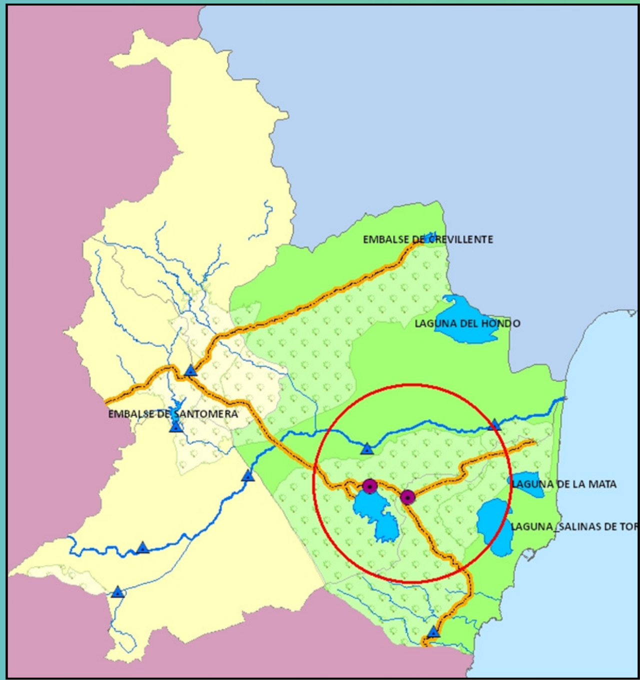

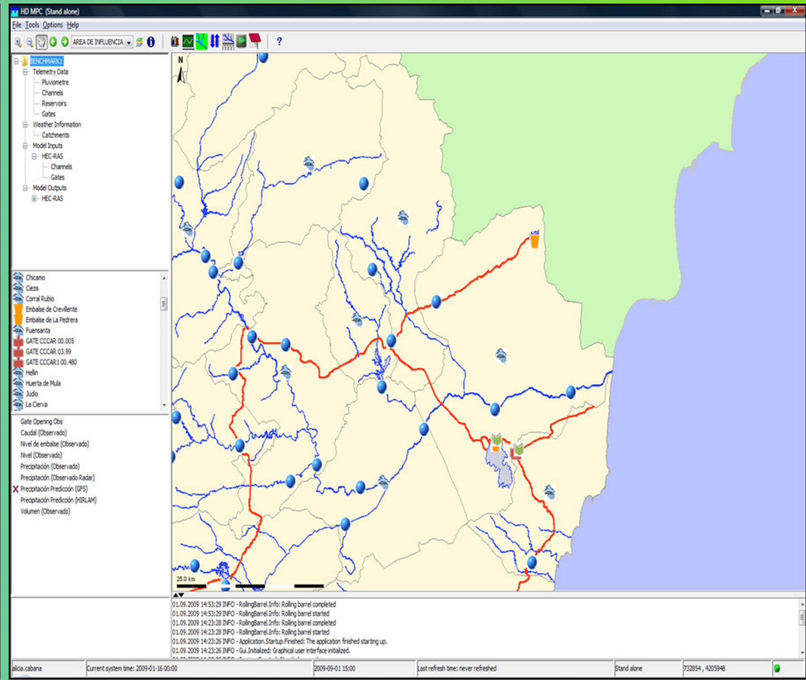

HD-MPC APPROACH TO IRRIGATION CANALS

Industry workshop on Hierarchical and Distributed Model Predictive Control (HD-MPC)

June 2011

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OUTLINE

- INOCSA: Business Line WATER. Key Projects
- Distributed control. Applications in the field of Water Management
  - Irrigation canals. Benchmark
  - Dams
- A Hierarchical Distributed Model Predictive Control Approach in Irrigation Canals: A Risk Mitigation Perspective

AECOM Spain (INOCSA)

Business Line
WATER

June 2011

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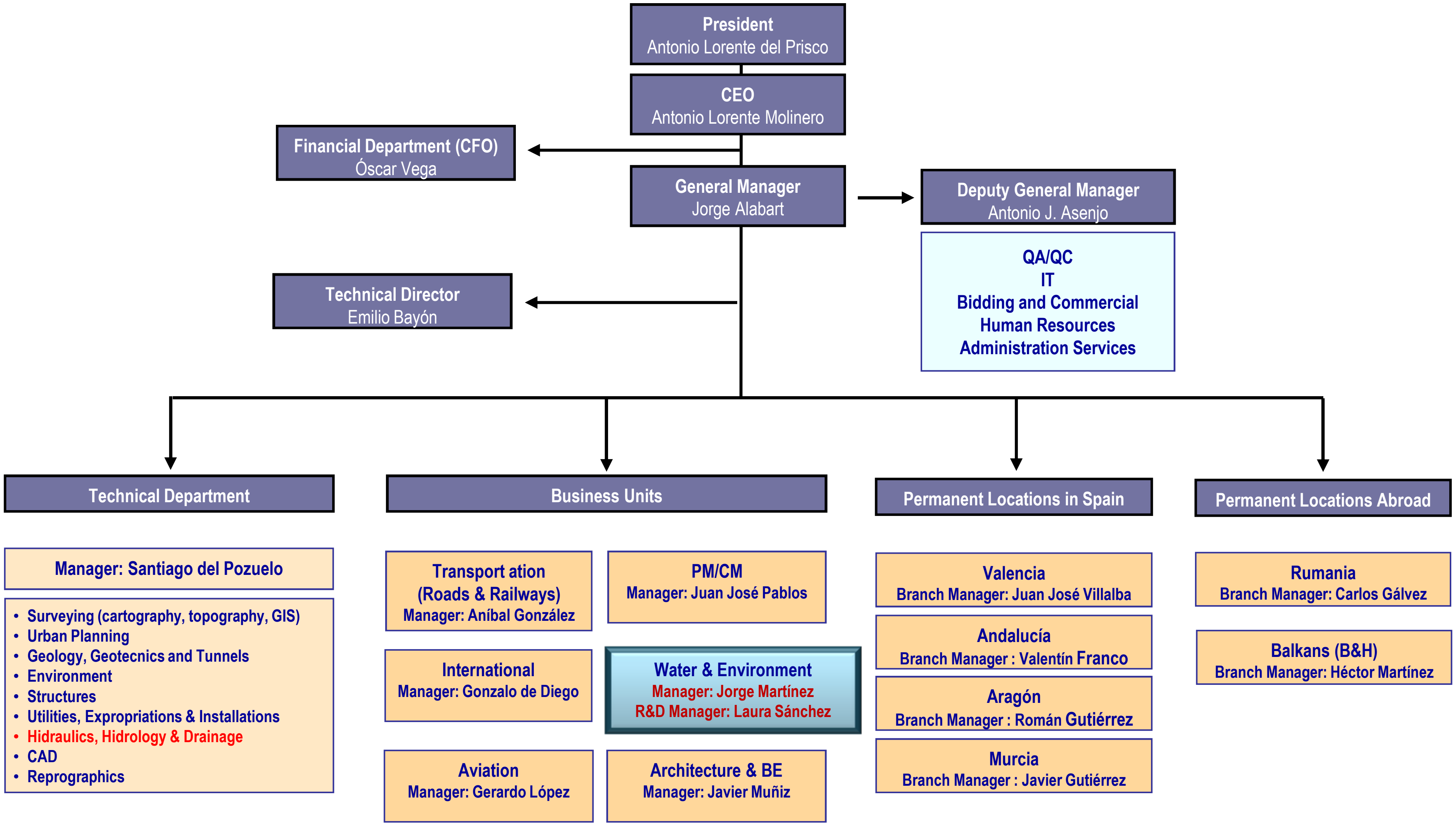
BL WATER INSIDE INOCSA



INOCSA (Spain)

- INOCSA: In business since 1976
- Legacy INOCSA: Spain, Balkans, Romania
- BU Water&Environment Spain:12 permanent staff

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Services Provided

- Modeling, Specific Studies, Feasibility Studies, Preliminary and Detailed Designs
- Works Supervision, Construction Management, Technical Assistance, Surveillance
- Hydrological and Hydraulic Studies

Fields of activity:

- Dams and reservoirs
- Waste Water treatment Systems
- Drinking Water Treatment Systems
- Irrigation systems and networks
- Water deposits, network and pumping systems
- Transportation infrastructures (drainage system)
- Desalinization Plants
- Research and Development (R&D)
- Automatic Systems for Hydrological Information
- Flooding areas and prevention

Key Projects (last 5 years)

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Dams and Reservoirs

REFERENCE	Contract Amount (€)
Consulting services and assistance for the control and supervision of the enlargement of Yesa Dam in the Aragon River.	10.832.019,06 (20%)
Environmental and Technical Feasibility Study, and solutions assessment for the new Sellent Dam	429.586,00
Consultancy and Assistance for inspection, studies and reports of the operation rules, classification proposals and emergency plans for non state dams of the North Basin	1.056.270,48
Technical Assistance for implementation of Exploitation and Emergency Plan Regulations for the Taibilla and Taibilla-Toma Dams of Mancomunidad de los Canales del Taibilla	679.690,78

Waste Water Treatment Systems

REFERENCE	Contract Amount (€)
Sampling and Water Quality Analysis for hazardous substances in North Basin	2.141.037,00
Construction Management of the General Interceptor Santoña-Laredo-Colindres. General Sanitation of Santoña Marsh	597.918,27
Construction Management of the General Sewer at River Saja	229.160,20

Drinking Water Treatment Systems

REFERENCE	Contract Amount (€)
Works Supervision of the enlargement of Letur Drinking Water Treatment Plant	327.972,66
Detailed Design of the Hydraulic Infrastructure Works for supplying water in L'Hospitalet de L'Infant	1.280.512,62

Irrigation Systems and network

REFERENCE	Contract Amount (€)
TA to the works for the modernization of the Genil's Irrigation area. Palma del Río (Córdoba)	187.733,00
Construction Management of Sástago Irrigation Channel. Aragon Irrigation systems. (Zaragoza)	839.870,19
Bidding Project for the construction and exploitation of infrastructures in 1st phase of the Navarra Channel Irrigation System	196.000,00

Water deposits, network and pumping

REFERENCE	Contract Amount (€)
Construction Management of the works for the water supply system from Cenajo Reservoir to the Mancomunidad of Taibilla	624.780,44
Technical Assistance for the Design of the improvement of the water supply to Badajoz and surrounding villages.	256.560,72
TA for the Detailed Design of the 5th Section of the 2nd supply water-ring in Madrid	132.240,00
Works Management, Inspection and Supervision of the construction works for: connection from the Palomarejos Deposit to Santa Bárbara and Santa María de Benquerencia (Water Supply to Picadas)	211.899,68

Desalinization

REFERENCE	Contract Amount (€)
Definition, Supervision and Follow up of architectural and environmental implementation criterion and use of renewable energy resources in ACUAMED´s desalinization plants in the North region	1.107.409,1
T.A. to Works Management for the desalination plant of Oropesa del Mar and complementary works, contained in the Law 11/2005.	1.441.442,12

Research & Development

REFERENCE	Contract Amount (€)
Hierarchical Distributed Model Predictive Control (HD-MPC)	300.000
Design of a pilot test against salt intrusion and Detailed Design for the implementation of the facilities	277.448,00

Automatic Systems for Hydrological Information

REFERENCE	Contract Amount (€)
Construction management of the works for the extension of the SAIH (Hydrological Information Automatic System). Segura Hydrographic Confederation	904.714,09
Technical Assistance for the management of the SAIH. Tajo Basin.	393.078,4
Construction management of the works for the implementation of the SAIH (Hydrological Information Automatic System). Guadalquivir Hydrographic Confederation	576.399,82

Flooding areas

REFERENCE	Contract Amount (€)
Consultancy and Assistance for the study of flooding areas and definition of the public hydraulic domain for the rivers of the North Basin in Cantabria	1.300.000,00
Preliminary and Detailed Design. Flooding prevention measures at Benimodo Stream.	714.154,21

Distributed control. Applications in the field of Water Management

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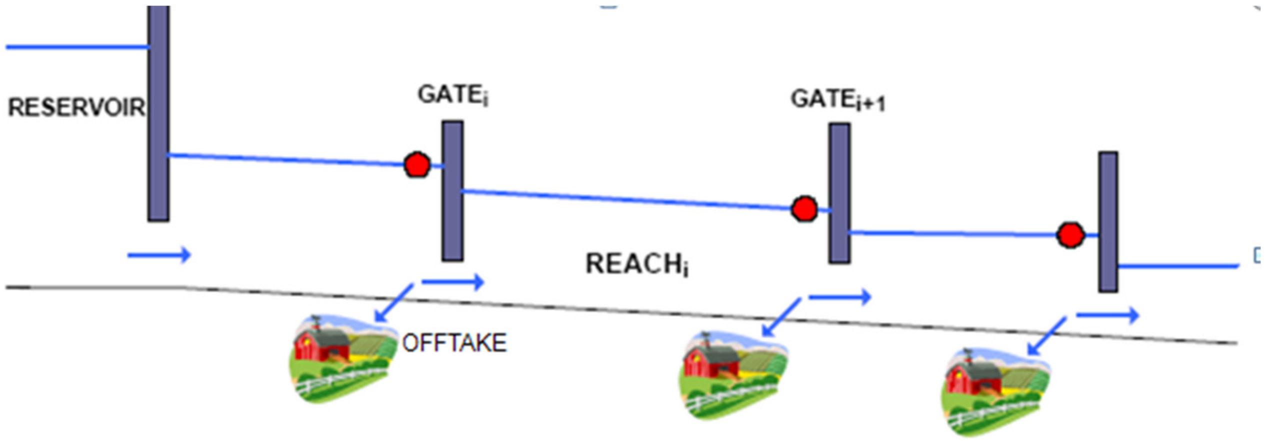
APPLICATION

WHAT KIND OF PROBLEMS CAN BE SOLVED IN THE FIELD OF WATER MANAGEMENT USING DISTRIBUTED CONTROL?

IRRIGATION CANAL SCHEME



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CONTROL STRUCTURES: GATES

Taintor Gate

Sluice Gates

Two Taintor Gates with side weirs

Side weirs

CANAL ELEMENTS

Gravity offtake

Wasteweirs

Syphon

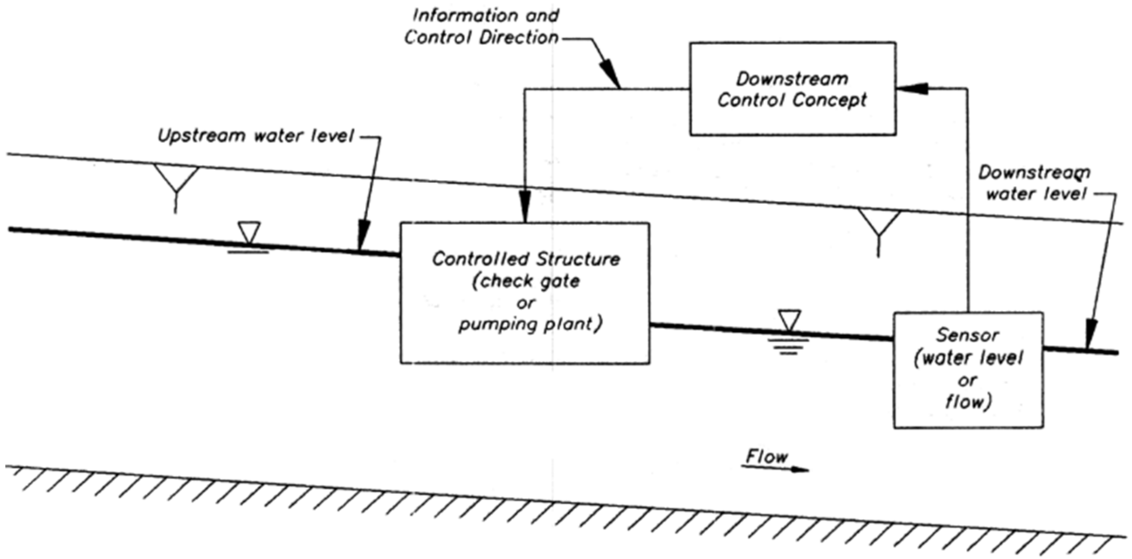
Canal Head

CANAL OPERATION CONCEPTS

- **Demand oriented 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

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

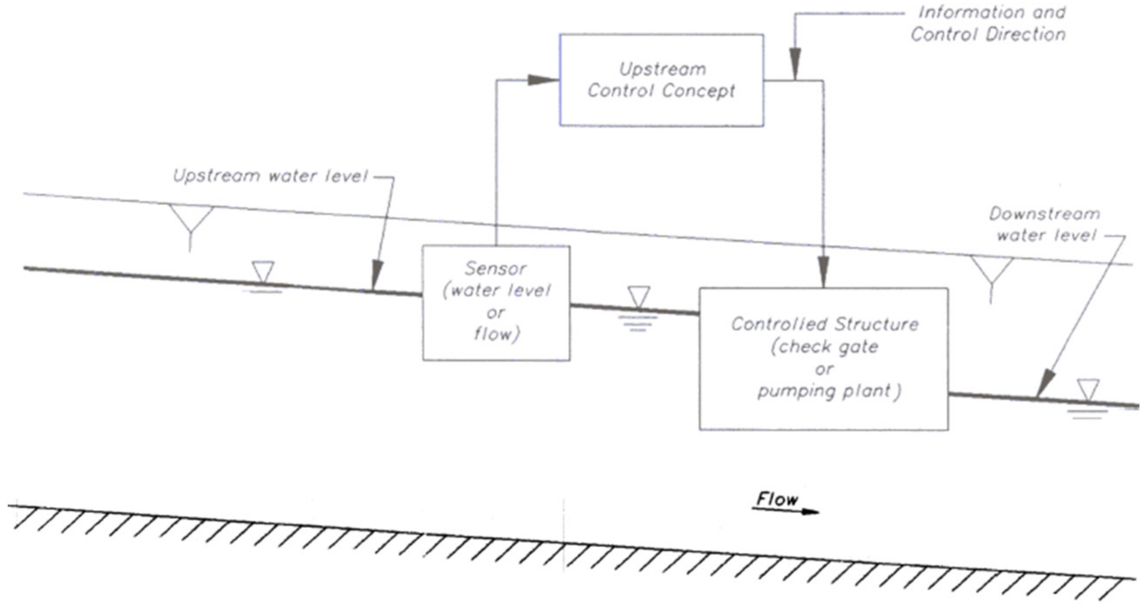
CONTROL CONCEPTS DOWNSTREAM CONTROL



(a) Downstream control concept

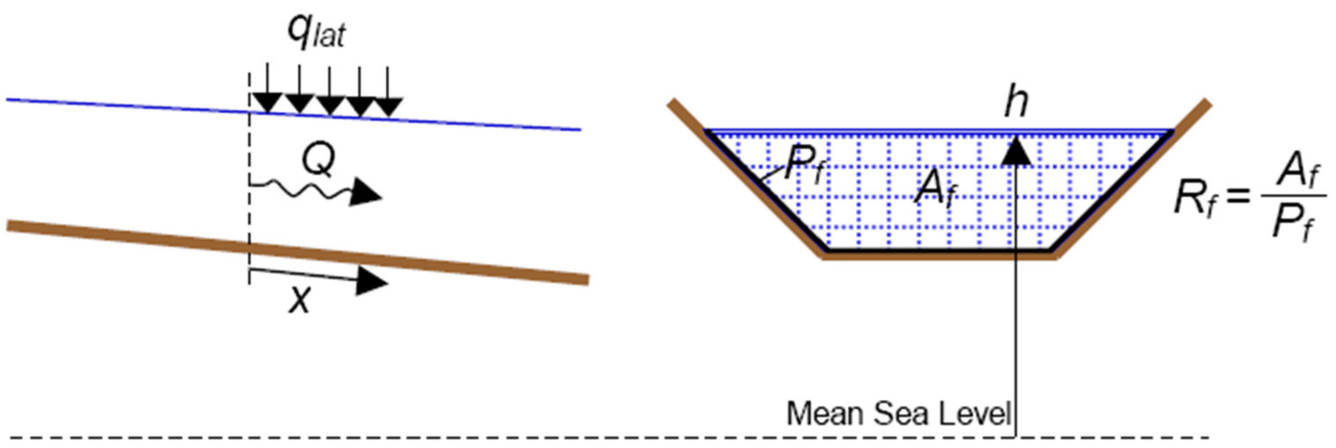
- Control structure adjustments (gates) are based upon information from downstream (usually levels)
- Downstream control transfers the downstream offtake demand to the upstream water supply source (flow at the head)
- Compatible with demand oriented operation
- Impossible with supply oriented operation: flow at the head can’t be fixed previously

CONTROL CONCEPTS 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
- Compatible with supply oriented operation: flow fixed at the head
- Inefficient with demand oriented operation

IRRIGATION CANAL MODEL: REACHES



$$\frac{\partial Q}{\partial x} + \frac{\partial A_f}{\partial t} = q_{lat}$$

Mass Balance

$$\underbrace{\frac{\partial Q}{\partial t}} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + \underbrace{g \cdot A_f \frac{\partial h}{\partial x}} + \frac{g \cdot Q|Q|}{C^2 \cdot R_f \cdot A_f} = 0$$

Momentum Balance

Partial Differential Saint-Venant Equations

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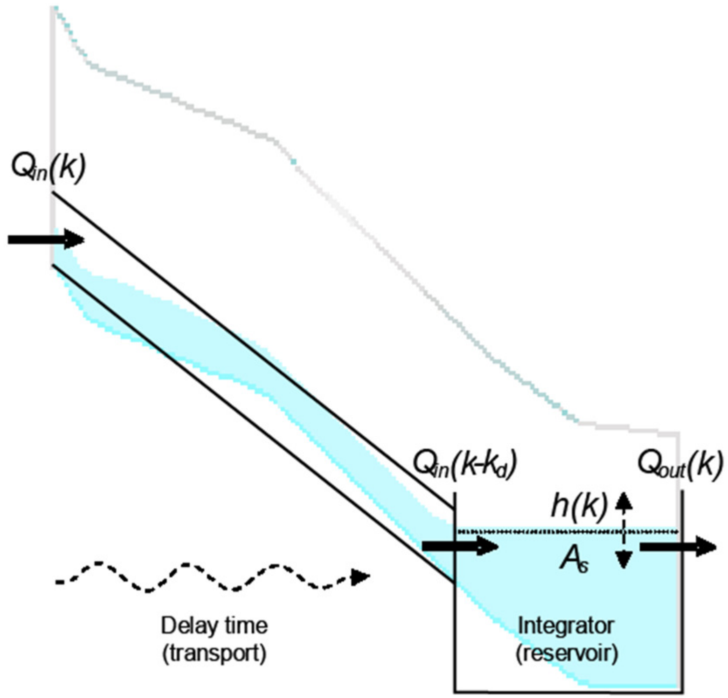
IRRIGATION CANAL MODEL: REACHES



Integrator-delay simplified model

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

T_d *Sampling time*

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

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

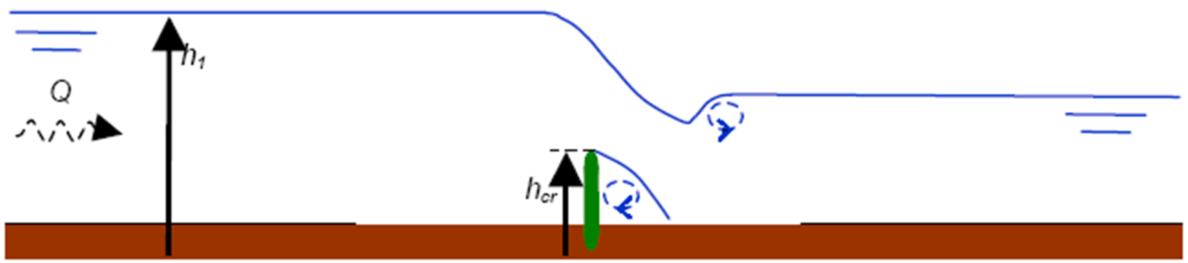
STRUCTURE MODELS: OVERSHOT GATES

Many theoretical or empirical formulas have been proposed, for example:

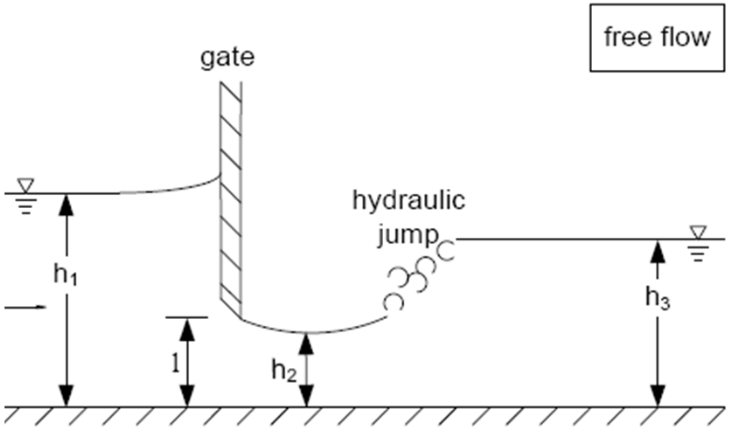
$$Q = C_d L \sqrt{\frac{2}{3} g} \, (h_1 - h_{cr})^{3/2}$$

L: With of gate

C_d : Discharge coeficient

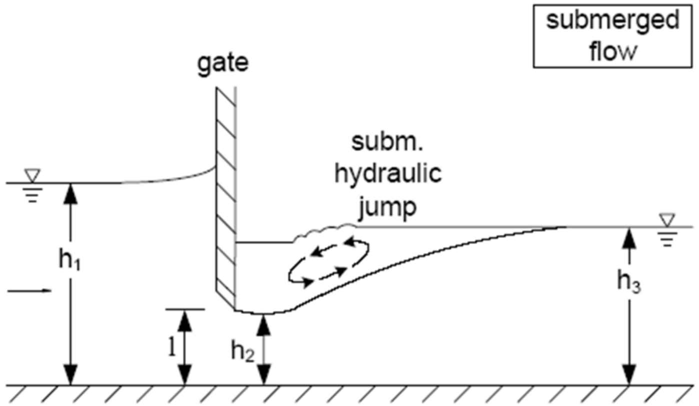


STRUCTURE MODELS: UNDERSHOT GATES



$$Q = C_d \cdot L \cdot u \sqrt{2 g h_1}$$

u : Gate opening



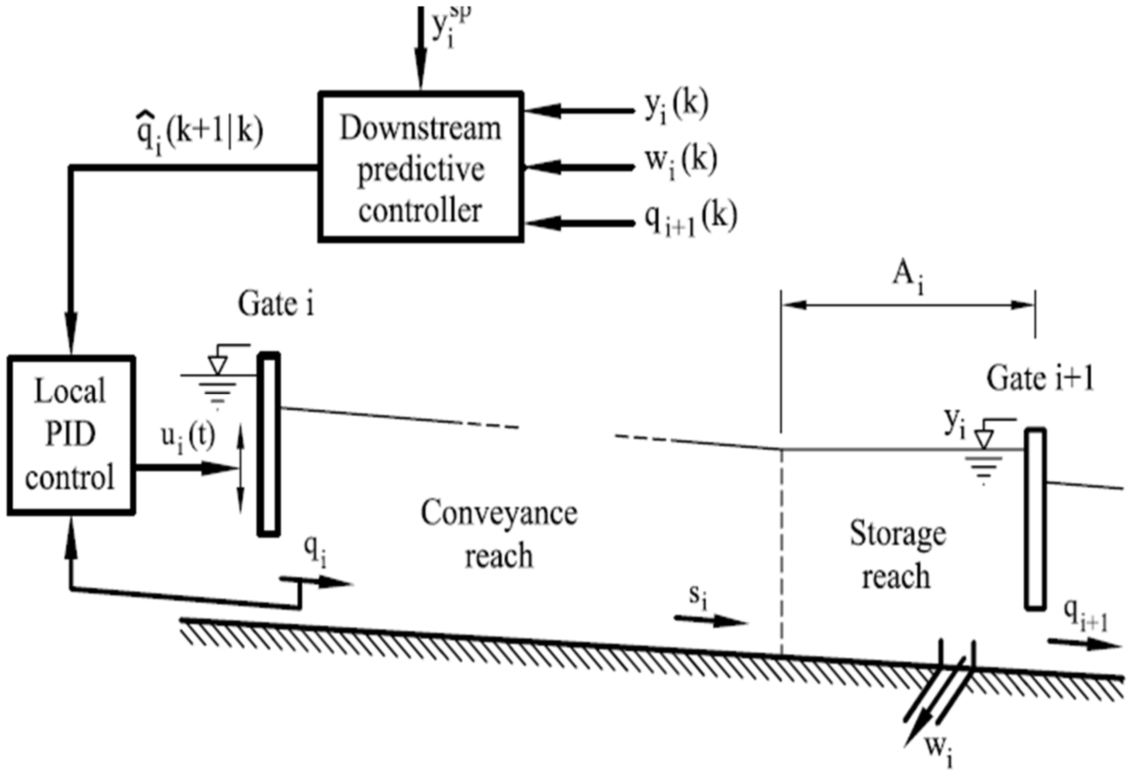
$$Q = C_d \cdot L \cdot u \sqrt{2 g (h_1 - h_3)}$$

IRRIGATION CANAL CONTROL: GENERAL IDEAS

- Controlled variables: ***Water level*** (most common), water volume or discharge

- Two global strategies:
  - Directly ***manipulate gate openings*** in order to ***control levels***
  - Two levels control
    - Compute required gate discharges in order to ***control water levels (discharge as manipulated variable)***
    - ***Manipulate gate openings*** to obtain the ***requested gate discharges***
      - Local Controller (Cascade control)
      - Inverting the gate discharge equation

IRRIGATION CANAL CONTROL: GENERAL IDEAS



Example of a two levels downstream controller. The first level is a predictive controller and the lower level controller is a PID

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IRRIGATION CANAL CONTROL: HD-MPC BENCHMARK

IRRIGATION CANAL CONTROL: HD-MPC BENCHMARK

System:

- Section of the canals of “postrasvase Tajo-Segura”, South-East of Spain. A set of canals which distribute water coming from the river Tajo in the basin of river Segura
- Y-shape canal: a main canal (“Canal de Cartagena”) that splits into 2 canals:
  - “Canal de la Pedrera”: the total length is 6.680 km
  - “Canal de Cartagena”: in our case-study only a part of this canal is used (17.444 km)
- Total: 24 kilometres

IRRIGATION CANAL CONTROL: HD-MPC BENCHMARK

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

Take-off gates in the canals: 17
Main gates: 7

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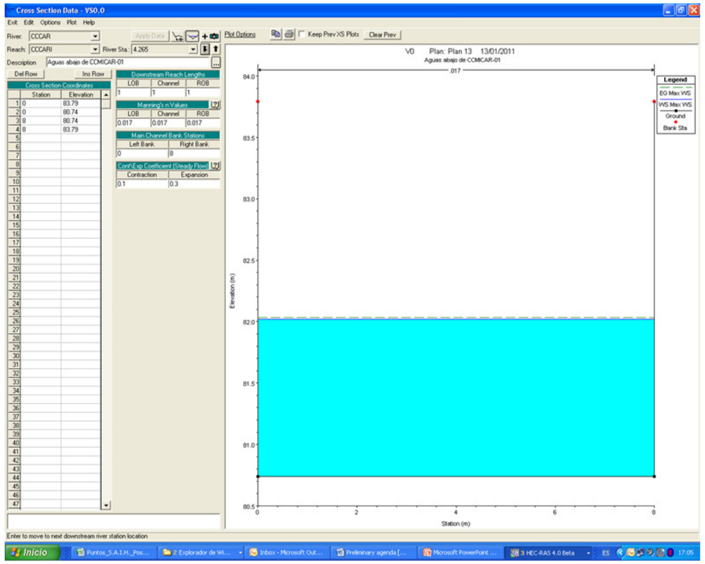
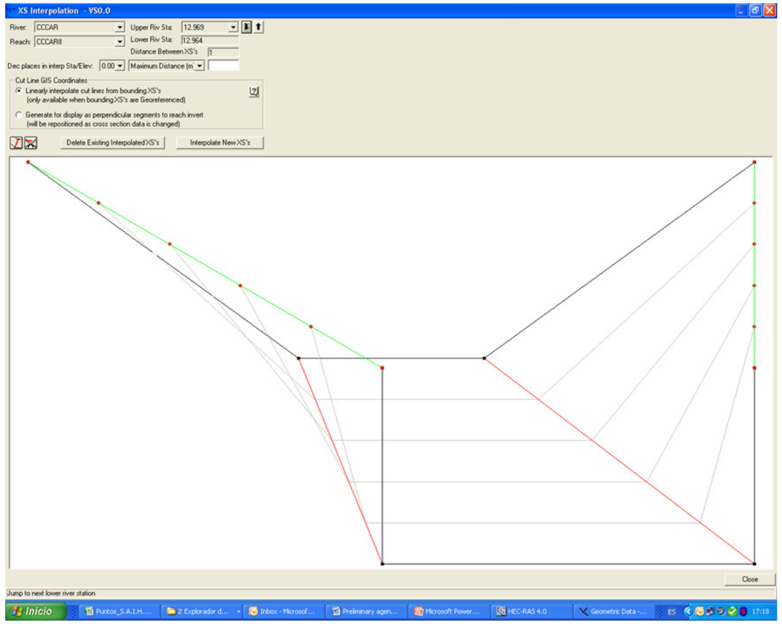
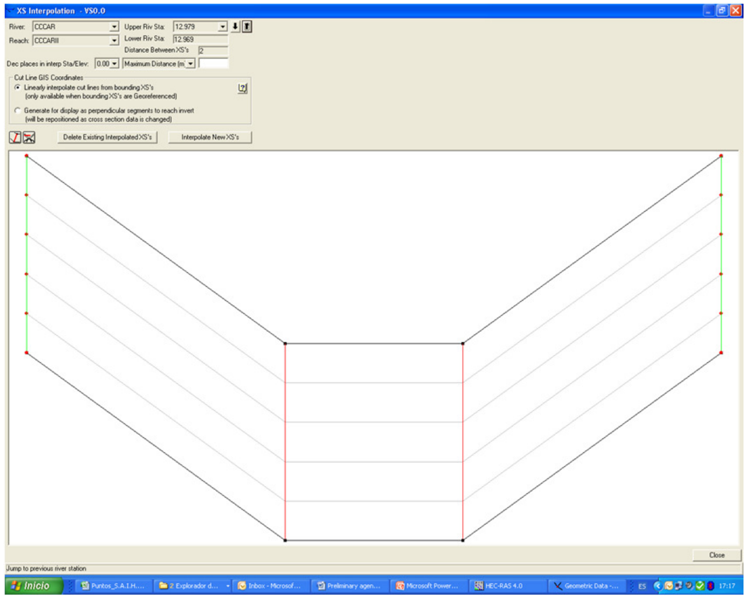
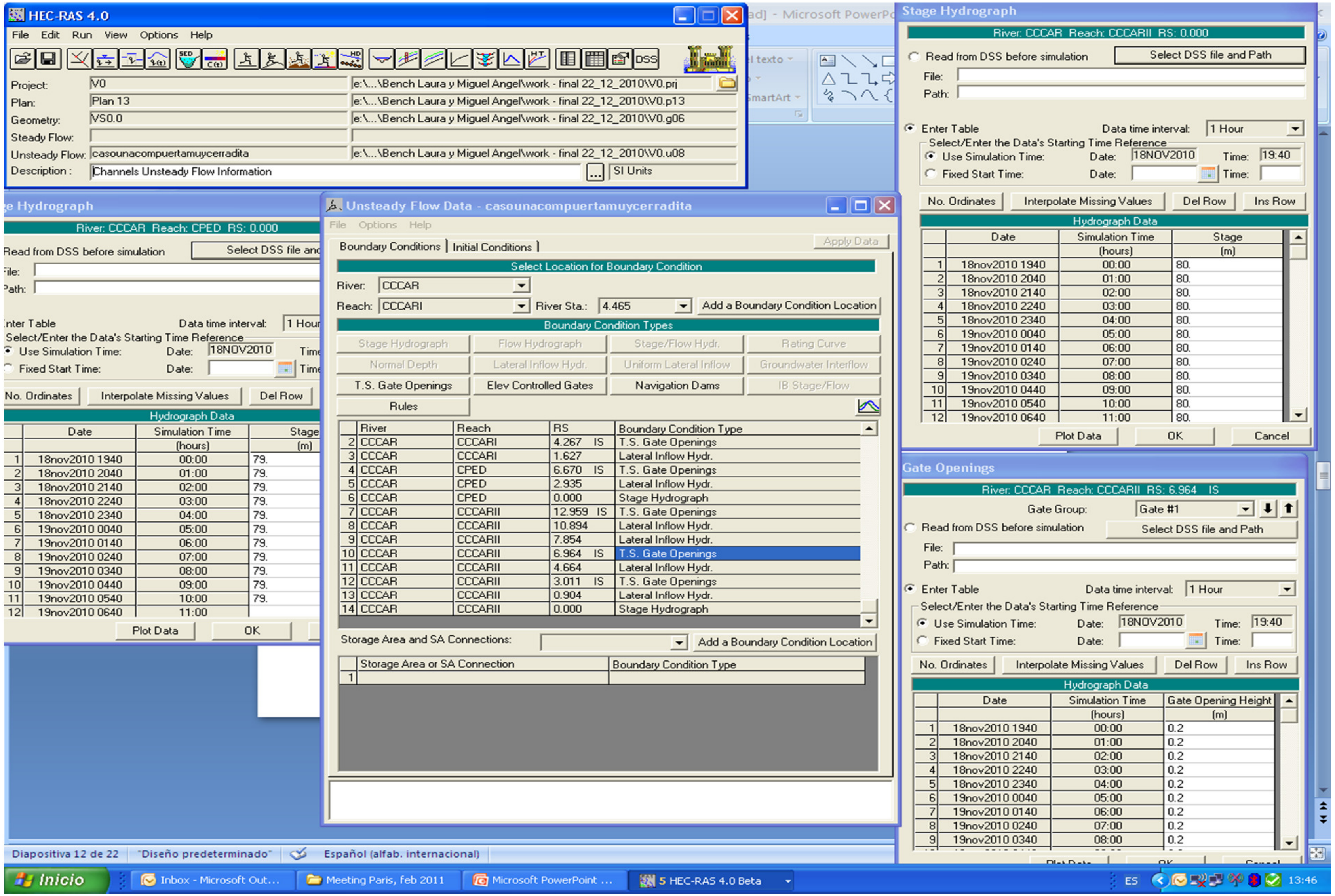
MODELING OF THE CANAL: HEC-RAS







HEC-RAS: UNSTEADY FLOW DATA



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MODELING THE CANAL: SIC

SIC software (Simulation of Irrigation Canals) is a commercial package developed at the Irrigation Division of Cemagref Montpellier (France). It has been particularly dedicated to irrigation canals. It can be used both by engineers and by canal managers.

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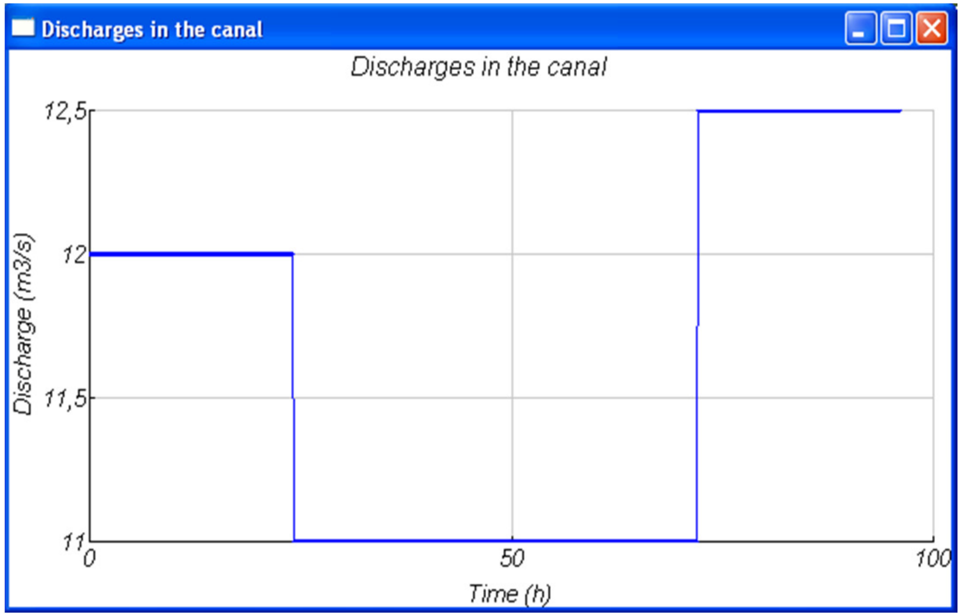
MODELING THE CANAL: SIC



Flow at the head not constant with time

Local controllers (PI) manipulating gate openings to control upstream levels (gates CCMICAR-01, CCMICAR-04, CCMICAR-05, CCMICAR-06, CCMICAR-07, CCMICAR-08), except for CCMIPED-01 (controlling flow)

Level has to maintain a constant value in all gates except for CCMICAR-08, where the level has to increase 0,2 m

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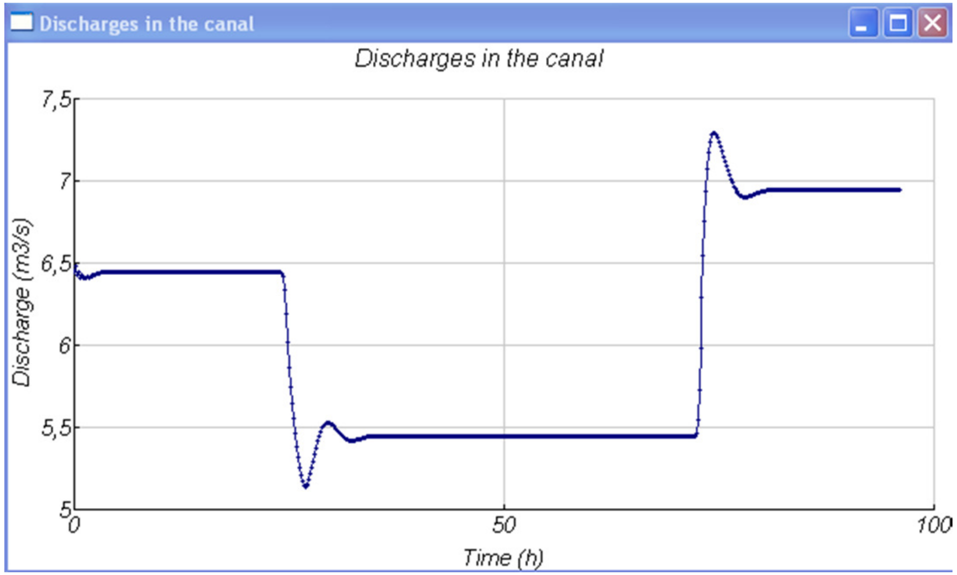
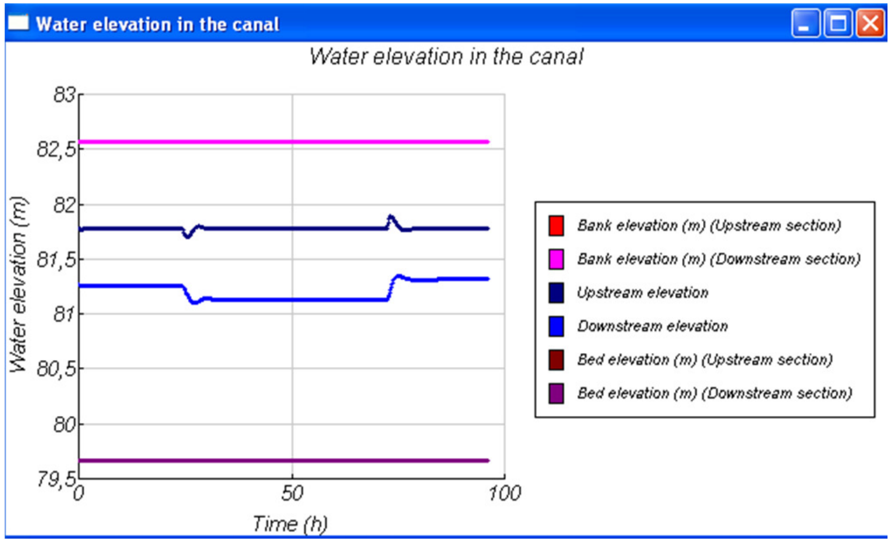
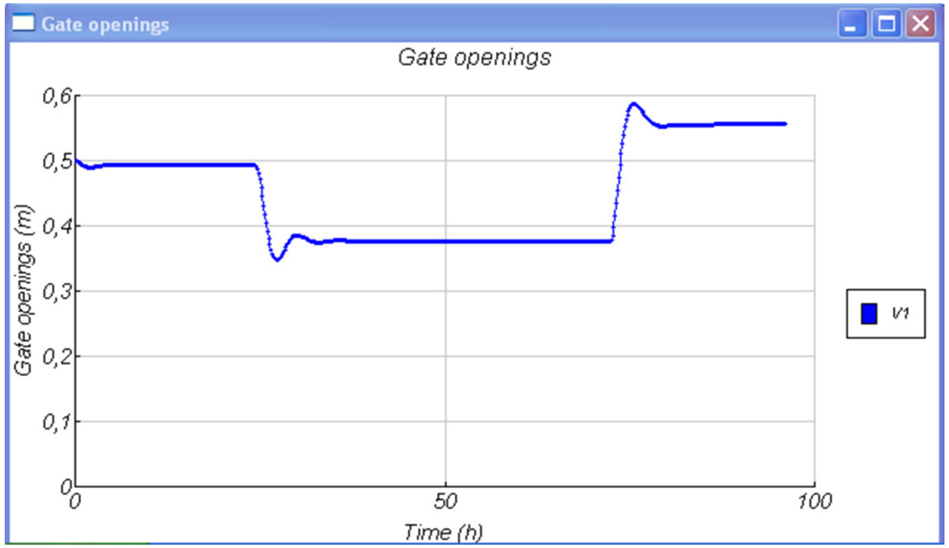
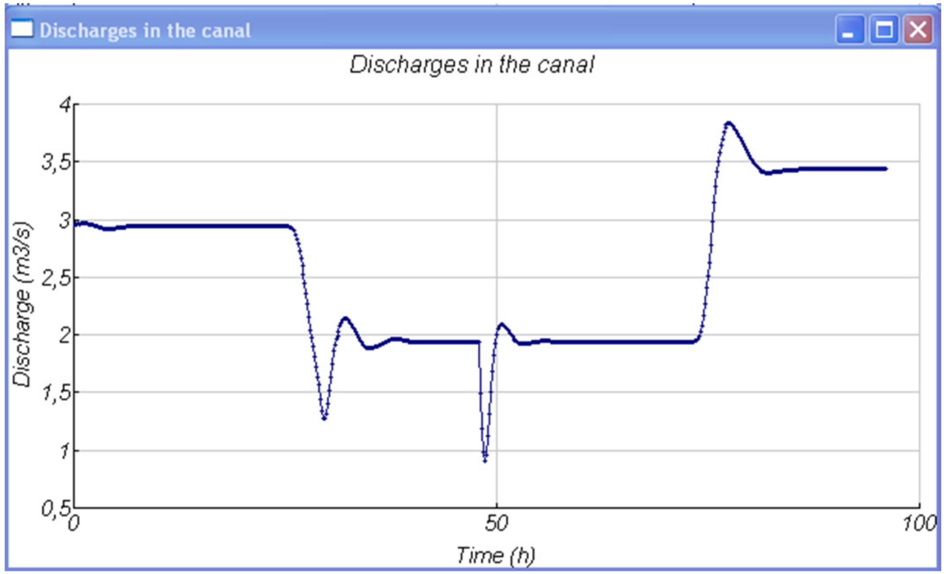
SIC: RESULTS IN GATE CCMICAR-06



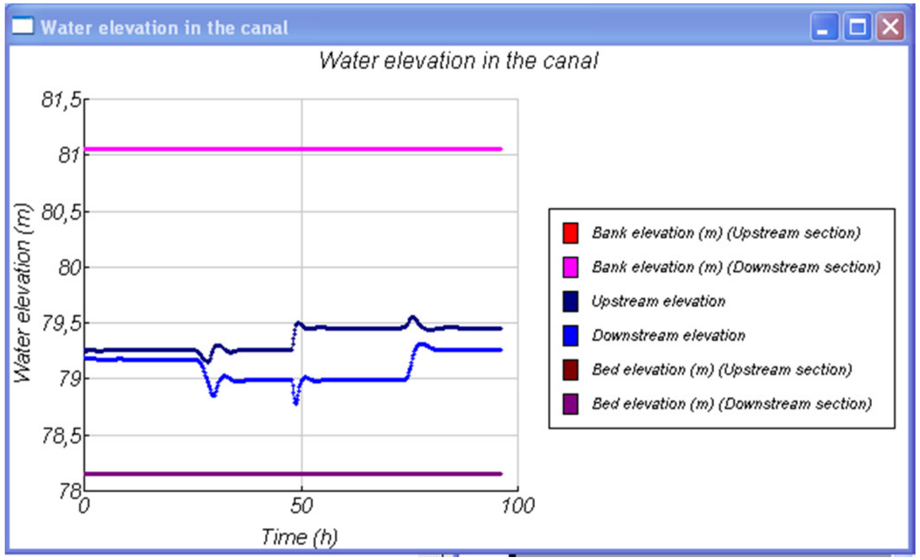


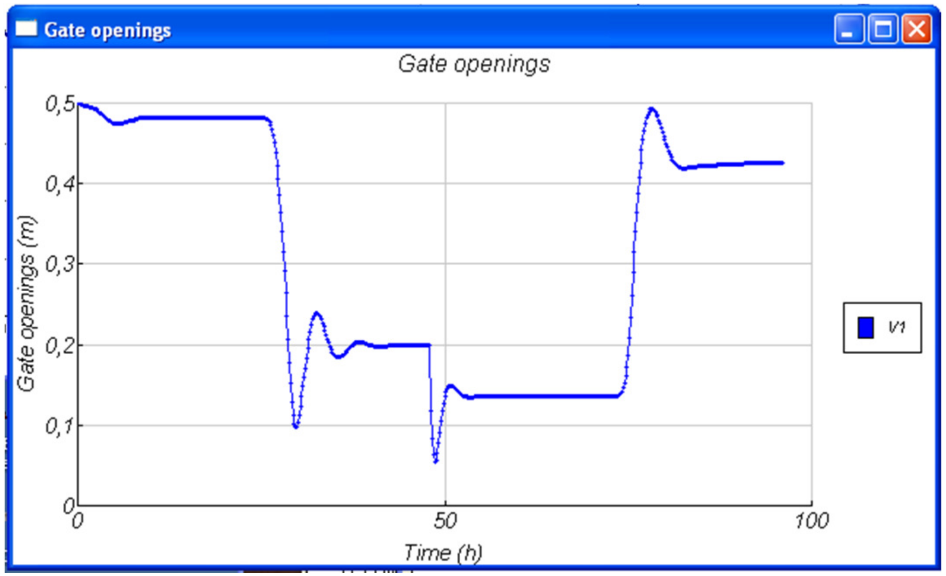


SIC: RESULTS IN GATE CCMICAR-08



In CCMICAR-08 the level has to increase 0,2 m





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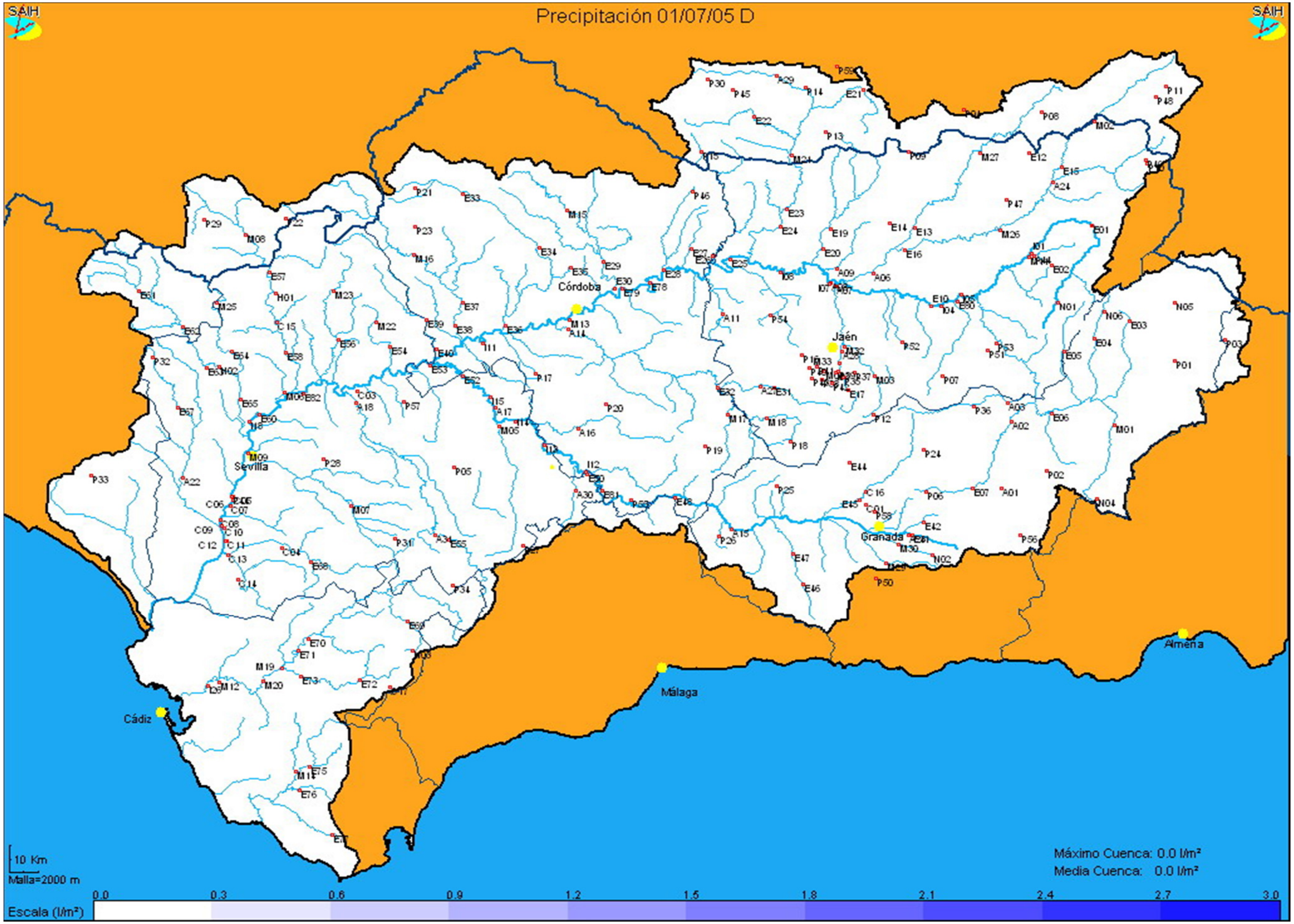

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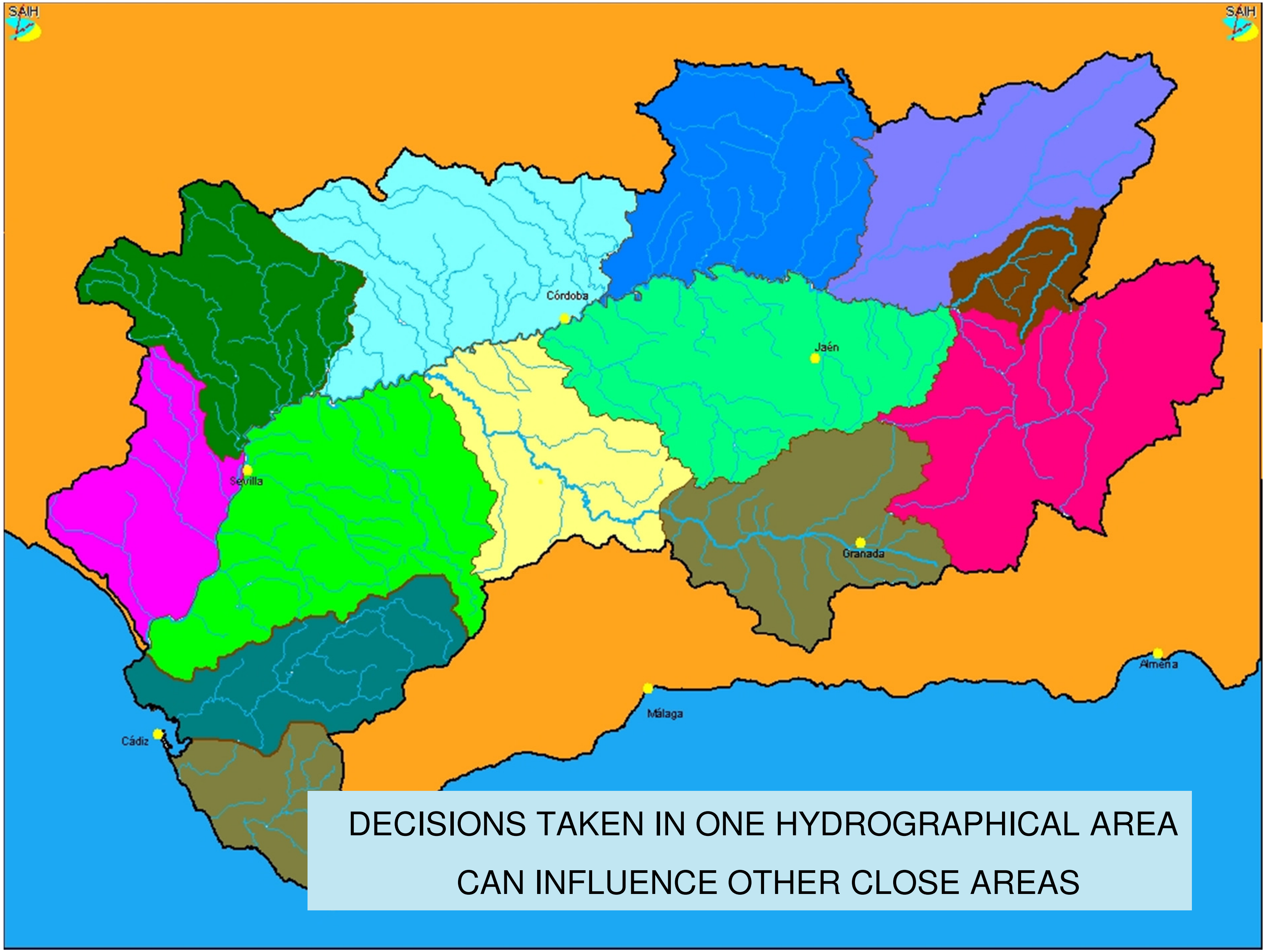
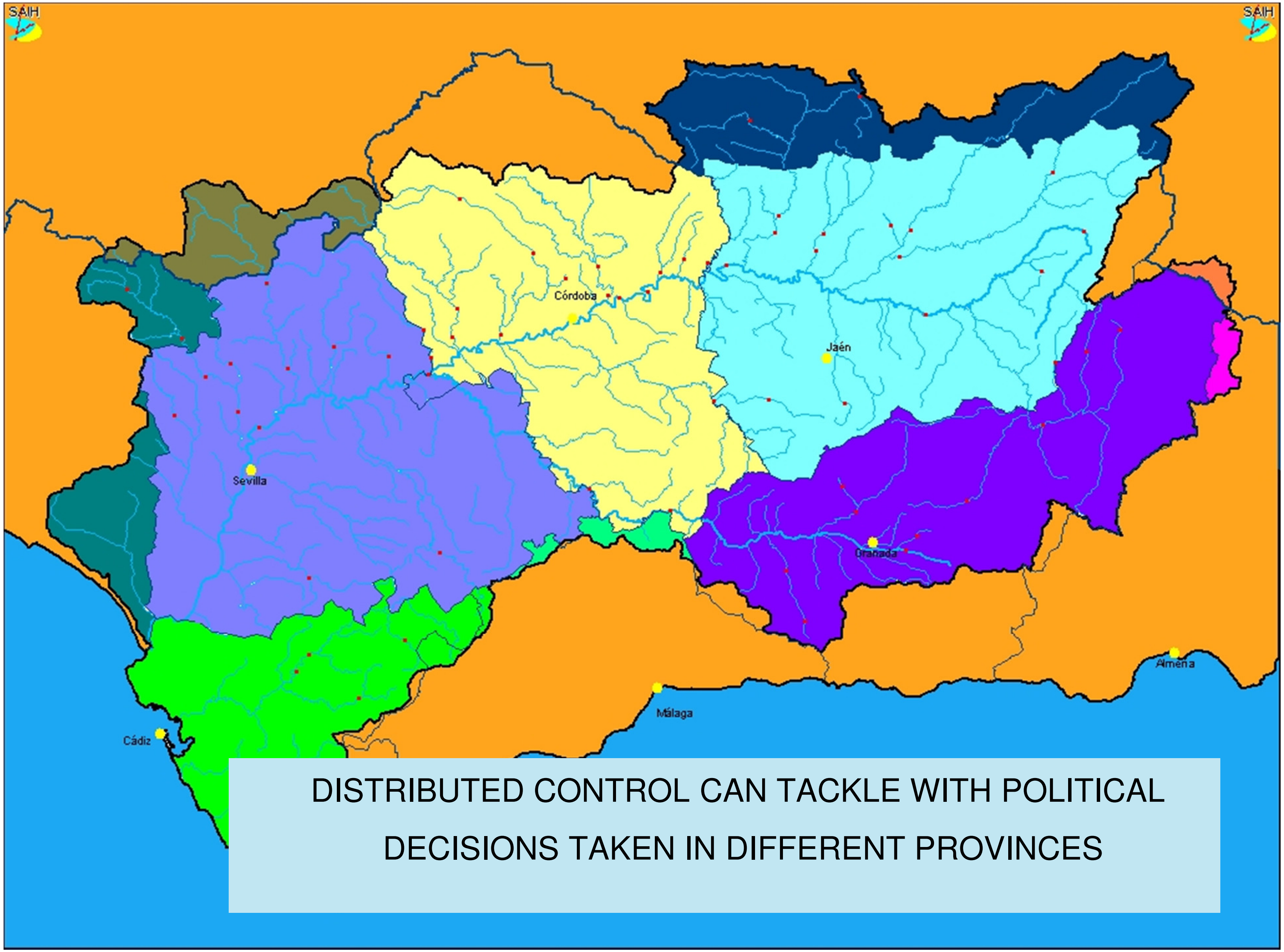

SAIH
SAIH
Córdoba
Jaén
Sevilla
Granada
Almería
Málaga
Cádiz
DECISIONS TAKEN IN ONE HYDROGRAPHICAL AREA
CAN INFLUENCE OTHER CLOSE AREAS



DISTRIBUTED CONTROL CAN TACKLE WITH POLITICAL DECISIONS TAKEN IN DIFFERENT PROVINCES

"A Hierarchical Distributed Model Predictive Control Approach in Irrigation Canals: A Risk Mitigation Perspective"

Ascensión Zafra-Cabeza (USE), J. M. Maestre (USE), Miguel A. Ridao (USE), Eduardo F. Camacho (USE) and Laura Sánchez (INOCSA)

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PAPERS

Journal of Process Control

Title: *"A Hierarchical Distributed Model Predictive Control Approach in Irrigation Canals: A Risk Mitigation Perspective"*

Authors: Ascensión Zafra-Cabeza (USE), J. M. Maestre (USE), Miguel A. Ridao (USE), Eduardo F. Camacho (USE) and Laura Sánchez (INOCSA)

XXXI Jornadas de Automática , Jaén, Spain, Sept. 2010

Title: *"Plataforma para el control y simulación en la gestión de sistemas de canales"*

Authors: A. Cabañas (UPM), L. Sánchez (INOCSA), M.A. Ridao (USE) and L. Garrote (UPM)

American Control Conference 2011

Title: *"Hierarchical Distributed Model Predictive Control: An Irrigation Canal Case Study"*

Authors: University of Seville and INOCSA

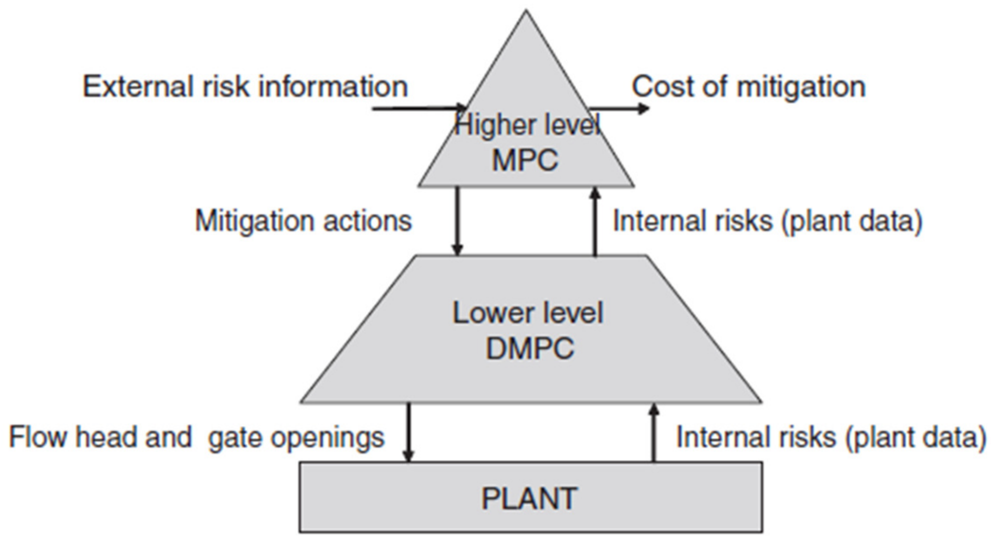
HD-MPC Approach in Irrigation Canals: Risk Mitigation Perspective

Two levels in optimization are presented:

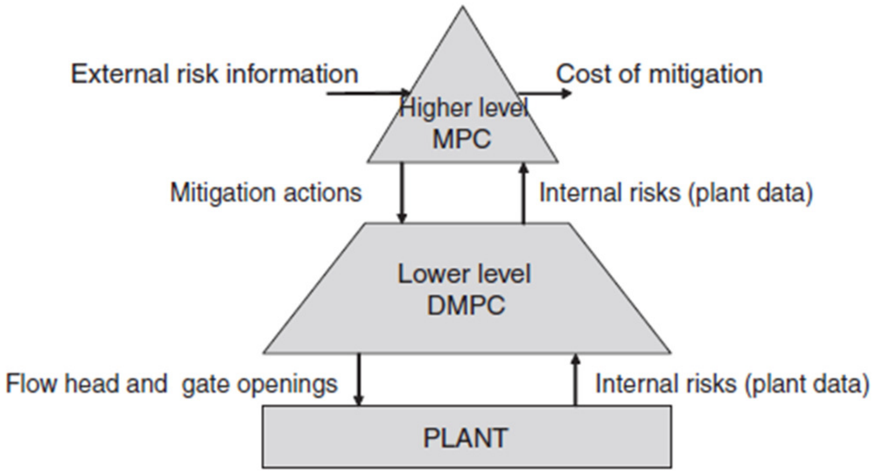
- At the **lower level**, a distributed model predictive controller optimizes the operation by manipulating flows / gate openings in order to follow the water level set-points
- The **higher level** implements a risk management strategy based on the execution of mitigation actions if risk occurrences are expected

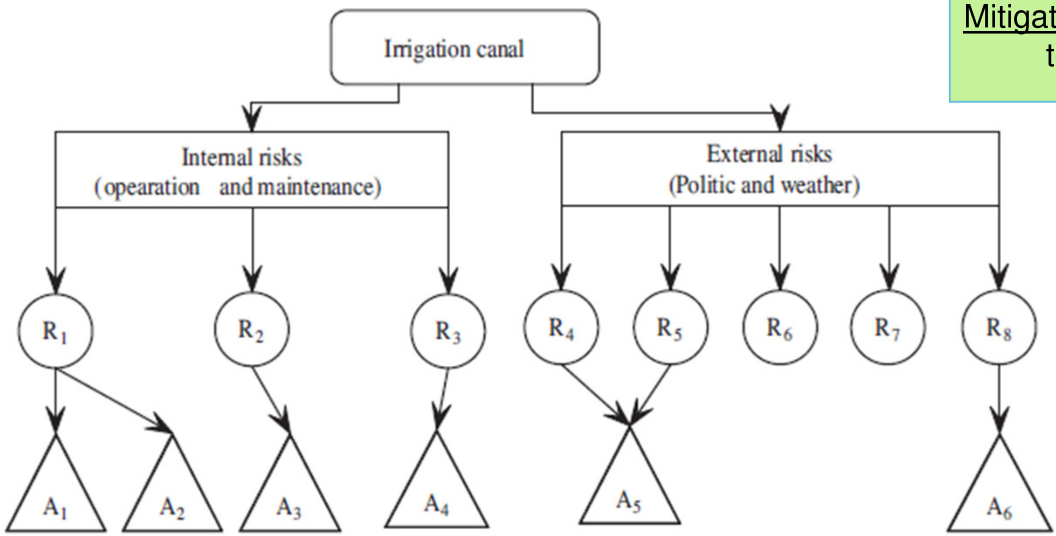
Risk factors:

- Unexpected changes in demand
- Failures in operation
- Maintenance costs



Higher level: risk management and MPC





<u>Risk (Rr)</u>: Event that can take place when operating IC and may cause consequences (<u>Impact: IIrc</u>)

- <u>External risks</u>: changing weather or financial data
- <u>Internal risks</u>: failure in the gates or seepage losses

<u>Mitigation actions (Aa)</u>: Each risk is associated to a set of actions that could mitigate it

Higher level: risk management and MPC

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

- Objective function to minimize: multicriteria weighted function where operating costs, demand satisfaction, mitigation actions and control efforts are involved
- A centralized MPC is used in the optimization problem
- Jint represents the optimization of the costs associated to internal risks
- Jext represents the optimization of the costs associated to external risks
- Cost is optimized and parameters at the lower level may be modified as a consequence of the mitigation actions applied. For example, level references may be changed as a result of a risk mitigation action
- The mitigation actions can be discrete or continuous

Pr(t): Probability of occurrence of the risk Rr at the instant t

Zc: different parameters that can be influenced by risks occurrences (i.e. time delays, demand)

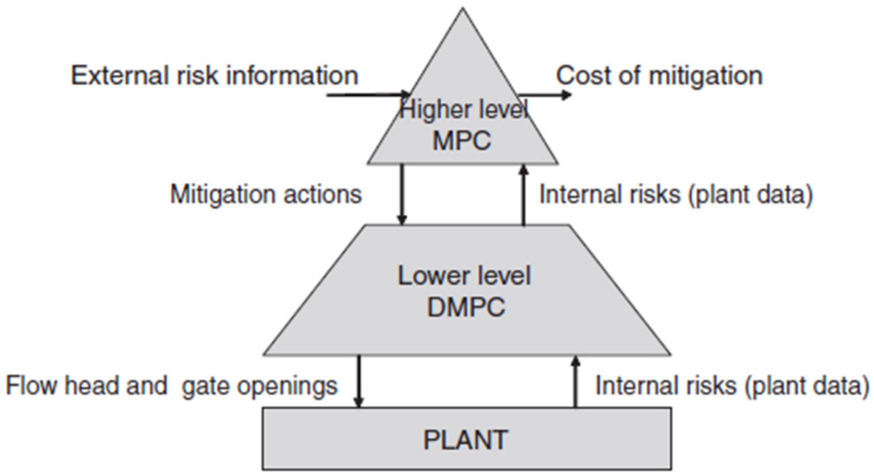
IIrc: initial impact of Rr on the parameter Zc

uMa: represents the decision variable for a mitigation action Aa

fca: reduction of the initial impact affecting parameter Zc when action Aa is applied

Lower level: DMPC

- **Subsystems in the canals**: they start after a gate and ends before next gate
- **Distributed algorithm**: negotiation among agents (subsystems of the canals). The agents don't have any knowledge of the dynamics of any of their neighbors, but can communicate freely amongst them in order to reach an agreement
- Each sampling time, the proposal or change proposed by a neighbor only is accepted **when the sum of the costs increments/decrements implied by the proposal regarding the neighbor affected, results in a cost decrement**
- The control objective is to minimize the sum of each of the local cost functions



Irrigation canal modelling for control

Two equations:

– **Equation (1)** expressing 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

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

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

Case study

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

Higher level:

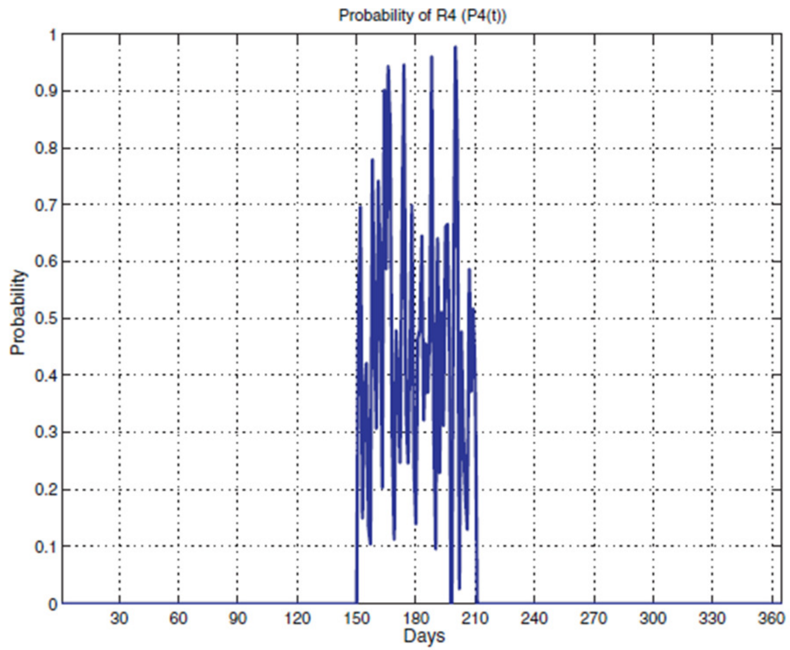
- Main target: to minimize costs due to internal and external risks
- There is a 365 days study period (1 year) and a 1 day sampling time
- Prediction horizon, N= 5 days
- Manipulated variables: mitigation actions, u_M

Offtake gates 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

Case study: Higher level

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



Pr(t): Probability of occurrence of the risk Rr at the instant t

IIrc: initial impacts are expressed on the parameters Z1 and Z2, with Z1 being the cost (euros/day) and Z2 the variation of reference levels in reaches (m)

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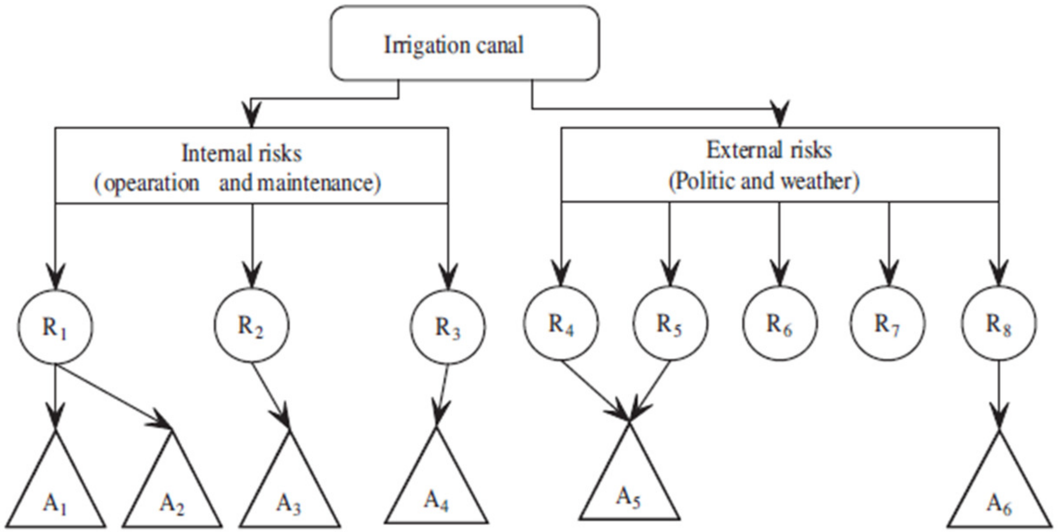
Case study: Higher level



f_{1a}, g_{1a}: reduction of impacts and cost of execution

$\{u_{M1}, \ldots\ldots u_{M6}\}$, where u_{M5} and u_{M6} are real and the rest are boolean

Period of validity of the action:

{D= Daily, W=Weekly, B=Biyearly, Y=Yearly}

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 ($u_{M_6} \in \mathbb{R}$)	$f_{16} = 225u_{M_6}$, $g_{16} = u_{M_6}$	B

Case study: Lower level

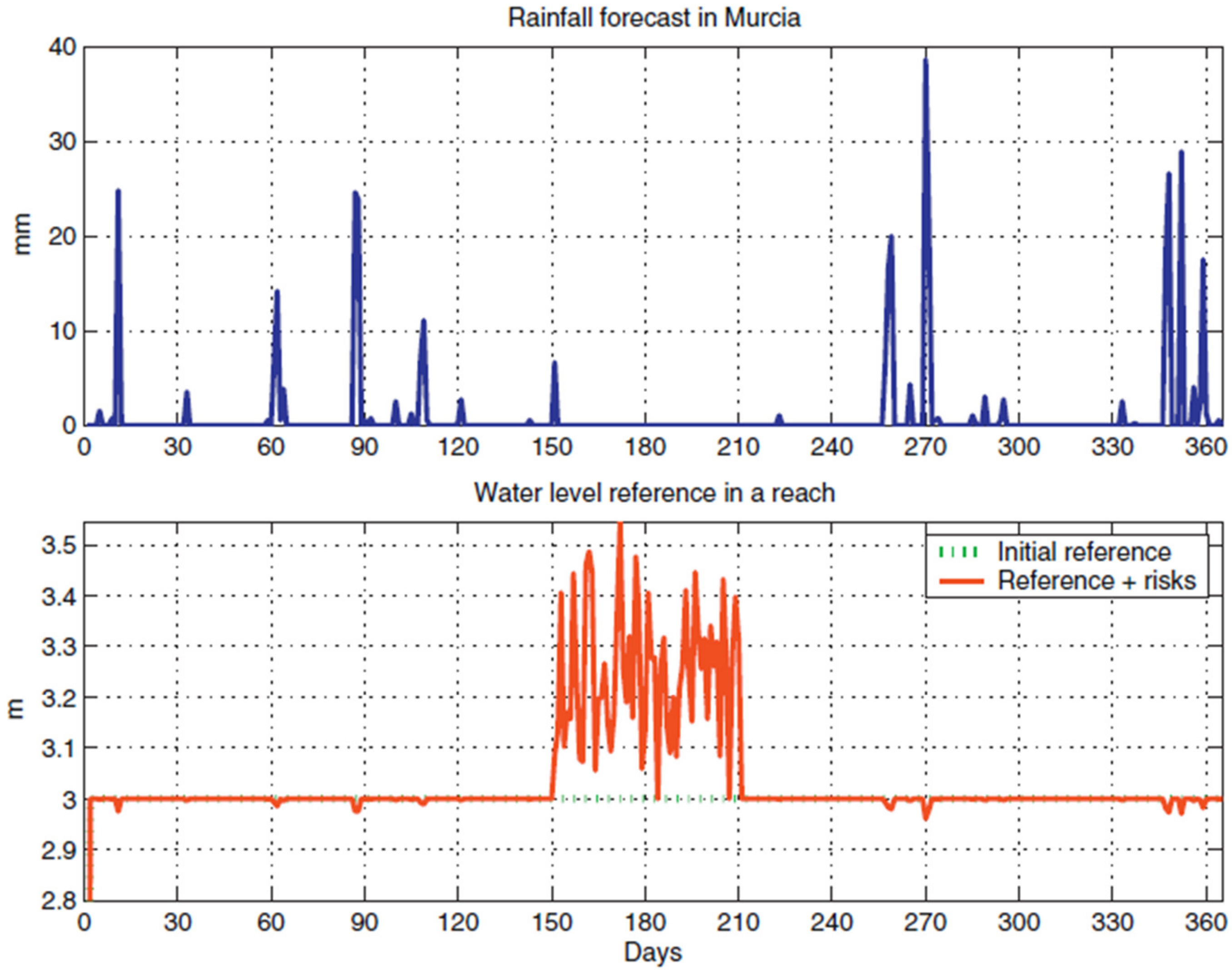
Lower level:

- Main target: to control water management in canals in order to guarantee flow demanded by users

For this purpose, it is necessary to maintain the level of the canal over the off-take gate when flow is requested

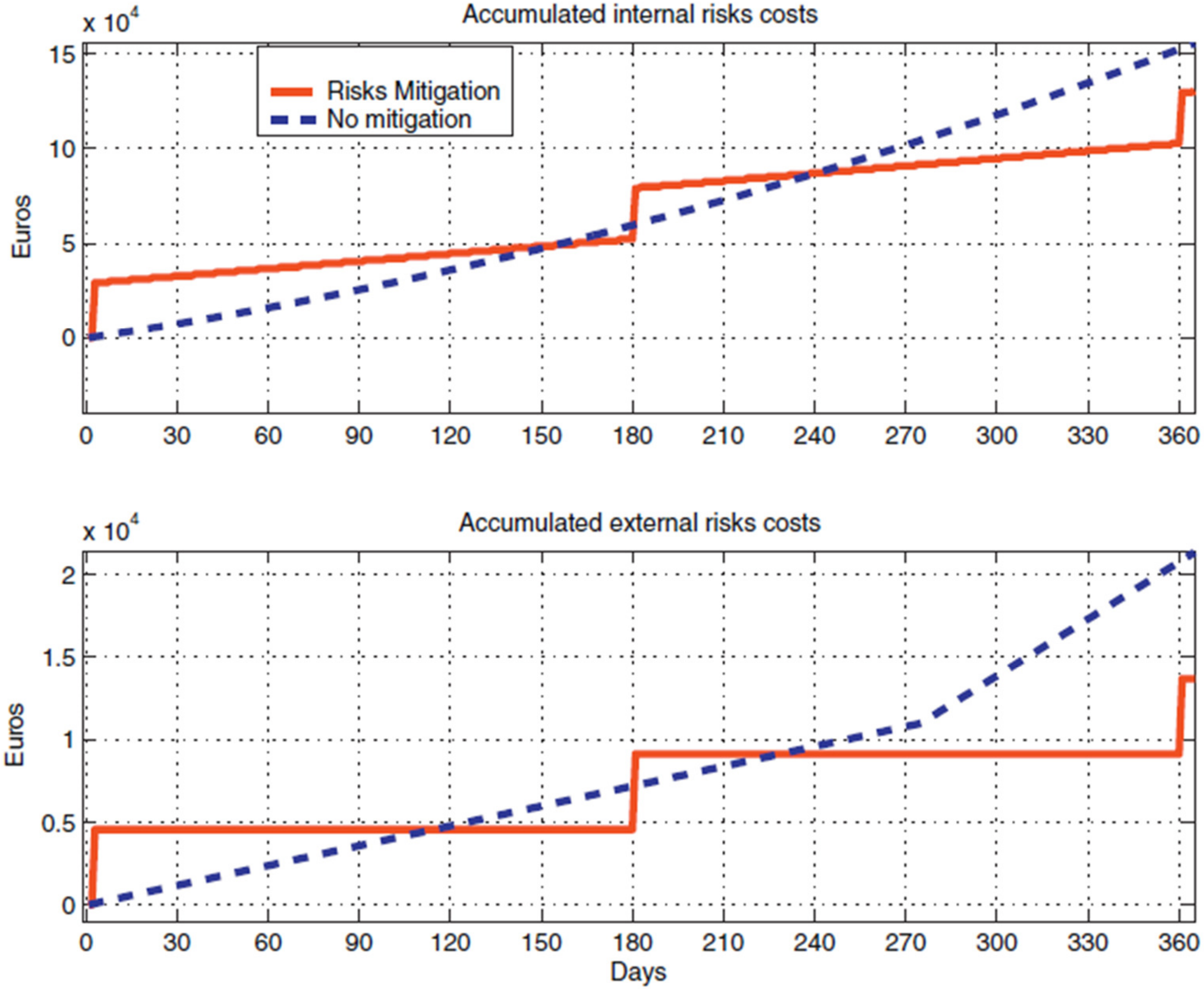
- Controlled variables: upstream levels at the gates, hi
- Manipulated variables: flow at the head of the canal and the position of the gates
- Constraints:
- Period: 1140 min (1 day)
- Sampling time: 1 min

Case study: Results



Top panel: rainfall forecast in Murcia. Lower panel: level reference in one reach by considering risks R_2, R_3 and action A_6.

Results: optimization of the costs considering risks



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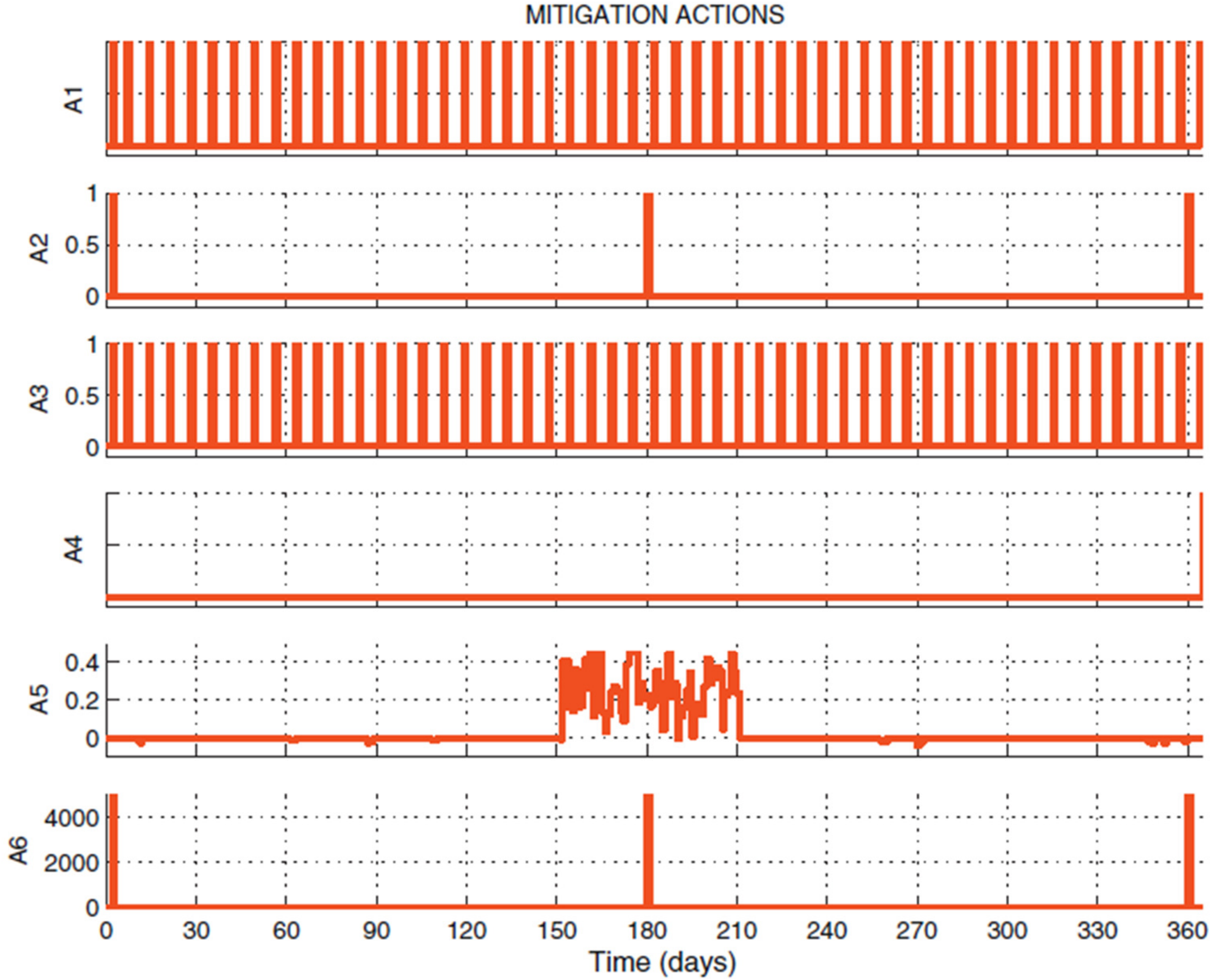
Results: mitigation actions for the reduction of impacts



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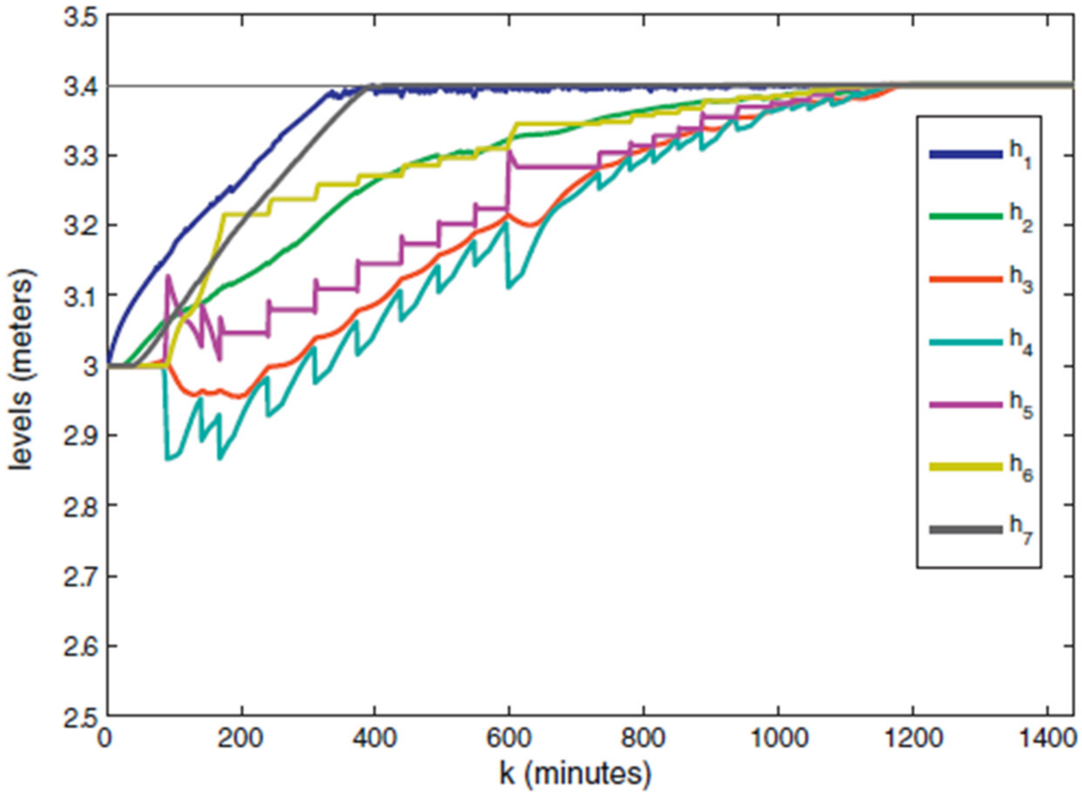
Results: levels in reaches (day 150)



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Thank you for your attention

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