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Research article

Improvement of sustainability indicators when traditional water management changes: a case study in Alicante (Spain)

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Abstract: Pressurized water systems are designed to guarantee the flow demanded by each user, considering the minimum required pressure. The pressurized water systems have increased water efficiency since their implantation, but they also increased the consumed energy and therefore, the greenhouse gasses emissions. The present manuscript develops the proposal of the sustainable indicators that were selected through deep review. These indicators are related to social-cultural, economic, and environmental criteria. Furthermore as novelty, they were described and applied on a pressurized water network, complementing the energy indexes usually used in the energy audit. To reach the improvement of the sustainability in water systems, new strategies should be developed to improve all sustainability criteria, included the water and energy efficiency. These strategies were developed and analyzed by using of specific hydraulic software (i.e., EPANET) and they were based on operation rules to estimate the hydraulic values (pressure and flow). The operation and the regulation strategies were applied on a particular case study, in which, the energy saving was 12.26%, the cost saving was 15.54%, the reduction of energy footprint of water was 15.04%, and the decrease of GHG was 12.26% although the increase of the distributed volume was 9.07%. Besides, the supply guarantee for both irrigation and urban water distribution systems was increased in the new proposal of water management. Finally, the proposal to replace of a pressure reduction valve by a sustainability recovery machine (e.g., pump working as turbine) contributed with a generation of renewable energy equal to 103,710 kWh/year.

Keywords: sustainability indicators; energy efficiency; pressurized water systems; GHG emissions; water efficiency

1. Introduction

The pressurized water systems (drinking and irrigation) are designed under pressure and flow requirements, which establish the design and operation of the network. The pressurized water systems have to guarantee the demanded flow by each user, with the minimum required pressure [1]. Sometimes, the compliance of these requirements such as the consideration of the topography where the network is located or the installation of the pump systems to guarantee the service conditions are necessary. The irrigation modernization also caused the installation of pumps in irrigated surfaces in which, the irrigation had always been developed by open channels flow. The increase of the installed capacity in these transformations was approximately estimated on between 1.5 and 2 kW/ha [2]. Therefore, the irrigation modernization improved the hydraulic efficiency, but the new operation also increased the energy consumption as well as the greenhouse gas emissions (GHG). Currently, these increases aren't considered correct, taking into account the new politics of energy savings (e.g., Kyoto Protocol) and the sustainability requirements embedded in environmental legislation of the European Union (e.g., Directive 2000/60/EC) [3]. These needs should be taken into account in the water resources management. Therefore, although the pressurized water systems and the energy sustainability appear to be confronted, the development of energy optimization strategies is necessary to minimize the used energy in the flow distribution in pressurized water systems [4].

The sustainability concept is quite well known, and its definition considers the need of reducing the use of the non-renewable resources and the emissions. However, the sustainability is a complex concept and it can be defined as a development that satisfies the needs of the present generation, but considering the future population needs. The main sustainability considerations are the use of the renewable sources (e.g., water) that shouldn't exceed the rate of renewal, the use of non-renewable resources (e.g., fossil fuels) should be contained, and the fundamental ecological processes and structures should be maintained [5].

The sustainability integrates both supply and irrigation pressurized systems. However, the consumed volume in irrigation systems is greater than supply networks (e.g., 70% of the consumed volume is assigned to irrigation [6]). Therefore, the significance of the irrigation consumed volume is crucial to develop the sustainability strategies in the pressurized networks. So, considering the previously cited premises, the water managers should embrace the sustainability concept by the generation of positive synergies between water and energy saving, as well as GHG reduction. To reach these synergies, a careful assessment on individual irrigation technologies across a range of cropping systems should be practiced in order to decide their implantation in the water systems [7].

Every distribution water system (supply or irrigation) has two different phases related to the water distribution [8]. The first stage is the transfer of the resource from the source to the main tank or reservoir. The second phase is the water distribution from the main tank to the users, in which the demand can be scheduled or not.

Under an energy cost point of view, the energy efficiency in pumped systems is more important than water systems that operated by gravity. The energy efficiency is usually increased when the irrigation is developed by rotation schedule and the sectors are properly selected, since the organization of the irrigation events and the demanded flow are exactly known. When the systems operate under on-demand, the demanded flow is not exactly known over time due to the number of open irrigation points changes depending on the number of users. Considering the previous comments, the real manometric head of the pumped systems in rotation schedule networks is usually more adjustable than in on-demand systems. Therefore, the stochastic nature in the water on demand causes the oversizing of the network and pumping station whether the selected hypotheses are not correctly considered.

The efficiency improvement in the irrigation networks is a known topic in the consulted references, in which, a high number of different methods can be found to reach the energy increase. These strategies were focused on developing the groups of the hydrants into sectors to optimize the energy management in the irrigation networks [9]. By using an adequate algorithm, the systems can achieve significant energy savings by the adoption of alternative management such as semi-arranged demand, dividing the network into sectors; or improving the pumping station allowing them to operate in the most efficient manner [9,10]. However, although pumped irrigation networks on demand are less efficient than scheduled irrigations, the first kind of irrigation increases the user’s freedom to manage their exploitations. Furthermore, in pumped systems, the installed machines must be very well selected and the design of the networks on demand must consider a percentile of circulating flow (e.g., 90–95%) [11,12] to define the maximum manometric head, supported by the pumped system. This percentile is smaller than the chosen value when the network operates by gravity. Therefore, this bad habit should be avoided to achieve energy improvement in the water networks. As an example, when many Spanish irrigation systems were designed, many designers decided the installation of closed valves partially to restrict the pumped flow in the pumping station [13], causing high energy losses. The replacement of this valve by a simple installation of driver speed in the pumped system increases the energy efficiency considerably [2].

Regarding the efficiency strategies, Table 1 shows the results for operational actions that were applied on pump stations in three pressurized irrigation networks, which were located in Spain. In each case, the researches applied different strategies to change the regulation of the pumping station, reducing energy consumption between 4 and 36% compared to the beginning consumption value. In the first example (Tarazona, Albacete), the pumps regulation was adjusted in order to reduce the pressure in the pressurized system according to demand flow [14]. This consumption was calculated through the development of a new methodology to estimate flows over time. In the second example (Villarreal), the developed strategy was based on the establishment of homogeneous irrigation turns. These turns depended on geometric level, and their association enabled to reduce the manometric head, and therefore, the consumed energy [15]. Finally, in the last case study (Picassent), the consumed energy was also reduced by the development of the irrigation turns, minimizing the manometric head. Furthermore, the consumed energy was improved by a new methodology to select the consumption point in each irrigation turn [9].

Table 1. Three case studies comparison [9,14,15].

Case study	Type of irrigation consumption	Energy Consumed (kWh/year)	Methodology applied to save energy	Energy Saved (%)	Energy Saved (kWh/year)
Tarazona (Albacete, Spain)	On-demand	54,750	improving regulation of the pumping station	4–8	4380
Cap de Terme (Villarreal, Spain)	Rotation schedule	2,409,000	improving regulation of the pumping station and changing turns	28	674,520
Picassent (Valencia, Spain)	Rotation schedule	657,000	improving regulation of the pumping station	36	238,490

These examples show that the energy efficiency increase is possible, and therefore, the implementation of an efficient water management is necessary to mitigate water stress and to embrace the sustainability concept [16]. This new management must be developed to improve the energy efficiency, to encourage water saving, and to promote the water reutilization. These strategies should be focused on:

- The cost recovery principle (Water Framework Directive). This principle must be applied for encouraging users to reduce the water consumption and to improve the efficiency in their facilities. Currently, many irrigators don't apply on saving idea because the water management and boundary conditions were different when they irrigated by open channels flow. Therefore, the water managers should develop strategies to motivate them to save water. This motivation can be reached by rewarding the production obtained per cubic meter of water used, instead of distributing the subsidies without considering production. Finally, it should be ensured that all the money users pay is invested in maintaining and improving these services [17].
- The renovation of the old or inefficient infrastructures. This crucial aspect should be considered by water managers in order to reduce water leakages. This reduction enabled the reduction of the water consumption and, therefore, the consumed energy [17].
- The farmers' education has to be focused on environmental issues. The implementation of these issues has to be motivated to the users (e.g., water saving) by the water managers [17].
- The development and the application of environmental techniques (e.g., water saving strategies, strategies to reduce leakages, installation of recovery systems such as pumps working as turbines [18,19]), which should be increased by incentivizing research in universities or institutions [17].
- The incorporation of sustainability assessment into decision making processes. The use of specific indicators is becoming a key task for water service providers (e.g., supply networks in United Kingdom) [3], for selecting the most appropriate criteria in this decision-making process, considering the manager's objective [20].

The present manuscript analyzed, on the one hand, a review of sustainability indicator and on the other hand, the water distribution from the source to reservoir tanks. To do so, a methodological strategy was proposed to be used in pressurized water systems, improving the sustainability of the water system. This strategy was applied on a network located in Spain, in order to improve environmental indexes through energy balance and new proposal of management. The analysis of this system was presented, considering different aspects related to sustainability criteria (e.g., social, environmental, economic) that are normally applied on pressurized water systems.

2. Materials and Method

The proposed methodology was focused on six main steps. The first step was to define, based on the consulted references (Input 1, Figure 1), the possible indicators to be used to characterize the sustainability in the pressurized water systems, seldom considered as environmental criteria in these networks. A deep review was developed to classify possible sustainability criteria, selecting those more representative in the pressurized water systems (Step 1). This classification was described on section 2.1. Inside of the sustainable criteria, the energy is an important indicator that has implications with other environmental criteria such as the consumed energy or the active power.

Both terms are related to the economic cost and the greenhouse gasses emissions (GHGs). Therefore, a selection of energy indicators was done through consulted references (Step 2). This group of indicators was classified in section 2.2. The quantification of the different energy indicators was proposed through an energy balance, adapted for pumped water systems (Step 3). This balance was developed by using EPANET software [21] (Step 4), and this tool was used to determine the flows and the pressures over time. The output results were used to determine the different indicators, analyzing their possible improvement. If it is possible, a new water management proposal is considered and analyzed by EPANET (Step 5), obtaining the new values of the indicators (Output 2) and developing the comparison between current and proposed water management (Step 6). Finally, the best water management is proposed.

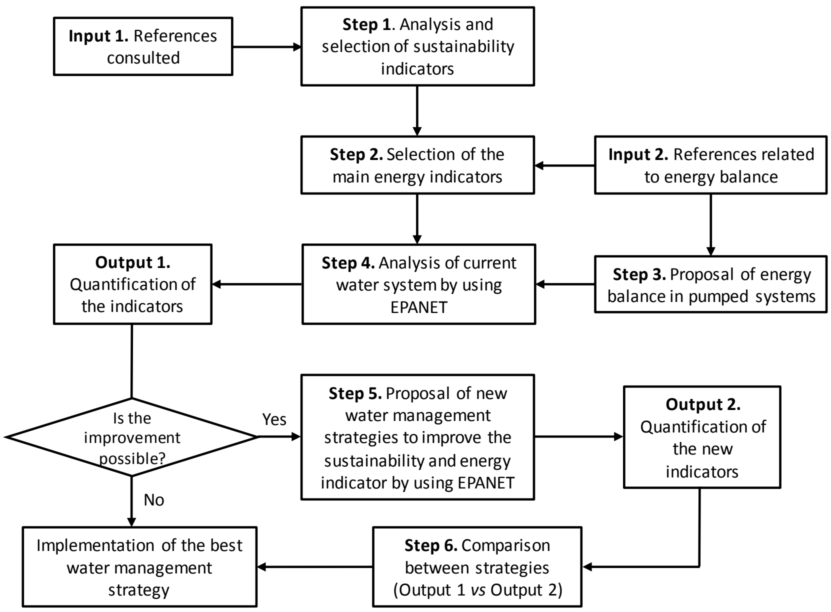

Figure 1. Methodology proposed for analyzing the sustainability improvement of the water system.

2.1. Sustainability criteria in water systems

In the sustainable development of the infrastructures, the result of a planning process is usually a specific solution, in which, people from various backgrounds are involved (e.g., society, institutions, and stakeholders). When the sustainability was analyzed, there are different perceptions of the urban infrastructures and their management. Different authors [22-26] defined different criteria to establish the sustainable indicators, which were summarized and classified by Helstrom et al., (2000) [25], according to the perspective of the relationship between people and the environment and the attitude with respect to norms and values, which are quantitative and qualitative terms respectively [5]. These aspects were defined on five basic criteria: (1) health and hygiene criteria, (2) social-cultural criteria, (3) environmental criteria, (4) economic criteria, and (5) functional and technical criteria [27]. For each criterion, various indicators can be suggested. However, other researches also categorize in similar criteria such as Texeira et al., (2016) categorized in four criteria (environmental, technical, social, and governance) [28]. From Table 2 to Table 4, different indicators were classified depending on previously cited criteria. Although there are many indicators, these were selected depending on available data in the case study analyzed. However, the knowledge of these indicators is useful to develop strategies to know the environmental sustainability indicators (ESI).

Each indicator was defined on the first column, in which, its measured unit was indicated. Before, for each indicator, the threshold risk was established according to consulted references. This threshold established the maximum level of the indicator that could be accepted. In some instances, the threshold wasn't defined because there were no values in the cited references. Other times, the threshold cannot be fixed because its value depends on intrinsic parameters of the analyzed system, such as groundwater level or other parameters.

Table 2. Indicators for environmental criteria.

Indicator	Description	Threshold of risk	Reference
N to water (kg/year)	Eutrophication	1.3	[29]
P to water (g/year)		23	[29]
$CO_{2\text{-eqv}}$ (kg/year)	Contribution to global warming	12	[27]
Cd, Hg, Cu, Pb (g/year)	Spreading of toxic compounds to water	Cd: <0.008 Hg: <0.02 Cu: 0.8 Pb: <0.08	[27]
Cd, Hg, Cu, Pb (g/year)	Spreading of toxic compounds to arable soils	Cd: 0.041 Hg: 0.061 Cu: 9.0 Pb: 1.2	[27]
Sludge to landfill (kg dissolved solids/year)	Contamination of media	--	[30,33]
Use of fresh water (m^3/year)	Use of natural resources, energy and related emissions	120	[27]
Total water use (m^3/year)		--	[34]
Recycling of P to agricultural land (kg/year)		--	[29,31,32]
Energy indexes		Defined in section 2.3	[37,38]

Table 3. Indicators for health-hygiene criteria.

Indicator	Description	Threshold of risk	Reference
Acceptable drinking water quality (% of samples)	Water quality is acceptable to drink	>99.5	[27]
Non-access time to drinking water (hour/person, year)	Time where the access to drinking water is not possible	3.5	[27]
Number of waterborne outbreaks (No./100,000 people, year)	Risk of infection	0.05–0.1	[27]
Number of affected persons (No./100,000 people, year)	Risk of infection	5–10	[27]

Table 4. Indicators for economic and technical criteria.

Criterion	Indicator	Description	Threshold of risk	Reference
Economic	Capital cost (€/person, year)	Total cost	34	[27]
	Operation and maintenance (€/person, year)		63	[27]
	Non access to clean water (hour/person, year)		3.5	[27]

To evaluate GHGs, all consulted emissions data (e.g., CO_2, CH_4 and N_2O) from different irrigation systems were converted into carbon dioxide equivalent value ($CO_{2\text{-eqv}}$) [7]. These emissions were defined based on:

- the use and consumption and diesel for various farm operations. These emissions were calculated using the following factors. If the resource was diesel and diesel oil, the energy content factor was 38.6 MJ/L and the GHGs were 75.2 g CO_2/MJ. If the resource was electricity, the energy factor was 11.93 MJ/kWh and the GHGs were 281 g CO_2/MJ [7];
- the production and the use of the farm machinery: these present a high relationship with GHGs in the consumption of fossil fuels due to operation of the machinery on the farm, so farm machinery production represents 14.4% of fossil fuel related emissions [7];
- the production, the packaging, the storage, and the transport of agrochemicals. The CO_2 emission factor for the major elements in the herbicides, the fungicides, the fertilizer and the plant growth regulators were defined on several studies of the soil-derived nitrous oxide (N_2O) as well as the pollution of the groundwater resources [38]. In this case, the biologically-fixed N cannot be reliably estimated.

At the same time, if the energy savings and the energy recovery are considered, these can contribute with average theoretical reduction of GHG equal to 730 g CO_2/kWh when these recovery systems are compared to non-renewable energy solutions (e.g., coal and gas) [40].

From the economic point of view, regarding to the available data for urban networks, the northern countries had a low per capita water consumption, despite the water resources abounded [41]. This occurred because every cost, generated by the management of the sustainable service, was recovered by the users that paid a high price for it. In contrast, in the countries of southern Europe (e.g., Spain), the water stress is too high and the subsidized tariffs are yet frequent. These determinants currently cause the lack of the maintenance in the hydraulic infrastructures. Considering the aforementioned, the water managers have to consider the need to motivate their user to abide them the cost recovery principle, because these politics are not yet applied. These interventions will improve their management as well as the users will benefit them, reducing their exploitation costs. All water managers should consider the greater cost recovery is the greater the efficiency.

Comparative economic studies analyzed the productivity in irrigation area, and its value depended on the source of water. Therefore, the water price paid by the farmer is key in the feasibility of their exploitations. As an example, in Spain, Andalusian farmers paid 0.01 €/m^3 for surface water in 2000, while they paid ten times more for groundwater, due to the cost of energy [42]. In Spanish Mediterranean region, the water price oscillated between 0.03 and 0.40 €/m^3 depending on the source (e.g., transfer, groundwater) [43]. Finally, it should be remarked the desalination isn't currently a sustainable solution, because the generated water needs a high value of energy, and therefore, an expensive price (around 60 €/m^3) is obtained and it cannot be used in the agriculture.

Currently, it is the most applied solution to address the problems in the Spanish supply networks when the drought makes impossible to obtain water through other sources. However, the use of desalination in the agriculture is today unviable due to high price, considering the profitability of agricultural exploitations. Moreover, the European Union and the Spanish government consider this source as the ultimate solution to be applied when the drought worsens [41].

2.2. Energy balance

The energy balance was studied by different authors both irrigation and drinking systems. Cabrera et al., (2014) proposed an energy balance to analyze audits in pressurized water network in terms of average values of flow rate [15]. Pardo et al., (2013) applied energy indicators in irrigation audits [37]. Pérez-Sánchez et al., (2016) improved the energy balance developing a methodology, which analyzed the energy balance in time intervals, and therefore, the energy balance was developed with variable flows [1]. Particularly, the possibility to define the energy balance with variable flows was the reason to select the last methodology. Therefore, the methodology, proposed for the energy cost analysis on generic systems, was developed in this section according to Pérez-Sánchez et al. (2016) [1]. Nevertheless, this methodology was adapted to consider pump systems that are integrated in the water pressurized system.

Figure 2 showed the scheme of the piezometric head and flows in a pressurized water system, where H_{i1} is the manometric head of the pump 1 in m w.c.; H_0 is the piezometric height of the initial tank in m w.c.; Q_{i1} is the flow pumped by the pump 1 in m^3/s; Q_{f1} is the flow circulating through pipe 1 in m^3/s; J_1 is the head lost by friction through pipe 1 in m w.c.; H_{r1} is the piezometric head of tank number 1 in m w.c.; Q_{r1} is the flow supplied by tank number 1 in m^3/s; Q_{f2} is the flow circulating through pipe 2 in m^3/s; H_V is the piezometric head before the pressure reduction valve in m w.c.; J_2 is the head lost by friction through pipe 2 in m w.c.; Q_l is the consumed flow by the users in m^3/s; Q_{f3} is the flow circulating through pipe 3 in m^3/s; H_l is the piezometric head of service in the consumption point in m w.c.; H_{VF} is the piezometric height after the pressure reduction valve in m w.c.; J_3 is the head lost by friction through pipe 3 in m w.c.; Q_{f4} is the flow circulating through pipe 4 in m^3/s; H_{r2} is the piezometric head of tank number 2 in m w.c.; H_{i2} is manometric head of pump number 2 in m w.c.; Q_{i2} is the flow pumped by pump number 2 in m^3/s; Q_{f5} is the flow circulating through pipe 5 in m^3/s; H_{r3} is the piezometric head of tank number 3 in m w.c.; J_5 is the head lost by friction through pipe 5 in m w.c..

If the energy input is analyzed in a network, two classifications can be proposed for performing such analysis. On the one hand, the energy, supplied by the pumping stations, when the network is pumped, and the other hand, the energy due to head difference between reservoirs when these systems operate by gravity.

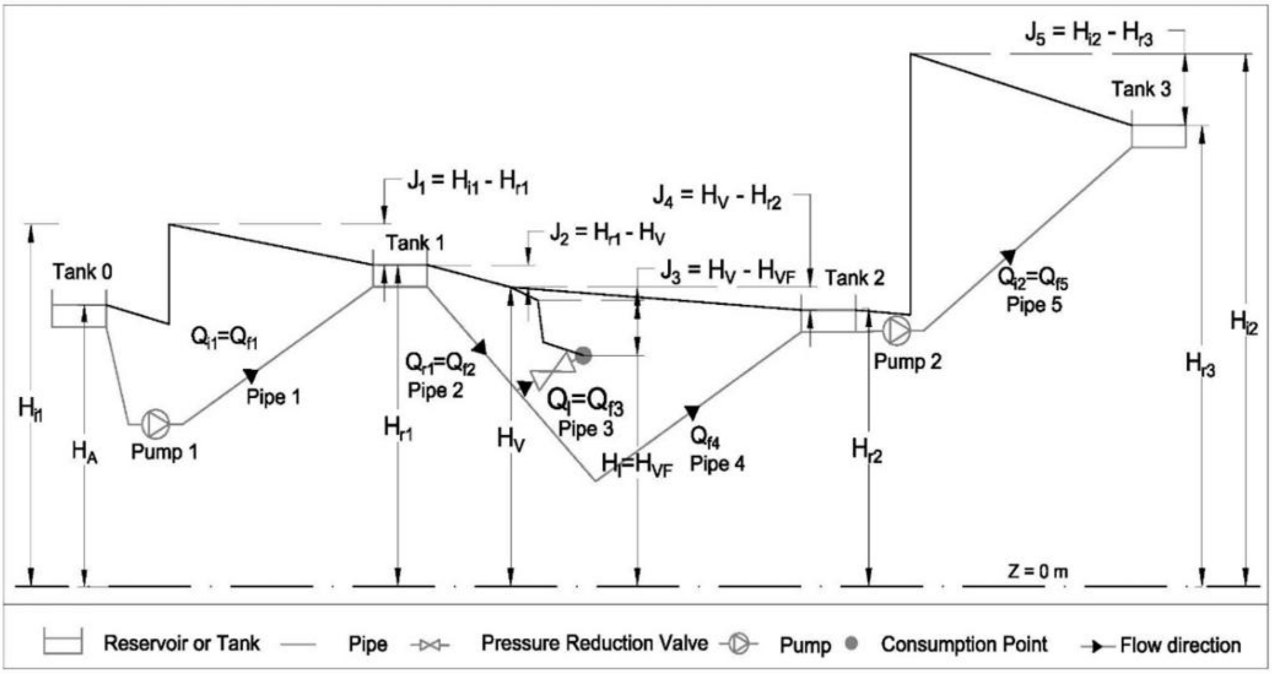

Figure 2. Manometric and piezometric heads in a general operation system.

In case of the supplied energy by the pumping stations, the energy balance is determined by the equation (1):

$$E_{T_i} = K * Q_i * H_i * \Delta t \quad (1)$$

where E_{T_i} is the energy supplied by pumping stations in kWh; K is the constant obtained when the fluid considered is water whose specific weight is 9.81 KN/m^3 and the conversion from seconds to hour is developed. K is equal to 2.725×10^{-3}; Q_i is the flow rate supplied by pumping station with the subindex i (m^3/s), H_i is the pumping manometric head of the pump with the subindex i (m w.c.); and Δt is the time interval of integration(s).

If the gravity system is considered, the supplied energy by the reservoirs is represented by equation (2):

$$E_{T_r} = K * Q_r * H_r * \Delta t \quad (2)$$

where E_{T_r} is the supplied energy by the reservoirs (kWh), Q_r is the supplied flow rate by reservoir r (m^3/s) and H_r is the piezometric head of the reservoir r (m w.c.).

Regarding to the output energy of the irrigation network, these can be divided into three types: the consumed energy in the irrigation point, the lost energy in the friction in pipes (which considers the located losses (e.g., valves, bellows, derivations, hydrants)), and the lost energy due to leakages.

Firstly, the available energy that is consumed by the consumption points (irrigation and drinking) and it is determined by equation (3):

$$E_{TA_I} = \mathrm{K} * Q_I * H_I * \Delta t \quad (3)$$

where E_{TA_I} is the available energy in the consumption point (kWh); H_I is the piezometric head of service in any consumption point of the network in m w.c.; and Q_I is the flow rate supplied to the consumption point in m^3/s.

Secondly, the friction energy in pipes is defined by the equation (4):

$$E_{FR_i} = K * Q_f * (H_O - H_f) * \Delta t \quad (4)$$

where E_{FR_i} is the friction energy that is dissipated in the network (kWh); Q_f is the flow through the pipe *"f"* in m^3/s; H_O is the piezometric head in the first node of the pipe *"f"* in m w.c.; and H_f is the piezometric head in the final node of the pipe *"f"* in m w.c.. The total friction energy in the systems is the sum of all friction terms.

When potential energy is accumulated in a reservoir, the E_{T_r} expression will be applied. In this case, Q_r is the flow in m^3/s, which supplies the reservoir.

In case of the losses in the reduction valve, it is characterized by the following expression (5):

$$E_{FV_i} = K * Q_f * (H_V - H_{VF}) * \Delta t \quad (5)$$

where H_V is the piezometric head before the valve in m w.c. and H_{VF} is the piezometric head after the valve in m w.c..

So, if all inputs (n) are considered, the total input of energy of the system (E_{INPUT}) is defined by equation (6):

$$E_{INPUT} = \sum_{i=1}^{n} E_{T_i} \quad (6)$$

If the all output energies (m) are considered, the total output energy (E_{OUTPUT}) can be considered by equation (7):

$$E_{OUTPUT} = \sum_{i=1}^{m} E_{TA_i} + \sum_{i=1}^{m} E_{FR_i} + \sum_{i=1}^{nm} E_{FV_i} \quad (7)$$

Finally, the total energy input must be equal to the total energy output in every system.

The leakages should be considered as part of the total output although, in the case study developed, the network was modelled without considering them, because the aim of the study wasn't to analyze the leakages and also, the system didn't have measurement devices to quantify it.

The determination of the provided hydraulic energy by the pump is defined by equation (8):

$$E_{HTP} = \mathrm{K} * Q_i * (H_i - H_A) * \Delta t \quad (8)$$

where E_{HTP} is the provided hydraulic energy by the pump *"p"* in kWh; H_i is the piezometric head downstream of the pump (discharge) in m w.c., H_A is the piezometric head upstream of the pump (suction) in m w.c..

If total provided energy by the pumps is determined, the hydraulic efficiency of the machine has to be considered by the expression (9):

$$E_{TP} = \mathrm{K} * \frac{Q_i * (H_i - H_A)}{\eta_i} * \Delta t \quad (9)$$

where E_{HTP} is the provided hydraulic energy by the pump *"p"* in kWh; η_i is the efficiency for each operating point of the pump.

2.3. Energy indexes

Table 2 showed some environmental indexes related to water consumption and used energy in the network. In order to address the study of the sustainability improvement in pressurized water systems, the specific energy indexes were selected to analyze the water system. These indicators were presented in Table 5. In this table, the different applied indexes were described, indicating name, calculus expression and their units.

Table 5. Proposed energy indexes.

Abbreviation	Indicator	Calculation	Reference
IEE (Dimensionless)	Network energy efficiency	$\text{IEE} = \frac{E_{TA_i}}{E_{INPUT}}$	[37]
ISE (Dimensionless)	Excess of supplied energy	$\text{ISE} = \frac{E_{INPUT}}{E_{min,\text{useful}}}$ *[1]	[37]
IED (Dimensionless)	Energy dissipation	$\text{IED} = \frac{E_{FR_i} + E_{FV_i}}{E_{INPUT}}$	[37]
IAE (kWh/year)	Annual consumed energy	Sum of the total active energy consumed in the network	[37]
IEFW (kWh/m^3)	Consumed energy per unit volume	Ratio between the active energy consumed and the total volume of water introduced in the system	[37]
IEC (€/m^3)	Energy cost per unit volume introduced	Ratio between energy cost and the total volume of water introduced in the system	[38]
IEB (Dimensionless)	Energy efficiency of pumps	$\text{IEB} = \frac{E_{HTP_i}}{E_{TP_i}}$	[38]
IER (kWh/year)	Energy recovered	Sum of the total energy recovered in the network	[29,31]
IEWW (kWh/year)	Electricity use for wastewater treatment	--	[29-35]

*[1] where $E_{min,useful}$ is the energy when delivering the flow from the minimum required head ($h_{min} = z_i + P_{min_i}$).

As a matter of fact, the previously defined indexes can be applied to improve the general aspects of the sustainability in a real system, as they enable modelers to compare the different energy and environmental implication of the systems. In order to illustrate this strategy that enable to analyze the performance in any water network, a real case study was presented in the next section.

3. Case study

The case study analyzed the flow distribution and water resource management in a pressurized water system (Figure 3). This water network was located on Callosa d'En Sarrià (Alicante, Spain). The system obtained the hydric resource through groundwater (Sacos and Torreta's wells) and the resource was distributed by pressurized pipe to the respective tanks. The flows were distributed since these points through pressurized network (drinking and irrigation) or by open channels flow (only irrigation).

The case study analyzed the current operation mode. Once the current water management was analyzed, new proposals were developed to improve the sustainability indicators. In addition to the new proposal, an operational regime was proposed to use both combined water for irrigation and urban supply. This new management will increase the security in the whole supply as well as improving the energy sustainability indexes in the system.

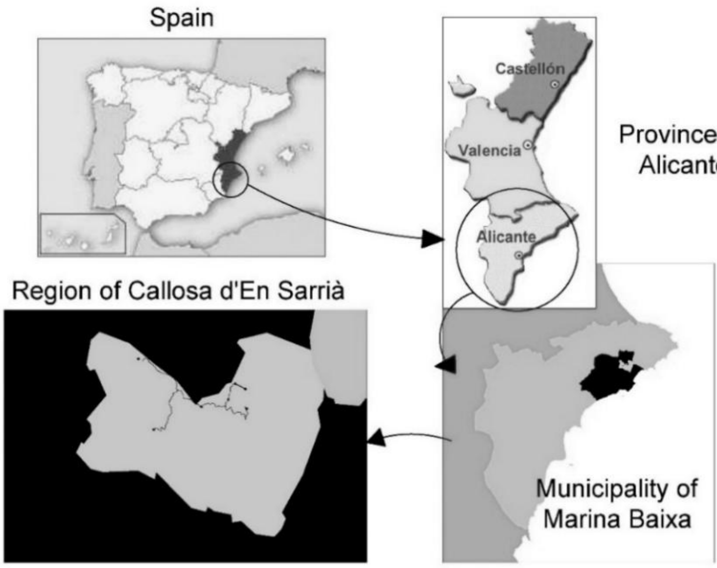

Figure 3. Water network's location: in the region of Callosa d'En Sarrià township, Alicante, Spain.

Current operation mode

The current operation mode of the network was shown in Figure 4. In this case, from the Saco wells water was boosted to Penya Severino manhole, where it was distributed by gravity to Margeve's manhole. When water reached the Margeve Pumping station, it was boosted to Onaer's raft again. Here, the Onaer's irrigation got the energy sufficient to be supplied and the rest of the water was distributed by gravity to the Council's tank, satisfying this demand too. In the case of the Torreta-Segarra's community, this demand was satisfied by the ground water, here so-called "Torreta's wells" that was situated not far from the tank. Every pump worked in off-peak hours.

Figure 4. Aerial photography of the installation's current operation mode.

At the same time, the following demands had to be satisfied (Figure 4): Font Major (from Penya Severino Manhole), Pinar, Onaer, Council and Torreta-Segarra's community. The details of the different facilities of the distribution network were enumerated below:

(1) Water was pumped from Sacos' wells to a storage tank. The pumps 1 and 2 were installed within this deposit. The operating point of pump 1 was 0.139 m^3/s and 105 m w.c.. For pump 2, the operating point was 0.111 m^3/s and 102 m w.c. and the efficiency was 0.7.
(2) The pipelines that connect from Sacos' wells to Penya Severino was formed by two fiber cement pipes DN250. The length of each one of these pipes was 470 m and the geometric difference level was 89 m.
(3) The Penya Severino Manhole had two different water outputs. The first output is a fiber cement pipeline. The diameter of this pipe was 200 mm and supplied Font Major's Community. The second pipe is a group of two parallel fiber cement pipelines. The diameter of these pipes was 400 millimeters, here named "Sifón I" and "Sifón II", which ended in the Margeve manhole. The lengths of these pipes were 1890 m and their maximum capacity was 110 L/s for each one. This flow was verified before defining the proposed regulation of the water system.
(4) There was a manhole that was installed in the pipeline "Sifón I". The water passed through a control motor-operated valve (DN150). This control element discharged the flow to open channel flow to supply the Pinar's irrigation point.
(5) From Margeve's tank, the flow was derived to the Onaer's raft, boosted by three pumps. The curves of these pumps are shown in Figure 5.
(6) The pipeline, which transferred water from Margeve's station to the Onaer's raft, had 3000 m of length and its diameter was 300 mm.
(7) The capacity of the Onaer's raft was 100,000 m^3.
(8) There is a pipeline, which transferred water from Onaer's raft to the Council's tank, its diameter was 300 mm and its length was 3580 m. The capacity of the Council's tank was 3000 m^3.
(9) In Torreta-Segarra's system, this demand was satisfied by the water wells, which was allocated in the proximities of the tank. The surface level in these wells was 172.70 m since terrain level. There were two installed pumps, and one of them boosted the water to the tank. The volume of the tank was 4000 m^3 and the water level could reach a maximum level of 6 m. At the same time, the pumped flow was 80 L/s, the head was 105 m w.c., and the pump efficiency was 85%.

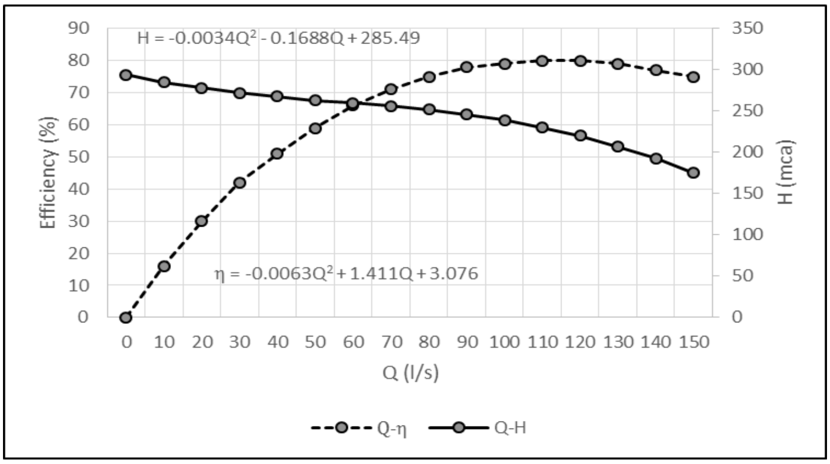

Figure 5. Characteristic and efficiency curve of the pump in Margeve.

Proposed operation mode

In the proposed operation mode (Figure 6), on the one hand, the objective was to optimize the operation rules of the pumps throughout on changing the rotational speed in the Margeve's station. On the other hand, a new pumped system was proposed to transport water from 'Sifón I' to 'Torreta-Segarra tank'. The objective of this connection was to increase the supply guarantee in the irrigation network as well as to reduce the water consumption in the wells allocated in Torreta-Segarra. The pipeline of this derivation was formed by a ductil iron, its diameter was 400 mm and its length was 1736 m. This system lacked the equipment to transport water from the 'Sifón I' to the tank, but in this analysis the design of this pump was contemplated. With the purpose to optimize the pumps in Margeve's station, instead of pumping the council's water when Onaer raft was received flows, a new proposal was considered to transfer from Margeve to Council tank because the last reservoir was situated at a lower height (approximately 80 m). Therefore, a new derivation was connected from the current main pipe to Council tank. This pipeline will be manufactured in ductile iron, its diameter and length will be 300 mm and 2159 m, respectively.

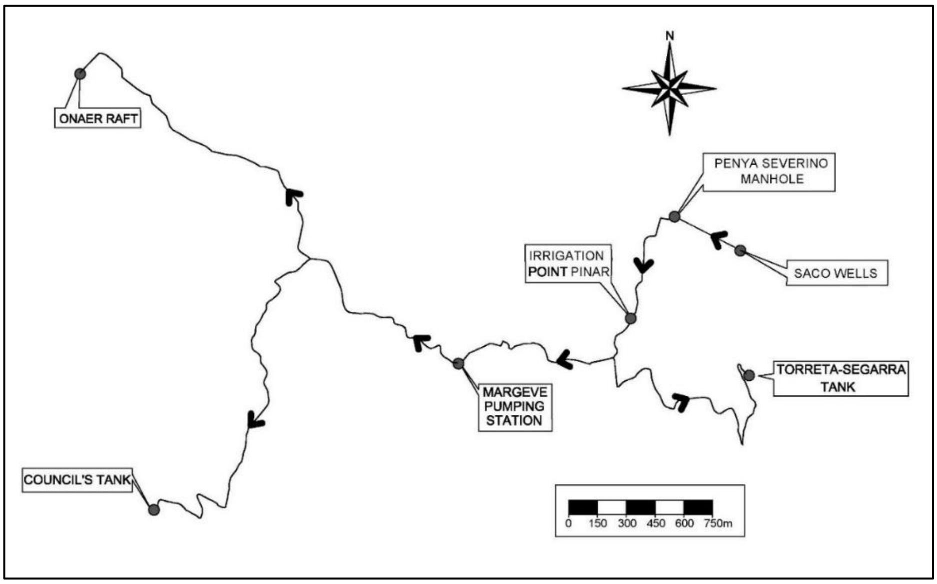

Figure 6. General ground plan of the proposed operation mode.

4. Results and Discussion

In Tables 6 and 7, the results of the energy balance are shown for both hypotheses, which were developed by EPANET, considering a simulation period equal to one year in the developed analysis. For the current operation mode, the total input and output energy was of 3,853,106 kWh/year. When the proposed operation mode was determined, the energy was 3,951,534 kWh/year.

As Table 7 showed, the lost energy by friction in the pressure reduction valve was 103,710 kWh/year. This value corresponded with the theoretically recoverable energy whether pump as turbine will be installed where the pressure reduction valve was currently installed. As the hydraulic machinery should be selected, considering the range of flows and pressures, the flow variation varied from 25 to 44.76 L/s and the available head varied from 118.4 to 123.44 m w.c., according to obtained results through simulation.

Table 6. Results of the energy balance for the network's current operation mode.

	INPUT		OUTPUT					
System	Hydraulic energy (kWh/year)		Consumed energy (kWh/year)					
	Supplied by pumps	Supplied by reservoirs	Friction losses	Pinar irrigation point	Font Major irrigation point	Valves	Potentially accumulated in tanks	Total
Saco-Severino's wells	1,593,888	-	128,492	-	-	-	1,465,387	1,593,879
Severino-Margeve	-	1,459,426	19,748	116,171	165,756	103,772	1,054,020	1,459,467
Margeve-Onaer	1,819,274	-	92,717	-	-	-	1,726,548	1,819,265
Torreta-Segarra	439,944	-	-	-	-	-	439,921	439,921
Total	3,853,106	-	240,957	116,171	165,756	103,772	3,226,450	3,853,106

Table 7. Results of the energy balance for the proposed operation mode.

			OUTPUT						
SYSTEM	Hydraulic energy (kWh/year)		Consumed energy (kWh/year)						
	Supplied by pumps	Supplied by reservoirs	Friction losses	Pinar irrigation point	Font Major irrigation point	Valves	Potentially accumulated in tanks	Derivation	Total
Saco-Severino's wells	1,855,957	-	149,853	-		-	1,706,215	-	1,856,068
Severino-Margeve	-	1,704,576	22,231	165,741	116,171	103,710	1,087,797	209,016	1,704,667
Margeve-Onaer	582,376	-	23,357	-		-	559,130	-	582,487
Margeve-Council	1,081,835	-	100,510	-		-	981,436	-	1,081,946
Derivation	226,282	-	1,731	-		-	224,663	-	226,393
Torreta-Segarra	205,084	-	-	-		-	204,549	-	204,549
Total	3,951,534	-	297,682	165,741	116,171	103,710	3,059,214	209,016	3,951,534

At the same time, the data of the pump stations both for the current and proposed operation mode were shown in Tables 8 and 9. The total energy cost and the active energy for the pumped stations decreased when the regulation improvements were defined. In Margeve's station, the total energy cost decreased from 62,342.17 to 52,666.93 €/year (the reduction was 15.50%), while the active energy decreased from 1,039,332.12 to 810,641.70 kWh (the reduction was 22%). When Torreta-Segarra system was analyzed, the total energy cost decreased from 26,792.12 to 16,482.75 €/year (the reduction was 38.48%) and the active energy decreases from 428,831.77 to 220,691.90 kWh (the reduction was 48.54%). Also, there was a difference in the pumped volumes for both cases. This difference was motivated by the different values in the tanks' levels, which was defined through the control rules. To obtain the total active energy cost, a tariff equal to 0.058231 €/kWh for off-peak hours was supposed, whilst to obtain the fixed energy cost, a fixed power equal to 0.697311 €/kW per month was supposed.

Table 8. Data of the pumping stations in case of the current operation's mode. Volume, active energy and energy cost.

Pumping Station	m^3	Hydraulic energy (kWh)	Active energy (kWh)	Active energy cost (€)	Fixed energy cost (€)	Total energy cost (€)
Sacos' wells	2,075,457.96	626,806.66	895,438.09	52,142.26	3,641.64	55,783.89
Margeve	1,515,596.90	767,657.95	1,039,332.13	60,521.35	1,820.82	62,342.17
Torreta-Segarra	581,582.77	364,507.00	428,831.77	24,971.30	1,820.82	26,792.12
Total	4,172,637.64	1,758,971.61	2,363,601.99	137,634.91	7,283.27	144,918.18

It is important to emphasize the energy data values, given for the pumps of the Torreta-Segarra's system in Table 9, included the consumed energy for both pumps (the derivation from 'Sifón I' and Torreta's wells), no considering the possibility to save energy whether the reduction pressure valve (located in Pinar's derivation) was changed by a recovery machine. The pump, installed in the derivation from pipeline 'Sifón I', contributed with 52.37% of the pumped volume in the Torreta-Segarra's system (298,060 m^3), while the pump from Torreta's wells contributed with 272,109 m^3.

Table 9. Data of the pumping stations in case of the proposed operation's mode. Volume, active energy and energy cost.

Pump Station	m^3	Hydraulic energy (kWh)	Active energy (kWh)	Active energy cost (€)	Fixed energy cost (€)	Total energy cost (€)
Sacos' wells	2,416,918.14	729,799.41	1,042,570.59	60,709.93	3,641.64	64,351.56
Margeve	1,565,202.06	578,663.29	810,641.70	47,204.48	5,462.46	52,666.93
Torreta-Segarra	569,170.12	187,184.29	220,691.90	12,851.11	3,641.64	16,492.75
Total	4,551,290.32	1,495,646.99	2,073,904.19	120,765.52	12,745.73	133,511.24

The results of the indicators, shown in Table 10, represented the environmental criteria related to energy efficiency for both the hypothesis (current and proposed mode operation). Also, the percentage of the sustainability improvement was estimated in the water system.

Table 10. Results of the energy indexes, both for the current and the proposed operation mode, and the percentage of improvement.

Indicator	Current Operation Mode	Proposed Operation Mode	% Improvement
IEE (Dimensionless)	0.073	0.071	2.56
ISE (Dimensionless)	0.070	0.068	2.49
IED (Dimensionless)	0.089	0.075	15.80
IAE (kWh/year)	2,363,602	2,073,904	12.26
IEFW (kWh/m^3)	0.566	0.456	19.56
IEC (€/m^3)	0.035	0.029	15.54
IEB (Dimensionless)	0.744	0.721	3.19
IER (kWh/year)	--	103,710	--

For both modes, about 7% of the input energy became the delivered energy to the crops (IEE), which was a small value, considering the described distribution network. For the proposed operation mode, this value decreased 2.54%, so it is an insignificant variation. In case of the IEB indicator, it slightly got worsen 3.19%, due to the installation of pumps operating at a lower rotational speed, meaning that efficiency takes lower values.

The ISE indicator showed the incoming energy of the system with respect to the minimum useful energy (required to guarantee the minimum pressure), and this value slightly decreased from 7% to 6.8%, resulting in an improvement of 2.49%.

If IED indicator in the current operation mode was analyzed, the friction dissipated energy by the network was 9%, whilst in the proposed operation mode this value decreased to 7.5%, considering the energy recovery whether reduction pressure valve was changed. The improvement with the new proposed system was 15.80%.

The IAE indicator also improved from 2,363,602 to 2,073,904 kWh/year, saving 12.26% of the energy. In the case of the energy footprint of water (IEFW), although the total water use increased 9.07%, the IEFEW decreased from 0.566 to 0.456 kWh/m^3. The IEFW reduction represented an improvement of 19.56%. The IEC indicator also decreased from 0.035 to 0.029 €/m^3, improving 15.54%.

The environmental indicators, described in Table 2, were also commented in this section. If the Spadaro's method [31] was followed, the GHG emissions indicator ($CO_{2\text{-eqv}}$) decreased from 1,725,429 to 1,513,950 kg/year. In contrast, when Musthaq's method [7] was applied, the $CO_{2\text{-eqv}}$ was reduced from 9,064,568 to 7,953,558 kg/year. Considering the previous values, GHG emissions decreased an average value of 12.26% when both methods were considered. Therefore, the proposed operation mode reduced the contribution of the network to global warming. When the presence of the mineral particle was analyzed, the presence of nitrogen in the irrigation consumed water presented a value of 1.05 mg/L, whilst the phosphate value was below 0.057 mg/L. Knowing the annual consumed volume in the irrigation points was 2,644,050 m^3, the irrigation water provided 2777 kg/year of nitrogen and 151 kg/year of phosphate. Both were distributed in all irrigation surfaces.

Regarding to the social indicators, which were shown in Table 3, the development of this strategy will improve the feasibility of the farm exploitation, and therefore, this will allow for the rural development with new jobs for the population, reducing the migratory flow from small town to the city [44]. This migratory movement has been a problem in the zone of study (Alicante) since 1970s. To consider the economic impact of the crop of loquat in this town, the loquat production was 13,000 tonnes (considering an unit prize equal to 0.95 €, the economic value of the production was M€12,350), when the Spanish production was 30,500 tonnes (Callosa was the biggest producer in Spain, when this town only represented 0.016% of the Spanish population) [44].

When healthy-cultural criteria were analyzed, considering the analysis water, the quality of drinking and irrigation water was acceptable for all developed samples as well as there no were environmental accidents, which could affect to water quality. Regarding with the non-access to the drinking or irrigation service, the new proposed system will guarantee the double security coefficient for the water system because Torreta's wells were connected with the system, and they could be used to transfer water from Torreta to Margeve throughout new proposed connection.

Lastly, the total pumped water increased by 9.07% from 4,172,638 m^3/year to 4,551,290 m^3/year in the proposed mode operation. As it was described before, this difference is due to the variation of the control rules that regulated the tanks from one mode to another.

5. Conclusion

The present document described the importance of Key Performance Indicators (KPI) to represent the behavior of the water systems to improve the sustainability and the security in the water service. Also, the analysis of a particular case study enabled the possibility to propose sustainable indicators related to social-cultural, economic, and environmental criteria. These indexes could be applied and analyzed on any pressurized water network. These indicators complemented the energy audit, which is currently carried out. Before, they enable managers to compare different pressurized water networks or to do comparisons between different water management strategies. The research showed that the use of specific software (e.g., EPANET) based on operation rules to model hydraulic values (pressure and flow), can be a powerful tool to improve the water management and to increase the sustainability (social, economic, and environmental) in the pressurized water systems.

Related to management of the operation rules as well as attending to different selected indicators, the substitution of regulating elements by recovery systems to recover or to reduce the consumed energy, improved the energy efficiency. The proposal of the pumps regulation also improved the energy efficiency and reduced the GHG emissions. Also, this strategy reduced the energy cost (economic criteria). This economic reduction, considering the indicators €/m^3 and kWh/m^3, were shown in the presented case study, in which, the energy and cost savings were 12.26% and 15.54%, respectively. The results obtained in the case study showed the impact that these techniques had in the social and healthy indicators.

Related to regulation of the hydraulic machines, the regulation by driver speed improved the energy parameters. Between different energy indicators, the energy footprint of water was 15.04%, in spite of the volume, distributed in the Severino-Margeve's system, and increased 9.07%. This reduction of the energy consumption can theoretically contribute with a decrease of 12.26% of GHG emissions.

Related to regulation elements, their replacement by sustainability recovery systems (e.g., pump as working turbine) can theoretically contribute with the generation of the recoverable energy, this value was estimated on 103,710 kWh/year. This recovery represented 2.62% of the provided energy in the system each year, considering only 7.50% of the total distributed volume (313,122 of 4,172,637 m^3/year) was regulated by this valve.

Under the management point of view in the water networks, the management of the resources as a whole as well as the application of the appropriate control rules improved the energy consumption, maintaining the supply conditions. At the same time, the proposal of an alternative resource guarantees the security of supply against possible droughts.

Finally, the proposal of sustainability indicators that was based on numerical simulations and management tools, contributed to the improvement of the sustainability and the supply security of the analyzed water systems, both irrigation and supply systems.

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Conflict of interest

The authors have declared that no competing interests exist.

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