Optimization of Underground Water Pumping

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Abstract: Nowadays, it is necessary to develop methodologies, tools, and actions that try to optimize the use of the energy resources. One of the main problems found was the improper dimensioning of the pumping for undergroundwater extractions that supply water to reservoirs. In this paper, a new methodology to obtain the minimum total cost (investment+operation costs) by optimizing the characteristic and efficiency curves, together with the pumping pipe diameter, was developed. This methodology was based on the theoretical relations between the characteristic and efficiency curves and it considered different variables such as: hydrologic, topographic, hydraulic, and economic variables. In addition, software implemented in MATLAB environment was developed to facilitate the transference of this methodology to engineers and managers of irrigable areas. The results show that the steepness of the characteristic curve is mainly associated with the water table level variation throughout the year, and the pumping pipe diameter is mainly associated with the water demand (volume). In addition, the operation point with the maximum efficiency should correspond with the month of highest demand.

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Introduction

Nowadays, under the context of climate change and the ascending trend of the energy price, it is necessary to develop methodologies, tools, and actions that try to optimize the use of the energy resources, which imply environmental and economic benefits. Although irrigation does not require as much energy as the industry or urban demand, energy costs are one of the main inputs for irrigators. In addition, irrigation is one of the sectors of agriculture which is increasing its energy consumption as a consequence of the modernization of irrigation water-distribution systems (Abadía et al. 2008).

The pumping for water distribution and for undergroundwater extraction are the main energy consumers in pressurized water networks. In fact, several writers have developed different algorithms to minimize the energy and investment costs in pumping stations (Moradi-Jalal et al. 2003, 2004; Pulido-Calvo et al. 2003; Alandi et al. 2005; Moreno et al. 2007). Studies have been focused on the determination of the most economic discharge of the well from a hydrological point of view (Helweg 1975; Scalmanini et al. 1979; Helweg 1982; Helweg et al. 1991; Helweg and Jacob 1991). However, considerations about the proper type of pump and size of it have not been found in the literature.

In Castilla-La Mancha, Spain, as well as in other regions in the world, the main water source is undergroundwater (more than 65% of irrigation and urban water). Water is extracted by using submersible pumps, and the water can be storage in a reservoir or injected directly in the irrigation system (Ortega et al. 2004, 2005). For large irrigation areas, the most common option is the use of reservoirs to storage the water and pumping stations to provide of pressure to the irrigation network (Moreno et al. 2007). The proper dimensioning and management of reservoirs have also been objective of numerous studies, which pointed the necessity of developing this kind of research (Sabet and Helweg 1989; Mehta and Goto 1992; Hirose 1997; Pulido-Calvo et al. 2006). One of the main problems found in these kinds of infrastructures was the improper dimensioning of the pumping for wells that supply water to reservoirs.

In Spain, the Ministry of Industry through the Regional Agencies of the Energy, is implementing a group of actuations in regards of the improvement of the energy efficiency in irrigable areas (IDAE 2007; Abadía et al. 2008). Important economic savings have been obtained with the development of 20 energy audits in irrigation societies of Castilla-La Mancha region.

In this paper, a new methodology to obtain the minimum total cost (investment+operation costs) by optimizing the characteristic and efficiency curves, together with the pumping pipe diameter, has been developed. This methodology is based on the theoretical relations between the characteristic and efficiency curves and it considered different variables such as: hydrologic and topographic variables (water table level, seasonal water table level variations, well flow rate, distance from well to discharge point, and elevation difference), hydraulic variables (head losses in pipes and demanded flow), and economic variables (energy

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rate, and pump and pipe costs). In order to obtain general results, different combinations of these variables were studied, obtaining general conclusions. In addition, software implemented in MATLAB environment was developed to facilitate the transference of this methodology to engineers and managers of irrigable areas.

Materials and Methods

The underground extraction process is optimized when the solution of minimum cost (investment+operation costs) is found. The main parameters to be considered in this optimization process are: the maximum flow rate of the well, obtained by performing a step-drawdown test (Jacob 1947; Hantush 1964; Bierschenk 1963), the water table level and its variation throughout the irrigation season, the volume to discharge, and the price of energy and pumps. Usually, in the pumps selection process for water extraction from an aquifer the most restrictive water table level and a discharge close to the maximum, determined by the maximum flow rate of the well, is considered. The pipe diameter can be selected using the economic sizing criteria (Labye et al. 1988; Lansey and Mays 1989). However, the evolution of the water table throughout the irrigation season and how it can affect to the energy efficiency when using the pump in different months of the irrigation season is not usually considered.

Formulation of the Model

In order to select the optimum pump for undergroundwater extraction, the shape of the characteristic and efficiency curves, together with the optimum sizing of the pumping pipe must be considered. These variables will determine the energy efficiency of the system during the whole irrigation season and the adjustment to the variable conditions of the aquifer.

The characteristic and efficiency curves of the pumps (H-Q and efficiency-Q) can be approximated by the Eqs. (1) and (2)

$$H = a + bQ + cQ^2 \tag{1}$$

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

where the coefficients a, b, c, e, and f determine the shape of the curves. In order to avoid obtaining two possible working points when solving the equation system, Jeppson (1977) proposed a variable change [Eq. (3)] to remove the b coefficient

$$Q' = Q + \frac{b}{2c} \tag{3}$$

With Eqs. (1) and (3) the characteristic curve of the pump is the following:

$$H = a' + cQ'^2 \tag{4}$$

and the coefficient a' is

$$a' = a - \frac{b^2}{4c} \tag{5}$$

Fig. 1 shows the effect of this variable transformation that permits coefficient "b" to be removed.

The coefficients e and f can be written in function of the coefficients a and c. Fig. 2 shows the relation between the head and efficiency curve.

The operating point (Q_d, H_d) is defined by the intersection of the pump characteristic curve and the system curve. Lamaddalena

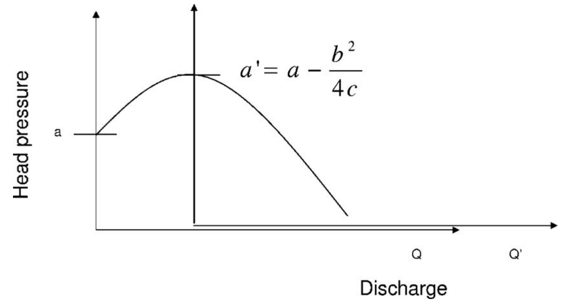

Fig. 1. Variable transformation to remove coefficient b from the characteristic curve

and Sagardoy (2000) and Calejo et al. (2008) show methodologies to obtain the characteristic curves of the distribution network. In this case, in which the distribution network is a sole pipe discharging into a reservoir, the determination of the system curve is easier, depending only on the water table level (Hg) and head losses in pumping pipe ($H=Hg+hQ^2$).

With the discharge Q_d and the efficiency curve, the efficiency ηd can be calculated. However, when the commercial pumps are selected, the head curve of the pump can intercept the system curve over the necessary operating point (Q_d, H_d), causing pressure excess if the pumps are not properly selected.

When H and η are equal to zero (Fig. 2), and considering the Eqs. (1) and (2) with $b=0$

$$Q_{\max} = \left(\frac{-a}{c}\right)^{0.5} \tag{6}$$

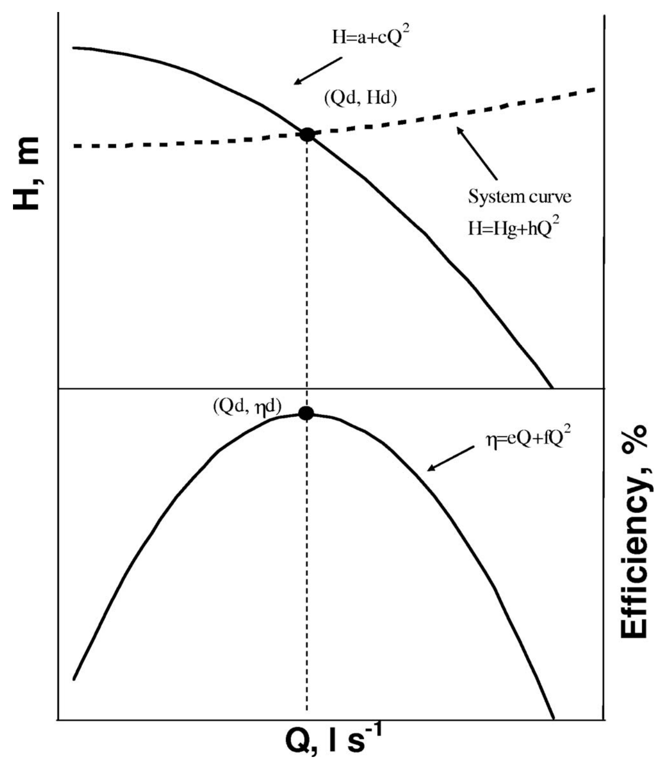

Fig. 2. Scheme of the characteristic and efficiency curves of the pumps

$$eQ_{\max} = -fQ_{\max}^2 \tag{7}$$

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

$$e = -f\left(-\frac{a}{c}\right)^{0.5} \tag{8}$$

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

$$\frac{d\eta}{dQ} = 2fQ + e = 0 \tag{9}$$

$$Q = -\frac{e}{2f} \tag{10}$$

With Eqs. (2) and (10) the following equation can be obtained:

$$\eta_{\max} = f\left(-\frac{e}{2f}\right)^2 + e\left(-\frac{e}{2f}\right) = -\frac{e^2}{4f} \tag{11}$$

Considering Eq. (8) and (11)

$$f = \frac{4 \cdot \eta_{\max}}{\left(\frac{a}{c}\right)} \tag{12}$$

From Eq. (1), with $b=0$, the following relation can be established:

$$a = H_d - c(Q_d)^2 \tag{13}$$

where H_d=design pressure head, Q_d=design discharge.

The pump power (N_p, kW) is described by Eq. (14)

$$N_p = \frac{9{,}81QH}{\eta} \tag{14}$$

with the following units: Q (m^3/s), H (m), and η (fraction).

The maximum efficiency can be determined from manufacturer information. In this study, a theoretical maximum pump efficiency of 80% was considered.

Objective Function and Optimization Variables

The optimization variables were discharge (Q), coefficient c of the characteristic curve, and the pumping pipe diameter (D). The optimization process (Fig. 3) was carried out by using the Downhill Simplex Method (Nelder and Mead 1965).

$$\mathrm{MIN}(C_{\mathrm{inv}} + C_{\mathrm{op}}) \tag{15}$$

where C_{inv}=investment annual cost [pump (C_p) and pumping pipe (C_{pp}) costs] and C_{op} is the operation cost.

Pump and pumping pipe cost can be described in Eqs. (16) and (17) (Alandi et al. 2005)

$$C_p = gN_p^3 + hN_p^2 + kN_p \tag{16}$$

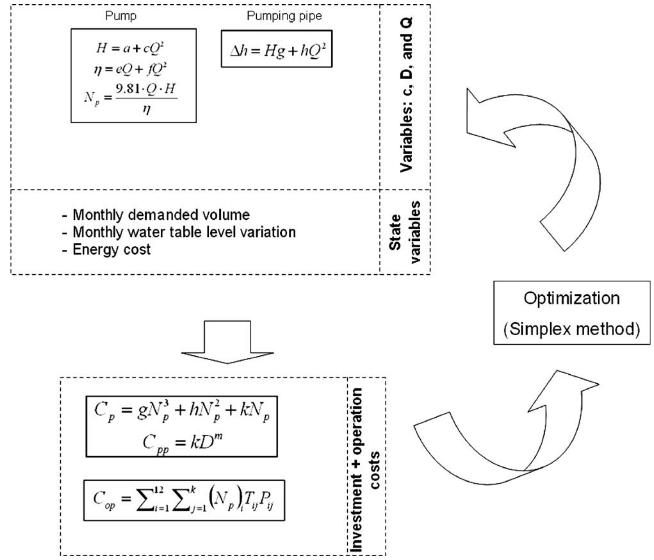

Fig. 3. Flowchart of the optimization process

$$C_{\mathrm{pp}} = KD^{\mathrm{m}} \tag{17}$$

where g, h, and k=coefficients of the third degree polynomial that describes the pump cost as a function of the pump power (N_p, kW) and K and m=coefficients of the potential curve that fits the cost of the pumping pipe as a function of pumping pipe diameter (D and m). These equations have been obtained by considering the pump and iron pipe price of different manufacturers. The coefficient of determination of the curves where 0.95 and 0.94, respectively, having both coefficients a high significance.

The annual cost of investment is calculated by multiplying the initial cost by the capital recovery factor (CRF)

$$\mathrm{CRF} = \frac{r(1+r)^t}{(1+r)^t - 1} \tag{18}$$

where t=useful life of the investment (year), and r=interest rate considered (%).

In the case study, t=10 years and r=5%. Therefore, CRF =0.13. Operating cost is determined by Eq. (19)

$$C_{\mathrm{op}} = \sum_{i=1}^{12}\sum_{j=1}^{k}(N_p)_i T_{ij} P_{ij} \tag{19}$$

where T=monthly operation time of the pump, hours; P =energy rate, €/kW; and i and j refer to month and the different energy rate periods (k) during the day, respectively.

In the case study, three periods have been considered because it is the most common case in Spain (low, medium, and high cost of energy). The available hours in each considered period are described in Table 1. The distribution of low-, medium-, and high-energy rate hours is detailed by the electrical company in a complex schedule. The main characteristics are that the low energy

Table 1. Available Number of Hours in Each Energy Cost Period for Each Month of the Year

Energy price	January	February	March	April	May	June	July	August	September	October	November	December
Low cost	368	320	407	584	712	432	392	664	560	481	360	424
Medium cost	156	152	240	136	32	228	264	72	160	220	210	156
High cost	220	200	96	0	0	60	88	8	0	44	150	164

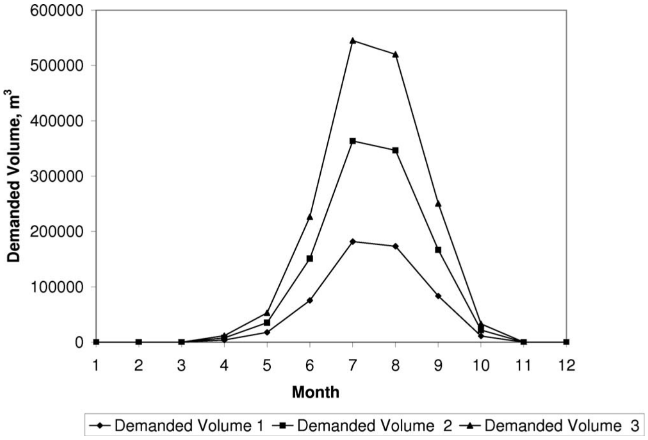

Fig. 4. Studied demanded volumes

rate period are mostly at night time (0 to 8 a.m.), weekends and national festivities. In addition, most of the month of May and August correspond to low energy rate for the whole day. Peak hour distribution is different for winter (9 a.m. to 2 p.m. and 5 p.m. to 10 p.m.) and spring and autumn (11 a.m. to 3 p.m.). The energy rate for each period is 4.55, 7.97, and 15.95 cent €/(kW·h) for low, medium, and high, respectively.

Considered Hypothesis

In order to obtain general results of 27 cases have been studied considering three volume demands (1, 2, and 3 at Fig. 4), three initial dynamic water table levels (DWTLs) (20, 50, and 100 m), and three variations of the DWTL (no variation, minor variation, and major variation).

The no variation considers that DWTL stays constant during the whole year. The minor variation considers that the DWTL decrease an accumulated 5% from February to August and increases an accumulated 10% from September to December. The major variation considers that the DWTL decrease an accumulated 10% from February to August and increases an accumulated 15% from September to December. Fig. 5 shows the three variations of the water table level though out the year for the case of an initial water table level of 100 m.

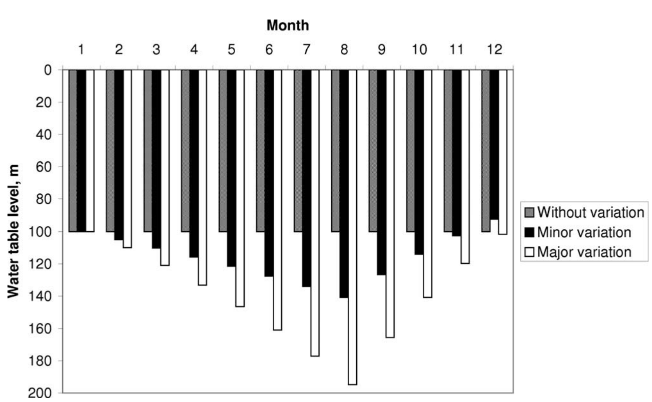

Fig. 5. Example of the three studied water table level patterns for an initial level of 100 m

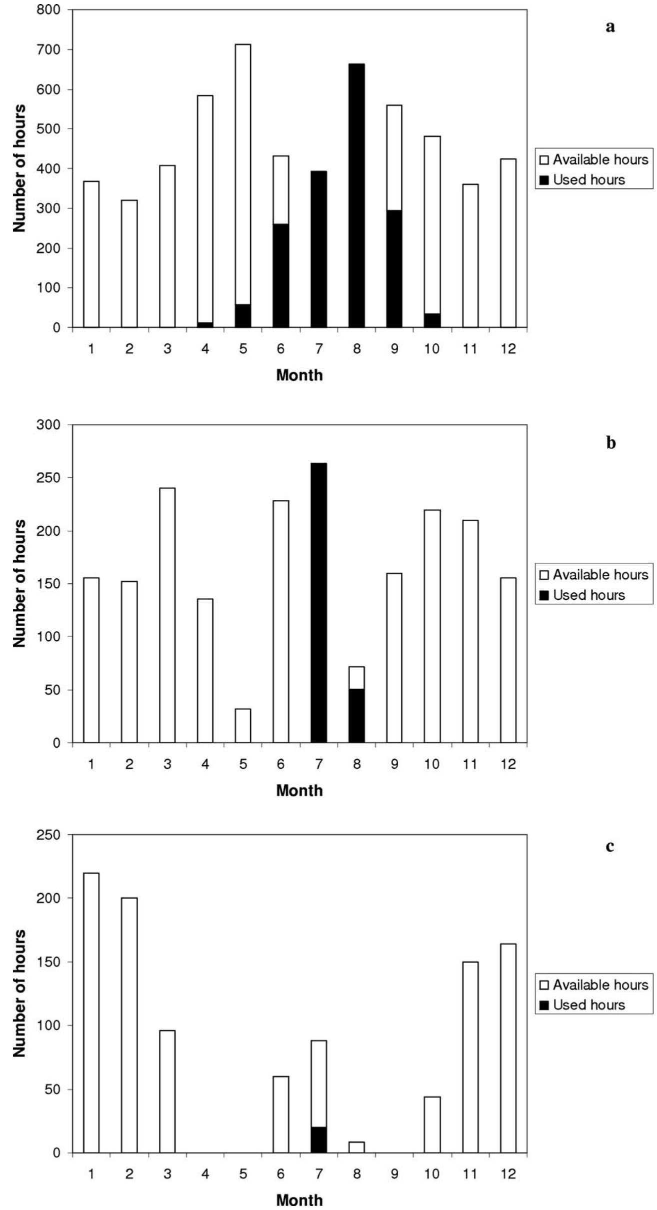

Fig. 6. Example of number of available and used hours for: (a) low-; (b) medium-; and (c) high-energy price, for each month of the year considering the Water Demand 1, an initial level of 100 m and a high variation of the water table level

Results and Discussion

Obtained results show that the optimal discharge of the pump (Q) is always greater than the minimum discharge (determined by the number of available hours in the day and the required volume of water). This is due to the high price of the energy rate in some of the hours of the day that must be avoided to reduce the operation cost. However, when the demanded volume is high it is convenient to use expensive periods (Fig. 6) in the peak period months (mostly in July) because the high energy cost is compensated with lower investment cost when installing smaller size pumps.

Fig. 7 shows the optimal discharge of the pump for the three different demanded volumes and nine different variations of the water table level considered (studied Cases 1 to 9 correspond to Volume Demand 1 (Fig. 4); studied Cases 10 to 18 correspond to Volume Demand 2 and studied Cases 19 to 27 correspond to

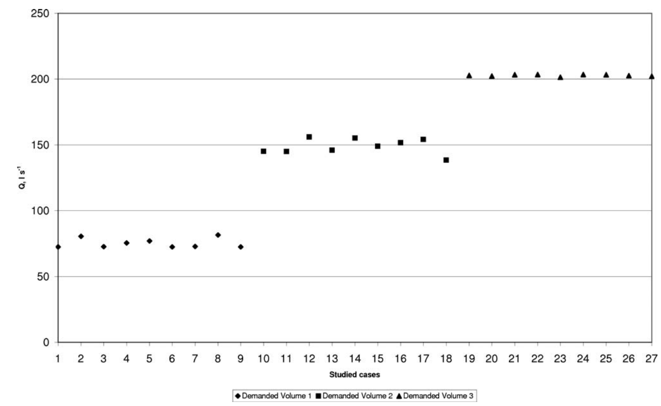

Fig. 7. Optimal flow rate for each studied demand and the nine scenarios of water table level variation

Volume Demand 3). It can be observed that, although there are high variations of the water table level, the optimal discharge is similar for each demanded volume. In addition, when the demanded volume is higher, the discharge is also higher to adjust the operation time of the pump to the available time.

However, variations of the water table level throughout the year have a clear effect on the pump characteristic curve steepness. Thus, the steepness of the *H*-*Q* curve is a main variable to adjust the pump to the required demand and to the variations of the water table level. The information of the variations of the water table level can be easily found from piezometers data registration. Fig. 8 shows the curves *H*-*Q* for each scenario of variation of the water table level throughout the year (no variation, minor variation, and major variation) for the case of 20 m of initial water table level. For the cases with higher variations of the water table level, the steepness of the *H*-*Q* curve is also higher than in the other cases, to have a better fitting with the variable conditions. Although it is obvious that when the water table decreases it is necessary to increase the pumping head, the results obtained in this paper show that not only the head should increase but also the steepness of the *H*-*Q* curve. In fact, if the steepness of the *H*-*Q* curve is high, high variation of pumping heads due to variations in water table level results in a lower range of the discharges with a high efficiency.

Fig. 9 shows the optimal flow rate for each month of the year for the Demanded Volume 1 (Fig. 4) and Demanded Volume 3 (Fig. 4). Fig. 9 shows that when the monthly demand increases,

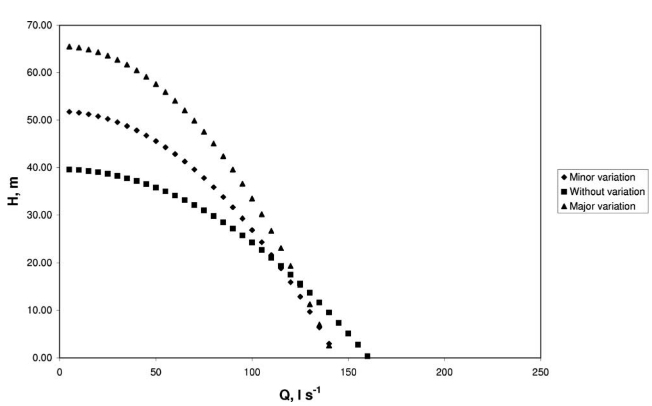

Fig. 8. Optimal characteristic curve (*H*-*Q*) for each variation of the water table level and for the Volume Demand 1

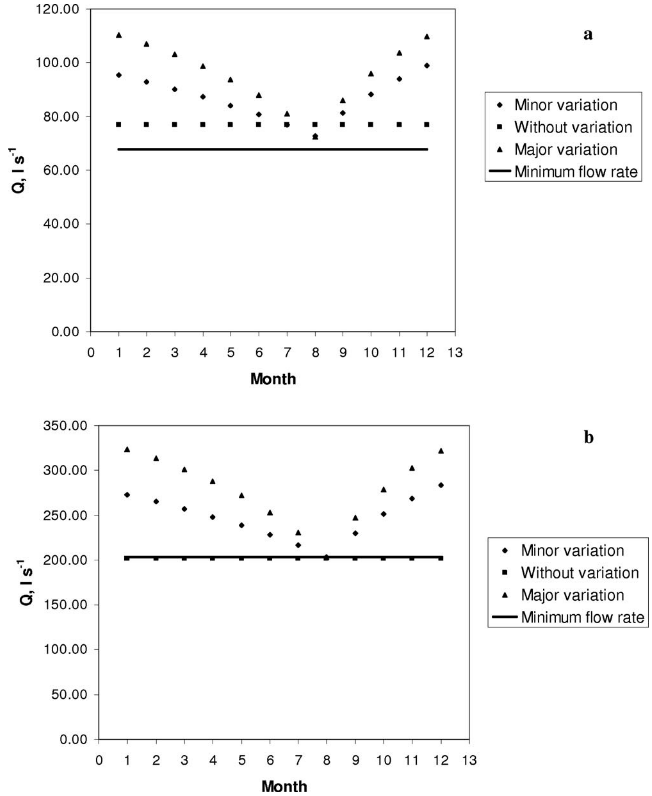

Fig. 9. Optimal flow rate for each month of the year and for each of the three considered water table level variation, considering the Demanded Volume 1 [Fig. 3(a)] and the demanded volume 3 [Fig. 3(b)]

optimal discharges are closer to the minimum flow rate, which indicates that for those months with high water demand (July and August in the case study) it is better to use expensive energy rates, than installing a bigger size pump to try to avoid them.

Fig. 10 shows the optimal *H*-*Q* and efficiency-*Q* curves and the operation points corresponding to all the months of the year for Demanded Volume 1, indicated in Fig. 4 (low demand), with an initial water table level of 50 m and high water level variation throughout the year. It can be observed that the optimal efficiency zone of the efficiency curve goes from the maximum efficiency toward the descendant part of the curve. In addition, the working point with maximum efficiency corresponds with the month of highest volume demand.

The optimal pipe diameter only depends on the demanded volume and not on the initial water table level or its variation throughout the year. This fact can be observed in Fig. 11, in which, for the three studied demanded volumes (Fig. 4), the optimal pipe diameter remains practically constant for all the different scenarios of initial water table and its variation throughout the year.

Conclusions

The characteristic and efficiency curves, together with the pumping pipe diameter, are the most important decision to take when selecting a pump for extracting water from an aquifer. The steepness of the characteristic curve is mainly associated with the water table level variation throughout the year, and the pumping pipe diameter is mainly associated with the water demand (volume). Thus, when the water table level variation is high through-

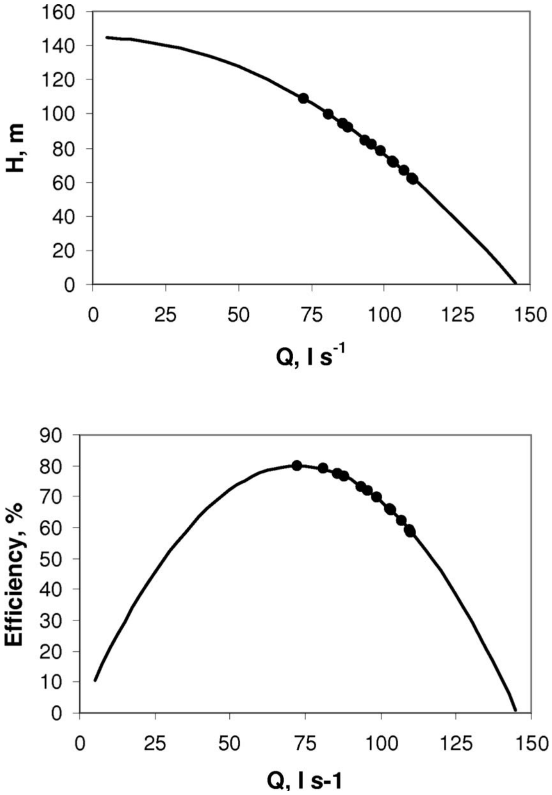

Fig. 10. Optimal characteristic and efficiency curves (H-Q and η-Q) and operation points for all the months of the year for Demanded Volume 1, with an initial water table level of 50 m, and high water level variation throughout the year

out the year, the steepness of the characteristic curve should also be high, for having a better fitting to the variable conditions. In addition, under this condition of high variable water table level, the operation point with the maximum efficiency should correspond with the month of highest demand. The flow rate and the optimal pumping pipe diameter remain practically constant for each considered demanded volume and they are not affected by the variations of the water table level.

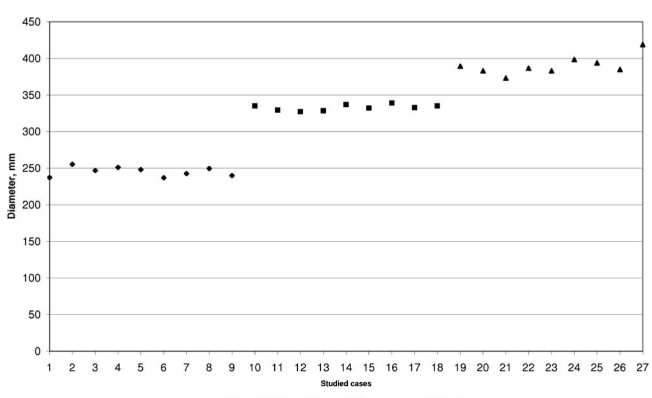

Fig. 11. Optimal pumping pipe diameters for the three studied demanded volumes and for the nine scenarios of water table level variation

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References

Abadía, R., Rocamora, C., Ruiz, A., and Puerto, H. (2008). "Energy efficiency in irrigation distribution networks I: Theory." *Biosyst. Eng.*, 101(1), 21–27.

Alandi, P. P., Perez, P. C., Álvarez, J. F. O., Hidalgo, M. A. M., and Martín-Benito, J. M. T. (2005). "Pumping selection and regulation for water distribution networks." *J. Irrig. Drain. Eng.*, 131(3), 273–281.

Bierschenk, W. (1963). "Determining well efficiency by multiple step-drawdown tests." *International Association of Scientific Hydrology*, 64, 493–507.

Calejo, M. J., Lamaddalena, N., Teixeira, J. L., and Pereira, L. S. (2008). "Performance analysis of pressurized irrigation systems operating on demand using flow-driven simulation modeling." *Agric. Water Manage.*, 95, 154–162.

Hantush, M. S. (1964). "Hydraulics of wells." *Adv. Hydrosci.*, 1, 281–442.

Helweg, O. J. (1975). "Determining optimal well discharge." *J. Irrig. and Drain. Div.*, 101(3), 201–208.

Helweg, O. J. (1982). "Economics of improving well and pump efficiency." *Ground Water*, 20, 556–562.

Helweg, O. J., and Jacob, K. P. (1991). "Selecting the optimum discharge rate for a water well." *J. Hydraul. Eng.*, 117(7), 934–939.

Helweg, O. J., VonHofe, F., and Quek, P. T. (1991). "Improving well hydraulics." *Proc., Irrigation and Drainage Specialty Conf.*, Honolulu.

Hirose, S. (1997). "Determination of the capacity of a regulating pond in a pipeline irrigation system." *Rural and Env. Engrg.*, 33, 66–78.

IDAE. (2007). *Ahorro y Eficiencia Energética en Comunidades de Regantes*, Universidad Miguel Hernández, Elche, Alicante (in Spanish).

Jacob, C. E. (1947). "Drawdown test to determine effective radius of artesian well." *Trans. Am. Soc. Civ. Eng.*, 112(2312), 1047–1070.

Jeppson, R. W. (1977). *Analysis of flow in pipe network*, Ann Arbor Science, Ann Arbor, Mich.

Labye, Y., Olson, M. A., Galand, A., and Tsourtis, N. (1988). "Design and optimisation of irrigation distribution network." *Irrigation and Drainage Paper 44*, Food and Agricultural Organization of the United Nations (FAO), Rome.

Lamaddalena N., and Sagardoy J. A. (2000). "Performance analysis of on-demand pressurized irrigation systems." *FAO Irrigation and Drainage Paper No. 59*, Rome.

Lansey, K. E., and Mays, L. W. (1989). "Optimization model for water distribution system design." *J. Hydraul. Eng.*, 115(10), 1401–1418.

Mehta, B., and Goto, A. (1992). "Design and operation of on-farm irrigation ponds." *J. Irrig. Drain. Eng.*, 118(5), 659–673.

Moradi-Jalal, M., Mariño, M. A., and Afshar, A. (2003). "Optimal design and operation of irrigation pumping stations." *J. Irrig. Drain. Eng.*, 129(3), 149–154.

Moradi-Jalal, M., Rodin, S. I., and Mariño, M. A. (2004). "Use of genetic algorithm in optimization of irrigation pumping stations." *J. Irrig. Drain. Eng.*, 130(5), 357–365.

Moreno, M. A., Carrión, P., Planells, P., Ortega, J. F., and Tarjuelo, J. M. (2007). "Measurement and improvement of the energy efficiency at pumping stations." *Biosyst. Eng.*, 98(4), 479–486.

Nelder, J. A., and Mead, R. (1965). "A simplex method for function minimization." *Comput. J.*, 7(4), 308–313.

Ortega, J. F., De Juan, J. A., and Tarjuelo, J. M. (2004). "Evaluation of the water cost effect on water resource management. Application to typical crops in a semi-arid region." *Agric. Water Manage.*, 66(2), 125–144.

Ortega, J. F., De Juan, J. A., and Tarjuelo, J. M. (2005). "Improving water management: The irrigation advisory service of Castilla-La Mancha (Spain)." *Agric. Water Manage.*, 77(1–3), 37–58.

Pulido-Calvo, I., Gutiérrez-Estrada, J. C., López-Luque, R., and Roldán, J. (2006). "Regulating reservoirs in pressurized irrigation water supply systems." *J. Water SRT-Aqua*, 55(5), 367–381.

Pulido-Calvo, I., Roldán, J., López-Luque, R., and Gutierrez-Estrada, J. C. (2003). "Water delivery planning considering irrigation simultaneity." *J. Irrig. Drain. Eng.*, 129(4), 247–255.

Sabet, M. H., and Helweg, O. J. (1989). "Peaking storage tanks for water supply systems." *Water Resour. Bull.*, 25(5), 1047–1053.

Scalmanini, J. C., Scott, V. H., and Helweg, O. J. (1979). "Energy and efficiency in wells and pumps." *Proc., 12th Biennial Conf. on Ground Water*, Sacramento, Calif., *California Water Resources Center Report No. 45*.