Agricultural Water Management 107 (2012) 112–121

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Optimal design of center pivot systems with water supplied from wells

M.A. Moreno*, D. Medina, J.F. Ortega, J.M. Tarjuelo

Regional Centre of Water Research (CREA), UCLM, Ctra. de las Peñas, km 3.2, 02071 Albacete, Spain

ARTICLE INFO

Article history:
Received 8 March 2011
Accepted 22 January 2012
Available online 17 February 2012

Keywords:
Pumps
Well
Aquifer
Characteristic curve
Energy efficiency
Center pivot

ABSTRACT

Irrigation is one of the sectors in which energy consumption is increasing, mainly due to modernized systems designed to conserve water through the use of pressurized water distribution. Energy is one of the principle costs in irrigation. In this study, a new methodology is developed to determine the minimum total water application cost (investment + operation costs) in center pivot systems withdrawing water from wells. The proposed methodology optimizes the characteristic and efficiency curves for the pump as well as the types and diameters of pipes for pumping and distribution. In addition, the method accounts for hydrological variables (dynamic water table level and temporal variation), soil variables (infiltration parameters, surface storage capacity, surface impermeability), hydraulic variables (head losses in pipes, flow demand) and economic variables (energy costs, pump and pipe costs). In order to facilitate the technology transfer to managers and technicians, free software (DOP, "Diseño Optimo de Pivotes," or Optimal Pivot Design) has been developed using MATLAB™. Results show that the best options are timing irrigation to avoid periods of high energy costs as well as increasing pumping power and pipe size, with a greater system capacity (1.5 L s^{-1} ha^{-1}), and shorter operation time (18 h day^{-1}). The minimum water application cost is obtained in all case studies in this paper for center pivot systems irrigating 75 ha, with lateral pipes of 254 mm (10 in.).

1. Introduction

Efficient water and energy use have increasing importance in agriculture due to reduced water availability and increasing energy costs, which determine the viability of irrigated agriculture in many areas of the world. Currently, the projected effects of climate change and increasing energy costs have stimulated development of methods, tools, and actions aimed at optimizing the use of energy resources for environmental and economic benefits.

Center pivot irrigation systems are among the most popular for irrigating field crops and are used on over half of sprinkler irrigated lands in the United States, Brazil, Argentina, and other countries (Allen et al., 2000). In Spain, 46% of the 3.4 Mha irrigated land are drip irrigation systems, with 14% set sprinkler irrigation systems and 8% mechanized sprinkler irrigation systems, mostly center pivot (ESYRCE, 2008). Application of this type of system requires consideration of energy issues in addition to water efficiency, which complicates the decision making process, especially from an economic point of view. Thus, the Spanish Ministry of Industry, through the Regional Energy Agencies, is implementing a group of actions for improving energy efficiency in irrigable areas (IDEA, 2007; Abadía et al., 2008; Jackson et al., 2010; Rodríguez Díaz et al., 2011). Important economic savings have been observed after 20 energy audits in Irrigation Societies in the Region of Castilla-La Mancha (Moreno et al., 2010a). These actions are extended to privately owned farms, in response to a need to design irrigation systems and pumping systems such that energy usage is considered.

In Castilla-La Mancha (Spain), as in other Regions in the world, the main source of water is groundwater (more than 65% of irrigation and urban water). Water is extracted by using submersible pumps and stored in a reservoir or injected directly into the irrigation system (Ortega et al., 2004a, 2005). Castilla-La Mancha is one of the Regions in Spain with the most center pivot systems for irrigation using groundwater extracted from different aquifers (Martín de Santa Olalla et al., 1999, 2007; Ortega et al., 2005).

For large irrigation areas, the most common structure includes a reservoir to store water which is then pressurized for irrigation by pumping stations (Moreno et al., 2007). In small farms water is usually pumped directly to the irrigation system because of the high cost of reservoirs. An analysis of the main performance indicators and energy costs has been performed by Córcoles et al. (in press).

Irrigation Advisory Services (IASs) are implemented to help farmers efficiently use resources, especially water, fertilizer, and energy. IASs provide farmers with adequate scientific and technical support to increase agriculture sustainability and compatibility

* Corresponding author.
E-mail addresses: MiguelAngel.Moreno@uclm.es (M.A. Moreno), Diego.Medina@uclm.es (D. Medina), Jose.Ortega@uclm.es (J.F. Ortega), Jose.Tarjuelo@uclm.es (J.M. Tarjuelo).

0378-3774/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2012.01.016

with the environment (Ortega et al., 2005). It is important to advise farmers on the design and management of irrigation water systems to reduce water application costs.

The Irrigation Advisory Service (IAS) in Castilla-La Mancha has developed methods for advising irrigators on the amount and uniformity of water applied that maximize the gross margin of different crops (Ortega et al., 2004a,b, 2005). These analyses and 10 years of experience of the IAS emphasize that the relationship between the amount of water applied in irrigation and the economic benefit is very complex and difficult to model (non-linear functions) (Tarjuelo and de Juan, 1999; Garrido, 2001; Ortega et al., 2004a). This relationship is highly dependent on the crop management by the farmer, which in turn depends on the irrigation system design (Córcoles et al., 2010, in press).

The amount of uncertainty in the agrarian market (high product variability between years, changes in the cropping pattern, etc.) can be balanced by making recommendations in irrigation system design, specifically to have high water application uniformity (>85%) by applying crop-specific irrigation depths for reaching maximum gross margin (Ortega et al., 2004b,c). Therefore, if the irrigation system is designed for high uniformity (85–90%) there is little influence of investment and management costs on water application costs (Montero et al., 2004; Ortega et al., 2004c). For this reason, this study does not consider the relationship between the amount of water and the economic benefit in the proposed design process for center pivot systems.

Pumping for water distribution and groundwater extraction are the main sources of energy consumption in pressurized water networks. Several authors have developed algorithms to minimize the energy and investment costs in pumping stations (Moradi-Jalal et al., 2003, 2004; Pulido-Calvo et al., 2003; Planells et al., 2005; Moreno et al., 2007). Other studies have been focused on determining the most affordable amount of well discharge from a hydrological point of view (Helweg, 1975, 1982; Scalmanini et al., 1979; Helweg et al., 1991; Helweg and Jacob, 1991). However, considering the proper pump type and size together with the irrigation system dimensions (center pivot in this case) has not been found in the literature.

The type of sprinklers normally used in center pivots are classic impact sprinklers and new generation sprinklers, which include moving spray plate sprinklers (MPS) or stationary spray plate sprinklers (SPS). Plates vary from being totally smooth to having coarse grooves and can have concave or convex shapes. Thus, throw and drop diameters can be regulated according to irrigation needs (Sourell et al., 2003). Classic impact sprinklers usually operate at a medium pressure, between 250 and 300 kPa, with a small angle (6–15°), requiring direct assembly along the pipe of the center pivot. The newest generation of sprinkler heads can also be assembled on the pipe. Recommended installation is close to the ground using flexible drop pipes, which allows for sprinkler installation at different heights, or even releasing water directly onto the ground (known as a LEPA system; Low Energy Precision Application) (Schneider and Howell, 1999; Tarjuelo, 2005).

The objective of this study is to develop a new methodology for determining the minimum total water application cost (investment + operation costs) in center pivot systems with water supplied from wells. This approach requires optimization of the characteristic and efficiency curves of the pump, the diameters of pumping pipes, distribution pipes, and lateral pipes considering hydrological, hydraulic, soil, and energy conditions.

2. Materials and methods

This optimization process aims to minimize the total water application cost per area irrigated by a center pivot system (C_T, € ha^{-1} year^{-1}) throughout the irrigation season. This cost is the sum of investment (C_{inv}), maintenance (C_m) and operational costs (C_{op}). The only investment costs considered are those of the infrastructure involved in the optimization process (pumps, pumping pipes, distribution pipes, and lateral pipes, including the triangular structure, towers with wheels and the sprinkler package as a set). The remaining elements (control panel, alignment and security systems, central concrete base, etc.) are considered constant for similarly sized machines.

The main parameters considered in optimizing the water application process (Fig. 1), pumping directly from the well to the center pivot, are: the maximum flow rate of the well from a step-drawdown test (Jacob, 1947; Hantush, 1964; Bierschenk, 1963), crop water requirements, water table level and variation throughout the irrigation season, sprinkler pressure and height, time of day in terms of low, medium, and high energy cost hours, and the price of energy, pumps, and pipes. In center pivot systems, discharge is usually determined by considering the time of day irrigation occurs to coincide with peak crop water requirements and by soil infiltration limitations (Allen et al., 2000). Lateral pipe diameter is usually selected by considering the length of the center pivot and discharge. However, the change in the water table level throughout the irrigation season and its effects on energy efficiency in different months is not usually considered in conjunction with energy costs.

The discharge of the center pivot is one of the variables to be optimized. This depends on the crop water requirements and the time of day in terms of energy rates, as irrigation during certain hours is more expensive than others. If discharge is low, energy costs are higher because this coincides with a need to irrigate during peak energy cost hours, but the overall investment is cheaper. However, if discharge is high, irrigation can be scheduled during the cheapest energy rate hours, but this requires a higher investment cost (larger pumps and pipes). The optimization process recommends a discharge that minimizes the total cost of the center pivot system.

In order to easily transfer this methodology to managers and technicians, DOP (Optimal Pivot Design) free distribution software has been developed using MATLAB™.

2.1. Model formulation

In order to select the optimum pump for supplying the center pivot directly from the well, the shape of the characteristic (Q–H) and efficiency (Q–η) curves, optimum sizes of the pumping and lateral pipes must be considered. These variables will determine the energy efficiency of the system as a whole during the entire irrigation season and are adjusted to variable aquifer conditions.

The characteristic and efficiency curves of the pumps (H–Q and efficiency–Q) can be approximated by 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.

To avoid obtaining two possible working points when solving the equation system, Jeppson (1977) proposed [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:

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

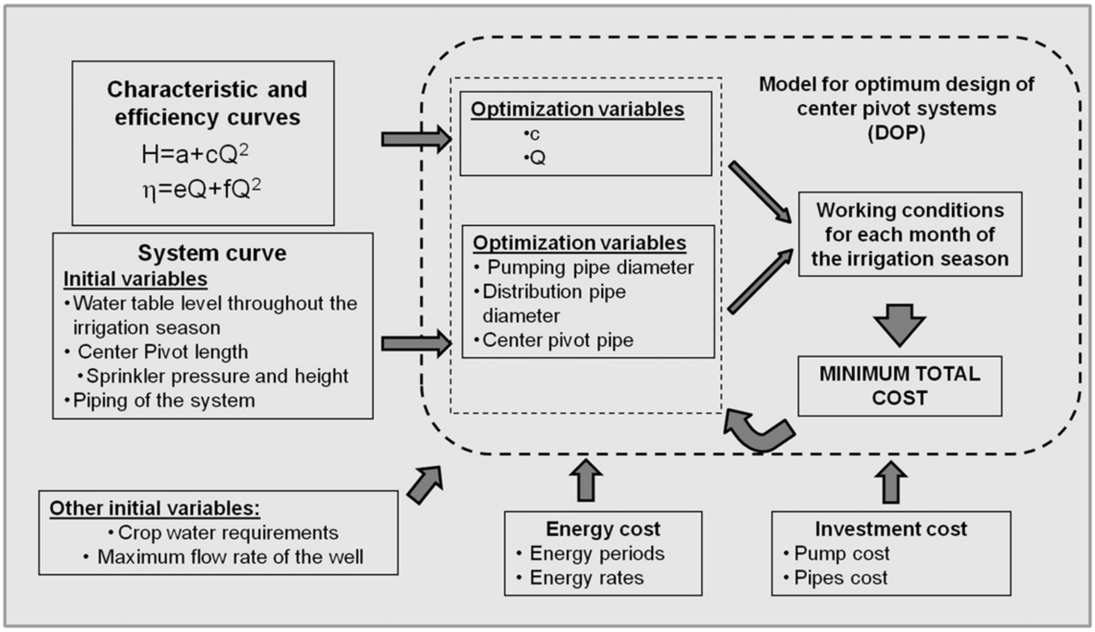

Fig. 1. Diagram of the optimization process.

And coefficient a' is:

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

Fig. 2 shows the effect of this variable transformation with coefficient "b" removed.

Coefficients e and f can be written as a function of coefficients a and c (Moreno et al., 2010b). Fig. 3 shows the relationship between the characteristic and efficiency curves.

The operating point (Q_d, H_d) is defined by the intersection of the pump characteristic curve and the system curve. The system curve fits an equation of the type $H = H_g + \Delta h$, where H_g is the vertical distance the water is pumped and Δh are the head losses in the pipes. Thus, the system curve depends on the dynamic water table level and head losses from the lateral pipe.

When H and η are equal to zero (Fig. 3) and considering Eqs. (1) and (2) with $b = 0$:

$$H = 0 \Rightarrow a = -cQ_{\max}^2 \Rightarrow Q_{\max} = \left(\frac{-a}{c}\right)^{0.5} \tag{6}$$

$$\eta = 0 \Rightarrow eQ_{\max} = -fQ_{\max}^2 \tag{7}$$

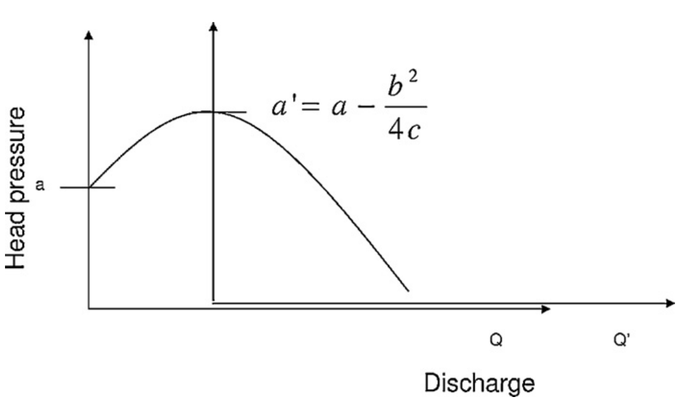

Fig. 2. Change of variable of the characteristic curve.

Thus coefficient e is defined in Eq. (8) as

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

The relationship between coefficient f and coefficients a and c, considering maximum efficiency, is obtained as follows:

$$\eta_{\max} \Rightarrow \frac{d\eta}{dQ} = 2fQ + e = 0 \Rightarrow Q = -\frac{e}{2f} \tag{9}$$

With Eqs. (2) and (9) the following equation can be obtained:

$$\eta_{\max} \Rightarrow \frac{d\eta}{dQ} = 2fQ + e = 0 \Rightarrow Q = -\frac{e}{2f} \tag{10}$$

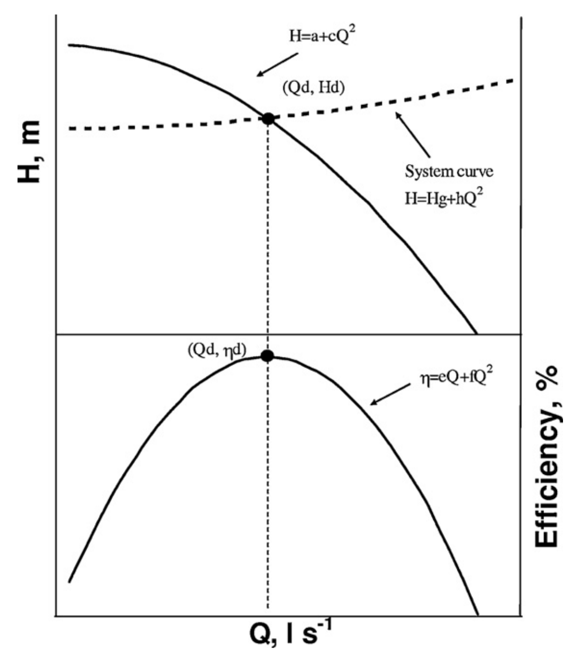

Fig. 3. Relationship between the characteristic and efficiency curves.

Considering Eqs. (8) and (10):

$$f = \frac{4 \cdot \eta_{max}}{a/c} \quad (11)$$

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

$$a = H_d - c(Q_d)^2 \quad (12)$$

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

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

2.2. Hydraulics of the center pivot system

Head pressure, H_o, can be calculated with Eq. (13)

$$H_o = H_e + h_r + H_g + \Delta Z \quad (13)$$

where H_e = nominal sprinkler operating pressure (H_e = 15 m in the case study), H_g = height of the sprinkler above the ground (H_g = 2.5 m in the case study), ΔZ is the difference in elevation for the slope (m) (ΔZ = 0 m in the case study), and h_r is friction losses in the pipe, calculated in the case study with the Hazen–Williams equation (Keller and Bliesner, 1990):

$$h_r = 0.548 \times h_{ro} = 0.548 \times \left(10.646 \times \left(\frac{Q_0}{C'}\right)^{1.852} \times D_{cp}^{-4.87} \times R\right) \quad (14)$$

where h_{ro} = head losses in a pipe considering a flow rate Q_0 in a pipe of internal diameter D_{cp} and with a length of R, Q_0 = flow rate at the pipe entrance ($m^3 s^{-1}$); C' = friction coefficient (C' = 115 for galvanized steel pipe used in the case study); D_{cp} = internal diameter of the lateral pipe (m); R = irrigated area radius (m).

Friction losses for the pumping pipe (steel) (h_{rpp}) are calculated with the Hazen–Williams equation as follows:

$$h_{rpp} = 10.646 \times \left(\frac{Q_0}{C'}\right)^{1.852} \times D_{pp}^{-4.87} \times L \quad (15)$$

where L = length of the pump pipe and D_{pp} = internal diameter of the pump pipe.

The friction losses of the distribution pipe (h_{rdp}) (PVC), connecting the well with the center pivot point, is calculated with Eq. (16) by Veronese–Datei.

$$h_{rdp} = 9.2 \times 10^{-4} \left(\frac{Q_0^{1.8}}{D_d^{4.8}}\right) \times L \quad (16)$$

where D_d = internal diameter of the distribution pipe.

In all pipes, local losses due to friction have been estimated at 10%.

Thus, the pressure head that the pump must supply (H_T) is:

$$H_T = H_o + h_{rpp} + h_{rdp} + \mathrm{DWTL} \quad (17)$$

where DWTL = dynamic water table level in the well.

The general application efficiency (E_a) for a defined percentage of adequately irrigated area (pa) can be calculated as (Keller and Bliesner, 1990):

$$E_a = \mathrm{ED}_a \times P_{ef} \times O_e \quad (18)$$

where ED_a = distribution efficiency (ratio of minimum depth on wettest pa% of the field, D_n, to average depth of water infiltrated into the soil, D_{rs}); P_{ef} = fraction of applied water that reaches the soil surface; and O_e = ratio of water effectively discharged through sprinkler orifices or nozzles to the total system discharge.

Table 1
Costs obtained from manufacturers and distributors.

Pump cost (€)	$C_{pu} = 0.0016N_p^3 + 0.924N_p^2 + 268, 28N_p$ with N_p in kW
Pumping pipe cost (steel) (€)	$C_{pi} = 0.1007D_p^{1.0853}(D_{pp}, \mathrm{mm})$
Distribution pipe cost (PVC 0.6 MPa) (€)	$C_{pd} = 0.001D_d^{1.8459}(D_d, \mathrm{mm})$
Center pivot pipe cost (€)	$C_{pp} = 0.7198D_{cp}^{0.969}(D_{cp}, \mathrm{mm})$

Assuming water distribution through the irrigation system follows a normal distribution (Keller and Bliesner, 1990), the ED_a value can be easily deduced as a function of the irrigation uniformity coefficient (CU) and the percentage of adequately irrigated area (a).

In this study, for an SPS (Spray) sprinkler type, an application efficiency of E_a = 0.82 was considered, which corresponds to a soil water uniformity during the irrigation season of CU = 88% (Ortiz et al., 2010) at an adequately irrigated area of pa = 80% (Ortega et al., 2004a) (equivalent to ED_a = 87.3%) and a proportion of water reaching the soil P_{ef} = 94% (equivalent to evaporation and drip losses EDLs = 6%) (Ortiz et al., 2009).

2.3. Objective function and optimization variables

The optimization variables were discharge (Q), coefficient c from the characteristic curve, the pumping pipe diameter (D_{pp}), the distribution pipe diameter (D_d) and the lateral pipe diameter (D_{cp}). The optimization process (Fig. 1) was performed using the Downhill Simplex Method (Nelder and Mead, 1965), which aims to minimize the total cost:

$$\mathrm{MIN}(C_{inv} + C_m + C_{op}) \quad (19)$$

where C_{inv} = annual investment cost (including the pump (C_p), pump pipe (C_{pp}), distribution pipe, and lateral pipe (C_{pivotp}) costs), C_m = annual maintenance cost, and C_{op} = annual operational cost, which includes energy costs.

2.4. Annual investment cost

In order to calculate the investment cost for the center pivot system, the following diameters, which are the most commonly used, have been considered (external diameter): 127 mm (5 in.), 152.4 mm (6 in.); 168.3 mm (6 5/8 in.), 219 mm (8 5/8 in.), and 254 mm (10 in.). The thickness of the pipe was 2.4, 2.6, 2.8, 3.2, and 3.4 mm for these diameters, respectively.

The investment cost (C_{inv}) are pump, pump pipe, distribution pipe, and center pivot costs, including the lateral pipe as well as the triangular structure of spans, towers with wheels and the sprinkler package with drops at 2.5 m in height because they are a integrated set of each lateral pipe diameter. In order to analyze the results, these costs will be divided by the irrigated area.

To determine the total investment cost (C_i, in €) for each case study, the average prices of different manufacturers and distributors in Spain were considered.

The components of the investment cost are shown in Table 1.

The coefficients of determination of the cost regression curves were higher than 0.94, and both coefficients were highly significant.

The investment annuity (A = CRF C_i, in € year^{-1}) for the total investment cost (C_{inv}, in €) was computed considering an equipment life of n = 24 years (considering that the pump, sprinklers, and the lateral pipe are changed after 12 years), and an interest rate (i) of 5%. The capital recovery factor (CRF) and the investment annuity per unit of irrigated area (C_a, in € ha^{-1} year^{-1}) were calculated using Eqs. (20) and (21):

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (20)$$

Table 2
Monthly hours of each energy rate period.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	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 3
Energy rates of power access and energy consumption.

Energy rate period	Power access (€ kW^{-1})	Energy (€ kWh^{-1})
Low period	3.33	0.0867
Medium period	14.52	0.1232
High period	23.54	0.1392

$$C_a = \frac{A}{S} = \frac{\mathrm{CRF} \times C_{\mathrm{inv}}}{S} \tag{21}$$

where S = area irrigated by the center pivot (ha).

2.5. Annual operation cost

The power consumed in water application (N_p, in kW) was calculated from the pressure (H_T, in m) and discharge (Q_0, in m^3 s^{-1}) necessary for the proper functioning of the center pivot system (Eq. (22)):

$$N_p = \frac{9.81\, Q_o H_T}{\eta} \tag{22}$$

where η = efficiency of the pumping system (a fraction), and H_T and Q_o were determined by considering the sprinkler pressure and flow rate required, as well as losses due to friction in the pipes and differences in elevation.

The annual energy cost (C_{op}) is calculated with Eq. (23):

$$C_{op} = \sum_{i=1}^{12} \sum_{j=1}^{k} (N_p)_i T_{ij} P_{ij} \tag{23}$$

where T = monthly operation time of the pump (h); P = energy rate, € kW^{-1} h^{-1}, and i and j refer to the months and the energy rate hours (k) during the day, respectively.

The energy cost per irrigated area (C_e, € year^{-1} ha^{-1}) is calculated by dividing the operational cost (C_{op}) by the irrigated area (S, in ha).

Calculations are based in energy prices in Spain, with the available hours in each period described in Table 2. The distribution of low, medium, and high energy rate hours is detailed by the electrical company in a complex schedule. It can be simplified into three periods: (1) low energy rate period, which is mostly at night (0:00 to 8:00 am), (2) medium energy rate period (10 h) and (3) high energy rate period (6 h). The energy rates for each period are detailed in Table 3.

To consider the possibility that energy prices will change at rates different from the general rate of inflation, Eq. (24) (Keller and Bliesner, 1990) has been implemented in the developed software. Thus, a sensitivity analysis has been performed to evaluate the effect of the rate of energy escalation and the general inflation rate on the final center pivot design.

$$\mathrm{EAE} = \left[\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \times \left[\frac{i}{(1+i)^n - 1}\right] \tag{24}$$

where e = annual rate of escalation in energy costs.

2.5.1. Annual maintenance cost

In this case, an additional 1% of the investment cost is considered for maintenance costs (C_m) to reach an equipment life of 24 years.

2.6. Center pivot system performance

One of the main problems in design and management of center pivot systems is the possibility of finding runoff at the moving end. To avoid this, the peak application rate of the system should be determined, as well as the minimum wetted width, depending on the type of sprinkler, and the minimum speed in the lateral pipe to avoid runoff (Keller and Bliesner, 1990; Allen, 1991; Allen et al., 2000). In the methodology proposed here, the pumping and center pivot systems are jointly optimized by minimizing the total water application cost. Then, peak application rate in the moving end of the center pivot (P_{mR}) is calculated using Eq. (25). The assumption is an elliptically shaped application pattern (Keller and Bliesner, 1990; Allen, 1991; Tarjuelo, 2005):

$$P_{mR} = \frac{28{,}800 Q_s}{\pi R W_R} \tag{25}$$

where P_{mR} = peak application rate from the moving end (mm h^{-1}), R = radius of irrigation (m), and W_R = wetted width (m) in the moving end of the lateral pipe, and $Q_s = Q_o\, P_{ef}$, is the discharge that reaches the ground, Q_o = discharge obtained with the optimization process, and P_{ef} = the fraction of applied water that reaches the soil surface.

The possibility of runoff is evaluated using the methodology proposed by Allen (1991), by calculating the peak application rate in the moving end (P_m), minimum wetted width and the speed of the machine required for avoiding runoff. Comparison of these values with the real values (P_{mR} and wetted width of the used sprinkler) yields the probability of runoff. In this methodology, to avoid runoff problems the application rate of the system should not surpass the infiltration capacity of the soil, considering the storage capacity of the soil and impermeability.

Allen (1991) used the Kostiakov equation (Eq. (26)) to estimate water infiltration into the soil:

$$i = K \times t^n \tag{26}$$

where i = soil infiltration rate (mm min^{-1}), K and n are experimental parameters for equation fitting, and t is the time since the water application starts in a point until it finishes (min).

Two equations (Eqs. (27) and (28)) are produced, which can be solved with iterative processes. This determines the peak application rate of the system that the soil is able to infiltrate without runoff (P_m, in mm min^{-1}).

$$P_m = \frac{\left(1 - \mathrm{SR}\frac{P_m}{K}\right)(D - \mathrm{AS})^{n/(n+1)}(n+1)^{n/(n+1)} K^{1/(n+1)}}{\left[1.05 - 1.6\,(\pi/2)^2 (D/D_{rs} - 0.5)^2\right]^{1/2}} \tag{27}$$

$$D = \left(\frac{\left[1.05P_m^2 - 1.6P_m^2(\pi/2)^2(D/D_{rs} - 0.5)^2\right]^{-1/2}\left[-1.6P_m^2(\pi/2)^2(D/D_{rs} - 0.5)/D_{rs}\right]}{(1 - \mathrm{SR}(P_m/K))K^{1/(n+1)}(n+1)^{-1/(n+1)}n}\right)^{-(n+1)} + \mathrm{AS} \tag{28}$$

Table 4
General values for microdepression and foliage storage.

Type of crop or cover	$SS_m + SS_f$
Bare weathered soil	1
Newly tilled land	2–3
Pasture and grass cover	3
Drilled crops (alfalfa, grain)	2
Short row crops	2
Tall row crops (corn)	3

where SR = surface sealing (with values of 0.36 when ground is tilled, 0.20 for ground tilled a long time ago, and 0.16 for alfalfa stubble); D = water applied during a time t (mm); SS = surface storage capacity, which can reach 8 mm (Allen, 1991; Allen et al., 2000); D_{rs} = total water depth applied by the system to one point on the ground (mm).

Keller and Bliesner (1990) recommend Eq. (29) for estimating the average depth of surface storage:

$$SS = SS_m + kSS_d + SS_f \tag{29}$$

where SS_m = storage capacity of microdepressions (mm), SS_d = storage capacity of small depressions (mm), SS_f = storage of plant foliage (mm) and k = 0.5 for furrowed fields and 1.0 for smooth fields.

SS_d values can be predicted using Eq. (30):

$$SS_d = \frac{(6-s)(12-s)^2}{144} \tag{30}$$

where s = general fields slope in area under study (%) (and $s \leq 6\%$).

The value of SS_m depends on the microcharacterictics of the soil surface and is essentially independent of slope. Foliage storage, SS_f, is a function of vegetation density, leaf structure and height. General values for SS_m and SS_f are listed in Table 4.

Tillage implements are available to provide what is called "reservoir tillage" or "furrow dikes" for increasing the intake rate of the furrows (by the ripping) and the SS by incorporating a series of small reservoirs (Allen et al., 2000).

To calculate the maximum irrigation time at the moving end of the lateral (t_p) for avoiding runoff Eq. (31) is used, assuming a semi-elliptical shape of the application pattern.

$$t_p = \frac{4D_{rs}}{\pi P_m} \tag{31}$$

where P_m = vertical semi-axis of the ellipse, and D_{rs} = area of the semi-ellipse.

The minimum speed of the center pivot (V_m) to avoid runoff at the end is calculated with Eq. (32):

$$V_m = \frac{2\pi L_t N_{n\,max}}{60 ED_a D_{rs} OT} \tag{32}$$

where L_t = distance from the pivot point to the last tower, N_{nmax} = crop water requirements during the peak period (mm day^{-1}), ED_a = distribution efficiency, and OT = operation time (fraction of time that the system is turned on for a day in the peak period) (18 h day^{-1} for instance).

The minimum wetted width at the moving end of the machines to avoid runoff is calculated with Eq. (33):

$$MW_R = t_p V \tag{33}$$

To avoid runoff, the following must be true: $P_{mR} < P_m$; $W_R > MW_R$ and $V > V_m$, where V = the speed of the last tower on the center pivot system.

Table 5
Analyzed scenarios of variation of the DWTL.

Scenario	Initial DWTL (Jan)	Decrease DWTL (%) Feb–Aug	Increase DWTL (%) Aug–Dec
0.0	0	0	0
1.1	40	2.5	4.2
1.2	70	2.5	4.2
1.3	120	2.5	4.2
2.1	40	5.0	8.2
2.2	70	5.0	8.2
2.3	120	5.0	8.2
3.1	40	7.5	12.0
3.2	70	7.5	12.0
3.3	120	7.5	12.0

2.7. Case studies

To examine the influence of the most important variables in water application costs in center pivot systems, 50 case studies were analyzed. These cases consider five sizes of plots irrigated with center pivot systems (30, 50, 75, 100, and 125 ha), three initial dynamic water table levels (DWTL) in the wells (40, 70, and 120 m), each affected by three variations in DWTL throughout the year. Pumping water from a surface water source is assigned an initial DWTL of 0 m and no variation in DWTL during the year. Table 5 summarizes the scenarios of DWTL variation. January has the initial DWTL value, with increasing depth from January to August and decreasing from September to December such that the next January returns to the initial DWTL.

For each case study, the DOP model was applied to obtain the required pump, pipe diameters, and working conditions of the center pivot system as well as the investment and operation costs per irrigated area.

3. Results and discussion

3.1. Optimum diameters of the center pivot pipes

The optimal pipe diameter for minimum water application costs depends mainly on the area that is irrigated and, therefore, on the length of the center pivot lateral pipe. The diameter of the center pivot has been found to be independent of DWTL values and variation (Fig. 4) in most of the cases. The optimal diameters for each size plot is 168.3 mm (6 5/8 in.) for an area of 30 ha, 219 mm (8 5/8 in.) for 50 ha, and 254 mm (10 in.) for 75, 100, and 125 ha. These results are contrary to the widespread use of a lateral pipe size of 168.3 mm (6 5/8 in.) to irrigate up to 60–70 ha (Tarjuelo, 2005). This standard was used in Spain by the most important center pivot manufacturers and installers under a context of low energy costs (half those utilized in the present study). Thus, the increasing trend in energy

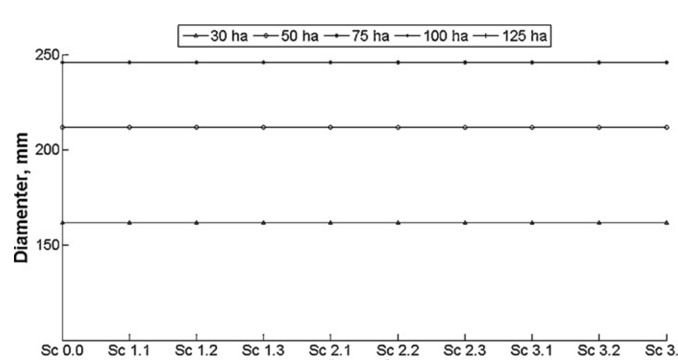

Fig. 4. Optimum lateral pipe diameter for each analyzed scenario and for each irrigated area considered.

Table 6
Values of the optimal pump power, system capacity, and pivot pipes diameters for different values of *e* and for $i = 5\%$.

e (%)	Pivot pipe diameter (mm)	System capacity ($l\,s^{-1}\,ha^{-1}$)	Pump power (kW)
1.0	207	1.55	109.5
5.0	217	1.53	106.3
7.5	229	1.54	104.9
10.0	252	1.53	103.9

costs would lead to an increase in pipe diameters. Currently, energy costs (kWh^{-1}) in Spain have increased by more than 100% from 2008 to 2011 due to energy dependency and the end of subsidies for electricity in agriculture. This generates further support for the usefulness of the tool developed in this study.

In all cases, the distribution pipe commercial diameters have been found to be between 315 and 400 mm, depending on the area irrigated. Similar results were obtained for the pumping pipe, resulting in commercial diameters between 200 and 250 mm, independent of DWTL values and variation.

These results have yielded general recommendations for optimal diameters relative to plot size. However, the DOP tool can be used to determine the exact diameters required under specific conditions for investment and energy costs. Hence, a sensitivity analysis on changes in the discount rate (i) values and the annual rate of escalation in energy cost (e) was performed. This analysis indicated very few changes in the results for values of the discount rates of 3–15%. For discount rate values higher than 15%, the optimal pipeline diameter and the system capacity decrease. As a consequence of the system capacity decrease the pump power also decreases. However, this high discount rate is unlikely in Europe or the USA. During the last decade, the interest rate has not increased over 5% in Europe, even considering the economic crisis and market variability (ECB, 2011).

In the case of changes of *e*, the pump power decreases when increasing the e, the pivot pipe diameter increases, and the system capacity remains practically constant. As an example, for the scenario 1.1, four values of e were considered (1, 5, 7.5, and 10%) for an interest rate of 5%. Table 6 shows the values of the optimal pump power, system capacity, and pivot pipes diameters when changing *e* values.

For other countries, the tool developed can be used to consider other discount rates and energy costs.

3.2. Analysis of the effect of the DWTL on the total water application cost with a center pivot system

As an example, Fig. 5 shows the total annual water application cost, the investment cost, and operational cost per irrigated area for each of the plot sizes analyzed in this study with an initial DWTL of 70, and a decrease 5% in DWTL (scenario 2.2), considering energy prices from 2010.

The minimum cost is obtained for an irrigation system operating on 75 ha (490 m of center pivot lateral length), with a total annual cost per unit irrigated area of 1159 €/ha.

The main characteristics of the irrigation system in this minimum cost scenario are a system capacity of $1.5\,L\,s^{-1}\,ha^{-1}$, a 181 kW pump, a pumping pipe of 250 mm (steel), a distribution pipe of 400 mm (PVC – 0.6 MPa), and a lateral pipe of 254 mm (10 in.). The operation time is $18\,h\,day^{-1}$ and the minimum speed for avoiding runoff is $2.9\,m\,min^{-1}$.

The results of the total water application cost for each area (Fig. 6) show that the minimum cost is for a center pivot that irrigates 75 ha. This is due to the high increase in energy cost when the center pivot irrigates more than 75 ha. This increases costs at a higher rate than the decrease in the investment + maintenance

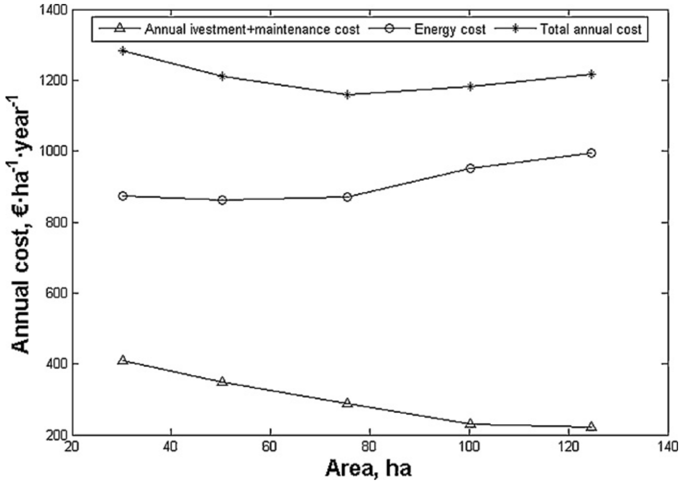

Fig. 5. Annual water application cost for the DWTL scenario 2.2.

costs (Fig. 5). These differences are higher at a deeper initial DWTL and greater variation throughout the year.

3.3. Analysis of the effect of the DWTL on the power of the center pivot pump

The required power of the pumping system increases with the area irrigated, increasing more quickly when the DWTL is deeper. There is a direct relationship between variations in DWTL throughout the irrigation season and the power required, with greater differences when the initial DWTL is deeper (Fig. 7). The initial DWTL has a greater influence on the final power installed than variation in DWTL. However, higher variation in DWTL throughout the irrigation season leads to higher differences in the power installed for cases with the same initial DWTL.

3.4. Analysis of the pump characteristics that minimize the total water application cost of the scenarios analyzed

For each irrigated area and DWTL condition there is an optimum power, which corresponds with a specific discharge and head pressure. The system capacity is near $1.5\,L\,s^{-1}\,ha^{-1}$ for most cases and the head pressure depends on the DWTL and area irrigated. This system capacity is slightly higher than the usual value, which

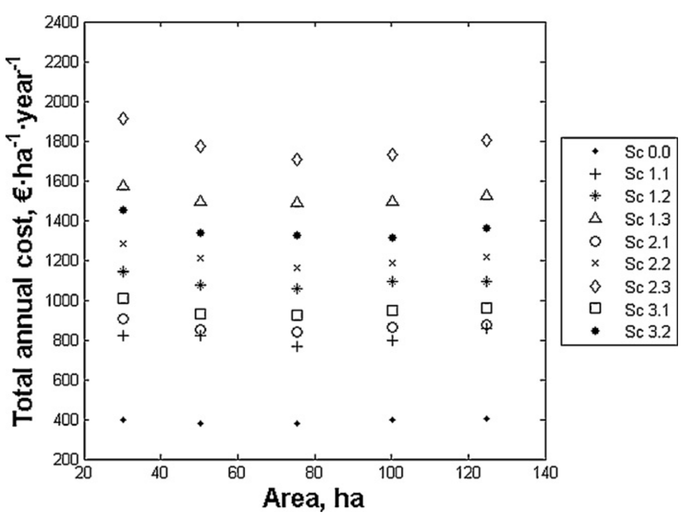

Fig. 6. Water application cost for each analyzed area and for the scenarios 0, 2.1, 2.2, and 2.3.

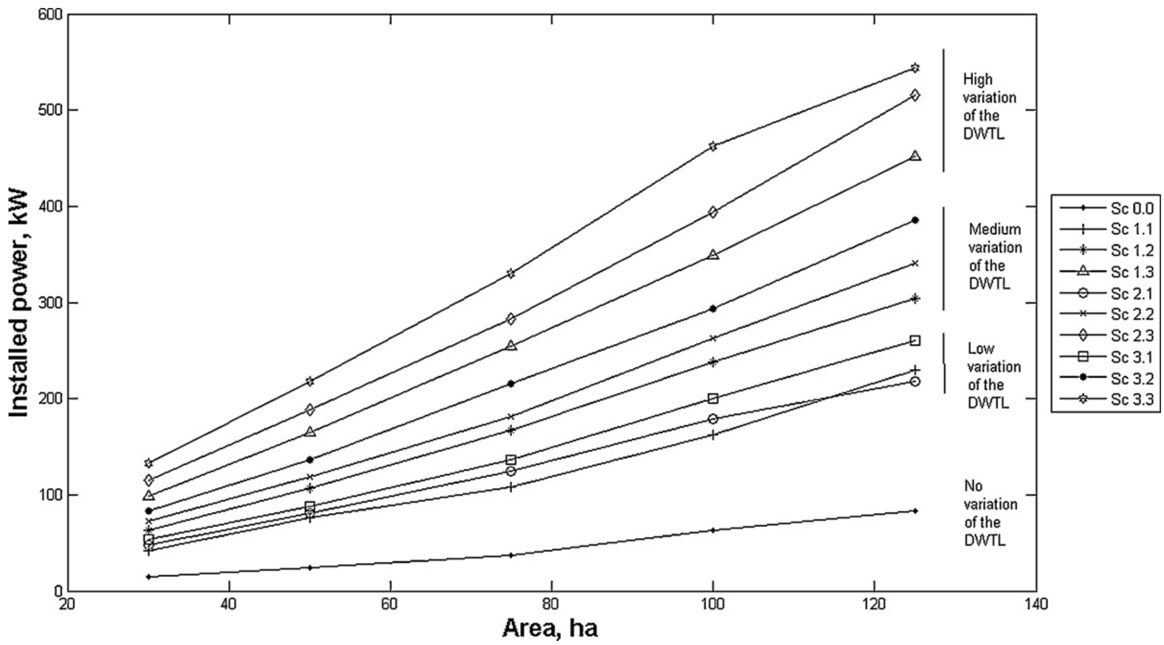

Figure 7. Power requirements for each analyzed scenarios.

is 1.2–1.3 L s^{-1} ha^{-1} (Keller and Bliesner, 1990; Allen et al., 2000; Tarjuelo, 2005) when operation time (OT) is 20 h day^{-1}. In this case, as will be explained later, the optimal OT is 18 h day^{-1}, due to the energy rate schedule.

The steepness of the characteristic curve of the pump that minimizes the total water application cost is also obtained with the DOP model, which is represented by coefficient "c" (Eq. (1)). With the characteristic curve of the pump and the working conditions of the center pivot, the operation point of the pump can be obtained for each month in each scenario. Fig. 8 shows the operation points for all the areas analyzed with scenario 1.2 (initial DWTL of 70 m and a decrease in DWTL of 2.5% until August) for the month with the deepest DWTL (August). The operation point for this month coincides with the maximum pump efficiency.

The slope of the H–Q curve of optimal total water application cost is higher for machines that irrigate small areas and higher when initial DWTL is deeper (Fig. 9). In addition, the slope of the H–Q curve is nearly constant for center pivots that irrigate large areas, nearly independent of the DWTL characteristics. An accessory application which recommends a certain commercial pump from a catalogue that best fits the shape of the Q–H and Q–efficiency curves could be easily added. However, in this study this was not included.

Another important aspect of the operation point of the pump for each month of the irrigation season is for the operation point to reach the maximum efficiency for the month with the deepest DWTL (August). During other months the operation point is the same as in August, when pressure regulators are used in each sprinkler, making the discharge of each sprinkler constant. Fig. 10 shows a diagram of the system and characteristic curves of the month with the deepest DWTL (August in the case studies), and the system curves if pressure regulators are present before water intake into

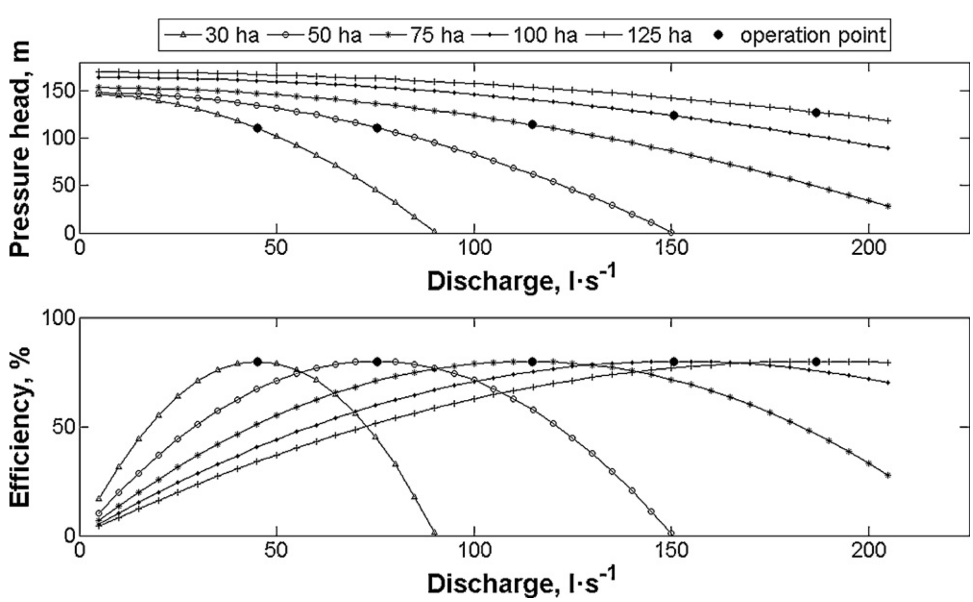

Fig. 8. Operation points of the pumps (a) H–Q and (b) efficiency for the different irrigated areas and for the scenario 1.2.

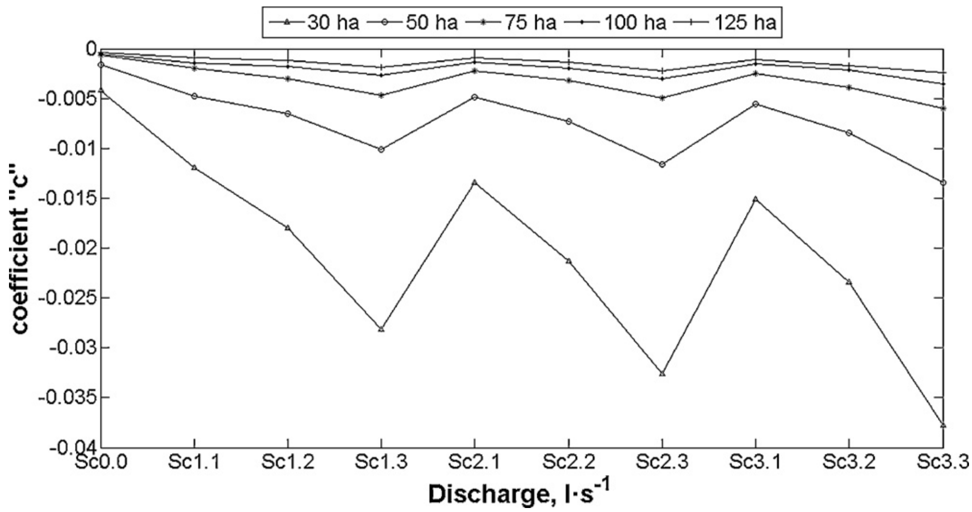

Fig. 9. Variation of the steepness of the *H–Q* curve for each analyzed scenario and for each irrigated area.

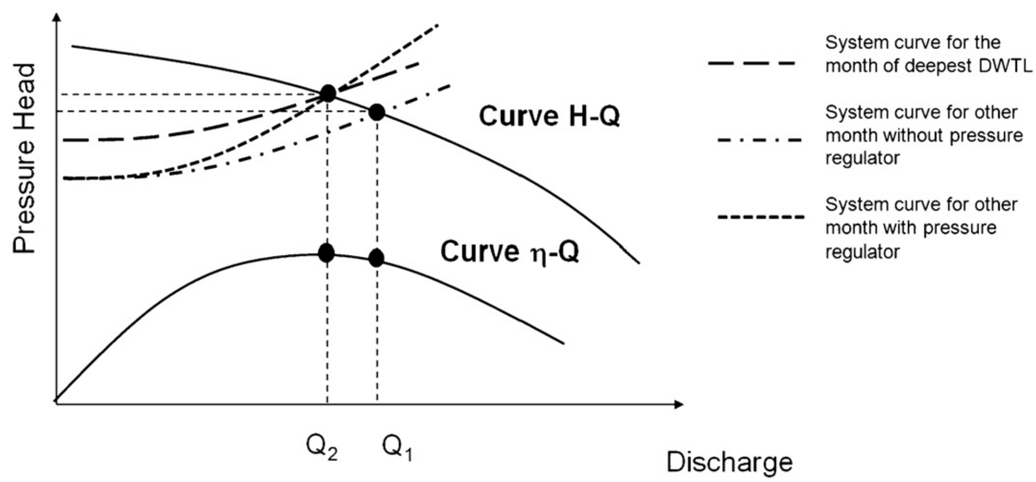

Fig. 10. Scheme of the operation point of the system when the center pivot is working in the month with deepest DWTL and when it is working in other months.

the sprinkler. This could lead to a waste of energy that should be evaluated, with a possible option for energy saving in controlling the pump with a frequency speed drive. However, the economic viability of this option must be studied.

3.5. Operation time and system capacity of the system

As expected, the energy rate schedule has a high influence on determining the best operation time (OT) of the irrigation system. This also affects the system capacity. Considering a maximum OT of 20 h day^{-1} in prevision of maintenance tasks and failures, the optimal OT in all cases was 18 h day^{-1} with an optimal system capacity of approximately 1.5 L s^{-1} ha^{-1}. However, for the largest center pivot lateral pipes with conditions of deep DWTL and high DWTL variation throughout the irrigation season, optimal OT could reach 24 day^{-1} if this restriction is not included. This is due to the distribution of low, medium, and high energy rates (8 h of low, 10 of medium, and 6 of high energy rates).

3.6. Minimum velocity of the center pivot lateral and wetted width to avoid runoff

In the case studies, a gross water depth of 8 mm was considered for the peak period. The minimum speed for avoiding problems associated with runoff were 1.8 m min^{-1} for an irrigated area of 30 ha, 2.3 m min^{-1} for 50 ha, 2.9 m min^{-1} for 75 ha, 3.3 m min^{-1} for 100 ha, and 3.65 m min^{-1} for 125 ha. The wetted width varies between 6 and 10 m for sandy soils, reaching 25 m when the soil is clay. This wetted width is not affordable for the current moving plate sprinklers (MPS) or stationary plate sprinklers (SPS), which can reach 16–18 m and 9–12 m, respectively. Thus, the tool permits users to set the dimensions of the center pivot system with a maximum discharge to avoid runoff and obtain a reasonable wetted width.

4. Conclusions

A powerful tool has been developed to design and dimension the whole center pivot system in terms of the optimum pumping system together with the optimum pumping, distribution and lateral pipes. This is done considering energy rates and the dynamic water table level conditions for each month of the irrigation season, for minimum total water application cost (investment + operation costs). In addition, the tool calculates the conditions of system performance to avoid runoff.

The increase in energy rates is driving an increase in the power required by the pumping system. Recommendations of this study include using larger pipe diameters and avoiding energy periods with high costs, reducing the operation time to 18 h day^{-1} from the usual 20–22 h day^{-1}, and increasing the system capacity to 1.5 L s^{-1} ha^{-1} instead of the usual 1.2–1.3 L s^{-1} ha^{-1}.

The results show the minimum water application costs are seen in center pivot systems that irrigate 75 ha, with a lateral pipe size of 254 mm (10 in.). This shows that the widespread use of 168.3 mm (6 5/8 in.) pipe size for surfaces between 35 and 60 ha is not recommended as they lead to increased energy costs.

References

Abadía, R., Rocamora, C., Ruiz, A., Puerto, H., 2008. Energy efficiency in irrigation distribution networks. I. Theory. Biosyst. Eng. 101, 21–27.

Allen, R.G., 1991. USUPIVOT (Centre Pivot and Linear Move Nozzle Selection Program). User's manual. Dept. Biological and Irrigation Engineering. Utah State University.

Allen, R.G., Keller, J., Martin, D., 2000. Centre Pivot System Design. The Irrigation Association, 654 Arlington Boulevard, Falls Church, VA 22042-6638, RiJuPeLo Editions, www.irrigation.org.

Bierschenk, W., 1963. Determining well efficiency by multiple stepdrawdown tests. Int. Assoc. Sci. Hydrol. 64, 493–507.

Córcoles, J.I., de Juan, J.F., Ortega, J.F., Tarjuelo, J.M., Moreno, M.A., 2010. Management evaluation of Water Users Associations using benchmarking techniques. Agric. Water Manage. 98, 1–11.

Córcoles, J.I., de Juan, J.A., Ortega, J.F., Tarjuelo, J.M., Moreno, M.A. Evaluation of irrigation systems by using benchmarking techniques. J. Irrig. Drain. Eng., doi:10.1061/(ASCE)IR.1943-4774.0000386, in press.

ECB, 2011. The Monetary Policy of the ECB. European Central Bank, Frankfurt and Main, Germany.

ESYRCE, 2008. Encuesta de Superficies y Rendimientos de Cultivos en España. Ministerio de Medioambiente y Medio Rural y Marino (MARMA).

Garrido, A., 2001. Recent evolution and trends in agricultural eater pricing: a worldwide overview. In: Transnational Workshop on Managing Water Demand in Agriculture Through Pricing: Research Issues and Lessons Learned, Telese Terme, Italy, 24–26 May.

Hantush, M.S., 1964. Hydraulics of wells. Adv. Hydrosci. 1, 281–442.

Helweg, O.J., 1975. Determining optimal well discharge. J. Irrig. 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., 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., Quek, P.T., 1991. Improving well hydraulics. In: Proc. Irrigation and Drainage Specialty Conf., Honolulu.

IDEA, 2007. Ahorro y Eficiencia Energética en Comunidades de Regantes. Universidad Miguel Hernández, Elche, Alicante.

Jackson, T.M., Khan, S., Hafeez, M., 2010. A comparative analysis of water application and energy consumption at the irrigated field level. Agric. Water Manage. 97, 1477–1485.

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, MI.

Keller, J., Bliesner, R.D., 1990. Sprinkle and Trickle Irrigation. Van Nostrand Reinholh, New York.

Martín de Santa Olalla, F.J., Brasa, A., Fabeiro, C., Fernández, D., López, H., 1999. Improvement of irrigation management towards the sustainable use of groundwater in Castilla-La Mancha, Spain. Agric. Water Manage. 40, 195–205.

Martín de Santa Olalla, F.J., Domínguez, A., Ortega, J.F., Artigao, A., Fabeiro, C., 2007. Bayesian networks in planning a large aquifer in Eastern Mancha, Spain. Environ. Model. Softw. 22, 1089–1100.

Montero, J., Martínez, R.S., Tarjuelo, J.M., 2004. Analysis of wáter application cost with permanent set sprinkler irrigation systems. Irrig. Sci. 23, 103–110.

Moradi-Jalal, M., Mariño, M.A., 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., 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.A., Planells, P., Ortega, J.F., Tarjuelo, J.M., 2007. Measurement and improvement of the efficiency at pumping stations. Biosyst. Eng. 98, 479–486.

Moreno, M.A., Ortega, J.F., Córcoles, J.I., Martínez, A., Tarjuelo, J.M., 2010a. Energy analysis of water systems for irrigation: proposal, monitoring, and evaluation of measures for improving the energy efficiency. Irrig. Sci. 28, 445–460.

Moreno, M.A., Corcoles, J.I., Moraleda, D.A., Martinez, A., Tarjuelo, J.M., 2010b. Optimization of underground wáter pumping. J. Irrig. Drain. Eng. 136, 414–420.

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

Ortega, J.F., de Juan, J.A., Tarjuelo, J.M., López, E., 2004a. MOPECO: an economic optimization model for irrigation water management. Irrig. Sci. 23, 61–75.

Ortega, J.F., Tarjuelo, J.M., de Juan, J.A., Carrión, P., 2004b. Distribution uniformity and its economics effects in the irrigation management of semi-arid zones. J. Irrig. Drain. Eng. 130 (4), 257–268.

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

Ortega, J.F., De Juan, J.A., Tarjuelo, J.M., 2005. Improving water management: the Irrigation Advisory Service of Castilla-La Mancha (Spain). Agric. Water Manag. 77, 37–58.

Ortiz, J.N., Tarjuelo, J.M., de Juan, J.A., 2009. Characterisation of evaporation and drift losses with centre-pivots. Agric. Water Manage. 96, 1541–1546.

Ortiz, J.N., de Juan, J.A., Tarjuelo, J.M., 2010. Analysis of water application uniformity in a centre-pivot and its effect on sugar beet (*Beta vulgaris* L.) yield. Biosyst. Eng. 105 (3), 367–379.

Planells, P., Carrión, P., Ortega, J.F., Moreno, M.A., Tarjuelo, J.M., 2005. Pumping selection and regulation for water distribution networks,. J. Irrig. Drain. Eng. 131 (3), 273–281.

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

Rodríguez Díaz, J.A., Camacho Poyato, E., Blanco Pérez, M., 2011. Evaluation of water and energy use in pressurised irrigation networks in Southern Spain. J. Irrig. Drain. Eng. doi:10.1061/(ASCE)IR.1943-4774.0000338.

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

Schneider, A.D., Howell, T.A., 1999. LEPA and spery irrigation for grain crops. J. Irrig. Drain. Eng. ASCE 125 (4), 167–172.

Sourell, H., Faci, J.M., Playán, E., 2003. Performance of rotating spray plate sprinklers in indoor experiments. J. Irrig. Drain. Eng. ASCE 129, 1–5.

Tarjuelo, J.M., 2005. El riego por aspersión y su tecnología, 3ª Edición. Ediciones Mundi-Prensa, Madrid, España.

Tarjuelo, J.M., de Juan, J.A., 1999. Crop water management. In: van Lier, N.H., Pereira, L.S., Steiner, F.R. (Eds.), CIGR Handbook of Agricultural Engineering. Vol. I. Land and Water Engineering. ASAE and CIGR, St. Joseph. MI, USA.