Jiménez Bello, MA.; Martínez Alzamora, F.; Bou Soler, V.; Bartolín Ayala, HJ. (2010). Methodology for grouping intakes of pressurised irrigation networks into sectors to minimise energy consumption. Biosystems Engineering. 105(4):429-438. doi:10.1016/j.biosystemseng.2009.12.014

Elsevier Editorial System(tm) for Biosystems Engineering
Manuscript Draft

Manuscript Number: YBENG-D-09-00385

Title: A methodology for grouping irrigation intakes into sectors to minimize the energy consumption in pressurised irrigation networks.

Article Type: Full Length Article

Keywords: Irrigation water management, pressurised irrigation networks, energy optimization,genetic algorithm, network sectorizacion, geographic information systems, decission support systems

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With that purpose in mind, a new methodology using a Genetic Algorithm and the hydraulic network model has been developed to group intakes into sectors in order to minimize energy consumption. It has been applied to a study case. Several scenarios have been run and compared with the study case by means of energy performance indicators. Results show the existing improvement margin in the system energy performance. At the same time, operational network conditions improve due to minimum required pressure at consumption points is guaranteed.

Suggested Reviewers:

Opposed Reviewers:

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With that purpose in mind, a new methodology using a Genetic Algorithm and the hydraulic network model has been developed to group intakes into sectors in order to minimize energy consumption. It has been applied to a study case. Several scenarios have been run and compared with the study case by means of energy performance indicators. Results show the existing improvement margin in the system energy performance. At the same time, operational network conditions improve due to minimum required pressure at consumption points is guaranteed.

Notation

C_{PumpD} : Economic cost of an irrigation day

$C_{PumpDSwf:}$ Economic cost of the non-fertigating shift

DSS: Decision Support System

FSP: Fixed Speed Pump

GA: Genetic algorithm

GIS: Geographic Information Systems

H_{temp}: Total Head temporary assigned to the pumping station

$H_{i,j}$: Total head of pump i in the shift j

$N_{i,j}$: Speed of pump i in shift j

n_{Pump}: Nº of pumps

n_{Shift}: Number of irrigation shifts

p_{Hid}: Lower hydrant pressure

p_{MinH} :Minimum pressure of service in an irrigation hydrant

P_N : Nominal power

$P_{i,j}$: Pump input power for a pump i in the shift j

P_j : Total pump input power of shift j

p_{st}: Pressure setting

$Q_{i,j}$: Flow of pump i in shift j

Q_j: Total pumping flow in shift j

T_j : Duration of shift j

T_{Shift} : Irrigation time set for each shift

VSP: Variable Speed Pump

VFD: Variable Frequency Drive

W_j: Energy consumption in shift j

W_{PumpD}: Energy consumption per irrigation day

$W_{PumpDSwf}$: Energy consumption per irrigation day excluding shift without fertigation

WUA: Water Users Associations

W_{RD}: Real energy consumption per irrigation day

z_{Hid}: Lower pressure hydrant elevation

z_W : Water elevation

Δh_{Filt}: Head losses produced by the filter system

Δh_{Net}:Network head loss

γ: specific weight of water

$\eta_{i,j}$: Global efficency of pump i in shift j, including electric engine and VFD

1 Introduction

A common practice in the Mediterranean region of Spain is the modernization of irrigation systems in Water User's Association by replacing open-channel gravity-based systems with pressurized irrigation systems. Since these systems require energy, it has to be used in the most efficient way as is set forth in the Spanish Strategy Plan for Energy Saving and Efficiency (IDAE 2005). Each year, water irrigation uses more than 2280 GWh of electric energy which accounts for 1 % of total consumption in Spain and a 155 million (€) bill. While in 2001 the energy consumption by agricultural machinery accounted for 47% of total agricultural consumption, and irrigation water 22% of the total consumption for agriculture, the forecast for 2012 is the first one will decrease to 42 % and the second one will increase to 32 %

The energy criteria has been considered in the designing of irrigation networks by calculating pipe size diameters in such a way that satisfies operating conditions, minimum pressure requirements and stipulated flow requirements, while seeking to minimizing the investment and energy cost (Labye et al., 1988; Lansey and Mays, 1989; DIOPRAM, 2003). In the same way, the design of pumping station has been taken into account to search for pump units that better fit the forecast demands (Moradi-Jalal et al.; 2003; Pulido-Calvo et al.; 2003; Moradi-Jalal et al.; 2004; Planells et al.; 2005; Moreno et al 2009).

From the irrigation management viewpoint, tools and protocols have been developed to assess the system performance (Lamaddalena and Sagardoy 2000). Focusing on pump units, Luc et al. (2006) elaborated performance indicators to assess their operating efficiency. Abadía et al (2008) proposed a methodology to evaluate the energy efficiency of the whole system taking into account the layout and spatial distribution of the network.

Likewise, by means of collecting electric and hydraulic data, a model for analyzing energy efficiency at pumping stations was developed to determine the sequence of pump activation that might minimize the energy cost for real demand scenarios (Moreno et al 2007).

The aforementioned methodologies focus on the analysis of pump units to improve efficiency. However a different way to improve energy efficiency is to arrange the irrigation scheduling by grouping the irrigation intakes in irrigation sectors. These operate in scheduled irrigation shifts, reducing the users' freedom to irrigate when they desire. From the design point of view, the extra large dimensioning of pipe layout and pumping groups is avoided (Arviza et al 2003; IDAE 2008).

In Water Users Associations (WUA) that practice central fertigation, network sectorization is the only logical way to apply fertilizers efficiently because knowing the operation times of the irrigation intakes is necessary in the preparation of suitable fertilizer concentrations and in the efficient distribution of fertilizer through the system.

Once the irrigation system is in operation, a methodology that groups intakes into sectors so as to minimize energy consumption would be desirable. Until now, the procedure was to group intakes into sectors of homogenous area or elevation, depending on the criteria chosen by the personnel in charge of the management system.

This work presents a methodology for grouping intakes into sectors in systems regulated by pump units. Moreover a case study is analyzed and several scenarios are analyzed applying the developed approach.

2 Methodology

2.1 Study case

The WUA of Senyera is located in the municipality of the same name in the province of Valencia (Spain). It consists of 387 plots; a plot belongs to the WUA if it is connected to an irrigation intake. The total area of the WUA is 116 ha, from which 77.5 ha are irrigated (283 plots). Average plot size is 3093 m^2. The system has 52 multi-outlet hydrants and a total of 331 intakes, 224 of which were in operation in 2006. The network topology is of a branched type.

Water supply is by gravity through an open channel that feeds an irrigation pond. This has an inlet and a spillway to ensure that the pond is always full without water overflow. Water control is carried out by two pumping units: one fixed speed pump (FSP) and one variable speed pump (VSP) monitored by a Variable Frequency Drive (VFD). Pump power is 37 kW, engine efficiency is 82% and VFD efficiency is 97%. They operate in a staggered way (Martínez et al 1996). By means of the Control Unit a setting pressure (p_{st}) is assigned and the pumps have to maintain it. The pumping station has a collective filter with self-cleaning system that works when losses reach 0.05 MPa.

A Central Control system regulates intake operation with electrically activated valves,, assigning them a specific irrigation time or volume. The system allows the automatic reading of water consumption for each intake and specific irrigation period.

The WUA is managed by a company in charge of the system control and maintenance. The technical staff consists of a technician responsible for system planning and control, and an operator whose task is to verify the correct operation of the facility during irrigation and maintenance and to supervise flow meter readings. On the first day of each month, the intake meters are read and the water consumption is billed to the users, charging an extra amount to users that fertigate.

Irrigation is arranged into shifts, and the intakes are distributed over 6 irrigation sectors (S1, S2, S3, S4; S5, S6). The strategy followed by the technical staff responsible for the sectorization of the system consists of grouping the intakes into sectors of similar size. Each sector is irrigated at one scheduled shift.

The technician schedules in advance the days to irrigate and to fertigate. In the season under study, fertigation was performed two days per week with intermediate irrigation days without fertilizer. Each irrigation shift lasts two hours. The sectors are irrigated in sequence throughout the day. The last irrigation shift (S6) corresponds to the sector that does not want fertigate. Irrigation begins at 6:00am and ends at 18:00pm. The fertilizer pump begins at 6:00am and ends at 15:30pm, 30 minutes before the irrigation shift without fertilizer begins to operate (S6). Table 1 shows the schedule of the irrigation shifts for 2006.

2.2 Tools to assess performance system

In order to assess the hydraulic performance system, the WUA is modelled in a Decision Support System (DSS) named HuraGIS (Jimenez et al 2006). This DSS is developed in a Geographic Information System (ArcGIS 9.x). HuraGIS can store data required to simulate the agronomic and hydraulic processes involved in pressurized irrigation management systems. The hydraulic simulation is carried out using EPANET (Rossman 2000). This software performs extended period simulations of hydraulic behaviour and water quality in pressurized networks. HuraGIS can generate time patterns, which make node demands vary in a periodic way over the course of a day, assign them to an EPANET scenario and analyze the results with EPANET toolkit.

The mathematical model of the network represents the network elements at the level of multioutlet hydrants where each hydrant is assigned to a demand node in the EPANET scenario. The model was calibrated by means of pressure sensors placed at four hydrants and the network head. The water flow meters of each intake were used to measure the water flows. Since intake flows and pipe diameters were known, pipe roughness of each diameter size was chosen as calibration variable. Due to the restricted number of pressure sensors, criterion used to choose hydrants was to maximize the number of equations that will include the eight diameter sizes existing in the network. For this reason selected hydrants were located at the end of network branches. The total number of equations was 6, one for each hydrant plus two extra equations because there were two hydrants having intakes operating in two different sectors. The goal function was to minimize the quadratic error of estimated pressure versus measured pressure. The model was assumed as demand driven (Reddy and Elango 1989) instead of pressure-driven demand (Wagner et al 1988) because no meaningful differences were observed at flow rates in the case hydrant pressure changed. Furthermore model implementation is simpler since tuning of pressure-demand curve for each network is avoided. The relative pressure error in the model was 2.8%.

In the same way, data regarding energy consumption by pump units and operating hours are collected.

Afterwards performance indicators have been calculated (Malano and Burton 2001; Rodríguez et al 2005; Ruiz .et al 2007) for the period comprising 2006 season. Thus study case can be compared with proposed scenarios.

2.3 Methodology to optimize intakes grouping in sectors from energy point of view

A genetic algorithm (GA) is a heuristic method based on the mechanisms of evolution and natural selection (Goldberg 1989). A GA represents an efficient method of finding solutions to problems of non-linear optimization. This method is used frequently among the scientific community dedicated to the planning and management of water resources (Savic and Walters 1997). These algorithms share the attributes of the Monte Carlo techniques on local optimization methods, which do not require assumptions or calculation of linear partial derivatives and avoid numerical instabilities associated with the inverse matrix. Besides, its sample space of solutions is preferably a global rather than local. This reduces the tendency to get caught in a local minimum and avoids dependence on the solution of the starting point of search.

The first step is to represent a valid solution to the problem to be solved by taking a string of genes, where each one can take a value within a specific range. The string of genes that represents a solution is called chromosome. At the beginning of the process a random population of chromosomes is built. In every generation the fitness of each chromosome is quantified. The chromosomes that have better fitness are selected to produce offspring of the next generation, which inherited the best traits of both parents. After many generations, selecting the fittest chromosomes, it is expected that the result shows better skill that the initial population. All genetic algorithms consist of the Chromosome Codification, an Initial Population, a Fitness Evaluation, a Selection process, a Crossover method, a Mutation process and a Finalization Condition.

To carry out the optimization process by GA, an ActiveX control called OPTIGA has been used (Salomons 2008), which has been embedded in HuraGIS.

$$P_{i,j} = \frac{\gamma \cdot Q_{i,j} \cdot H_{i,j}}{\eta_{i,j}} \quad (1)$$

The Pump input power for a pump *i* in a shift *j* ($P_{i,j}$) is given by

The total Pump input power for an irrigation sector or shift *j* (P_j) is given by

$$P_j = \sum_{i=1}^{n_{Pump}} \frac{\gamma \cdot Q_{i,j} \cdot H_{i,j}}{\eta_{i,j}} \quad (2)$$

The energy consumption for an irrigation sector *j* (W_j) is given by

$$W_j = \sum_{i=1}^{n_{Pump}} \frac{\gamma \cdot Q_{i,j} \cdot H_{i,j}}{\eta_{i,j}} \cdot T_J \quad \textbf{(3)}$$

Finally, the energy consumption of a certain grouping of intakes for an irrigation day (W_{PumpD}) is given by

$$W_{PumpD} = \sum_{j=1}^{n_{Shift}} W_j \quad \textbf{(4)}$$

The goal function of the optimization process is to minimize Eq (4). Once the function to optimize is known, the parameters to be defined before starting the optimization process are summarized in Table 2.

Then the process is initialized. To each intake or multioutlet hydrant, according to the chosen automation degree, a gene is assigned for each chromosome of the initial population. Genes are codified as integer variables, which mean the shift or sector randomly assigned to the corresponding intake or hydrant. For each chromosome, according to its gene values, time patterns are created in an INP file that is run by means of EPANET toolkit (Rossman 2000). These time patterns represent when the intakes are operating.

For each chromosome, the hydraulic simulator will return the required pump pressure setting p_{st} and the pump scheduling (number and speed of operating pumps), to guarantee a minimum pressure p_{MinH} at all demand nodes. However, although EPANET supplies the total Q_j demanded to pump units, it is not able to provide the minimum pressure setting and the pump scheduling when the VFD controls the pump speed.

There are two solutions to solve this problem:

1. Replace the pump element with the reservoir element

In this case, the reservoir is assigned a total head equivalent to the p_{st} plus the elevation of the pumping station. When results are obtained from EPANET, an auxiliary module is used. In this module by means of pumps curves, demand flow and p_{st}, the pumping groups response is given. The disadvantage of this solution lies in the inability to adapt the response of pumping groups, when they do not have sufficient capacity to supply the required flow at the p_{st}.

2. Inserting a Pressure Reducing Valve (PRV)

Now a p_{st} is assigned to the PRV as a setting parameter. In this case, when the pressure downstream of the valve is higher than p_{st} the behaviour of pumping groups is simulated as in the previous paragraph. If it is lower, PRV opens completely and system status is determined by applying the equivalent curve of all groups operating at nominal speed. Thus pressure and demand flow are ascertained. As discussed above, in order to establish energy consumption, an assistant module is used. Fig 1 shows the schema simulation in EPANET.

When the pumping station is simulated as a reservoir, this is assigned temporary a Total Head (H_{temp}) large enough to make sure negative pressure will not be achieved. Otherwise, Epanet will launch an error. For each shift, the hydrant with the lower pressure is selected. This pressure is called p_{Hid}. The total head losses from the pumping station to that hydrant where Z_{Hid} is the hydrant elevation is obtained as

$$\Delta h_{Net} = H_{temp} - (Z_{Hid} + p_{Hid}) \qquad \textbf{(5)}$$

Thus the required head at pumping station to guarantee the minimum required pressure at the most adverse hydrant is given as.

$$H_{i,j}= \Delta h_{Net} + p_{MinH} + \Delta h_{Filt} + (z_{Hid} - z_{W}) \quad \textbf{(6)}$$

This $H_{i,j}$ will correspond with p_{st}. Highlight pumps are considered as submerged.

Once H_{ij} and Q_j are known, the energy consumed by the pump units is calculated by means of their curves. Previously the number of pumps required to satisfy the demand is determined and for each one the rotation speed N_{ij}, the pump flow Q_{ij}, the global efficiency η_{ij} and the pump input power P_{ij} are calculated

If pump units do have not enough power to supply Q_j at H_{ij}, its Wj value is penalized, increasing its value sufficiently so that this chromosome will be penalized in the selection process.

Having determined the W_j for each shift by Eq.(2), the value of W_{PumpD}, is determined by Eq.(3), as it characterizes each chromosome when it is assessed his fitness or adaptability. Since not all Control Units allow us to assign a variable p_{st} as time goes by, that is, assign a different pressure for each shift, it is possible to recalculate the $P_{i,j}$ of each shift with the worst $H_{i,j}$ of all shifts.

This process is repeated until the condition of termination mode is reached. The results produced by the process are:

a) Hydrants or intakes in sectors, depending on the degree of automation that minimize W_{PumpD} fulfilling requirements defined in advance.

b) The values of $H_{i,j}$ $Q_{i,j}$ and $P_{i,j}$ for each pump in each shift. In case the pressure sensor is placed after the filtering system, p_{st} is determined by subtracting the Δh_{Filt}.

Fig 2 summarizes the process of energy optimization for irrigation sectorization.

3 Results and discussion

3.1 Energy consumption. Year 2006

The Fig 3 illustrates the real energy consumption (kWh) for 2006 season. The consumption is showed for each month, according to the billing frequency. As expected, the highest consumptions correspond to the summer months, those with higher water requirements in the study area.

The total area was 116 ha, while the irrigated area was just 77.5 ha. Table 3 shows the energy performance indicators (Malano and Burton 2001; Rodriguez et al 2005; Ruiz et al 2007) for the period reflected in Fig 3

From the irrigation hours carried out during the irrigation season, energy consumption per irrigation hour has been estimated. This means an average for each irrigation hour of 60.75 kW, so a 12 h irrigation day for the study case represents a real consumption W_{RD} of 729 kWh.

3.2 Rate structure

The rate on 2006 had a contracted power of 79 kW. The structure is differentiated into two blocks that correspond to summer (from April to September) and winter (from October to March) period, as shown in Table 4. Hourly billing belongs to groups that are classified as peak, plain or off-peak. For Saturdays, Sundays and official non-working days all hours are considered off-peak. Irrigation shifts are shown hashed.

Table 5 summarizes hourly distribution for winter and summer periods according to rate structure.

Irrigation scheduling is not suited to the most economical hours. In the summer period irrigation is performed for half of time during peak hours, resulting in a significant additional cost.

3.3 Analysis of hydraulic performance

The simulation of the calibrated hydraulic model has been carried out for an irrigation day of 2006, obtaining the power required for pumping groups and energy consumption for each shift.

The p_{st} considered has been the average logged by the pressure sensor placed at pumping station (0.35 MPa). This pressure has been increased by 0.05 MPa due to filter system (D_{hFilt}). Outcomes for each irrigation shift are shown in Table 6. It shows the pressure H_j, flow Q_j, power P_j and energy W_j required by pump units at each shift.

The total estimated consumption per irrigation day W_{PumpD} is 733.25 kWh. Comparing the estimated consumption with W_{RD} the relative error is 0.05%.

Table 7 shows flows and efficiencies for each pump unit at each irrigation shift.

The efficiency of VSP is quite far from the nominal efficiency (79 % for 41 l/s and 0.65 MPa) in spite of the VFD.

Fig 4 shows the Head Flow curves (H-Q) of the pumping station. Zone 1 and Zone 2 delimit regions where VSP works with efficiencies higher than an acceptable value, in this case 72%. The Zone 1 is delimited by H-Q curve of VSP at minimum speed, H-Q curve of VSP at nominal speed and iso-efficiency curves. Zone 2 is delimited by H-Q curve of VSP at minimum speed plus FSP, H-Q curve of VSP at nominal speed plus FSP and VSP iso-efficiency curves. The horizontal line represents the characteristic curve of the irrigation network. Discontinuous vertical lines illustrate Q_j at the p_{st} .

Five of the six sectors are out of the zones of higher efficiency, which means lower efficiencies for the pump units. The criterion chosen by the technical operators was grouping intakes into sectors of homogenous surface, except sector S6, where intakes belonged to the same sector due to the fact that there was no central fertigation. With this criterion it is not guaranteed that the pumps will operate in the useful zones.

The Table 8 shows the number of intakes classified by sectors with an operating pressure under 0.25 MPa in 2006, the minimum pressure required for a proper working of irrigation subunits.

Due to the lack of a hydraulic model to assist irrigation scheduling, it becomes difficult to estimate a p_{st} to program the VFD and guarantee a minimum pressure at all hydrants. The decision is taken by the operator based on his own criteria.

Moreover the daily energy cost has been estimated for the winter period (71,04 €) and for the summer period (103,35 €). The considered price for the kWh has been 0,095 €.

3.4 Improvement of the sectorization from the energy point of view

The methodology depicted in Fig 2 -to search for the intakes grouping that would minimize energy consumption- has been used. For that aim a series of scenarios have been analyzed taking into account the following parameters:

- There is a shift without fertigation (S_{wF})

The fact that some plots are not fertigated, restricts their operation period due to the fact that they must not receive fertilizer. The intakes of the non-fertigated plots must necessarily be part of the same irrigation sectors (in the case study, these are grouped into one sector). It is possible to exclude them from the analysis because this sector is predetermined beforehand.

- Number of irrigation Shifts (n_{Shift})

5, 6 and 7 shifts or sectors scenarios have been analyzed including the non-fertigated intakes. For a lower number of sectors, the pump units do not have enough power. A higher number of shifts are not economically profitable due to the structure of hourly billing. When non-fertigated intakes were excluded, an analysis was performed for 4, 5 and 6 shift scenarios. The T_{Shift} set up for all analyses was 2 h.

- Minimum pressured required at hydrant (P_{MinH})

It has been considered a p_{MinH} of 0.25 Mpa

- Automation level (*Aut*)

Indicates if intakes of one multioutlet hydrant must operate at the same time (H) or they do not necessarily operate at the same time (I).

- Filter head loss (D_{hFilt})

The Dh_{Filt} used in the analysis was 0.05 MPa.

With regard to the parameters related to the genetic algorithm, the values adopted are described in Table 9, depending on the automation option chosen.

The generation number depends on the level of automation previously fixed. The advisable number has been decided after several trials when results did not significantly improve after increasing the generation number. In the same way the optimization process converges faster for a mutation rate of 10%.

Table 10 shows the analysis results of scenarios. Given the constraint of shift with non-fertigation in analysis 7-12, energy per irrigation day has been optimized without taking into account this shift ($W_{PumpDSwf}$). Subsequently the energy consumption of this shift has been added to get W_{PumpD}. This has been calculated taking into account the p_{MinH} required at hydrant (0.25 MPa). Parameters used were p_{st} (MPa) = 0.48, $W_{PumpDSwf}$ (kWh)=161 and $C_{PumpDSwf}$ (€)=15.3.

Highlight that p_{st} is higher for this shift than rest of shifts and energy consumption has not been recalculated for these shifts. Billing hour assigned has been the plain one, due to non-fertigating users want to irrigate during day hours to fertilize by their own.

As an example, Fig 5 shows the operating points of each sector for scenario 3 as result of the optimization process, which numbers are showed in detail in Table 11. The process tends to set the operating points of pump units in zones 1 and 2, where efficiency is higher.

Fig 6 represents the energy consumption of an irrigation day for scenarios 1 to 12. The series are grouped according to their automation degree and whether it has a shift without fertigation (S_{WF}) or does not. The X-axis represents n_{Shift}.

Observe as n_{Shift} decreases, W_{PumD} increases due to required power at the irrigation head for each shift is higher because there are more operating intakes. The intake automation level allows greater freedom for set sectors, allowing them better allocation of intakes and they hence obtain better operation points. This is translated into lower energy consumption. Although the differences are not very significant (2.3% maximum for scenarios 5 and 6).

The non-fertigating shift means more consumption if scenarios are compared with those where non-fertigating shift is not considered. The presence of these users restricts the application of the most efficient scenarios. This extra cost is charged to all users.

Fig 7 shows the economic cost of each scenario according to n_{Shift} grouped into the same series than Fig 6. The cost has been calculated assigning the sectors with higher consumption firstly to the off-peak hours, and subsequently to plain and peak hours.

The economic cost for 6 shifts is lower if there is a non-fertigation shift contemplated. For costs, the trend is reversed and the n_{Shift} which is more desirable from an economic point of view is 7. This is due to differences in the pump behaviour and the different placings of the shifts in pricing bands.

The differences between the scenarios that do not consider non-fertigating shift and those which do for scenarios with the same parameters, range between 14.5% and 20% ,ensuring differences between 4.68 € and 6.12 € per irrigation day.

3.5 Comparison of energy performance indicators

Table 12 shows ratios in order to compare scenarios proposed for the scenario that occurred in 2006. The purpose of comparison is to highlight the potential for energy saving.

In the first column, the energy consumptions are compared. Observe the energy consumption decreases for all scenarios in comparison with the study case. The highest saving is achieved for scenario 2 (36.4%). Taking into account the non-fertigating shift, then scenario 8 offers better results. Both have 7 shifts and automation level is intake.

In terms of economic cost, during the summer period irrigation is carried out 50% of time during peak hours, savings are higher than in winter. The highest saving is achieved for scenario 4 with a 70.3 % in summer and 56.8% in winter. Taking into account the non-fertigating shift, the best results are obtained for scenario 8 with a saving of 64.2 % in the summer period and 47.9% in winter period.

3.6 Estimation of annual saving

With the aim of estimating the energy saving for the irrigation season, energy performance indicators have been calculated for scenario 9, the most similar to the given conditions happened on 2006. In this scenario we consider the non-fertigating shift and hydrant intakes operating at the same time. This last option facilitates the supervision task for the technical staff when they have to check the proper working of the intakes during irrigation. Likewise, the same shift number is kept.

Table 13 shows performance indicators for scenario 9, using the irrigation hours recorded for *2006*. In turn, these indicators have been compared with case study indicators. All indicators show meaningful improvements. The annual energy consumption decreases 29484 kWh and the cost is 9018 €.

Savings are important; nevertheless the case study is a small size WUA, so savings in other larger WUAs could be higher in absolute numbers. Although due to the big heterogeneity existing in irrigation schemes, results are difficult to extrapolate to other schemes.

4 Conclusions

The grouping of irrigation intakes into sectors or shifts is an efficient strategy to decrease energy consumption; in the case users accept irrigation arranged into shifts. Nevertheless a robust methodology taking into account energy criteria is required to group intakes in an efficient way. Until now, the criteria used by technicians was to create sectors by grouping intakes into sectors of homogenous area or grouping intakes into sectors of homogenous elevation, both criteria based on decisions taken by the technicians in charge.

GA together with hydraulic models has proven to be a powerful tool to achieve this goal, enabling the grouping of intakes into sectors that make pump units operate in a most efficient way. Even if frequency speed drives are devices that allow the adaption of pump operation according to the system curve, they do not guarantee to work in the most efficient way.

Furthermore, In the same way it is possible to know beforehand the setting pressure in order to program the unit control of the pumping station and guarantee the minimum operating pressure in each intake.

The degree of automation in the system enables more autonomy in designating irrigation sectors. In the study case, the grouping at intake level achieves better results than hydrant grouping, but the results are not highly significant.

A proper sectorization leads to lower energy consumption. Besides, if irrigation scheduling is to fit a low energy cost timetables, the system energy cost also decreases.

If the irrigation scheduling is restricted by some users, like those in the case study who do not want central fertigation, the improvement margin is reduced, as the most efficient scenarios from an energy point of view cannot be applied

5 Acknowledgements

This work has been funded by IMPIVA of Comunidad Valenciana and the Spanish Ministry of Education and Science by means of the project CICYT BIA 2004-06444. The authors also wish to thank the company TECVASA (Técnicas Valencianas del Agua S.A.) for their collaboration in this comprehensive study.

6 References

Abadia R; Rocamora C; Ruiz A; Puerto H (2008) Energy efficiency in irrigation distribution networks I: Theory. Biosystems Engineering. 101(1), 21-27.

Arviza J; Martínez F; Llopis E. (2003). Propuesta de una metodología para la distribución óptima de tomas en sectores n redes de riego a presión con organización por turnos. XXI Congreso Nacional de Riegos. Mérida. España

DIOPRAM (2003). Diseño Óptimo de Redes Ramificadas 3.0. Manual de Usuario. Grupo Multidisciplinar de Modelación de Fluidos, Universidad Politécnica de Valencia, Valencia.

Goldberg D E (1989). *Genetic algorithms in search, optimization and machine learning.*, Addison-Wesley, Reading, MA.

IDAE (2005) Ahorro y Eficiencia Energética en las Comunidades de Regantes. Ministerio de Industria, Turismo y Comercio. Madrid

Jiménez-Bello M A; Martínez F; Arviza J; Manzano J (2007) Herramientas para el uso racional del agua con el apoyo de un GIS (HuraGIS). Riegos y drenajes XXI. 152,.54-61

Labye Y; Olson M A; Galand A; Tsourtis N (1988). Design and optimisation of irrigation distribution network. Irrigation and Drainage Paper 44. FAO, Rome.

Lamaddalena N; Sagardoy J A (2000). Performance analysis of on demand pressurized irrigation systems. In: Proceedings of FAO Irrigation and Drainage, Rome

Lansey K E; Mays L W (1989). Optimization model for water distribution system design. Journal of Hydraulic Engineering,115, 1401–1418.

Luc J P; Tarhouni J; Calvez R; Messaoud L; Sablayrolles C (2006). Performance indicators of irrigation pumping stations: application to drill holes of minor irrigated areas in the Kairouan plains (Tunisia) and impact of malfunction on the price of water. Irrigation and Drainage, 55, 85–98.

Malano, H., Burton M. (2001).Guidelines for benchmarking performance in the irrigation and drainage sector.IPTRID Secretariat. Food and Agriculture Organization of the United Nations. Rome, 2001

Martínez F; Fuertes V; Sancho H (1996). Estaciones de bombeo de inyección directa a red. En Ingenieria Hidraulica aplicada a los Sistemas de Distribucion de Agua. Unidad docente de Mecanica de Fluidos, Universidad Politecnica de Valencia (Spain)

Moradi-Jalal M; Mariño M A; Afshar A (2003). Optimal design and operation of irrigation pumping stations. Journal of Irrigation and Drainage Engineering, 129(3), 149–154.

Moradi-Jalal M; Rodin S I; Mariño M A (2004). Use of genetic algorithm in optimization of irrigation pumping stations. Journal of Irrigation and Drainage Engineering, 130(5), 357–365

Moreno M A; Carrión P; Planells P; Ortega J F; Tarjuelo J M (2007). Measurement and improvement of the energy efficiency at pumping stations. Biosystems Engineering, 98, 479–486.

Moreno M A; Planells P; Corcoles J I; Tarjuelo J M; Carrion P A (2009)Development of a new methodology to obtain the characteristic pump curves that minimize the total cost at pumping stations. Biosystems Engineering, 102(1), 95-105.

Planells P; Carrión P A; Ortega J F; Moreno M A; Tarjuelo J .(2005). Pumping selection and regulation for water distribution networks. Journal of Irrigation and Drainage Engineering, 131(3), 273–281.

Pulido-Calvo I; Roldán J; López-Luque R; Gutiérrez-Estrada J C (2003) Demand forecasting for irrigation water distribution systems. Journal of Irrigation and Drainage Engineering 129 (6), pp. 422–431

Reddy L; Elango R(1989) Analysis of water distribution networks with head-dependent outlets. Civ. Eng. Syst. 6(3),pp. 102–110

Rodríguez J A; Camacho E; López R; Perez L (2005). IGRA. A tool for applying the benchmarking initiative to irrigated areas. Irrig. and Drain. 54: 307–31

Rossman L A (2000). *Epanet 2, Users Manual.* Water Supply and Water Resources Division. National Risk Management Research Laboratory. Cincinnati. USA

Ruiz A; Abadía R; Rocamora M C; Cámara J M; Puerto H; Andreu J; Vera J; Melián A (2007). Indicadores de Gestión en comunidades de regantes. XV Congreso Nacional de Riegos. Pamplona. España

Salomons E (2008) OptiGA Manual. URL://www.optiwater.com/optiga/manual.html

Savic D; Walters G (1997).Genetic Algorithms for least-cost design of Water Distribution Netowrks. Journal of Water Resources Planning and Management. 123 (2), 67-77

Wagner J M; Shamir U; Marks D H (1988) “Water distribution reliability: Simulation methods”. J. Wat. Res. Plan. and Manag., 114(3), pp. 276-294

List of figures

Figure

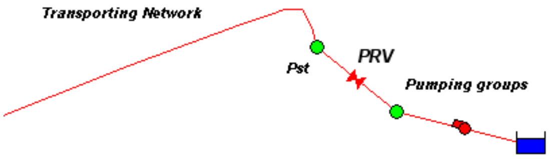


Fig 1 Simulation of VSP with a p_{st} in EPANET

Figure

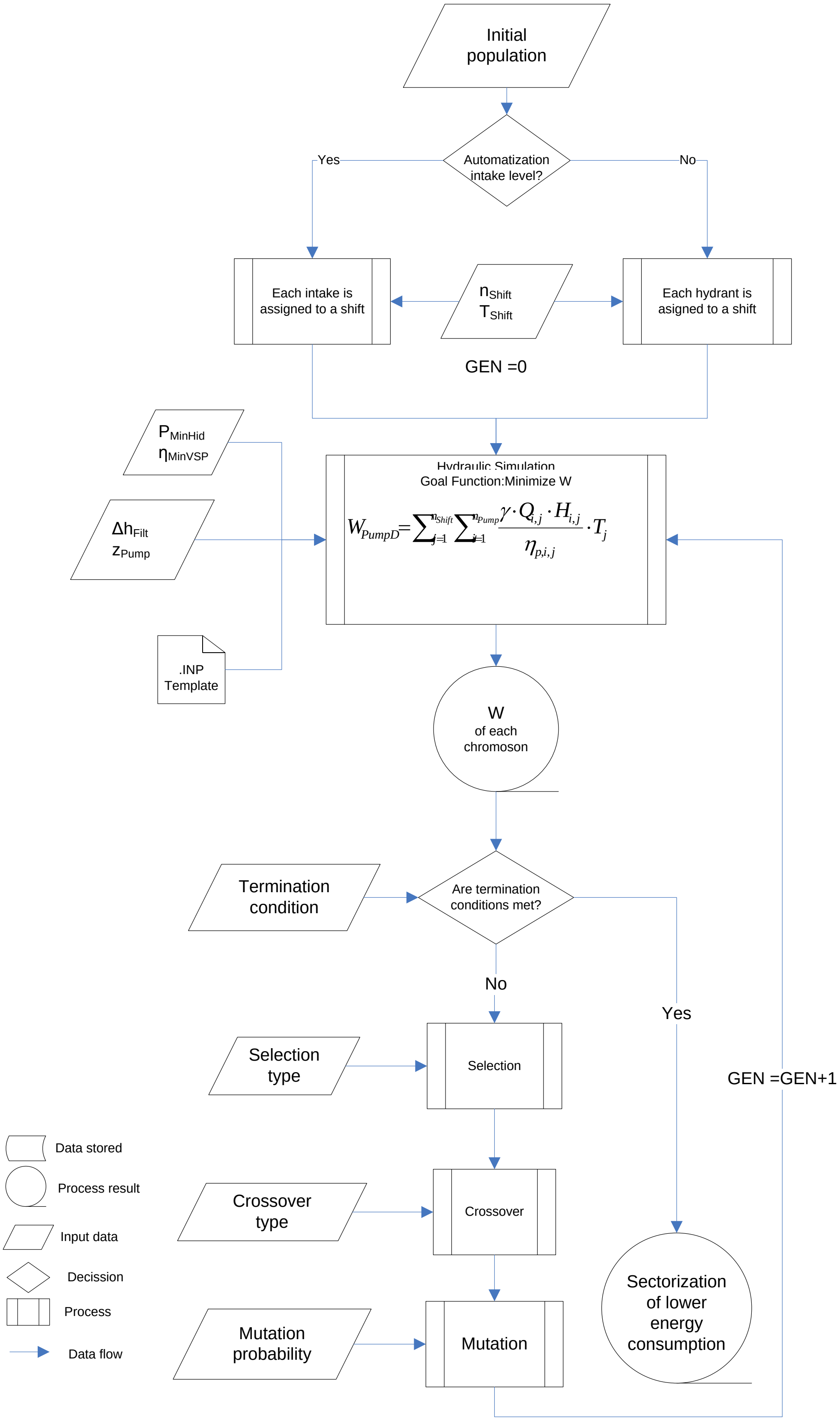


Fig 2 Energy optimization process by GA

Figure

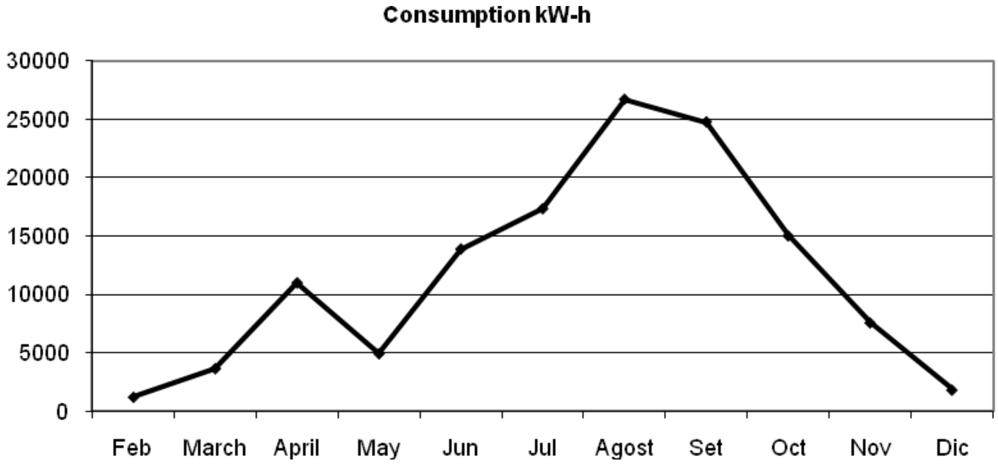


Fig 3 Energy consumption year 2006

Figure

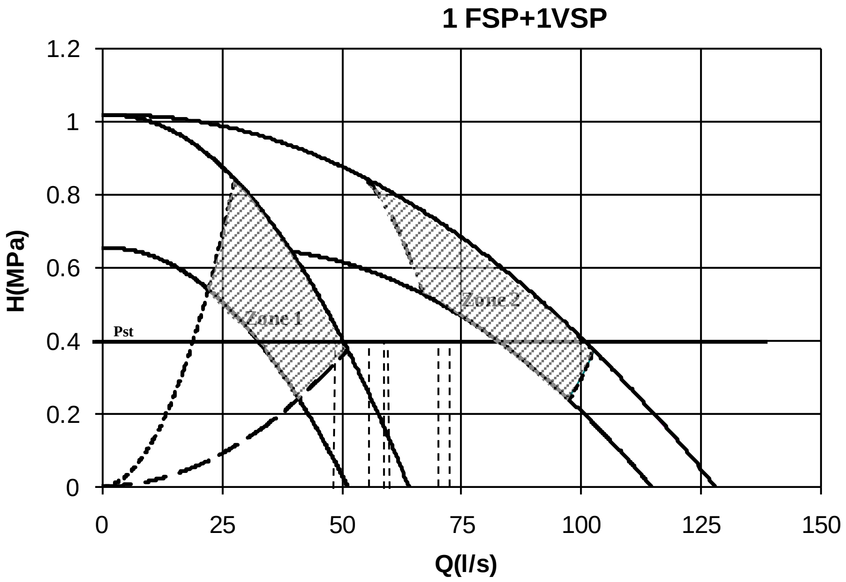


Fig 4 Regulation with 1FSP and 1VSP Year 2006

Figure

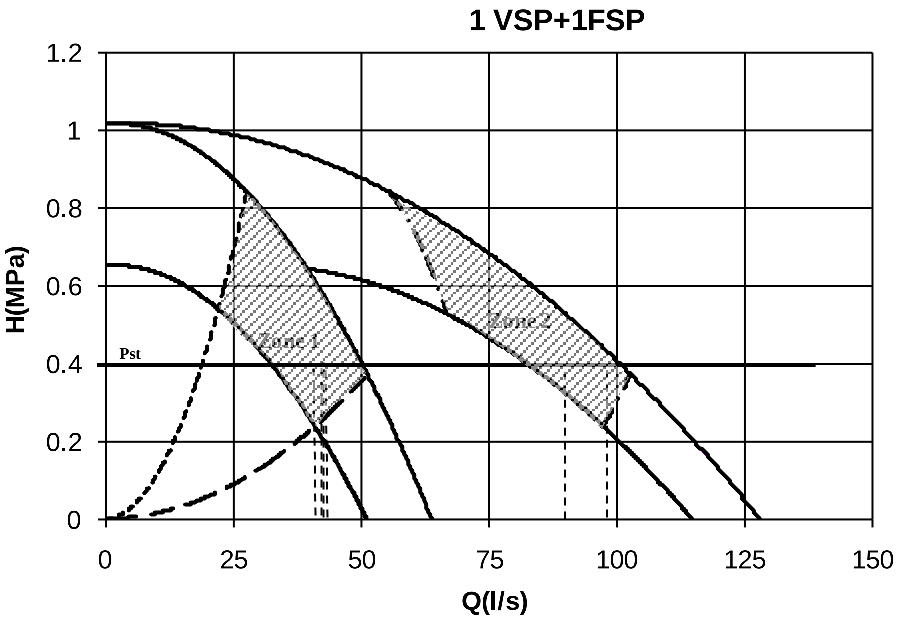


Fig 5 Results of optimizing the regulation of pumping through GA

Figure

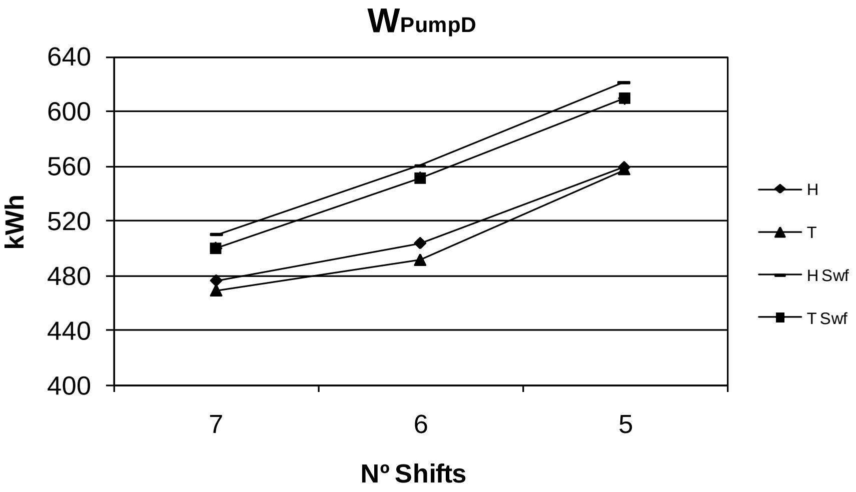


Fig 6 Energy consumption of scenarios

Figure

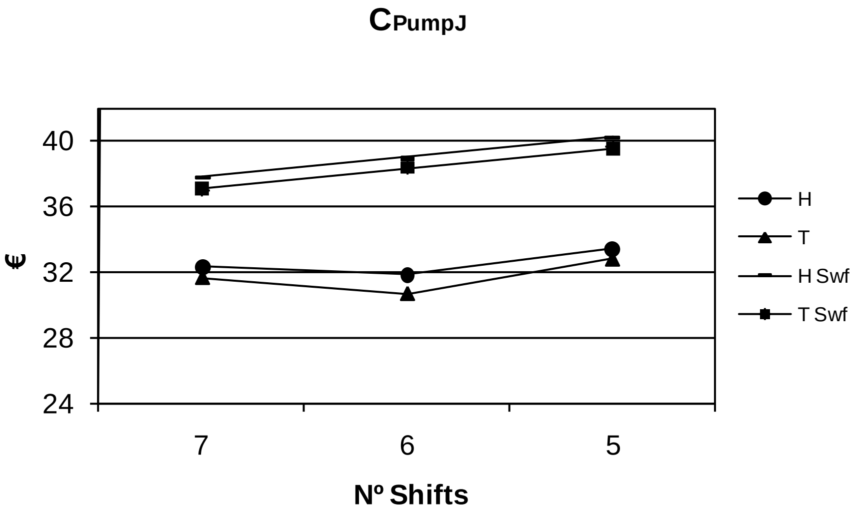


Fig 7 Economic cost of scenarios

Table

Table 1 Fertigation and irrigation schedule for an irrigation day

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Irrigation							■	■	■	■	■	■	■	■	■	■	■	■						
Fertigation							▨	▨	▨	▨	▨	▨	▨	▨	▨	▌								

Table

Table 2 Parameters optimization process through AG

Parameter	**Description**
p_{MinH}	Pressure minimum required in any hydrant
Δh_{Filt}	Head losses produced by the filter system
z_{W}	Water elevation
n_{Shift}	Number of irrigation shifts
T_{Shift}	Irrigation time set up for each shift
$\mathrm{n}_{\mathrm{chromosomes}}$	Initial population
Codification type	Binary, Integer, Decimal
Selection type	Top mate, Roulette rank/cost, Tournament, Random
Crossover	One point, two pints, Uniform, Blending
Mutation probability	Mutation probability of a gene
Termination mode	Maximum generations, Elapsed time, No change in fitness

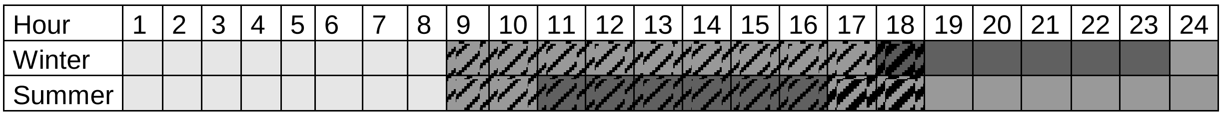
Table

Table 3 Energy indicators year 2006

Indicator	**Value**
Energy consumption (kWh)	124931
Energy cost (€)	14641
Energy consumption per total area(kWh/ha)	1077.45
Energy consumption per irrigated area(kWh/ha)	1612.6
Energy cost per total area (€/ha)	126.26
Energy cost per irrigated area (€/ha)	188.98
Energy cost per m^3 injected to the system (€/m^3)	0.043
Power efficiency per total area (kW/ha)	0.5
Power efficiency per irrigated area (kW/ha)	0.75

Table

Table 4 Daily tariff structure depending on periods and irrigation schedules in 2006



Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Winter	░	░	░	░	░	░	░	░	▒▨	▒▨	▒▨	▒▨	▒▨	▒▨	▒▨	▒▨	▒▨	▓▨	▓	▓	▓	▓	▓	▒
Summer	░	░	░	░	░	░	░	░	▒▨	▒▨	▓▨	▓▨	▓▨	▓▨	▓▨	▓▨	▒▨	▒▨	▒	▒	▒	▒	▒	▒

░ Off-peak (discount 43%) ▒ Plain ▓ Peak (mark up 100%)

Table

Table 5 Hourly distribution of irrigation shifts according to rate structure

	Winter (%)	Summer(%)
Off-peak	16,66	16,66
Plain	75	33,33
Peak	8,33	50

Table

Table 6 Analysis outcomes for pumping station

Shift	**H_j (MPa)**	**Q_j(l/s)**	**P_j(kW)**	**W_j(kWh)**
S1	0.40	61.54	65.18	130.37
S2	0.40	67.30	60.71	121.43
S3	0.40	69.53	60.23	120.46
S4	0.40	56.52	80.46	160.93
S5	0.40	47.468	29.33	58.66
S6	0.40	58.88	70.68	141.37

Table

Table 7 Efficiencies of pump units, according shifts

	FSP		**VSP**	
Shift	**$Q_{i,j}$(l/s)**	**$\eta_{i,j}$ FSP(%)**	**$Q_{i,j}$ (l/s)**	**$\eta_{i,j}$VSP(%)**
S1	50.29	59.98	11.2	14.21
S2	50.29	59.98	17.01	25.04
S3	50.29	59.98	19.23	28.82
S4	50.29	59.98	6.23	5.314
S5	-	-	47.16	64.75
S6	50.29	59.98	8.59	9.25

Table 8 Intakes with pressure lower than 0.25 MPa

Sector	**Nº Intakes**
S1	0
S2	0
S3	23
S4	0
S5	0
S6	1

Table

Table 9 Parameters used in the genetic algorithms

	Automation	
	Hydrant	Intake
Initcial Population	100	100
Generation number	2000	4000
% Mutation	10	10
Selection type	Roulette rank	Roulette rank
Termination mode	Max nº generation	Max nº generation

Table

Table 10 Scenario results using GA

Esc	S_{wf}	n_{Shift}	p_{MinH} (MPa)	Aut	Δh_{Filt} (MPa)	p_{st} (MPa)	$W_{PumpDSwf}$ (kWh)	$C_{PumpDSwf}$ (€)	W_{PumpD} (kWh)	C_{PumpD} (€)
1	No	7	0.250	H	0.05	0.406	-	-	475.8	32.32
2	No	7	0.250	I	0.05	0.402	-	-	468.99	31.65
3	No	6	0.250	H	0.05	0.415	-	-	503.41	31.82
4	No	6	0.250	I	0.05	0.405	-	-	491.18	30.68
5	No	5	0.250	H	0.05	0.453	-	-	559.46	33.43
6	No	5	0.250	I	0.05	0.440	-	-	557.24	32.76
7	Yes	$6+1S_{wF}$	0.250	H	0.05	0.360	348.77	22.5	509.83	37.80
8	Yes	$6+1S_{wF}$	0.250	I	0.05	0.349	338.53	21.73	499.59	37.03
9	Yes	$5+1S_{wF}$	0.250	H	0.05	0.388	399.15	23.64	560.21	38.94
10	Yes	$5+1S_{wF}$	0.250	I	0.05	0.379	390.32	23.04	551.06	38.34
11	Yes	$4+1S_{wF}$	0.250	H	0.05	0.425	459.84	24.9	620.90	40.20
12	Yes	$4+1S_{wF}$	0.250	I	0.05	0.413	448.18	24.26	609.24	39.56

Table 11 Results by shift for Scenario 3

SHIFT	p_{st} (MPa)	Q_j(l/s)	P_j(kW)	W_j(kWh.)
S1	0.41	44.70	28.80	57.6
S2	0.41	42.28	27.34	54.69
S3	0.41	97.63	71.01	142.03
S4	0.41	45.07	29.02	58.04
S5	0.41	88.87	66.95	133.9
S6	0.41	44.31	28.56	57.12

Table

Table 12 Comparison of indicators compared to the 2006 season

Esc	$(W_{PumpJ}/W_{PumpJ2006})\%$	$(C_{PumpJ}/C_{PumpJ2006})\%$ Summer	$(C_{PumpJ}/C_{Pump2006})\%$ Winter
1	64.89	31.27	45.50
2	63.96	30.62	44.55
3	68.65	30.79	44.79
4	66.99	29.69	43.19
5	76.30	32.35	47.06
6	76.00	31.70	46.11
7	69.53	36.57	53.21
8	68.13	35.83	52.13
9	76.40	37.68	54.81
10	75.15	37.10	53.97
11	84.68	38.90	56.59
12	83.09	38.28	55.69

Table 13 Estimation of potential savings

Indicator	**Esc 9**	**Rat(Esc 9/ Year 2006)%**
Energy consumption (kWh)	95447	76.40
Energy cost (€)	5623	38.41
Energy consumption per total area(kWh./ha)	823.17	76.40
Energy consumption per irrigated area(kWh./ha)	1232.05	76.40
Energy cost per total area (€/ha)	48.49	38.40
Energy cost per irrigated area (€/ha)	72.58	38.41
Energy cost per m^3 injected to the system (€/m^3)	0.016	37.21
Power efficiency per total irrigated area (kW/ha)	0.31	62.00
Power efficiency per irrigated area (kW/ha)	0.46	61.33