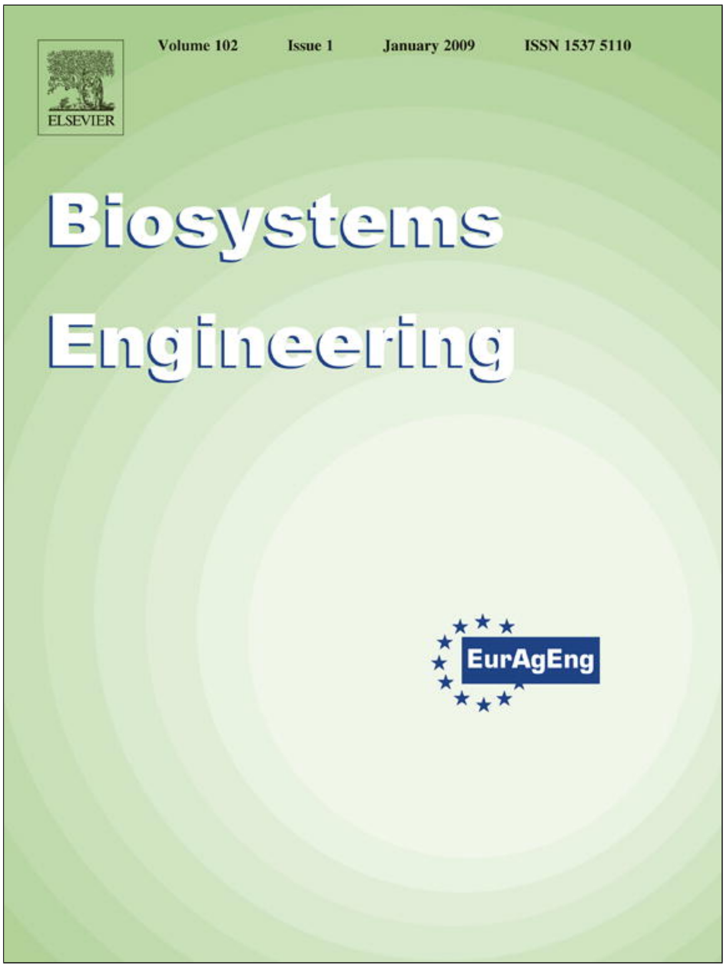
Volume 102
Issue 1
January 2009
ISSN 1537 5110
ELSEVIER
Biosystems
Engineering
EurAgEng

BIOSYSTEMS ENGINEERING 102 (2009) 95–105

Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper: SW—Soil and Water

Development of a new methodology to obtain the characteristic pump curves that minimize the total cost at pumping stations

M.A. Moreno*, P. Planells, J.I. Córcoles, J.M Tarjuelo, P.A. Carrión

Centro Regional de Estudios del Agua, Castilla-La Mancha University, 02071 Albacete, Spain

ARTICLE INFO

Article history:
Received 25 February 2008
Received in revised form
6 August 2008
Accepted 29 September 2008
Available online 28 November 2008

In this paper, a new methodology to obtain the optimal characteristic and efficiency curves (Q–H and Q–η) at pumping stations is presented. The design flow, the design pressure head, and the discharge distribution throughout the irrigation season are the three main parameters to design pumping stations. The purpose of this study is to develop a decision support tool to obtain the theoretical characteristic and efficiency curves of the pumps, the number of pumps, and the number of frequency speed drives that minimize the total cost (investment and operation costs) for a specific pumping station demand (design flow, pressure head, and frequency of the discharges). The results obtained in this paper make evident that the optimal shape (slope) of the Q–H curve varies depending on the discharge distribution throughout the irrigation season, mainly when there are few pumps installed at the pumping station. When there is a high frequency of low discharges, the desired slope of the Q–H curve is higher. In cases when the discharge distribution is unknown, increasing the number of pumps ensures high energy efficiency. When installing a pump with an optimal characteristic curve, it is not necessary to increase the number of frequency speed drives.

1. Introduction

The design of a collective pressurized on-demand irrigation network can be summarized in five stages (Labye et al., 1988): optimum network layout in order to minimize the total cost of the network (Bhave and Lam, 1983; Awumah et al., 1989; Granados, 1990); calculation of the hydrant discharge according to plot sizes (Planells et al., 2001); determination of design flow per pipeline (associated with a determined supply guarantee) (Clément and Galand, 1979; Pulido-Calvo et al., 2003a; Moreno et al., 2007a); calculation of the optimum pipe size diameters, minimizing the investment and energy cost (Labye et al., 1988; Lansey and Mays, 1989; Pérez et al., 1996; DIOPRAM, 2003); and analysis of the network performance under different operating conditions (Aliod et al., 1997; Rossman, 1997) to determine the possible supply failure situations of the network or of the pumping plant (Lamaddalena and Sagardoy, 2000).

One of the main problems in the design of water distribution networks is obtaining the type of pump that best fits the water demand under specific pressure head requirements. Different algorithms for minimizing the total cost of pumping stations (investment and operation costs) have been developed (Moradi-Jalal et al., 2003; Pulido-Calvo et al., 2003a; Moradi-Jalal et al., 2004; Planells et al., 2005). These algorithms consider characteristic curves of existing pumps. However,

* Corresponding author.
E-mail address: miguelangel.moreno@uclm.es (M.A. Moreno).
1537-5110/$ – see front matter © 2008 IAgrE. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.biosystemseng.2008.09.024

Nomenclature

CRF	capital recovery factor (–)
f_i	frequency of the discharge Q_i (fraction)
H_d	design pressure head (m)
η_i	average pumping station efficiency for each flow Q_i (%)
H_i	pressure head (m)
η_j	efficiency of the pump j that supplies a flow Q_j (%)
η_{max}	maximum efficiency of the pump (%)
n	number of pumps of the pumping station (–)
N_{abs}	average absorbed power (kW)
PLC	programmable logic controller (–)
Q_d	design discharge ($m^3 s^{-1}$)
Q_i	average flow for the flow interval i ($m^3 s^{-1}$)
Q_{max}	maximum discharge of the pump ($m^3 s^{-1}$)
r	interest rate (%)
RDDC	Random Daily Demand Curve Methodology (–)
t	useful life of the project (year)
α	relative speed of the pump (fraction)

none of them proposes an algorithm to obtain the desirable types of the characteristic and efficiency curves.

Several methodologies have been developed to obtain the design flow in each pipe of a network. The Clément methodology (Clément, 1966) is the most commonly used model because it is easy to implement. Recent studies have shown that this methodology does not fit properly with the real network behaviour. Thus, a new methodology, named Random Daily Demand Curves (RDDC) Method, was developed to obtain the flow rate in each pipe, and therefore in the main pipe (Moreno et al., 2007a). RDDC was shown to have a better fit with the measured data than the Clément methodology, which underestimated the design flow by 35–40% in some of the studied networks.

The main required parameters to design pumping stations are the design flow and the pressure head. In addition, the discharge distribution throughout the irrigation season is an essential parameter for carrying out a proper energy study of pumping stations. 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 the utilization of complex forecasting tools such as neural networks (Pulido-Calvo et al., 2003b). Moreno et al., 2007b obtained the discharge distribution of a pumping station by measuring the electrical parameters, which resulted in a better approximation than other methodologies. Usually, only the design flow and the pressure heads are considered when designing pumping stations, without taking into account remaining discharges. However, it has been found that the majority of pumping stations supply mostly low or medium discharges and not maximum discharges (Moreno et al., 2007b). Thus, it is necessary to improve the efficiency for low and medium discharges, and not only for high discharges (design flow). Different standard distributions can be used to simulate the effect on the pumping station efficiency of different types of flow demand. A model called ENE was developed, which utilizes the discharge distribution at the pumping station in order to obtain the average absorbed power and the average efficiency.

The main goal of this study is to develop a decision support tool to obtain the theoretical characteristic and efficiency curves of the pumps, the number of pumps, and the number of frequency speed drives that minimize the total cost for a specific pumping station requirement (design flow, pressure head, and frequency of the discharges).

2. Materials and methods

2.1. The case study

This methodology was applied to the irrigable area of La Pinada (Cuenca, Spain). This irrigation society covers an irrigable area of 170 ha. The primary irrigation system is drip irrigation for vineyards and olive tree crops. The pumping station is composed of four pumps (36 kW each), two of which have frequency speed drives and the remainder have electronic starters. A manometric regulation is carried out with 51 m pressure head, which was obtained by using the hydraulic model implemented in EPANET 2.0 (Fig. 1).

In order to achieve manometric regulation of the pumping station, a pressure transducer is installed in the pumping collector. This pressure transducer sends a current of between 4 and 20 mA, corresponding to a pressure of 0–10 bar. This signal is received by a programmable logic controller (PLC) that activates the different pumps to keep a pressure head of 51 m (in this case). In this on-demand network, a pressure of 25 m at hydrant level is required. Several demand scenarios were studied to determine the pressure head that warrants 25 m at hydrant, in most of the cases. The utilized hydraulic network was calibrated by using the methodology developed by Moreno et al., 2008.

2.2. Calculation of the design parameters of the pumping station

To properly design a pumping station it is necessary to carry out an exhaustive analysis of the network behaviour and its

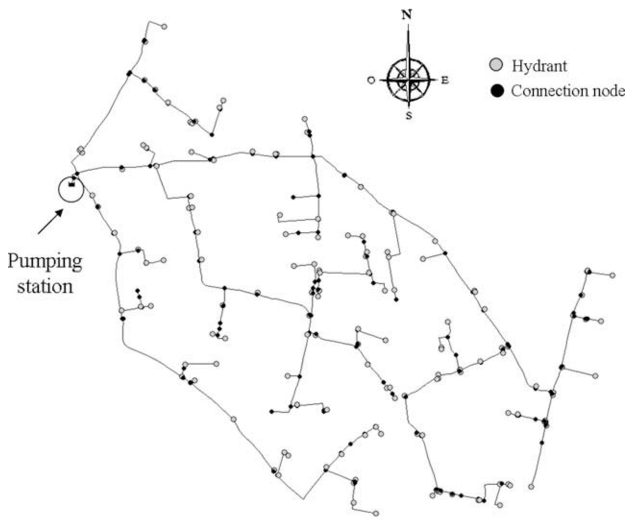

Fig. 1 – Irrigation network implemented in EPANET 2.0.

management. The three main parameters to design pumping stations are design flow, pressure head, and discharge distribution throughout the irrigation season.

Different statistical distributions will be used to determine the effect of the discharge distribution on the final result. In addition, the real discharge distribution in the studied network will be compared with the standard distributions. The discharge distributions considered in this study were four types of Poisson distributions [Eq. (1)] and the discharge distribution measured at the pumping station in the 2007 irrigation season (Figs. 2 and 3, respectively). Each type of Poisson distribution (A, B, C, and D) corresponds with the following lambda values of Eq. (1): 2.5, 3.0, 4.0, and 7.5.

$$p = F(x|\lambda) = e^{-\lambda}\sum_{i=0}^{x}\frac{\lambda^i}{i!} \tag{1}$$

Fig. 3 shows a higher frequency of low and medium discharges, and an absence of high discharges. Thus, the pumping station must operate with a proper efficiency for low and medium discharges.

2.3. *Development of the model for analysis of energy efficiency at pumping stations (ENE)*

Once all of the design parameters were obtained, it was then necessary to simulate the behaviour of the pumping station. A simulation model was required to analyze the energy efficiency of the pumping station. The developed model simulates the pumping station behaviour when a variable demand of flow and pressure head is required by the network.

The model, which was implemented in MatLab 7.4, requires the following input data: head and efficiency curves of the pumps, *Q–H* and *Q–η* (theoretical or measured if they are available), number of pumps, pressure head, and the discharge distribution throughout the irrigation season (measured, if it is available, or following different standard distributions). The model simulates the behaviour of the variable-speed pumps by using affinity laws and the working points for the fixed pumps. Thus, the model calculates the discharge–efficiency relation for the entire discharge range of the pumping station.

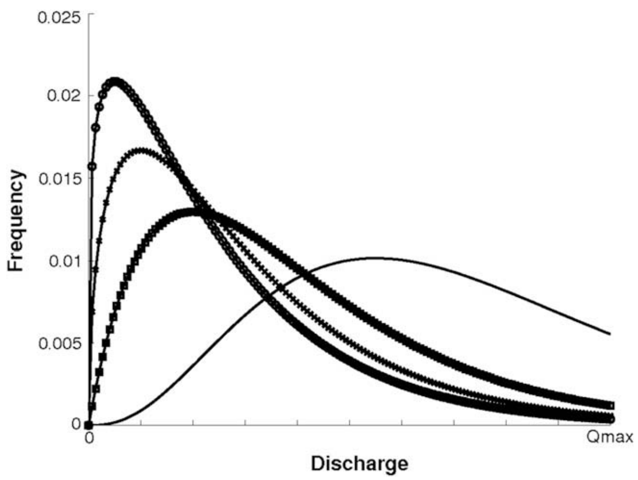

Fig. 2 – Utilized standard distribution (⊟ Poisson A, ⊖ Poisson B, ⋊ Poisson C, — Poisson D).

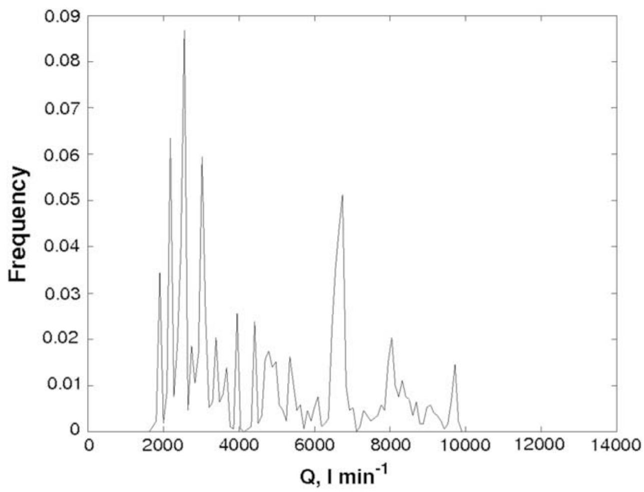

Fig. 3 – Discharge distribution of La Pinada for the 2007 irrigation season.

The average efficiency of the pumping station can be calculated by Eq. (2).

$$\eta_i = \frac{\sum_{j=1}^{n}\eta_j Q_{i,j}}{Q_i} \quad \text{for } j = 1,..,n \text{ and for all } i \tag{2}$$

where η_i is the average pumping station efficiency for each flow Q_i, $m^3\,s^{-1}$; Q_i is the average flow for the flow interval *i* in which the flow range has been divided into, $m^3\,s^{-1}$; η_j is the efficiency of the pump *j* that supplies a flow Q_j; and *n* is the number of pumps in the station.

The sum of the discharges of each pump (Q_j) is equal to Q_i [Eq. (3)].

$$Q_i = \sum_{j=1}^{n} Q_{i,j} \quad \text{for } j = 1,..,n \text{ and for all } i \tag{3}$$

When measured discharges throughout an irrigation season are available, ENE calculates the frequency of discharges by introducing the discharge data as a text file. If measured data are not available, ENE permits the user to select different standard distributions (Poisson A, B, C, and D; random uniform; or others). The user should select the standard distribution that best fits the real discharge distribution based on previous experience or based on different algorithms that can be found in the literature (Lamaddalena, 1997; Pulido-Calvo et al., 2003a; Khadra, 2004). In order to evaluate the effect of the discharge distribution on the final result, different standard distributions can be studied. Thus, the most appropriate distribution, considering the available information, can be applied.

Based on the results obtained in previous studies (Planells et al., 2005; Moreno et al., 2007b) three regulation types of the pumping station were implemented in ENE, although any other type of regulation can be also implemented: one variable-speed pump with the remainder as fixed pumps; two variable-speed pumps activated simultaneously and with the remainder as fixed pumps; two variable-speed pumps activated sequentially and with the remainder as fixed pumps. In this study the first and third options were considered because the first option is the most commonly used and the third has been shown to improve the energy efficiency in some cases (Moreno et al., 2007b).

The average absorbed power (N_{abs}) was calculated by considering the discharge distribution and the corresponding pumping station efficiency. To obtain the most efficient regulation type, ENE calculates the value of the average absorbed power [Eq. (4)].

$$\overline{N_{abs}} = \sum_{i=1}^{n} \frac{9.81 Q_i H_i}{\eta_i} f_i = \sum_{i=1}^{n} (N_{Q_i} f_i) \tag{4}$$

where f_i is the frequency of the discharge Q_i, fraction, H_i is the pressure head, m corresponding to the flow interval i (constant for manometric regulation), and η_i is the total average pumping station efficiency for the discharge Q_i, fraction.

2.4. *Optimization of the pump characteristic curves*

The optimization process of the characteristic and efficiency curves will be applied to fixed speed pumps. Once the optimal characteristic and efficiency curves are known, the study of the efficiency for variable-speed pumps can be done by utilizing the affinity laws.

The characteristic and efficiency curves of the pumps (Q–H and Q–η) are approximated by Eqs. (5) and (6) for fixed pumps and by Eqs. (7) and (8) for variable-speed pumps, by using affinity laws.

$$H = a + bQ + cQ^2 \tag{5}$$

$$\eta = eQ + fQ^2 \tag{6}$$

$$H = \alpha^2 a + \alpha bQ + cQ^2 \tag{7}$$

$$\eta = \frac{e}{\alpha} Q + \frac{f}{\alpha^2} Q^2 \tag{8}$$

where α is the relative speed of the pump and the coefficients a, b, c, e, and f determine the shape of the curves. In this study, the coefficient b was considered to be zero, which means that the maximum head of the Q–H curve is obtained when Q is zero. This is a desirable characteristic in order to avoid double working points. Jeppson (1977) proposed a variable change [Eq. (9)] to remove the coefficient b.

$$Q' = Q + \frac{b}{2c} \tag{9}$$

With Eqs. (5) and (9) the characteristic curve of the pump is the following:

$$H = a' + cQ'^2 \tag{10}$$

and the coefficient a' is:

$$a' = a - \frac{b^2}{4c} \tag{11}$$

Fig. 4 shows the effect of this variable transformation that permits coefficient b to be removed.

The objective function to minimize is the average absorbed power by the pumping station during an irrigation season [Eq. (4)]. The coefficients e and f can be written as functions of the coefficients a and c. Fig. 5 shows the relation between the head and efficiency curve.

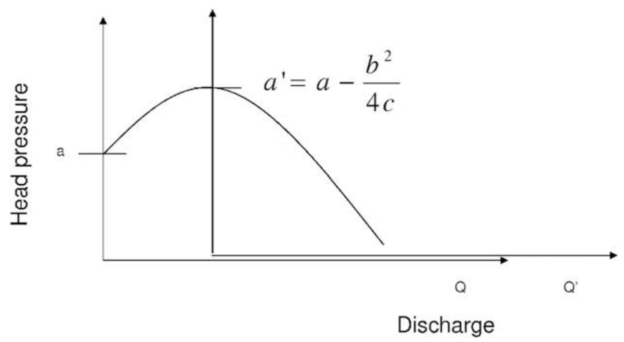

Fig. 4 – Variable transformation to remove coefficient *b* from characteristic curve.

The operating point (Q_d, H_d) is defined by the intersection of the pump characteristic curve and the system curve. With the discharge Q_d and the efficiency curve, the efficiency η_d can be calculated. However, when the commercial pumps are selected, the head curve of all the pumps of the pumping station can intersect the system curve above the operating point (Q_d, H_d), causing small pressure excess if the pumps are properly selected.

When H and η are equal to zero and considering Eqs. (5) and (6) with $b = 0$:

$$Q_{max} = \left(\frac{-a}{c}\right)^{0.5} \tag{12}$$

$$eQ_{max} = -fQ_{max}^2 \tag{13}$$

Thus, the coefficient e is defined in the next equation as:

$$e = -f\left(-\frac{a}{c}\right)^{0.5} \tag{14}$$

In addition, the relation between the coefficient f and the coefficients a and c is obtained, considering the maximum efficiency as follows:

$$\frac{d\eta}{dQ} = 2fQ + e = 0 \tag{15}$$

$$Q = -\frac{e}{2f} \tag{16}$$

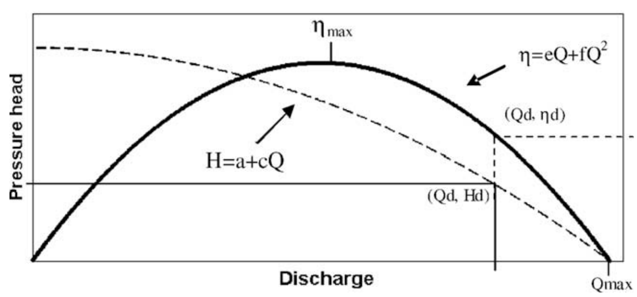

Fig. 5 – Scheme of the characteristic curves of the pumps.

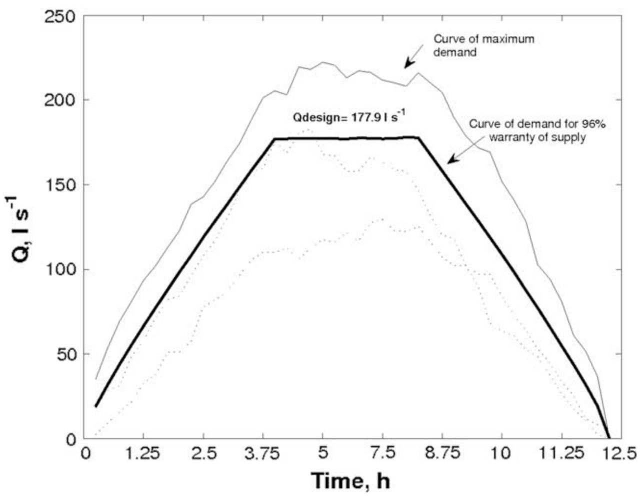

Fig. 6 – Design flow by utilizing RDDC methodology.

With Eqs. (6) and (15) the following equation can be obtained:

$$\eta_{\max} = f\left(-\frac{e}{2f}\right)^2 + e\left(-\frac{e}{2f}\right) = -\frac{e^2}{4f} \tag{17}$$

Considering Eq. (14) and (16):

$$f = \frac{4\eta_{\max}}{(a/c)} \tag{18}$$

With all pumps being equal, the most common case in this type of pumping station in which the variable-speed and fixed pumps can be switched to have the same level of wear, from Eq. (5), with $b = 0$, the following relation can be established:

$$a = H_d - c\left(\frac{Q_d}{n}\right)^2 \tag{19}$$

where H_d = design pressure head, Q_d = design discharge, and n = number of pumps installed at the pumping station.

When Eq. (19) could not be used because of, for example, having different pump sizes in the pumping station, the optimization process would be more complex because of having the coefficients a and c as variables. In this case, convergence problems in the optimization process have been found.

The maximum efficiency can be determined from manufacturer information. In this study, a theoretical maximum pump efficiency of 80% was considered. Thus, the optimization variable is only c. The optimization was carried out by using the Downhill Simplex Method (Nelder & Mead, 1965). For each number of pumps considered, the optimal characteristic and efficiency curves for the design condition were obtained.

Once the optimal characteristic curve and the optimal number of pumps were obtained for the design condition, a cost analysis was developed considering the energy and investment costs. Thus, the proper number of pumps is selected from an economic point of view. In the application, the annual cost is calculated by multiplying the initial cost by the capital recovery factor (CRF):

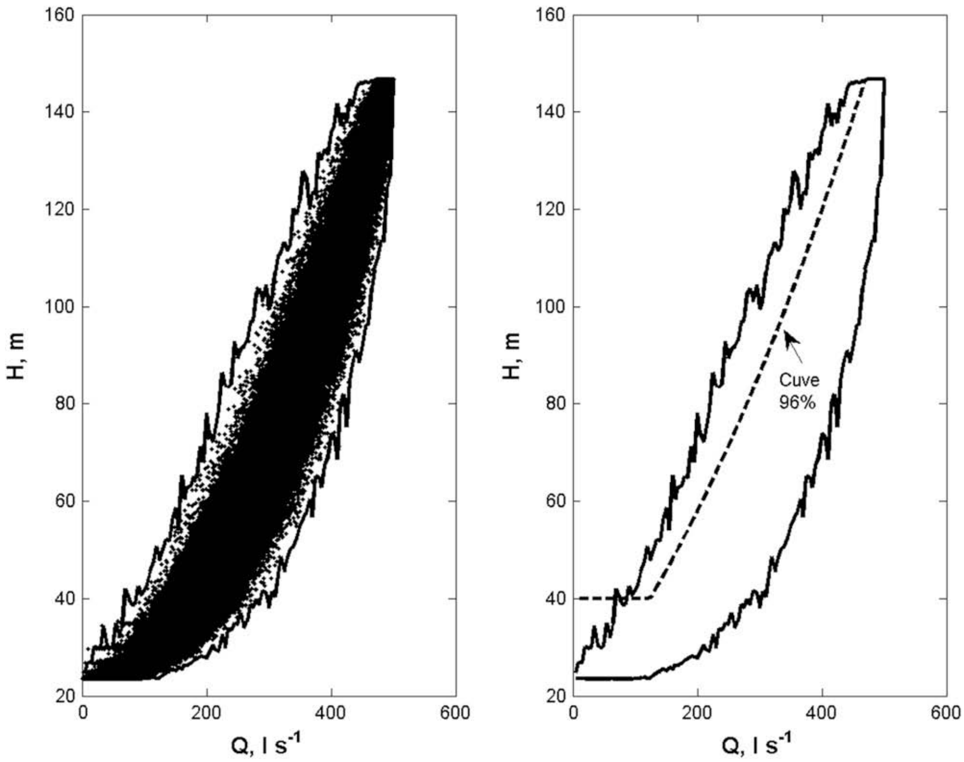

Fig. 7 – Generation of the maximum and minimum demand curve (left) and generation of the demand curve for the 96% of warranty of supply (right).

$$\mathrm{CRF} = \frac{r(1+r)^t}{(1+r)^t - 1} \tag{20}$$

where t = useful life of the project, year; and r = interest rate considered, %.

In the case study, $t = 10$ years and $r = 5\%$, and therefore CRF = 0.13. Operating cost is determined for an energy rate of 0.08 € kW h^{-1}.

2.5. *Determination of the design flow and pressure head*

RDDC methodology was used to obtain the design flow at the pumping station. To obtain the demand curve, different methodologies can be utilized (Lamaddalena and Sagardoy, 2000; Moreno, 2005; Planells et al., 2005). In this study, the methodology proposed by Lamaddalena and Sagardoy (2000) was implemented. Software in MatLab 7.4 environment was developed that uses the EPANET calculation engine by using the EPANET toolkit. This software calculates the required pressure head for each demanded discharge, taking into account different scenarios of open hydrants and a minimum pressure at hydrant level (25 m in the case study). Thus, for each demanded discharge, there are different values of required pressure head depending on the location of the open hydrants. A maximum and a minimum curve of demand can be obtained as well as a curve considering a specific guarantee

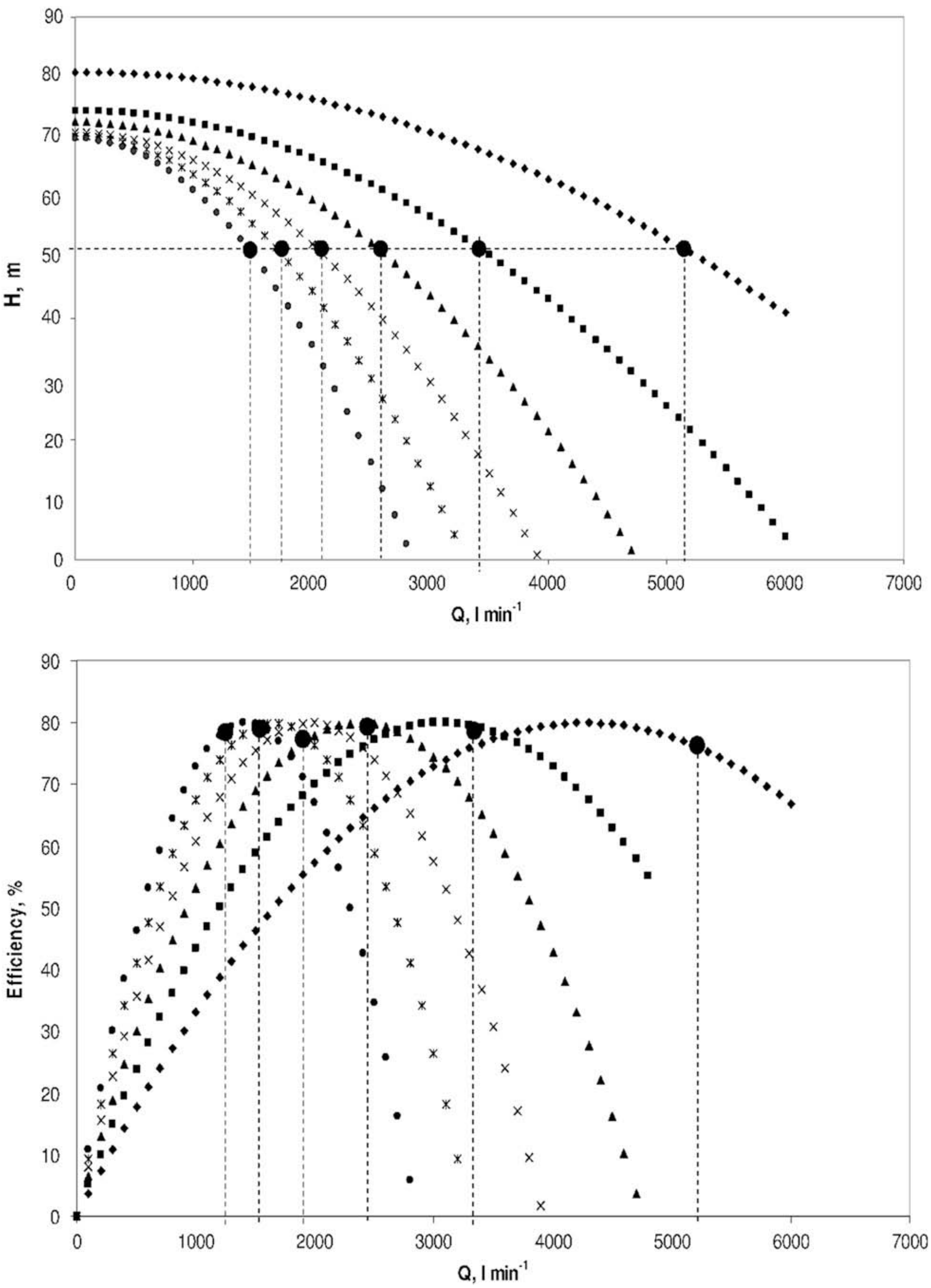

Fig. 8 – Efficiency curve for varied number of pumps, taking into account the measured discharge distribution (◆ 2 pumps, ■ 3 pumps, ▲ 4 pumps, × 5 pumps, ⋇ 6 pumps, ● 7 pumps).

of supply (96% in the case study). Once the demand curve is obtained, the pressure head can be calculated with an understanding of the design flow. To obtain an accurate demand curve, the hydraulic model of the network should be calibrated with pressure measurements (Moreno et al., 2008).

3. Results

The design flow obtained by the RDDC methodology was $178\ \mathrm{l\,s^{-1}}$, for a 96% of guarantee of supply (Fig. 6).

The discharge distribution throughout the 2007 irrigation season was measured and it validated the RDDC methodology because the measured discharge for a 96% rate of guarantee of supply was $173\ \mathrm{l\,s^{-1}}$, which is very close to that obtained with the RDDC methodology.

The pressure head corresponding to a design flow of $178\ \mathrm{l\,s^{-1}}$ was 51 m (Fig. 7).

The optimal characteristic and efficiency curves, which fulfil the discharge and pressure head requirements and take into account the measured discharge distribution, for a different number of pumps, are presented in Fig. 8.

When the number of pumps increases, the steepness of the curve also increases. In addition, when the number of pumps is high, the working point is closer to the zone of maximum efficiency than when the number of pumps is low.

The discharge distribution throughout the irrigation season has an important effect on the shape of the optimal

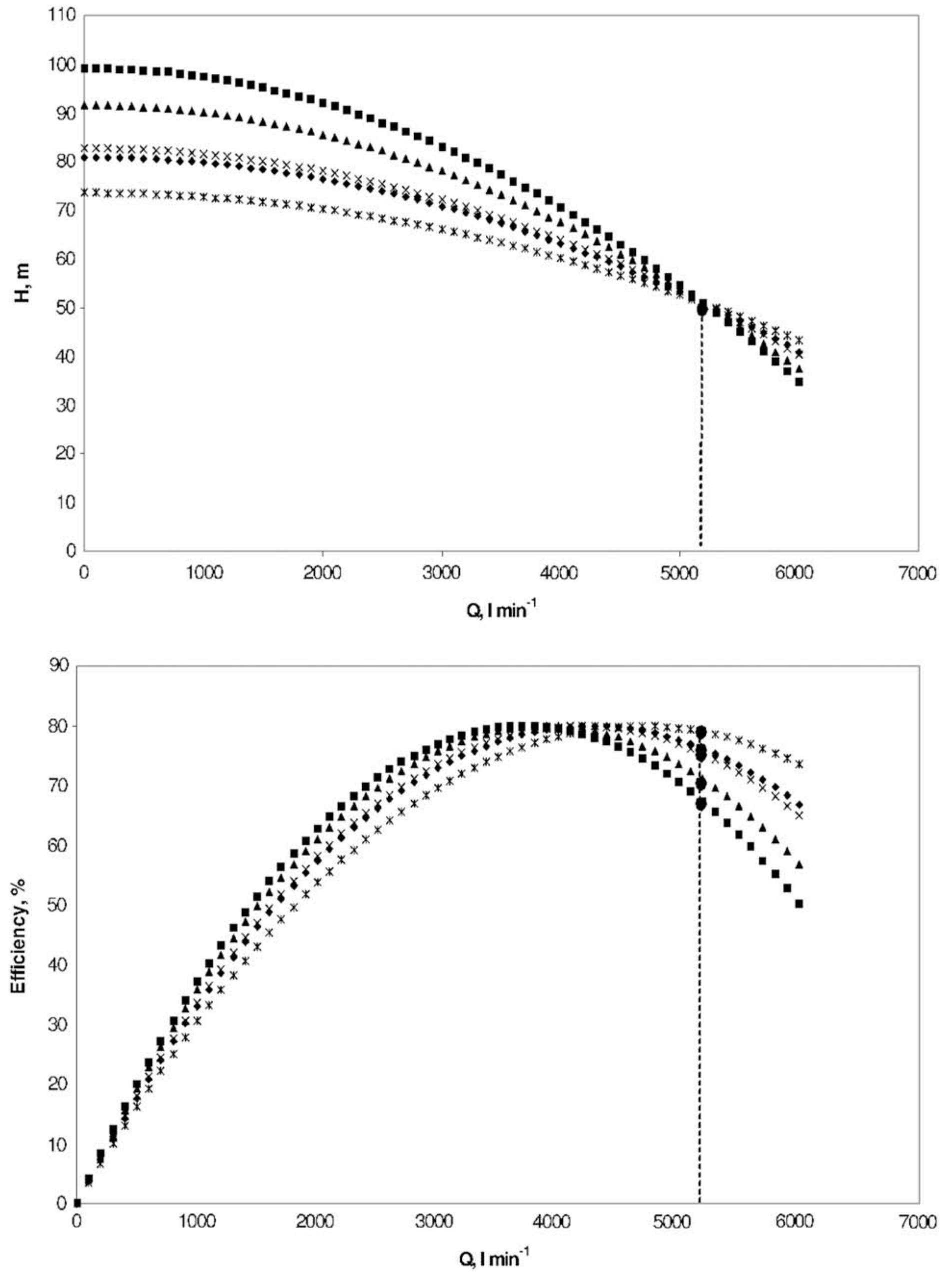

Fig. 9 – Q–*H* and efficiency curves when 2 pumps are installed and different discharge distributions are considered (◆ measured, ■ Poisson A, ▲ Poisson B, × Poisson C, ⋇ Poisson D).

characteristic and efficiency curves of the pumps. Fig. 9 shows the Q–H and efficiency curves, respectively, considering two pumps and different Poisson discharge distributions together with the measured distribution during the irrigation season.

When there are few pumps at the pumping station, the optimal characteristic curves are different depending on the discharge distribution that is considered (Fig. 9). When there is a higher frequency of low discharges (Poisson A and B), the optimal *Q–H* curve is steeper than when the discharges are more uniform (Poisson C, D, and the measured distribution). When the *Q–H* pump is steeper, the working point (defined by a pressure head of 51 m and the characteristic curves) is in the descendent zone of the efficiency curve. If the curve *Q–H* is flatter, which corresponds with more uniform discharge distributions in the range of discharges, the working point is in the zone of maximum efficiency. In none of the cases is the working point in the ascending zone of the efficiency curve. Therefore, when selecting the pumps, the working point should be in the zone of maximum efficiency or in the descendent zone of the efficiency curve, but never in the ascending zone of the efficiency curve.

If the number of pumps increases, these differences are minimal, the optimal characteristic and efficiency curves having the same shape for all the discharge distributions (Fig. 10). Thus, if the discharge distribution throughout the irrigation season is not known, increasing the number of pumps and optimizing the characteristic curves can ensure

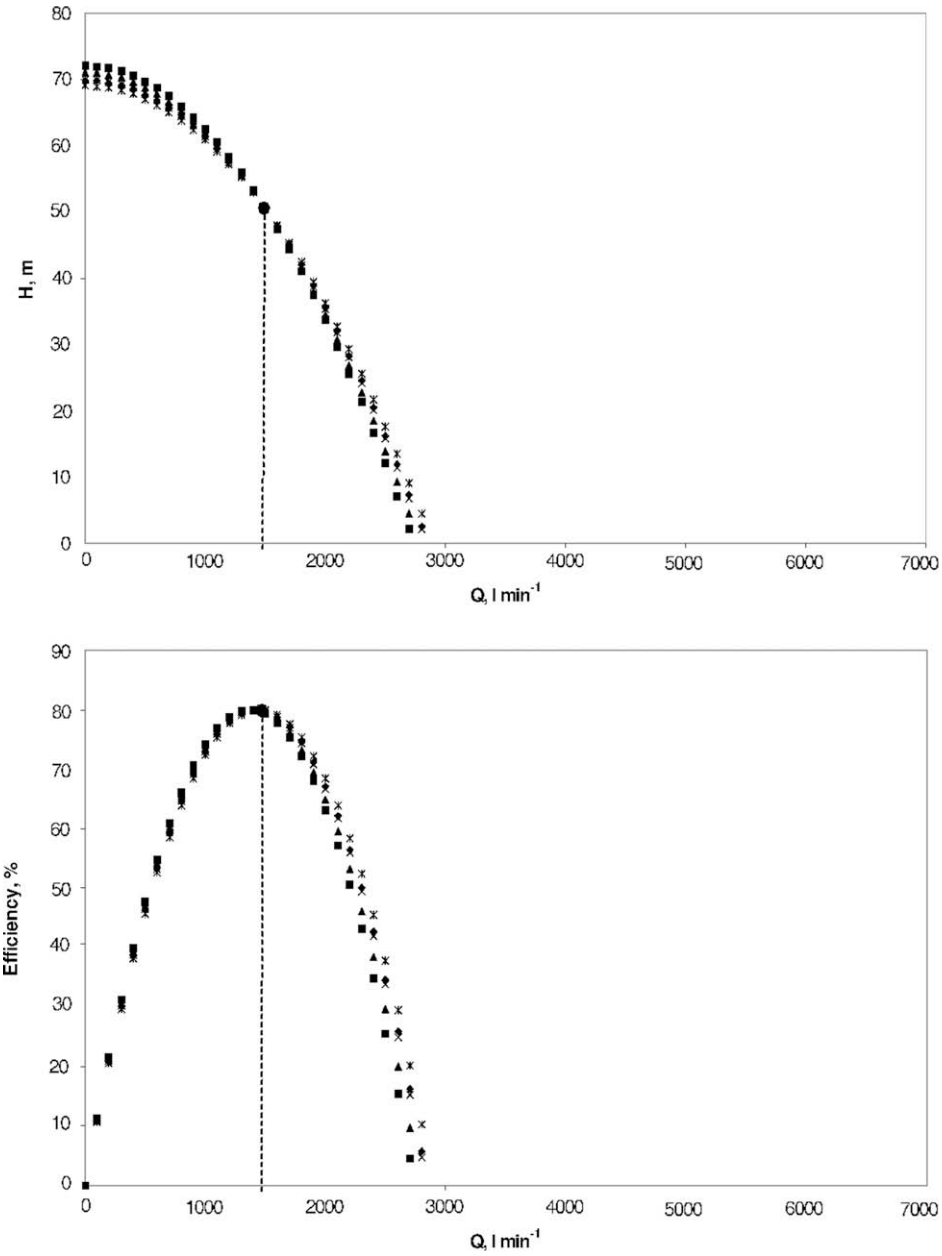

Fig 10 – Efficiency curves when 7 pumps are installed and different discharge distributions are considered (◆ measured, ■ Poisson A, ▲ Poisson B, × Poisson C, ⨯ Poisson D).

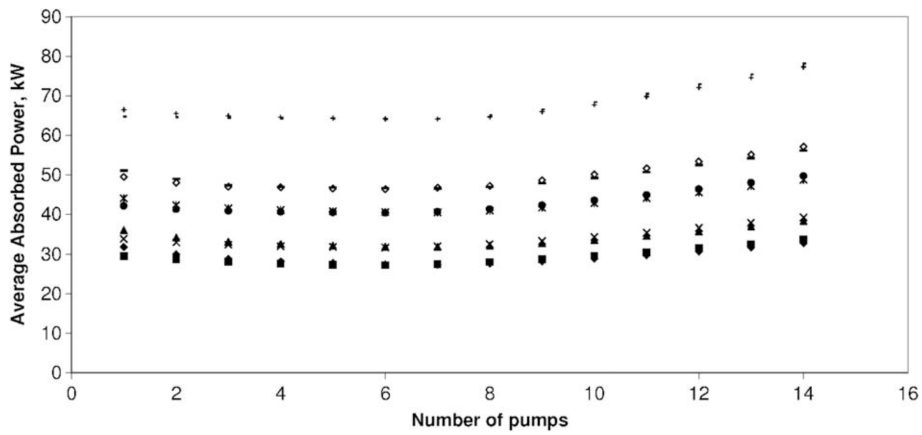

Fig. 11 – Relation between the number of pumps and the average absorbed power for different discharge distributions using 1 variable-speed pump (1VSP) (◆ Poisson A, ▲ Poisson B, ⁎ Poisson C, and + Poisson D, and — the measured) or 2 variable-speed pumps (■ PoissonA, × Poisson B, ● Poisson C, and — Poisson D, and ◇ the measured).

proper energy efficiency. In addition, the working point of the pumps is in the zone of maximum efficiency.

In order to determine the optimal number of pumps, it is necessary to carry out energy and cost analyses. From the energy point of view, Fig. 11 shows the relation between the number of pumps and the average absorbed power for the four standard distributions studied, and that measured in the irrigation season 2007. The effect of installing a second variable-speed pump (2VSP) is also shown in Fig. 11.

Fig. 11 illustrates that the number of pumps that makes N_{abs} the minimum is seven, in the studied irrigation network. However, the slight differences indicate that the range of reasonable number of pumps is between 3 and 10. When the pump selection is performed correctly, there are not significant differences in the average absorbed power when using one variable or two variable-speed pumps activated sequentially. However, when the pumps are not properly selected or when the variables on which the selection of the pumps was based are changed, the installation of a second frequency speed drive usually improves the energy efficiency (Moreno et al., 2007b).

In the case study, the average absorbed power in 2007 was 69.14 kW, and the pumping station had 4 pumps. If the pumps had been selected by using the proposed methodology, the average absorbed power would have been 46.8 kW (Fig. 11, considering 4 pumps and the measured discharge distribution). Therefore, an energy saving in the pumping station of 32.3% would have been obtained.

A cost analysis was carried out to determine the number of pumps that minimized the total cost at the pumping station (investment and operation costs). Results of the energy cost analysis, when the actual operation time (315 hours year^{-1}) was considered, are shown in Fig. 12.

In the case in which the pumping station is working for a few hours a year, the minimum cost is obtained with the use of only two pumps. This is due to the higher price of installing a greater number of pumps (more valves, pipes, and other elements), which is not compensated by higher energy efficiency. However, the actual operation time of this irrigation network is low and not representative of the rest of the irrigable areas. Therefore, Fig. 13 shows the relation between the number of hours of operation and the number of pumps that

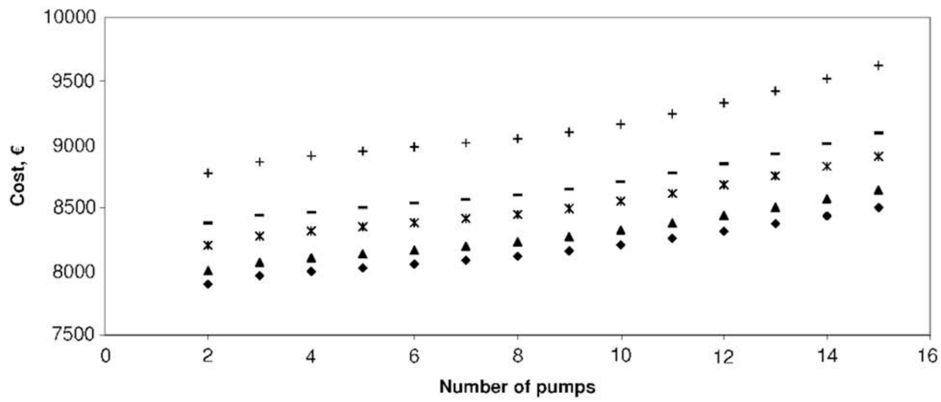

Fig. 12 – Relation between number of pumps and the total cost for different discharge distributions (◆ Poisson A, ▲ Poisson B, ⁎ Poisson C, and + Poisson D, and — the measured), considering 1 variable-speed pump (1VSP).

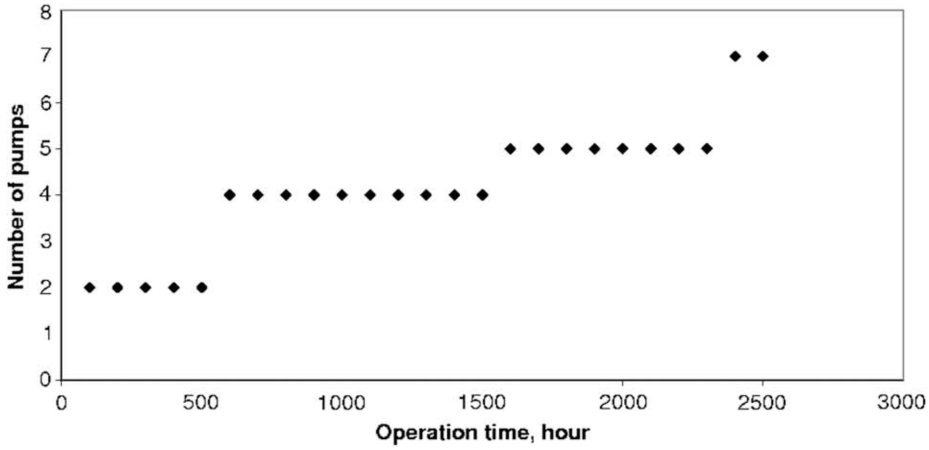

Fig. 13 – Operation time in hours *versus* the number of pumps that minimizes the total cost.

minimizes the total cost. When the operation time of the pumping station in the irrigation season is long, the number of pumps that minimizes the total cost is higher. This is due to the higher energy cost when the number of operating hours is higher, and due to the improvement of the energy efficiency when there is a high number of pumps in the pumping station (Figs. 8 and 11). To obtain the minimum total cost with seven pumps, which is the number of pumps that best minimizes energy consumption (Fig. 11), the operation time should be 2390 h. This operation time is too long for the actual operation condition in the majority of the irrigable areas.

4. Conclusions

In this paper, a new methodology to obtain the optimal characteristic and efficiency curves (Q–H and Q–η) at pumping stations is presented. It considers the design flow, the design pressure head, and the discharge distribution throughout the irrigation season.

The optimal shape (slope) of the Q–H curve varies depending on the discharge distribution throughout the irrigation season, mainly when there are few pumps installed at the pumping station. For high frequency of low discharges, the recommended Q–H curve is steeper than for high frequency of medium and high discharges. These differences are negligible when a large number of pumps are installed. Therefore, when the discharge distribution is not known, increasing the number of pumps can improve the energy efficiency. Because the discharge distribution is not usually known, increasing the number of pumps can help to decrease the negative effect of choosing an inappropriate pump. However, when the operation time is lower, the number of pumps that minimizes the total cost (investment + exploitation) is also lower.

If the pumps are properly chosen, no improvement of the energy efficiency is found by installing a second variable-speed pump. This and the price of this equipment make its installation unprofitable. However, if the pumps have not been adequately chosen, a second variable-speed pump can help to improve the energy efficiency at the pumping station, if it is correctly operated.

Acknowledgment

This research was funded by the Consejería de Educación y Ciencia de Castilla-La Mancha within the project PCI08-0117 and the Regional Agency of Energy in Castilla-La Mancha (AGECAM) within the project ''Auditorías energéticas en Castilla-La Mancha''.

REFERENCES

Aliod R; Eizaguerri A; Estrada C; Perna E (1997). Dimensionado y análisis hidráulico de redes de distribución a presión en riego a la demanda: Aplicación del programa GESTAR. Riegos y Drenajes XXI, **92**, 22–38.

Awumah K; Bhatt S K; Goulter I C (1989). An integer programming model for layout design of water distribution networks. Engineering Optimization, **15**, 57–70.

Bhave P R; Lam C F (1983). Optimal layout for branching distribution networks. Journal of Transportation Engineering, **109**, 534–547.

Clément R (1966). Calcul des débits dans le réseaux d'irrigation fonctionnant á la demande. La Houille Blanche, **5**, 553–575 (in French).

Clément R; Galand A (1979). Irrigation par aspersion et réseaux collectifs de distribution sous pression. Eyrolles, Paris.

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

Granados A (1990). Infraestructura de regadíos. Redes colectivas de riego a presión (2ª edición). Escuela Técnica Superior de Ingenieros de Caminos Canales y Puertos, Universidad Politécnica, Madrid.

Jeppson R W (1977). Analysis of Flow in Pipe Network. Ann Arbor Science, Ann Arbor, Michigan.

Khadra R (2004). Development of an Integrated Tool for the Analysis of Irrigation Systems under Water Scarcity Conditions. Dipartamento di Scienze della Produzion Vegetali, Universitat degli Studi di Bari, Bari, Italy.

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

Lamaddalena N (1997). Integrated simulation modelling for design and performance analysis of on-demand pressurised irrigation systems. Ph.D. Dissertation, Universidade Técnica de Lisboa, Instituto Superior de Agronomía, Lisboa, Portugal.

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

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

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

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

Moreno M A (2005). Análisis hidráulico y energético de redes de riego a la demanda. Ph.D. Dissertation, Centro Regional de Estudios del Agua, Universidad de Castilla-La Mancha (in Spanish)

Moreno M A; Planells P; Ortega J F; Tarjuelo J M (2007a). New methodology to evaluate flow rates in on-demand irrigation networks. Journal of Irrigation and Drainage Engineering, **133**(4), 298–306.

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

Moreno M A; Planells P; Ortega J F; Tarjuelo J M (2008). Hydraulic networks models calibration. Journal of Irrigation and Drainage Engineering, **134**(1), 36–42.

Nelder J A; Mead R (1965). A simplex method for function minimization. Computation Journal, **7**(4), 308–313.

Pérez R; Andreu M; Izquierdo J (1996). Diseño de redes de distribución. In: Curso de ingeniería hidráulica aplicada a los sistemas de distribución de agua (Cabrera E; Espert V; García-Serra J; Martinez F; Andris M; García M eds), pp. 653–727. Universidad Politécnica de Valencia, Valencia, Spain.

Planells P; Tarjuelo J M; Ortega J F; Casanova M I (2001). Design of water distribution networks for on-demand irrigation. Irrigation Science, **20**, 189–201.

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

Pulido-Calvo I; Roldán J; López-Luque R; Gutierrez-Estrada J C (2003a). Water Delivery Planning Considering Irrigation Simultaneity. Journal of Irrigation and Drainage Engineering, **129**(4), 247–255.

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

Rossman L A (1997). EPANET: User Manual. Risk Reduction Engineering Laboratory Office of Research and Development. United States Environmental Protection Agency, Cincinnati, OH.