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

3

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16

17 **Abstract**

18

19 A methodology to optimise the amount of energy consumed in pressurized irrigation
20 systems was presented by (Jiménez-Bello et al. 2010a). These authors proposed
21 grouping pressurized irrigation network intakes, each of the water turnouts resulting
22 from a shared hydrant, into sectors via a genetic algorithm. In the present research, the
23 methodology was applied and validated in a water users association. Several energy
24 efficiency indicators were calculated and compared during five consecutive seasons
25 (2006-2010). The first two seasons, when the methodology was not employed, were
26 used as reference for the results obtained from 2008 onwards, when the methodology
27 was applied to the management of irrigation network. Results obtained in seasons 2008
28 to 2010 showed that the average energy savings were 16% in comparisons to the 2006
29 season. However, it should be noted that the potential, theoretical savings, could have
30 been as high as 22.3% if the modelled grouping networks would have been accurately
31 followed. There was in fact some discrepancy between the theoretical model outputs
32 and the final groupings due to some intake restrictions. In addition, during the irrigation
33 campaigns, the number of irrigation intakes that operated within each sector was not
34 always equal to the modelled sectoring, a fact that reduced the overall water users
35 association energy efficiency. This occurred particularly during rainy periods, when
36 some users deliberately decided to close their manual irrigation intakes valves. Overall,
37 results showed the potential of the validated methodology for optimising energy use.
38 However, the final overall system efficiency might depend on specific constraints that
39 need to be taken into account when attempting to use model output predictions.

40

41

42 **1. Introduction**

43

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

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

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

63 With this objective in mind, Rodriquez et al (2009) studied the potential savings in a
64 case study by simulating the change of the operation system from on-demand (no
65 restrictions) to scheduled periods. It was concluded that energy savings could be as high

66 as 27%. However, there is still some additional improvement potential because in
67 Rodriguez et al. (2009) the network sectoring was performed following empirical
68 criteria without employing any energy specific decision support system. More recently,
69 Moreno et al (2010) compared several irrigation schemes operated either on-demand or
70 with scheduled irrigation periods. It was concluded that greater energy savings could be
71 achieved in the networks operated by sectors, where water can only be applied in
72 predetermined periods than in on-demand networks. However, Moreno et al. (2010)
73 highlighted that in the case of irrigation schemes operated in defined periods, it was
74 easier to fall in an inefficient management due to the difficulty of sectoring the network
75 with optimum energy efficient criteria.

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

90 scenario and may lead to the choice of a scenario where the efficiency of irrigation
91 pumping groups is low (Moreno et al 2010).

92 Jiménez -Bello et al (2010a) developed a methodology based on genetic algorithms
93 (GA) and hydraulic models that, for the case of networks regulated by direct injection
94 by pumps, grouped the intakes in efficient sectors in terms of energy. The goal was to
95 optimise energy consumption per irrigation event, i.e. reducing the amount of energy
96 used per m³ of pumped water. As a result, irrigation sectors could be established that
97 minimized energy consumption. Additionally, the head pressure required for proper
98 operation of each irrigation sector was known in advance. The model results showed
99 that the theoretical savings in energy consumption could reach 36%, for the case study
100 tested in that irrigation season (2006). Nevertheless model outputs were not compared
101 with the real energy saving values if the methodology was actually employed.

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

110 **2. List of abbreviations for terms, definition, formulas and** 111 **units**

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

113 ACESr: Annual consumed energy per irrigated area. Relation between the annual
114 consumed energy and the irrigated area during the irrigation season.
115 $\frac{\text{Annual consumed energy}}{\text{Irrigated area}}(\text{kWh ha}^{-1})$.

116 ACEVT: Annual consumed energy per total annual volume of irrigation water
117 delivered. Relation between the annual consumed energy and the total annual volume of
118 irrigation water supply. $\frac{ACE}{VT}$ (kWh/m³).

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

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

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

127 EEPS: Energy efficiency of the pumping system. Average energy efficiency of the
128 pumping system during the irrigation season. $E EPS(\%) = 0.002725 \frac{\sum_{k=1}^n V_k \cdot H_k}{\sum_{i=1}^n E_{ibilled}} \cdot 100$
129 where V_k is the volume supplied by pump k (m³), H_k is the pumping head supplied by
130 pump k (m) and $E_{ibilled}$ is the energy(kWh) consumed by the n pumps.

131 EES¹:Efficiency of the energy supply. Relation between the necessary energy to
132 supply to the system and the actually applied (Abadia et al 2008). $ES = \frac{WHD-WHI}{PHI}$
133 (dimensionless number) where WHD is the water head demanded by the irrigation
134 supplied (m) and WHI is the water head at the source point (m).

135 EES²: Efficiency of the energy supply. Relation between the necessary energy to
136 supply to the system and the actually applied (Moreno et al 2010). $ES = \frac{H_R}{H_B} = \frac{H_R}{PHI}$
137 where H_R is the pumping head demanded by the network (m) and H_B the pumping head
138 actually applied (m).

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

140 FSP: Fixed speed pump.

141 GA: Genetic algorithms.

142 GEE: General Energy Efficiency Global energy efficiency of the WUA, which
143 considers the energy efficiency of the pumping system and the energy efficiency of the
144 distribution network. $GEE = E EPS \cdot E ES$ (dimensionless number).

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

146 MCEVT: Monthly consumed energy per total annual volume of irrigation water
147 delivered. Relation between the monthly consumed energy and the total annual volume
148 of irrigation water supply (kWh m⁻³)

149 Nsect: Number of irrigation sectors.

150 PHI: Pumping head injected by pumping stations (m). Pumping head injected to the
 151 pumping stations with respect to the total volume injected into the network. $PHI =$
 152 $\frac{\sum V_k \cdot H_k}{V_T}$ (m³) where V_k is the volume supplied by pump k (m³) and H_k is the pumping
 153 head supplied by pump k (m³)

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

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

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

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

158 Vs: Total annual volume of irrigation water delivery. Quantified volume of water
 159 supplied to the users at hydrant level (m³).

160 VSP: Variable speed pump.

161 VT : Total annual volume of irrigation water supply. Total volume that is pumped from
 162 the source of water to the reservoirs (m³).

163 VTSa: Annual irrigation water supply per unit. Relation between the total annual
 164 volume of water supply and the total command
 165 area. $\frac{\text{Total annual volume of irrigation supply}}{\text{Total command area}}$ (m³ ha⁻¹)
 166

167 VTSr: Annual irrigation water supply per unit irrigated area. Relation between the total
 168 annual volume of irrigation water supply and the total irrigated area (m³ ha⁻¹)
 169

170 WHD: Water head demanded by the irrigation supplied. Average head demanded by the
 171 irrigation system $WHD = \frac{\sum S_j (Z_j + H_{dj})}{S_T}$ (m) where S_T is the Total surface of the irrigation
 172 area supplied (ha), S_j is the Surface of irrigation area located at constant geographical
 173 elevation j , (ha), Z_j is the elevation of irrigation surface j , (m), H_{dj} is the pressure head
 174 demanded by the on-farm irrigation system located in the irrigation area j (m)
 175

176 WHI: Water head at the intake point. Average head supplied by the pumping Systems.
 177 $\frac{\sum V_i \cdot H_i}{V_T}$ where V_i is the pumped volume (m³) of the pumping system, H_i is the pumping
 178 head (m), and V_T is the total volume supplied by the pumping system (m³)

179 W_{PD} : Estimated energy consumption (, kWh/m³).

180 WUA : Water Users Association.

181 W_{PD} : Estimated energy consumption (kWh/m³).

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191 **3. Material and methods**

192 **3.1 Case study**

193

194 Data were collected at the WUA of Senyera, located in the municipality of the same
195 name in the province of Valencia, Spain (39° 03' N, 0° 30' O). The total area of the
196 Senyera WUA is 125 ha and the WUA consists of 387 plots with an average plot size of
197 3,093 m². A plot is considered part of a WUA if it is connected to an irrigation intake
198 (i.e. each of the water turnouts resulting from a shared hydrant). The system has 52
199 multi-outlet hydrants and a total of 331 intakes. A multioutlet hydrant has several
200 intakes, a common solution adopted by engineers for network design when plot size is
201 small. In this way, network pipe lengths are shorter and more economic. As a result,
202 users connect their sub-units to the water supply system through water intakes. Indeed,
203 the network topology is branched (Fig.1).

204 Water control is carried out by two pumping units: one fixed speed pump (FSP) and
205 one variable speed pump (VSP) monitored by a variable frequency drive (VFD). They
206 operate in a staggered way (Martínez et al. 1996). Both pumps were powered by a 37
207 kW engine with an efficiency of 80% (Bombas Ideal S.A., Massalfassar, Spain) and
208 VFD efficiency of 97% (Power electronics, Valencia, Spain). A more detailed
209 description of the study case can be found in Jimenez- Bello et al (2010a).

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

213 The WUA was managed by a company in charge of the system control,
214 maintenance, irrigation scheduling and payment collection. Users were charged
215 according to their water consumption with a fixed price per m³ of water they used,
216 independently of how much energy was used to supply water. Those users that
217 fertigated paid an extra amount per m³.

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

227

228 **3.2 Methodology description**

229 The sectoring model of Jimenez-Bello et al (2010) was applied to the Senyera
230 WUA, starting in 2008. Briefly, the model allows to group sectors in a way that the sum
231 of the intake flows for a given pressure head, drops in areas where pump efficiency is
232 higher (See Fig 4 in Jimenez-Bello et al 2010a). The required data is a calibrated
233 mathematical model of the irrigation network. This is possible to obtain because the

234 modern irrigation systems dispose of pressure sensors and flow meters that allow the
235 model calibration. The required input parameters are pressure head at hydrant, number
236 of sectors and those parameters related with GA. The decision variables are the possible
237 sectors that each hydrant or intake can belong to. Once the GA model is run, the best
238 solution to the sectoring problem is achieved after some termination conditions, as a
239 maximum generation number. Indeed, this procedure guarantees that irrigation can be
240 carried out at the lowest possible estimated energy consumption (W_{PD} , kWh/m³) and
241 consequently with low annual consumed energy (ACEVT, kWh/m³). However, there
242 were some constraints in the network that influenced the final model sectoring
243 decisions. For example, there were intakes that needed to receive fertilizer collectively,
244 but others had to be individually fertigated. This fact conditioned the network sectoring,
245 because depending on the fertilization user's criterion (individual or collective) intakes
246 were forced to be part of determinate sectors.

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

258 values. The model error for the different scenarios was calculated and reasons for
259 inaccurate results were analysed.

260 **3.3 Energy indicators**

261

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

272 Irrigation seasons were classified according to the General Energy Efficiency
273 (GEE) following the energy audit protocol (IDAE 2008). According to this protocol, a
274 GEE value greater than 50% is considered excellent. If GEE is between 40% and 50%,
275 the WUA is classified as good, $30 < \text{GEE} < 40\%$ is normal, $20 < \text{GEE} < 30\%$ is acceptable
276 and if $\text{GEE} < 20\%$ performance is not acceptable.

277

278 **4. Results and discussion**

279 **4.1 Climatic characterization of the irrigation seasons and** 280 **water applications**

281

282 The average annual Reference Evapotranspiration (ET_o, Allen et al 1998) for the
283 five irrigation seasons was 1,117 mm and its standard deviation was 50 mm. The
284 average annual effective rainfall (Pr, Dastane 1998) was 580 mm and its standard
285 deviation was 220 mm. While the ET_o was fairly constant during the five irrigation
286 seasons (Fig 2), rainfall rates showed relevant interseasonal variability. Year 2006 was
287 the driest one with only 382 mm of total precipitation. On the other hand, seasons 2007,
288 2008 and 2009 had rainfall above the ten-year average (614 mm). On a seasonal basis,
289 rainfall was mostly concentrated during September and October. (614 mm).

290 Water application varied among seasons from 4,238 m³/ha in 2010 to 3,323 m³/ha
291 in 2008. These variations were mostly due to the different seasonal rainfall (Fig 2).
292 Water application in the study area resulted similar to those commonly applied in well
293 watered citrus trees grown in the same area (González-Altozano and Castel 1999). In all
294 seasons, the main system water delivery efficiency (ED) was very high, being 99% for
295 the first season and 98% for the rest of seasons (Table 2).

296

297 **4.2 Energy performance assessment**

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

305 During 2006, the annual consumed energy per total volume of irrigation water
306 delivered (ACEVT) was 0.310 kWh (Table 3). The sector flows fell outside the
307 optimum pump working conditions. In 2007, the ACEVT was 0.279 kWh, representing
308 9% in energy conservation respect to 2006. Without carrying out any intended action to
309 reduce energy consumption, savings resulted from increasing the number of intakes,
310 leaving unchanged the number of sectors. As a consequence, the increased flows
311 resulted in a more efficient pumping. Starting in 2008, GA sectoring was applied. The
312 ACEVT decreased by 14.3 % respect to 2006 and by 4.5% respect to 2007. In 2009, the
313 savings were 16.0% respect to 2006 and 6.6% respect to 2007. Similar energy savings
314 were achieved in 2010.

315 Using GEE^1 as an indicator, as suggested by Abadia et al (2008), energy
316 performance was classified as unacceptable for all studied seasons. This was due to the
317 low energy efficiency of the pumping system (EEPS), caused by high pipe head losses.
318 These were 36 kPa/km on average. This feature is difficult to improve once the network
319 has already been built. In the study case, a decrease of 50 kPa in water head intake
320 (WHI) represents a 10% reduction in energy consumption per unit volume of water. As
321 suggested by Moreno et al (2010) GEE^2 can be also computed without taking into
322 account the design factors. This is considering the efficiency of the energy supply (EES)
323 as the ratio between the necessary energy to supply the system and the actually applied
324 energy. When using the GEE^2 indicator, the WUA energy performance rank improved
325 from a normal classification in the 2006-2007 seasons to a good one for the years 2008-
326 2010.

327

328

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

354 October 2009, the coefficient of variation (CV) for number of irrigation hours by intake
355 was 2.27, much higher than during the rest of the year when it was about 0.50 (Table 4).
356 This led to a MCEVT of 0.315 kWh, while the average annual MCEVT was 0.260
357 kWh. On the other hand, in 2010, precipitation was more regular throughout the season
358 (Fig. 2). The only month without rain was July. As a consequence, the CV for number
359 of irrigation hours by intake was more constant along the season (Table 4). Despite the
360 highest MCEVT generally occurred then during the rainy months, in that period the
361 irrigation volumes applied were low, and consequently the energy consumption during
362 those periods did not greatly affect the total ACEVT. In fact, it should be noted that
363 70% of total annual energy consumption occurred during the June-September interval
364 (Fig. 5).

365 Overall the results presented indicated that in commercial situations, the theoretical
366 sectoring proposed by the model cannot be always strictly followed. This highlights
367 some of the difficulties of applying model predictions in a real case, where final
368 decisions are often motivated not only by technical limitations but also by empirical
369 reasons. The first step to improve the overall WUA energy efficiency is scheduling
370 irrigation in order to match the crop water requirements. In addition, users should be
371 more confident in the irrigation scheduling programmed by system managers. Last, but
372 not least, the billing system used could also play a major role for energy and water
373 saving. In this WUA, similarly to many others existing in this region, users were
374 charged a fixed amount per m³ of irrigation water they used regardless the energy
375 needed to supply the water. Therefore the users were not motivated to obtain energy
376 savings and, in addition, they were often not conscious of the repercussion of their
377 deliberate actions of closing their valves. Another irrigation water billing system should

378 be considered taking into account the amount of both water and energy used by each
379 users.

380 As previously mentioned, this case study was characterized by central
381 fertigation, with the option to let users decide if they wanted to receive fertilizer or not.
382 This situation frequently happens in the WUAs in the area and it is mostly due to large
383 variations between plots of the citrus cultivars used. The varieties used often have
384 different phenological growth cycles what might imply different seasonal fertigation
385 requirements. Because fertigating and non-fertigating intakes could not be grouped in
386 the same sectors it was not possible to achieve better energy performance, and the
387 obtained solution for the optimization problem is not as good as without this restriction
388 (Jimenez.Bello et al 2010a). In order to evaluate the potential energy savings without
389 any restriction, W_{PD} was calculated for six irrigation sectors with no restrictions for the
390 intakes. The result was of 593 kWh and ACEVTp of 0.232 kWh/m³, which would have
391 meant an improvement ranging between 12.9 and 7.4% compared to ACEVTp for the
392 period 2008-2010 described in Table 3. Assuming an error of - 4% in the estimation, the
393 potential energy saving could have been 22.3 % and 13.4 % lower with respect to years
394 2006 and 2007, respectively.

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

402 station. The drawback is that the optimum water flow range of 44-50 l/s (i.e when only
403 a VSP operates, Fig 3) is lost.

404 **5. Conclusions**

405 In an irrigation network operated on turns the grouping of irrigation intakes into
406 optimal sectors from the energy point of view using GA produced savings of around
407 16% in the energy performance. These savings could have been higher (22%) if there
408 had not been restrictions that limited the grouping of intakes into sectors. Indeed the
409 reliability of the methodology lies in the accuracy with which it determines the intake
410 number that will operate simultaneously and their flow rate. If the intake number that
411 actually operates differs from intake number for which sectoring was modelled the
412 energy efficiency will decrease. The analysed methodology has proved its practical
413 application to manage irrigation networks that operate by turns and monoculture
414 predominates but it could be applied to networks operated on demand with restrictions
415 and different kind of crops to analyse and compare the obtained results.

416

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422

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502 the analyzed seasons.

503

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

506

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

507

508

509 **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(m³)	354046	352022	349263	426874	448083
Vs(m³)	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

511 **Table 3** Comparison between estimated energy consumption and real consumption for
512 each operational sectoring. Each column represents predicted irrigated surface (Sr_p , ha)
513 number of predicted operating intakes (N_{PInt}), irrigated surface (Sr ,ha), fertigated surface
514 (Sf , ha) number of irrigation sectors (N_{sect}), number of sectors non fertigated
515 ($N_{Sectwfert}$), predicted annual consumed energy per total annual volume of irrigation
516 water delivered $ACEVT_p$ (kWh/m^3), annual consumed energy per total annual volume
517 of irrigation water delivered ($ACEVT_R$, kWh/m^3) and Error model (Er , %).
518

Season	Sr_p (ha)	N_{PInt}	Sr (ha)	N_{OI} _{nt}	Sf (ha)	N_{sect}	N_{Sect} _{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 °Oct 2009 Dec	107.4	289	103,1	266	0	5	5	0.244	0.263	-7.2
2010 Jan 2010 Jun	104.7 5	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

519
520

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

524

		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/m³)		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/m³)	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/m³)	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/m³)	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/m³)	0.260	0.252	0.247	0.285	0.257	0.268	0.236	0.267	0.257

525

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527

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529 Fig 1 Network sectoring for water use association of Senyera during the 2010 season.

530 All the irrigated subplots were grouped into six irrigation sectors (S1 to S6).

531 Fig 2 Monthly Reference evapotranspiration (ET, mm) and precipitation (Pr, mm)

532 during the entire experimental period, seasons 2006 to 2010.

533 Fig 3 Relation between the energy cost of irrigation water supplied (kWh/m^3) and the

534 demanded flow by each irrigation sector (l/s) for the pumps of the study case, a variable

535 speed pump and one fixed speed pump when is set a pumping head of 400 kPa.

536 Fig 4 Monthly irrigated area (S_r , ha), number of predicted operating intakes (NPint) and

537 number of operating intakes (NOint) for each irrigation season.

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

539 Fig 6 Relation between volume of irrigation water supply (kWh/m^3) and the demanded

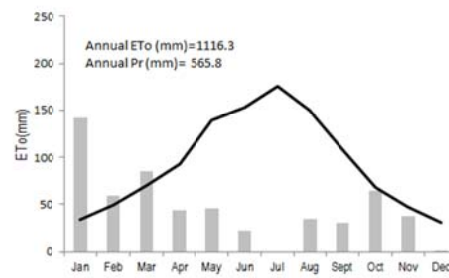
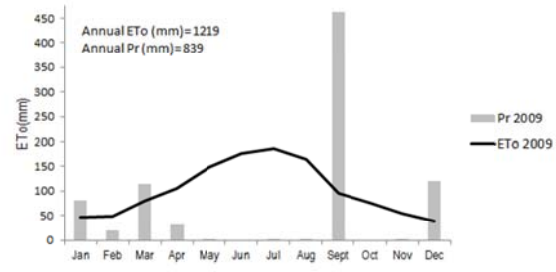
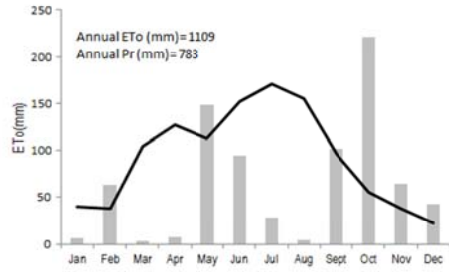
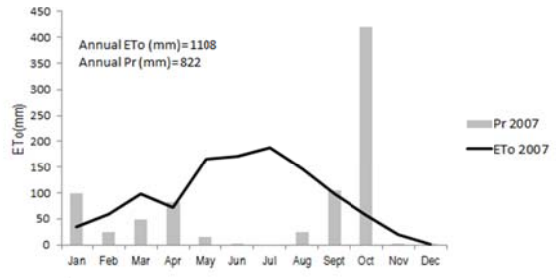
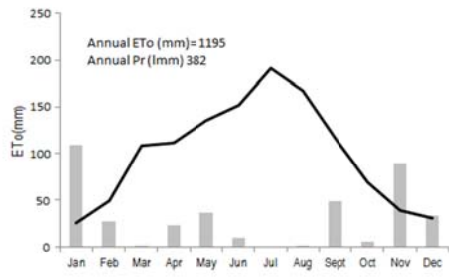
540 flow by each irrigation sector (l/s) for the pumps of the study case, assuming two

541 variable speed pumps, when is set a pumping head of 400 kPa.

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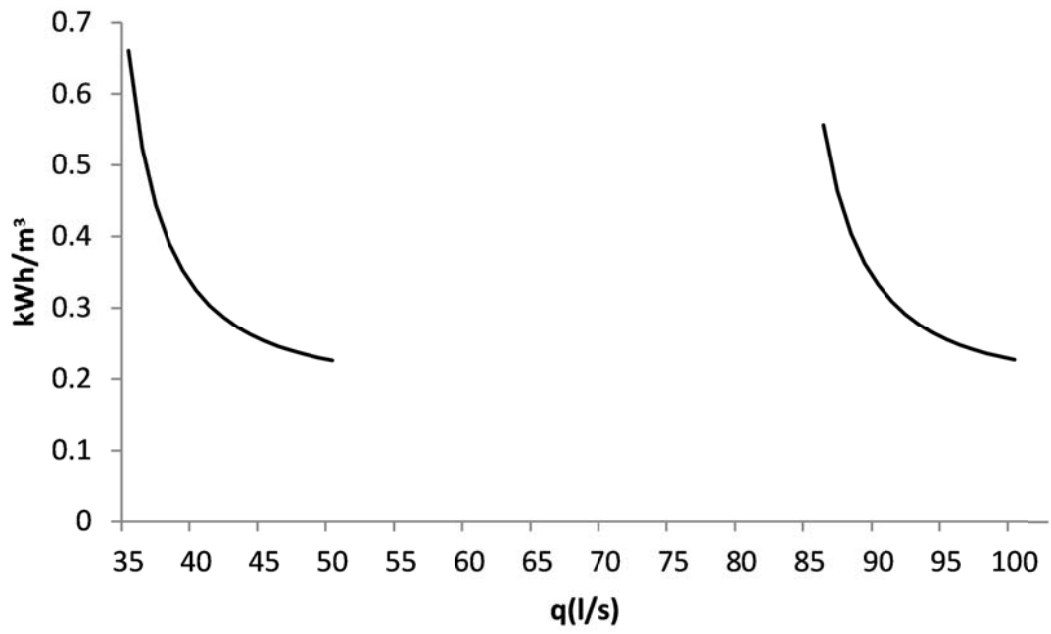


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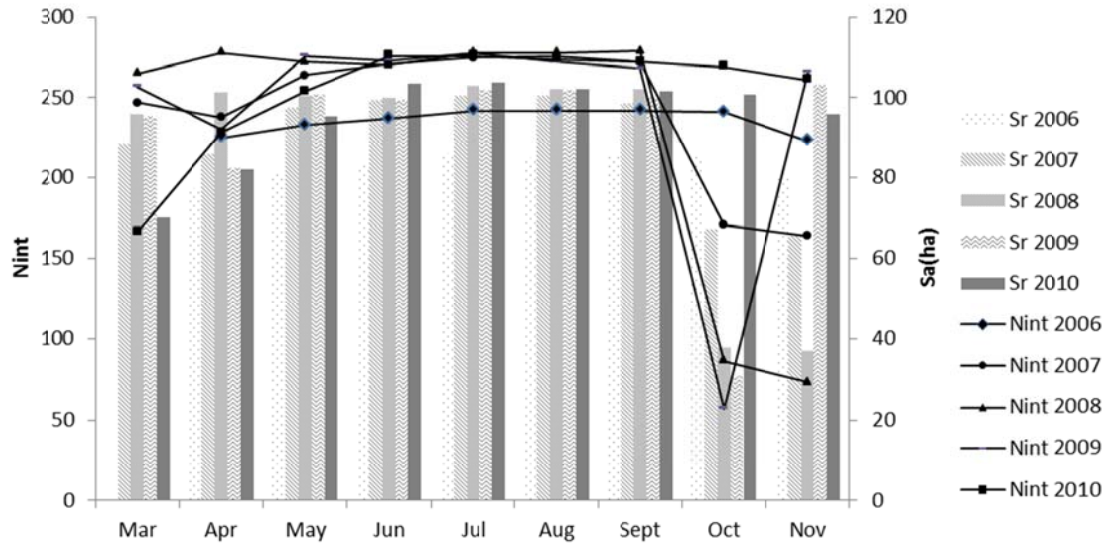


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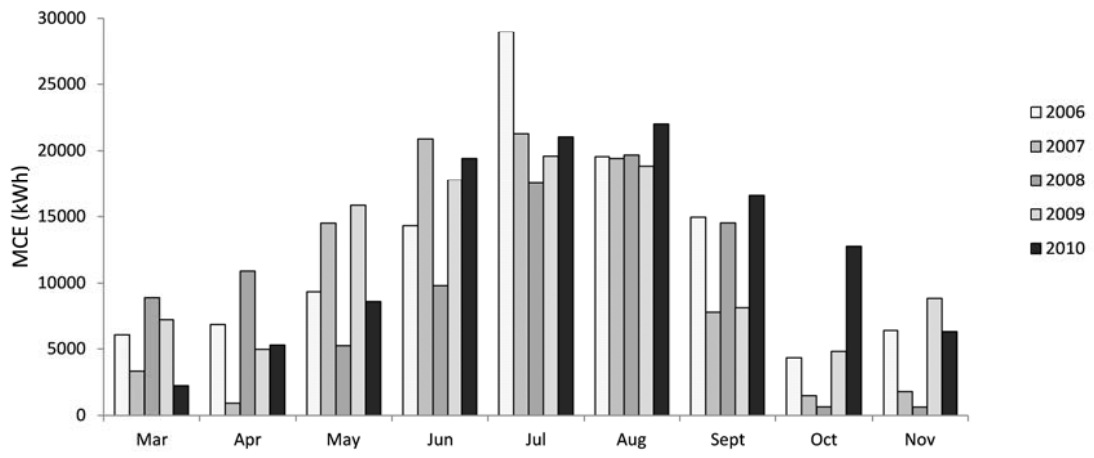
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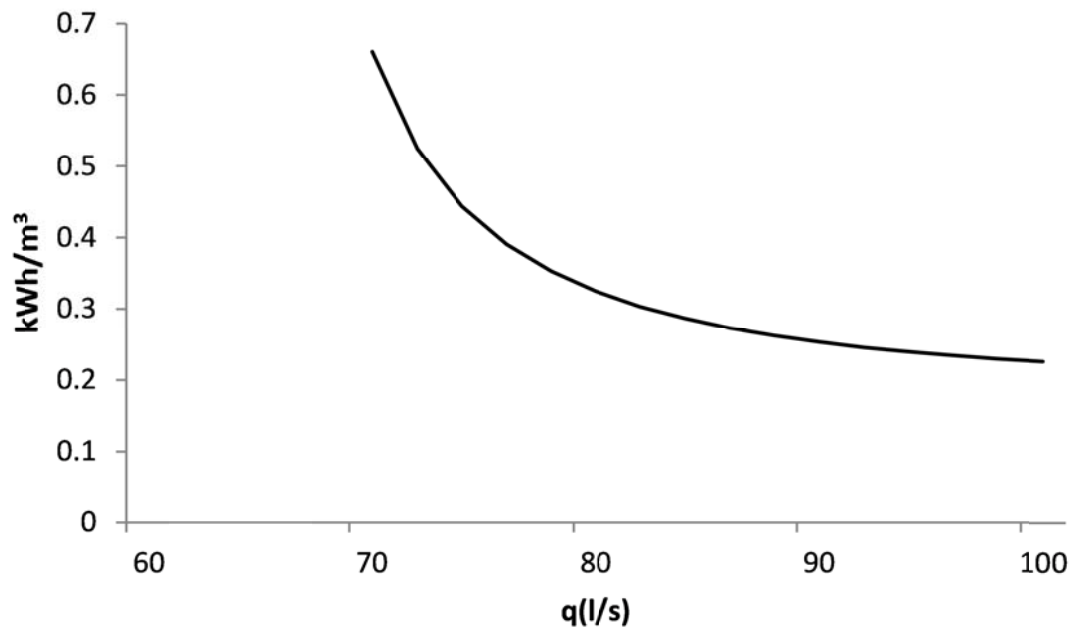
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