Groundwater Extraction with Minimum Cost. Application to Sprinkler Irrigation Systems for Corn Crop in Spain

Sanchez Vizcaino J[1], Corcoles JI[1], Moreno M A[1], Tarjuelo J M*[1]

[1]*Centro Regional de Estudios del Agua de la Universidad de Castilla La Mancha.*
E-mail: jose.tarjuelo@uclm.es

Abstract

The aim of this study was to develop a DSS tool named DC-WAT, which linked with the already developed PRESUD tool, aims to optimize, in a holistic manner, the process of water extraction from an aquifer and its application in plot with a pressurized irrigation systems, obtaining the minimum total water application cost (CT) (operation (Cop) + investment (Ca)) per unit irrigated area improving water and energy management. This tool permits identifying the cost for transporting water from the source to the irrigation subunit inlet (Cws) and analyzing the irrigation system as a whole, from the water source to the emitter. An application to permanent sprinkler irrigation systems using groundwater of two types of aquifer (confined and unconfined aquifers) for corn crop in Spain is analyzed, evaluating the effects on CT of parameters such as the static water table in the aquifer (SWT), irrigated area (S), sprinklers and laterals spacing and average application rate (ARa). Results showed that Cws increased lineally with SWT and decreased exponentially with S. The timing of crops water requirements, the efficiency of the irrigation system, and the size of the irrigation subunit, among other factors, determine the optimal pumping flow rate and the cost of energy. For the aquifers studied, the Cws was mainly conditioned by the borehole investment cost, being the confined aquifer 30-60% more expensive than the unconfined for the studied cases. The Ce is the most important cost of CT (65-70 % in the studied cases). DC-WAT is a useful tool to optimize the design and sizing of water pumping facilities in irrigation systems, which considers the aquifer performance in a holistic manner.

Keywords: sprinkler irrigation design, water application cost, energy cost

Introduction

Efficient water and energy use take on greater importance in agriculture due to the widespread tendency of reduced water availability as a result of increasing water demands in other sectors, including for environmental integrity, and increasing energy costs, which determine the viability of irrigated agriculture in many areas of the world, and mainly where groundwater is the main source of water.

Throughout the history of sprinkler and drip irrigation, there has always been interest in finding those system characteristics that produce the cheapest results with irrigation (Kumar *et al.,* 1992; Lamaddalena *et al.,* 2007, Ortiz *et al.,* 2006, Montero *et al.,* 2013). 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).

Maize (*Zea Mays* L.) achieves high yields under semiarid conditions but with high water requirements, which in many areas around the world means an important restriction due to water scarcity (Plan, 2004; Martín de Santa Olalla *et al.,* 2007). As this crop is one of the most important cereals in terms of production (FAO, 2014), more efforts have been dedicated to both improving water use efficiency and minimizing irrigation water application costs by improving the design and management of irrigation systems.

The specific capacity (q) (flow capacity per meter of decline in the water level (m^3 day^{-1} m^{-1}), usually obtained from well capacity testing, can be used to analyze the cost of extraction of ground water. This parameter is directly related to the efficiency or performance of the well, which in turn depends on the constructive design and maintenance, as well as permeability (K, in m d^{-1}) and transmissivity (T= K Hs, in m^2 d^{-1}, where Hs is the saturated depth of the aquifer before pumping, in m) (Kalf and Woolley 2005; Srivastava *et al*. 2007). Aquifers are not isotropic, which means that the above mentioned parameters are usually variable along the aquifer.

The wide variety of parameters that influence the water application cost with a pressurized irrigation system leads to partial studies of the problem, but it is necessary to analyze the irrigation system as a whole, from the water source to the emitter, and not separately, to avoid errors that may be significant.

The optimum hydraulic design of a sprinkler irrigation system is reached by determining the sizes of pump and distribution pipes that ensure proper flow and intake pressure head in the sprinkler, with minimum annual water application cost. Thus, the aim of this study is to apply the DSS tool named DC-WAT (Design and Cost for Water) to obtain the minimum total water application cost (CT) (operation (Cop)+ investment (Ca)) per unit irrigated area in pressurized irrigation, identifying the cost for transporting water from the source to the irrigation subunit inlet (Cws), analyzing the irrigation system as a whole, from the water source to the emitter, improving the water and energy management in irrigation. An application to permanent sprinkler irrigation systems using groundwater in two types of aquifer for corn crop in Spain is analyzed, evaluating the effects on CT of parameters such the static water table in the aquifer (SWT), irrigated area (S), sprinklers and laterals spacing or average application rate (ARa). All the data assumed for the case studies can be modified in the tool to fit the requirements of any case study.

Methodology

DC-WAT tool was developed using MATLABTM. It aims to optimize the shape of the characteristic and efficiency curves of the pump and the pumping and distribution pipe of the system with a holistic approach. In order to evaluate the tool it has been applied to different case studies, considering in the design rectangular subunits of permanent sprinkler irrigation systems, with the borehole in the centre of the plot because this layout leads to lower investment costs. The optimum lateral and manifold pipes are previously calculated using the PRESUD (Pressurized Subunit Design) tool (Carrión *et al.,* 2014), which is linked to DC-WAT tool. However, any other shapes and location of the wells can be implemented in the tool.

Since the distribution pipes used are made of smooth material (polyvinylchloride (PVC)), and the diameters are small, the Veronesse-Datei head loss equations have been used for the hydraulic calculations. For pumping pipes (carbon steel), the Hazen-Williams equation has been used. Minor singular head losses (hs) are considered to comprise 15% of hf in the distribution pipe network and pumping pipe.

Types of Studied Aquifers and its Hydrogeological Properties

To analyse the cost of groundwater extraction two large aquifers of Castilla La Mancha have been considered (confined and unconfined aquifers, Fig. 1). They are the source of water for more than 430.000 ha of irrigated land. The first hydrogeological unit is the Western Mancha (HU 04-04), located in the Guadiana River basin, that covers an area of more than 5.500 km^2 and approximately 320.000 ha of irrigated land (67 and 31% of drip and sprinkler irrigation respectively). This is a not very thick unconfined aquifer (between 100 and 200 m), with transmissivity values (T)

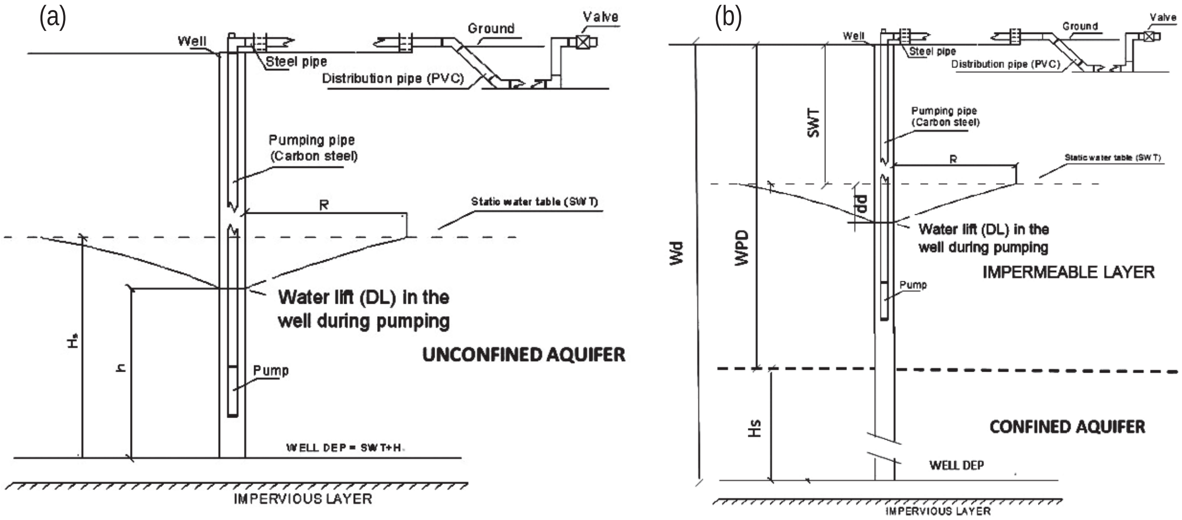


Figure 1. Scheme of the infrastructure of the sprinkler irrigation system: (a) unconfined aquifer; (b) confined aquifer.

between 300 and 700 m^2 day^{-1}. The second is the Eastern Mancha (HU 08.29), with an area of 7.260 km^2 and 110,000 ha of irrigated land (78 and 20 % of sprinkler and drip irrigation respectively). This is a confined and deep aquifer, with 300-600 m thickness, with T values that can exceed 30.000 m^2 day^{-1} (Sanz *et al.,* 2009).

Modelling the Well Performance

For permanent operating conditions, the specific discharge (q) of a borehole located in an unconfined aquifer and in steady state can be estimated in a simplified manner with Eq. 1 (Custodio and Llamas, 1983; Hamm *et al.,* 2005).

$$q = \frac{Q}{dd} = \pi \frac{T}{H_s} \frac{2H_s - dd}{\ln\left(\frac{2R}{D_{wp}}\right)} \qquad (1)$$

$$h = H_s - dd = \sqrt{H_s^2 - \left(\frac{QH_s}{\pi T} \ln\left(\frac{2R}{D_{wp}}\right)\right)} \qquad (2)$$

where q= specific capacity (m^3 day^{-1} m^{-1}), Q= system flow from the aquifer (m^3 day^{-1}); dd= theoretical drawdown in the well (m); T = transmissivity of the aquifer (m^2 day^{-1}), Dwp = inner diameter of well pipe (m); R = the radius of the cone of influence (m); H_s= saturated depth of aquifer before pumping (m) (with static water table (SWT)) (Fig. 1); h= the saturated depth of drilled aquifer after pumping (m).

For permanent operating conditions, the specific capacity (q) of a borehole located in a confined aquifer and in steady state was estimated with the simplified Eq. 3

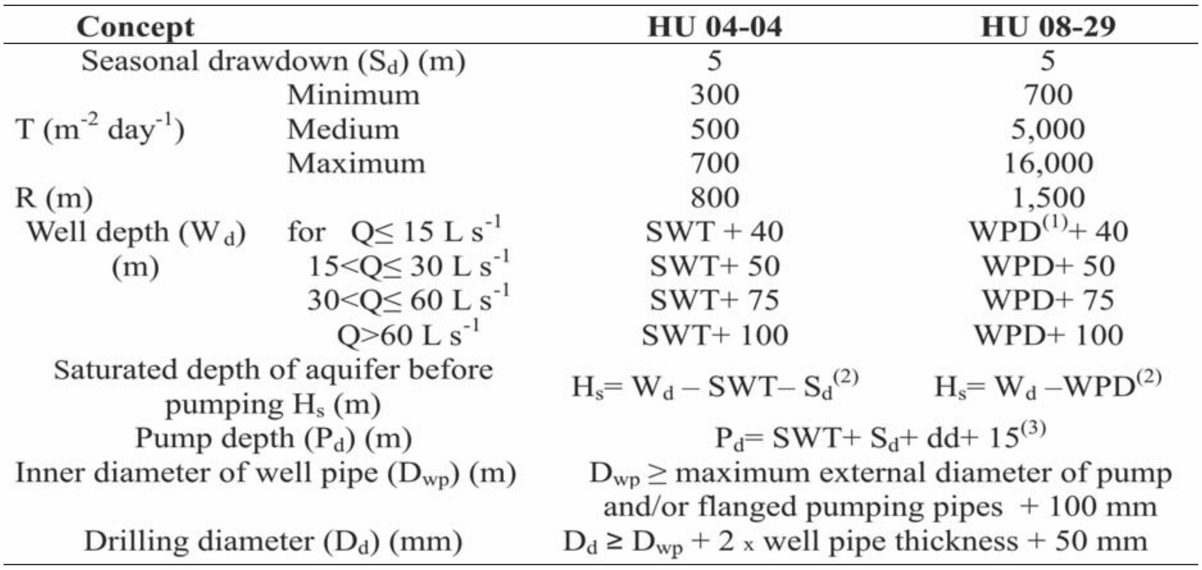
$$q = \frac{Q}{dd} = \frac{2\pi T}{\ln\left(\frac{2R}{D}\right)} \qquad (3)$$

The dynamic lift (DL) is the depth to the SWT plus the drawdown (DL = SWT + dd,) (Fig. 1).

According to Eqs.1 and 3, the theoretical specific capacity (q) is independent of the extracted flow rate (Q) and only depends on the characteristics of the aquifer and the inner diameter of well pipe (Dwp) (Custodio and Llamas, 1983). The actual specific capacity is always lower than the theoretical and the actual drawdown during pumping is higher than in the rest of the aquifer due to head losses in the tube-well.

In this study the theoretical equations were used, with the values of the main hydrological parameters of Table 1 for the two types of selected aquifers. However, DC-WAT tool permits to use the other approach in case required data are available.

Table 1. Summary of the average hydrogeologic data considered in the aquifers used for this study.



Concept		HU 04-04	HU 08-29
Seasonal drawdown (S_d) (m)		5	5
T (m^{-2} day^{-1})	Minimum	300	700
	Medium	500	5,000
	Maximum	700	16,000
R (m)		800	1,500
Well depth (W_d) (m)	for $Q \leq 15$ L s^{-1}	SWT + 40	WPD(1)+ 40
	$15 < Q \leq 30$ L s^{-1}	SWT+ 50	WPD+ 50
	$30 < Q \leq 60$ L s^{-1}	SWT+ 75	WPD+ 75
	$Q > 60$ L s^{-1}	SWT+ 100	WPD+ 100
Saturated depth of aquifer before pumping H_s (m)		$H_s = W_d - SWT - S_d$(2)	$H_s = W_d - WPD$(2)
Pump depth (P_d) (m)		$P_d = SWT + S_d + dd + 15$(3)	
Inner diameter of well pipe (D_{wp}) (m)		$D_{wp} \geq$ maximum external diameter of pump and/or flanged pumping pipes + 100 mm	
Drilling diameter (D_d) (mm)		$D_d \geq D_{wp}$ + 2 x well pipe thickness + 50 mm	

(1)WPD = waterproof depth in the top of confined aquifers (m) (it is considered 350 m in this study).

(2)Sd= seasonal drawdown ((it is considered 5 m in this study).

(3)To ensure a water height above the suction of the pump.

Model Design. Objective Function and Optimization Variables

Figure 2 summarizes the optimization process implemented in DC-WAT tool. The optimization variables were: the coefficient of the characteristic curve of the pump (c) (Moreno *et al.,* 2009), the pumping pipe diameter (Dp), and the distribution pipe diameter (D). The optimal results of the in-plot subunits, which were obtained with PRESSUD tool (Carrion *et al.,* 2014) were incorporated in the total cost. The optimization process was carried out using the Downhill Simplex Method (Nelder and Mead, 1965), which aims to minimize the total cost.

$$\mathrm{MIN}(C_a + C_m + C_e) \qquad (4)$$

where C_a = annual investment cost, C_m = annual maintenance cost, and C_e = annual energy cost.

To select the optimum pump that minimizes the cost for transporting water from the source to the irrigation subunit inlet (Cws) and the total cost (CT) for feeding the irrigation system directly from the borehole, the software considers the shape of the characteristic (Q-H) and efficiency (Q-Ep) curves (Moreno *et al.,* 2009), as well as the optimum sizing of the pumping pipe and the distribution pipe for each specific type of aquifer. These variables will determine the energy efficiency of the whole system through the irrigation season, as well as fitting it to the varying conditions of the aquifer. Other characteristics of the well are derived from these variables, such as the well diameter and the pumping pipe depth being also optimized in the process.

The characteristic and efficiency curves of the pumps (H-Q and Ep-Q) can be approximated by Eqs. (5) and (6) (Moreno *et al.,* 2009).

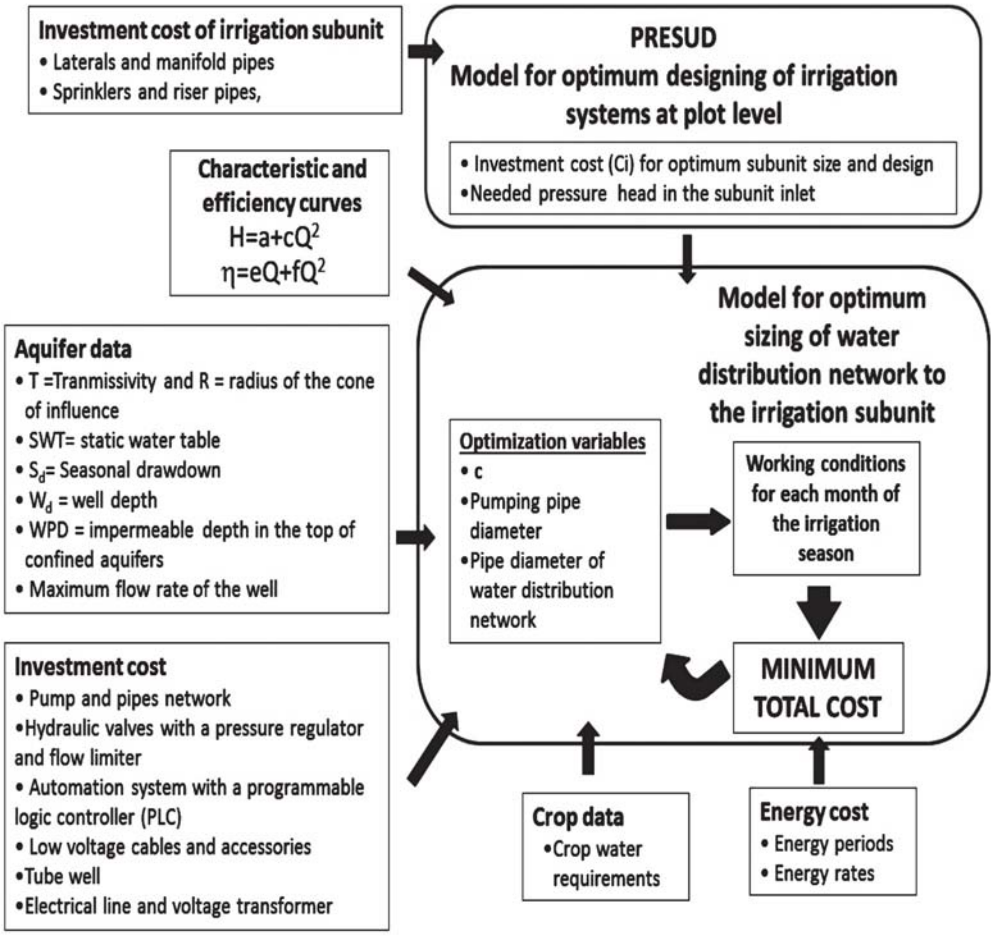


Figure 2. Diagram of the optimization process in DC-WAT tool.

$$H = a + cQ^2 \quad (5)$$

$$E_p = eQ + fQ^2 \quad (6)$$

where the coefficients a, c, e, and f determine the shape of the curves.

Moreno *et al.* (2009) propose an algorithm to obtain the desirable types of characteristic and efficiency curves considering the theoretical relation between the two curves for a specific pump as a function of the coefficient c. Thus, during the optimization process, different values of c, D and Q were obtained, obtaining also the power of the pump, which is directly related with the investment cost and energy cost. The rest of the optimization variables drive to the remaining investment and energy costs.

Investment Costs

The investment costs (C_i) considered were: well drilling and well pipe, pump, electrical line and voltage transformer for using conventional electrical energy, pipe and assembly costs (laterals, manifold and distribution (PVC), and well pumping pipes (steel), sprinkler, riser pipes, opening and closing of ditches, hydraulic valves with a pressure regulator and flow limiter for each irrigation subunit, the automation system with a programmable logic controller (PLC), the low voltage cables and accessories.

The investment annuity ($A = CRF\ C_i$, in € yr^{-1}) for the total investment cost (C_i, in €) was computed considering a useful life (N) of 12 years for the pump and 24 years for the pipes, borehole, electrical line, valves, electrical line, voltage transformer (Scherer and Weigel, 1993), and an interest rate (i) of 0.05. The capital recovery factor (CRF) and the investment annuity per unit of irrigated area (Ca, in € $ha^{-1}yr^{-1}$) were calculated using equations (7) and (8):

$$\mathrm{CRF} = \frac{i\,(1+i)^N}{(1+i)^N - 1} \quad (7)$$

$$C_a = \frac{A}{S} = \frac{\mathrm{CRF}\ .\,C_i}{S} \quad (8)$$

where S is the area irrigated by the irrigation system (in ha). To determine the total investment cost (C_i), the average prices of equipment from different manufacturers and distributors in Spain were considered (Table 2).

The considered cost of well drilling in the area is included in Table 3. These costs also include the costs of transportation and installation of machinery, technical documents and restoration.

Table 2. Average prices of different manufacturers and distributors in Spain.

Concept	Material	Cost (€ $unit^{-1}$)	R^2
Distribution pipe	PVC 0.6 MPa	$C = 0.001253D^{1.632397}$	0.99
Pumping pipe	Steel	$C = 0.0009D^{1.8013}$	0.99
Hydraulic valves	Cast iron	$C = 0.017385D^2 + 0.010499D - 26.648651$	0.99
Pump		$C = 0.0016\ P_p^3 + 0.924\ P_p^2 + 268.28P_p$	0.94
Electrical wire	Cooper	$C = 0.0025318P_p^2 + 0.0823262P_p + 5.7296411$	0.99
Electrical panel		$C = 224.418612P_p^{0.329085}$	0.99
Electronic starter		$C = -0.023988P_p^2 + 25.423305P_p + 758.163174$	0.98
Controller and auxiliary		C = 800 (€)	
Voltage transformer		$C = 0.012140P_t^2 + 9.699422P_t + 4051.880598$	0.97

D= inner pipe diameter (mm); Pt= power of the transformer (kVA); Pp= power of the pump (kW).

Table 3. Cost of well drilling.

Concept	Drilling type	Well depth (W_d) (m)	Drilling diameter (Dd) (mm)						
			350	400	450	500	550	600	650
Well pipe, inner diameter (D_{wp}) (mm)			250	300	350	400	450	500	550
Average cost (€ m^{-1})	P(1)	W_d<250	165	198	225	248	264	286	308
	RC(2)	250<W_d<600	205	215	223	228	232	237	245

(1)P = Percussion; (2)RC= Reverse Circulation.

The estimated cost of the electric line is included in Table 4. The electrical line length is considered 500 m plus half square side assigned to each plot size, since the borehole and the pump are located in the centre of the plot.

Carrión *et al.* (2014) reported the typical permanent sprinkler irrigation subunit design (Table 5) of minimum cost as function of the subunit size for corn crop. In this case only the identified option of lower cost (Table 6 and 7) were considered.

Table 4. Cost of electric line.

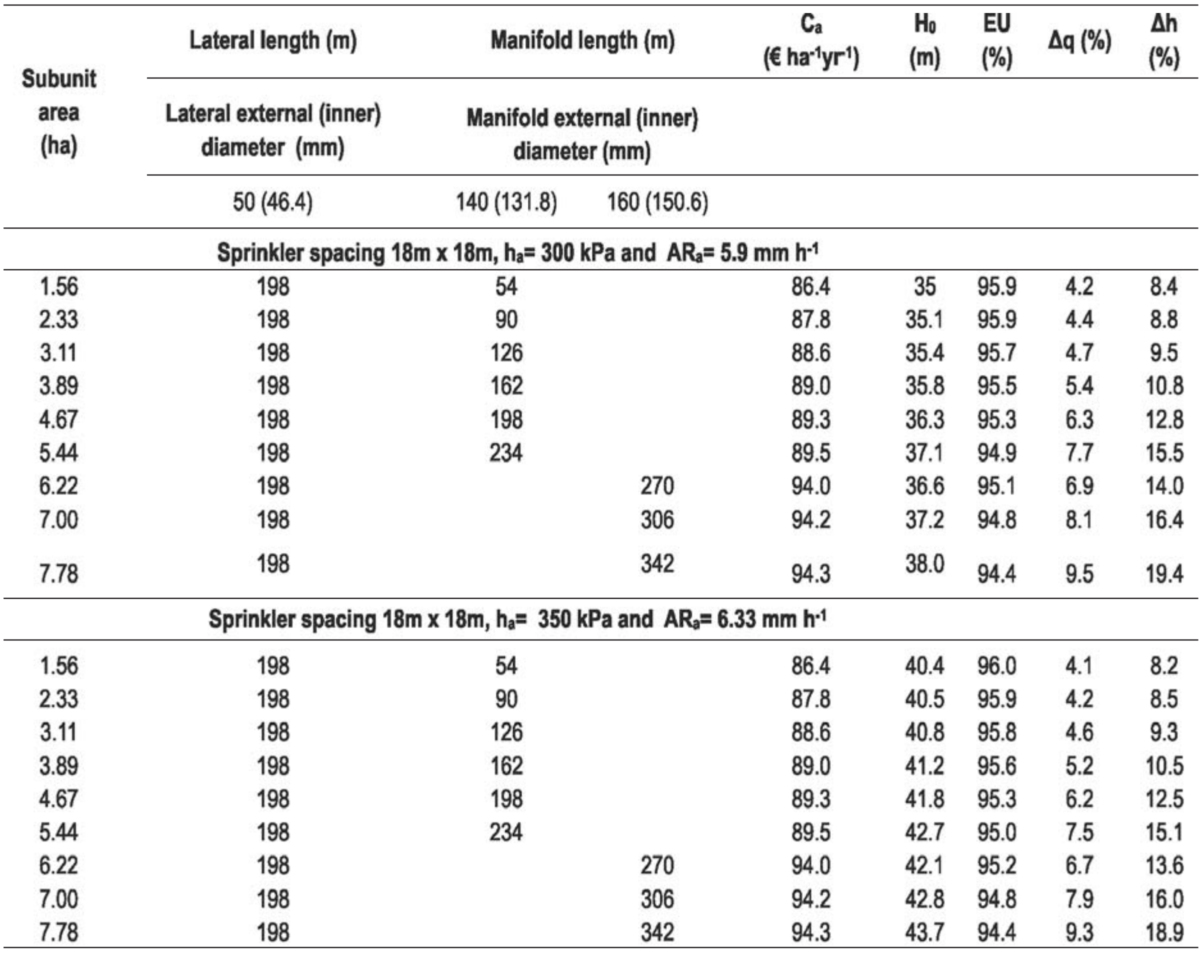
	Plot area (ha)			
	< 10	10 to 20	20 to 40	40 to 60
Cost of electric line (€ km^{-1})	4,550	6,500	7,800	8,500

Table 5. Values of the different parameter related with the sprinkler irrigation system considered in this study.

Spacing of sprinklers (m x m)	h_a (kPa)	E_a (dimensionless)	AR_a (mm h^{-1})	Diameter of nozzles (mm)	Corn gross water requirement ($m^3 ha^{-1} yr^{-1}$)
18 x 18	300	0.77	5.90	4.8 + 2.4	8.249
	350	0.79	6.33	4.8 + 2.4	8.049
15 x 15	350	0.82	8.00	4.4 + 2.4	7.766

h_a = Average sprinkler working pressure = average pressure head in the subunit (kPa); E_a= general application efficiency for the irrigation system (Keller and Bliesner, 1990); $AR_a = q_a (s_s s_l)^{-1}$ average application rate of the irrigation system (mm h^{-1}); q_a = average emitter flow in the subunit (L h^{-1}); s_s= sprinkler spacing in the lateral (m); s_l= lateral pipe spacing (m).

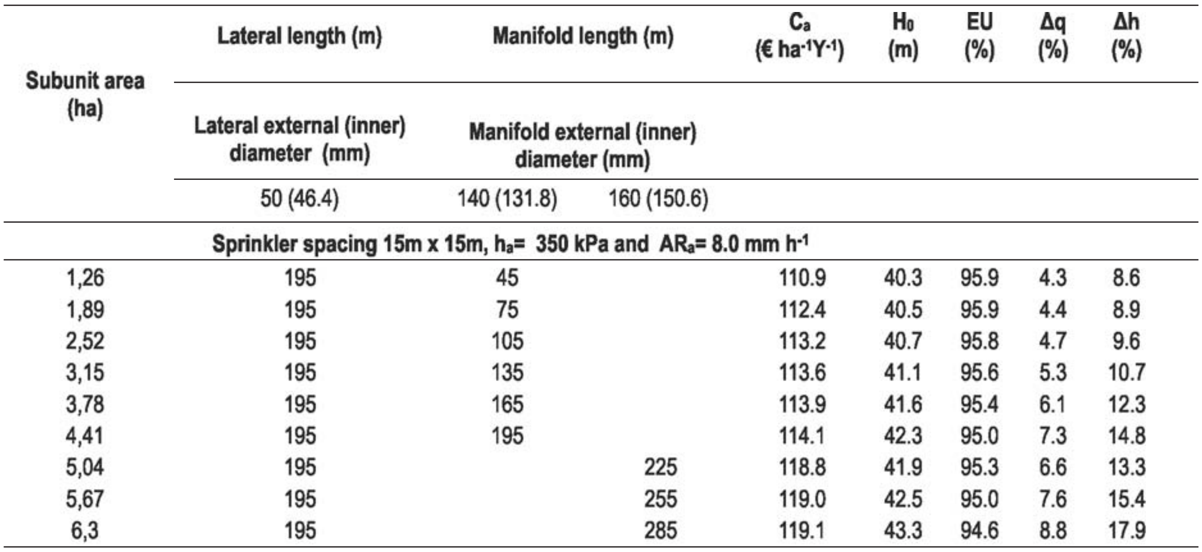
Table 6. Investment annuity cost (C_a) of a permanent sprinkler irrigation subunit with 18 m x 18 m spacing for minimum total cost C_T (Carrión *et al.,* 2014) as function of the subunit area, including the diameter and length of lateral and manifold pipes, H_0, EU, Δq and Δh values.



Subunit area (ha)	Lateral length (m)	Manifold length (m)		C_a (€ $ha^{-1}yr^{-1}$)	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		86.4	35	95.9	4.2	8.4
2.33	198	90		87.8	35.1	95.9	4.4	8.8
3.11	198	126		88.6	35.4	95.7	4.7	9.5
3.89	198	162		89.0	35.8	95.5	5.4	10.8
4.67	198	198		89.3	36.3	95.3	6.3	12.8
5.44	198	234		89.5	37.1	94.9	7.7	15.5
6.22	198		270	94.0	36.6	95.1	6.9	14.0
7.00	198		306	94.2	37.2	94.8	8.1	16.4
7.78	198		342	94.3	38.0	94.4	9.5	19.4
Sprinkler spacing 18m x 18m, h_a= 350 kPa and AR_a= 6.33 mm h^{-1}								
1.56	198	54		86.4	40.4	96.0	4.1	8.2
2.33	198	90		87.8	40.5	95.9	4.2	8.5
3.11	198	126		88.6	40.8	95.8	4.6	9.3
3.89	198	162		89.0	41.2	95.6	5.2	10.5
4.67	198	198		89.3	41.8	95.3	6.2	12.5
5.44	198	234		89.5	42.7	95.0	7.5	15.1
6.22	198		270	94.0	42.1	95.2	6.7	13.6
7.00	198		306	94.2	42.8	94.8	7.9	16.0
7.78	198		342	94.3	43.7	94.4	9.3	18.9

H_0 = pressure head required at the inlet of the irrigation subunit (m); EU= sprinkler emission uniformity (Keller and Bliesner 1990); Δq = difference in extreme sprinkler flow in the irrigation subunit (% of q_a); Δh = difference in extreme pressure heads in the irrigation subunit (% of h_a); h_a = average pressure head in the subunit (m).

Table 7. Investment annuity cost (C_a) of a permanent sprinkler irrigation subunit with 15 m x 15 m spacing for minimum total cost C_T (Carrión *et al.,* 2014) as function of the subunit area, including the diameter and length of lateral and manifold pipes, H_0, EU, Δq and Δh values.



Subunit area (ha)	Lateral length (m)	Manifold length (m)		C_a (€ $ha^{-1}Y^{-1}$)	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= 350 kPa and AR_a= 8.0 mm h^{-1}								
1,26	195	45		110.9	40.3	95.9	4.3	8.6
1,89	195	75		112.4	40.5	95.9	4.4	8.9
2,52	195	105		113.2	40.7	95.8	4.7	9.6
3,15	195	135		113.6	41.1	95.6	5.3	10.7
3,78	195	165		113.9	41.6	95.4	6.1	12.3
4,41	195	195		114.1	42.3	95.0	7.3	14.8
5,04	195		225	118.8	41.9	95.3	6.6	13.3
5,67	195		255	119.0	42.5	95.0	7.6	15.4
6,3	195		285	119.1	43.3	94.6	8.8	17.9

Energy costs

The annual operation costs (Cop= Power access + Energy consumption) can be calculated with Eq.(9).

$$C_{op}=\sum_{i=1}^{12}\sum_{j=1}^{k}\left(N_p\right)Pa_{ij}+\sum_{i=1}^{12}\sum_{j=1}^{k}\left(N_p\right)Ot_{ij}P_{ij} \quad (9)$$

where: N_p= power absorbed for irrigation water application (kW);O_t= monthly operation time of the pump (h); Pa= power access price (€ kW^{-1} $month^{-1}$); P= energy rate (€ kW^{-1} h^{-1}); *i* and *j* refer to the month and the different time-of-use energy rate periods (*k*), respectively.

The N_p was calculated according to the pressure head (H, in m) and flow rate (Q_{0s}, in m^3 s^{-1}) necessary for the proper operation of the least favourable sprinkler irrigation subunit:

$$N_p = \frac{9.81 \cdot Q_{0s} \cdot H}{E_p} \quad (10)$$

where: E_p = efficiency of pumping system (decimal).

The pressure head (H) can be obtained with the equation (11):

$$H=DL+h_f+h_s+H_{su} \quad (11)$$

where: H_{su} pressure head required at inlet of the valve located in the origin of subunit, equal to the H0 value of Tables 6 y 7 increased in 3 m for considering the head losses in the valve.

The number of operating hours per month (O_t) was calculated from the monthly distribution of net crop irrigation water requirement (R_n) (Table 8).

The gross crop irrigation water requirement (R_g) for the subunit can be calculated with Eq.(12):

$$R_g = \frac{R_n}{E_a} \quad (12)$$

where: R_n = net corn crop irrigation water requirement (m^3 ha^{-1} yr^{-1}) E_a= general application efficiency for the irrigation system (Table 5).

In the case studies, located in Spain, the energy rates of this country were utilized. For these energy rates, the available hours in each period considered are described in Table 9.

Table 8. Monthly distribution of net irrigation water requirement (Rn) for corn crop in the Albacete area, Spain.

Crop	Monthly net crop irrigation water requirement (m^3 ha^{-1})						
	April	May	June	July	August	September	Annual (Rn)
Corn	113.4	580.2	1,096.4	2,112.0	2,058.0	540.0	6,500.0

Table 9. Monthly hours of each energy rate period.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High (P1)	186	168	186	180	186	180	186	186	180	186	180	186
Medium (P2)	310	280	310	300	310	300	310	310	300	310	300	310
Low (P3)	248	224	248	240	248	240	248	248	240	248	240	248

Table 10. Energy rates of power access and energy consumption.

Energy rate period	Power access (Pa) (€ kW^{-1} yr^{-1})	Energy (P) (€ kWh^{-1})
High (P1)	24.49	0.13544
Medium (P2)	15.10	0.12010
Low (P3)	3.46	0.07562

The distribution of high, medium, and low energy rate times was detailed by the electrical company in a complex schedule. It can be simplified in three energy rate periods: P1) high energy rate period (6 h day^{-1}), P2) medium energy rate period (10 h day^{-1}), and P3) low energy rate period, at night (0:00 to 8:00 am). The energy rates for each period are detailed in Table 10.

The annual energy cost per irrigated area (C_e, € ha^{-1} yr^{-1}) was calculated by dividing the operation cost (C_{op}) by the irrigated area (S, in ha).

Maintenance costs

An additional average cost of 5% above investment costs was considered for the maintenance needs of the irrigation system (C_m), to reach a useful life (N) of 12 years for pump and 24 years for pipes, tube well, electrical line, valves, electrical line, voltage transformer.

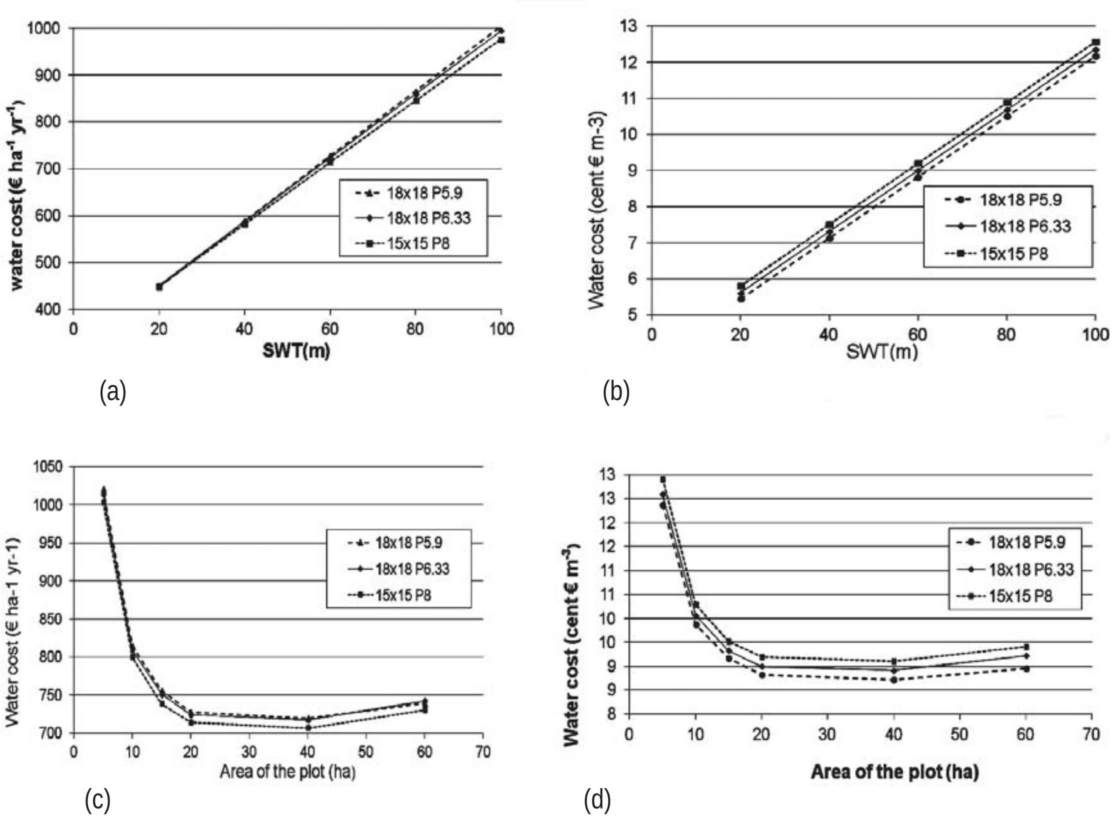
Results

Determination of water cost (Cws).

Water cost (Cws) in this study is defined as the cost of pumping water from the source to the origin of the irrigation subunit, which includes investment and operation costs, without considering the head pressure required at the head of the irrigation subunit. Figure 3 a and b shows the relationship between Cws and SWT in an unconfined aquifer (UH 04-04) for a 20 ha plot divided into 12 subunits (1.66 ha per subunit) with sprinkler spacing 18 x 18 m, and into 15 subunits (1.33 ha per subunit) with sprinkler spacing 15 x 15 m, both with corn. Results showed that Cws increased lineally with SWT. These values were conditioned by the temporal distribution of the water requirements, which depends on the crop, the efficiency of the irrigation system, the subunit size, among other. All of these parameters influenced the discharge and energy cost.

Figure 3 c and d shows the relationship between Cws and area of the irrigated plot in an unconfined aquifer (UH 04-04). Results showed that Cws decreases exponentially with the plot area, until near 40 ha, slightly increasing for larger areas (Fig. 3c and 3d), and with slight differences caused by sprinkler spacing. The increase of Cws for the larger areas is due to the large increase in energy cost when increasing the flow rate as seen in Figure 5b. Regarding the cost per cubic meter, the differences observed due to sprinkler spacing are higher than when analyzing the cost per unit of area because for 18 x 18 with ARa = 5.9 mm h^{-1} requires a lower flow rate than the 15 x 15 with ARa = 8.0 mm h^{-1} and therefore, lower investment costs. However, energy costs are similar because 18 x 18 spacing supplied more water than 15 x 15 due to its lower application efficiency (8.249 m^3 ha^{-1} yr^{-1} for 18 x 18 and 7.766 m^3 ha^{-1} yr^{-1} for 15 x 15 in Table 6), which made that the difference of cost of water per unit of area were very similar.

The high effect on Cws of plot area and SWT shows that those studies that consider a fixed value for water cost can commit errors in cost analysis. This is one of the main contributions of this work, highlighting the importance of analyzing the irrigation system as a whole, from the water source to the emitter, and not separately, to avoid errors that may be significant.



(a) (b)

(c) (d)

Figure 3. Cost of water transporting from the source to the subunit inlet (C_{ws}), for a corn crop in the unconfined aquifer, with different sprinkler spacing and ARa, calculated versus the SWT for a S= 20 ha (a and b) and the irrigated area, for SWT= 60m (c and d); both per unit of irrigated area (a and c), and per unit volume (b and d).

Effect of irrigated area (S) over total cost (CT)

The C_T decreased exponentially when increasing the plot area (Fig. 4), although slightly increase for areas larger than 40 ha, because the energy cost is higher as seen in Figure 5. Moreover, C_T is increased when increasing the SWT for the different sprinkler spacing and ARa considered. The C_T is very high for plots smaller than 15 ha, due to the large weight of the costs of borehole and electricity line on C_T. Results indicated that the lowest C_T was obtained with the spacing 18 x 18 with ARa = 5.9 mm h^{-1}, although the differences were very slight, and were even shortened when the SWT increased. These results improved the results obtained by Carrión *et al.* (2014) that concluded that the solution with the lower C_T was 15 x 15 with ARa= 8.0 mm h^{-1}. This was because they analyzed the subunits of irrigation using constant C_{ws} and an average value for C_e, regardless of tariff periods. However, the slight differences could drive to farmers to install 15 x 15 systems in case of restrictions in water availability, since with less amount of water (Table 6) and a similar cost they could supply the crop water requirements and ensure a proper yield.

Regarding Figures 4 and 3c, subunit for 15 x 15 sprinkler spacing and 350 kPa, showed higher investment and energy costs than subunit for 18 x 18 with 300 kPa. It is explained because subunit for 15 x 15 reached the lowest C_{ws} (Fig. 3c) while subunit 18 x 18 showed the lowest CT (Fig. 4). The Ca and Ce increase for spacing sprinkler 15 x 15 is not compensated for the higher amount of water consumed during the irrigation season for spacing sprinkler 18 x 18, due to its less application efficiency for the irrigation system (Table 6).

Analysis of the components of the CT and its variation with NS and SWT

In all the cases analyzed, the energy cost (C_e) was the component of the CT with the highest weight (about 70%). Investment and maintenance costs (C_a+C_m) tend to decrease when increasing the NS, as the pump, the transformer and

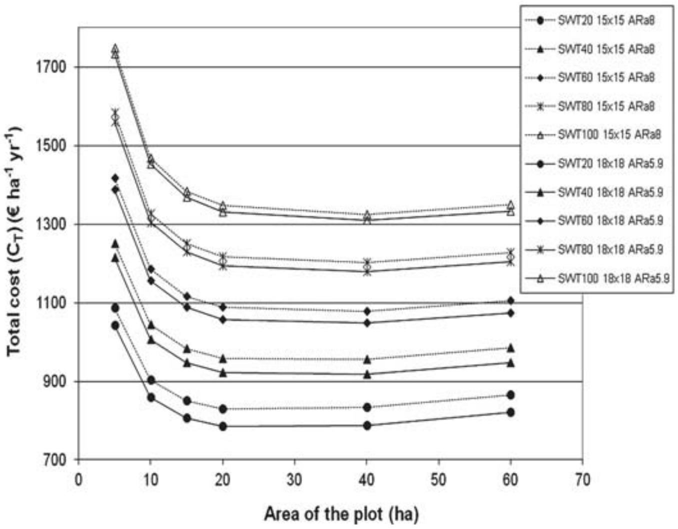


Figure 4. Pattern of C_T with the plot area for different sprinkler spacing and SWT analyzed in the unconfined aquifer, using 12 subunits in 18 x 1 8 spacing and 15 subunits in 15 x 15.

the necessary piping are smaller, being less the pumped flow rate to the subunit. The C_e usually increase with NS because increase the required number of hours of operation in the medium (P2) energy rate period.

As expected, Ce increased notably with increases of SWT (mainly by the higher power necessary in the pump), and Ca also increased but to a lesser extent, thereby increasing C_T. Thus, is crucial to minimize the C_e though a proper selection of pipe diameters and pump type.

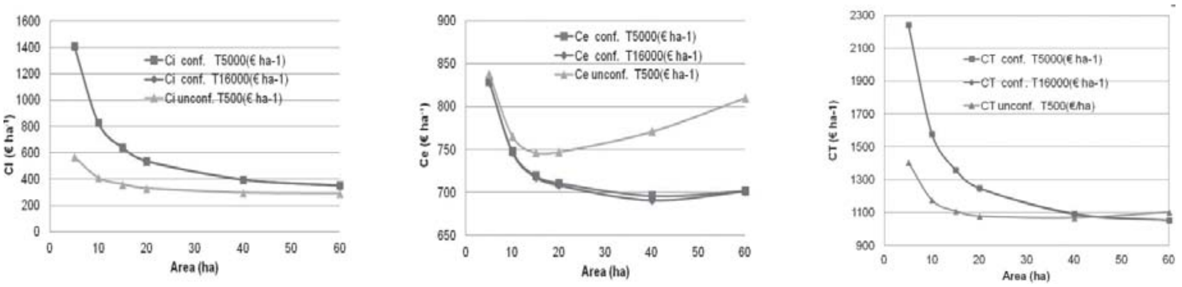
The results highlight the high participation of Cws in C_T, and its high dependence of SWT. Despite the negligible differences between spacing sprinklers, pressure heads and ARa, the 18 x 18 spacing sprinkler with ARa = 5.9 mm h^{-1} reached the lowest C_T values.

Comparative between unconfined and confined aquifer

At first it is should be highlighted that the minimum CT is highly influenced for the tube well sizing, related to the drilling diameter intervals (each 50 mm) which are available (Table 1). According to this, in some cases it might be justified the use of lower diameters of pumping pipe, for not increasing the diameter of pipe well, despite the increase of energy costs. This is and other important contribution of this work, that it is not easy to identify without a full analysis of the process.

With regard to Ca, the differences are significant between both type of aquifers, being higher in confined aquifers (ranged from 20 % to 150 %)(Fig. 5a) because in this study a fixed WPD value of 350 m is considered, decreasing exponentially when the plot surface is increased, although it needs more flow rate and therefore more drilling diameter and deeper well, which depends on Q, SWT and WPD (Table 1).

C_e is higher in unconfined aquifer with differences between 1 % and 15 %, being higher when the plot surface is increased, due to the required power increase. It is explained because the drawdown in the well (dd) reaches a high value because of the low transmissivity (T) in unconfined aquifer.



(a) (b) (c)

Figure. 5. Comparative between unconfined and confined aquifer for spacing sprinkler 18 x 18, ARa=6.33 mm h^{-1} and SWL = 60 m regarding a) Ca b) Ce and c) C_T.

The differences between C_T are explained by the borehole investment costs, being in the confined aquifers much more expensive than the unconfined aquifers considered in this study. The C_T is lower in the aquifer confined in larger plots of 45 ha due to the higher value of Ce in unconfined aquifers by the low T value (results norshow).

The transmissivity (T) increase in unconfined aquifers, from 5.000 to 16.000 m^{-2} day^{-1} did not cause relevant differences between Ce and, therefore, of C_T (results norshow).

The drawdown in the well (dd) increase with the plot size, reaching 22 m for S = 60 ha in an unconfined aquifer with T= 500 m^{-2} day^{-1}, but only 2 m for a confined aquifer with T= 5.000 m^{-2} day^{-1}, and 0.7m with T= 16,000 m^{-2} day^{-1}. This highlights the important role of T in the water extraction cost.

Conclusions

Water cost (C_{ws}), including extraction and transport from the source to the point where is used, increase lineally with static water table (S_{WT}) in the aquifer and decrease exponentially with the irrigated plot size (S), having lower influence on C_T the remainder factor as number of subunit, the sprinkler spacing or the average application rate for the studied cases. Thus, the studies that consider a constant Cws to analyze different scenarios of relationships between parameters involved in the process irrigation water application can have errors. This is one of the main contributions of this work, highlighting the importance of analyze the irrigation system as a whole, from the water source to the emitter, and not separately, to avoid errors that may be significant.

For the studied aquifers, the Cws is mainly conditioned by the borehole investment cost, being the confined aquifer 20-150% more expensive than the unconfined in the studied cases. Energy annuity cost (Ce) is more expensive in the unconfined aquifer than a confined aquifer (between 1-15 %) because of its low transmissivity value (500 in comparison with 5.000 or 16.000 m^{-2} day^{-1}). This fact causes relevant differences in the drawdown in the well (dd) (between 0.7 and 22 m).

For plots smaller than 15 ha, the CT have a large increases due to the high contribution of the borehole and electrical line costs on necessary investment cost.

The energy (Ce) is the main component of C^T, getting to represent more than 70 % in the studied cases. Thus, it is really important to take into account the contracted tariff period in the design system and water distribution during the irrigation season. This indicates the necessity for developing algorithms and tools to optimize the performance of water pumping facilities in irrigation systems.

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