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Measurement and improvement of the energy efficiency at pumping stations

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Rational and efficient use of energy is essential for sustainable development. In Spain, as in many other countries, electrical energy is the main source of energy in irrigation; therefore, research with the aim of increasing the efficient use of electrical energy should be arranged.

The goal of the research performed was to develop a model for analysing energy efficiency at pumping stations, which permitted the determination of the sequence of pump activation that minimised the energy cost for real demand scenarios. The model was calibrated for the pumping station of Tarazona de La Mancha (Spain) by measuring hydraulic and electrical parameters for each pump.

One of the main aspects to consider when carrying out the energy cost analysis at pumping stations is to estimate the discharge distribution throughout the irrigation season. The optimum sequence of activation of pumps was the option that best fitted the discharge distribution in terms of efficiency.

This paper illustrates that simple electrical and hydraulic measurements at pumping stations can help to improve their management. In the case study, a cost saving of 16% was obtained by changing the regulation of the pumping station. In only one season, the additional costs of applying this methodology (electrical network analysers, flowmeters, and pressure transducers) would have been recovered with the energy efficiency improvement. Results could vary in other cases depending on the discharge distribution and the working points of the pumps.

1. Introduction

Rational and efficient use of energy is essential for sustainable development. In Spain, as in many other countries, agriculture requires high energy consumption, mainly for machinery and irrigation. This consumption is increasing due to the irrigation energy requirements when using pressurised irrigation systems (sprinkler and drip irrigations). These systems permit easy management and automation, and a proper adjustment to cropping pattern changes, depending on crop market trends. Research with the objective of increasing the efficient use of electrical energy in irrigation should be developed.

Some research has been carried out to optimise the total cost (investment and energy costs) in pumping stations (Moradi-Jalal *et al.*, 2003, 2004; Pulido-Calvo *et al.*, 2003a; Planells *et al.* 2005). They attempted to obtain the combination of variable and fixed-speed pumps that best minimised costs. These studies considered the theoretical characteristic curves of the pumps, which means only considering the pump and

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Nomenclature

C_i	average energy cost for the discharge interval *I*, €
C_j	energy cost in the tariff period *j*, €
f_i	frequency of every discharge *i* in the irrigation season
H	pressure head, m
HU	hydrogeologic unit
i	discharge increment
j	tariff period
k	calibration coefficient, %
N_{abs}	measured absorbed power, kW
n	number of flow values for carrying out the calibration process
N_{Qi}	total absorbed power by the pumping station for every discharge i, kW
PLC	programmable logic controller
Q	discharge, $l\,s^{-1}$
t_{ij}	time that discharge *i* occurs in the tariff period *j*, hours
$\eta_{b_{Qi}}$	theoretical pump efficiency for Q_i discharge, %
η_c	cables efficiency, %
η_l	efficiency related to head losses in pump pipes, %
η_m	motor efficiency, %
η_p	pump efficiency, %
η_t	total pumping station efficiency, %
$\eta_{tm_{Qi}}$	total efficiency measured for Q_i discharge, %
η_v	variable speed drive efficiency, %

motor efficiencies and not the efficiency of other components of the pumping station. With these methodologies, energy saving was mainly obtained by means of the improvement of the sequence of activation of the pumps. In fact, Moradi-Jalal *et al.* (2003) emphasised that the major portion of the cost reduction results from energy savings through employing a better operation rule.

The goal of the research performed was to develop a model for analysing energy efficiency at pumping stations, which permitted the determination of the sequence of pump activation that minimised the energy cost for real demand scenarios. The model was calibrated for the pumping station of Tarazona de La Mancha (Spain) by measuring hydraulic and electrical parameters for each pump.

2. Methodology

2.1. *The case study*

The pumping station supplied water to an on-demand irrigation network. Water obtained from five wells, located in the Júcar basin (Hydrogeologic Unit (HU) 08.29), was pumped into a 23,000 m^3 reservoir. The pumping station, consisting of ten 103 kW pumps (Table 1; Fig. 1), delivered the water from the reservoir to the irrigation network. One of the pumps is reserved and works only when one of the fixed-speed pumps breaks down. A pressure head of 62 m (manometric regulation) was required to attempt to guarantee a pressure head of 45 m in all the hydrants of the network.

The pumping station had two pumps with variable speed drives and the remainder with fixed speed drives. All pumps were controlled by a programmable logic controller (PLC), which received data from a pressure transducer located in the pumping station collector. This PLC controls the sequence of activation of the variable and fixed-speed pumps to maintain the set pressure (62 m). Permanent solid-set sprinkler irrigation systems were used for 95% of the area, the rest being irrigated by drip irrigation systems.

In this case, each pump discharged water to a collector from which several pipes distributed the flow into the network. Under these conditions, total discharge (Q) could be obtained by measuring the electrical parameters and by obtaining the efficiency curve of the pumping station, as described in a later section.

Table 1 – Characteristics of the pumps installed in the irrigable area of Tarazona de La Mancha

Brand	INDAR®
Type of pump	Submerged electrical pump
Model of pump	345–2
Model of motor	25–30
Power (kW)	103
Frequency (Hz)	50
Speed (r.p.m.)	2900

2.2. *Measured data*

Electrical parameters. Current and voltage data of each pump were measured every 10 min to obtain power and the power factor. Two portable supply network analysers, each one placed upstream of each variable speed drive, and a set

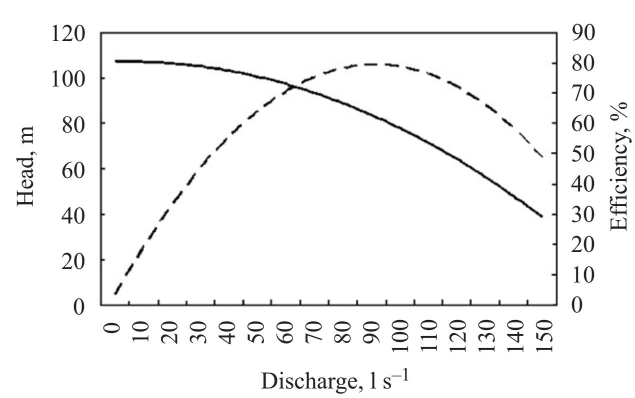

Fig. 1 – Theoretical characteristic curves Q–H and Q–η of the pumps.

network analyser, located next to the low-voltage switch, were used to measure all pumping station electrical parameters. These instruments measure, calculate and store to memory the main parameters of three-phase electrical supply networks such as phase-to-neutral voltage, current, frequency, power (active, reactive and apparent), power factor, energy and quality parameters (harmonics, flickers, etc.). They are portable and easy to install. The measurement error of these instruments is 1.5%.

Hydraulic parameters. Discharge at each pump was measured with a portable ultrasonic flowmeter (measurement error lower than 2.5%). An extra portable ultrasonic flowmeter was used to measure both variable speed pumps simultaneously during a 3 week period. It was shown that they were working with the same speed and discharge. Therefore, only measuring one of them during the entire irrigation season was enough to control both variable speed pumps. For the fixed-speed pumps, discharge was measured every 2 weeks to monitor the variability in the discharge of these pumps, which was found to be negligible. Pressure head was measured every minute with a pressure transducer and a datalogger (measurement error lower than 1%).

Pumping station data could only be collected during the 2004 irrigation season.

Once power is measured for different discharge-pressure head conditions, the pumping station efficiency can be determined. The components of the pumping station efficiency are shown in as.

$$\eta_t = \eta_p \cdot k = \eta_p \cdot \eta_m \cdot \eta_c \cdot \eta_v \cdot \eta_l, \tag{1}$$

where: $\eta_t =$ total pumping station efficiency, $k =$ calibration adjustment coefficient, $\eta_p =$ pump efficiency, $\eta_m =$ motor efficiency, $\eta_c =$ cables efficiency, $\eta_v =$ variable speed drive efficiency, and $\eta_l =$ efficiency related to head losses in pump pipes.

2.3. Development of pumping station simulation model

The developed pumping station simulation model reproduces the behaviour of all of the pumps that compose the pumping station for different sequences of activation of the pumps. This model was implemented in Microsoft® Excel and considered the characteristic head pressure and efficiency curves of the pumps (Q–H and Q–η). The model was run considering both the discharge interval of $1\,\mathrm{l\,s^{-1}}$, and the required pressure for each discharge. Pressure head was a constant value in case of manometric pumping station regulation, or a variable value in case of other pumping station regulation. Using affinity laws for those pumps controlled by variable speed drivers, and the working point (Q–H) for fixed-speed pumps, the pumping station efficiency for each demanded flow could be obtained. This model is useful for establishing the best working condition of pumping stations, for evaluating their efficiency and for studying the effect of pump ageing on pumping station behaviour. To obtain an accurate result, the pumping station model must be calibrated with measured data.

2.4. General methodology for carrying out the calibration of hydraulic models

Hydraulic model calibration is a two-step process: (1) comparison of measured and calculated flows and pressures; and (2) adjustment of initial parameters of the model, based on theoretical relationships, to improve the fitting of the measured and calculated values (Walski, 1983). In the pumping station calibration process, several aspects should be considered such as the following: pump and motor ageing; efficiency of cables, pumping pipes and controllers; and failures when acquiring pumping station data.

The steps for carrying out the calibration process are as follows (García-Serra 1988):

1. *Data acquisition*: One of the most important steps to obtain a useful hydraulic model is to carry out a proper data measurement. These data can be obtained from the pumping station design document and by checking the pumping station conditions in the field. In this case, type (characteristic curves) and number of installed pumps, number of variable and fixed-speed pumps, and the pumping station regulation were considered.
2. *Inserting data into the model*: To obtain an accurate model, as many measured data as are available should be inserted. However, some simplifications can be considered in order to ease the development of the model. In this step, the standard characteristic curves and the regulation pressure (manometric regulation at 62 m) were input. The model differentiates between the pumps that work with variable speed and those that work with fixed speed. To run the model with standard data, only pump and motor efficiencies were considered and not the rest of the components of the pumping station efficiency [Eq. (1)].
3. *Provisional running of the model*: The model should be run using only the pump and motor efficiencies. Thus, the characteristics of the system, relative to these efficiencies and for some specific working conditions, could be obtained.
4. *Pumping station data measurement*: To study the real behaviour of the pumping station, accurate data should be collected. In this case, measured data were discharge and pressure head as previously described.
5. *Calibration of the model*: Parameters that should be considered in the calibration process are the pumping pipe head losses, cable efficiency, variable speed drive efficiency and the efficiency of the other components of the pumping station [Eq. (1)]. With the calibrated characteristic curves of each pump, the efficiency curve for different sequences of activation of the pumps could be obtained.

Calibration procedures can be divided into experimental and optimisation procedures (Batista *et al.*, 2000; Abadía, 2003; Wu *et al.*, 2004). The experimental procedures are based on test-error methodology, which means changing calibration parameters for obtaining the values that have the best agreement with those measured. This procedure requires calibration in a working condition and validation for other working conditions. The optimisation techniques use non-linear optimisation methods, considering different parameters as variables, for minimising the difference between the measured data and the theoretical results of the model (Dias *et al.*, 2000).

In this study, a quasi-Newton optimisation method included in Solver tool (Microsoft® Excel) was applied to calibrate the simulation model. Flows from 0 to 120 l s^{-1} (in increments of 1 l s^{-1}) were used for calibrating each pump. The difference between the theoretical and measured values of the efficiency, for each discharge value, was minimised by adjusting the k value [Eq. (1)]. The objective function was:

$$\left[\left(k_{Q1}\eta_{b_{Q1}} - \eta_{tm_{Q1}}\right)^2 + \left(k_{Q2}\eta_{b_{Q2}} - \eta_{tm_{Q2}}\right)^2 + \cdots + \left(k_{Qi}\eta_{b_{Qi}} - \eta_{tm_{Qi}}\right)^2 n\right]^{0.5}, \tag{2}$$

where i = discharge index (between 1 and n), n = number of flow values for carrying out the calibration process η_{bQi} = theoretical pump efficiency for Q_i discharge, and η_{tmQi} = total efficiency measured for Q_i discharge.

In this case, the number of discharge values for carrying out the calibration process (n) was 18 for each variable speed pump.

2.5. Application of the calibrated pumping station model

Developing the calibrated pumping station model permits an energy cost analysis and the determination of the sequence of pump activation that best minimises this cost. The following aspects were considered in performing the energy cost analysis for different types of sequences of pump activation:

- Discharge distribution throughout the irrigation season.
- Pumping station efficiency for each demanded discharge and for each type of sequence of pump activation.
- Energy cost (€ kW h^{-1}).

The determination of the discharge distribution throughout the irrigation season has been the subject of several studies, from simple soil moisture balance (Lamaddalena, 1997; Khadra, 2004), to complex forecasting tools such as neural networks (Pulido-Calvo *et al.*, 2003b). In this study, discharge distribution was obtained by measuring electrical data in the pumping station every 10 min. These electrical data were related to flow data by means of the total pumping station efficiency [Eq. (3)], obtaining the curve discharge-absorbed power (Q–N_{abs}). To obtain the discharge histogram, intervals of discharge of 10 l s^{-1} were utilised. A monthly histogram, and one for the entire irrigation season were obtained.

$$N_{abs} = \frac{9.81QH}{\eta_t}, \tag{3}$$

where Q = discharge (m^3 s^{-1}), H = pressure head (m), and η_t = total pumping station efficiency.

Energy cost (€ kW h^{-1}) was established from the contract between the electrical company and the irrigation society (Table 2). In many countries, such as Spain, electrical energy costs vary depending on the hour, day, week and month that energy is consumed. To each discharge interval, an average energy cost was assigned depending on the proportion that the discharge was within every tariff period throughout the entire irrigation season

$$C_i = \frac{\sum_{j=1}^{6}(t_{ij}C_j)}{\sum_{j=1}^{6}t_{ij}}, \tag{4}$$

where C_i = average cost of kWh for the discharge interval i (€ kW h^{-1}), t_{ij} = time that discharge i occurs in the tariff period j, and C_j = energy cost in the tariff period j.

Thus, the annual energy cost (E) is expressed as follows:

$$E_i = \sum_{i=1}^{n} N_{Qi} f_i t_i C_i, \tag{5}$$

where N_{Qi} = the total absorbed power by pumping station for every discharge i, and f_i = frequency of every discharge i in the irrigation season.

For each type of sequence of pump activation, and considering the discharge distribution during the irrigation season, energy consumption and its cost were compared. From this, the sequence of activation of the pumps that best minimised the energy cost was established.

3. Results

3.1. Measurements of pumps and calibration of the pumping station

Through the analysis of measured data, the efficiency curve for variable speed pumps was obtained (Fig. 2). This curve includes all the components of the efficiency [Eq. (1)]. Fitting the curve was achieved by means of Statgraphics® 5.0 for different adjustment degrees. Residuals were similar for all adjustments, so adjustment to a second degree polynomial was used. The theoretical pump efficiency (η_p) was always higher than the total measured efficiency (η_t) because the latter considered the rest of the components of the efficiency (Fig. 3).

Results of the calibration process illustrate that the calibration coefficient k increases with flow (Fig. 4), which means that the rest of components of efficiency (η_c, η_v, and η_l) increase when flow increases. Even when theoretical motor

Table 2 – Prices of installed and consumed power contracted in the irrigable area of Tarazona de La Mancha

Period[a]	1	2	3	4	5	6
Installed power (€ kW year^{-1})	10.84	5.43	3.98	3.98	3.98	1.81
Consumed power (€ kW h^{-1})	0.090909	0.080073	0.076364	0.069171	0.062615	0.042342

[a] Tariff period depends on the hour, day, week, and month that energy in consumed.

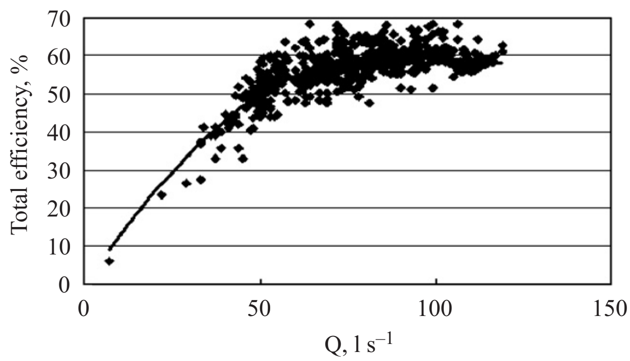

Fig. 2 – Measured efficiency curve of the variable speed pumps.

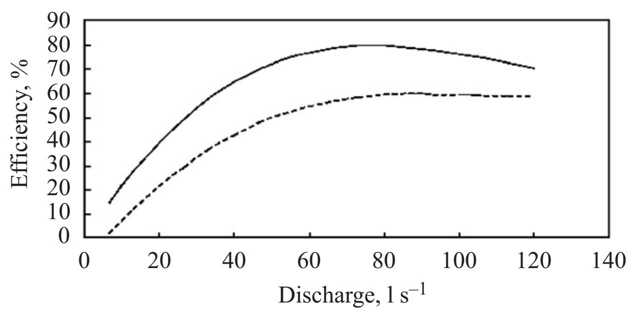

Fig. 3 – Comparison between theoretical (——) and measured (- - - -) efficiency curves of the variable speed pumps.

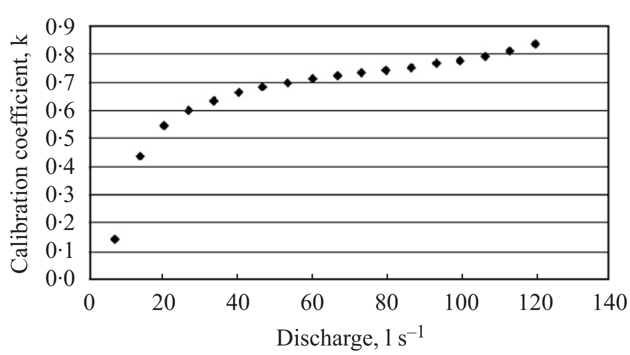

Fig. 4 – Progession of the calibration coefficient "k" with discharge.

and pump efficiency (Fig. 3) decrease with high flow (90–120 $l\,s^{-1}$) the k coefficient increases due to an improvement in the rest of the components of efficiency.

From measured data, it was confirmed that fixed-speed pumps always worked in the same working point for the regulation pressure head (62 m), with a discharge of around 120 $l\,s^{-1}$ (Table 3). The relation between theoretical and measured data for fixed speed pumps are shown in Fig. 5 (Q–H points) and in Fig. 6 (Q-η points). The majority of the pumps fit with the theoretical curve, but P3 and P6 did not. This could be due to the ageing of these pumps, water losses in pumping pipes or head losses in single elements between the pump and the collector. In this pumping station, it is common to find water losses in the joint between the pump and the pumping pipe.

Table 3 – Discharge and pressure measurements and their descriptive statistics of fixed-speed pumps of the irrigable area of Tarazona de La Mancha

		Average	Max	Min	SD	CV
Pump 2	η, %	66	67.7	64.5	0.9	1.4
	Q, $l\,s^{-1}$	121.7	125	120	1.4	1.2
	H, bar	6.2	6.3	6.1	0	0.7
	P, kW	111.9	112	111.6	0.1	0.1
Pump 3	η, %	58.6	60	57.6	0.6	1
	Q, $l\,s^{-1}$	98.4	99	98	0.5	0.5
	H, bar	6.2	6.4	6.1	0.1	0.8
	P, kW	102.4	102.6	102.2	0.1	0.1
Pump 4	η, %	68.1	69.9	66.3	0.8	1.2
	Q, $l\,s^{-1}$	124.9	129	124	1.1	0.9
	H, bar	6.2	6.3	6.1	0.1	0.9
	P, kW	111.3	111.6	111.2	0.1	0.1
Pump 5	η, %	65.2	66.1	64.2	0.7	1.1
	Q, $l\,s^{-1}$	122.1	125.5	121.2	0.6	0.5
	H, bar	6.2	6.3	6.1	0.1	0.9
	P, kW	112.3	112.5	112.1	0.1	0.1
Pump 6	η, %	59.8	61.1	58.6	0.5	0.9
	Q, $l\,s^{-1}$	111.4	114	109	1	0.9
	H, bar	6.1	6.2	6	0	0.6
	P, kW	112.2	112.7	111.8	0.2	0.1
Pump 7	η, %	65.5	66.2	64.7	0.4	0.6
	Q, $l\,s^{-1}$	119.8	120	119	0.4	0.3
	H, bar	6.2	6.3	6.1	0	0.5
	P, kW	111.5	111.7	111.3	0.1	0.1
Pump 8	η, %	65.6	66.5	64.8	0.4	0.6
	Q, $l\,s^{-1}$	128.1	129	127	0.7	0.6
	H, bar	5.9	6	5.8	0	0.6
	P, kW	113.1	113.7	112.5	0.2	0.2

η, pump efficiency; Q, discharge; H, head pressure; SD, standard deviation; CV, coefficient of variation.

3.2. *Results of energy study using calibrated pump curves*

Fig. 7 shows the efficiency curve of the pumping station using calibrated curves of each pump and considering the current sequence of pump activation (two variable speed pumps working simultaneously and the rest with fixed speed). When calibrated curves are used, an overlapping of lines appears because the total efficiency of the pumping station depends on which fixed-speed pumps are activated at each moment. Thus, when a pump with low efficiency (e.g. pump 3) is activated, the total efficiency of the pumping station is lower than when a fixed-speed pump with higher efficiency (e.g. pump 4) is activated.

Some studies have concluded that the best regulation is achieved by using two variable speed pumps working sequentially (Planells *et al.*, 2005). This occurs when the pump

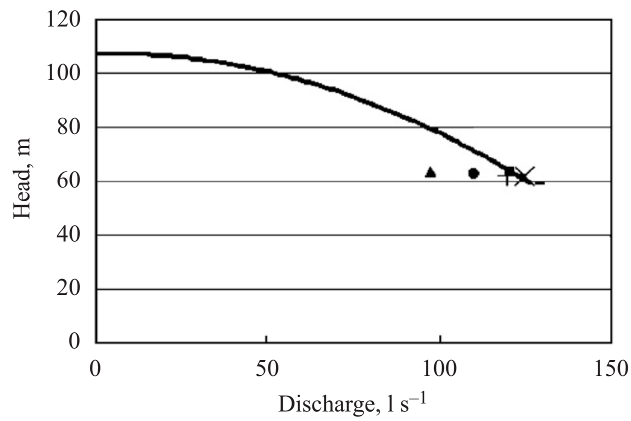

Fig. 5 – Measured working points of the fixed speed pumps (■P2 ▲ P3 × P4 —P5 ●P6 +P7 –P8) and theoretical characteristic curve Q–*H*.

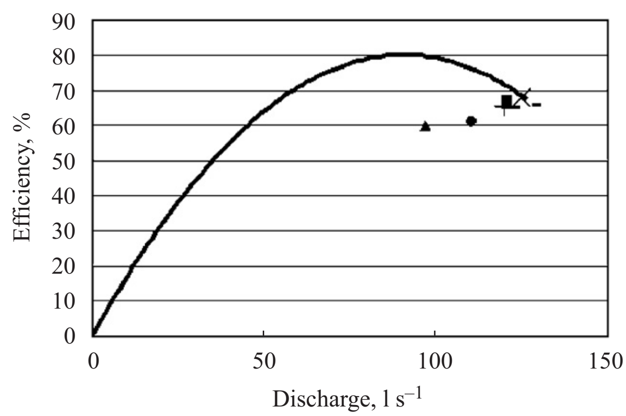

Fig. 6 – Efficiency point of each fixed speed pump (same symbols than caption of Fig. 5) and theoretical characteristic curve Q–η.

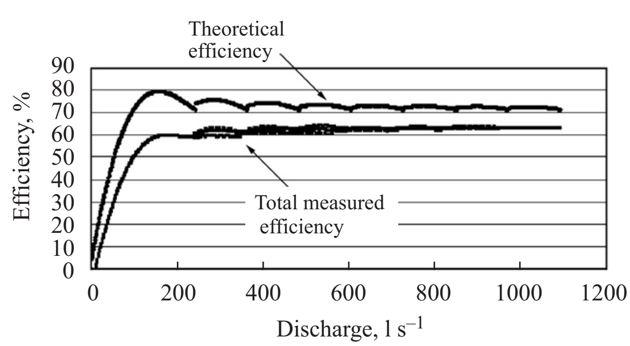

Fig. 7 – Theoretical and measured efficiency for different discharges considering the present regime.

type and the working conditions offset the investment cost of the extra variable speed drive with the improvement in energy efficiency. Therefore, the model was run considering this sequence of activation and using the calibrated pump curves. A comparison between both types of regulation is shown in Fig. 8. With this second option, efficiency improvement for low flows was obtained.

To determine the energy consumption in pumping stations, discharge distribution during the entire irrigation season was considered. In this case, cumulative frequencies of discharges are shown in Fig. 9 for every month and for the entire irrigation season of 2004. Fig. 9 shows that high discharges were lower in frequency than low discharges, mainly between 40 and 90 l s^{-1} (6–10% of maximum discharge). In June, July and August, high discharges were more frequent, but discharges between 40 and 90 l s^{-1} still predominated.

In order to determine the economic saving when a different sequence of pump activation was carried out, it was necessary to obtain the relation between energy price and discharge [Eq. (4)]. The energy price depends on the tariff period in which each discharge was included. Low discharges were associated with high energy prices (Fig. 10) because there were a higher proportion of these types of discharges within the expensive tariff period.

Considering the discharge distribution, the average absorbed power during the entire irrigation season was calculated for each different sequence of pump activation. Even regulation considering only one variable speed pump obtained a better result than the current regulation, because it obtained better efficiency for low discharges. Energy analysis results in an energy saving of 14% and an economic saving of 16% when the pumping station was controlled by two variable speed drives working sequentially and not simultaneously. The average energy bill that this irrigation

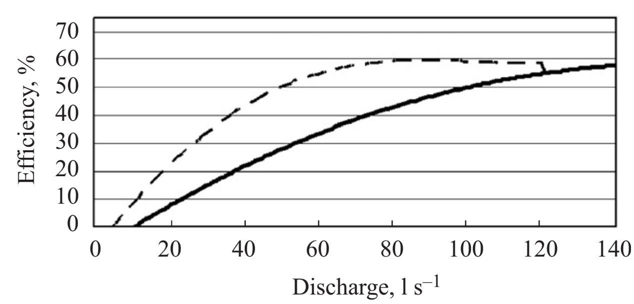

Fig. 8 – Comparison between calibrated efficiency curves considering an activation of the variable speed pumps in a sequential (—) and simultaneous (– –) manner.

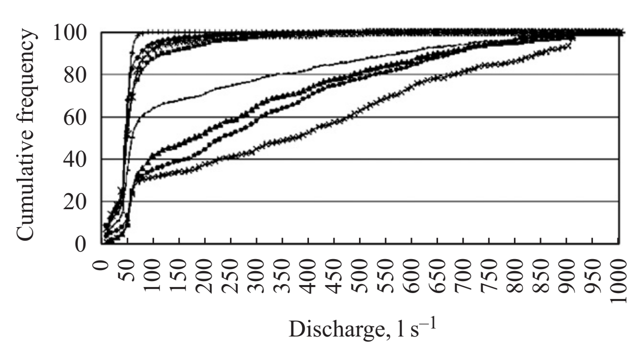

Fig. 9 – Cumulative frequency of the discharges for each of the months of the irrigation season (—♦— April —■— May —▲— June —×— July —●— August —✱— September —+— October —— Whole season.

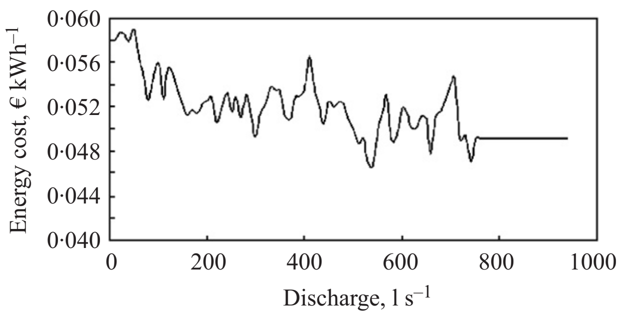

Fig. 10 – Variation in the average cost of energy with the discharge.

society pays for the studied pumping station is approximately 60,000 €. Therefore, the obtained cost savings utilising the calibrated model would be around 9,600 € for every season.

4. Discussion

Different algorithms for minimising the total cost of pumping stations (investment and operation costs) have been developed (Moradi-Jalal *et al.*, 2003, 2004; Pulido-Calvo *et al.*, 2003a; Planells *et al.* 2005). However, none of these considered the calibrated pump characteristic curves. These studies showed that the main cost saving is obtained by improving the energy efficiency and not by reduction in the investment cost (Moradi-Jalal *et al.*, 2003). Moradi-Jalal *et al.* (2003) obtained an energy saving of 32%, but had to utilise several different types of pumps, which involve a lot of maintenance and regulation problems. Pulido-Calvo *et al.* (2003a) obtained an energy saving of 41% by selecting the proper pumps and their regulation.

However, the behaviour of the irrigation networks can substantially vary from the initial conditions in which their design was based, causing a lack of energy efficiency when the pumping stations are working. Problems can be detected and solved by applying the developed model to each pumping station, and possible changes in the sequence of pump activation to improve energy efficiency can be proposed.

Understanding the actual network demand curve is useful in improving the energy efficiency at pumping stations. Once the Q–N_{abs} curve is calculated, the actual network demand curve can be easily obtained by measuring consumed power.

The instruments utilised in this methodology (electrical network analysers, ultrasonic flowmeters, and pressure transducers) are easy to use in monitoring pumping stations. In general, with the obtained energy saving, the investment cost in this kind of material is quickly recovered. The monitoring of pumping stations permits the detection of breakdowns in pumps, which improves the maintenance and quick detection of anomalies in the pumping station.

Thus, the developed model can help to save energy in pumping stations because the majority of the pumping stations are not properly designed in agreement with the actual operational conditions.

5. Conclusions

This study shows that simple electrical and hydraulic measurements at pumping stations helped to improve their management, obtaining, as a result, a high reduction in the energy cost by carrying out a proper sequence of pump activation.

These measurements permitted the calculation of the discharge distribution throughout the irrigation season with a higher accuracy than the traditional processes found in the literature, while integrating the behaviour of the farmers when irrigating their plots. Considering the discharge distribution throughout the irrigation season was an essential step to carry out a proper energy study of pumping stations.

In the case study, a cost saving of 16% was obtained by changing the pumping station regulation from the current sequence of pump activation, in which two variable speed pumps worked simultaneously, to a sequence of pump activation that considered two variable speed pumps working sequentially.

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