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# OPTIMAL HYDRAULIC AND ENERGY DESIGN OF PIVOTS DIRECTLY FED WITH GROUNDWATER

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**ABSTRACT** Nowadays, under a context of climatic change and ascending trend of the energy costs, it is necessary to develop methodologies, tools, and actuations with the aim of optimizing the energy resources use, which imply environmental and economic benefits. In Spain, as in the rest of Europe, several measures to improve the energy efficiency in irrigation systems are being implemented. Thus, important energy and economic savings have been obtained by the development of energy analysis in Irrigation Societies, which are also being implemented in private farms. This makes it necessary to determine optimal design of the irrigation systems in plots together with the pumping systems. In this work, a new methodology to determine the minimum total cost (investment+operation costs) in pivot systems fed directly from wells by optimizing the characteristics and efficiency curve of the pump together with the pumping pipe diameter and the pivot diameter, considering soil, hydraulic, and energy conditions. This methodology is based upon the theoretical relations between the characteristic and efficiency curves of the pumps, and considers different aspects such as: hydrological variables (water table and its temporal variation), hydraulic variables (head losses in pipes, demanded flow), and economic variables (energy cost, pump and pipes costs), soil variables (surface sealing and Kostiakov infiltration parameters). In order to facilitate the transfer of this methodology to designers and engineers, the DOP software has been developed under MATLAB$^{TM}$ environment.

**Keywords:** pumps, well, aquifer, optimization, characteristic curve, energy efficiency, pivot.

**INTRODUCTION** The pumping for water distribution and for ground water extraction are the main energy consumers in pressurized water networks. In fact, several authors have developed different algorithms to minimize the energy and investment costs in pumping stations (Moradi-Jalal et al., 2003; Pulido-Calvo et al., 2003; Moradi-Jalal et al., 2004; Planells 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 its size together with the irrigation system dimensioning (pivot system in this case) 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 ground water (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 and 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). However, in small farms usually water is pumped directly to the irrigation system, because of the high cost of the 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; Abadia 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 addition, these actuations are extended to the private farms, which concluded the necessity of developing methodologies to perform a proper design of the irrigation systems, together with the pumping systems, taking into account energy considerations.

In this work, a new methodology to determine the minimum total cost (investment+operation costs) in pivot systems fed directly from wells, which optimizes the characteristic and efficiency curve of the pump together with the pumping pipe diameter and the pivot diameter, by considering soil, hydraulic, and energy conditions. This methodology is based upon the theoretical relations between the characteristic and efficiency curves of the pumps, and consider different aspects such as: hydrological variables (water table and its temporal variation), hydraulic variables (head losses in pipes, demanded flow), and economic variables (energy, pump, and pipes costs), and soil variables (surface sealing and Kostiakov infiltration parameters). In order to facilitate the transference of this methodology to designers and engineers, the DOP software has been developed under MATLAB$^{TM}$ environment, being available upon requirement to the authors.

## 1. MATERIALS AND METHODS

The main parameters to be considered in the optimization process of pumping water from the well to the pivot system are: the maximum flow rate of the well, obtained by performing a step-drawdown test (Jacob (1947), Hantush (1964), Bierschenk (1963)), the crop water requirements, the water table level and its variation throughout the irrigation season, the height of the emitters, the required pressure in the emitters, the available hours (cheap, medium, and high energy price hours), and the price of energy, pumps, and pipes. In pivot systems, usually the discharge is only determined by considering the available time to irrigate in peak period, and by the infiltration problems. The pipe diameter is usually selected by considering the length of the pivot and its discharge. 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, together with the energy cost, is not usually considered.

### 1.1. Formulation of the model

In order to select the optimum pump for the pivot system directly fed from the well, the shape of the characteristic and efficiency curves, together with the optimum sizing of the pumping pipe and the pivot pipe must be considered. These variables will determine the energy efficiency of the entire system as a set 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) (Moreno et al., 2009).

$$H = a + bQ + cQ^2 \qquad (1)$$

$$\eta = eQ + fQ^2 \qquad (2)$$

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.

$$Q' = Q + \frac{b}{2c} \qquad (3)$$

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

$$H = a' + cQ'^2 \qquad (4)$$

And the coefficient *a'* is:

$$a' = a - \frac{b^2}{4c} \qquad (5)$$

The coefficients *e* and *f* can be written in function of the coefficients *a* and *c*.

The operating point (Qd, Hd) is defined by the intersection of the pump characteristic curve and the system curve. Lamaddalena and Sagadoy (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 the pivot system, the determination of the system curve is easier, depending only on the water table level (Hg) and head losses in pumping pipe and the pivot system. Gilley (1989) and Keller (1990) recommend using the Hazen-Williams equation corrected for pivots by the coefficient proposed by Shu Tung Chu et al. (1972):

$$h_p = 0.548 \cdot 10.646 \left( \frac{Q_0}{C} \right)^{1.852} \cdot D^{-4.87} \cdot R \qquad (6)$$

Where $Q_0$ is the flow in the head of the pivot, C is the Hazen-William friction factor, which is recommended to be 128 for new pipes and 115 for old pipes, D is the pivot pipe diameter, and R the length of the pivot.

With the discharge Qd and the efficiency curve, the efficiency ηd can be calculated.

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

$$Q_{\max} = \left( \frac{-a}{c} \right)^{0.5} \qquad (7)$$

$$e\,Q_{max} = -f\,Q_{max}^2 \qquad (8)$$

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

$$e = -f\left(-\frac{a}{c}\right)^{0.5} \qquad (9)$$

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

$$\frac{d\eta}{dQ} = 2\,f\,Q + e = 0 \qquad (10)$$

$$Q = -\frac{e}{2\,f} \qquad (11)$$

With Eqs. (2) and (11) the following equation can be obtained:

$$\eta_{max} = f\left(-\frac{e}{2\,f}\right)^2 + e\left(-\frac{e}{2\,f}\right) = -\frac{e^2}{4\,f} \qquad (12)$$

Considering Eq. (9) and (12):

$$f = \frac{4\cdot\eta_{max}}{\left(\frac{a}{c}\right)} \qquad (13)$$

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

$$a = H_d - c\left(Q_d\right)^2 \qquad (14)$$

Where: $H_d$= design pressure head, $Q_d$= design discharge.

The pump power ($N_p$, kW) is described by Eq. (15):

$$N_p = \frac{9{,}81\;Q\;H}{\eta} \qquad (15)$$

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.

### 1.2. Objective function and optimization variables

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

$$\mathrm{MIN}(C_{inv} + C_{op}) \qquad (16)$$

where $C_{inv}$ is the investment annual cost (pump ($C_p$), pumping pipe ($C_{pp}$), and pivot pipe ($C_{pivotp}$) costs) and $C_{op}$ is the operation cost. The cost of the auxiliary components that, in any case, should be installed, are not considered, since it does not change the result of the optimization process.

Pump, pumping pipe, and pivot pipe costs are described in Eqs. (17), (18), and (19) (Planells et al. 2005)

$$\mathrm{C_p} = g\ \mathrm{N_p^3} + h\mathrm{N_p^2} + k\mathrm{N_p} \qquad (17)$$

$$\mathrm{C_{pp}} = K\ D^{\mathrm{m}} \qquad (18)$$

$$\mathrm{C_{pivotp}} = q\ D_{\mathrm{pivot}}^{\mathrm{s}} \qquad (19)$$

where *g*, *h*, and *k* are the coefficients of the third degree polynomial that describes the pump cost as a function of the pump power ($N_p$, kW), *K*, *m*, *q*, *and s* are the coefficients of the potential curves that fit the cost of the pumping pipe as a function of pumping pipe diameter (D, en m) and the pivot pipe as a function of the pivot pipe diameter ($D_{pivot}$). These equations have been obtained by considering the pump, iron pipe, and pivot pipe prices of different manufacturers. The coefficient of determination of the curves where 0.95, 0.94, and 0.95, 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)

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

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. (21)

$$C_{op} = \sum_{i=1}^{12} \sum_{j=1}^{k} \left(N_p\right)_i T_{ij} P_{ij} \qquad (21)$$

where *T* is the monthly operation time of the pump, hours; *P* is the energy rate, €/kW, and *i* and *j* refers 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 rate period are mostly at night time (0:00 to 8:00 am), weekends and national festivities. Peak hour distribution is different for winter (5:00pm-11:00 pm) and summer (10:00 am-4:00pm). The energy rate for each period is 7.21, 10.3074, and 11.374 cent €/(kW h) for low, medium, and high energy prices, respectively .

## 1.3. Pivot performance

One of the main problems when facing the design and management of the pivot systems is the possibility to find runoff in the extreme of the pivot. In order to avoid this problem, the maximum precipitation of the system should be determined, as well as the minimum wetted width. Both depends on the speed of the pivot and the type of emmiter (Allen 1991). In the methodology proposed in this work, the pumping and pivot system is optimized as a set by minimizing the total cost, and after that, the maximum precipitation in the pivot extreme is calculated by using eq. (22). It supposes an elliptical model of water distribution (Allen 1991, Tarjuelo 2005).

$$\mathrm{Pm} = \frac{28800\,\mathrm{Q}_0}{\pi\,\mathrm{R}\,\mathrm{AM}_\mathrm{R}} \qquad (22)$$

Where Pm is the maximum precipitation in the pivot extreme (mm/h), R is the length of the pivot (m), and $\mathrm{AM}_\mathrm{R}$ is the wetted width (m) in the pivot extreme.

Finally, the runoff is evaluated by using the methodology proposed by Allen (1991), and calculating the minimum wetted width and the speed for not having runoff. This methodology considers that, in order to avoid the runoff problems, the precipitation of the system should not overpass the infiltration capacity of the soil, after considering the storage capacity of the soil surface and the surface sealing.

Allen (1991) utilized the Kostiakov equation (Eq. 23) to estimate the water infiltration in the soil, and two equations (Eqs. 24 and 25) were deduced, which can be solved by iterative processes. This determines the maximum precipitation of the system that can have the extreme of the pivot without problems of runoff.

$$i = K \cdot t^n \qquad (23)$$

Where i is the infiltration rate (mm/min), K and n are experimental data for equation fitting, and t is the time since the precipitation start in a point until it finish (min).

$$Pm = \frac{(1 - SR\frac{Pm}{K})(D - AS)^{n/(n+1)}(n+1)^{n/(n+1)}K^{1/(n+1)}}{[1.05 - 1.6(\pi/2)^2(D/Dba - 0.5)^2]^{1/2}} \qquad (24)$$

$$D = \left( \frac{[1.05Pm^2 - 1.6Pm^2(\pi/2)^2(D/Dba - 0.5)^2]^{-1/2}[-1.6Pm^2(\pi/2)^2(D/Dba - 0.5)/Dba]}{\left(1 - SR\frac{Pm}{K}\right)K^{\frac{1}{n+1}}(n+1)^{-1/(n+1)}n} \right)^{-(n+1)} + AS \qquad (25)$$

where SR is the surface sealing; D is the water applied in a time t (mm); AS is the surface storage capacity (mm); Dba is the total applied water by the pivot (mm).

### 1.4. Analyzed scenarios

The wide number and characteristic of the analyzed scenarios try to represent the major part of the conditions that can be found in real life. Therefore, the analysis of these scenarios can result in a generalization of the main characteristics of the pivot and pumping system required. The analyzed scenarios can be summarized in the following list:

- Five machine lengths (30, 50, 75, 100, and 125 m)

- Three initial dynamic water table levels (DWTL). referred to January (40, 70, 120 m). Another analyzed scenario is considered in which the DWTL is zero and its variation throughout the year is also zero, which tries to represent the case of pumping from a reservoir.
- Three variations through out the year (2.5, 5.0, and 7.5%). The minor variation considers that the DWTL decrease an accumulated 2.5% from February to August and increases an accumulated 4.2% from September to December. The medium variation considers that the DWTL decrease an accumulated 5% from February to August and increases an accumulated 8.2% from September to December The major variation considers that the DWTL decrease an accumulated 7.5% from February to August and increases an accumulated 12% from September to December.
- Three different energy rates, which result in different energy cost per kWh. The number of hours in each month for each energy period is the same for the three scenarios (Table 1). However. the prices for power access and energy consumption are different (Table 2).

Table 1. Monthly hours of each energy rate period

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Low period | 248 | 224 | 248 | 240 | 248 | 240 | 248 | 248 | 240 | 248 | 240 | 248 |
| Medium period | 310 | 280 | 310 | 300 | 310 | 300 | 310 | 310 | 300 | 310 | 300 | 310 |
| **High period** | 186 | 168 | 186 | 180 | 186 | 180 | 186 | 186 | 180 | 186 | 180 | 186 |

Table 2. Energy rates of power access and energy consumption

| | Energy rate period | Power access € $kW^{-1}$ | Energy € $kWh^{-1}$ |
|---|---|---|---|
| Scenario 1 (low rate) | Low period | 1.56 | 0.0467 |
| | Medium period | 2.34 | 0.0820 |
| | High period | 3.90 | 0.1640 |
| Scenario 2 (Medium rate) | Low period | 2.13 | 0.0754 |
| | Medium period | 9.31 | 0.1071 |
| | High period | 15.09 | 0.1211 |
| Scenario 3 (High rate) | Low period | 3.33 | 0.0867* |
| | Medium period | 14.52 | 0.1232* |
| | High period | 23.54 | 0.1392* |

The different scenarios of initial DWTL and its variation throughout the year can be summarize in Table 3.

Table 3. Analyzed scenarios of initial DWTL and its variation throughout the year

| Scenario | DWTL | Variation of de DWTL |
|---|---|---|
| 0.0 | 0 | 0 |
| 1.1 | 40 | 2.5 |
| 1.2 | 70 | 2.5 |
| 1.3 | 120 | 2.5 |
| 2.1 | 40 | 5 |
| 2.2 | 70 | 5 |
| 2.3 | 120 | 5 |
| 3.1 | 40 | 7.5 |

| | | |
|---|---|---|
| 3.2 | 70 | 7.5 |
| 3.3 | 120 | 7.5 |

# 2. RESULTS

## 2.1. Water application cost analysis

In this epigraph the effect of the watertable level and its variation throughout the year on the total cost of irrigation (investment+operation) is analyzed. Thus, to obtain general conclusions about pivot systems design and dimensioning, it has been evaluated the effect of having three different initial water table (40, 70, and 120 m) with the same level of variation (5%), and afterwards, the effect of different variation of the DWTL (2.5, 5, and 7.5%) for a medium initial water table level (70 m).

### 2.1.1. Analysis of the initial DWTL on the pivot dimensioning

Fig. 1 represents the trend of the cost per hectare with the area. In most of the cases, the area that minimizes the total cost is between 75-100 ha.

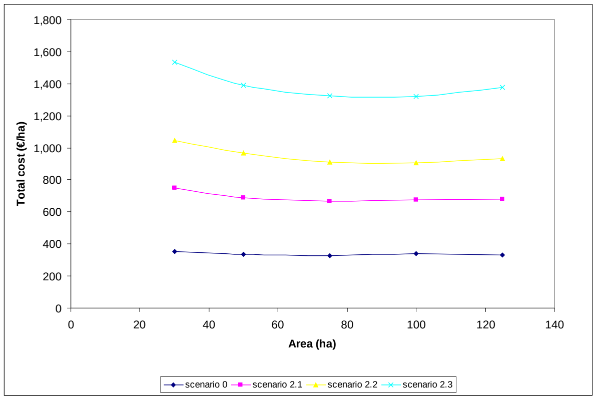

Figure 1. Total cost per hectare of the analyzed cases

Regarding energy cost, for all the scenarios, the energy cost per unit of area is similar for each irrigated area. However, this difference is more evident for those large analyzed areas, which can lead to a higher total cost per unit of area due to energy cost.

Regarding the investment and maintenance costs, it decreases with the irrigated area and that the differences between 100 and 125 ha are almost insignificant. This effect, together with the commented energy costs, explains that the pivot with minimum cost is between 75-100 ha.

The required power is a key point to perform a proper design of pivot systems. There is a good lineal fitting of the required power with the irrigated area. In addition, it is concluded that the slope of the linear fitting increases with the DWTL, which means that the demand of energy increase in a higher rate the higher is the DWTL. This can lead to a high demand of power in those pivot systems that irrigates large areas in areas with deep DWTL.

### 2.1.2. Analysis of the variation of the DWTL on the pivot dimensioning

In this epigraph the results of the dimensioning of those scenarios corresponding to a DWTL of 70 m and variations of the DWTL of 2.5, 5, and 7% (scenarios 2.1, 2.2., and 2.3) are shown.

The results of these scenarios show a similar trend than the previous analysis about energy, investment and maintenance, and total cost. However, there was less differences between scenarios since the variation of the DWTL were lower than in the previous cases. The best results are also obtained for areas between 75-100 ha. Also, the slope of the linear fitting of the power with the area is higher the higher the variation of the DWTL but less pronounced than in the previous cases.

## 2.2. Analysis of the pumping system

The results of the required power to install for each area and each scenario of DWTL and its variation throughout the year, each irrigated area, and each scenario of energy rates shows that the energy rate do not have a high effect on the required power.

In addition to determine the power requirements, it is necessary to establish the ideal working conditions of the pumping system (working pressure and discharge). A key issue is the slope of the characteristic curve that optimize the pumping system performance. This slope is represented by the coefficient “c” of the characteristic curve (eq. 1). Fig. 2 shows an example of the working points for pivots with different areas for an analyzed scenario 1.2 and high energy rate.

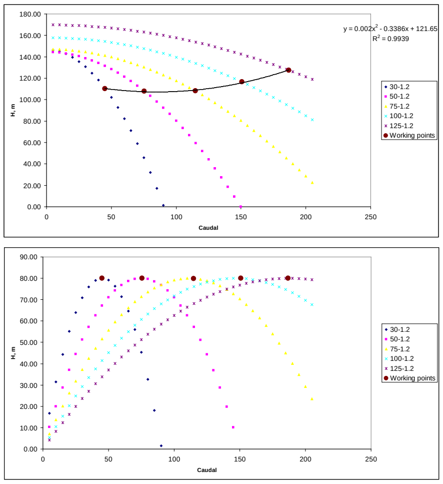

Figure 2. a) Working point Q-H and b) working point Q-efficiency, for pivoto f different size in the case of the scenario 1.2 for the high energy rate

It is shown that for the working point Q-efficiency is always in the maximum values for the moment of deepest DWTL and the rest of the months (with higher DWTL) the working points goes to the decreasing zone of the Q-efficiency curve.

The proper selection of the slope of the characteristic curve is necessary to perform an adequate dimensioning of the pumping system. The pivots that irrigate low areas, have a high variability of the optimum slope depending on the analyzed scenario. However, those pivots that irrigated large areas, have a practically constant slope. Thus, it is more important to select a pump with a proper slope in small pivots, considering that the higher the variation of the DWTL, the higher the slope of the pumping system.

### 2.3. Discharge and irrigation time.

Most of the analyzed cases shows that the optimum irrigation time is 18 h/day, which matches the sum of the available cheap and medium price of energy hours. This leads to a discharge of 1.5 l/s/ha when considering a peak water demand of 8 mm/day. However, those pivot systems that irrigates large areas under a context of deep DWTL and high variation DWTL (DWTL= 120 m with a 7.5% of variation), the optimum irrigation time is 24 h/day. This is not practicable, since it is necessary to have some hours during the day to perform maintenance works, among others. Thus, the irrigation time was restricted to 20 h/day. When implementing this restriction, the optimum time for the large pivots and high DWTL did selected 20 h/day but 18 h/d, because it is not adequate to contract the power in the high period rate for using only 2 hours of it. Thus, it can be concluded that the proper irrigation time is in all the cases 18 h/day, and in the case of peak water demand of 8 mm/day, the discharge of the pivot is in all the cases around 1.5 l/s/ha.

### 2.4. Pivot pipe sizing

The pivot pipe size does not change depending on the scenario of DWTL analyzed but only with the irrigated area. Thus, recommendation of pivot pipe sizing can be easily performed for each analyzed area. For 30 ha the optimum diameter is 162 mm, between 196 and 212 mm for 50 ha, and 246 mm for the remainder areas.

**CONCLUSION** It is presented a study and a tool that help to perform the decision making process about design and dimensioning of pivot systems directly fed with groundwater. It is concluded the importance of the proper selection of the characteristics of the pumping system together with the adequate dimensioning of the pivot pipe. The effect of the DWTL and its variation shows that it is crucial to select an adequate type of pump, characterized by the slope of the Q-H curve. The irrigation time and, therefore, the pivot discharge is greatly influenced by the energy rate periods, being in this case an optimum irrigation time 18 h/day.

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