Optimal Design of Pressurized Irrigation Networks to Minimize the Operational Cost under Different Management Scenarios

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Abstract The adoption of measures leading to higher efficiencies in the use of both water and energy in water distribution networks is strongly demanded. The methodology proposed combines a multi-objective approach and a financial analysis to determine de optimal design of pressurized irrigation networks which entails the minimization of both the investment cost and operational cost under three operating scenarios that incorporate energy saving strategies: 1- all hydrants operate simultaneously; 2- hydrants are grouped into sectors and irrigation turns are established; 3- the on-demand operation of the network is assumed. This methodology has been applied in a real irrigation network located in Southern Spain showing that the lowest overall design cost (investment and operational costs) is achieved in scenario 2. The comparison of the selected solutions in the three proposed scenarios with the current network design considering the total fulfillment of irrigation requirements showed that operational cost savings between 65% and 76% could be achieved.

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1 Introduction

The objectives pursued in the Energy Union Strategy Framework consider a reduction of 40% of greenhouse gas emissions in 2030 with respect to the emissions in 1990, an increase of 25% in the energy saving and a more important role of renewable energy sources, among other aspects (EEA 2009). These objectives have to be assumed in all economic sectors.

Water withdrawals for irrigated agriculture are around 24% of the total water use in Europe, although this figure is higher than 70% in Southern European countries (EEA 2009). Taking into account the importance of improving water management, different measures focused on increasing the water use efficiency have been adopted in the irrigated sector. The main measures have been the modernization of hydraulic infrastructures, shifting from open channel systems to pressurized irrigation networks and the adoption of more efficient irrigation systems (e.g. drip irrigation) (Carrillo Cobo et al. 2011).

Although upgraded hydraulic infrastructures have increased water use efficiency, the energy requirements have significantly raised (Tarjuelo et al. 2015). Hence, strategies focused on the optimization of energy use in pressurized irrigation networks have been developed (Moreno et al. 2007; Jiménez-Bello et al. 2010).

One of the most successful measures to reduce the energy requirements is network sectoring by grouping hydrants into sectors with similar energy requirements and hence, establishing irrigation turns (Carrillo Cobo et al. 2011; Navarro Navajas et al. 2012). By adopting this strategy, reductions in energy consumption between 20 and 30% were estimated in the irrigation districts analyzed. Another important measure to optimize the energy use in irrigation networks is the detection and control of critical points (Rodríguez-Díaz et al. 2012), which can entail energy savings of 30%, without losing quality in the service provided to farmers (González Perea et al. 2015). However, the aforementioned strategies were proposed for irrigation networks originally designed to operate on-demand (water is continuously available to farmers). Therefore, these strategies consider changes in management of networks designed to operate under different circumstances without considering the simultaneous optimization of the network design and energy saving strategies. Thus, one step forward would be the design of new irrigation networks but incorporating energy saving strategies and taking into account the minimization of both the investment and operational costs (closely linked to energy consumption).

The optimum design of water distribution networks has been widely analyzed during the last years (Chandapillai et al. 2012; Shibu and Janga Reddy 2013; Creaco and Franchini 2014). These strategies have been also applied to irrigation networks (Farmani et al. 2007; Reca et al. 2008; Baños et al. 2010; González-Cebollada et al. 2011). However, the methodologies developed have not taken into account the optimization of the operational cost, which involves significant reduction of farmer's incomes.

Farmani et al. (2007) stated the optimization of the design of an irrigation network under two operational scenarios: on- demand and operated by turns (two sectors). They highlighted the important reduction of the investment cost when the network operation by sectors was considered. Nevertheless, they did not analyze the energy savings associated to the network operation by sectors.

Nowadays the increasing world population demands irrigation systems that use both water and energy efficiently to satisfy its food needs. As the simultaneous optimization of the design and the operational cost under different management operation has not been considered yet, this paper presents a new methodology to determine de optimal design of pressurized irrigation

networks that minimizes the investment cost and operational cost under three different operating scenarios that incorporate energy saving strategies: 1- all hydrants operate simultaneously; 2- hydrants are grouped into sectors and irrigation turns are established; 3- the on-demand operation of the network is assumed. The stated methodology has been applied to a real irrigation network, comparing the operation of the three scenarios with the current network design.

2 Methodology

2.1 Problem Definition

The methodology described in this paper aimed at determining the optimal design (pipe diameters) of new pressurized irrigation networks considering the investment in pipes and the operational costs related to the energy consumption at the single pumping station under different operating scenarios. To simplify the procedure, the investment in the pumping station has not been considered in this work since only the optimization of pressure head and flow provided by the pump station, assuming a fixed efficiency, has been taken into account. These conflicting objectives require two functions to cope with the stated problem. The first objective function, OF1, considers the minimization of the network design cost (€) while the second function, OF2, not applicable for irrigation networks operating by gravity, minimizes the annual energy cost (€ year^{-1}) when a single pumping station works:

$$OF1 = \sum_{j=1}^{nj} C_j \cdot L_j \tag{1}$$

$$OF2 = \left[\frac{1}{1000} \cdot \frac{1}{\eta} \cdot \gamma \cdot \sum_{m=1}^{nm} \sum_{d=1}^{nd} OD_{dm} \sum_{h=1}^{nh} \frac{\sum_{c=1}^{nc} F_{chdm} \cdot H_{chdm}}{nc} \cdot P_{hdm} \right] + FC \tag{2}$$

Where j is the pipe index, nj the number of pipes, C_j the unit cost associated with pipe diameter D_j (€ m^{-1}), L_j (m) the length of pipe j, m the month index, d the day index, h the hour index, c the demand pattern index, nm the number of months of the irrigation season, nd the number of days per month in which the electricity tariff structure varies, nh the daily irrigation time, η the pump efficiency (0.7 was assumed in this work (Fernández García et al. 2014)), γ the water specific weight (9810 N m^{-3}), OD_{dm} the number of days with the same electricity tariff per month, F_{chdm} the flow supplied by the pump station (m^3 s^{-1}), $Hreq_{chdm}$ the pressure head provided by the pump station (m), P_{hdm} the energy price according to the hour, the day and the month (€ kWh^{-1}) and FC the fixed cost related to the power contracted (€ year^{-1}).

The energy price and the fixed costs are established according to the electricity tariff. Usually, two different electricity tariffs are offered: a flat rate (the energy price is the same during the whole day) or time-of use rate (energy prices vary according to the time of consumption), thus establishing tariff periods. The electricity market established the energy price whereas the energy authorities usually regulate the fixed costs that include the transport and distribution cost, the environmental cost and taxes. In Spain, for example, the main component of the fixed cost is associated to the

power contracted (Fernández García et al. 2016), which depends on the maximum power absorbed in a certain period of time:

$$FC = \sum_{p=1}^{np} Power_{maxp} \cdot Ppower_p \tag{3}$$

Where p is the period index, np is the number of tariff periods, $Power_{maxp}$ is the contracted power according to the maximum demanded value in period p (kW) and $Ppower_p$ the power term price in period p (€ kW^{-1}).

The objective functions considered are subject to the fulfillment of several constraints. On the one hand, pressure in the critical hydrant, P_{crit}, (hydrant with the lowest pressure) has to be higher than the service pressure, P_{ser}, in all simulations performed. Service pressure is that that guarantees the proper operation of all emitters, i.e. that all emitters received the minimum pressure required to apply the nominal flow. On the other hand, the physical laws of mass and energy conservation have to be satisfied.

2.2 Network Operating Scenarios

To determine the optimal network design, three different operating scenarios of the irrigation network were defined.

– Scenario 1. All hydrants are simultaneously open. This scenario represents the most unfavourable condition which may occur in certain cases, for example when the irrigation is concentrated in certain hours trying to avoid the peak price hours.
– Scenario 2. The irrigation network is organized into sectors. This scenario is proposed since many works have shown the significant energy savings obtained by the irrigation management by sectors.
– Scenario 3. The on-demand network operation is considered in this scenario, i.e., farmers can irrigate whenever they want. This scenario is commonly adopted in irrigation networks.

2.3 Optimization process

The objective functions considered in this work represent conflicting objectives since when one of them drops the other increases. On the other hand, when the optimization problem is posed considering a multiobjective approach rather than a single-objective, the decision maker may select the best option according to his/her preferences. Hence, a multiobjective genetic algorithm was used as optimization tool. The multiobjective approach has been widely used to solve optimization problems related to water distribution networks (Reca et al. 2008; Baños et al. 2010; Marques et al. 2015; Wang et al. 2015). One of the most successful multiobjective algorithms used in this type of optimization problems is the Non Sorted Genetic Algorithm II, NSGA-II (Deb et al. 2002). It has been applied to design optimization problems (Chandapillai et al. 2012), to optimal operation of networks (Fernández García et al. 2016) and to leakage attenuation (Creaco and Pezzinga 2010), among other problems related to pressurized water networks.

The main steps of NSGA-II are described next. Firstly, a random initial population is generated which is made up by individuals defined by different combination of the values of the variables involved in the optimization problem. Then, each individual is evaluated by determining the aforementioned objective functions and the population is sorted according to the values of these functions. Afterwards, the selection, crossover and mutation processes take place to generate the offspring individuals, whose values of the objective functions are calculated. The offspring individuals are incorporated into the initial population and the least fit individuals according to the values of the objective functions are removed to maintain the size of the population. These stages (selection, crossover- mutation- evaluation of the objective functions and removal of individuals) are repeated until the convergence criterion is achieved (Deb et al. 2002), usually after the occurrence of a prefixed number of successive generations.

To apply the NSGA-II to the stated problem, the generation of individuals and the evaluation of the objective functions were adapted according to each operating scenario (Fig. 1).

The optimization process was carried out in MATLAB™ (Pratap 2010) using EPANET (Rossman 2000) as hydraulic simulator.

2.3.1 Generation of the Population

For scenarios 1 and 3, the number of variables of each individual was the number of pipes of the irrigation network. Thus, each variable represents a possible combination of the main pipe features (internal diameter, material and thickness) that define the hydraulic behavior and cost of each pipe. However, for scenario 2, an additional variable associated to each hydrant was considered. The new variable was an integer number related to the irrigation turn of each hydrant. It may vary from 1, which means this hydrant was associated to sector 1, up to the number of operating sectors established at the beginning of the optimization process, ns. Given that organization in turns implies less time to irrigate each field, the number of operating sectors depends on the daily required irrigation time according to the crop pattern of the irrigation network and on the irrigation management scenario (if deficit irrigation strategies are considered) (Carrillo Cobo et al. 2011). An excessive number of sectors implies that farmers would not have time to apply the daily irrigation depth and therefore these situations should be avoided by the system. For this reason the maximum number of sectors is limited by the irrigation time required at the peak demand month.

2.3.2 Objective Function Evaluation

Scenario 1 In this scenario, the simultaneous operation of all hydrants was considered. EPANET's inputs were the pipe diameters defined in each individual and the base demand of each hydrant, obtained by multiplying the maximum flow allowed per hydrant, $F_{max,}$ (L s^{-1} ha^{-1}) by the irrigated area associated to this hydrant, S_{hy} (ha) (Carrillo Cobo et al. 2011). From these data and starting from a hypothetical pressure head in the pumping station according to hydrant elevations and the network topology (H_i) the pressure in the critical hydrant was determined, $Pcrit$. Then, the required pressure at the pumping station, H_{req}, to ensure that all hydrants receive unless the service pressure was determined by the following expression:
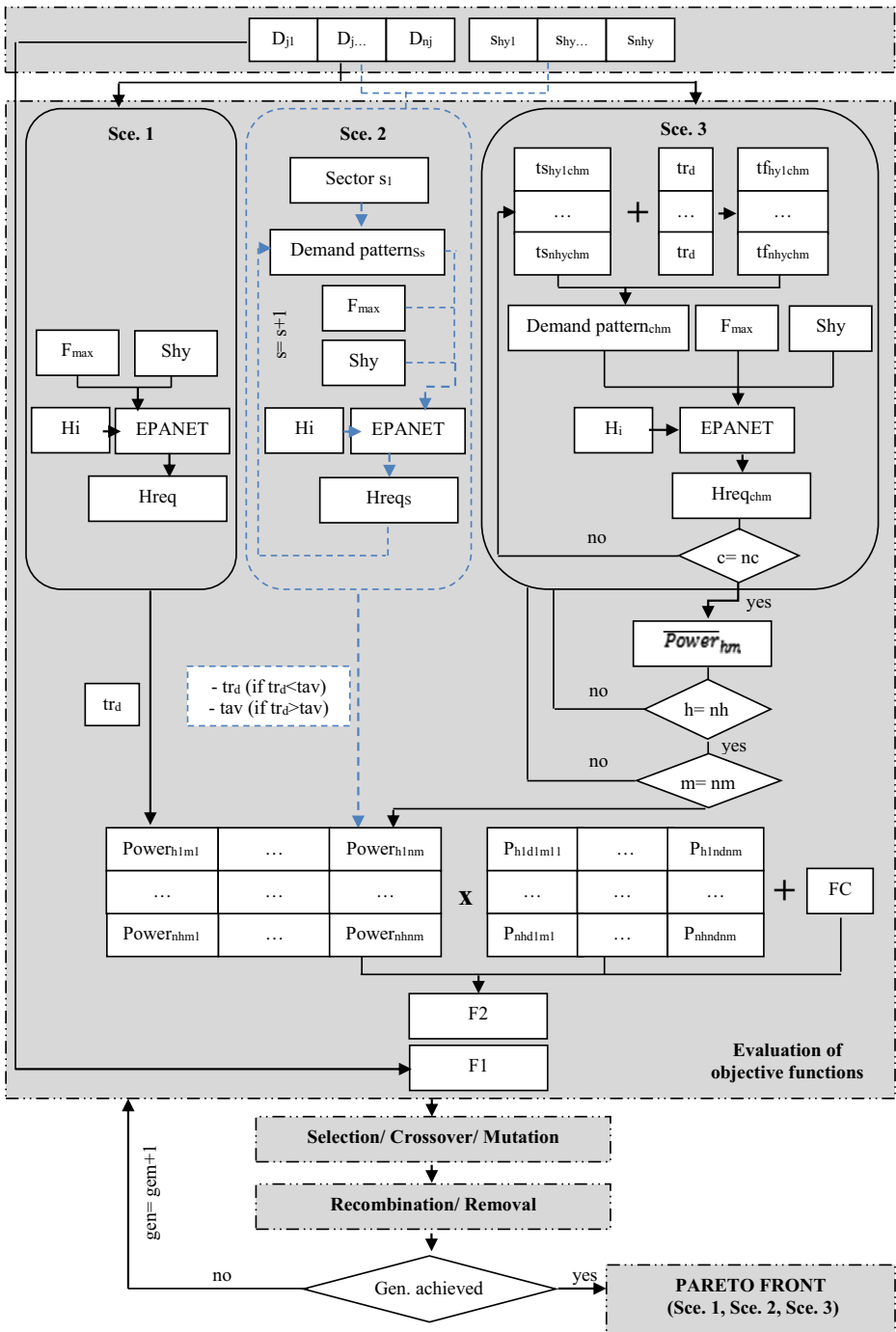
$$H_{req} = H_i + (P_{ser} - P_{crit})$$ (4)

Fig. 1 Flow chart of the optimization process according the each scenario

As the simultaneous operation of all hydrants was taken into account, the value of H_{req} was the same for each hour and each day of the irrigation season. The number of operating hours during the day, nh, was the time required to satisfy crop water requirements, tr_d, calculated from the theoretical crop irrigation requirements (Allen et al. 1998) and the design maximum flow (Ls^{-1} ha^{-1}). Considering the differences in the power and energy prices according to the electricity tariff structure, the operating hours of the irrigation network were adapted to reduce the operational cost (Fernández García et al. 2016). Thus, in this scenario, the irrigation time was concentrated in the cheapest hours. The hourly energy prices were sorted in increasing order and the hourly energy cost was determined by multiplying the hourly power absorbed by the sorted energy price, until fully satisfying the required time according to the crop irrigation needs. This procedure was carried out for each day with different electricity tariff per month and for each month of the irrigation season. Finally, the annual energy cost was obtained by summing the daily energy cost during the whole irrigation season. By adding the fixed cost to the annual energy cost, the objective function OF2 was calculated. OF1 was determined from the cost of the combination of diameter-material- thickness per pipe assigned to each individual of the population.

Scenario 2 In this scenario, different irrigation turns occurred according to the number of operating sectors fixed at the beginning of the optimization process. The second set of variables contained information about the irrigation turn of each hydrant. Thus, starting from hydrants operated in the first irrigation turn ($s = 1$), the base demand of this group of hydrants was determined by following the same procedure as in scenario 1. Then, the hydraulic simulation of sector 1 was carried out taking into account the flow demanded by the sector. As in scenario 1, H_{req} was obtained by Eq. 4. When the value of H_{req} for sector 1 was determined, the hydraulic simulation of sector 2 was performed and H_{req} for this sector was calculated. This procedure was carried out until H_{req} for all operating sectors was determined. The daily irrigation time for each sector depended on both tr_d and the available time according to the sectoring option, tav. Thus, when tr_d was greater than the time required to satisfy crop water requirements, the daily irrigation time was tr_d whereas otherwise, the daily irrigation time was tav. A vector with the hourly absorbed power by each sector during nh was created. This vector was sorted in descending order according to the power absorbed. On the other hand, the hourly energy prices were sorted in increasing order and finally, the hourly energy cost was determined by multiplying the hourly power by the sorted energy price. Thus, the sector operation sequence was determined. As in scenario 1, this procedure was carried out for each day with different electricity tariff per month and for each month of the irrigation season and the annual energy cost was calculated by summing the daily energy costs. Finally, the annual operational cost was determined by adding up the fixed cost to the annual energy cost.

Scenario 3 This scenario considered the on-demand operation of the network. Thus, multiple random combinations of open/closed hydrants were generated. To create the demand patterns, a random number indicating the start of the irrigation time, ts_{hychm}, was generated for every hydrant using the random number generation provided by MATLAB™ (Pratap 2010). Hence, the end of the hydrant operation time, tf_{hychm}, was determined adding the daily required irrigation time, tr_d, to its start time. As tr_d is calculated for each month of the irrigation season, a representative day for each month was considered and c demand settings for each hour h were generated (Fernández García et al. 2015). Hence, the total number of demand patterns evaluated was obtained by multiplying the number of hourly demand patterns (nc) by the daily operating time (nh) and by the number of representative days per month of the irrigation season (nm).

Each hourly demand pattern along with the diameter set defined in the individuals of the population were evaluated in EPANET, which provided the required pressure at the pumping station, $Hreq_{chdm}$, to ensure the service pressure in all hydrants. From this information, the hourly absorbed power for each c demand pattern and each day was calculated. The average value of the hourly absorbed power obtained from each c demand pattern was calculated. The hourly energy cost was determined by multiplying the hourly absorbed power by the hourly energy price. This process was carried out for each representative day and the annual energy cost was determined by summing the daily energy cost during the whole irrigation season. Finally, the annual operational cost was calculated by summing the fixed cost to the energy cost.

2.4 Financial Analysis

The outputs of the previous optimization process are Pareto fronts for each operational scenario. The Pareto front offers the decision maker the possibility of selecting the best solution according to his/her preferences. However, a financial analysis was also performed to determine the most economical solution bearing in mind the lifetime of the water distribution system. Thus, the overall cost for the useful life, T, of each solution of the three Pareto fronts was calculated. The overall cost, OvC (€), takes into account the network design cost, $OF1$, and the operational cost over the lifetime of the system (Fernández García et al. 2015):

$$OvC = OF1 + \sum_{y=0}^{T} \frac{OF2}{(1+r)^y} \tag{5}$$

Where y is an index related to year and r the total recovery factor.

2.5 Case Study

The methodology described above has been applied to "compare" its best design alternatives with the current design of the irrigation water distribution system of El Villar irrigation district (Andalusia, Spain) (Fig. 2). This irrigation district has an irrigable area of 3017 ha although the irrigated area is 2514 ha, supplied by a pumping station. The irrigation network is organized in 42 hydrants, with an average associated area of 59.86 ha mainly devoted to cotton, wheat, sunflower and olive trees. Each hydrant is designed to supply a maximum flow of 1.2 L s^{-1} ha^{-1} at a service pressure of 30 m as the irrigation system is mainly trickle. The on-demand irrigation management is currently adopted in this irrigation network. The annual irrigation water supply per unit of irrigated area is 1435 (m^3 ha^{-1}) and the energy consumption per unit of irrigated area is 1232 kWh ha^{-1} (Rodríguez Díaz et al. 2011).

3 Results

3.1 Electricity Tariff

According to the Spanish legislation, the 6-periods electricity tariff has been considered in the optimization process since the contracted power in this irrigation district is higher than 450 kW. This tariff is structured in 6 periods, each one with different energy and power prices.
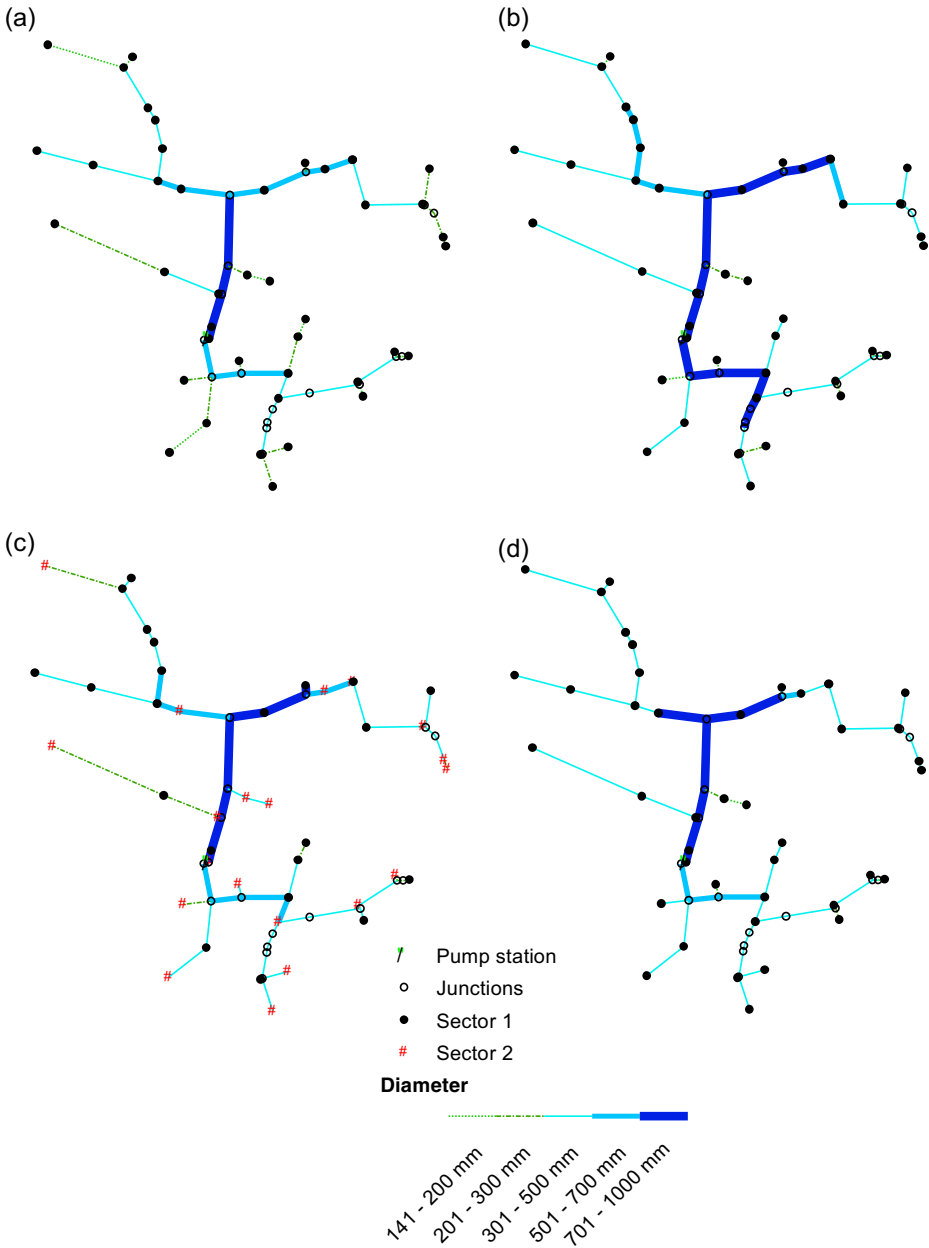
Fig. 2 Network design according to the original network (**a**), scenario 1 (**b**), scenario 2 (**c**) and scenario 3 (**d**)

Period P1 is the most expensive and the price decreases gradually to period P6, the cheapest period. Weekends and holidays are not structured in different periods and the hourly energy and power price is associated to period P6. The electricity tariff structure varies per month and as weekends and holidays are always charged to period P6, two different types of days per month ($nd = 2$) were defined. Furthermore, the energy cost has two terms: one is regulated by

the energy authorities whereas the other is established by the electricity market. The applicable electricity tariff structure and the energy and power price associated to the term regulated by the energy authorities (BOE 2014) are shown in Table 1. The non-regulated term has been obtained from the energy price established in the electricity market during 2014 (OMIE 2014).

3.2 Optimization Process

The methodology proposed was applied to El Villar irrigation district taken into account the following parameters. The number of both individuals and generations was set at 100 in scenarios 1 and 3 while the number of variables, related to the number of pipes, was 59. In scenario 2, the number of variables, 101, was the sum of the number of pipes and the number of hydrants (42 hydrants). The number of both individuals and generations in this scenario was set at 200. As deficit irrigation was not considered in this work, only 2 sectors were defined in this network since more operating sectors would imply the reduction of the available watering time that would be insufficient to satisfy crop irrigation needs in some months (Table 2). In

Table 1 6-periods electricity tariff and energy and power charge in each period (only the charge regulated by the Spanish Government, MINETUR 2014)

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00–01	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
01–02	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
02–03	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
03–04	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
04–05	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
05–06	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
06–07	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
07–08	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
08–09	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2
09–10	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2
10–11	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
11–12	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
12–13	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
13–14	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
14–15	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2
15–16	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2
16–17	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2
17–18	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2
18–19	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
19–20	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
20–21	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
21–22	P1	P1	P1	P5	P5	P3	P3	P3	P3	P3	P1	P1
22–23	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2
23–24	P2	P2	P2	P5	P5	P4	P4	P4	P4	P4	P2	P2

	Energy Price, € kWh^{-1}	Power Price, € kW^{-1} year^{-1}
P6	0.0021	6.5402
P5	0.0034	14.3342
P4	0.0053	14.3342
P3	0.0106	14.3342
P2	0.0199	19.5867
P1	0.0267	39.1394

*Weekends are always in P6

Table 2 Information associated to the selected solution from each scenario (according to Fig. 3)

				Apr	May	Jun	Jul	Aug	Sep	
				Daily required irrigation time, h						
Cost, €				0.8	6.9	11.8	12.5	7.6	1.9	
Sce	Design	Operation (annual)	Hreq, m	Energy consumption, MWh						Total
A[a]	2,643,783	815,185	3÷180[c]	56.8	805.8	1976.5	2366.7	1012.0	136.2	6354.0
1	4,480,867	249,893	48	60.5	437.9	726.5	813.2	500.5	121.1	2659.7
2	3,278,949	196,082	43 (s1)[b] 44 (s2)	55.1	398.4	661.0	683.0	455.3	110.2	2363.0
3	3,876,778	283,027	5÷54[c]	43.1	384.3	720.3	817.3	449.2	92.9	2507.0

[a] Annual operational cost and energy consumption according to the current network design and considering the total fulfillment of irrigation requirements

[b] Required head when sector 1 operates (s1) and required head for sector 2 (s2)

[c] Minimum and maximum required head

scenario 3, 2880 demand patterns were simulated, a figure obtained by multiplying 20 hourly demand patterns × 24 h per day × 6 months, which is the length of the irrigation season (from April to September). The total number of demand patterns evaluated is consistent with the number suggested by Rodríguez-Díaz et al. (2012), who concluded, for this irrigation network, that after evaluating around 3000 open/closed hydrants configurations, the energy consumption associated to each pattern became stable.

The required simulation time for scenario 1 was 431 s while scenarios 2 and 3 needed a simulation time 8 and 262 times higher, respectively, than scenario 1.

The possible values for the variables associated to pipe diameters were obtained from commercial catalogs (Table 3). The diameters range was selected taking into account values close to current network diameters. The pipe material was polyethylene and the set of pipes are suitable for use at pressures up to 10 bar. The values for the variables associated to hydrants were 1 or 2, indicating the sector in which each hydrant was grouped.

Table 3 Unit cost according to pipe diameter

External diameter, mm	Thickness, mm	Unit cost, (€ m^{-1})
160	9.5	11.28
180	10.7	14.58
200	11.9	17.58
225	13.4	22.40
250	14.8	27.50
280	16.6	34.94
315	18.7	44.13
355	21.1	55.80
400	23.7	69.93
450	26.7	88.54
500	29.7	109.97
560	33.2	136.27
630	37.4	175.89
710	42.1	219.12
800	47.4	275.50
900	53.3	353.04
1000	59.3	432.57

   Once the optimization process finished, a Pareto front was obtained for each scenario (Fig. 3). The design cost varied from 1,060,127 € to 5,098,930 € and the corresponding operational costs were 6,752,810 € and 242,170 €, respectively, in scenario 1, whereas in scenario 2 the design cost varied from 474,475 € up to 5,940,451 € and the associated operational costs were 17,436,739 € and 169,647 €, respectively. In scenario 3, the design cost ranged from 845,805 €, with operational costs of 8,601,723 €, to 6,802,546 €, with an associated value of the operational cost of 248,504 €.

   The comparison of the three scenarios showed that scenario 2, in which 2 irrigation turns were established, offered the best results (Fig. 3). This is consistent with the methodology to optimize the design of pressurized irrigation networks by Farmani et al. (2007). They highlighted that adopting a rotation scheduling in the network, a design cost saving of 50% with respect to the on-demand operation could be achieved. The best performance of scenario 2 is more noticeable when the design cost was lower than 2 M € (Fig. 3). Reduced design costs are associated to lower pipe sizes and hence, establishing 2 sectors, the pressure head at the pumping station could be adjusted according to the requirements of each sector. When the design cost increased (values higher than 2 M €), the network operation by sectors did not imply significant differences in the operational cost with respect to scenarios 1 and 3. The most expensive design costs were related to greater pipe diameters. In these cases, head loss decreased and the network operation by sector did not entail significant operational cost saving with respect to the other scenarios. Scenario 3 implied lower design cost than scenario 1 although the operational cost associated to scenario 3 was higher. However, this scenario offers farmers greater flexibility to irrigate than the other scenarios.
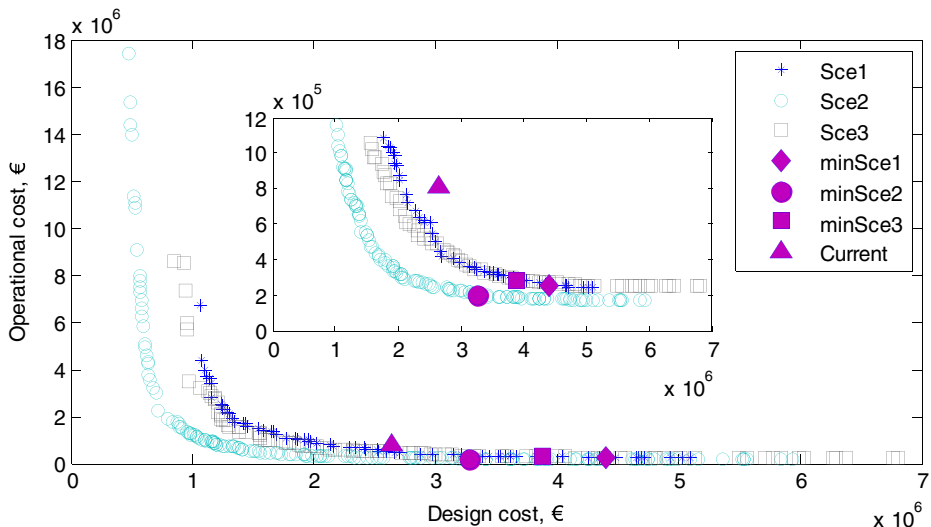

Fig. 3 Pareto front obtained in each scenario (Sce1, Sce2 and Sce3), value associated to the minimum overall cost in each scenario after performing the financial analysis (minSce1, minSce2 and minSce3) and design and operational cost associated to current network (current)

3.3 Financial Analysis

The Pareto front obtained in each scenario provided a set of quasi-optimal solutions from which the decision maker can select the best solution according to his/her preferences. Additionally, a financial analysis was carried out to determine the best option taking into account the overall cost (design cost plus operational cost) and the lifetime of each solution. A useful life of 50 years was assumed, a reasonable value for irrigation networks while values of 0.05 and 0.03 of the total recovery factor were analyzed (Fernández García et al. 2015). As it could be expected, scenario 2 achieved the lowest overall cost, 7.05 M €, associated to a design cost of 3.28 M € when the value of the total recovery factor was 0.05. Likewise, the minimum overall cost was achieved by scenario 2 (8.52 M € associated to a design cost of 3.28 M €) for a total recovery factor value of 0.03. As for the rest of scenarios, the minimum overall cost for scenario 1 was 9.29 M € (associated to a design cost of 4.40 M €) for a total recovery factor of 0.05 whereas scenario 3 achieved a minimum overall cost of 9.33 M € related to a design cost of 3.88 M €. When a value of 0.03 for the total recovery factor was considered, scenario 1 showed an overall cost of 11.16 M € associated to a design cost of 4.48 M € whereas scenario 3 showed an overall cost of 11.44 M € associated to a design cost of 3.88 M €. When the overall cost of the three scenarios was compared with the current network cost over the useful life considering the total fulfillment of the irrigation requirements, a significant decrease in all scenarios was determined. When the total recovery factor was 0.05, the overall cost associated to the current network was 18.34 M € whereas when a value of 0.03 for the total recovery factor was considered, the overall cost associated to the current network was 24.43 M €. Therefore, the three scenarios offered lower overall cost.

3.4 Scenarios Comparison

The annual operational cost associated to the selected solution of each scenario according to the financial analysis (taking into account the analysis performed for a total recovery factor of 0.03) was lower than the estimated operational cost considering the total fulfillment of irrigation requirements in the current design, 815,185 €. This operational cost does not correspond to the real expenditure in the irrigation district where deficit irrigation, mainly due to the high energy cost, is a common practice and farmers typically apply less than half the theoretical irrigation requirements (Carrillo Cobo et al. 2011). Thus, the reduction of the operational cost with respect to the operation of the current network considering the total satisfaction of the irrigation requirements was 565,293 € (69%), 619,104 € (76%) and 532,158 € (65%) in scenarios 1, 2 and 3. The design cost of the current diameters was estimated at 2,647,499 € (this cost has been estimated taking into account the catalog shown in Table 3 since material of several pipes in the current network is no longer made). The lowest design cost of the current diameters with respect to the design cost obtained in the three scenarios shows that the irrigation network is undersized and was not designed to fully satisfy the irrigation requirements.

As for the energy consumption, scenario 2 achieved the lowest value, 2363.0 MWh, in comparison with 2507.0 MWh and 2659.7 MWh for scenarios 3 and 1, respectively. As Fernández García et al. (2015b) reported, the consideration of the electricity tariff structure in the optimization models entails higher operational cost when the on-demand operation of the network is considered. Thus, scenario 1, in which the irrigation is concentrated during the non-peak hours, showed lower operational cost than scenario 3. However, the energy consumption

in scenario 1 was higher than in scenario 3, in which farmers can irrigate whenever they want. The energy consumption determined in the three scenarios was lower than the value associated to the current network considering the full satisfaction of irrigation requirements. Thus, a decrease in the annual energy consumption with respect to the current network operation of 3694 MWh (58%), 3991 MWh (63%) and 3847 MWh (61%) for scenarios 1, 2 and 3, respectively, was determined.

As for the pressure head required in each scenario, this variable was 48 m in scenario 1, 43 m and 44 m for sector 1 and 2, respectively, in scenario 2, while the pressure head ranged from 5 m to 54 m, according to the demanded flow, in scenario 3. The low values of pressure head detected in scenario 3 were associated to demand patterns with few open hydrants. More specifically, the value of 5 m was related to a demand pattern in which only one hydrant (with an elevation of 154 m) was open (the pump station elevation is 184 m). The optimal pressure head detected in each scenario, i.e. the minimum pressure head which guaranteed the service pressure at all hydrants, was also lower than the pressure head determined in the current network design if farmers applied the total irrigation requirements (from 3 m to 180 m).

Taking into account the objectives stated in this work, scenario 2 showed the best results. The reduced design cost determined when 2 sectors operated bears relation with the lower pipe size proposed in this scenario (Fig. 2). As for the sector configuration, 20 hydrants were grouped in sector 1, with an absorbed power of 949.37 kW whereas sector 2 grouped 22 hydrants, with an absorbed power of 886.72 kW. The main disadvantage of this scenario is related to the loss of flexibility for farmers, although this is reasonably justified considering the important saving obtained in both design and operational cost. Scenario 1 did not entail any advantage with respect to scenario 2 since the irrigation was concentrated in certain hours. Hence, farmers cannot irrigate whenever they want. Scenario 3 implied the highest operational cost. However, it is the most flexible operation scenario since there is not any restriction to irrigate.

4 Conclusions

The 2020 targets of reducing greenhouse gas emissions by 20%, incrementing the energy efficiency by 20% and increasing the use of renewable energy sources by 20% affects all economic sectors, including agriculture. Water use efficiency in irrigated agriculture has increased by updating the hydraulic infrastructures to pressurized water distribution networks and by adopting more efficient on-farm irrigation systems. However, the energy consumption has risen considerably and measures to optimize the use of this resource are urgently required.

This paper presents a methodology in which the optimal design of pressurized irrigation networks is jointly considered with the optimization of the operational cost. Three different operating scenarios have been analysed: the simultaneous operation of all hydrants (scenario 1), the network operation in two sectors (scenario 2) and the on-demand operation (scenario 3).

After carrying out the optimization process using the NSGA-II algorithm and a financial analysis to determine the best solution, scenario 2 showed the best results, with a design cost of 3.3 M € and annual operational cost of 196,082 € in the studied pressurized network. Scenario 1 showed lower operational cost than scenario 3 but higher design cost. However, scenario 3 was the most flexible since it allowed farmers to irrigate whenever they wanted.

The three analyzed scenarios offered lower values of both the annual operational cost and the energy consumption than the values associated to the full satisfaction of irrigation requirements considering the current diameters. In the case study, the undersized network has led farmers to apply less water than the irrigation requirements, entailing lower productions than the potential value. The proposed scenarios imply lower operational cost and higher yields due to the full satisfaction of irrigation needs.

The methodology developed offers the irrigation district managers a wide range of possibilities to find the most suitable design of pressurized irrigation networks taking into account the minimization of the operational cost under different operating scenarios.

The optimization of both resources, water and energy, is currently being a major concern considering the satisfaction of the needs of a growing population and the effects of climate change. The aforementioned methodology may be extended incorporating renewable energy sources as well as deficit irrigation techniques wherever possible in the search process of a more sustainable irrigated agriculture.

γ [N m^{-3}], Water specific weight; η, Pump efficiency; c, Demand pattern index; C_j [€ m^{-1}], Unit cost associated with j pipe diameter; d, Day index; D_j[mm], Pipe diameter; FC [€ year^{-1}], Fixed cost related to the power contracted; F_{chdm} [m^3 s^{-1}], Flow supplied by the pump station; F_{max},[L s^{-1} ha^{-1}], Maximum flow allowed per hydrant; h, Hour index; H_i [m], Hypothetical pressure head; Hreq [m], Pressure head provided by the pump station; j, Pipe index; L_j [m], Length of pipe j; m, Month index; nc, Number of demand pattern evaluated; nd, Number of days per month with different electricity tariff structure; nh, Number of operating hours during day d; nj, Number of pipes; nm, Number of months of the irrigation season; np, Number of tariff periods; ns, Number of operating sectors; OD_{dm}, Number of days with the same electricity tariff per month; OF1, Objective function 1; OF2, Objective function 2; OvC [€], Overall cost; p, Period index; P_{crit} [m], Pressure in the critical hydrant; P_{ser} [m], Service pressure; P_{hdm} [€ kWh^{-1}], Energy price according to the hour, the day and the month; Power$_{maxp}$ [kW], Contracted power according to the maximum demanded value in period p; Ppower$_p$ [€ kW^{-1}], Power term price in period p; r, Total recovery factor; s, Sector index; S_{hy} [ha], Irrigated area associated to hydrant hy; T, Network useful life; tav, Available irrigation time; tf$_{hychm}$, Random number indicating the end of the irrigation time; tr$_d$, Time required to satisfy crop water requirements; ts$_{hychm}$, Random number indicating the start of the irrigation time; y, Index related to year.

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