaluating two different proposals at the same time. Such simultaneous evaluation by an agent might lead to a global cost increment due to possible crossed interactions between two proposals. For this reason, the various negotiation/communication protocols that may be implemented must guarantee that each proposal is evaluated independently. In this paper, we propose to implement a controller in which, a fixed number of proposals made sequentially by random agents are considered at each sampling time.

A simple way to do this is the following: before trying to communicate, an agent listens to the communication channel to check if there are other agents communicating. In case that the channel is free, the agent places its proposal. Otherwise it waits a small random time before retrying to make a proposal. Every time a proposal is made, the agents update a counter. Once it exceeds a given threshold no more proposals can be made during the current sample time.

Note that this algorithm can be easily enhanced to admit the parallel evaluation of proposals. As we said, several proposals can be evaluated in parallel as long as they do not involve the same set of agents; that is, at any given time an agent can only evaluate a single proposal. However, note that the communication protocol to implement the algorithm in parallel is beyond the scope of this work.

5.4 Irrigation Canal modeling for control

In this subsection, we introduce the models that have been used for the controller.

We have used two equations:

$$A_i(h_i(k+1) - h_i(k)) = T_d(Q_{\text{in},i}(k - t_d) + q_{\text{in},i}(k) - Q_{o,i}(k) - q_{o,i}(k)) \qquad (1)$$

$$Q_o(t) = C_d L \sqrt{2g} u(t) \sqrt{h_{\text{up}}(t) - h_{\text{dn}}(t)}, \qquad (2)$$

Equation (1) expresses the balance between the inflows and outflows of one subsystem (canal reach):

- Inflows:
    - From the upstream canal reach.
    - Flow due to rainfall, failure in the upstream gate.
- Outflows:
    - To a downstream canal reach.
    - Known offtake outflows by farmers, considered as measurable perturbations.

Equation (2) describes the discharge through a submerged flow gate.

5.5 *Case study*

The proposed algorithm will be tested with data from a real system, a section of the postrasvase Tajo-Segura in the south-east of Spain:

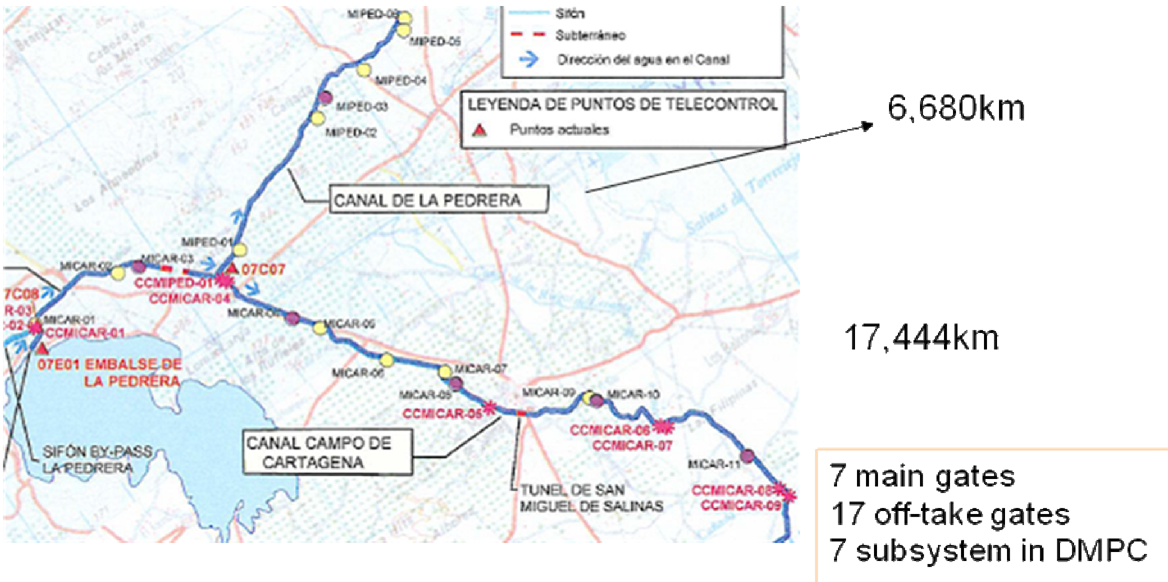


Figure 36

Data of Cartagena-La Pedrera irrigation canal.

Code	Type	P/G	Description	km
Canal del Campo de Cartagena				
Start of the Campo de Cartagena canal				0.000
CCMICAR-01	Gate	G	Initial Gate	0.200
MICAR-01	Off-take	G	Off-take 5 – Fuensanta and Estafeta	1.170
MICAR-02	Off-take	G	Off-take 5′ – Palacete	2.540
MICAR-03	Off-take	P	Off-take 6 – Santo Domingo	2.840
CCMICAR-04	Gate		Gate Canal Pedrera	4.485
MICAR-04	Off-take	P	Off-take 7 – Campo Salinas	5.970
MICAR-05	Off-take	G	Off-take 8 – San Miguel	6.550
MICAR-06	Off-take	G	Off-take 9 – Las Cañadas	8.050
MICAR-07	Off-take	G	Off-take 10 – San Miguel	9.390
MICAR-08	Off-take	P	Off-take 11 – Campo Salinas	9.590
CCMICAR-05	Gate		Gate Tunel San Miguel	10.480
MICAR-09	Off-take	G	Off-take 12 – San Miguel	12.630
MICAR-10	Off-take	P	Off-take 13 – Campo Salinas	12.780
CCMICAR-06	Gate		Gate La Rambla La Fayona (start)	14.433
CCMICAR-07	Gate		Gate La Rambla La Fayona (end)	14.579
MICAR-11	Off-take	P	Off take 14 – Villamartin	16.540
CCMICAR-08	Gate		Gate Cañada La Estacada	17.444
Canal de la Pedrera				
CCMIPED-01	Gate		Starting of the canal La Pedrera	0.000
MIPED-01	Off-take	G	Off-take 1P – Santo Domingo	0.770
MIPED-02	Off-take	G	Off-take 2P – Santo Domingo y Mengoloma	3.740
MIPED-03	Off-take	P	Off-take 3P – Santo Domingo	4.260
MIPED-04	Off-take	G	Off-take Riegos Levante 1	5.260
MIPED-05	Off-take	G	Off-take 4P – Santo Domingo	6.440
MIPED-06	Off-take	G	Off-take Riegos Levante 2 and 3	6.680

Table 7

The basic data of the benchmark is summarised as follows:

- Off-takes in the canals: 17.
- Main gates: 7.

- At the lower level, we consider 7 subsystems.
- Each of them at one of the main gates and ends at the next one.

The parameters and the rest of considerations for the case study are the following:

- Higher level:
  - β=[1 1 1] internal and external risks.
  - Sampling time: 1 day.
  - Nc=5.
  - Manipulated variables: mitigation actions $u_{M.}$
- Lower Level
  - Control water management in canals by satisfying demands.
  - Controlled variables: **downstream** levels.
  - Manipulated variables: flow at the head and the position of the gates.
  - Sampling time: 1 minute.
  - Nc=5.
  - The prediction horizon for each reach is the control horizon plus the delay of the reach :Np(i)=Nc+Ki.
  - 7 agents.
- Parameters considered:
  - Z1, operation cost (euros/day).
  - **Z2, variation on reference level in reaches.**

A number of potential risks can be encountered when the IC is operating. Figure 38-1 shows the risks that have been considered in this example. Initial impacts (II) are expressed on the parameters Z={Z_1,Z_2} with Z_1 being the cost (euros/day) and Z_2 the variation on reference level in reaches (meters).

A description of the actions used to mitigate risks is shown in Figure 38-2. The third column represents functions f and g that model the reduction of impacts and cost of execution, respectively. The fourth column is the period of validity of the action (D=Daily, W=Weekly, B=Biyearly, Y=yearly). That means if an action is executed, it not will be reassessed until past the time of validity.

For example, an insurance contract may be executed every 180 days (if estimated) and a water analysis may be undertaken every week.

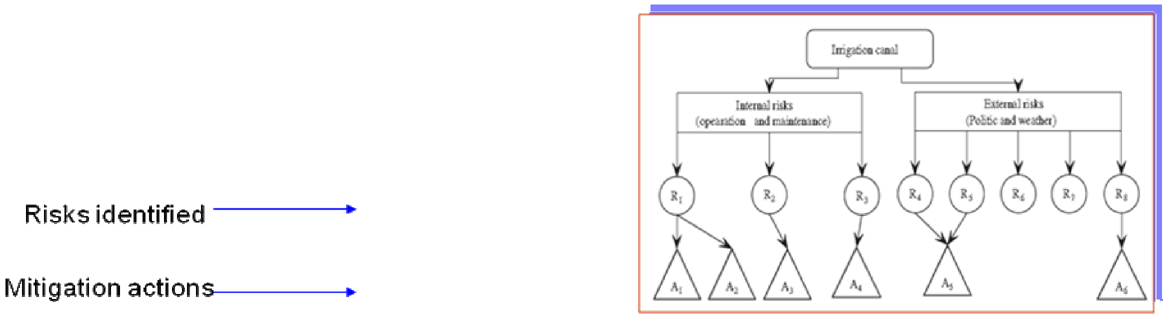


Figure 37

Risk description (case study).

R_r	Description	Impacts	$P_r(t)$
Internal risks			
Operation and Maintenance			
R_1	Inadequate fresh water quality.	$II_{11}=2000/II_{12}=0$	0.1
R_2	Failure in gates due to wear and tear	$II_{21}=400/II_{22}=0$	$0.1+\theta_1(u,t)$
R_3	Seepage losses	$II_{31}=10/II_{32}=0$	$0.1+\theta_2(h_i,t)$
External risks			
Politics and Weather			
R_4	Farmers, water demand varies from forecast	$II_{41}=0/II_{42}=+0.15h_i(t)$	$P_4(t)$
R_5	Rainfall changes water level of canal, producing water logging of adjacent lands	$II_{51}=0/II_{52}=-RF(t)$	$P_5(t)$
R_6	Changes in politics modify the strategy	$II_{61}=250/II_{62}=0$	$P_6(t)$
R_7	State policies provide incentives for IC systems	$II_{71}=-2000/II_{72}=0$	0.01
R_8	Uninsured events of force majeure	$II_{81}=6000/II_{82}=0$	0.01

Figure 38-1

Mitigation actions description (case study).

A_a	Description	f_{1a}, g_{1a} on Z_1 (cost)	PV
A_1	Periodic water analysis	$f_{11}=0.7II_1 u_{M_1}$, $g_{11}=250u_{M_1}$	W
A_2	Control weed growth	$f_{12}=0.3II_1 u_{M_2}$, $g_{12}=1500u_{M_2}$	B
A_3	Appropriate monitoring or control over devices	$f_{13}=II_1 u_{M_3}$, $g_{13}=250u_{M_3}$	W
A_4	Lining Irrigation Canal	$f_{14}=0.95II_1 u_{M_4}$, $g_{14}=2700u_{M_4}$	Y
A_5	Modify set-points of water levels ($u_{M_5}\in\mathbb{R}$)	$f_{15}=0$, $g_{15}=0$	D
A_6	Insurance policy ($u_{M_5}\in\mathbb{R}$)	$f_{16}=225u_{M_6}$, $g_{16}=u_{M_5}$	B

Figure 38-2

5.6 Case study: results

Upper level results

The results of the mixed integer problem have been obtained using the commercial solver CPLEX(ILOG) (u_{M1}-u_{M4} are boolean).

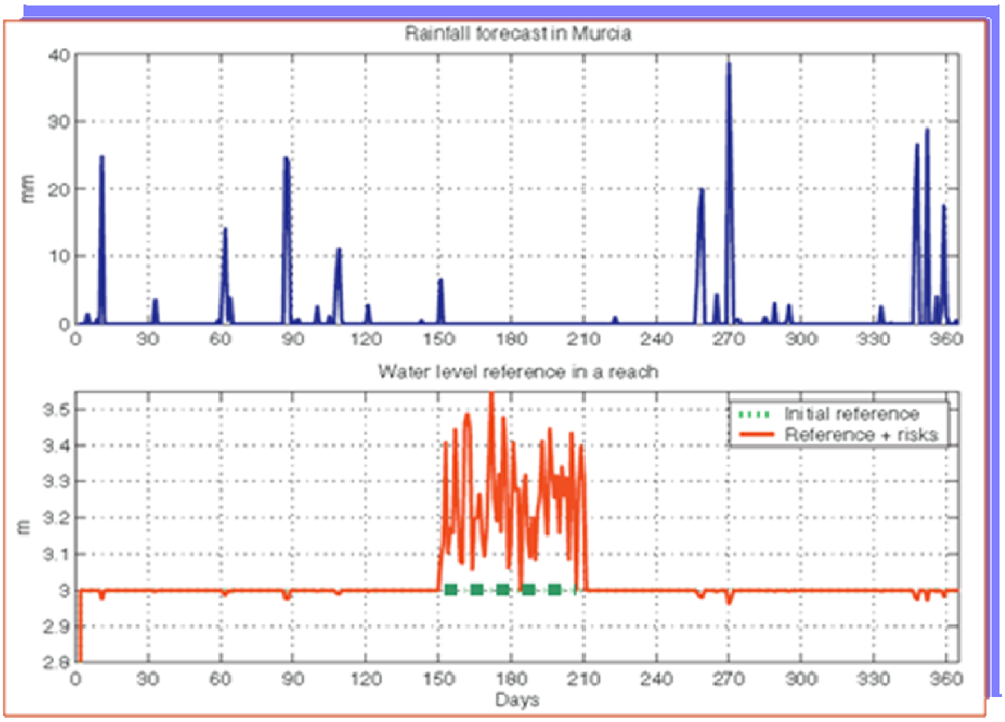


Figure 39

For risks R_4 and R_5, the rainfall forecast for the city of Murcia and the discharge from farmers have been considered during 2009. Figure 39 shows the rainfall forecast in the top panel; the initial level is represented by a dotted green line. This level is modified by R_2 and R_3, giving rise to an actual level reference shown by the solid red line (this is because action A_6 is executed). Note that in the summer season the level is increased as farmers may demand more water as a result of drought.

Figure 40 shows the following costs:

- Without risks (dotted green line) where risk management is not considered (cost is zero).
- With risks but no mitigation (dashed blue line) where impacts are considered but no actions are executed to reduce them.
- With mitigation (solid red line) where mitigation actions are executed to reduce impacts.

The no mitigation case (dashed blue line) is computed considering the accumulative impacts on cost day to day. The mitigation line takes into account the reduction of the impact and the cost of the actions when they are carried out. Note how the no mitigation option reflects the highest cost. As expected, the proposed cost is lower than the no mitigation line.

Lower level results

If the reference changes, the higher controller sends the modifications to the DMPC at the lower level.

Several simulations have been performed for the DMPC controller for a one day period. In these simulations, all the reaches begin with a water level of 3.0 meters and there is a change of reference for all the reaches to 3.40m at time k=0. This change is originated at the higher control level as a function of the risk mitigation policy. In particular, the change of reference corresponds to the day 150.

The simulation shown in Figure 41 corresponds to the nominal case, that is, the simulation was performed without disturbances. It can be seen how the reference is followed for all the reaches. In Figure 42 non measurable disturbances are considered. In particular, we have focused on the effect of the farmers' activity. For this reason, we have only considered disturbances which decrease the water level in the reaches. As it can be seen, there is a steady state error due to the effect of the disturbances.

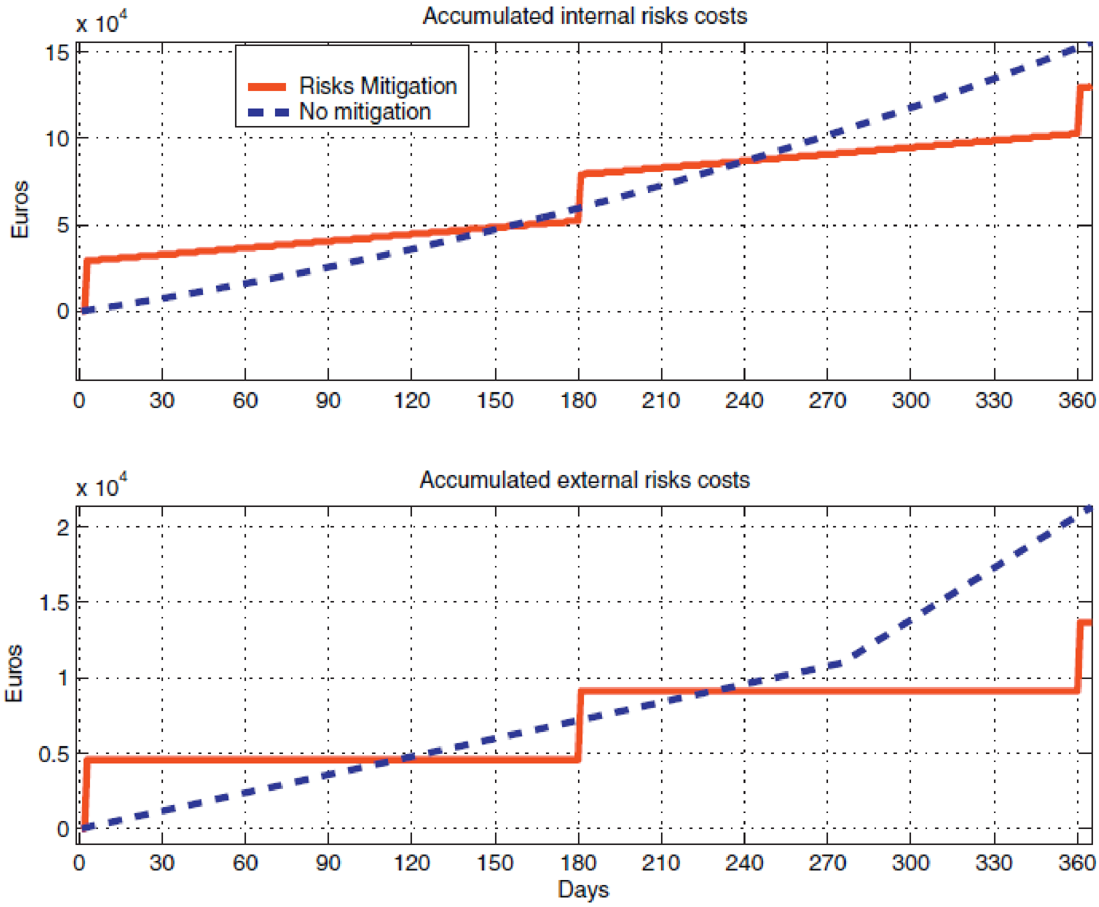


Figure 40

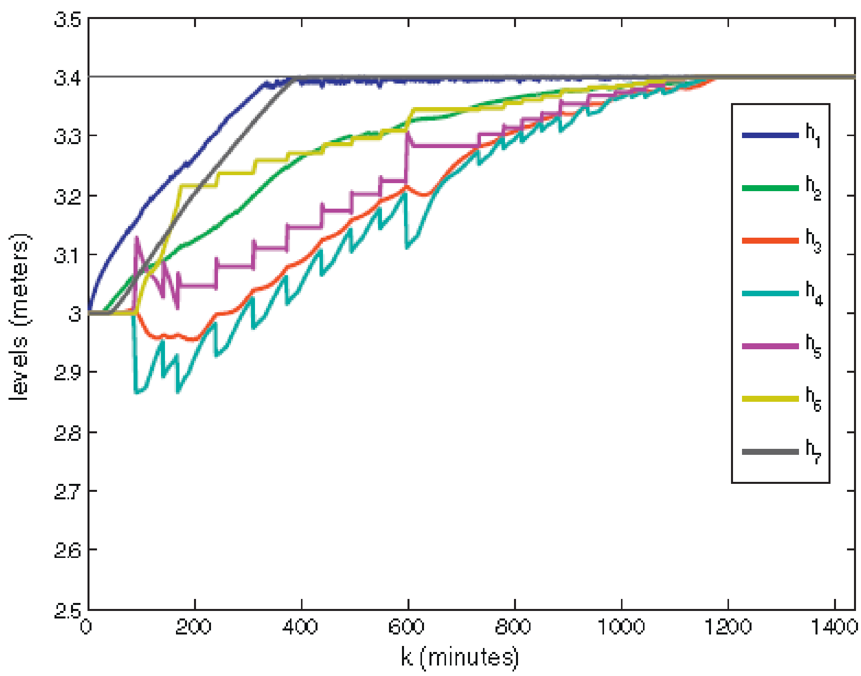


Figure 41

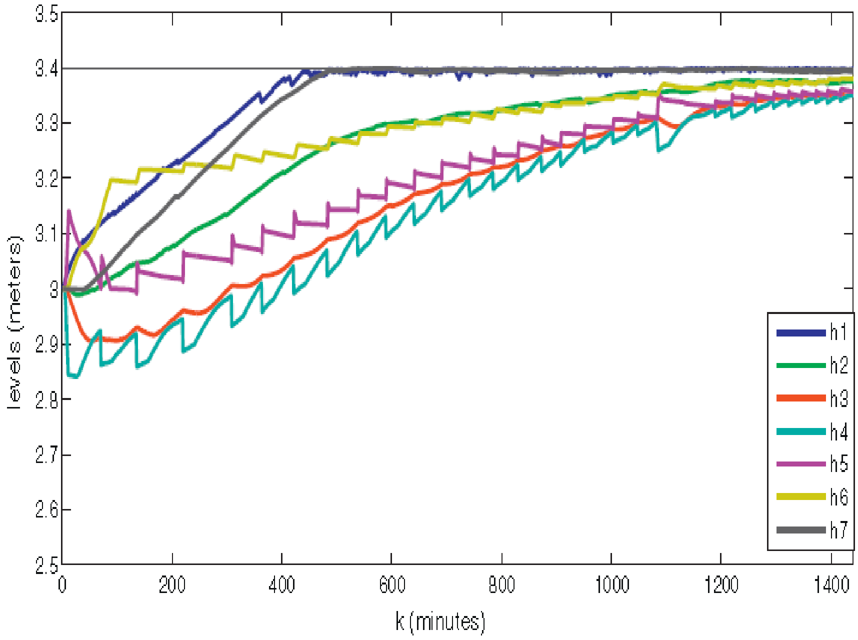

3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
levels (meters)
0
200
400
600
800
1000
1200
1400
k (minutes)
h1
h2
h3
h4
h5
h6
h7

Figure 42

6 CONCLUSIONS

The irrigation canal benchmark has been tested with decentralized and distributed approaches. The first tests were performed with classical control solutions, PIs with feedforward and decoupling actions.

The results with these controllers are quite good, but nevertheless in some situations the behavior was not completely satisfactory mainly due to constraints violation and the effect of the coupling among reaches.

Next, a control-based methodology for decision making in irrigation canals to address prevention and control problems in the plant based on a hierarchical and distributed scheme has been designed and applied to the benchmark. The objective is to optimize the operation of the system, taking into account explicitly modeled risks that can be identified prior to the planning.

MPC is particularly meaningful for the given problem given because of its favorable properties, such as ease of constraint handling, extension to multivariable case, time delays inclusions or changing objectives. The extension to the distributed approach has improved the results; the system has been divided into agents that exchange information about the control variables.

Risk modeling involves risk identification, assigning probabilities, and devising a strategic plan to mitigate risks; therefore, getting information from weather forecasts, failures in operations and trained personnel to generate these models is crucial to the success of this approach. The presented approach provides recommendations on the actions to undertake in order to mitigate risks that could appear. The procedure can be considered as a helpful tool to assist experts in evaluating different scenarios providing a definitive set of mitigation actions and values of control variables.

Finally, it is worthwhile to mention that the control policy at the lower level can be implemented in a distributed fashion that requires a small amount of communication between the nodes in order to get a cooperative solution.

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