

Methodology for Detecting Critical Points in Pressurized Irrigation Networks with Multiple Water Supply Points

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Abstract The modernization processes of hydraulic infrastructures from old open channels to pressurized networks have increased water use efficiency along with a dramatic increase of energy consumptions. The significant energy requirements associated with the increment of the energy tariffs for irrigation involve higher production costs for farmers. Therefore, strategies to reduce energy consumption in irrigation districts are strongly demanded. Methodologies based on sectoring and critical points control have been applied to branched networks with a single water supply point, obtaining significant energy savings. In this work, a new critical point control methodology for networks with multiple sources has been developed: the WEPCM algorithm, which uses the NSGA-II multi-objective evolutionary algorithm to find the lowest energy consumption operation rule of a set of pumping stations connected to an irrigation network that satisfies the pressure requirements, when the critical points are successively disabled. WEPCM has been applied to a real irrigation district in Southern Spain. The obtained results were compared with those achieved by the WEBSOM algorithm, developed for sectoring multiple source networks. The control of critical points by the replacement of two pipes and the installation of four booster pumps provided annual energy savings of 36 % compared to the current network operation. Moreover, the control of critical points was more effective than sectoring, obtaining an additional annual energy saving of 10 %.

Keywords Efficiency · Energy savings · Water supply systems · Spain

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Notation

γ	Water specific weight
η	Global efficiency of pumps
EC (EC_{norm})	Energy consumption (normalized term of EC)
CMPD ($CMPD_{norm}$)	Penalty factor depending on the magnitude of pressure (normalized term of CMPD)
h_j^*	Hydraulic dimensionless coordinate
H_i	Pressure head of pumping station i
H_{w-j}	Required weighted pressure head when hydrant j operates
H_{w-mch}	Required weighted pressure head when the most critical hydrant operates
i	Pumping stations index
j	Hydrant index
l_j^*	Topological dimensionless coordinate related to friction losses in pipes
l_{j-i}	Distance between the hydrant j and the pumping station i
l_{max-i}	Distance between the furthest hydrant and the pumping station i
n_v	Number of decision variables
N	Number of pumping stations
Pf	Pressure failure percentage
Q_i	Pumped flow by pumping station i
t_{rs}	Daily irrigation time required during month s
z_j^*	Topological dimensionless coordinate related to the hydrant elevation j
z_i	Pumping station elevation i
z_j	Hydrant elevation j

1 Introduction

In order to reduce the water consumption in agriculture, many irrigation districts have switched from old open channels distribution systems to pressurized networks. By this modernization process higher both the conveyance efficiency and the water use efficiency at field scale are achieved. In Spain, this transformation has meant a dramatic rise of the energy consumption, which has increased from 206 kWh ha⁻¹ in 1950 to 1,560 kWh ha⁻¹ in 2007, while the water use efficiency has risen by 21 % over the same period (Corominas 2010). Similar trends were observed in other countries such as Australia where the modernization of water distribution systems has resulted in higher energy requirements, with estimated increased up to 163 % (Jackson et al. 2010). Nevertheless, the transformation of hydraulic infrastructures has not led farmers to obtain higher profits. On the one hand, a fourfold rise in amortization and maintenance costs was reported by Rodríguez Díaz et al. (2012b). On the other hand, the rise of the energy tariffs for irrigation about 120 % since 2008 in Spain (Rodríguez Díaz et al. 2011) has also influenced the production costs. Thus, the net electricity consumption per unit of water in the Spanish irrigation systems has grown by 10 % from 2002 to 2008 (Hardy et al. 2012). The same trends were observed in other countries such as South Africa with increases in electricity tariffs of 31 % only from 2009 to 2010 (Brazilian et al. 2011).

In order to face the high costs, farmers have replaced traditional irrigated crops, with lower water requirements, by higher value crops but more water demanding (Playán and Mateos 2006; Lecina et al. 2010). Related to this, Rodríguez Díaz et al. (2012a) estimated an increase on

theoretical crop evapotranspiration (ET_c) around 20 % after the transformation of an irrigation district, in Southern Spain, from surface irrigation system to pressurized irrigation system.

Methodologies to improve the energy efficiency in pressurized irrigation networks have been developed (Abadia et al. 2008; Moreno et al. 2009; Lamaddalena and Khila 2012). Likewise, the Spanish Institute for Diversification and Energy Savings (IDAE) has proposed energy saving measures suitable for irrigation districts with pressurized networks. Some of these measures consisted in network sectoring by grouping hydrants with similar energy demand and in the control of critical points, which are hydrants with higher energy requirements due to their elevation or their distance to the water source (Rocamora et al. 2008).

Carrillo Cobo et al. (2011) developed the WEBSO algorithm (Water and Energy Based Sectoring Operation) which provided monthly sectoring strategies based on the hydrants' topological characteristics. Potential energy savings of around 9 % to 27 % in two irrigation districts were achieved by WEBSO. Jiménez Bello et al. (2010) proposed a methodology to group intakes into sectors using genetic algorithms and achieving energy savings of 36 % in the studied area. Sectoring changed the operation of the network and implied the re-organization of farmers in turns according to their energy demand.

There are fewer examples of useful methodologies to detect and control critical points. Khadra and Lamaddalena (2010) developed a decision support system to identify unsatisfied hydrants although energy saving actions in these hydrants were not considered. Related to this, Rodríguez Díaz et al. (2012b) proposed an algorithm named WECP (Water and Energy optimization by Critical Points control) which detected the critical points of a network according to their hydraulic behaviour and proposed improvements to enhance their performance. Also, Rodríguez Díaz et al. (2012b) compared the obtained results of WEBSO and WECP in two Spanish irrigation districts. The algorithm WECP obtained higher energy savings than the WEBSO (between 10 and 31 %) in both irrigation districts when theoretical irrigation requirements were considered.

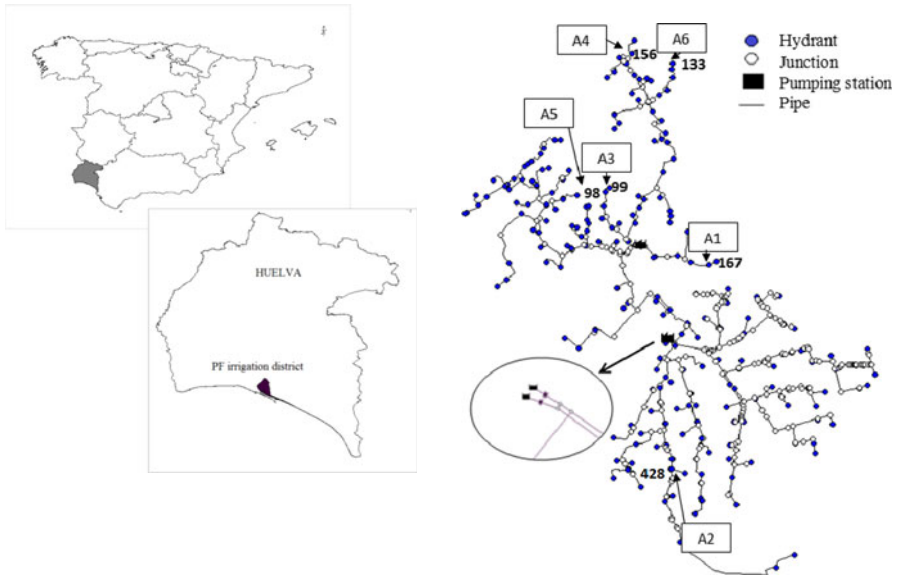
However, both methodologies (WEBSO and WECP) were developed for branched networks with a single water supply point and cannot be applied to networks with multiple water sources, also common in irrigation areas. The optimization of looped water networks is more complex because the pressure head in each pumping station must be estimated simultaneously. Fernández García et al. (2013) addressed this problem and proposed a useful methodology to identify the optimum sectoring strategy for this sort of networks (WEBSOM) using the multiobjective genetic algorithm NSGA-II (Non-dominated Sorting Genetic Algorithm) (Deb et al. 2002) in the optimization process. Conversely, methodologies to detect critical points when the water is supplied from several sources have not been developed yet.

In this work, a methodology based on the control of critical points for multiple source networks is developed and applied to a real irrigation district in Southern Spain. Then, the results are compared with those obtained by Fernández García et al. (2013) when sectoring was considered as energy saving strategy.

2 Methodology

2.1 Study Area

The Palos de la Frontera (PF) irrigation district is placed in the Guadiana river basin in Southern Spain (Fernández García et al. 2013) (Fig. 1). The area is mainly flat, with elevations between 5 to 48 m. The total cropped area is 3,343 ha where strawberry accounts for nearly 75 %. Other crops in the area are citrus, fruit trees and winter vegetables. The irrigation network has three



Booster stations	Pipe change: replacement by bigger pipes
A3: 10 m of elevation	A1: 158 m from 129.2 mm to 200 mm
A4: 10 m of elevation	A2: 284 m from 104.6 mm to 200 mm
A5: 10 m of elevation	
A6: 10 m of elevation	

Fig. 1 Location of Palos de la Frontera irrigation district and energy saving actions in the irrigation network

pumping stations that can provide maximum pressure heads of 85 m, 45 m and 55 m, respectively. Irrigation is organized on-demand and it is monitored by a telemetry system that records in real time information related to volumes, flows and pressures (Pérez Urrestarazu et al. 2009).

2.2 Critical Points Detection for Multiple Source Networks

The WECP algorithm, proposed by Rodríguez Díaz et al. (2012b), was modified to cope with multiple water source networks. Thus, a new algorithm, WECPM (Water and Energy optimization by Critical Points control for Multiple supply sources), was developed. WECPM included a heuristic multiobjective optimization procedure to identify the best management of the critical points.

Genetic algorithms (GA) constitute one of the most used heuristic techniques to solve problems related to the operation and design of water distribution networks (Montesinos et al. 1999, Moradi-Jalal et al. 2004; van Dijk et al. 2008; Jamieson et al. 2007). The main stages of GA are briefly described as follows. First, a random initial population is generated. Then, all individuals of the initial population are evaluated and ranked according to their values of the objective function. Finally, selection, crossover and mutation processes are carried out until the convergence criterion or the fixed number of generations is achieved (Goldberg 1989). A typical GA minimizes or maximizes a single objective function and gives a unique optimal solution. However, to solve problems with several conflicting objectives, a multiobjective genetic algorithm (MOGA) can be used. The result of a multiobjective problem is not a single solution, but a set of optimal solutions known as Pareto optimal front (Savic 2007; Chandapillai et al. 2012; Siew and Tanyimboh 2012).

The NSGA-II has been adapted to detect critical points in multiple source networks linked to the hydraulic model EPANET (Rossman 2000) by using its dynamic link library (DLL). The optimization algorithm was developed in MATLAB (Pratap 2010).

The flow chart of WECPM is shown in Fig. 2 and its main features are described next.

– Initial Population

Firstly, the initial population was randomly generated. In this work, individuals or chromosomes that contained n_v variables corresponding to the daily pressure heads of the pumping stations during the peak demand month formed this population.

– Objective functions

The individuals previously generated were evaluated, that is, the values of the objective functions for each individual were calculated. The objective functions used in this work were the minimization of the daily energy consumption (Eq. 1) and the minimization of the pressure deficit (Eq. 2) considering that the network was operated on demand:

$$F1 = EC_{norm} \quad (1)$$

$$F2 = Pf + CMPD_{norm} \quad (2)$$

Where EC_{norm} is the normalized daily energy consumption, Pf the pressure failure percentage and $CMPD_{norm}$ the normalized term that shows the magnitude of the pressure deficit.

The calculation of the term EC_{norm} (Eq. 1) requires the previous estimation of EC (kWh day^{-1}), that was calculated as follows:

$$EC = \frac{1}{1000} \frac{1}{\eta} \cdot \gamma \cdot t_{rs} \sum_{i=1}^N Q_i \cdot H_i \quad (3)$$

Where i is the pumping stations index, N the number of pumping stations, η the global efficiency of pumps (assuming a pumping efficiency of 0.8), γ water specific weight ($9,800 \text{ Nm}^{-3}$), Q_i the pumped flow by station i (m^3s^{-1}), H_i the pressure head of pumping station i (m) and t_{rs} the daily irrigation time (h) to satisfy crop irrigation requirements estimated as described in Allen et al. (1998).

Regarding $F2$, the term Pf was determined as the ratio between the number of hydrants that did not reach the service pressure and the number of operating hydrants. In this equation, $CMPD_{norm}$ was derived from $CMPD$, calculated as the difference between the pressure in the most critical hydrant and the service pressure.

In order to compare the values of $F1$ and $F2$, the terms EC and $CMPD$ were normalized (EC_{norm} and $CMPD_{norm}$) by the continuous uniform distribution $U(0,1)$. EC_{norm} varied from 0 to 2 while Pf and $CMPD_{norm}$ ranged from 0 to 1, respectively.

The constraints of this minimization problem were the physical laws of energy and mass conservation.

To determine the objective functions and their constraints, the hydraulic simulation of the network was carried out using EPANET, a free and widely used software in the evaluation of water distribution systems (Chandapillai et al. 2012; Siew and Tanyimboh 2012). Also, the EPANET engine can be easily integrated into external programs through its Dynamic Link Library (DLL). The required data were the network's topology, the pressure head of the N pumping stations of every individual created by NSGA-II and the hydrant base demand (Carrillo Cobo et al. 2011). The flows supplied by each pumping station and the pressures at every hydrant were obtained from the hydraulic simulator.

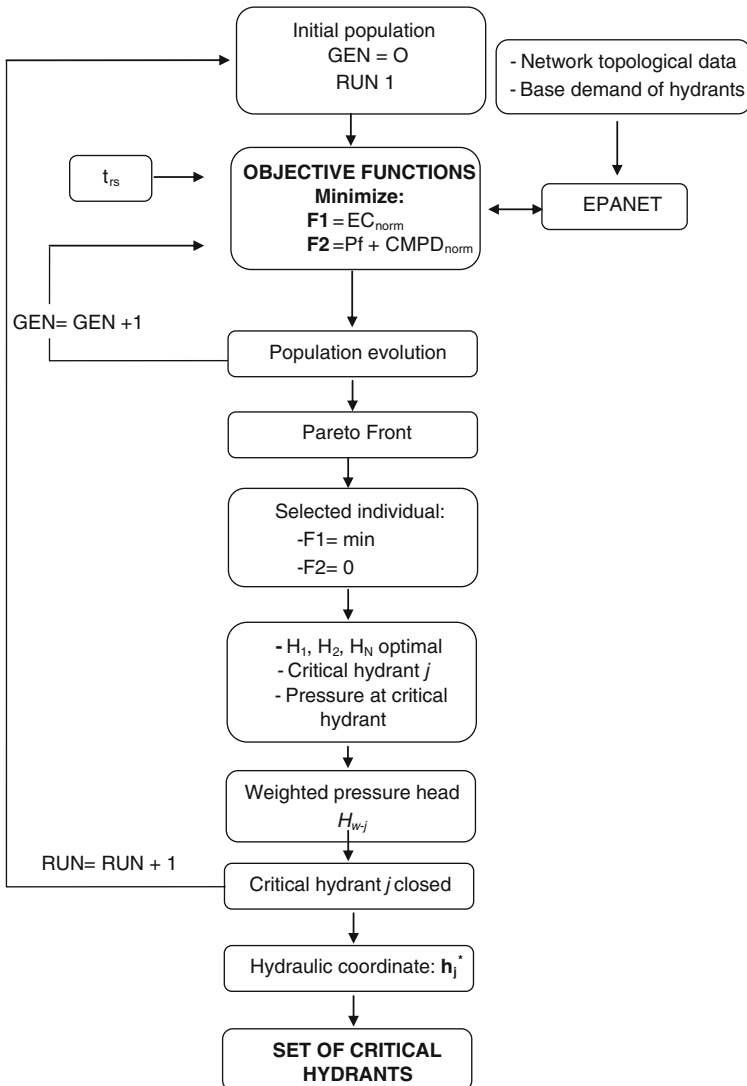


Fig. 2 Schematic representation of the critical point identification

– Selection, crossover- mutation, recombination

The processes of selection, crossover- mutation and recombination were performed as described in Deb et al. (2002) for a number of generations (GEN) fixed at the beginning of the process.

– Critical point detection

The optimization process finished providing the set of individuals (Pareto front) whose hydrants worked at least with the service pressure and their energy consumptions were the lowest. Among the individuals in the Pareto front, the most frequent critical hydrant was identified and then, the individual that having that hydrant as critical involved the minimal energy consumption was selected. This individual contained information of the optimal

pressure heads of the N pumping stations and, as result of the hydraulic simulation, the energy consumption during the maximum demand month and the pressure in the most limiting hydrant (critical point or hydrant with the lowest pressure).

From these results, the weighted pressure head provided by the set of pumping stations when hydrant j was the most critical, H_{w-j} , was determined by the following equation:

$$H_{w-j} = \frac{\sum_{i=1}^N Q_i \cdot H_i}{\sum_{i=1}^N Q_i} \tag{4}$$

Once the first critical point was detected, all the optimization process described above was carried out again. However, in this case, the detected critical point was considered closed and its base demand was set to zero. Thus, a second critical point and its weighted pressure head were obtained. This process continued until the differences in energy consumption in several consecutive critical hydrants was negligible. Then all critical points were identified and their weighted pressure heads were calculated.

Finally, a dimensionless coordinate (h_j^*) associated to each critical hydrant, was defined to characterize its hydraulic behaviour and was calculated as follows:

$$h_j^* = \frac{H_{w-j}}{H_{w-mch}} \tag{5}$$

Where H_{w-mch} is the weighted pressure head of the first detected critical point (run 1). Thus, the maximum value of h_j^* was 1 for the first detected critical point and it was gradually reduced for the following critical hydrants. In the end, all hydrants were ranked according to this criterion. Hydrants with highest h_j^* were selected (critical points) and improvement measures to reduce their energy demand were proposed.

2.3 Sectoring Strategy for Multiple Source Networks

To optimize the energy demand, Fernández García et al. (2013) developed a methodology based on multiple sources networks sectoring (WEBSOM). The sector configuration was performed by grouping hydrants according to the network’s topology. Thus, two dimensionless coordinates, z_j^* , related to the hydrant elevation, and l_j^* , related to the distance between the source nodes and demand nodes, were proposed for every hydrant:

$$z_j^* = \frac{\sum_{i=1}^N \frac{z_j - z_i}{|z_j - z_i|_{\max}}}{N} \tag{6}$$

$$l_j^* = \frac{\sum_{i=1}^N \frac{l_{j-i}}{l_{\max-i}}}{N} \tag{7}$$

Where z_j is the hydrant j elevation, z_i is the pumping station i elevation and $|z_j - z_i|_{\max}$ is the maximum elevation difference between each hydrant and the pumping station i (absolute value). l_{j-i} is the distance between the hydrant j and the pumping station i , determined by the Dijkstra’s graph search algorithm (Dijkstra 1959) and $l_{\max-i}$ is the distance between the furthest hydrant and the pumping station i .

Once the possible sectors were determined, the monthly optimal sectoring operation calendar for irrigation networks with several supply points that required the minimum energy consumption could be identified. The optimal network operation was established using a procedure based on NSGA-II.

2.4 Selection of Best Energy Saving Strategy

After the detection of the critical points and assuming that the network improvement strategies to reduce their energy demand were implemented, WECPM was run for every month of the irrigation season and the potential annual energy savings were compared with those achieved by WEBSOM. Thus, both methodologies' results were compared and the best energy saving strategy could be selected.

3 Results and Discussion

3.1 Irrigation Water Demand

The WECPM was applied to the PF irrigation network for the peak water demand month (May) assuming that the irrigation requirements were fully satisfied. As shown in Table 1, the peak crop water requirements occurred in May (4.1 mm day^{-1}), while January and December were the lowest water demanding months (0.7 mm day^{-1}). Thus, the maximum daily irrigation time required per month, which directly affects the energy consumption, was 9.5 h in May.

3.2 Critical Points Detection

Three decision variables ($n_v=3$) were contained in each individual since this irrigation district has three pumping stations. The minimum values of pressure head at each pumping station were 55, 50 and 45 m while the maximum values were 95, 65 and 55 m, respectively. Concerning the NSGA-II parameters, 100 individuals and 50 generations were considered in each run. The crossover probability was 0.9 and the mutation probability 0.1 (Deb et al. 2002).

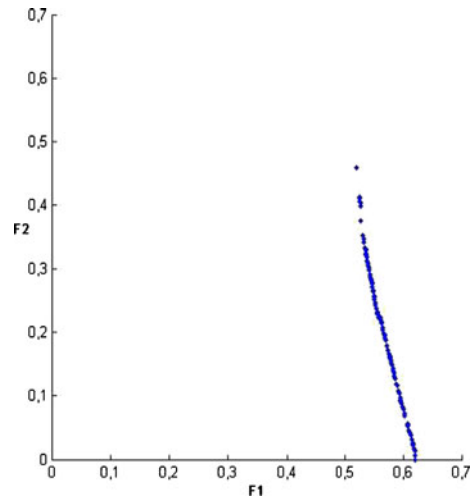
Figure 3 represents the Pareto Front obtained in the first run when all hydrants were open. The minimum value of $F1$ was 0.52 that implies an energy consumption of 623.2 MWh. However, this value was associated to the maximum value of $F2$, 0.46, which indicated that 13 hydrants did not get the pressure service and the pressure in the most critical hydrant was only 18 m. In contrast, the maximum value of $F1$ was 0.62 (energy consumption of 744.6 MWh) corresponding to the minimum value of $F2$ (0). This value is related to an individual that ensured the service pressure in all hydrants. From this set of solutions, we selected the individual with $F2$ equal to 0. In this run, the detected critical point was hydrant 167. In order

Table 1 Monthly crop water requirements, IN , irrigated area, IA and daily irrigation time required per month, t_{rs}

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$IN \text{ mmday}^{-1}$	0.7	1.1	2.1	2.9	4.1	1.5	0.9	2.0	1.7	2.0	0.9	0.7
$IA^a \%$	79	79	91	94	94	94	16	21	95	79	79	79
$t_{rs} \text{ hours}$	1.7	2.5	4.8	6.7	9.5	3.5	2.0	4.4	3.9	4.7	2.2	1.5

^aPercentage of the total area that is irrigated every month

Fig. 3 Pareto Front of the first run when all hydrants are considered open



to identify the next critical point, hydrant 167 was removed and a second run was performed. Thus, in every run a new critical point was sequentially detected and removed (hydrant 428 was eliminated after the second run) and while the critical points were eliminated, the network's pressure requirements were progressively reduced.

Table 2 summarizes the WECPM's outputs for 20 consecutive runs: 20 critical points, which are ranked according to their weighted pressure head. This table also shows the corresponding pressure heads for the three pumping stations when each critical hydrant was open, the pressure in each critical hydrant, the daily pumped flow, the energy consumption and the energy consumption per unit of supplied water in each run.

As critical points were removed from the analysis, the pumped flow was progressively reduced. Thus, to obviate the effect of the reduction in pumped flow on the decrease of energy consumption, the energy consumption per unit of supplied water was evaluated. The weighted pressure head was reduced in the consecutive runs as well as the energy consumption and the energy consumption per unit of irrigation water supplied. However, after run 8 (hydrant 155), H_{w-j} was reasonably constant because the following critical points had similar pressure requirements. Considering the first 8 runs, H_{w-j} was reduced from 62.8 to 52.6 m after disabling 7 critical points, which were responsible of 20 % of the energy consumption (4,794 kWh day⁻¹). Likewise, the unit energy demand (kWh m⁻³) diminished from 0.21 to 0.17 when these critical hydrants were not operating.

After obtaining the H_{w-j} for all the critical hydrants, the hydraulic dimensionless coordinate h_j^* was calculated and plotted against both topological coordinates, z_j^* and l_j^* (Fig. 4). The seven detected critical points had h_j^* values over 0.85. The two first critical hydrants (167 and 428) show low values of z_j^* (negative values denote that the point is below the pumping stations) and medium values of l_j^* (this indicates that the hydrants are located at an intermediate distance from the water sources). Therefore, the high values of h_j^* are due to the existence of undersized pipes. The other critical points (99, 156, 133, 115 and 38) show high values of z_j^* , hence these hydrants were located in the highest areas.

3.3 Improvement Actions

After analyzing the hydraulic and topological coordinates, several energy saving actions were proposed for every critical point in order to improve the network operation (Fig. 1). These

Table 2 Critical hydrants, optimal pressure heads of the pumping stations H_i , weighted pressure head H_{w-j} , pressure P in the critical hydrants, pumped flow $\sum Q_i$, energy consumption EC and energy consumption per unit of irrigation water supplied E_w

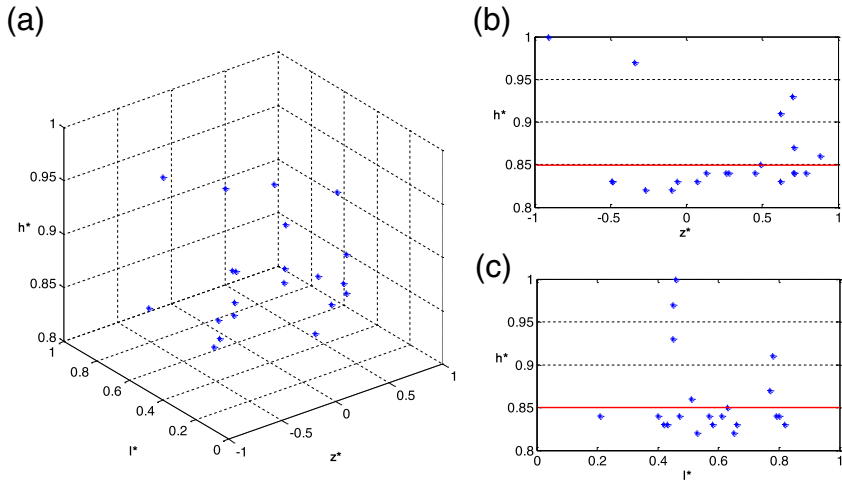
Run	Hydrant	H_1 m	H_2 m	H_3 m	H_{w-j} m	P m	$\sum Q_i$ $m^3 day^{-1}$	EC $kWh day^{-1}$	E_w $kWh m^{-3}$
1	167	66.3	57.5	0.0	62.8	30	112,388	24,019	0.214
2	428	62.6	59.7	45.9	61.1	30	110,387	22,941	0.208
3	99	62.6	50.0	0.0	58.6	30	109,319	21,796	0.199
4	156	61.2	50.0	51.4	57.3	30	108,762	21,188	0.195
5	133	57.9	50.0	47.1	54.6	30	108,495	20,163	0.186
6	115	57.1	0.0	49.8	54.0	30	108,171	19,866	0.184
7	38	55.8	50.0	0.0	53.1	30	107,701	19,458	0.181
8	155	55.1	50.0	0.0	52.6	30	107,235	19,225	0.179
9	120	55.0	50.1	0.0	52.6	31	106,806	19,114	0.179
10	114	55.1	50.0	0.0	52.6	31	106,635	19,089	0.179
11	119	55.0	50.0	0.0	52.6	32	105,796	18,916	0.179
12	382	55.2	50.1	0.0	52.7	33	105,158	18,860	0.179
13	152	55.0	50.0	0.0	52.6	33	103,922	18,576	0.179
14	98	55.0	50.0	50.3	52.4	34	103,365	18,421	0.178
15	213	55.1	0.0	49.7	52.4	30	103,056	18,373	0.178
16	106	55.0	50.0	0.0	52.5	34	102,556	18,329	0.179
17	186	55.1	0.0	48.2	52.0	30	102,222	18,090	0.177
18	202	55.0	0.0	47.7	51.9	30	101,540	17,915	0.176
19	182	55.0	0.0	45.0	51.5	32	100,106	17,532	0.175
20	467	55.4	0.0	45.0	51.9	32	98,765	17,447	0.177

measures implied changes in pipe sizes when z_j^* was low and the installation of booster pumps for the hydrants with the highest elevations. These measures were sequentially applied in order to analyze their potential impacts in the network operation. Figure 1 details the improvement actions and shows their location.

3.4 Potential Energy Savings after the Improvement Actions

To estimate the potential energy savings after the improvement actions, the new optimal pressure heads at pumping stations were recalculated using a new network’s model which included all these changes. Then, following a similar approach, the new critical points for the improved network were detected (Fig. 4). These changes affected to the coordinate h_j^* but did not modify z_j^* and l_j^* , which depend on the network’s topology only.

Hydrants 167 and 38 were not identified as critical points after the improvement actions and hydrants 98 and 213, which were not in the original list, appeared in the new set of the 7 most critical hydrants. In fact, after the introduction of the four first energy saving actions, hydrant 98 (which was not in the initial list of critical points) was detected as critical point and an improvement measure was designed for this hydrant. Furthermore, the values of coordinate h_j^* after the measures were significantly higher than before the changes and the difference between the first and the seventh critical point was smaller. This increase in h_j^* was related to the decrease of H_{w-mch} , which was now much closer to the H_{w-j} values.



BEFORE				AFTER			
Hydrant	z_i^*	l_i^*	h_i^*	Hydrant	z_i^*	l_i^*	h_i^*
167	-0.91	0.46	1.00	428	-0.34	0.45	1.00
428	-0.34	0.45	0.97	99	0.70	0.45	0.96
99	0.70	0.45	0.93	156	0.62	0.78	0.94
156	0.62	0.78	0.91	98	0.62	0.43	0.91
133	0.71	0.77	0.87	133	0.71	0.77	0.90
115	0.88	0.51	0.86	115	0.88	0.51	0.89
38	0.49	0.63	0.85	213	0.49	0.63	0.88

Fig. 4 Dimensionless coordinates z_i^*, l_i^* and h_i^* of the critical points detected and comparison for the first seven critical hydrants before and after the proposed measures

In order to estimate the monthly and annual energy savings achieved if these measures were adopted, a similar analysis was carried out for all the months of the irrigation season. Thus, the monthly energy requirements were included in the WECPM model and a new set of optimal pressure heads for the three pumping stations (those with the minimum value of $F1$ and $F2=0$) was obtained for every month. Pumping pressure heads before and after the improvement actions are shown in Table 3.

In all months, H_{w-j} decreased after the improvement actions. The average value of H_{w-j} was reduced from 58 to 52 m whereas the peak value of H_{w-j} , obtained in September, decreased from 64 to 54 m. Although May is the peak demand month, September has the largest irrigated area because most of the crops coincides in the field (Table 1). It should be noted that the simultaneous operation of all hydrants, each one supplying the volume of water required to irrigate its associated area, was considered in this work. Thus, the H_{w-j} values were very similar in the peak demand months because more crops are simultaneously in the field. However, the daily volume of pumped water was higher in May than in other peak demand months since more irrigation time was needed (Table 1). Because of this, the control of critical points is the most appropriate management measure for the highest water demand months (related to both irrigated area and irrigation requirements). In this case, months with higher H_{w-j} (April, May, June and September) were associated to the largest irrigated area as well as irrigation needs

Table 3 Optimal pressure heads (m) of the three pumping stations and weighted pressure head (m) obtained with WECPM, before and after the proposed actions

	Before				After			
	H ₁	H ₂	H ₃	H _{w-j}	H ₁	H ₂	H ₃	H _{w-j}
Jan	59	0	53	57	55	0	48	52
Feb	59	50	0	56	55	0	48	52
March	63	56	48	60	56	0	48	53
April	66	58	48	63	57	51	53	54
May	66	58	0	63	57	0	50	54
Jun	66	58	0	63	57	50	53	54
Jul	0	0	50	50	0	0	48	48
Aug	0	0	51	51	0	0	49	49
Sept	67	58	48	64	57	50	50	54
Oct	59	0	48	56	55	50	48	53
Nov	59	0	48	56	55	0	45	52
Dec	59	50	0	56	56	0	45	53
Average				58				52
Max				64				54
Min				50				48

(Table 1). Moreover, the control of critical points resulted more effective in these months because the decrease in H_{w-j} after the actions was more significant. The minimum value of H_{w-j} occurred on July with 50 m and 48 m before and after the actions, respectively (only 16 % of irrigated area).

The annual energy consumptions obtained when the improvements actions were sequentially introduced are shown in Fig. 5. Thus, the relation between the number of improvement actions and energy savings was obtained. The three first actions entailed almost 60 % of the energy savings achieved when all measures were introduced. Hence, managers of irrigation districts can decide the number of actions to be applied taking into account the energy saving versus the investment cost linked to each of them.

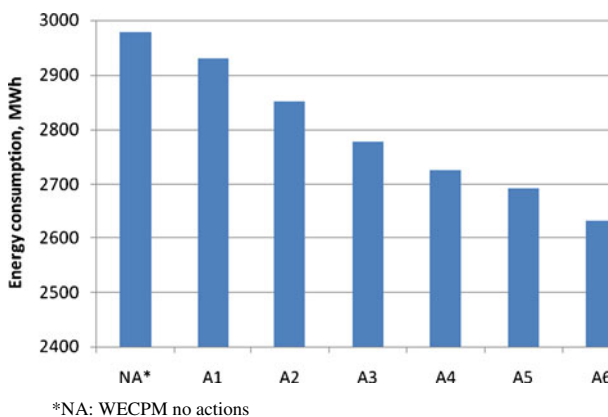


Fig. 5 Annual energy consumption after the sequential introduction of the energy saving actions

3.5 WEBSOM vs. WECPM

Table 4 shows the monthly energy consumptions obtained when WEBSOM and WECPM strategies were adopted and compared with the monthly energy demand required for the current operation of the network. WECPM with improvement actions achieved lower energy requirements than WEBSOM in all months. In contrast to the current operation of the network, annual energy savings of 1195.4 MWh (29 %) and 1483.7 MWh (36 %) were obtained when WEBSOM and WECPM were considered, respectively. Therefore, WECPM with actions was more effective than WEBSOM in the PF irrigation district which has a flat topography with 43 m as maximum difference between hydrant elevations. Using the strategy of critical point control Rodríguez Díaz et al. (2012b) also achieved higher energy savings than with sectoring in irrigation districts with flat topography (the maximum elevation difference among hydrants was 45.6 m). Assuming the WECPM with actions, the peak energy demand month was May with an energy consumption of 640.8 MWh while the lowest energy demand occurred in July (20.3 MWh).

Comparing the potential energy savings of WECPM without actions versus the current operation of the network, the annual energy saving was the 28 % (1137.1 MWh). Moreover, this strategy achieved lower energy requirements than WEBSOM in some months (January, February, April, July, August) and the annual energy consumption was only 2 % higher than the obtained by WEBSOM. Additionally, the sectoring strategy implies irrigation in turns while WECPM with and without actions allows on demand irrigation. The annual energy demand optimized by WEBSOM is 10 % higher than the value obtained by WECPM with actions. A cost/benefit analysis is required before selecting the best management option for any irrigation network according to its particular conditions (e.g. availability of telecontrol systems and only its set up would be required). The investment cost of the improvement actions (e.g. pipe replacement) must be compensated with the economical value of the energy savings.

Table 4 Monthly energy consumption (MWh) required for the current operation of the network, after sectoring and after WECPM with and without improvement actions

	Actual operation	WEBSOM	WECPM	
			No actions ^a	Actions
Jan	151.4	135.0	102.6	94.7
Feb	217.2	159.9	131.0	122.9
Mar	470.2	320.4	345.6	304.7
Apr	676.3	508.8	506.6	438.5
May	962.8	707.4	744.6	640.8
Jun	352.8	241.9	264.3	228.3
Jul	36.0	27.5	21.3	20.3
Aug	104.8	68.1	62.8	59.8
Sep	402.0	281.7	306.5	260.8
Oct	415.3	265.1	278.1	262.5
Nov	191.1	119.1	124.1	115.3
Dec	135.2	84.9	90.4	82.6
Total	4115.0	2919.6	2977.9	2631.3

^aOptimal pressure heads detected using WECPM

4 Conclusions

A useful methodology to detect and control critical points for multiple source networks has been proposed. This methodology is based on the algorithm WECPM, which uses the NSGA-II genetic algorithm along with a hydraulic simulation model.

The analysis of WECPM on a real irrigation network has provided a potential annual energy saving of 36 % in relation with the current operation of the network, if minor improvement measures, such as the replacement of two pipes and the installation of four booster pumps, were adopted. Even without improvement actions, WECPM could reduce 12 % of the energy consumption of the current network operation.

The strategy of controlling critical points has been compared with sectoring. The energy savings were 10 % higher compared to the results obtained by WEBSOM.

A cost/benefit analysis is required before selecting the best energy saving strategy for any irrigation network according to its particular conditions (e.g. topography, availability of telecontrol systems). Furthermore, farmers' management preferences should also be considered. The adoption of a sectoring strategy implies the organization of the farmers in turns, losing one degree of flexibility while the control of critical points allows farmers to irrigate on demand. In contrast to sectoring, the critical points control strategy involves investment costs to perform the proposed energy saving actions. The incorporation of the energy tariff to these algorithms would help to determine which methodology achieves higher economic savings for each particular network, that is the main target for farmers and it is not always linked to the reductions in energy consumption.

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References

- Abadia R, Rocamora C, Ruiz-Canales A, Puerto H (2008) Energy efficiency in irrigation distribution networks I: theory. *Biosyst Eng* 101(1):21–27
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and drainage paper no. 56. Food and Agricultural Organization of the United Nations (FAO), Rome
- Brazilian et al (2011) Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39:7896–7906
- Carrillo Cobo MT, Rodríguez Díaz JA, Montesinos P, López Luque R, Camacho Poyato E (2011) Low energy consumption seasonal calendar for sectoring operation in pressurized irrigation networks. *Irrig Sci* 29:157–169
- Chandapillai J, Sudheer KP, Saseendran S (2012) Design of water distribution network for equitable supply. *Water Resour Manag* 26:391–406
- Corominas J (2010) Agua y energía en el riego en la época de la sostenibilidad. *Ingeniería del Agua* 17(3):219–233
- Deb K, Pratap A, Agarwal S, Meyarivan T (2002) A fast elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans Evol Comput* 6(2):182–197
- Dijkstra EW (1959) A note on two problems in connexion with graphs. *Numer Math* 1:269–271
- Fernández García I, Rodríguez Díaz JA, Camacho Poyato E, Montesinos P (2013) Optimal operation of pressurized irrigation networks with several supply sources. *Water Resour Manag* 27:2855–2869
- Goldberg DE (1989) Genetic algorithms in search, optimization and machine learning. Addison-Wesley Longman Publishing Co, Inc, Boston
- Hardy L, Garrido A, Juana L (2012) Evaluation of Spain's water-energy nexus. *Water Resour Dev* 28(1):151–170

- Jackson TM, Khan S, Hafeez M (2010) A comparative analysis of water application and energy consumption at the irrigated field level. *Agric Water Manag* 97:1477–1485
- Jamieson DG, Shamir U, Martinez F, Franchini M (2007) Conceptual design of a generic, real-time, near-optimal control system for water distribution networks. *J Hydroinf* 9(1):3–14
- Jiménez Bello MA, Martínez Alzamora F, Bou Soler V, Bartolí Ayala HJ (2010) Methodology for grouping intakes of pressurised irrigation networks into sectors to minimise energy consumption. *Biosyst Eng* 105: 429–438
- Khadra R, Lamaddalena N (2010) Development of a decision support system for irrigation systems analysis. *Water Resour Manag* 24:3279–3297
- Lamaddalena N, Khila S (2012) Energy saving with variable speed pumps in on-demand irrigation systems. *Irrig Sci* 30:157–166
- Lecina S, Isidoro D, Playán E, Aragón R (2010) Irrigation modernization and water conservation in Spain: the case of Riegos del Alto Aragón. *Agric Water Manag* 97:1663–1675
- Montesinos P, García-Guzmán A, Ayuso JL (1999) Water distribution network optimization using a modified genetic algorithm. *Water Resour Res* 35:3467–3473
- Moradi-Jalal M, Rodin SI, Mariño MA (2004) Use of genetic algorithm in optimization of irrigation pumping stations. *J Irrig Drain Eng* 130(5):357–365
- Moreno MA, Planells P, Córcoles JL, Tarjuelo JM, Carrión PA (2009) Development of a new methodology to obtain the characteristic pump curves that minimize the total costs at pumping stations. *Biosyst Eng* 102:95–105
- Pérez Urrestarazu L, Rodríguez Díaz JA, Camacho Poyato E, López Luque R (2009) Quality of service in irrigation distribution networks: case of Palos de la Frontera irrigation district (Spain). *J Irrig Drain Eng* 135(6):755–762
- Playán E, Mateos L (2006) Modernization and optimization of irrigation systems to increase water productivity. *Agric Water Manag* 80:100–116
- Pratap R (2010) *Getting started with Matlab. A quick introduction for scientist and engineers*. Oxford University Press, USA
- Rocamora MC, Abadía R, Ruiz A (2008) *Ahorro y Eficiencia energética en las Comunidades de Regantes*. Ministerio de Industria, Turismo y Comercio, IDAE, Madrid
- Rodríguez Díaz JA, Camacho Poyato E, Blanco Pérez M (2011) Evaluation of water and energy use in pressurized irrigation networks in Southern Spain. *J Irrig Drain Eng* 137(10):644–650
- Rodríguez Díaz JA, Pérez Urrestarazu L, Camacho Poyato E, Montesinos P (2012a) Modernizing water distribution networks. Lessons from the Bembézar MD irrigation district, Spain. *Outlook Agric* 41(4): 229–236
- Rodríguez Díaz JA, Montesinos P, Camacho Poyato E (2012b) Detecting critical points in on-demand irrigation pressurized networks - a new methodology. *Water Resour Manag* 26(6):1693–1713
- Rossman LA (2000) *EPANET 2. Users manual*. US Environmental Protection Agency (EPA), USA
- Savic D (2007) Single-objective vs. multi-objective optimization for integrated decision support. Proceedings of the first biennial meeting of the international environmental modeling and software society 1:7–12 Lugano, Switzerland, June 24–27
- Siew C, Tanyimboh T (2012) Penalty-free feasibility boundary convergent multi-objective evolutionary algorithm for the optimization of water distribution systems. *Water Resour Manag* 26:4485–4507
- van Dijk M, van Vuuren SJ, van Zyl JE (2008) Optimising water distribution systems using a weighted penalty in a genetic algorithm. *Water SA (Online)* 34(5):537–548