Design of sprinkler irrigation subunit of minimum cost with proper operation. Application at corn crop in Spain

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Abstract

MATLAB™ software named PRESUD (Pressurized Subunit Design) was developed to identify the optimum solid set sprinkler irrigation subunit design with a criterion of minimizing the annual water application cost (C_T). This C_T is defined as the cost per cubic meter of water applied to the soil for crop use. In this study, only rectangular subunits are considered, using an iterative method for calculating the lateral and manifold pipelines. The results indicate that water cost (C_w), which includes the investment and operation costs for pumping water from the source to the subunit inlet, makes up 75% of C_T. Another important factor is energy cost, which comprises 14% of C_T. The remaining variables, such as sprinkler spacing and layout, or application rate (AR_a), have a lower impact on C_T. In cases of use groundwater, the proportion of energy cost in C_W can reach 40%; thus, energy is an important part of C_T. Results shows that the criterion of limiting the maximum difference in pressure heads in the irrigation subunit (Δh < 20%), widely used when designing a sprinkler irrigation subunit, does not always lead to a minimum C_T, and the use of tools such as PRESUD can help obtain better solutions.

Keywords: solid-set sprinkler irrigation design, water application cost, energy cost.

1. Introduction

Increasing water scarcity in agriculture as a result of increasing water demands in other sectors, including for environmental integrity, makes it necessary to reduce water use by improving water and energy use efficiency.

Water application uniformity by irrigation systems has a great influence on water and energy consumption as well as crop production and possible environmental impacts (Louis and Selker, 2000).

Sprinkler irrigation systems are adopted widely throughout the world. For example, about 50% of irrigated land in the USA uses sprinkler systems (Kulkarni et al. 2006), and they are widely used in most Australian states (Wood et al 2007). In Spain, this system is applied in 23% of the 3.5 Mha of irrigated land, with preference for centre pivot and solid-set or permanent systems (ESYRCE 2011).

The water application in set systems depends mainly on: a) the water distribution model of the sprinkler, b) the sprinklers spacing and layout, and c) wind (mainly speed) (Tarjuelo et al. 1999b). The water distribution model of the sprinkler depends on the type of sprinkler, the number and design of the nozzles, and the working pressure (Keller and Bliesner 1990).

Tarjuelo et al. (1999b) report that greater spacing between sprinklers leads to lower irrigation uniformity. These differences became more pronounced with high wind speeds. Uniformity is higher when using two nozzles under low wind speeds (W<3 m/s), but higher with a single nozzle under high wind speeds (Tarjuelo et al. 1999b).

Adoption of more uniform sprinkler systems involves a trade-off between increased investment cost and the benefits associated with reduced water application when application is more uniform. Economic analysis demonstrates that there are clear incentives for adopting more water-efficient systems despite higher investment and energy costs because of the negative effect of overwatering on yield (Brennan 2008).

Available water in the root area is conditioned by the effect of accumulated irrigation depth, interception of the water by the canopy and later redistribution, soil water dynamics, and the development of the root system (Stern and Bresler, 1983; Li and Kawano, 1996; Chen *et al.*, 2004; Martinez-Cob et al. 2008). A good approximation of soil water uniformity is the value corresponding to the set of irrigation events, at least when the irrigation time interval is less than three or four days. Ortiz et al (2010) report that a Christiansen's uniformity coefficient (CUC) value of around 80% for individual irrigation events can be sufficient to provide good crop yield uniformity since the corresponding CUC_s in the soil can easily exceed 90% since values of CUC> 90% in individual irrigation events do not significantly increase water uniformity in the soil. In this sense, it is important to emphasize that in this study, CUC_s values for different sprinkler spacing are considered, which best represents the efficiency of water application, and water availability to the plant. The aim of this study was to analyze the effect of water application uniformity (CUC) on soil water content and crop yield uniformity (CUCs and CUCyiel) in a centre pivot operating under real field conditions using Rotating Spray Plate Sprinklers and Fixed Spray Plate Sprinklers at different sprinklers spacing and height above the ground. The soil was a Xeric torriorthent (Soil Taxonomy) with a loam texture (4% coarse sand, 28% fine sand, 44% silt and 24% clay) according to USDA (1979), and good drainage. Soil moisture content throughout the profile (0 – 60 cm) was measured by means of a sensor based on the Frequency Domain Reflectometry (FDR) technology (Diviner 2000TM ,Sentek Pty Ltd., Stepney, Australia), both before and after each irrigation event. *In order to quantify soil moisture uniformity, PVC access tubes were installed* spaced 2 m apart in the radius direction, next to the catch cans used in the sixty evaluations made to measure the water applied by the centre pivot using the methodology proposed by Merrian and Keller (1978) and ISO 11545 (2001). In each of these points, soil moisture measures were carried out every 10 cm, reaching 60 cm depth. Lamaddalena et al. (2007) focused on the effect of the pressure variations in collective irrigation networks on the on-farm sprinkler irrigation performance.

During sprinkler irrigation, water losses due to wind drift and evaporation occur in their path from the nozzles to the crop (WDEL) and evaporation of intercepted water by stems and leaves (Martinez-Cob et al. 2008). Several studies have characterized, quantified and modelled WDEL, with varying results due to different experimental conditions (Tarjuelo et al., 2000). In general, WDEL range from 6 to 20 % of applied water (Playán et al., 2005; Ortiz et al. 2009). Several equations have been developed to predict WDEL from factors such as operating pressure, nozzle size, and meteorological variables (wind speed, air temperature, relative humidity, vapour pressure deficit).

Throughout sprinkler irrigation history, there has always been concern about the system characteristics that lead to the lowest cost results with irrigation (Kumar et al. 1992). Numerous cost-benefit analyses have studied optimal water use with different systems (López-Mata et al. 2010). The cost of the sprinkler irrigation system depends on the equipment and its design, materials and automation level. This cost is also influenced by other factors such as shape, layout and size of the plot, distance from the water source to the plot and pumping requirements (Van der Gulik 2003). The wide variety of design alternatives makes it necessary to identify the lowest total cost, including investment and operation costs.

The aim of this study is to develop a tool for hydraulic design of a solid set sprinkler irrigation subunit with the minimum cost of water application (investment and operating cost) per unit area. The effects of the main factors considered in the design (lateral layout and sprinkler spacing, emission uniformity of sprinklers (EU), slope, length and diameter of lateral and manifold, among others) are also analysed using an iterative method for the calculation of lateral and manifold pipes. A case study of corn crop irrigation in Spain is analysed to determine the main factors affecting the total cost of water application.

2. Methodology

To identify the optimum solid-set sprinkler irrigation subunit design, the annual water application cost per unit of irrigated area is calculated. This is defined as the cost of the volume of water applied to the soil for crop use, calculated as the sum of investment, maintenance, energy, and water costs. In this study only rectangular subunits are considered. The investment and operation costs of the infrastructure for water delivery to the subunit inlet is taken into account in the water costs as an average cost, because this depends on water source (surface or ground water) and its distance to the subunit inlet.

2.1 Solid set sprinkler irrigation subunit design

Since the pipe material for lateral and manifold pipes is smooth, polyvinylchloride (PVC), and the diameters are small, the Veronesse-Datei ($R < 10^{-6}$) (Eq. 1) head loss equations can be used for hydraulic calculations.

$$h_f = 0.0099\, \nu^{0.172}\, D^{-4.80}\, Q_0^{1.8}\, L \qquad (1)$$

where: h_f= pipe head loss (m); ν = water kinematic viscosity($m^2.s^{-1}$); D= inner diameter of pipe (m); Q_0= inflow rate to the pipe ($m^3.s^{-1}$); L= pipe length (m);

The head losses relative to minor singularities (h_s) are considered 15% of h_f in lateral and manifold pipes.

To identify the manifold pipe position in the case of paired lateral pipes on a uniformly sloping field (Carrion et al. 2012), Equation (2) is used (Kang and Nishiyama, 1996, Montalvo, 2007). Although Eq. (2) was developed assuming a continuous and steady discharge, in practice it can be used for many sprinklers and drip irrigation systems as an approximation.

$$\Psi(r_L) = (1 - r_L)^{m+1} - r_L^{m+1} = \frac{0,5\, S_0\, (1+m)}{0.74\;\, M\, q_u^m\, L^m} \qquad (2)$$

with $r_L = \frac{L_a}{L}$ and $M = 0.0099\, \nu^{0.172}\, D^{-4.80}$

where: L= length of the paired lateral pipe (L), L_a= lateral length uphill of the manifold pipe (L), S_0= lateral slope ($L\ L^{-1}$), q_u= emission rate by unit of length ($L^3.T^{-1}\ L^{-1}$); D= inner diameter of lateral pipe (L), m= flow exponent in the head loss equation (1.8 in Eq. 1).

The emission sprinkler equation can be expressed as Eq. (3):

$$q_e = K\, h_e^{X} \qquad (3)$$

where: q_e= emission rate of the sprinkler at a specific head pressure at the device inlet ($L^3.T$); K= emission coefficient; x= emission exponent (x≈0.5 for sprinklers); h_e= inlet pressure head of the sprinkler (L).

Assuming sprinkler flow distribution in an irrigation subunit fits a normal distribution, the influence of the coefficient of variation of sprinkler manufacturer (CV_{qmf}) and the variation in sprinkler flow due to pressure variation within the subunit in emission uniformity (EU) can be estimated as (Karmeli and Keller, 1975)

$$EU = \left(1 - \frac{1{,}27 CV_{qmf}}{\sqrt{e}}\right)\frac{q_{mh}}{q_{ah}} 100 \tag{4}$$

where: e= number of sprinkler per plant (two in this case, as average), q_{mh}= minimum sprinkler flow in the subunit due to the pressure, q_{ah}= mean of all sprinkler flow values due to variations in pressure.

After testing many sprinklers in the laboratory with different nozzle combinations from different manufacturers to obtain the sprinkler equations, we observed that the CV_{qmf} varied between 1 and 4% (unpublished data). In this study, CV_{qmf}=0.03 is considered.

Christiansen's Uniformity Coefficient CUC of water application, defined as Eq. (5), is also widely used in sprinkler irrigation

$$CUC = \left(1 - \frac{\sum_{i=1}^{n} | y_i - y_a |}{y_a\, n}\right) 100 \tag{5}$$

where y_i= individual depth of catch observations from uniformity test; y_a= mean depth of observations; n= number of catch observations

MATLAB™ software named PRESUD (Pressurized Subunit Design) was developed to determine the optimum microirrigation subunit design by minimizing the annual water application cost in Carrión et al. (2013). This has been extended in this paper for a solid-set sprinkler irrigation system design.

In summary, the procedure uses the following calculation stages:

1. Stage 1. *Identification of the inlet point and first approximation of pressure head required at the subunit inlet (H_0).* The procedure begins by assuming that all sprinklers discharge the average flow q_a, identifying a point of supply with Eq. (2) for the previously selected diameter of lateral or manifold pipes. Next, it calculates a first estimate of the pressure head in the inlet subunit (H_0), using Christiansen's reduction factor (F_G) method to calculate the lateral and manifold pipe head losses (h_{fl}= h_f F_{G},, where h_{fl}= lateral pipe head loss) (Keller and Bliesner 1990).
2. Stage 2. *Determination of sprinkler pressure (h_{ei}) and discharge (q_{ei}) of each sprinkler within the subunit.* For the H_0 value determined in Stage 1, the pressure head is estimated at each sprinkler insertion point (h_{ei}) (or lateral insertion point in the manifold) by applying the energy equation

$$h_{ei} = h_{e\,i-1} - h_{f(i-1)-i} \pm S_0\, s_e \tag{6}$$

where $h_{f(i-1)-i}$=head losses between two consecutive sprinklers i-1 and i (L) (Eq. (1)) considering q_{ei}= q_a in the first iteration, S_0= slope (L L^{-1}) and s_e= sprinkler spacing (L).

Once the pressure of each sprinkler (h_{ei}) has been estimated, sprinkler flow (q_{ei}) is calculated with Eq. (3)

Then, an iterative process begins calculating the discharge of each sprinkler (q_{ei}), keeping the same H_0 value to facilitate convergence. The distribution of flows and pressures in each pipe is calculated, considering the sum of the sprinkler discharge downstream of a specific point and satisfying the continuity principle. The process is repeated until the difference in sprinkler pressure between two consecutive iterations is lower than 0.0001 m for all sprinklers.

3. Stage 3. *Determination of the manifold pipe position in the case of paired lateral pipes that make equal the pressure difference upstream and downstream side.* This stage calculate the average pressure in the manifold pipe to identify the average lateral pipe, and changes the manifold pipe position until the pressure difference upstream and downstream side of paired lateral pipes is less than 0.001 m.
4. Stage 4. *Calculation of the H_0 value that matches the average flow of all sprinklers to the average flow desired in the subunit (q_a).* This stage repeats Stage 2, but changes the value of H_0 until the difference between the average discharge from the sprinklers in the subunit and the desired average flow (q_a) is less than 0.001 L h^{-1}.
5. Stage 5. *Calculation of the coefficients describing the suitability of water distribution in the subunit:* EU (Eq. 4), Δq= maximum difference in sprinkler flow in the irrigation subunit, Δh= maximum difference in pressure heads in the irrigation subunit, and the total water application cost in the subunit (C_T) (Eq. 7), for a given water price (P_w), average energy price (En_c), and gross annual crop irrigation water requirement (R_g), using the calculation method below.

With this methodology, the PRESUD software makes it possible to perform a sensitivity analysis of the main design parameters: length, diameter and slope of lateral and manifold pipes (L_l, L_m, D_l, D_m, S_{0l}, S_{0m}), sprinkler spacing and layout (18m x 18m and 15m x 15m), sprinkler working pressure, water and energy prices (P_w, En_c), and average application rate of the irrigation system (AR_a). For all cases, the coefficients that define the suitability of water application in the subunit (EU, Δq, Δh, and C_T) are calculated.

2.2 Total cost

The total annual cost of water application with the irrigation system (C_T, in € ha^{-1} yr^{-1}) per unit of irrigated area is the sum of the investment (C_a), energy (C_e), water (C_w) and maintenance (C_m) annuity per unit of irrigated area costs, calculated below.

$$C_T = C_a + C_e + C_w + C_m \tag{7}$$

The components of C_T are described in the following sections. All these estimations of costs can be introduced in PRESUD software to analyse case studies other than the one presented in this paper.

2.3 Investment costs

For investment cost (C_i), only the pipes (lateral and manifold), sprinkler, riser pipes and assembly costs have been included. In addition, since a permanent sprinkler irrigation system is considered, the opening and closing of ditches has been included.

The annuity (A= CRF Ci, in € Y^{-1}) for the total investment cost (C_i, in €) was computed considering a useful life (N) of 24 years for pipes and 12 years for sprinklers (Scherer and Weigel 1993) and an interest rate (i) of 0.06. The capital recovery factor (CRF) and the investment annuity per unit of irrigated area (C_a, en € $ha^{-1}yr^{-1}$) were calculated using equations (8) and (9):

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{8}$$

$$C_a = \frac{A}{S} = \frac{CRF.C_i}{S} \tag{9}$$

where S= irrigated area by the irrigation subunit (in ha).

To determine the total investment cost (C_i) the average prices of different manufacturers and distributors in Spain were considered (Table 1).

2.4 Energy cost

The annual energy cost per unit of irrigated area (C_e, in € $ha^{-1}yr^{-1}$) was calculated using equation (10)

$$C_e = \frac{P.O_t.En_c}{S} \quad (10)$$

where P= the power required (in kW, (Eq.11)) for water application; O_t= annual operating time of the irrigation system (in h yr^{-1}, (Eq. 14) considering irrigation water requirements for corn crop in Spain as an application example (650 mm in this study); En_c= average energy rate (in €·kWh^{-1}); S= irrigated area (in ha)

Table 1. Average prices of different manufacturers and distributors in Spain

Concept	External (inner) diameter (mm)	**Price (€ m^{-1})** [1]
Sprinkler		10 €/unit
Riser pipe		0.30
Lateral pipe PVC 0.6 MPa (mm)	50 (46.4)	0.65
	63 (59.2)	0.97
	75 (70.6)	1.34
Manifold pipe PVC 0.6 MPa (mm)	140 (131.8)	3.52
	160 (150.6)	4.45
	180 (168.4)	5.63
	200 (188.2)	6.78
Riser coupler		0.6 €/unit

[1] The pipe price includes the opening and closing of ditches and assembly costs.

The power consumed for irrigation water application (P, in kW) was calculated using the pressure head (H_0, in m) and flow rate (Q_{0s}, in $m^3 s^{-1}$) (Eq. 12) necessary at the inlet of the irrigation subunit:

$$P = \frac{9,81.Q_{0s}.H_0}{E_p} \quad (11)$$

$$Q_{0s} = \frac{AR_a \; A_{sp} \; N_{spr}}{3.6 10^6} \quad (12)$$

where E_p= efficiency of pumping system (dimensionless); AR_a= average application rate of the irrigation system (mm h^{-1}) (Eq 13); q_a= average sprinkler discharge (L h^{-1}); A_{sp}= area irrigated by one sprinkler (m^2) (A_{sp}= s_s s_l); s_s= sprinkler spacing in the lateral (m); s_l= lateral spacing in the manifold (m); N_{spr}= number of sprinklers in the subunit.

$$AR_a = q_a (s_s s_l)^{-1} = q_a A_{sp}^{-1} \quad (13)$$

Pumping system efficiency of 0.65 was considered based on the energy analysis of irrigation systems in the Castilla-La Mancha Region (Moreno et al. 2010).

The number of operating hours per year (O_t) was calculated with equation (14):

$$O_t = \frac{R_n}{E_a \; AR_a} \quad (14)$$

where R_n= net crop irrigation water requirement per year (650 mm yr^{-1} for corn in Albacete, Spain, in this study) (Martin de Santa Olalla et al. 2003), E_a= general application efficiency for the irrigation system (dimensionless) (Eq. 15).

The E_a for a defined percentage *a* of adequately irrigated area can be calculated as (Keller and Bliesner 1990)

$$E_a = ED_a \cdot P_{ef} \tag{15}$$

where ED_a= distribution efficiency (ED_a= R_n D_{rs}^{-1}); D_{rs}= gross average water depth that reaches the soil surface; P_{ef}= effective proportion of water from the sprinklers that reaches the soil surface (Eq. 17)

$$R_g = D_{rs} P_{ef}^{-1} \tag{16}$$

where R_g= gross crop water requirement per year ($R_g = R_n E_a^{-1}$)

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

In this study, the values of CUC_s, *a*, ED_a, P_{ef} and E_a of Table 2 have been considered for the different spacings and working pressure. The selected values of CUC_s and P_{ef} are obtained from different references (Keller and Bliesner 1990, Tarjuelo et al. 1999b, Tarjuelo et al. 2000, Montero et al. 2001, Playán et al 2005, Ortiz et al. 2010)

Table 2. Values of the different parameter related with the sprinkler considered in this study.

Spacing of sprinklers (m x m)	h_a (kPa)	CUC_s (%)	*a* (%)	ED_a (dimension-less)	P_{ef} (dimension-less)	E_a (dimension-less)	AR_a (mm h^{-1})	Diameter of Nozzles (mm)
18 x 18	300	85	80	0.84	0.92	0.77	5.90	4,8+2.4
	350	87	80	0.86	0.92	0.79	6.33	4,8+2.4
	350	87	80	0.86	0.92	0.79	7.30	5.2+2.4
15 x 15	300	86	80	0.85	0.92	0.78	6.33	4.0+2.4
	300	87	80	0.86	0.92	0.79	7.30	4,4+2.4
	350	90	80	0.89	0.92	0.82	8.00	4,4+2.4

h_a= average sprinkler working pressure in the subunit = average pressure head in the subunit.

To consider the possibility of changing energy prices to rates different from the general rate of inflation, Eq. (17) (Keller and Bliesner, 1990) has been implemented in the PRESUD software.

$$EAE = \left[\frac{(1+ee)^N - (1+i)^N}{(1+ee)-(1+i)}\right] \cdot \left[\frac{i}{(1+i)^N - 1}\right] \tag{17}$$

where ee= annual rate of escalation in energy costs.

In the case studies, the rate of energy escalation is assumed to be the same as the general inflation rate for the other components of the subunit and, therefore, can be ignored.

2.5 Water costs

Irrigation water price (P_w) is the cost of obtaining water from the source (investment in infrastructure and operational costs for water delivery to the subunit inlet).

The cost of the irrigation water (C_w, € yr^{-1} ha^{-1}) is:

$$C_w = \frac{R_g P_w}{S} \tag{18}$$

Three different water prices were considered in the sensitivity analysis: 0.06, 0.1, and 0.15 € m^{-3}. This P_w mainly depend on water availability and the initial water energy (surface or groundwater) and range widely. The adopted values represent the real conditions over time in Spain and in many other regions of the world.

2.6 Maintenance costs

An additional average cost of 5% above investment cost was considered for maintenance of the irrigation system (C_m) to reach a useful life of 24 years.

2.7 Influence of the main factors over the total cost

To analyse the influence of the main factors on C_T, the reference values of Table 3 have been considered. Afterwards, sensitivity analysis is performed for the most influential factors from those described in Table 3.

Table 3. Summary of the reference parameter considered in the study

Parameter	**Value in reference conditions**	
Slope in lateral pipe (S_{0l})	0%	
Slope in manifold pipe (S_{0m})	0%	
Emission exponent (x)	0.5	
Coefficient of variation of sprinkler manufacturer CV_{qmf}	0.03	
Lateral diameter D_l	50 (46.4 mm inner diameter) PVC 0.6 MPa	
Number of lateral pipes in the subunit	12	
Water price (P_w) (€ m^{-3})	0.10	
Average energy price (En_c) (€ kWh^{-1})	0.10	
Annual crop irrigation water requirement (R_n) (mm yr^{-1})	650(1)	
Height of the sprinkler riser (m)	2.5	
Sprinkler spacing (m x m)	18 x 18	15 x 15
Average sprinkler working pressure (h_a) (kPa)	350	300
Average application rate of the irrigation system AR_a (mm h^{-1})	6.33	7.30

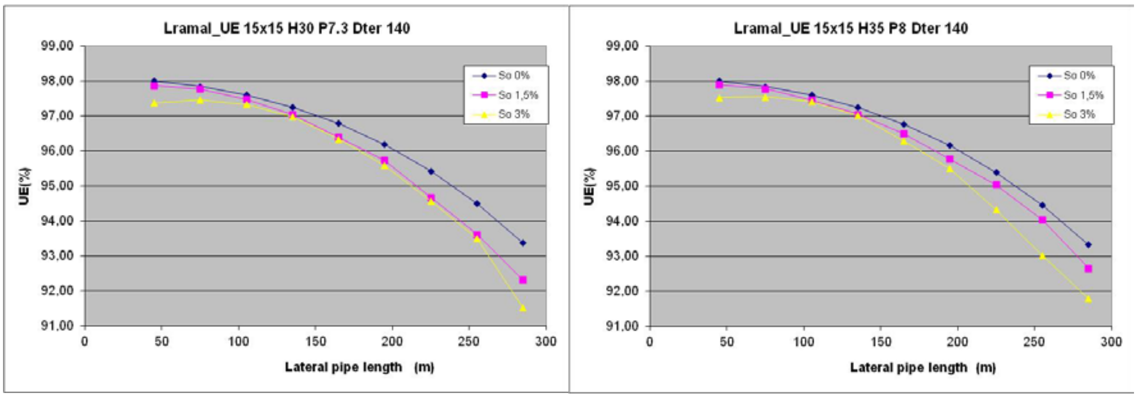
(1) typical data for corn in the Albacete area, Spain (Martin de Santa Olalla et al., 2003; de Juan et al, 2009).

3. Results

All results are presented for rectangular shaped subunits, and paired manifold and lateral pipes. First, the effect of the slope and length of the lateral pipe over EU is evaluated. In addition, for two sprinkler spacings (18x18 and 15x15) and two average sprinkler working pressures (h_a) (300 and 350 kPa), the effect on C_T of L_l, L_m, D_l, D_m S_{0l}, S_{0m}, P_w, and En_c are analysed. To evaluate the suitability of the water application in the subunit, EU, C_T, H_0, Δq, and Δh are calculated. The D_l that minimizes the C_T is 50 (46.4 mm) PVC 0.6 MPa for all cases. Thus, in the following analyses only this diameter will be considered

3.1 Effect of S_{0l} and L_l on EU

Figure 1 shows the effect of L_l and S_{0l} on EU for a sprinkler spacing of 15x15, with h_a=350 kPa (AR_a= 8.0 mm h^{-1}), considering D_m = 140 mm, S_{0l}= 0.0, 1.5, and 3.0 %. The remaining variables are set to standard values.



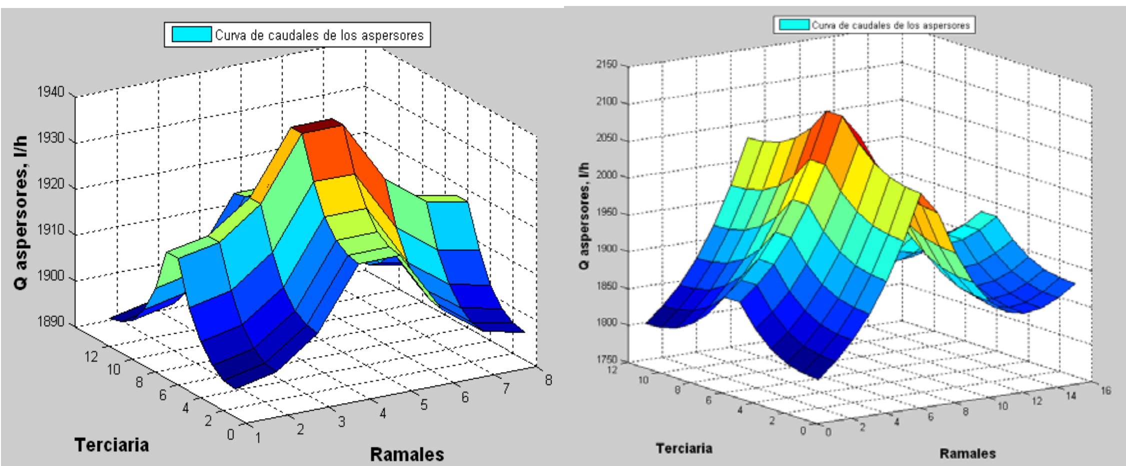
(a) (b)

Fig. 1 Effect of L_l and S_{0l} on EU for a sprinkler spacing of 15x15, with a working pressure of (a) h_a=300 kPa (AR_a= 7.3 mm h^{-1}) and (b) h_a=350 kPa (AR_a= 8.0 mm h^{-1}), considering D_m = 140 mm, S_{0l}= 0.0, 1.5, and 3.0 %. All other variables are set at reference values.

For all cases, EU values are high (higher than 90%), although the values of CUC are slightly lower. This is caused by the influence of wind in the process of water distribution, which is a typical limitation of sprinkler irrigation systems. In this paper, CUC_s values between 85-90% are considered (Table 2) (Ortiz et al 2010). Similar behaviour has been found considering sprinkler spacing of 18 x 18 m and with changes in pressure values.

Results show that EU decreases when increasing L_l, obtaining slightly lower values with high slope values, which implies an increase in Δq. However, the decrease in EU with S_{0l} are insignificant for L_l < 200 m with the slopes analysed.

For example, Figures 2a and 2b show the discharge distribution of the sprinkler in different irrigation subunits, with 18x18 spacing, D_m=140 mm and H_o= 350 kPa. Figure 2a for a subunit area of 3.1 ha (12 laterals with 8 sprinkler each) and S_{ol}=0%, resulting in EU= 97.3% and Δq=2.3%, and Figure 2b for a subunit area of 6.2 ha (12 laterals with 16 sprinklers each) and S_{ol}=3%, resulting in EU= 92.3% and Δq=15.7%.



(a) (b)

Fig. 2 Discharge distribution of the sprinkler for 18x18 spacing and H_o= 350 kPa, with subunit area 3.1 ha (12 laterals with 8 sprinkler each) (a), and 6.2 ha (12 laterals with 16 sprinklers each) (b)

3.2. Effect of D_m over C_T

Figure 3 shows the effect of D_m on C_T for different L_l in case of: a) sprinkler spacing 18x18 with h_a=300 kPa (AR_a= 5.9 mm h^{-1}), and b) sprinkler spacing 15x15 with h_a= 350 kPa (AR_a= 8.0 mm h^{-1}).

The minimum C_T in both cases (flat terrain) is given for a D_m=140 mm and an L_l slightly less than 150 m.

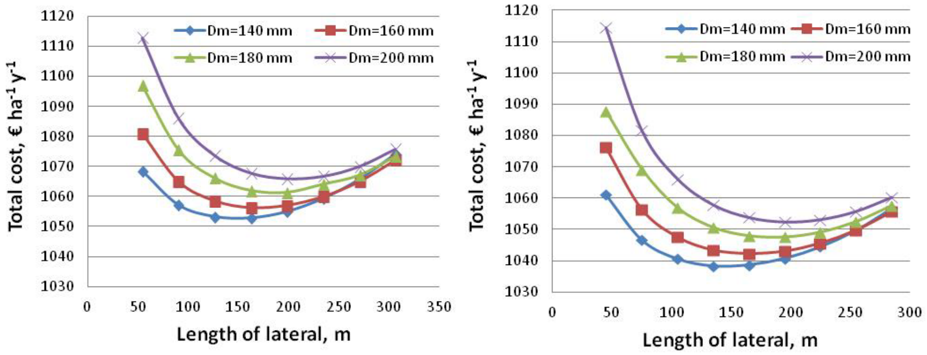
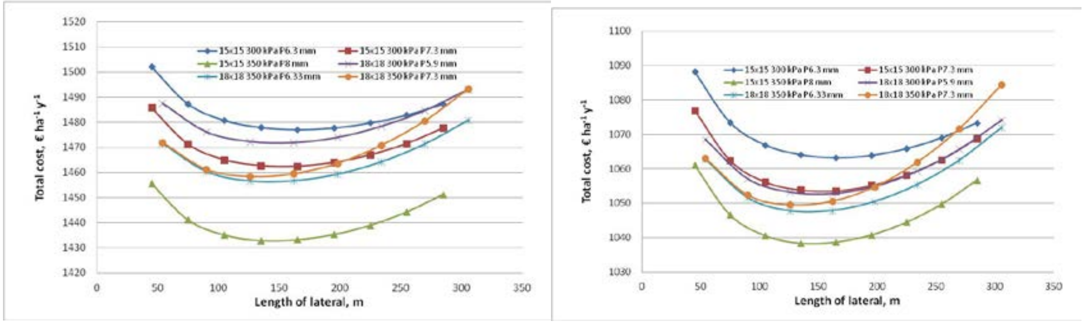


Figure 3. Effect of D_m on C_T for different L_l in case of: a) sprinkler spacing 18x18 with h_a= 300 kPa and AR_a= 5.9 mm h^{-1}, and b) sprinkler spacing 15x15 with h_a= 350 kPa and ARa= 8.0 mm h^{-1}. With 12 lateral pipes in the subunit, P_w= 0,10 € m^{-3}, En_c= 0.10 € kWh^{-1} and D_l= 50 mm.

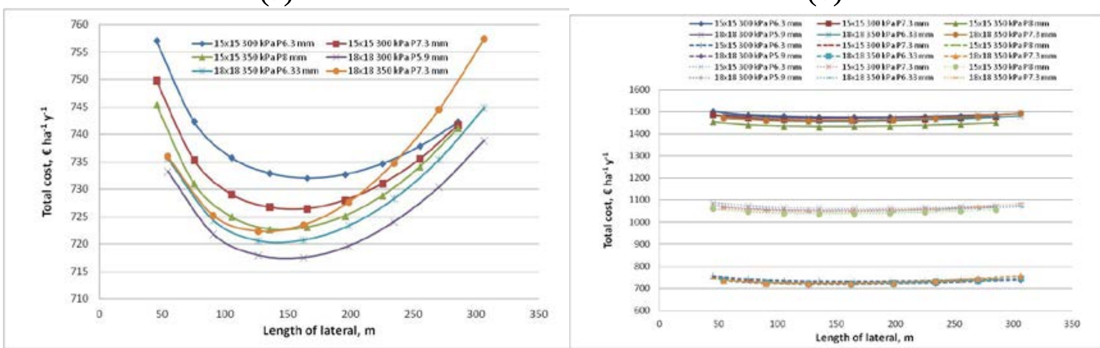
3.3. Effect of P_w and E_a over C_T

In the case study, three different P_w are considered (0.15, 0.10, and 0.06 € m^{-3}), which represents the P_w in Spain (Moreno et al., 2010) and many other regions in the world.

Figure 4 shows the effect of P_w on C_T for different L_l values, with D_m=140 mm, for different sprinkler spacings and pressures.



(a) (b)



(c) (d)

Figure 4. Effect of P_w on C_T for different L_l values for two sprinkler spacing and h_a values, with D_m=140 mm, with 12 lateral pipes in the subunit, En_c= 0.10 € kWh^{-1} and D_l= 50 mm., a) P_w=0.15 € m^{-3}, b) P_w=0.10 € m^{-3}, c) P_w=0.06 € m^{-3}, d) comparison between all the cases.

For high P_w ($\geq$ 0.10 € m^{-3}), the minimum C_T is obtained with 15x15 and h_a=350 kPa (with AR_a= 8 mm h^{-1}). However, for low P_w (0.06 € m^{-3}), the minimum C_T is obtained with 18x18 and h_a= 300 kPa (with AR_a= 5.9 mm h^{-1}). This is due to the difference in E_a for the different layouts (0.82 versus 0.77) (Table 2). In the case of 15x15, the higher investment cost is compensated by lower water consumption (for increasing E_a) when P_w is high. In addition, Figure 4d shows that C_T is practically the same for all sprinkler spacings and pressures with low P_w, but differences occur when P_w increases.

Consequently, in the scenario of increasing energy cost for the future, P_w will follow an ascending trend and the sprinkler spacing of 15x15 with h_a=350 kPa can be the solution with lowest C_T.

For cases other than those explored in this paper, the PRESUD tool facilitates the decision making process, since it is able to account for a wide range of variables that affect C_T in sprinkler irrigation. Therefore, it is important to have this type of tool for technicians, engineers or Irrigation Advisory Services (IASs) (Ortega et al. 2005), to analyse all variables and select or recommend to farmers the best option, since traditional behaviour has significant weight on the decision making process and can lead to erroneous decisions.

3.4. Effect of En_c and AR_a over C_T

Firstly, it is important to emphasize that the energy costs (C_e) considered in this study take into account only the energy required to supply enough water pressure in the subunit intake for proper sprinkler performance. The energy required by the water source to reach the subunit head is considered in P_w.

Figure 5 shows the effect of En_c and AR_a on C_T for different L_l values, with D_m=140 mm, for the two sprinkler spacings and AR_a analysed. The En_c values considered are 0.06, 0.10, and 0.15 € kWh^{-1}, which represents different types of electrical energy rates and costs of different energy sources (gas-oil, electricity) that can be found in different regions of the world.

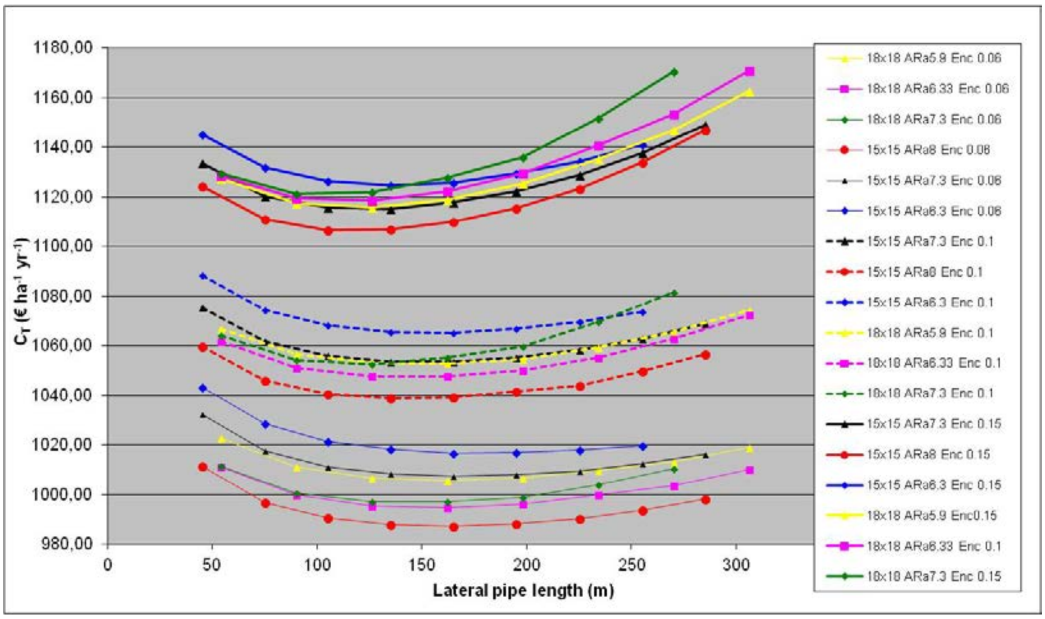


Figure 5. Effect of En_c (0.06, 0.10, and 0.15 € kWh^{-1}) and AR_a on C_T for different L_l values, with D_m=140 mm, for the different sprinkler spacings and AR_a analysed. With 12 lateral pipes in the subunit, P_w=0,10 € m^{-3} and D_l= 50 mm

The increase in C_T when increasing En_c is not too high (around 6%) both when increasing En_c a 67 % (from 0.06 to 0.1 € kWh^{-1}) and when increasing En_c a 50 % (from 0.10 to 0.15 € kWh^{-1}). This is because the weight of C_e on C_T is not very high, as will be described in the following epigraph.

Figure 5 also shows a low effect of AR_a on C_T, conditioned by the E_a linked to each AR_a, which depends on sprinkler spacing and h_a (Table 2). Thus, in the case of 15x15 m, AR_a= 8 mm h^{-1} implies a minimum C_T for all the En_c analysed. In the case of 18x18, minimum C_T is obtained with AR_a= 6.33 mm h^{-1}, except in the case of En_c=0.15 € m^{-3} (the highest En_c value analysed), in which a value of AR_a= 5.9 mm h^{-1} minimizes C_T.

3.5. Main components of C_T

The C_w comprises around 75% of C_T. The C_e (only the energy required to reach H_o in the subunit head) makes up 14%, and C_a + C_m makes up 11% of C_T. However, it is necessary to emphasize that C_w includes the energy, investment, and maintenance costs of the infrastructure for pumping water from the source to the subunit inlet. In cases in which the initial water energy is low (groundwater) the impact of the percent energy cost for pumping water to the subunit inlet on C_W can reach 40%, as in the case of Albacete (Spain), with C_w= 0.1 € m^{-3} and a water table depth of 80 m (Tarjuelo et al. 2010). Therefore, it can be concluded that energy plays a main role when analysing C_T, reaching more than 50 % of C_T, including the energy required for water application in the subunit (approx. 10-15 % of C_T)

3.6. Effect of the subunit size over C_T

Figure 6 and Tables 4 and 5 show the variation in C_T with the subunit size for the different sprinkler spacings, h_a and AR_a analysed in this study. For all the cases, L_l= 198 m is considered (12 sprinklers) for 18x18 spacing, and L_l= 195 m (14 sprinklers) for a 15x15 spacing. When increasing subunit size, only the manifold length is changed because this results in minimum C_T. The observed changes in the slope of the tendency curves are the result of changes in the manifold diameter from D_m= 140 mm to D_m= 160 mm when the subunit size increases. For all cases, EU values were very high (95-97%). In the case of 18x18 spacing, Δq was 4-12% and Δh was 8-24%. For 15x15 spacing these values were slightly lower (Tables 4 and 5). .

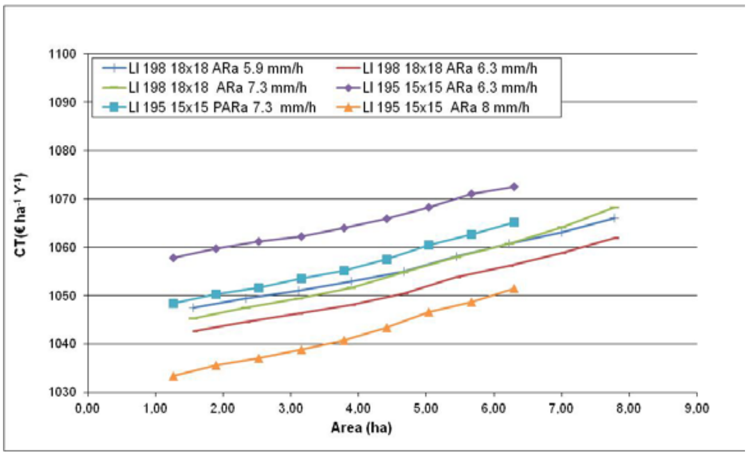


Figure 6. Variation in C_T with subunit size for the different sprinkler spacings, h_a and AR_a analysed in this study. With P_w= 0,10 € m^{-3}, En_c= 0.10 € kWh^{-1} and the data included in Tables 3 and 4.

Comparison of these results with those of Fig. 3, that shows the effect of D_m on C_T for different $L_{l,}$ highlight the importance of the subunit form in the C_T. Thereby, in Fig. 3b, for 15x15 spacing, the minimum C_T= 1038.4 € ha^{-1} Y^{-1} is for L_l= 135 m (10 sprinklers) and 12 lateral pipes in the subunit (L_m= 165 m), with D_m= 140 mm, resulting 2.7 ha of subunit area. In Table 5 and Fig. 6 the minimum C_T= 1038.8 € $ha^{-1}Y^{-1}$ for a 3.15 ha subunit formed by L_l= 195 m and L_m= 135 m, with Dm= 140 mm for 15x15 spacing. This demonstrate that the lower C_T is obtained maximizing the capacity of the 50 mm as lateral pipe diameter (for L_l= 195 m and 14 sprinklers as maximum) and increasing the length and size of manifold pipe for increase the subunit size.

Table 4. Minimum C_T in irrigation subunit of different area for 18x18 spacing with different h_a and AR_a values, indicating the diameter and length of lateral and manifold pipes as well as $H_{0,}$ EU, Δq and Δh values, with P_w=0,10 € m^{-3}, En_c= 0.10 € kWh^{-1}.

Subunit area (ha)	**Lateral length (m)**	**Manifold length (m)**		**C_T (€ $ha^{-1}Y^{-1}$)**	**H_0 (m)**	**EU (%)**	**Δq (%)**	**Δh (%)**
	Lateral external (inner) diameter (mm)	Manifold external (inner) diameter (mm)						
	50 (46.4)	140 (131.8)	160 (150.6)					
Sprinkler spacing 18m x 18m, h_a= 300 kPa and AR_a= 5.9 mm h^{-1}								
1.56	198	54		1047.5	35	95.9	4.2	8.4
2.33	198	90		1049.4	35.1	95.9	4.4	8.8
3.11	198	126		1051.1	35.4	95.7	4.7	9.5
3.89	198	162		1053.0	35.8	95.5	5.4	10.8
4.67	198	198		1055.0	36.3	95.3	6.3	12.8
5.44	198	234		1058.1	37.1	94.9	7.7	15.5
6.22	198		270	1060.8	36.6	95.1	6.9	14.0
7.00	198		306	1063.1	37.2	94.8	8.1	16.4
7.78	198		342	1066.0	38.0	94.4	9.5	19.4
Sprinkler spacing 18m x 18m, h_a= 350 kPa and AR_a= 6.3 mm h^{-1}								
1.56	198	54		1042.7	40.4	96.0	4.1	8.2
2.33	198	90		1044.6	40.5	95.9	4.2	8.5
3.11	198	126		1046.3	40.8	95.8	4.6	9.3
3.89	198	162		1048.1	41.2	95.6	5.2	10.5
4.67	198	198		1050.5	41.8	95.3	6.2	12.5
5.44	198	234		1053.8	42.7	95.0	7.5	15.1
6.22	198		270	1056.25	42.1	95.2	6.7	13.6
7.00	198		306	1058.8	42.8	94.8	7.9	16.0
7.78	198		342	1062.0	43.7	94.4	9.3	18.9
Sprinkler spacing 18m x 18m, h_a= 350 kPa and AR_a=7.3 mm h^{-1}								
1.56	198	54		1045,30	41.2	95.6	5.3	6.7
2.33	198	90		1047,50	41.4	95.5	5.5	7.9
3.11	198	126		1049,40	41.7	95.3	6.0	9.3
3.89	198	162		1051,70	42.3	95.1	6.7	13.6
4.67	198	198		1054,80	43.1	94.7	7.9	16.1
5.44	198		234	1058,00	42.7	94.9	7.5	15.2
6.22	198		270	1060,70	43.4	94.6	8.6	17.5
7.00	198		306	1064,20	44.4	94.1	10.1	20.5
7.78	198		342	1068,20	45.5	93.6	11.9	24.3

Results show that C_T increases with subunit size, and that AR_a has a low effect on C_T, with E_a being the most important variable. Thus, the solution with minimum C_T is the one that results in lower water consumption (higher E_a), even in cases with higher investment cost. This is due to the high weight of C_w on C_T (75%). Thus, the optimal characteristics of the subunit are the 15x15 sprinkler spacing, h_a= 350 kPa, and AR_a= 8 mm h^{-1} (Fig. 5), with E_a= 0.82 (Table 2).

However, this analysis has to be completed with the cost of the pipes that supply water to all the subunits, valves, and automation costs, among others, in order to consider all the variables to select the subunit size with a minimum cost.

These results show that the traditional criteria that consider the optimal subunit the one with Δh= 20 %, does not always lead to the minimum cost of the subunit, making software such as PRESUD necessary to optimally size irrigation subunits.

Table 5. Minimum C_T in irrigation subunit of different area for 15x15 spacing with different h_a and AR_a values, indicating the diameter and length of lateral and manifold pipes as well as H_0, EU, Δq and Δh values, with P_w=0,10 € m^{-3}, En_c= 0.10 € kWh^{-1}.

Subunit area (ha)	**Lateral length (m)**	**Manifold length (m)**		**C_T (€ $ha^{-1}Y^{-1}$)**	**H_0 (m)**	**EU (%)**	**Δq (%)**	**Δh (%)**
	Lateral external (inner) diameter (mm)	Manifold external (inner) diameter (mm)						
	50 (46.4)	140 (131.8)	160 (150.6)					
Sprinkler spacing 15m x 15m, h_a= 300 kPa and AR_a= 6.3 mm h^{-1}								
1,26	195	45		1057.8	34.3	96.3	3.3	6.6
1,89	195	75		1059.7	34.4	96.2	3.4	6.8
2,52	195	105		1061.2	34.6	96.2	3.6	7.3
3,15	195	135		1062.3	34.8	96.0	4.1	8.2
3,78	195	165		1064.0	35.2	95.8	4.7	9.4
4,41	195	195		1065.9	35.7	95.6	5.6	11.2
5,04	195	225		1068.2	36.3	95.2	6.7	13.6
5,67	195	255		1071.1	37.1	94.8	8.2	16.7
6,3	195		285	1072.6	36.2	95.2	6.8	13.8
Sprinkler spacing 15m x 15m, h_a= 300 kPa and AR_a= 7.3 mm h^{-1}								
1,26	195	45		1048.4	34.9	96.0	4.2	8.5
1,89	195	75		1050.3	35.0	95.9	4.4	8.8
2,52	195	105		1051.7	35.2	95.8	9.5	4.7
3,15	195	135		1053.5	35.6	95.6	5.2	10.6
3,78	195	165		1055.2	36.0	95.4	6.0	12.2
4,41	195	195		1057,5	36,6	95,1	7,2	14,6
5,04	195	225		1060,5	37,4	94,6	8,7	17,7
5,67	195		255	1062.6	36.7	95.0	7.5	15.2
6,3	195		285	1065.2	37.4	94.6	8.7	17.8
Sprinkler spacing 15m x 15m, h_a= 350 kPa and AR_a= 8.0 mm h^{-1}								
1,26	195	45		1033.4	40.3	95.9	4.3	8.6
1,89	195	75		1035.6	40.5	95.9	4.4	8.9
2,52	195	105		1037.0	40.7	95.8	4.7	9.6
3,15	195	135		1038.8	41.1	95.6	5.3	10.7
3,78	195	165		1040.7	41.6	95.4	6.1	12.3
4,41	195	195		1043.4	42.3	95.0	7.3	14.8
5,04	195		225	1046.6	41.9	95.3	6.6	13.3
5,67	195		255	1048.7	42.5	95.0	7.6	15.4
6,3	195		285	1051.5	43.3	94.6	8.8	17.9

4. Conclusions.

Emission Uniformity (EU) for minimum total annual cost of water application with solid-set sprinkler irrigation system (C_T) is high for all case studies (greater than 94%), and decreases slightly with an increase in lateral slope and subunit size. However, several authors have demonstrated that the uniformity coefficient of water in the soil (CUC_s) with these irrigation systems is smaller when the sprinkler spacing increases and wind speed is high (Keller and Bliesner 1990, Tarjuelo et al. 1999a).

Water cost (C_w) is the main factor that conditions the C_T. In the case of maize crop in Albacete, Spain, with 650 mm of net crop water requirements, C_w comprises 75% of C_T.

The subunit configuration that yields a minimum C_T, for C_w=0.10 € m^{-3} is a sprinkler spacing of 15m x 15m with an average sprinkler working pressure h_a=350 kPa, even though the investment and energy costs are higher than in the case of sprinkler spacing of 18m x 18m with h_a=300 kPa. This can be attributed to a higher value for general application efficiency of irrigation system (E_a) in the first case, which requires a lower volume of water.

In cases in which the initial water energy is low (groundwater), the impact of the energy cost to pump the water from the source to the subunit inlet on C_W can reach 40%, as in the case of Albacete (Spain), with C_w= 0.1 € m^{-3} and a water table depth of 80 m. Therefore, it can be concluded that the energy plays an important role in C_T, reaching more than 50 % of C_T.

Results shows that the criterion of limiting Δh= 20 %, widely used when designing a sprinkler irrigation subunit, does not always lead to solutions of minimum C_T, and the use of tools such as PRESUD can help farmers reach better solutions.

The C_T increases with the subunit size and the lower C_T is obtained maximizing the capacity of the 50 mm as lateral pipe diameter and increasing the length and size of manifold pipe for increase the subunit size.

Notation

The following symbols are used in this paper:

a = percentage of adequately irrigated area
A = investment annuity (€ T^{-1})
AR_a= average application rate of the irrigation system (LT^{-1})
A_{sp} = area irrigated by one sprinkler (L^2)
C_a = investment annuity per unit of irrigated area (€ $L^{-2}T^{-1}$)
C_e = energy cost annuity per unit of irrigated area (€ $L^{-2}T^{-1}$)
C_i = total investment cost (€)
C_m = maintenance cost per unit of irrigated area (€ $L^{-2}T^{-1}$)
CRF = capital recovery factor
C_T = total annual cost of water application per unit of irrigated area (€)
CUC=Christiansen's uniformity coefficient of water application with the irrigation system
CUCs= Christiansen's uniformity coefficient of water in the soil
CV_{qmf}= coefficient of variation of sprinkler manufacturer
C_w = cost of irrigation water (€ T^{-1} L^{-2})
D= inner diameter of pipe (L)
D_l= nominal diameter of lateral (L)
D_m= nominal diameter of manifold (L)
D_{rs} = gross average water depth that reaches the soil surface (dimensionless)
EAE= annual rate of escalation in energy costs
e= number of emitters per plant
ee= annual rate of escalation in energy costs
E_a= general application efficiency for the irrigation system (dimensionless)
ED_a = distribution efficiency (dimensionless)
E_p = efficiency of pumping system (dimensionless)
En_c = average energy rates (€·kWh^{-1})
EU= emission uniformity (dimensionless)

h_e = inlet pressure head of the emitter (L)
h_a = average sprinkler working pressure= average pressure head in the subunit (L)
h_f = pipe head loss with constant flow rate (L)
h_{mh} = minimum pressure heads in the subunit (L)
H_0 = pressure head required at the inlet of the irrigation subunit (L)
i = interest rate (dimensionless)
K = emission coefficient (L^{3-x} T^{-1})
L = pipe length (L)
L_a= lateral pipe length uphill of the manifold (L)
L_l= lateral pipe length (L)
L_m= manifold pipe length (L)
m = flow exponent in the head loss equation
n= number of catch can used in for sampling the irrigation water application
N = useful life (T)
N_{spr}= number of sprinklers in the subunit
O_t = annual operating time of the irrigation system (T T^{-1})
P= power consumed for irrigation water application (kW)
P_{ef} = effective proportion of water from the sprinklers that reaches the soil surface (dimensionless)
P_w = water price (€ L^{-3})
q_a = average sprinkler flow in the subunit (L^3 T^{-1})
q_{ah} = mean of all sprinkler flow values due to variations in pressure (L^3 T^{-1})
q_e = emission rate of the sprinkler at a specified pressures at the device inlet (L^3 T^{-1})
q_{mh} = minimum sprinkler flow in the subunit due to the pressure (L^3 T^{-1})
Q_0= inflow rate to the pipe (L^3 T^{-1})
$Q_{0s=}$ flow rate required at the inlet of the irrigation subunit (L^3 T^{-1})
q_u= emission rate by unit of length (L^3 $T^{-1}L^{-1}$)
R_n = net crop irrigation water requirement per year (L T^{-1})
R_g = gross crop irrigation water requirement per year (L T^{-1})
S = irrigated area (L^2)
s_s= sprinkler spacing in the lateral (L)
s_l= lateral pipe spacing in the manifold (L)
S_0= slope (L L^{-1})
x = emission exponent
y_a= average depth of catch (L)
y_i = depth of catch in each individual catch can (L)

Greek symbols
ν = water kinematic viscosity ($L^2.T^{-1}$)
Δh = maximum difference in pressure heads in the irrigation subunit (% of h_a)
Δq = maximum difference in emitter flow in the irrigation subunit (% of q_a)
$\Psi(r_L)$ = function of $r_L= L_a\ L^{-1}$

5. Acknowledgements

The authors wish to express their gratitude to the Spanish Ministry of Education and Science (MEC), for funding the PET2008_0175_02, and AGL2011-30328-C02-01 projects (Co-funded by FEDER).

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