Validation of a methodology for grouping intakes of pressurized irrigation networks into sectors to minimize energy consumption

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Abstract

A methodology to optimise the amount of energy consumed in pressurized irrigation systems was presented by (Jiménez-Bello et al. 2010a). These authors proposed grouping pressurized irrigation network intakes, each of the water turnouts resulting from a shared hydrant, into sectors via a genetic algorithm. In the present research, the methodology was applied and validated in a water users association. Several energy efficiency indicators were calculated and compared during five consecutive seasons (2006-2010). The first two seasons, when the methodology was not employed, were used as reference for the results obtained from 2008 onwards, when the methodology was applied to the management of irrigation network. Results obtained in seasons 2008 to 2010 showed that the average energy savings were 16% in comparisons to the 2006 season. However, it should be noted that the potential, theoretical savings, could have been as high as 22.3% if the modelled grouping networks would have been accurately followed. There was in fact some discrepancy between the theoretical model outputs and the final groupings due to some intake restrictions. In addition, during the irrigation campaigns, the number of irrigation intakes that operated within each sector was not always equal to the modelled sectoring, a fact that reduced the overall water users association energy efficiency. This occurred particularly during rainy periods, when some users deliberately decided to close their manual irrigation intakes valves. Overall, results showed the potential of the validated methodology for optimising energy use. However, the final overall system efficiency might depend on specific constraints that need to be taken into account when attempting to use model output predictions.

1. Introduction

The modernization of irrigation systems in many cases involves the replacement of open-channel gravity-systems with pressurized irrigation systems. The new networks enable using more water use efficient irrigation techniques such as drip and sprinkler irrigation instead of surface irrigation (Playan and Mateos 2006). However, this change often results in higher energy consumption (Jackson et al 2010).

Various measures can be adopted to reduce energy consumption during the operation of pressurized irrigation systems. First, the irrigation network design should take into account the energy criterion for determining the optimum pipe diameter (Labye et al., 1988; Lansey and Mays, 1989; DIOPRAM, 2003). In addition, pumping station selection should be done considering the forecasted water demands (Moreno et al 2009). On the other hand, more efficient management and operation of irrigation systems can be achieved using protocols and tools developed for assessing the performance using management indicators (Lamaddalena and Sagardoy 2000, Malano and Burton 2001, Luc et al. 2006, Abadía et al 2008, Corcoles et al 2010).

An alternative way to improve energy efficiency in an irrigation system is to group individual irrigation intakes into sectors that can operate only over during specific periods. This implies restricting users' freedom: they can only irrigate during some predetermined periods. Following this modus operandi, the pressure required at the head is the lowest possible and the performance of the pumping units is close to the optimum.

With this objective in mind, Rodriquez et al (2009) studied the potential savings in a case study by simulating the change of the operation system from on-demand (no restrictions) to scheduled periods. It was concluded that energy savings could be as high as 27%. However, there is still some additional improvement potential because in Rodriguez et al. (2009) the network sectoring was performed following empirical criteria without employing any energy specific decision support system. More recently, Moreno et al (2010) compared several irrigation schemes operated either on-demand or with scheduled irrigation periods. It was concluded that greater energy savings could be achieved in the networks operated by sectors, where water can only be applied in predetermined periods than in on-demand networks. However, Moreno et al. (2010) highlighted that in the case of irrigation schemes operated in defined periods, it was easier to fall in an inefficient management due to the difficulty of sectoring the network with optimum energy efficient criteria.

Several procedures have been previously analysed for efficient energy use in irrigation systems organized in sectors. Carrillo et al (2010) proposed a methodology based on the sectoring of the irrigation network by topological criteria. In this methodology, irrigation hydrants were grouped according to their distance and height to the injection point of the network by means of clustering techniques. In addition, Monte Carlo techniques were used to provide irrigation schedules according to the monthly probability of operation of each of the hydrants. Then, by means of hydraulic simulations, each proposed irrigation scenario was analysed and the more appropriated number of irrigation sectors was determined. As pointed out by Carillo et al. (2010) the disadvantage of this sectoring network approach is that it does not ensures optimum performance from the energy point of view. In fact, this approach tends to group nearby hydrants into sectors, thus increasing the head loses in the pipes. Another important limitation of the procedure proposed by Carillo et al. (2010) is that it assumes a fixed efficiency of pumping units, but this could be very variable depending on the demand scenario and may lead to the choice of a scenario where the efficiency of irrigation pumping groups is low (Moreno et al 2010).

Jiménez -Bello et al (2010a) developed a methodology based on genetic algorithms (GA) and hydraulic models that, for the case of networks regulated by direct injection by pumps, grouped the intakes in efficient sectors in terms of energy. The goal was to optimise energy consumption per irrigation event, i.e. reducing the amount of energy used per m^3 of pumped water. As a result, irrigation sectors could be established that minimized energy consumption. Additionally, the head pressure required for proper operation of each irrigation sector was known in advance. The model results showed that the theoretical savings in energy consumption could reach 36%, for the case study tested in that irrigation season (2006). Nevertheless model outputs were not compared with the real energy saving values if the methodology was actually employed.

The objective of the present research is to compare several energy efficient indicators for pressurized irrigation system in a water users association (WUA) before and after the grouping methodology proposed by Jimenez-Bello et al. (2010a) was employed. The difference in sectoring among seasons is accurately explained paying attention to how sectoring affected the energy performance of the irrigation system. Since the current energy prices have suffered an important increase (+34%) during the experimental period (2006 to 2010), the present paper focuses on energy consumption rather than on the economic cost of energy.

2. List of abbreviations for terms, definition, formulas and units

ACE: Annual consumed energy. Annual consumed energy in the WUA (kWh).

ACESr: Annual consumed energy per irrigated area. Relation between the annual consumed energy and the irrigated area during the irrigation season. $\frac{\text{Annual consumed energy}}{\text{Irrigated area}}$(kWh ha^{-1}).

ACEVT: Annual consumed energy per total annual volume of irrigation water delivered. Relation between the annual consumed energy and the total annual volume of irrigation water supply. $\frac{\text{ACE}}{\text{VT}}$ (kWh/m^3).

CV: Coefficient of variation. It is the ratio of the standard deviation (s) to the mean (m) (dimensionless number).

ED: Water delivery efficiency. Relation between total annual volume of irrigation water delivery and total annual volume of irrigation water supply. $ED = \frac{\text{Total annual volume of irrigation water delivery}}{\text{Total annual volume of irrigation water supply}}$ (dimensionless number).

EDI: Energy dependence index. Relation between the volume of water that has to be pumped and the one that has not to be pumped for supplying to users enough discharge and pressure. $\frac{\text{Pumped volume}}{\text{Total annual volume of irrigation water supply}}$ (dimensionless number)

EEPS: Energy efficiency of the pumping system. Average energy efficiency of the pumping system during the irrigation season. $EEPS(\%) = 0.002725\,\frac{\sum_{k=1}^{n} V_K \cdot H_k}{\sum_{i=1}^{n} E_{ibilled}}\cdot 100$ where V_k is the volume supplied by pump k (m^3), H_k is the pumping head supplied by pump k (m) and $E_{ibilled}$ is the energy(kWh) consumed by the n pumps.

EES[1]:Efficiency of the energy supply. Relation between the necessary energy to supply to the system and the actually applied (Abadia et al 2008). $ES = \frac{WHD-WHI}{PHI}$ (dimensioless number) where WHD is the water head demanded by the irrigation supplied (m) and WHI is the water head at the source point (m).

EES[2]: Efficiency of the energy supply. Relation between the necessary energy to supply to the system and the actually applied (Moreno et al 2010). $ES = \frac{H_R}{H_B} = \frac{H_R}{PHI}$ where H_R is the pumping head demanded by the network (m) and H_B the pumping head actually applied (m).

ETo:Reference Evapotranspiration (Allen et al 1998, mm)

FSP: Fixed speed pump.

GA: Genetic algorithms.

GEE: General Energy Efficiency Global energy efficiency of the WUA, which considers the energy efficiency of the pumping system and the energy efficiency of the distribution network. $GEE = EEPS \cdot EES$ (dimensionless number).

MCE: Monthly consumed energy. Monthly consumed energy in the WUA (kWh)

MCEVT: Monthly consumed energy per total annual volume of irrigation water delivered. Relation between the monthly consumed energy and the total annual volume of irrigation water supply (kWh m^{-3})

Nsect: Number of irrigation sectors.

PHI:Pumping head injected by pumping stations (m). Pumping head injected to the pumping stations with respect to the total volume injected into the network. $PHI = \frac{\sum V_k . H_k .}{V_T}$ (m^3) where V_k is the volume supplied by pump k (m^3) and H_k is the pumping head supplied by pump k (m^3)

Pr: The average annual effective rainfall (Dastane 1998,mm)

Sa: Total command area. Design area provided with irrigation infrastructure (ha).

Sf: Total fertigated area. Total irrigated area that is fertilized by central fertilization (ha).

Sr: Total irrigated area. Total annual irrigated area during the year (ha).

Vs: Total annual volume of irrigation water delivery. Quantified volume of water supplied to the users at hydrant level (m^3).

VSP: Variable speed pump.

VT :Total annual volume of irrigation water supply. Total volume that is pumped from the source of water to the reservoirs (m^3).

VTSa: Annual irrigation water supply per unit. Relation between the total annual volume of water supply and the total command area. $\frac{\text{Total annual volume of irrigation supply}}{\text{Total command area}}$ (m^3 ha^{-1})

VTSr: Annual irrigation water supply per unitirrigated area. Relation between the total annual volume of irrigation water supply and the total irrigated area (m^3 ha^{-1})

WHD: Water head demanded by the irrigation supplied. Average head demanded by the irrigation system $WHD = \frac{\sum S_j (Z_j + H_{dj})}{S_T}$ (m) where S_T is the Total surface of the irrigation area supplied (ha), S_j is the Surface of irrigation area located at constant geographical elevation j, (ha),Z_j is the elevation of irrigation surface j, (m),H_{dj} is the pressure head demanded by the on-farm irrigation system located in the irrigation area j (m)

WHI: Water head at the intake point. Average head supplied by the pumping Systems. $\frac{\sum V_i \ H_i}{V_T}$ where V_i is the pumped volume (m^3) of the pumping system, Hi is the pumping head (m), and VT is the total volume supplied by the pumping system (m^3)

W_{PD} : Estimated energy consumption (, kWh/m^3).

WUA : Water Users Association.

W_{PD}: Estimated energy consumption (kWh/m^3).

3. Material and methods

3.1 Case study

Data were collected at the WUA of Senyera, located in the municipality of the same name in the province of Valencia, Spain (39º 03’ N, 0º 30‘ O). The total area of the Senyera WUA is 125 ha and the WUA consists of 387 plots with an average plot size of 3,093 m^2. A plot is considered part of a WUA if it is connected to an irrigation intake (i.e. each of the water turnouts resulting from a shared hydrant). The system has 52 multi-outlet hydrants and a total of 331 intakes. A multioutlet hydrant has several intakes, a common solution adopted by engineers for network design when plot size is small. In this way, network pipe lengths are shorter and more economic. As a result, users connect their sub-units to the water supply system through water intakes. Indeed, the network topology is branched (Fig.1).

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). They operate in a staggered way (Martínez et al. 1996). Both pumps were powered by a 37 kW engine with an efficiency of 80% (Bombas Ideal S.A., Massalfassar, Spain) and VFD efficiency of 97% (Power electronics, Valencia, Spain). A more detailed description of the study case can be found in Jimenez- Bello et al (2010a).

The WUA was designed to provide users with fertilizers using a central fertigation procedure as described in detail in Jiménez-Bello et al. (2010b). However, users could still decide if they wanted to make use of the central fertigation or not.

The WUA was managed by a company in charge of the system control, maintenance, irrigation scheduling and payment collection. Users were charged according to their water consumption with a fixed price per m^3 of water they used, independently of how much energy was used to supply water. Those users that fertigated paid an extra amount per m^3.

Irrigation was arranged into scheduled periods, and the intakes were distributed over irrigation sectors, usually six. The strategy followed by the technical staff responsible for sectoring the system until the 2007 season was to group the intakes into sectors of similar size. Each sector was irrigated at a scheduled period of two hours duration. Irrigation was scheduled on a monthly basis based on the historic weather data available. As a consequence, the technician decided in advance the days to irrigate and to fertigate and this information was communicated to users. Weather data were taken from the meteorological station of Villanueva de Castellón. located 800 m away from the WUA station.

3.2 Methodology description

The sectoring model of Jimenez-Bello et al (2010) was applied to the Senyera WUA, starting in 2008. Briefly, the model allows to group sectors in a way that the sum of the intake flows for a given pressure head, drops in areas where pump efficiency is higher (See Fig 4 in Jimenez-Bello et al 2010a). The required data is a calibrated mathematical model of the irrigation network. This is possible to obtain because the modern irrigation systems dispose of pressure sensors and flow meters that allow the model calibration. The required input parameters are pressure head at hydrant, number of sectors and those parameters related with GA. The decision variables are the possible sectors that each hydrant or intake can belong to. Once the GA model is run, the best solution to the sectoring problem is achieved after some termination conditions, as a maximum generation number. Indeed, this procedure guarantees that irrigation can be carried out at the lowest possible estimated energy consumption (W_{PD}, kWh/m^3) and consequently with low annual consumed energy (ACEVT, kWh/m^3). However, there were some constraints in the network that influenced the final model sectoring decisions. For example, there were intakes that needed to receive fertilizer collectively, but others had to be individually fertigated. This fact conditioned the network sectoring, because depending on the fertilization user's criterion (individual or collective) intakes were forced to be part of determinate sectors.

From 2008, at the beginning of each season WUA technicians prepared a list of intakes planned to be operated that season separating them in two classes, those that will receive fertilizer collectively and those that will not. The GA model was run and results were transmitted to technicians that programmed the Unit Control for intake sectoring. Over the 2008 to 2010 campaigns, sectoring was changed due to different circumstances (Table 1). This fact allowed to quantify the effects of different sectoring decisions on the WUA energy performance. At the end of each irrigation season, results were reported to the WUA staff to assess energy performance. By means of energy indicators, the different irrigation seasons were compared. In order to assess energy performance, seasons 2006 and 2007 were taken as reference. To validate the model, the energy used during the study seasons was compared with the theoretical predicted values. The model error for the different scenarios was calculated and reasons for inaccurate results were analysed.

3.3 Energy indicators

Descriptors and indicators were used to characterize the WUA energy performance along the studied campaigns. These indicators were taken from the protocol for energy audit in WUAs (IDAE 2008). These indicators are commonly used in the related literature (Abadía et al. 2008, Corcoles et al. 2009, Moreno et al. 2010, Carrillo et al. 2010). Some of these indicators were monthly applied in order to study in more detail the irrigation scenarios. Water meter readings and energy bills were used for the estimation of the indicators. These data were periodically supplied by the WUA technicians. The system water delivery efficiency (ED) was calculated by comparing the water meter readings taken at the pumping units with the sum of the water meter readings taken at each user level.

Irrigation seasons were classified according to the General Energy Efficiency (GEE) following the energy audit protocol (IDAE 2008). According to this protocol, a GEE value greater than 50% is considered excellent. If GEE is between 40% and 50%, the WUA is classified as good, 30<GEE<40% is normal, 30<GEE<40% is acceptable and if GEE <25% performance is not acceptable.

4. Results and discussion

4.1 Climatic characterization of the irrigation seasons and water applications

The average annual Reference Evapotranspiration (ETo, Allen et al 1998) for the five irrigation seasons was 1,117 mm and its standard deviation was 50 mm. The average annual effective rainfall (Pr, Dastane 1998) was 580 mm and its standard deviation was 220 mm. While the ETo was fairly constant during the five irrigation seasons (Fig 2), rainfall rates showed relevant interseasonal variability. Year 2006 was the driest one with only 382 mm of total precipitation. On the other hand, seasons 2007, 2008 and 2009 had rainfall above the ten-year average (614 mm). On a seasonal basis, rainfall was mostly concentrated during September and October. (614 mm).

Water application varied among seasons from 4,238 m^3/ha in 2010 to 3,323 m^3/ha in 2008. These variations were mostly due to the different seasonal rainfall (Fig 2). Water application in the study area resulted similar to those commonly applied in well watered citrus trees grown in the same area (González-Altozano and Castel 1999). In all seasons, the main system water delivery efficiency (ED) was very high, being 99% for the first season and 98% for the rest of seasons (Table 2).

4.2 Energy performance assessment

The first year of operation of the irrigation system after modernization of the distribution network was 2006. During 2007, additional users (15 ha) joined the WUA. The irrigated area remained constant during the following seasons (Table 2). The Water Head Intake (WHI) was 350 kPa from the 2007 campaign. WHI was the same for all sectors, since the central system did not allow setting different WHI for each sector. This value was manually set by the field technician, and it did not guarantee proper pressure head at the hydrants (250 kPa).

During 2006, the annual consumed energy per total volume of irrigation water delivered (ACEVT) was 0.310 kWh (Table 3). The sector flows fell outside the optimum pump working conditions. In 2007, the ACEVT was 0.279 kWh, representing 9% in energy conservation respect to 2006. Without carrying out any intended action to reduce energy consumption, savings resulted from increasing the number of intakes, leaving unchanged the number of sectors. As a consequence, the increased flows resulted in a more efficient pumping. Starting in 2008, GA sectoring was applied. The ACEVT decreased by 14.3 % respect to 2006 and by 4.5% respect to 2007. In 2009, the savings were 16.0% respect to 2006 and 6.6% respect to 2007. Similar energy savings were achieved in 2010.

Using GEE^1 as an indicator, as suggested by Abadia et al (2008), energy performance was classified as unacceptable for all studied seasons. This was due to the low energy efficiency of the pumping system (EEPS), caused by high pipe head losses. These were 36 kPa/km on average. This feature is difficult to improve once the network has already been built. In the study case, a decrease of 50 kPa in water head intake (WHI) represents a 10% reduction in energy consumption per unit volume of water. As suggested by Moreno et al (2010) GEE^2 can be also computed without taking into account the design factors. This is considering the efficiency of the energy supply (EES) as the ratio between the necessary energy to supply the system and the actually applied energy. When using the GEE^2 indicator, the WUA energy performance rank improved from a normal classification in the 2006-2007 seasons to a good one for the years 2008-2010.

4.3 Assessment results

The energy used and the water volumes actually applied during the study seasons were compared with the theoretical values predicted by the Jimenez-Bello et al. (2010a) model. These results are presented in Table 3. The actual energy system efficiency was lower than the theoretical optimum for the best possible scenario. This deviation between the predicted annual energy consume and the actual values was however small (3-7%) and it was because the sectoring actually used by the WUA could not reproduce the modelled scenario. This was mostly because users could deliberately shut off their manual valves. Under these circumstances, the number of intakes that were actually operating was different from the number of intakes per sector indicated by the model. This conditioned the pump performance because the operating flow was different from the estimated model flow. As it is shown in Figure 3, ACEVT depends on the flow demanded by the network. Due to the characteristic curves of the pumping system of the case study, (VSP and VSP+FSP) there is a narrow optimum range of water flow for optimising ACEVT (Figure 3). Considering that the average intake flow is 1.56 l/s, it is interesting to note that if just six intakes stop operating the flow variations will most likely move the operation point from the optimal points leading to a decrease in the pump performance increasing the energy cost of the water pumped. This fact indicates that optimum energy performance can be only achieved when users do not deliberately operate their valves.

The seasonal variation of the MCEVT index shows that during campaigns 2008-2010 the highest rates were in most cases obtained during the rainy periods (Fig. 2) of the autumn months (Table 4). During these periods, in order to reduce their water costs, some users decided to manually shut off their manual valves (Fig 4), because they thought that the crop water requirements were fulfilled by the rainfall. For instance, in

October 2009, the coefficient of variation (CV) for number of irrigation hours by intake was 2.27, much higher than during the rest of the year when it was about 0.50 (Table 4). This led to a MCEVT of 0.315 kWh, while the average annual MCEVT was 0.260 kWh. On the other hand, in 2010, precipitation was more regular throughout the season (Fig. 2). The only month without rain was July. As a consequence, the CV for number of irrigation hours by intake was more constant along the season (Table 4). Despite the highest MCEVT generally occurred then during the rainy months, in that period the irrigation volumes applied were low, and consequently the energy consumption during those periods did not greatly affect the total ACEVT. In fact, it should be noted that 70% of total annual energy consumption occurred during the June-September interval (Fig. 5).

Overall the results presented indicated that in commercial situations, the theoretical sectoring proposed by the model cannot be always strictly followed. This highlights some of the difficulties of applying model predictions in a real case, where final decisions are often motivated not only by technical limitations but also by empirical reasons. The first step to improve the overall WUA energy efficiency is scheduling irrigation in order to match the crop water requirements. In addition, users should be more confident in the irrigation scheduling programmed by system managers. Last, but not least, the billing system used could also play a major role for energy and water saving. In this WUA, similarly to many others existing in this region, users were charged a fixed amount per m^3 of irrigation water they used regardless the energy needed to supply the water. Therefore the users were not motivated to obtain energy savings and, in addition, they were often not conscious of the repercussion of their deliberate actions of closing their valves. Another irrigation water billing system should be considered taking into account the amount of both water and energy used by each users.

As previously mentioned, this case study was characterized by central fertigation, with the option to let users decide if they wanted to receive fertilizer or not. This situation frequently happens in the WUAs in the area and it is mostly due to large variations between plots of the citrus cultivars used. The varieties used often have different phenological growth cycles what might imply different seasonal fertigation requirements. Because fertigating and non-fertigating intakes could not be grouped in the same sectors it was not possible to achieve better energy performance, and the obtained solution for the optimization problem is not as good as without this restriction (Jimenez.Bello et al 2010a). In order to evaluate the potential energy savings without any restriction, W_{PD} was calculated for six irrigation sectors with no restrictions for the intakes. The result was of 593 kWh and ACEVTp of 0.232 kWh/m^3, which would have meant an improvement ranging between 12.9 and 7.4% compared to ACEVTp for the period 2008-2010 described in Table 3. Assuming an error of - 4% in the estimation, the potential energy saving could have been 22.3 % and 13.4 % lower with respect to years 2006 and 2007, respectively.

In addition, to the use of the GA model proposed, other possible technical solution for improving energy efficiency are related with the correct use of VFD. For instance, in the case study reported adding a second VFD to the FSP would have allowed increasing the water flow range with low energy consumption ranges (i.e. between 0.262 to 0.226 kWh/m3, Figure 6). In this case, the optimum water flow range will be 88-100 l/s, duplicating the range as to when operate a VSP and FSP. Indeed each sector flows has a greater range to fluctuate without increasing power consumption by the pumping station. The drawback is that the optimum water flow range of 44-50 l/s (i.e when only a VSP operates, Fig 3) is lost.

5. Conclusions

In an irrigation network operated on turns the grouping of irrigation intakes into optimal sectors from the energy point of view using GA produced savings of around 16% in the energy performance. These savings could have been higher (22%) if there had not been restrictions that limited the grouping of intakes into sectors. Indeed the reliability of the methodology lies in the accuracy with which it determines the intake number that will operate simultaneously and their flow rate. If the intake number that actually operates differs from intake number for which sectoring was modelled the energy efficiency will decrease. The analysed methodology has proved its practical application to manage irrigation networks that operate by turns and monoculture predominates but it could be applied to networks operated on demand with restrictions and different kind of crops to analyse and compare the obtained results.

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Table 1. Summary of the events that occurred during the entire experimental period that conditioned the sectoring decisions procedure.

Table 2. Energy indicators for 2006-2010 seasons.

Table 3. Comparison between estimated energy consumption and actual consumption for each operational sectoring. Each column represents predicted irrigated surface (Sr_p, ha) number of predicted operating intakes (**N_{PInt}**), irrigated surface (Sr,ha), fertigated surface (Sf, ha) number of irrigation sectors (Nsect), number of sectors non fertigated (NSectwfert), predicted annual consumed energy per total annual volume of irrigation water delivered ACEVTp (kWh/m^3), annual consumed energy per total annual volume of irrigation water delivered (ACEVT, kWh/m^3) and Error model (Er, %).

Table 4. Estimated number of irrigation hours by intake (Avg (h)), the standard deviation (Std (h)), the variation coefficient (CV) and MCEVT (kWh) for each month of the analyzed seasons.

Table 1 Summary of the events that occurred during the entire experimental period that conditioned the sectoring decisions procedure.

Date	Event
Jan 2006	Sectoring for the 2006 seasons was set up according to empirical reasons.
Jan 2007	Sectoring was not modified but more intakes per sector were added.
Jan 2008	Sectoring for the 2008 season was set up based on the Jimenez-Bello et al. (2010a) model
Jan 2009	New sectoring for the 2009 season was set up based on the Jimenez-Bello et al. (2010a) model
Sept 2009	Sectoring was changed due to fertilization period finished
Oct 2009	Automation system was replaced and water delivery did not work properly.
Jan 2010	New sectoring for the 2009 season was set up based on the Jimenez-Bello et al. (2010a) model
Jul 2010	New sectoring was set up based on the Jimenez-Bello et al. (2010a) model modified from 5 to 6 sectors due to insufficient pressure in some hydrants

Table 2 Energy indicators for 2006-2010 seasons.

	Seasons				
	2006	**2007**	**2008**	**2009**	**2010**
Sr(ha)	85.8	100.5	103	103.1	103.6
Nsect	6	6	6	6	6
VT(m^3)	354046	352022	349263	426874	448083
Vs(m^3)	350505	344981	342278	418336	439122
VTSa (m3 ha^{-1})	2804	2759	2738	3346	3512
VTSr (m3 ha^{-1})	4085	3432	3323	4058	4239
ACE (kWh)	109964	98305	93140	111325	116543
ED(%)	99	98	98	98	98
ACESr (kWh ha^{-1})	1281.6	978.1	904.3	1079.8	1124.9
ACEVT (kWh m^{-3})	0.311	0.279	0.266	0.260	0.260
EDI (%)	100	100	100	100	100
WHI(kPa)	320	350	350	350	350
WHD (kPa)	215	221	223	217	216
EEPS (%)[1]	73.8	64.1	65.7	64.3	62.8
EEPS (%)[2]	100	100	100	100	100
EES (%)	32.7	38.9	41.1	42.3	41.7
GEE (%)[1]	22.1	23.1	25.0	25.5	24.5
GEE (%)[2]	32.7	38.9	41.1	42.3	41.6

Table 3 Comparison between estimated energy consumption and real consumption for each operational sectoring. Each column represents predicted irrigated surface (Sr_p, ha) number of predicted operating intakes (**N_{PInt}),** irrigated surface (Sr,ha), fertigated surface (Sf, ha) number of irrigation sectors (Nsect), number of sectors non fertigated (NSectwfert**),** predicted annual consumed energy per total annual volume of irrigation water delivered ACEVTp (kWh/m^3), annual consumed energy per total annual volume of irrigation water delivered (ACEVT, kWh/m^3) and Error model (Er, %).

Season	**Sr_p (ha)**	**N_{PInt}**	**Sr (ha)**	**N_{OInt}**	**Sf (ha)**	**Nsect**	**NSect wfert**	**$ACEVT_p$ (kWh/m^3)**	**$ACEVT_R$ (kWh/m^3)**	**Er (%)**
2006	-		85,8	246	60.4	6	1		0.311	
2007			100,5	281	76,9	6	1		0.279	
2008	103	281	103,0	282	77.8	6	1	0.256	0.267	-4.1
2009 Jan - 2009 Aug	107.4	289	103,1	282	58.7	6	2	0.242	0.255	-5.1
2009 Sept- 2009 Sept	107.4	289	103,1	268	20.1	6	5	0.238	0.245	-2.83
2009 [c]Oct 2009 Dec	107.4	289	103,1	266	0	5	5	0.244	0.263	-7.2
2010 Jan 2010 Jun	104.75	282	103,6	276	64,5	5	2	0.257	0.263	-2.3
2010 Jul 2010 Dec	104.7	282	103,6	276	64,5	6	2	0.243	0.251	-3.2

Table 4 Estimated number of irrigation hours by intake (Avg (h)), the standard deviation (Std (h)), the variation coefficient (CV) and MCEVT (kWh) for each month of the analysed seasons.

		Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov
2006	**Avg(h)**		25.44	26.45	37.9	55.5	69.3	45.1	38.0	7.8
	Std(h)		10.2	12.8	18.3	18.7	30.8	16.1	14.9	6.7
	CV		0.4	0.5	0.5	0.3	0.5	0.4	0.4	0.9
	MCEVT(kWh/m^3)		0.255	0.259	0.252	0.325	0.354	0.328	0.498	0.710
2007	**Avg(h)**	15.3	7.3	35.3	45.0	53.8	50.2	22.3	5.6	7.5
	Std(h)	8.2	4.9	19.2	15.5	17.4	18.6	8.9	8.5	10.5
	CV	0.5	0.7	0.5	0.3	0.3	0.4	0.4	1.5	1.4
	MCEVT(kWh/m^3)	0.271	0.289	0.309	0.319	0.262	0.271	0.258	0.278	0.204
2008	**Avg(h)**	28.1	31.3	9.0	14.3	47.5	50.5	41.6	2.3	4.7
	Std(h)	12.6	13.3	3.1	5.9	12.9	12.4	12.2	1.8	6.1
	CV	0.6	0.4	0.4	0.4	0.3	0.3	0.3	0.8	1.3
	MCEVT(kWh/m^3)	0.236	0.225	0.359	0.296	0.259	0.263	0.259	0.547	0.329
2009	**Avg(h)**	23.8	7.2	37.3	49.5	50.78	50.0	24.1	15.4	27.9
	Std(h)	20.5	11.5	24.5	16.5	18.6	20.3	11.9	34.9	18.2
	CV	0.9	1.6	0.7	0.3	0.4	0.4	0.5	2.3	0.7
	MCEVT(kWh/m^3)	0.242	0.286	0.250	0.263	0.268	0.269	0.255	0.315	0.276
2010	**Avg(h)**	14.7	19.9	49.8	51.2	56.4	57.1	31.8	22.5	21.8

	Std(h)	12.1	15.2	39.2	33.8	34.9	58.8	18.7	11.9	11.4
	CV	0.8	0.8	0.8	0.7	0.6	1.0	0.6	0.5	0.5
	MCEVT(kWh/m^3)	0.260	0.252	0.247	0.285	0.257	0.268	0.236	0.267	0.257

List of figures

Fig 1 Network sectoring for water use association of Senyera during the 2010 season. All the irrigated subplots were grouped into six irrigation sectors (S1 to S6).

Fig 2 Monthly Reference evapotranspiration (ET, mm) and precipitation (Pr, mm) during the entire experimental period, seasons 2006 to 2010.

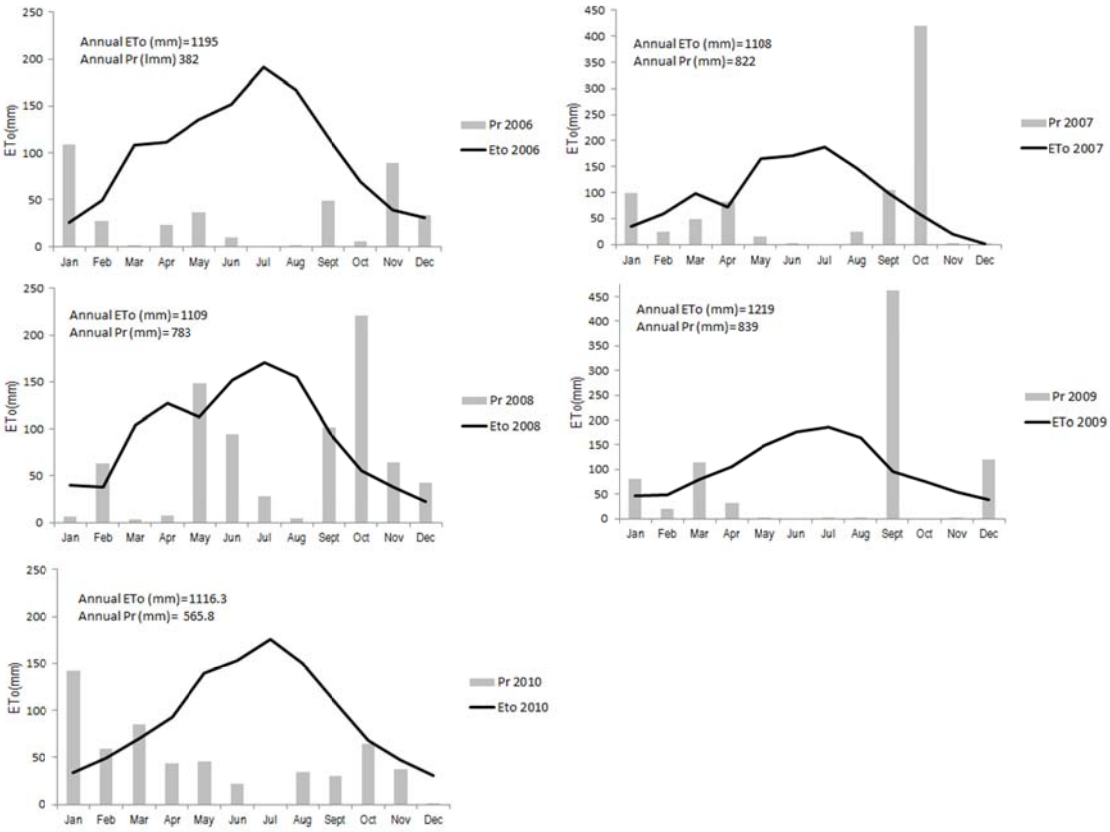
Fig 3 Relation between the energy cost of irrigation water supplied (kWh/m^3) and the demanded flow by each irrigation sector (l/s) for the pumps of the study case, a variable speed pump and one fixed speed pump when is set a pumping head of 400 kPa.

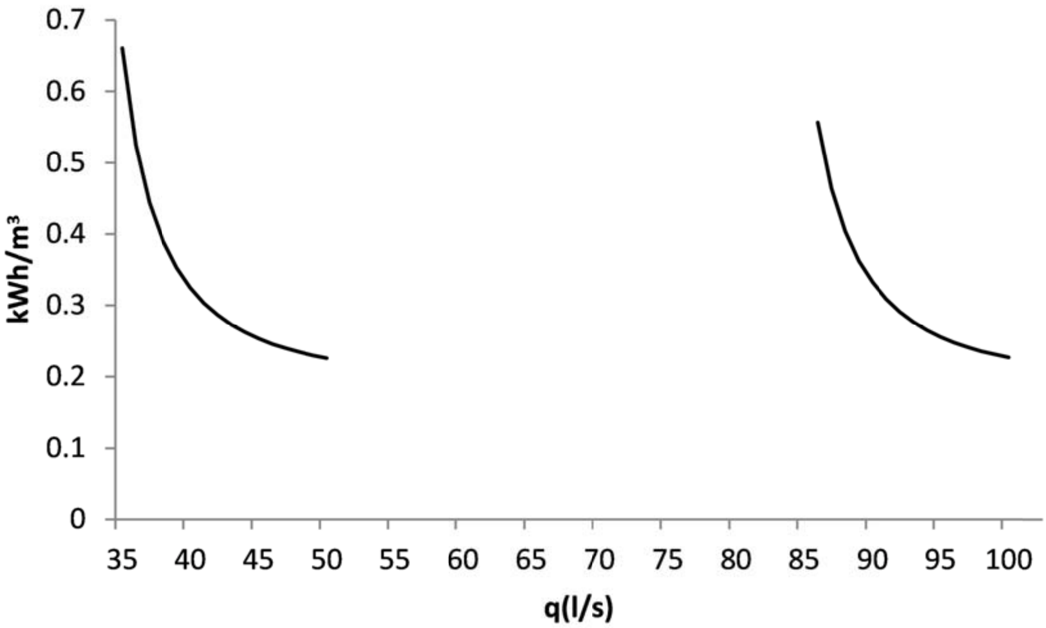
Fig 4 Monthly irrigated area (Sr, ha), number of predicted operating intakes (NPint) and number of operating intakes (NOint) for each irrigation season.

Fig 5Monthly consumed energy (MCE, kWh)) for seasons 2006-2010.

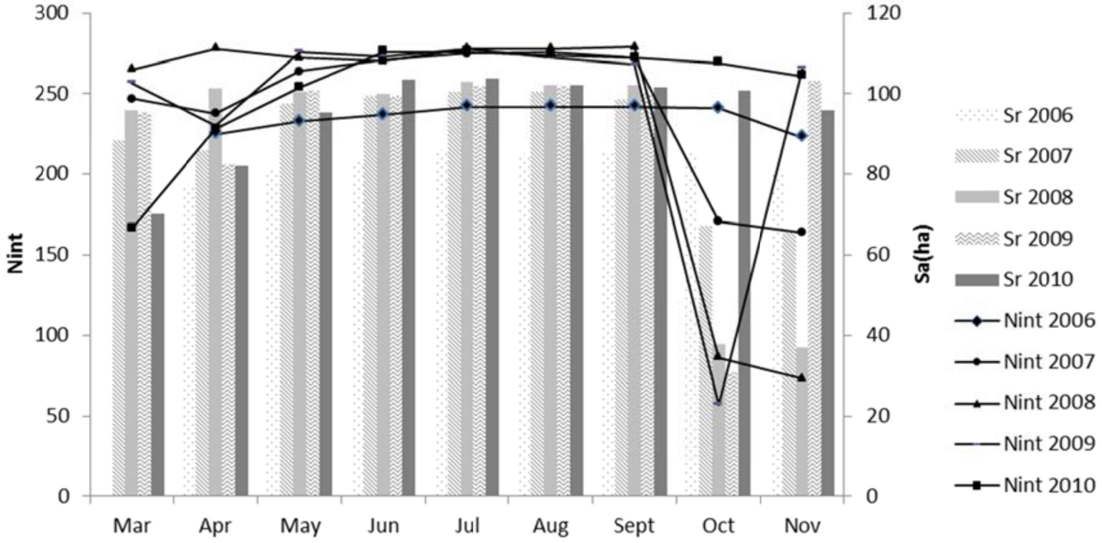
Fig6 Relation between volume of irrigation water supply (kWh/m3) and the demanded flow by each irrigation sector (l/s) for the pumps of the study case, assuming two variable speed pumps, when is set a pumping head of 400 kPa.

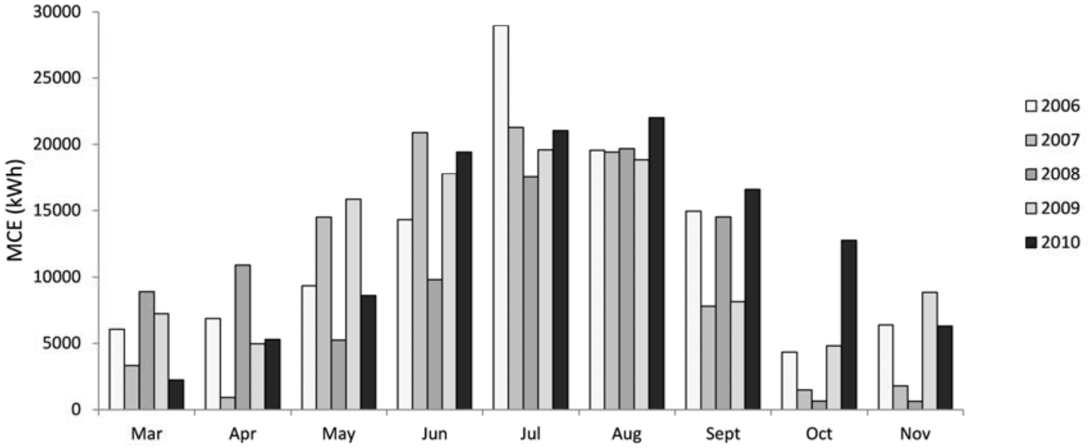

N
H-52
H-54
H-55
H-57
H-56
H-47
H-46
H-42
H-51
H-35
H-40
H-41
H-30
H-29
H-28
H-38
H-39
H-34
H-36
H-32
H-37
H-33
H-31
H-22
H-23
H-20
H-18
H-7
H-6
H-Noemi
H-17
H-11
H-15
H-3
H-4
H-2
H-1
H-16
H-14
H-13
H-10
H-9
H-12
Multiuser Hydrants
Pipes
Irrigation pond
Subparcels
Sector
S1
S2
S3
S4
S5
S6
0
100
200
400
600
800
Meters

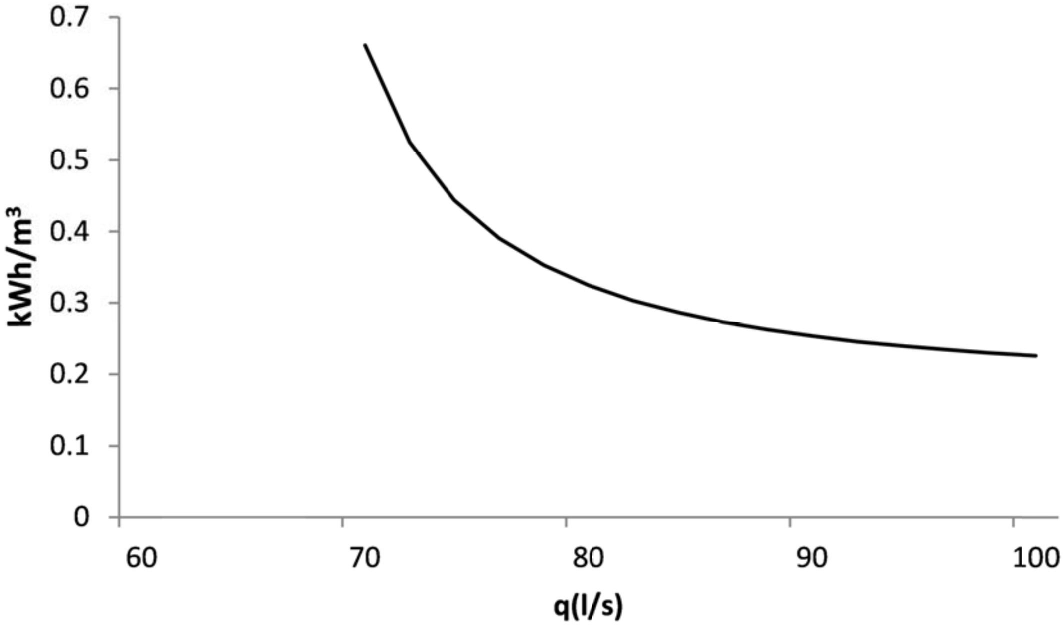

Annual ETo (mm)=1195
Annual Pr (lmm) 382
Pr 2006
Eto 2006
Annual ETo (mm)=1108
Annual Pr (mm)=822
Pr 2007
ETo 2007
Annual ETo (mm)=1109
Annual Pr (mm)=783
Pr 2008
Eto 2008
Annual ETo (mm)=1219
Annual Pr (mm)=839
Pr 2009
ETo 2009
Annual ETo (mm)=1116.3
Annual Pr (mm)= 565.8
Pr 2010
Eto 2010
ETo(mm)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Dec



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
kWh/m³
35
40
45
50
55
60
65
70
75
80
85
90
95
100
q(l/s)


Nint
Sa(ha)
300
250
200
150
100
50
0
120
100
80
60
40
20
0
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
Sr 2006
Sr 2007
Sr 2008
Sr 2009
Sr 2010
Nint 2006
Nint 2007
Nint 2008
Nint 2009
Nint 2010


30000
25000
20000
15000
10000
5000
0
MCE (kWh)
Mar
Apr
May
Jun
Jul
Aug
Sept
Oct
Nov
2006
2007
2008
2009
2010


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
kWh/m3
60
70
80
90
100
q(l/s)