

Low energy consumption seasonal calendar for sectoring operation in pressurized irrigation networks

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Abstract Pressurized irrigation networks and organized on-demand are usually constrained by the high amounts of energy required for their operation. In this line, sectoring, where farmers are organized in turns, is one of the most efficient measures to reduce their energy consumption. In this work, a methodology for optimal sectoring is developed. Initially it groups similar hydrants in homogeneous groups according to the distance to the pumping station and their elevation, using cluster analysis techniques and certain dimensionless coordinates. Second, an algorithm based on the EPANET engine is implemented to search for the best monthly sectoring strategy that accomplish supplying the actual irrigation demand under minimum energy consumption conditions. This methodology is applied to two Spanish irrigation districts (Fuente Palmera and El Villar). Results showed that organizing the networks in sectors, annual

energy savings of 8 and 5% were achieved for Fuente Palmera and El Villar when the theoretic irrigation needs were considered. However, these savings rose up to 27 and 9%, respectively when the local practices, deficit irrigation, were taken into account. Thus, they confirm that water and energy efficiency cannot be optimized independently and need to be considered together.

List of symbols

| | |
|--------------|---|
| α | Excess of pressure in the worst open hydrant |
| D | Number of working hours |
| E | Daily energy consumption |
| F_{mjl} | Demanded flow in month m , sectoring option j and operating sector l |
| H_{\max} | Maximum theoretic pressure head |
| H_{pmjl} | Pressure head at the pumping station in month m , sectoring option j and operating sector l |
| H_{ei} | Elevation from the water source to the hydrant i |
| H_i | Energy required to supply water to the hydrant i |
| H_j | Pressure in the worst open hydrant |
| H_{li} | Friction losses in pipes |
| H_{reqi} | Required pressure head at hydrant |
| IN_{im} | Daily irrigation need |
| l_i | Distance from the pumping station to the hydrant i |
| l_{\max} | Distant to the furthest hydrant |
| l_i^* | Dimensionless coordinate for sectoring |
| p_{imj} | Probability of open hydrant in month m and sectoring option j |
| Power | Power requirements at the pumping station |
| q_i | Base demand in hydrant i |
| $q_{\max i}$ | Maximum flow allowed per hydrant |
| R_{imj} | Random number based on the (0, 1) uniform distribution |
| t_{aj} | Number of hours available for irrigation in sectoring option j |

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| | |
|----------|--|
| t_{im} | Number of hours needed to irrigate for every hydrant (i) and every month (m) |
| γ | Water specific weight |
| η | Pumping system efficiency |
| z_i | Elevation of hydrant i |
| z_{ps} | Elevation of the pumping station |
| z_i^* | Dimensionless coordinate for sectoring |

Introduction

Trying to improve the efficiency in the use of the irrigation water, modernization processes of irrigation schemes have been a common practice in recent years. The hydraulic infrastructures have been improved and the old open channel distribution networks have been replaced by new pressurized networks arranged on-demand (Plusquellec 2009). This change increases the conveyance efficiency reducing water losses throughout the distribution system. Additionally, with the new systems arranged on-demand, farmers get a much greater degree of flexibility allowing the use of more efficient systems such as trickle or sprinkler and therefore increasing uniformity and irrigation frequency (Rodríguez Díaz et al. 2007a; Lamaddalena et al. 2007; Pérez Urrestarazu et al. 2009).

But in return the pressurized networks require large amounts of energy for their operation. For example in Spain, where an ambitious modernization plan of irrigation schemes has been carried out (MAPA 2001), Corominas (2009) reported that while water use has been reduced from 8,250 to 6,500 m³/ha (−21%) from 1950 to 2007, the energy demand was increased from 206 to 1,560 kWh/ha (+657%) in this period. Thus, several authors have highlighted the necessity of reducing the energy requirements improving the performance of the different irrigation network's elements such as the pumping efficiency, optimum network's design, on-farm irrigation systems or using renewable energy resources (ITRC 2005; Moreno et al. 2007, 2009; Pulido-Calvo et al. 2003; Abadia et al. 2008; Vieira and Ramos 2009; Daccache et al. 2010).

In this way, the Institute for Diversification and Energy Savings of Spain (IDAE) proposes several measures to optimize energy demand in pressurized networks. These measures include network sectoring according to homogeneous energy demand sectors and organize farmers in irrigation turns, pumping station adaptation to several water demand scenarios, detection of critical points within the network and energy audits (IDAE 2008).

Rodríguez Díaz et al. (2009) developed a methodology for evaluating the energy savings measures proposed by IDAE (2008) and tested them in the irrigation district of

Fuente Palmera (FP) (Southern Spain). Thus, potential energy savings were calculated for each measure. In that study, sectoring was the most effective measure with average potential savings of around 20%. This is consistent with other authors' findings (Sánchez et al. 2009; Jiménez Bello et al. 2010) who proposed methodologies based on genetic algorithms but do not take into account the network's topology.

However, the work done by Rodríguez Díaz et al. (2009) had some limitations: (1) the network was simulated using real demand data but for the peak demand period only and the proposed measures were optimum only for that period; (2) a homogeneous cropping pattern was assumed for all fields within the district when in reality each field had different crops; (3) a wide range of open hydrant probabilities were used in the simulations, but without taking into account the most likely value of probability in relation with the allocated flow per hydrant and the water demand scenario; (4) the sectoring criteria was based on the hydrants' elevations what is useful for abrupt areas but not for flat areas where friction losses are more significant than elevations.

This work represents a step further in the methodology developed by Rodríguez Díaz et al. (2009) and its previously cited limitations have been addressed. Thus, a sectoring method based on the topological characteristics of the network is developed, as well as a methodology for searching low energy consumption monthly calendars for sectoring operation in irrigation networks for different irrigation demand patterns. Both procedures have been applied to Fuente Palmera (FP) and El Villar (EV) irrigation networks of which topology are steep and flat, respectively.

Methodology

Study area

Two Andalusian (Southern Spain) on-demand pressurized systems, FP and AV, were selected for this work (Fig. 1). Both networks are placed in the Guadalquivir river basin (Rodríguez Díaz et al. 2007b). The climate in the region is predominantly Mediterranean, with rainfall mainly in autumn and spring and dry spells in summer (Rodríguez Díaz et al. 2004). The average monthly rainfall and evapotranspiration, measured in meteorological stations within the irrigation districts, are shown in Fig. 2.

FP irrigation district (Córdoba province) has an irrigated area of 5,611 ha. Most of the district is devoted to extensive field crops, being the most representative citrus, cereals, and olive trees (Carrillo 2009).



Fig. 1 Location of Fuente Palmera and El Villar irrigation districts

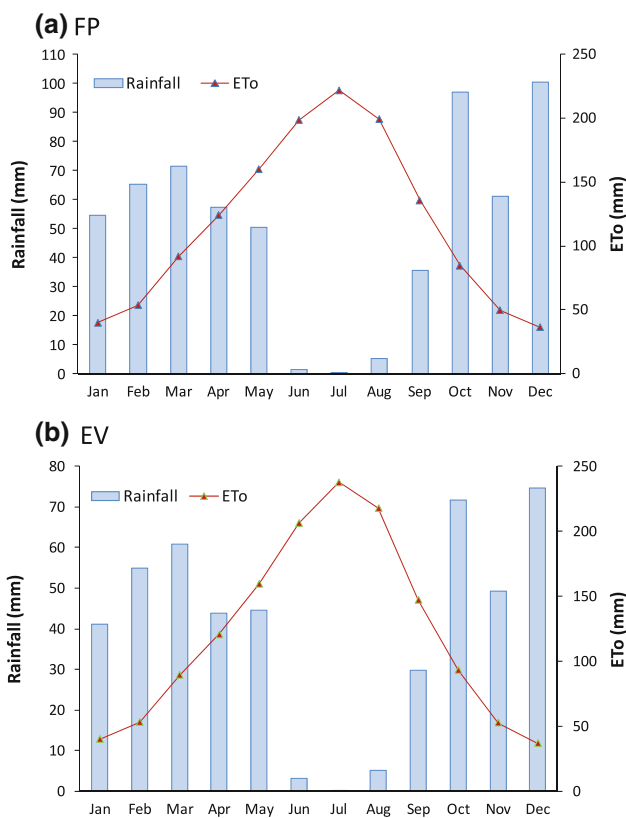


Fig. 2 Average monthly rainfall and evapotranspiration

Water is taken from the Guadalquivir River and stored in a pond from where it is pumped directly to 85 hydrants. The main pipe network length is over 46 km. It was designed to supply on demand. Hydraulic valves installed

in every hydrant limit the flow to 1.2 L/s/ha. Topography is quite steep and the maximum difference among hydrant elevations is 79 m.

The pumping station has 6 pumps of 1,825 kW, 2 of 495 kW and one variable speed pump of 540 kW. A service pressure of 30 m for all hydrants in the network is guaranteed. The pumping station has a telemetry system which records the pressure head and pumped flows every minute.

EV irrigation district (Seville province) irrigates 2,729 ha. Due to the climatic and soil condition, there is a wide variability of crops in the area. The most representative crops are cereals, cotton and olive trees, which sum 80% of the irrigation area.

In this irrigation district, water is taken from the Genil River and conveyed to a reservoir from where is pumped through a pumping station with 6 main pumps of 383 kW and 2 auxiliary pumps of 127 and 271 kW, respectively. Then water is delivered by the irrigation network. It is composed of 31 km of main pipes, which carry water to 47 hydrants, guaranteeing a service pressure of 30 m in all hydrants, as well as in FP irrigation network.

Topological coordinates algorithm for defining sectors in irrigation networks

Energy requirement at a pumping station to supply water to a certain hydrant i , H_p , was calculated using the following equation:

$$H_p = H_{ei} + H_{li} + H_{reqi} \tag{1}$$

where H_{ei} represents the hydrant elevation measured from the water source elevation, H_{li} are the friction losses in pipes and H_{reqi} is the pressure head required at hydrant to be able to operate the irrigation system properly (30 m in the study cases).

H_{reqi} was considered a design constraint and was assumed invariable. However, the other two terms could vary for every hydrant, H_{ei} depending on hydrant elevation and H_{li} on hydrant water demand and its distance from the pumping station.

To take these variables into account, a simplistic methodology was proposed. Thus, the following topological dimensionless coordinates were used:

$$z_i^* = \frac{z_{ps}}{z_i} \tag{2}$$

$$l_i^* = \frac{l_i}{l_{max}} \tag{3}$$

being z_i^* , the dimensionless hydrant elevation, which is directly related to H_{ei} ; z_{ps} and z_i are the pumping station and hydrant i elevations, respectively. The second dimensionless coordinate, l_i^* , affects H_{li} ; l_i and l_{max} are the

distances from the pumping station to hydrant i along the distribution network and to the furthest hydrant, respectively. Therefore, with these two coordinates, the network topology could be characterized in relation to the pumping station location. The use of dimensionless coordinates allows comparison among networks of different sizes.

When all the hydrants within the network were identified by these coordinates, they were classified into statistically homogeneous groups using cluster analysis techniques. With this aim, the K-means algorithm was used herein (Holden and Brereton 2004). By means of this algorithm, groups of homogeneous data were formed with no vertical structure or dependence. The objective of the K-means algorithm is to minimize variance within clusters and maximize variance between clusters (Jain 2000). This algorithm is based on minimizing a performance index, which is defined as the sum of the distances of all the objects inside the cluster to its centroid. The Euclidean distance has been used to measure the distance between elements (Rodríguez Díaz et al. 2008). When using the K-means algorithm it is necessary to fix the number of clusters to be created *a priori*. In this paper, the clustering algorithm was applied for 2 and 3 cluster. Each cluster represented a homogeneous irrigation sector. Every level of sectoring implied a proportional reduction in the number of hours available for irrigation. Thus, no more sectoring levels (4 or 5) were considered because they would make impossible the application of the required depths in most of the hydrants.

Sectoring operation algorithm to reduce monthly energy consumption

The algorithm WEBSO (Water and Energy Based Sectoring Operation) that has been developed to reduce monthly energy consumption according to the previous sectoring definition is summarized in Fig. 3. As energy management is directly related to irrigation water demand, two objectives were considered simultaneously: minimize both energy consumption for the whole network and provide irrigation water to all the hydrants. WEBSO was implemented in visual basic and simulated the network hydraulic behavior for every month under different loading conditions randomly generated.

Initially the existing crops associated with each hydrant during the irrigation season were recorded. From these data, the theoretic daily average irrigation needs per month and hydrant (mm) were estimated as described in FAO 56 (Allen et al. 1998), using the computer model CROPWAT (Clarke 1998). This information can be easily transformed into daily irrigation need, IN_{im} in (l/ha/day).

Clément (1966) suggested that the probability of open hydrant might be estimated as the quotient between hours

needed to irrigate the field associated to each hydrant and the water availability time in hours. Then, the irrigation time required in hours, per hydrant and month, t_{im} was calculated as follows:

$$t_{im} = \frac{1}{3600} \cdot \frac{IN_{im}}{q_{max}} \quad (4)$$

where q_{max} is the maximum flow allowed per hydrant, equal to 1.2 L/s/ha for the analyzed networks. It was considered as a network design criterion.

Local irrigation practices were considered, adjusting theoretic irrigation needs to actual values by means of the irrigation adequacy performance indicator Annual Relative Irrigation Supply (RIS). RIS is the ratio of the total annual volume of water diverted or pumped for irrigation and total theoretic irrigation needs required by the crops (Rodríguez Díaz et al. 2008) and is calculated per irrigation season. RIS values below 1 indicate that the crop water requirements were not completely fulfilled and therefore deficit irrigation, on the contrary RIS over 1 indicates excess irrigation. Theoretically the best RIS value is 1 (satisfy irrigation needs); however, it can be far from actual values in real irrigation districts. For this reason, different RIS values were considered, as they modify t_{im} as follows:

$$t_{im} = \frac{1}{3600} \cdot \frac{IN_{im} \cdot RIS}{q_{max}} \quad (5)$$

RIS below 1 diminishes t_{im} in relation with its value to fulfill theoretic irrigation needs and RIS over 1 increases it.

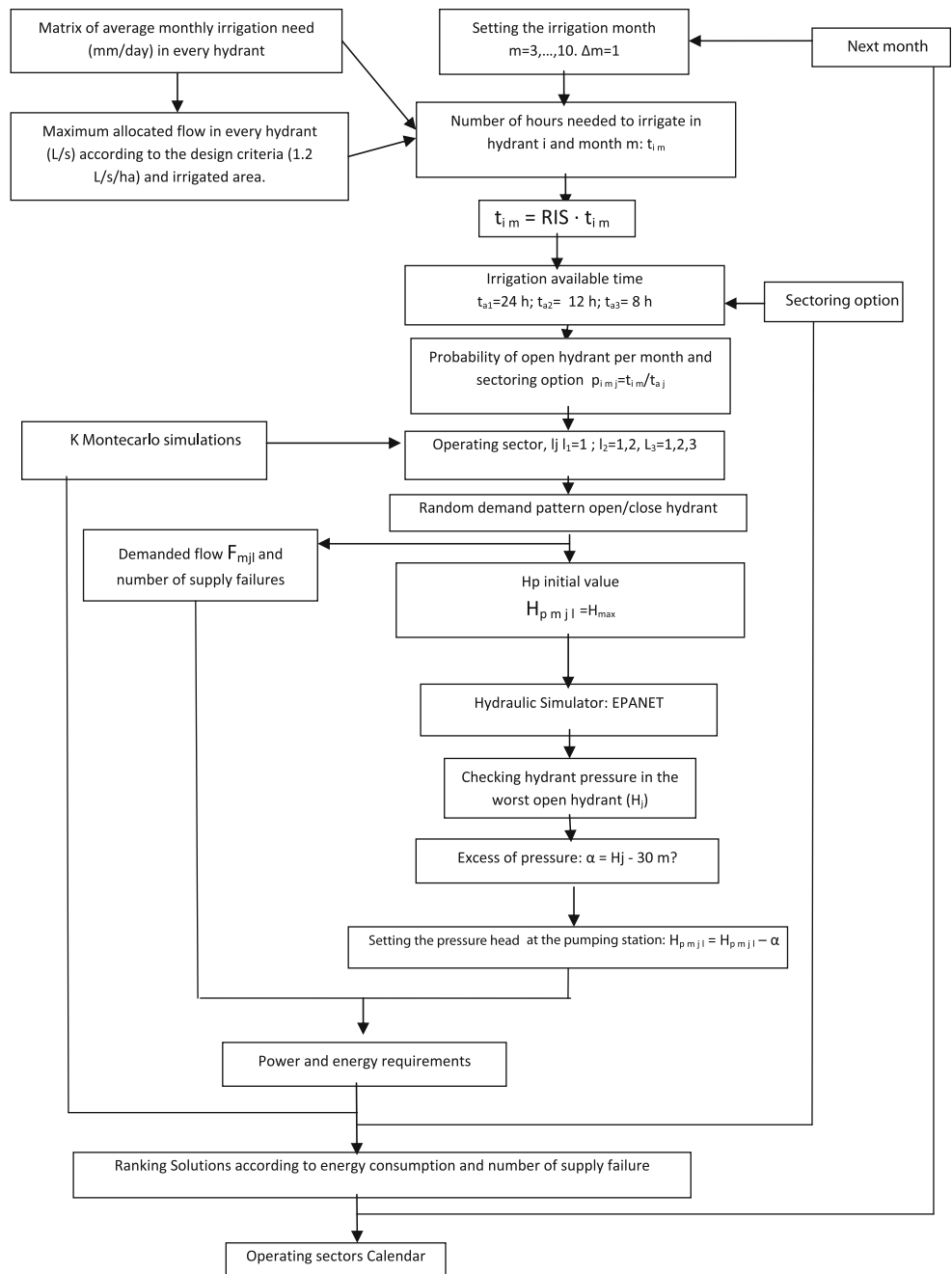
One unique RIS value for each system (FP and EV) was calculated considering water consumption and crop rotations in the 2008 irrigation season. The theoretic irrigation needs were calculated according to Allen et al. (1998).

The water availability time, t_{aj} , depends on the number of operating sectors. Using the previous sector identification, the networks might operate considering the whole network (1 sector) or 2 or 3 sectors, working one after another everyday what means that farmers could only irrigate in turns. Thus, t_{aj} was assigned three possible values according to the number of operating sectors, j , per day: 24 h when the network was operated on demand (1 sector); 12 h for two operating sectors and finally 8 h for 3 operating sectors. Thus, farmers could irrigate on-demand but only in certain hours of the day. Then the open hydrant probability according to the number of operating sectors per month (p_{imj}) was calculated according to the following equation:

$$p_{imj} = \frac{t_{im}}{t_{dj}} \quad (6)$$

when t_{im} was bigger than t_{dj} , it was considered as a supply failure as the hydrant did not have enough time to satisfy irrigation needs according to RIS. These hydrants did not

Fig. 3 Schematic representation of the optimization algorithm



accomplish the implicit water demand satisfaction constraint. An open hydrant probability matrix, OHPM, made up by probabilities per hydrant, month and operating sectors was created then.

Per each m month, j sectoring option, and operating sector l , k Montecarlo simulations were carried out using OHPM data to generate random demand patterns (distribution of open and close hydrants for a certain iteration), based on the $[0,1]$ uniform distribution. Thus, in each iteration, a random number, R_{imjl} , was generated for every hydrant to define if it was open or close. When p_{imjl} was

greater or equal to R_{imjl} , the hydrant was assumed open and the base demand, q_i , was calculated by:

$$q_i = q_{max} \cdot S_i \tag{7}$$

where S_i is the irrigation area associated with each hydrant. If not, R_{imjl} was greater than p_{imjl} , the hydrant was assumed closed and its base demand was set to zero. A new random demand pattern of open and close hydrants was generated in every iteration.

Then the network was simulated for each loading condition (RIS and open/close hydrant distribution) using

EPANET (Rossman 2000) as hydraulic simulator. It was integrated within the visual basic program through its dynamic link library (.DLL).

Starting from the maximum theoretic pressure head, H_{\max} , that ensures that when all hydrants were open received at least 30 m pressure head, the lowest pressure head, H_{pmjl} , needed at the pumping station to supply water to all open hydrants was calculated. After simulating the network for the maximum theoretic pressure head (H_{\max}), the pressure in the most restrictive hydrant (the hydrant which minimum pressure) is determined (H_j). Then, if the pressure is higher than the required 30 m, the excess pressure (α) is determined (H_j minus the required 30 m). After that, this excess of pressure is reduced in pressure head at the pumping station obtained the minimum pressure head that guarantee the required working pressure in all the hydrantes (H_{pmjl}). This minimum pressure that ensured that the working hydrants for a certain loading condition got at least the required pressure was taken as the dynamic pressure head defined by Rodríguez Díaz et al. (2009).

The pumped flow, F_{mjl} in (m^3/s) and the minimum pressure head required at the pumping station, H_{pmjl} were obtained for every demand pattern and operating sector. Then power requirements, $\text{Power}_{\text{mjl}}$, (in kW) at the pumping station were calculated according to the following equation:

$$\text{Power}_{\text{mjl}} = \frac{\gamma \cdot F_{\text{mjl}} \cdot H_{\text{pmjl}}}{\eta} \quad (8)$$

where γ is the water specific weight ($9,800 \text{ N m}^{-3}$) and η the pumping system efficiency (in this work 0.75 pumping efficiency has been assumed). Consequently, energy consumption in kilowatt-hour per working day and operating sector under each loading condition was estimated as follows:

$$E_{\text{mjl}} = \frac{\text{Power}_{\text{mjl}}}{1000} \cdot t_{\text{aj}} \quad (9)$$

The process was repeated k times for every operating sector and month of the irrigation season (from March to October). The outputs (pumped flow, dynamic pressure head, power and energy) were all recorded. The k values of all outputs per operating sector and month were averaged. Then averaged pumped flow and energy consumption per sector were aggregated to get the whole water and energy consumption for the entire network when two or three sectors were operating.

All generated solutions were ranked according to both energy consumption and the percentage of supply failure, with the aim of helping water managers to evaluate the set of generated alternatives, being flexible or tolerant with failures in pressure or demand, taking into account

simultaneously the number of failing hydrants and the irrigation deficit magnitude. The top solution for each sectoring strategy was the lowest energy alternative that ensured demand satisfaction (no supply failure).

Results and discussion

Optimal network sectoring

Figure 4 shows the topological characterization of both irrigation networks by the dimensionless coordinates z^* and l^* , allowing the comparison of network of different total pipe length (46 km in FP and 31 km in EV) and with nearly a double number of hydrants and double irrigated area in FP (85 hydrants and 5,611 ha) than in EV (47 hydrants and 2,729 ha). Graphs differ considerably due to the two different topologies. FP coordinate z^* varied from 0.7 to 1.1, being $z_p = 113.9 \text{ m}$ and z_i varying between 86.1 and 158.2 m. Most hydrants were over the pumping station elevation ($z^* < 1$) and only a few were below. The wide z^* interval was a measure of the elevation difference among hydrants, the maximum being 72 m resulting from the

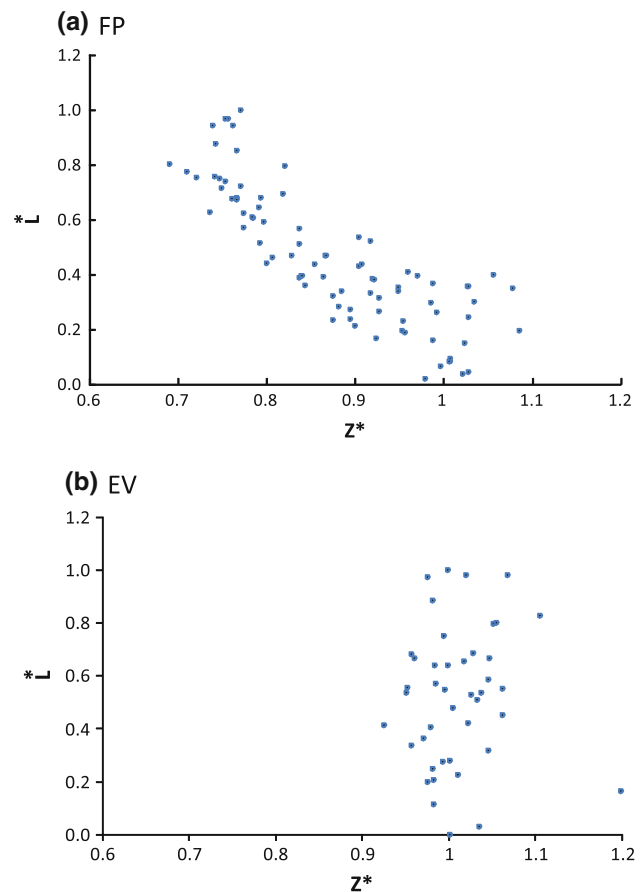


Fig. 4 Coordinates z^* and l^* for all the hydrants

rough terrain. This circumstance combined with the regular distribution of l^* values (from 0 to 1) being $l_{i,\min} = 244$ m and $l_{i,\max} = 11,299$ m, implied that the pumping head was related to both coordinates. EV network was located in a flatter area (the maximum elevation difference among hydrants was 45.6 m) as the narrower z^* interval showed, varying only between 0.9 and 1.1, being $z_p = 184.7$ m, $z_{i,\min} = 154$ m and $z_{i,\max} = 200$ m. The l^* varied in the whole range, with $l_{i,\min} = 9$ m and $l_{i,\max} = 6233$ m, this value was 1.8 times smaller than l_{\max} in FP due to the central location of its pumping station. Thus, in the case of EV, hydrant distances to the pumping station was the most important driver of energy consumption.

Using cluster analysis techniques, homogeneous groups were created according to the coordinates system defined by l^* and z^* . The clustering method k-means was applied for 2 and 3 clusters in both networks. Every cluster defined an irrigation sector. The proposed sectoring options (two and three sectors) for both networks are shown in Figs. 5 and 6. Figure 5a shows two-sectors sectoring option in FP where it can easily detect the combined influence of hydrant elevation and distance to the pumping station. In Fig. 5b, hydrant elevation is more relevant than distance and sectors distribution is less clear. In relation with sectoring options in EV, in Fig. 6a, b sectors definition are directly related to hydrant distance to the pumping station, being distributed in concentric rings around the pumping station.

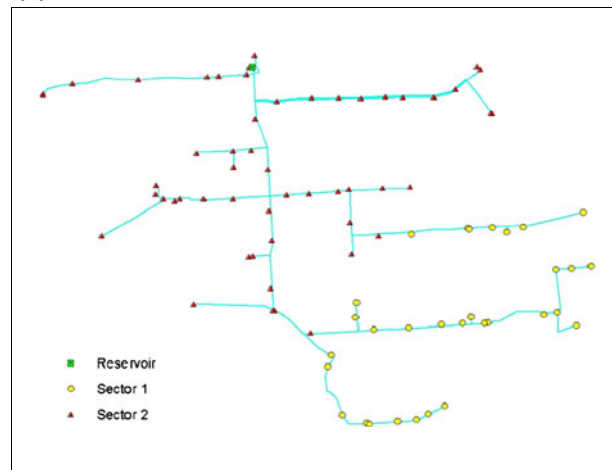
Seasonal calendar for sectoring operation

The algorithm described in Fig. 3 was applied to both irrigation districts according to the sectors established in the previous section. Thus, the networks were simulated for the whole irrigation season (from March to October) and for different operation strategies: one sector only (on-demand), two sectors and three sectors with $RIS = 1$ for both irrigation networks and with $RIS = 0.4$ in the case of FP and $RIS = 0.24$ for EV. In this work, k , the number of Montecarlo simulations, was set to 500 carrying out 24,000 hydraulic simulations [$24,000 = 500(\text{simulations}) \cdot 8(\text{months}) \cdot (1 + 2 + 3)$ (operating sector per sectoring option)], providing enough different possibilities to be evaluated by water managers.

The analysis were initially carried out for $RIS = 1$. The first output was the open hydrant probability (Eq. 6) which was related to both sectoring operation and the variability of irrigation needs from 1 month to other.

The open probabilities for all hydrants and sectoring strategy were averaged and are shown in Table 1 for $RIS = 1$. Sometimes these values were higher than 1 (highlighted in Table 1) what implied that this sectoring option was not fully adequate because averaged hydrant

(a) 2 homogeneous irrigation sectors



(b) 3 homogeneous irrigation sectors

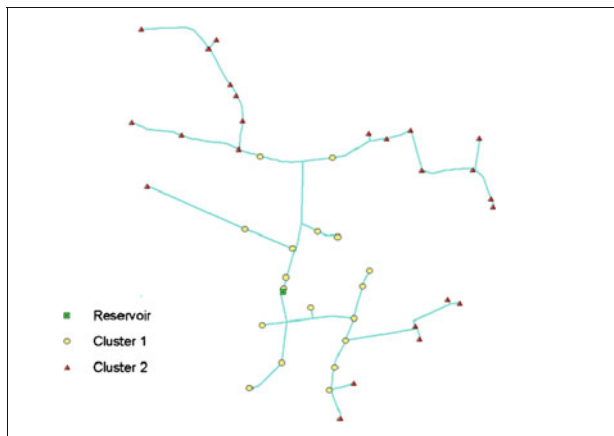


Fig. 5 Proposed network's sectoring for FP

operating time was not enough to supply irrigation demand. This situation occurred in both networks during the highest demand months when three sectors were operating. Moreover in the case of EV, it also happened for two operating sectors during the peak demand month (June) implying that this network did not admit any sectoring during this period. Hence, it reflected the fact that this network offered fewer possibilities for sectoring.

Table 1 shows average probabilities of all hydrants estimated from hydrant probability per month and sectoring strategy (standard deviations are showed as well). So, even in case of average values less than 1, it was possible to find some hydrants with probability to be open over 1. This circumstance was defined as supply failure. In this way, Table 2 shows average percentage of supply failure hydrants in the 500 iterations carried out per month, sectoring option and each operating sector for both irrigation networks. Thus, in EV, in June for the two sectors option

(a) 2 homogeneous irrigation sectors



(b) 3 homogeneous irrigation sectors

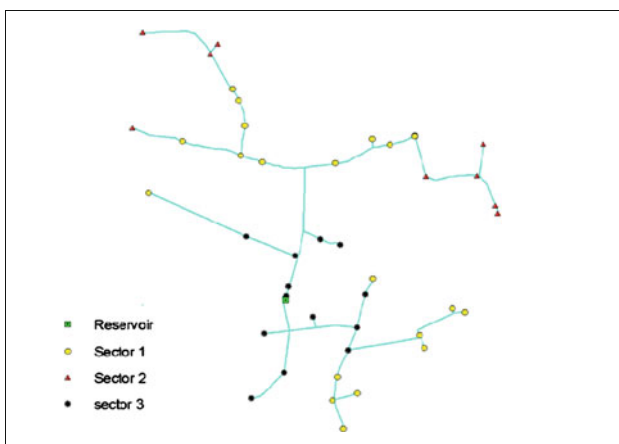


Fig. 6 Proposed network’s sectoring for EV

and when sector 1 was operating, all open hydrants were unable to supply irrigation needs during the available time for irrigation. On the contrary in FP during the same period, the maximum supply failure value was 20% for the sector option and sector two was operating, and during July this value diminished to 9%. Thus, only a small percentage of hydrants would not have been operating enough time to satisfy their full monthly irrigation needs. Additionally, taking into account that FP’s average probability for June and for two operating sectors was 0.85 with standard deviation of 0.17, what means that only few farmers would be slightly below the full satisfaction of irrigation needs and the proposed reduction in time available for irrigation would not necessarily imply a dramatic change for them. A different situation was found in EV for the same month and sectoring option, where the average of open hydrant probability was 1.18, pointing out that the farmers needed an increment of approximately 20% of the available irrigation time for full demand satisfaction. Therefore in this

Table 1 Average values of $p_{m,i}$ and standard deviations for the theoretic irrigation needs

| Sectoring option | Average $p_{m,i}$ (SD) (RIS = 1) | | EV | | | | | | | | | | | | | |
|------------------|----------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| | | | Month | | | | | | | | | | | | | |
| | FP | EV | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | | | | | | |
| 1 | 0.08 (0.03) | 0.05 (0.03) | 0.11 (0.06) | 0.42 (0.09) | 0.37 (0.09) | 0.27 (0.10) | 0.13 (0.07) | 0.04 (0.03) | 0.09 (0.04) | 0.04 (0.02) | 0.29 (0.09) | 0.59 (0.04) | 0.47 (0.15) | 0.35 (0.17) | 0.22 (0.10) | 0.04 (0.02) |
| 2 | 0.16 (0.05) | 0.11 (0.06) | 0.22 (0.12) | 0.85 (0.17) | 0.75 (0.17) | 0.54 (0.20) | 0.27 (0.14) | 0.09 (0.06) | 0.19 (0.07) | 0.08 (0.05) | 0.59 (0.18) | 1.18 (0.08) | 0.93 (0.31) | 0.70 (0.33) | 0.43 (0.21) | 0.08 (0.04) |
| 3 | 0.24 (0.08) | 0.16 (0.09) | 0.33 (0.17) | 1.27 (0.26) | 1.12 (0.26) | 0.81 (0.30) | 0.40 (0.21) | 0.13 (0.10) | 0.28 (0.11) | 0.12 (0.07) | 0.88 (0.26) | 1.77 (0.12) | 1.40 (0.46) | 1.05 (0.50) | 0.65 (0.31) | 0.12 (0.06) |

Table 2 Percentage of open hydrants where $t_{i,m}$ is bigger than t_a (supply failure)

| Sectoring option | Operating sector | FP | | | | | EV | | | | |
|------------------|------------------|-------|----|----|----|---|-------|-----|-----|----|----|
| | | Month | | | | | Month | | | | |
| | | 5 | 6 | 7 | 8 | 9 | 5 | 6 | 7 | 8 | 9 |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 2 | 1 | 0 | 14 | 9 | 0 | 0 | 0 | 100 | 56 | 23 | 0 |
| | 2 | 0 | 20 | 4 | 0 | 0 | 0 | 94 | 26 | 14 | 0 |
| 3 | 1 | 0 | 87 | 75 | 30 | 0 | 24 | 100 | 94 | 85 | 9 |
| | 2 | 0 | 79 | 57 | 30 | 0 | 42 | 91 | 81 | 66 | 25 |
| | 3 | 0 | 58 | 59 | 55 | 0 | 21 | 100 | 100 | 91 | 33 |

situation, irrigation districts managers must take the decision of adopting one strategy or another. As will be shown later when local farmers' behavior is taken into account by specific RIS values, different sectoring operation alternatives compared to those from full irrigation needs satisfaction (RIS = 1) are obtained. Tables 3 and 4 show the monthly average flow and required pressure head at the

pumping station for all the sectoring strategies, including those where supply failures were detected. The differences in required pressure head among operating sectors were significant in both networks. It is important to highlight that a dynamic pressure head model was used to calculate the required pressure to satisfy pressure requirement at the most energy demanding open hydrant at a certain time (Rodríguez Díaz et al. 2009). Especially in the maximum demand months of the year when some pipes were overloaded, a significant increase of the pumping head was required to compensate the increment of friction losses driven by higher circulating flows.

The required power was calculated in each iteration using Eq. 8. Thus, power demand curves were obtained for all the sectoring strategies. The curves corresponding to on-demand management are shown in Fig. 7. Differences in power, up to 1,000 kW for a given flow, are shown in Fig. 7a for FP network due to random selection of irrigating hydrants in every iteration. Figure 7b shows the case of EV where two separate branches are clearly distinguishable in the power demand curve. It indicates that there

Table 3 Average monthly demanded flow in FP and EV

| Sectoring option | Operating sector | Q (L/s) | | | | | | | | | | | | | | | |
|------------------|------------------|---------|-----|------|-------|-------|-------|------|-----|-------|-----|-------|-------|-------|-------|------|-----|
| | | FP | | | | | | | | EV | | | | | | | |
| | | Month | | | | | | | | Month | | | | | | | |
| | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 1 | 545 | 373 | 786 | 2906 | 2544 | 1840 | 911 | 305 | 279 | 141 | 830 | 1703 | 1371 | 1027 | 640 | 155 |
| 2 | 1 | 329 | 223 | 430 | 1774* | 1598* | 1155 | 527 | 160 | 216 | 129 | 648 | 1232* | 1165* | 961* | 621 | 141 |
| | 2 | 761 | 508 | 1128 | 3853* | 3471* | 2464 | 1272 | 466 | 329 | 163 | 1027 | 1689* | 1401* | 1048* | 648 | 144 |
| 3 | 1 | 1070 | 720 | 1641 | 4301* | 4148* | 3273* | 1703 | 587 | 397 | 177 | 1170* | 1420* | 1329* | 1244* | 903* | 181 |
| | 2 | 441 | 302 | 631 | 1968* | 1873* | 1502* | 746 | 228 | 189 | 117 | 498* | 638* | 555* | 468* | 310* | 95 |
| | 3 | 137 | 102 | 125 | 401* | 405* | 381* | 272 | 130 | 243 | 129 | 710* | 916* | 916* | 860* | 645* | 149 |

* Hydrants where the ratio $t_{i,m}$ and $t_a(p_{i,m})$ is bigger than one were found

Table 4 Required pressure head at the pumping station

| Sectoring option | Operating sector | H (m) | | | | | | | | | | | | | | | |
|------------------|------------------|-------|------|------|--------|--------|-------|------|------|-------|------|-------|-------|-------|-------|-------|------|
| | | FP | | | | | | | | EV | | | | | | | |
| | | Month | | | | | | | | Month | | | | | | | |
| | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 1 | 77.0 | 69.5 | 73.3 | 88.7 | 87.7 | 84.2 | 77.6 | 66.6 | 41.3 | 34.3 | 53.7 | 71.9 | 65.8 | 59.3 | 50.7 | 36.3 |
| 2 | 1 | 78.1 | 73.7 | 77.4 | 101.4* | 99.5* | 93.2 | 82.8 | 71.9 | 36.6 | 31.9 | 42.7 | 51.1* | 50.6* | 48.4* | 44.8 | 35.4 |
| | 2 | 58.3 | 55.4 | 58.7 | 84.4* | 80.1* | 70.2 | 62.6 | 55.7 | 44.9 | 40.1 | 69.8 | 97.8* | 92.4* | 76.7* | 60.3 | 34.7 |
| 3 | 1 | 67.0 | 65.0 | 67.8 | 91.6* | 86.8* | 78.5* | 69.3 | 62.2 | 39.7 | 36.0 | 47.7* | 48.5* | 46.1* | 44.7* | 41.3* | 33.0 |
| | 2 | 81.3 | 75.8 | 80.7 | 105.7* | 104.6* | 98.8* | 86.3 | 74.9 | 48.6 | 40.4 | 78.5* | 87.0* | 86.6* | 86.2* | 66.2* | 35.8 |
| | 3 | 34.4 | 36.2 | 41.2 | 42.2* | 42.2* | 35.5* | 32.8 | 33.0 | 37.6 | 32.2 | 44.0* | 50.7* | 50.7* | 50.5* | 47.0* | 37.5 |

* Hydrants where the ratio $t_{i,m}$ and $t_a(p_{i,m})$ is bigger than one were found

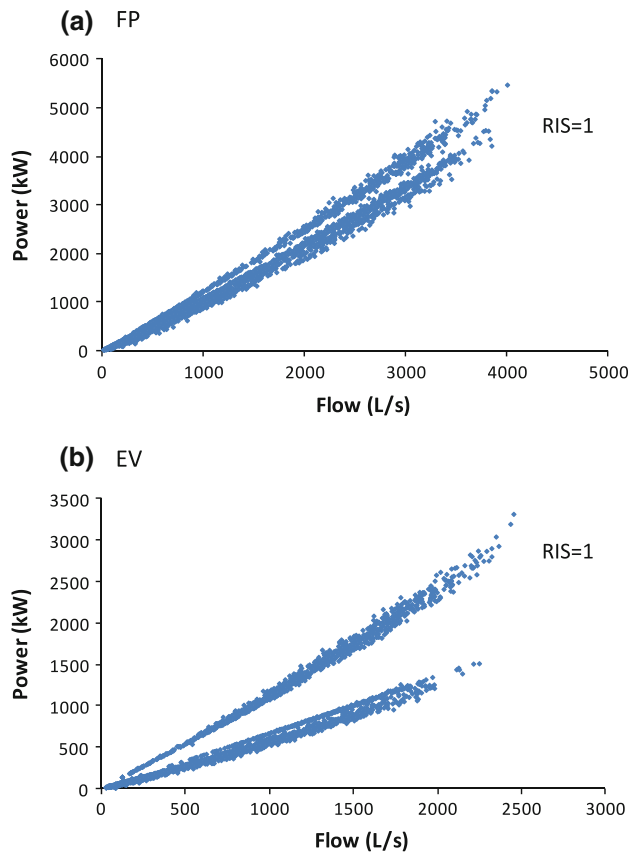


Fig. 7 Power demand curves for both networks when they are operated on demand (in EV the two separate branches indicate that there were some critical points with different energy requirements than the rest of the network)

were some critical points which are hydrants with special energy requirements because of their elevation or distance in relation to the pumping station. (Rodríguez Díaz et al. 2009). Given that EV was a flat network and elevation differences were not relevant, these critical points were far from the pumping station or located in some specific pipes with small diameters so that when they were overloaded the pressure requirements increased significantly due to higher friction losses. This fact reduced sectoring options in EV. Thus, an analysis of critical points in this network would be desirable in order to take the adequate measures to sort out these local problems.

The changes in power requirements depending on the water demand and location of the open hydrants led to potential energy savings compared to the current management when the network was operated on demand and fixed pressure head. Applying Eq. 9 to all simulations, the energy requirements per working day were obtained. The average values, as well as the percentage of reduction in energy consumption per month [in comparison with on-demand operation (1 sector)] are summarized in Table 5 where monthly energy consumptions are compared for all

sectoring strategies and the potential savings that would be achieved by adopting them. In FP, potential savings were very stable during the irrigation season for two operating sectors, as pressure head was mainly conditioned by elevation and the pipe diameters were not undersized. In contrast, in EV where friction losses were predominant, the savings were highly dependent on the time-spatial distribution of water demand.

The lowest energy consumption sectoring calendars for both irrigation districts are also shown in Table 5 by italicised cells. They are a combination of the best results for three analyzed sectoring strategies. Every month the lowest energy requirement strategy with no supply failures was selected. Accomplishing these restrictions, for FP two sectors were recommended but keeping the network working on-demand in June and July. Adopting this management strategy, potential energy savings of almost 8% over the annual energy consumption could be achieved (8,020 to 7,390 MWh). On the other hand, EV had less flexibility for sectoring and it was not allowed in June, July and August. Three sectors were optimum only for October and two for the rest of the irrigation season. Because of these limitations, only 5% of savings over the annual consumption were obtained (3,500 to 3,330 MWh). Assuming an average energy cost of 0.10 €/kWh, the adoption of these measures would lead to annual savings of approximately 63,000 € in FP and 17,500 € in EV.

In FP, there were few supply failure hydrants in June and July, the irrigation district manager might consider two sectors operating in the peak demand period, assuming some supply failures and saving up to 15% (8,020 to 6,855 MWh) over the on demand management (130,000 €/year). Thus, a good knowledge of the local farmers' practices was necessary before adopting these measures. For this reason, the analysis was repeated for the RIS values that characterized farmers' behavior in both irrigation districts. These values were calculated by Blanco (2009) for the studied irrigation season resulting $RIS = 0.41$ for FP and $RIS = 0.24$ for EV, showing that deficit irrigation is a common practice in both districts.

As it has been shown earlier, the optimum sectoring strategy has proven to be highly sensitive to water demand. When the water demand was reduced by smaller RIS values, the supply failures disappeared so farmers always had enough time to apply smaller irrigation depth independently of the sectoring strategy. In this case, the optimum sectoring calendars changes from the ones calculated for the full theoretic irrigation requirements, $RIS = 1$. The new power demand curves are shown in Fig. 8, differing from those in Fig. 7, in particular for EV (Fig. 7b) where the upper branch is significantly reduced

Table 5 Average energy requirements per working day (kWh/day), potential energy savings (%) and recommended sectoring calendar for the theoretic and the actual demand

| Sectoring option | FP (RIS = 1) | | | | | | | | | | EV (RIS = 1) | | | | | | | | | | | | | | |
|------------------|-----------------|-------|-------|--------|--------|--------|-------|-------|-------|-------|-----------------|--------|--------|--------|-------|-------|---|---|---|---|---|---|---|----|--|
| | Month | | | | | Month | | | | | Month | | | | | Month | | | | | | | | | |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| 1 | 13164 | 8127 | 18057 | 80802 | 69962 | 48593 | 22186 | 6373 | 3618 | 1517 | 13973 | 38412 | 28292 | 19099 | 10164 | 1759 | | | | | | | | | |
| 2 | 10610 | 6641 | 14248 | 68615* | 59909* | 41164 | 17943 | 4996 | 3050 | 1402 | 11328 | 29069* | 23391* | 16848* | 9444 | 1661 | | | | | | | | | |
| | (19%) | (18%) | (21%) | (15%) | (14%) | (15%) | (19%) | (22%) | (16%) | (8%) | (19%) | (24%) | (17%) | (12%) | (7%) | (6%) | | | | | | | | | |
| 3 | 11733 | 7679 | 17486 | 64720* | 59932* | 43764* | 20000 | 6053 | 3463 | 1610 | 14849* | 27934* | 23418* | 17162* | 9397* | 1458 | | | | | | | | | |
| | (11%) | (6%) | (3%) | (20%) | (14%) | (10%) | (10%) | (5%) | (4%) | (-6%) | (-6%) | (27%) | (17%) | (10%) | (8%) | (17%) | | | | | | | | | |
| Sectoring option | FP (RIS = 0.41) | | | | | | | | | | EV (RIS = 0.24) | | | | | | | | | | | | | | |
| | Month | | | | | Month | | | | | Month | | | | | Month | | | | | | | | | |
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| 1 | 4759 | 2765 | 6705 | 29638 | 24732 | 17213 | 7663 | 2814 | 1266 | 951 | 2790 | 5982 | 4811 | 3407 | 2149 | 947 | | | | | | | | | |
| 2 | 4105 | 2644 | 5515 | 24594 | 21050 | 14454 | 6432 | 2526 | 1174 | 905 | 2403 | 5182 | 4410 | 3204 | 2053 | 928 | | | | | | | | | |
| | (29%) | (14%) | (18%) | (31%) | (17%) | (15%) | (16%) | (16%) | (10%) | (7%) | (5%) | (14%) | (13%) | (8%) | (4%) | (2%) | | | | | | | | | |
| 3 | 3385 | 2456 | 4753 | 20354 | 18716 | 12780 | 6041 | 2136 | 1264 | 914 | 2707 | 6044 | 4592 | 3345 | 2086 | 932 | | | | | | | | | |
| | (29%) | (11%) | (29%) | (31%) | (24%) | (26%) | (21%) | (24%) | (0%) | (4%) | (3%) | (-1%) | (5%) | (2%) | (3%) | (2%) | | | | | | | | | |

Monthly optimums are italicized
* Systems failures occurred

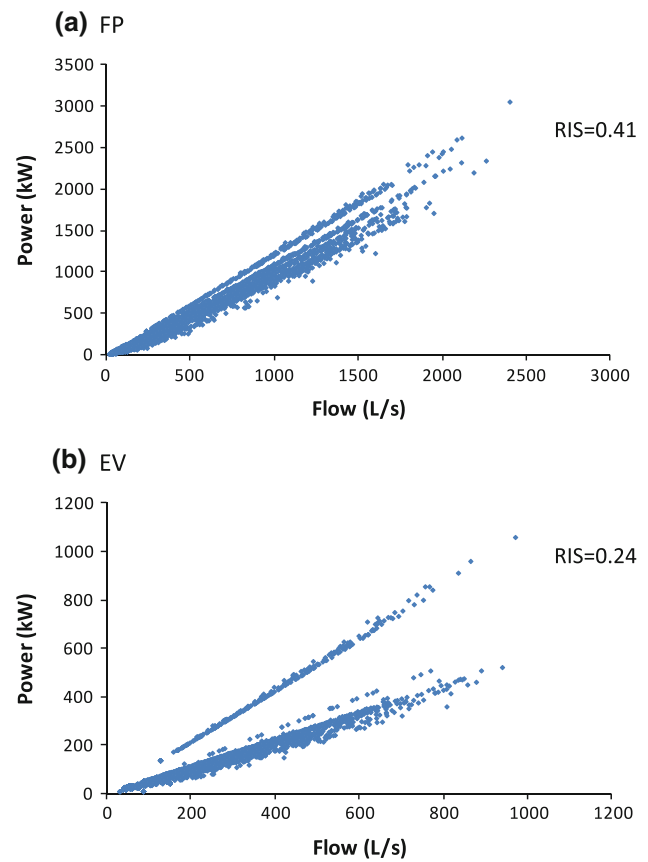


Fig. 8 Power demand curves for both networks when they are operated on demand for actual water demand

due to the smaller flows circulating along the critical pipes.

The optimum calendars for both networks under their real water demand are shown in Table 5 too. In this situation, the lowest energy requirement and fully demand satisfaction strategy for FP was to be operated in three sectors all the irrigation season and the potential savings in the annual energy consumption were 27%. In the case of EV, two sectors are recommended for the entire irrigation season (9% of energy savings).

Conclusions

Nowadays water and energy efficiency cannot be considered independently. Thus, although sectoring is an efficient measure to reduce the energy consumption in irrigation networks, it depends largely on the networks topology and its design as well as water demand in the network. As irrigation water demand tend to be very concentrated in some months of the year, the optimum measures and therefore the optimum sectoring strategy may differ from 1 month to other depending on the water

demanded at every hydrant. A particular analysis, taking into account the local farmers' irrigation practices, would be necessary for any network before the adoption of sectoring measures.

In this study, a methodology for sectoring based on dimensionless coordinates and cluster analysis techniques was developed. This methodology for grouping hydrants according to the same pipe length and land elevation characteristics cannot always be the best solution to reduce energy consumption as this definitely reduces the total amount of water flowing in the network but tends to concentrate all the water volume in the same pipe reach creating higher head losses. However, it is very useful when the networks are not undersized or farmers typically apply less water than the design flow. In other cases, it should be convenient to include a hydraulic coordinate to avoid the malfunction of the hydraulic elements. Also this methodology can be used in the networks design, providing an optimum sectoring strategy based on the hydrants' topological characteristics.

The proposed sectors were later evaluated by the algorithm WEBSO based on the EPANET engine. This model links energy saving measures with local irrigation practices. Thus, it generates monthly sectoring strategies, ranked according to their degree of accomplishment of minimum energy consumption and minimum irrigation deficit objectives.

Both methodologies have been applied to two different networks (FP and EV), obtaining significant savings in energy consumption. Results showed that organizing the networks in sectors, annual energy savings of 8 and 5% were achieved for FP and EV when the theoretic irrigation needs were considered. However, these savings rose up to 27 and 9%, respectively when the local farmers' practices, deficit irrigation, were taken into account. These practices have shown a significant influence on the optimum outcome, so a good knowledge of the irrigation districts is necessary before adopting these measures.

Finally these sectoring calendars can be easily implemented in remote-controlled pipe networks, where electrovalves are available in each hydrant, like the networks existing in most of the modernized irrigation districts.

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