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Economic model predictive control for interactions of water sources connected crop field

G.B. Cáceres * **M. Pereira** * **P. Millán** *

* *Universidad Loyola Andalucía. Avda. de las Universidades s/n 41704*
Dos Hermanas (Spain)(email: gbcaceres@uloyola.es,
mpereira@uloyola.es,pmillan@uloyola.es)

Abstract:
Interest in predicting and optimizing irrigation to minimize water usage in agriculture is growing. In this paper, we present how different water sources interconnected in a farm (surface and underground reservoirs) can provide the optimal amount of water to the crop, considering the water available in each water source and the energy cost associated with pumping, without compromising the crop yield. For this purpose, the formulated economic Model Predictive Control makes use of the dynamical non-linear agro-hydrological model, considering the Volumetric Water Content (VWC) at different depths of the soil and the mass balance of the surface reservoir to generate optimal interactions and flow control strategies from the water sources to the crop field to meet future irrigation demands and finally consider the use of these water sources to alleviate the effects of environmental changes and water scarcity.

1. INTRODUCTION

Global environmental change and the deficient water management in agriculture is a huge concern for users and managers of water resources (Navarro-Hellín et al. (2015)); thus, proper management and allocation of water sources is required for irrigation optimization (Abioye et al. (2020)).

Surface tank/reservoir irrigation has long been practiced in some countries where regions are subject to water stress, in which farmers use water reservoirs with their respective catchment basins to harvest rainwater and use it for supplemental irrigation (Agale and Gaikwad (2017)).

On the other hand, groundwater can serve as a substitute for stored surface water (surface reservoir) and potentially as a complementary source of irrigation water, see Bharati et al. (2008) and Portoghese et al. (2021). The conjunctive use of surface and groundwater reservoirs is an important area of irrigation research (O'Mara et al. (1988)). Some farms located in higher elevations utilize a pump to collect water from the groundwater reservoir and transfer it to the surface reservoir, in which electricity consumption is a concern (dela Cruz et al. (2017)).

According to Moradi-Jalal et al. (2007), the integration of surface reservoirs in irrigation areas is achieved through the objective of efficiently utilizing water storage for regulating the excess water for later use and for filling when the electricity cost is lower and emptying when the crop needs it at any time.

The operation of many water systems is based on heuristic approaches and operator judgment (Incrocci et al. (2020)), which can be quite complicated in large-scale linked systems. Therefore, decision support systems are the answer to this. Advanced control techniques provide an important contribution to system water management (Cembrano et al. (2011)).

Related research in MPC for irrigation control and water supply systems is very scarce. Puig et al. (2012) combines irrigation and water supply systems in which the Guardiana River provides water to the reservoir, so they control the gates and, hence, the volume of safety in the reservoir and the flow for the irrigation area. Ayaz et al. (2020) proposes a single MPC-based controller to interact with both the crop field water demand and the regulatory water level in the canal pools.

The previous works consider the interaction between farms having one water source and, from the energy viewpoint, focus on obtaining water from rivers without considering the pumping of water to reservoirs at a high level at times when the electricity cost is lower and storing it until empty when the crop needs it.

Motivated by the above, an economic MPC is adapted in this paper to an interaction of water sources (surface and groundwater reservoirs) and a crop field based on a farm-scale strawberry plot to optimize the irrigation scheduling and minimize the energy consumption associated with the pump, minimizing costs and without compromising the crop productivity. The case study is presented to exemplify and verify the proposed MPC applied to the water supply systems.

The paper is organized as follows: Section II describes the schematic of the system and the models utilized. Section III presents the MPC formulation for the combined crop field and water supply. In Section IV, we present the considered case study as well as the results of the simulation of the proposed modelling and control approach. Finally, Section V contains the main conclusions.

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2. MODEL LAYOUT AND FORMULATION

2.1 Schematic Model Layout

Our proposed water supply system consists of the use of two different water sources, specifically surface and underground water reservoirs.

The surface water reservoir is an important water catchment for precipitation and can be filled with water from the groundwater reservoir by pumping it to store it for a specified time to be able to irrigate the crop through a valve by gravity due to the height difference.

Aside from filling the surface reservoir, groundwater can also be used to pump directly into the crop field, which is important to note because it can pump water to the crop even when the surface reservoir is empty, i.e. as supplementary irrigation.

Next, Figure (1) presents the schematic of the interaction between surface-groundwater reservoirs and the crop field with the controller.

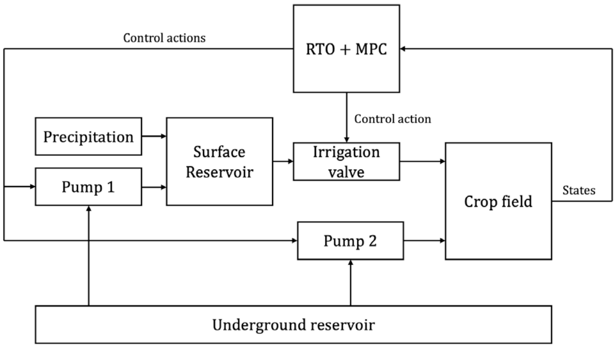

Fig. 1. A schematic of interaction between surface-groundwater reservoirs and crop field with the controller.

The controller receives the Volumetric Water Content (VWC) and the surface reservoir volume values with the purpose of optimizing the irrigation controls (pump 1, pump 2, and valve) and hence the amount of water and electricity costs associated with the pumps.

2.2 Surface Reservoir Dynamical Model

A water surface reservoir has the storage capacity of water at appropriate elevation levels to provide the water necessary to meet the crop's needs. The reservoir's dynamical evolution can be expressed as a differential equation (1) relating to the mass balance in the reservoir, considering all the inputs and outputs.

$$A\frac{dH}{dt} = P_t + Q_b - Q_v \tag{1}$$

where A is the reservoir area, H represents the reservoir water level, working within $\underline{H} \leq H \leq \overline{H}$, where $\underline{H}$ and $\overline{H}$ are its lower and upper bounds, respectively. P_t is the direct precipitation, Q_b denotes the inflows from the underground reservoir to the surface reservoir, and Q_v denotes the outflows from the surface reservoir to the crop field.

2.3 Crop field Agro-hydrological Model

The common way to measure this in the soil is by Volumetric Water Content (VWC), and the land surface water balance is extracted from Cáceres et al. (2021), which the authors developed and tested. The nonlinear partial differential equations are presented as:

$$\begin{aligned}
\frac{d\theta_1}{dt} &= \frac{1}{D_1}\left(I_{rr} - Q_{1,2}(\theta_1,\theta_2) - \frac{1}{\rho_w}E_g\right)\\
\frac{d\theta_i}{dt} &= \frac{1}{D_i}\left(\hat{Q}_i(\theta_i,\theta_{i+1}) - \frac{1}{\rho_w}\frac{E_{tr}}{n}\right), \forall i = 2\cdots N\\
\frac{d\theta_{N+1}}{dt} &= \frac{1}{D_{N+1}}\left(Q_{N,N+1}(\theta_N,\theta_{N+1}) - Q_{N+1}(\theta_{N+1})\right)
\end{aligned} \tag{2}$$

where $\theta_i, i \in \{1,\ldots,N+1\}$ is the VWC of each layer, operating within $\underline{\theta_i} \leq \theta_i \leq \overline{\theta_i}$. D_i is the soil thickness of i-th layer, I_{rr} represents the irrigation $I_{rr} = Q_v + Q_{p2}$, where Q_{p2} is the pump 2 flow, and the total irrigation is within $\underline{I_{rr}} \leq I_{rr} \leq \overline{I_{rr}}$. $Q_{i,i+1}$ is the water flux between layers with the nonlinear dependence of θ_i described by Qin et al. (2009), $\hat{Q}_i = Q_{i-1,i} - Q_{i,i+1}$ represents the water flux difference between root zone layers, E_g and E_{tr} represent evaporation from the soil surface and transpiration from the vegetation canopy, respectively. ρ_w is the water density, n represents the number of root layers.

3. ECONOMIC MPC FOR WATER SOURCES INTERCONNECTED FOR IRRIGATION

A MPC controller is formulated to optimize the interaction between surface, underground reservoirs, and the crop field in order to minimize water consumption and electricity costs associated with the pumps without compromising the crop productivity.

The controller consists of two layers: the upper layer is the Real-Time Optimizer (RTO), and the second layer is the MPC for tracking. The first layer computes the optimal trajectory using the highly non-linear equations (2) with the water reservoir dynamic (1), and the second layer uses a linearized model to predict the evolution of the VWC, the water reservoir level, the energy and water consumption, and the optimal irrigation, enforcing a set of constraints (maximum and minimum for the VWC, water reservoir level, pump flow and irrigation flow). This layer must move the system to maintain the parameters mentioned above as closely as possible to the RTO.

This second layer follows the development of Limon et al. (2015), with this layer the controller guarantees stability and recursive feasibility even when happening changes in certain reference parameters($\mathbf{u}^*$).

Remark 1. The controller is not a classic structure of an economic MPC, but an implementation in which the RTO takes care of economizing the cost function, so the controller is economic. $\circ$

3.1 MPC Formulation

As mentioned above, the first layer of the controller is given by the RTO using the non-linear model equations (1) and (2) and is presented as a non-linear discrete system:

$$x(k+1) = g(x(k), u(k), w(k)), \tag{3a}$$

being $x = [\theta_1, ...\theta_{N+1}, H]^\top$; $u = [Q_b, Q_v, Q_{p2}]^\top$, the control signals, and $w = [E_g, E_{tr}, I_{rr}]^\top$ the disturbances associated with this model.

The second layer uses a linearized model to predict, at the time window equivalent to the system period (1 day), the evolution of the VWC and the optimal surface, underground reservoirs, and crop field interactions considering the water and electricity consumption. Based on the non-linear agro-hydrological model equations (2) and (1), a Linear Time-Invariant (LTI) model is obtained from the linearization around the equilibrium points x_{eq}, and is presented as the following linear discrete system in the state-space:

$$x(k+1) = Ax(k) + Bu(k) + B_d w(k) \tag{4a}$$

$$y(k) = Cx(k) \tag{4b}$$

The model equations (4b) and (4b) have four constant matrices A, B , B_d and C, where A is the system matrix, B is the control matrix, B_d is the disturbance matrix, C is the output matrix and $y(k)$ is the output of the system. The states and control actions are explained before.

3.2 Cost Function Settings

RTO Economic cost function The operational goal for the water management in the proposed irrigation system is to provide the correct amount of water that the crop demands, while minimizing electricity use. For this, the first term weights deviations of VWC below the set-point established as the minimum soil water content permissible. The second term weights the minimization of the energy cost related to the water pumping amount from the underground reservoir to the surface reservoir. The third term weights the amount of water pumped directly from the underground reservoir to the crop field. The fourth and fifth terms weight the minimization of the water use from the surface pump and underground pump, respectively.

$$\begin{aligned} V_p^*(\mathbf{x}, \mathbf{u}) = {} & wp_1 f_1(x^{op}; \mathbf{x}) + wp_2 f_2(\mathbf{u_1}) \\ & + wp_3 f_3(\mathbf{u_3}) + wp_4 f_4(\mathbf{u_1}) + wp_5 f_5(\mathbf{u_3}) \end{aligned}$$

$$f_1(\mathbf{x}) = \sum_{k=0}^{T-1} \|x(k) - x^{op}\|_Q \tag{5a}$$

$$f_2(\mathbf{u}) = \sum_{k=0}^{T-1} C_{elec}(k) u_1(k) \tag{5b}$$

$$f_3(\mathbf{u}) = \sum_{k=0}^{T-1} C_{elec}(k) u_3(k) \tag{5c}$$

$$f_4(\mathbf{u}) = \sum_{k=0}^{T-1} C_{water} u_1(k) \tag{5d}$$

$$f_5(\mathbf{u}) = \sum_{k=0}^{T-1} C_{water} u_3(k) \tag{5e}$$

where x_{op} are the operational VWC points, C_{elec} is a time-varying electric cost, C_{water} is a fixed cost associated with the water per m^3, and wp_i are the corresponding weights, where $i=$ 1..5. The cost function does not involve $\mathbf{u_2}$, because it considers the irrigation through the valve by gravity due to the height difference.

MPC cost function To maintain the economic trajectory given by the RTO and to predict the best interaction between the water surface reservoir, water underground reservoir, and the crop field, the mathematical expression for the cost function V_N is formulated as a quadratic way and is contained by two terms. The first term, V_T (6a), minimizes the difference between the optimal reference of the RTO (x^r, u^r) and the reachable trajectory for the MPC (x^{T*}, u^{T*}), while the second term, V_S (6b), minimizes the differences between the MPC tracking trajectory (x, u) and the optimal reference of the reachable trajectory for the MPC.

$$\begin{aligned} V_N(x^r(0), \mathbf{u}^r, \mathbf{u}) = {} & V_T(x_0^r, \mathbf{u}^r) \\ & + V_S(x^r(0), \mathbf{x}^r, \mathbf{x}, \mathbf{u}^r, \mathbf{u}) \end{aligned}$$

and

$$\begin{aligned} V_T(x_0^r, \mathbf{u^r}) = {} & \sum_{k=0}^{T-1} \|x^r(k) - x^{T\star}(k)\|_W^2 \\ & + \|u^r(k) - u^{T\star}(k)\|_S^2 \end{aligned} \tag{6a}$$

$$\begin{aligned} V_S(\mathbf{x}^r, \mathbf{x}, \mathbf{u}^r, \mathbf{u}) = {} & \sum_{k=0}^{N-1} \|x(k) - x^r(k)\|_Q^2 \\ & + \|u(k) - u^r(k)\|_R^2 \end{aligned} \tag{6b}$$

where W, S, Q and R denote the respective matrix weights.

3.3 Optimization Problem

The control structure focuses on the periodic operation of a closed-loop system with a fixed period T of 24 hours. The quasi-periodic behavior of the main dynamic variables involved at a farm scale (crop transpiration, electricity costs) enables us to take advantage of a periodic, real-time optimizer and tracking layer to achieve better performance.

Real Time Optimizer The optimal interaction can be obtained from the solution of the following optimization problem at any given time, k, where $x(0)$ is a free variable and is denoted as:

$$\min_{x(0),u} \sum_{k=0}^{T-1} V_p^*(x(0), u^{T*}) \tag{7a}$$

$$s.t. \;\; x(k+1) = g(x(0), u(k), w(k)) \tag{7b}$$

$$(x(k), u(k)) \in Z_r, \quad \forall k \geq 0, \tag{7c}$$

$$x(0) = x(T) \tag{7d}$$

where Z_r is a closed polyhedron containing the maximum and minimum states and control action constraints, affecting the VWC (θ_i) and irrigation flow (I_{rr}).

The optimal solution to the problem (7) is used by the tracking optimization problem.

Tracking MPC The tracking MPC can be implemented by solving a finite-horizon optimization problem over a prediction horizon N, where the cost function is minimized subject to the prediction model and a set of system constraints. The objective of this problem is to move the real system as close as possible to the optimal trajectory given by the RTO. Hence, the optimization problem can be formulated as follows:

$$\min_{x_0^r, \mathbf{u}^r, \mathbf{u}} \; V_N(x, \mathbf{u}, \mathbf{w}; x^r(0), \mathbf{u}^r, \mathbf{w})$$

$$s.t. \; x^r(k+1) = Ax^r(k) + B_u u^r(k) + B_d w(k) \quad \text{(8a)}$$

$$(x^r, u^r) \in Z_r \quad \text{(8b)}$$

$$y^r(k) = Cx^r(k) + Du^r(k) \quad k \in \mathbb{Z}_T \quad \text{(8c)}$$

$$x^r(0) = x^r(T) \quad \text{(8d)}$$

$$x(0) = x \quad \text{(8e)}$$

$$x(k+1) = Ax(k) + B_u u(k) + B_d w(k) \quad \text{(8f)}$$

$$y(k) = Cx(k) + Du(k) \quad k \in \mathbb{Z}_N \quad \text{(8g)}$$

$$(x, u) \in Z_r \quad \text{(8h)}$$

$$x(N) = x^r(N) \quad \text{(8i)}$$

where $\mathbf{x^r}$ and $\mathbf{u^r}$ are reachable trajectories by the linear model of the MPC for tracking used to avoid the problematic situation (loss of recursive feasibility) for the MPC controller. That is why this structure is used. Note that the trajectory produced by the RTO does not have to be reachable by the system. For more details, see Limon et al. (2014).

4. CASE STUDY ON SIMULATED STRAWBERRY CROP

The case study in this paper corresponds to a strawberry farm located in Almonte (Spain), with a specific greenhouse type called tunnel greenhouses, in which precipitation does not affect the crop. The strawberry crop uses sandy soil, and this is a problem at the moment to irrigate because the sandy soil drains faster than other types of soil, so the farmers have to irrigate at specific times of the day so that water can be available before it is completely drained (between 8:00 a.m. and 4:00 p.m., when the crop needs water to transpire).

It happens that the electricity cost in those hours is the highest, so we propose the use of the surface reservoir to store the water pumping at a lower electricity tariff and take advantage of the precipitation, thus saving the water amount while also irrigating the amount of water that the crop needs.

Considering the equation (1), to determine the maximum and minimum level of water that can be stored in the surface reservoir, we consider an area of $10000cm^2$ of crop and the type of crop. The reservoir dimension is 500 cm^2. The underground reservoir is unlimited.

The water cost and electricity tariff are extracted from Cáceres et al. (2021) and presented in Fig.2 (d).

The system is subjected to disturbances. Holding the equation (2), the E_{tr} is presented in the Fig. 2 (e) and E_g is equal to zero because there is considered to be no evaporation from the soil. Precipitation is instant disturbance and is subject to seasonal variations. The values used are shown in Table 1. Finally, the soil thickness are D=[3 12 12 12 1] cm, is considered homogeneous soil and crop, ideal and uniform irrigation, and filling/emptying dynamics.

4.1 Case Description

Considering the structure of the system (water surface, underground reservoirs, and crop field), we proposed the comparison of two specific cases: the first is the on-off control activated with a relay, and the second is the proposed economic MPC controller.

Table 1. Table of soil hydraulic parameters and controller constraints and weight values

Soil hydraulic parameters			
Variables	Distribution	Values	Units
θ_{sat}	uniform	0.395	cm^3/cm^3
K_{sat}	uniform	1.056	cm/min
ψ_{sat}	uniform	12	cm
B	uniform	4.05	-
Constraints and weights			
	RTO	MPC	
Variables	Range/values		Units
$(\overline{\theta}, \underline{\theta})$	[0.29 0.115]	[0.29 0.10]	cm^3/cm^3
$(\overline{H}, \underline{H})$	[15 100]	[15 100]	cm^2
$(\overline{I_{rr}}, \underline{I_{rr}})$	[0 0.0098]	[0 0.0098]	cm/min
$(wp_1, ..wp_5)$	[0.01 10^6 10^6]	-	-
(W, S, Q, R)	-	[5 200 100 1]	-
E_g	0	0	cm/min

Case 1- On-off controller The on-off controller is one of the simplest closed-loop irrigation controls with widespread usage in practice. When the difference between θ_i and the $\underline{\theta_i}$ detected is less than a threshold λ, this controller adjusts the amount of irrigation. When the θ_i value is less than the λ, the controller applies a constant amount of water $\overline{I_{rr}}$ to the crop field, otherwise $I_{rr} = \underline{I_{rr}}$. The threshold prevents the crop from reaching the WP, the point where the plant cannot absorb water from the soil. The control law can be expressed as Flugge-Lotz (2015):

$$I_{rr} = \begin{cases} \overline{I_{rr}}, \text{ if } \theta_i - \underline{\theta_i} \leq \lambda \\ \underline{I_{rr}}, \text{ if } \theta_i - \overline{\theta_i} > \lambda \end{cases} \quad (9)$$

The on-off controller does not take into account the electricity prices and does not optimize the water consumption. Just change the state (0 or 1) depending on the threshold value.

In this specific case, the farmers take advantage of the surface water reservoir, so they pump water only at night, when the electricity prices are lower, see in 2(d). The pumping time is 75 minutes with constant water flow. After this, during the day, the on-off controller works in a close-loop.

Case 2- Economic MPC controller This controller optimizes the water consumption and the electricity cost associated with the pumping. The equations (1) and (2) were linearized around equilibrium points. The equilibrium points x_{eq}=[x_{eq1},x_{eq2}] are the points where the soil is in FC, points where it has the maximum crop productivity. In this paper $x_{eq} = x_{op}$. The x_{eq1} = [0.154, 0.153, 0.152, 0.151]$^\top$ $\frac{cm^3}{cm^3}$ for the VWC, and x_{eq2}=60 cm for the surface reservoir water level, u_{eq}= [0, 0, 0]$^\top$, w_{eq}=[0, 0, 0]$^\top$. The prediction horizon is chosen to be equal to the period, that is N=T=96 (24 hours).

The RTO and MPC for tracking constraints and weights are summarized in Table 1(b). The linear model used in this controller results in the following normalized system matrices:

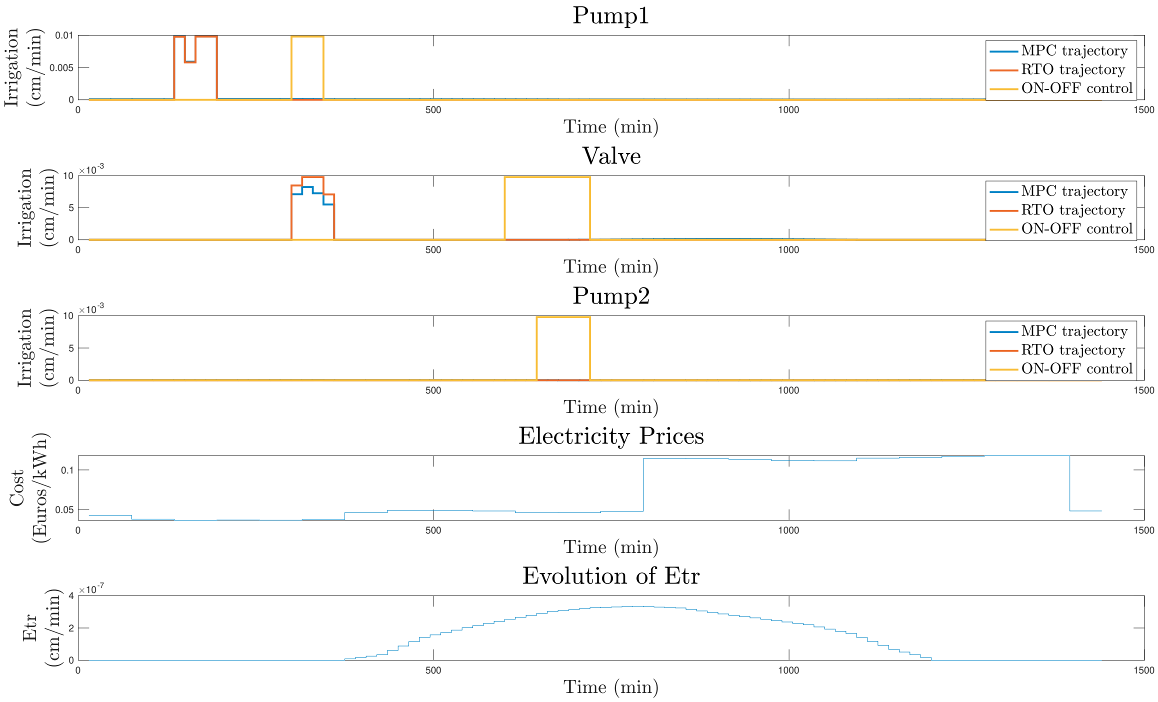

Fig. 2. (a) Comparison between irrigation flows for the Pump1 (b) Comparison between irrigation flows for the Valve (c) Comparison between irrigation flows for the Pump2 (d) Electricity prices (e) Evolution of the Etr

$$A = [A_d, A_{dd}] \tag{10a}$$

$$A_d = \begin{bmatrix} -0.125 & -0.006 & 0.010 \\ -0.037 & -0.012 & 0.002 \\ 0.296 & 0.258 & -0.002 \\ 0.596 & 0.117 & -0.036 \\ -0.013 & -0.002 & 8.42e-04 \end{bmatrix} \tag{10b}$$

$$A_{dd} = \begin{bmatrix} -0.023 & -0.008 \\ 3.693e-04 & -0.002 \\ -0.007 & 0.006 \\ 0.053 & 0.027 \\ -0.002 & -3.72e-04 \end{bmatrix} \tag{10c}$$

$$B = [B_d, B_{dd}] \tag{10d}$$

$$B_d = \begin{bmatrix} -9.69e-04 & -0.012 & -8.891 \\ 0.0012 & -5.06e-04 & 1.005 \\ -0.018 & -0.015 & 1.171 \\ -0.003 & 0.031 & 2.277 \\ -4.64e-04 & -4.27e-04 & -0.126 \end{bmatrix} \tag{10e}$$

$$B_{dd} = \begin{bmatrix} 8.66e+03 & -1.675 & 1.048 \\ -8.94e+03 & -1.438 & -1.367 \\ 1.67e+05 & 0.369 & 26.35 \\ 3.58e+04 & 0.518 & 7.658 \\ 671.45 & -0.010 & -0.013 \end{bmatrix} \tag{10f}$$

$$C = \begin{bmatrix} -3.728 & 2.174 & 0.417 & -0.577 & 0.496 \\ -0.892 & 2.033 & 0.201 & -0.213 & 0.487 \\ 0.109 & 0.079 & 0.027 & 0.081 & 0.687 \\ 0.248 & 0.477 & -0.018 & 0.105 & 0.760 \\ -1.014 & -0.506 & 0.162 & -0.490 & -7.603 \end{bmatrix} \tag{10g}$$

4.2 Interactions Between Water Surface, Underground Reservoirs and Crop Field

Both controllers were evaluated using the non-linear equations, and were initialized at the same points x_0=x_{eq}. A simulation of 30 days was conducted, to determine in permanent regime the irrigation amount given to the crop. To simplify the simulation, we assumed that the pump consumes 1 kWh/m^3.

The results of one day are presented in Figure (2) in both cases, the pump 1 extracts water from the underground reservoir when the electricity prices are lower. The valve irrigates the crop field when the roots need to absorb it. Pay attention to the on-off controller trajectory in Figure (2b). The amount of water irrigated is greater than the pump1 lead at the beginning of the simulation. That is because the surface reservoir has an initial amount of water storage (same in both cases). The pump 2 of the on-off controller irrigates when the VWC values are under the threshold and the surface reservoir does not dispose of the minimum water level. On the other hand, the pump 2 of the economic MPC controller pumps practically zero because it is not necessary to waste electricity because the water in the surface reservoir is sufficient.

The crops needs per day are 5,25 l/m^2. As can be checked in 30 days, the on-off strategy waste 25,07% of irrigated water, and the economic MPC controller waste 19,97% of the irrigated water.

According to Table 2(a), the economic MPC controller has better results than the on-off controller and uses the surface reservoir to store the water for later use, however, the on-off controller pumps less to the surface reservoir and utilizes the pump 2 to irrigate the crops, without considering the energy costs.

Table 2(b) show how the economic MPC controller pumps more into the surface reservoir because it suits the electricity price. However, the on-off controller uses pump 2, with a lot of difference in economic terms.

Table 2. Table of the comparison between classical irrigation and the proposed MPC controller

Irrigation amount			
Study terms	On-off controller	MPC controller	Units
Pump1	132.23	207.9	l
Valve	141.5	201.6	l
Pump2	74.84	2.65	l
Electricity costs			
Study terms	On-off controller	MPC controller	Units
Pump1	491.1	953.1	€
Valve	-	-	€
Pump2	1930	25.27	€

5. CONCLUSIONS

In this paper, we have formulated an economic MPC that combines irrigation and water supply systems. Based on the conducted simulations, it can be concluded that the MPC can optimize the surface and groundwater reservoirs with the crop field interaction, economizing the energy cost and water saving.

While we assume a particular configuration of two reservoirs and crop fields, the approach is generic and can easily be extended to multiple reservoirs and other energy sources (solar panels).

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