
Volume 127, September 2013
ISSN 0378-3774
ELSEVIER
Agricultural Water Management
An International Journal

Agricultural Water Management 127 (2013) 107–118

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

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

Low-cost microirrigation system supplied by groundwater: An application to pepper and vineyard crops in Spain

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ARTICLE INFO

Article history:
Received 10 August 2012
Accepted 5 June 2013
Available online 2 July 2013

Keywords:
Microirrigation design
Water application cost
Energy cost

ABSTRACT

The PRESUD tool was developed using MATLAB™ to identify the optimum microirrigation system design. The lowest cost was determined by calculating the annual water application cost per unit of irrigated area (C_T). This is defined as the cost of one cubic meter of water applied to crops, and is the sum of investment (C_a), maintenance (C_m) and energy (C_e) costs. This tool optimizes the shape of the characteristic and efficiency curves of the pump and the pumping pipe, distribution pipe, and irrigation system pipes diameters with a holistic approach.

All subunits are rectangular, with the well pipe in the center. The lateral and manifold pipe parameters are calculated using a stepwise method. The analysis includes the effects of the main factors in irrigation system design: dynamic lift in the aquifer (DL), number of subunits (NS), irrigated area (S) and crop irrigation water requirements (R_g), among others.

The tool was applied to the specific conditions in Spain. Results show that C_T decreases with an increase in plot size, and costs are high for plots smaller than 3–5 ha. This is due to the percentage of total costs that the tube well and electrical line contribute. C_T has a positive relationship with DL. In these case studies, diesel fuel electrical generators are recommended for plots <4 ha for pepper crops and up to 15 ha for grapevine if DL is 40 m. These limits vary with different DL values or changes in the cost and length of the electrical line.

1. Introduction

Recently in Spain and many other countries, energy demands for irrigation have increased considerably. This is mainly due to an increase in irrigated area and modernization processes, in which traditional open channels and surface irrigation systems are being progressively replaced by new, pressurized irrigation and on-demand water distribution systems (Moreno et al., 2009, 2010a,b; Rodríguez et al., 2012). In addition, under the context of climate change and rising energy costs, it is necessary to develop methodologies, tools, and actions to optimize energy use. This implies environmental as well as economic benefits.

Irrigation Advisory Services (IASs) are available in many areas of the world to help farmers efficiently use production factors, such as water, fertilizer, and energy. IASs provide farmers with adequate scientific and technical support so that agriculture is a sustainable activity that is compatible with the natural environment (Ortega et al., 2004). It is important to advise farmers on the design and management of irrigation systems to reduce water application costs. Decision support system (DSS) tools must be developed for providing this technical advice.

Pumping water for distribution and groundwater extraction are the main energy consumers in pressurized water networks. In fact, several authors have developed algorithms to minimize energy and investment costs in pumping systems (Moradi-Jalal et al., 2003, 2004; Pulido-Calvo et al., 2003; Planells et al., 2005; Moreno et al., 2007, 2012; Lamaddalena and Khila, 2012).

The optimum hydraulic design of a microirrigation subunit is reached by determining the sizes of lateral and manifold pipes that ensure proper emitter flow and intake pressure head in the emitters. This information is used to achieve optimal emission uniformity (EU) from an economic perspective.

The emitter flow equation with an unregulated emitter is expressed as (Karmeli and Keller, 1975):

$$q_h = K_e h_e^x, \quad (1)$$

where q_h is the emission rate of an unregulated emitter at a specified water pressure at the device intake; K_e is the emission coefficient; x is the emission exponent (usually $0 < x < 1$); h_e is the intake pressure head of the emitter.

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http://dx.doi.org/10.1016/j.agwat.2013.06.005

Notation

A	investment annuity (€T^{-1})
C_a	investment annuity per unit of irrigated area (€L^{-2} T^{-1})
C_e	energy annuity per unit of irrigated area (€L^{-2} T^{-1})
C_i	total investment cost (€)
C_m	maintenance cost (€L^{-2} T^{-1})
CRF	capital recovery factor
C_T	total annual cost of water application (€)
CV_{qmf}	coefficient of variation of emitter manufacturer (decimal)
D	inner diameter of pipe (L)
D_d	distribution pipe diameter
D_l	nominal diameter of lateral (L)
DL	dynamic lift
D_m	nominal diameter of manifold (L)
D_p	pumping pipe diameter (L)
D_{pp}	is the well pipe diameter (m)
e	number of emitters per plant
ee	annual rate of escalation in energy costs
E_a	general application efficiency for the irrigation system (decimal)
E_p	efficiency of pumping system (decimal)
EU	emission uniformity (decimal)
h	the saturated depth of drilled aquifer after pumping (m)
h_e	intake pressure head of the emitter (L)
h_a	average pressure head in the subunit (L)
h_f	pipe head loss with constant flow rate (L)
h_0	lateral pipe intake head (L)
H	pressure head required at the pump
H_d	design pressure head
H_0	pressure head required at the intake of the microirrigation subunit (L)
H_s	saturated depth of drilled aquifer before pumping
i	interest rate (decimal)
K	the permeability of the aquifer (m day^{-1})
K_e	emission coefficient (L^{3-x} T^{-1})
L	pipe length (L)
m	flow exponent in the head loss equation
N	useful life (T)
N_g	gross crop irrigation water requirement per year (L^3 L^{-2} T^{-1})
N_n	net crop irrigation water requirement per year (L^3 L^{-2} T^{-1})
N_p	power consumed for irrigation water application (kW)
NS	number of subunits
O_t	annual operating time of the irrigation system (T T^{-1})
Pa	power access price (€kW^{-1} T^{-1}),
P	energy rate (€kW^{-1} T^{-1})
Pi	time-of-use energy rate
P_l	lateral pipe price (€L^{-1})
P_m	manifold pipe price (€L^{-1})
q_a	average emitter flow in the subunit (L^3 T^{-1})
q_{ah}	average emitter flow due to the variation of pressure in the subunit (L^3 T^{-1})
q_h	emission rate (L^3 T^{-1})
q_{mh}	minimum emitter flow in the subunit due to the pressure (L^3 T^{-1})
Q_d	design flow rate
Q_0	inflow rate to the pipe (L^3 T)
Q_{0s}	inflow rate to the microirrigation subunit (L^3 T)
R	the radius of the cone of influence (m)
Re	Reynolds number
R_n	net crop irrigation water requirement (L^3 L^{-2} T^{-1})
R_g	gross crop irrigation water requirement (L^3 L^{-2} T^{-1})
S	irrigated area (L^{-2})
s_e	emitter spacing (L)
s_l	lateral pipe spacing (L)
SWT	static water table (m)
T	monthly operation time of the pump, (T);
Tr	transpiration relationship
x	emission exponent

Greek symbols

ν	water kinematic viscosity (L^2 T^{-1})
Δh	difference in extreme pressure heads in the irrigation subunit (% of h_a)
Δq	difference in extreme emitter flow in the irrigation subunit (% of q_a)
ΔZ	differences in elevation in the pipe (lateral or manifold)

Karmeli and Keller (1975) characterize the performance of drip irrigation subunits with an emission uniformity coefficient (EU), defined as

$$EU = \left(1 - \frac{1.27\,CV_{qmf}}{\sqrt{e}}\right)\frac{q_{mh}}{q_{ah}}100 \qquad (2)$$

where CV_{qmf}, coefficient of variation of emitter (a value supplied by the manufacturer); e, number of emitters per plant; q_{mh}, minimum emitter flow in the subunit due to pressure; q_{ah}, mean emitter flow due to variations in pressure.

This equation is practical, but has insufficient rigor and theoretical justification (Juana et al., 2004). With q_{mh} and Eq. (1), the value of h_{mh} at the emitter with the lowest pressure can be estimated. Thus, the value of q_{ah} corresponds to h_a (mean intake pressure head of the emitters) and the intake head (H_0) in the irrigation subunit can be obtained from these two pressure head values.

An increase in number of emitters per plant (e) and the proportion of wetted area is related to an increase in unit cost of the system (Keller and Bliesner, 1990). The same is true with the ground topography: more complicated terrain (undulating or slopes greater than 2%) leads to higher unit cost for reaching a certain EU.

Warrick and Yitayew (1988) present several graphs for determining the length and diameter of laterals and the intake head assuming a given average emitter flow and water application uniformity. Kang et al. (1999) use the finite element method and the golden section search (Kang and Nishiyama, 1996) for building contour maps that relate Christiansen's uniformity coefficient to the diameter and length of the microirrigation lateral, and relate the latter two variables to the intake head (H_0).

However, no references have been found that analyze the irrigation system as a whole, from the water source to the emitter, including the design and sizing of the pumping system and the pumping and distribution pipes, as well as the irrigation system itself. Every part of the system affects the design and sizing of the other parts.

Thus, the aim of this study is to develop a DSS tool, named PRESUD, which yields the optimal hydraulic design and sizing of microirrigation systems with a minimum total cost (operation + investment) per unit area. With this tool, several case studies located in Spain are analyzed to obtain general results on the design and sizing of microirrigation systems by evaluating the effects of

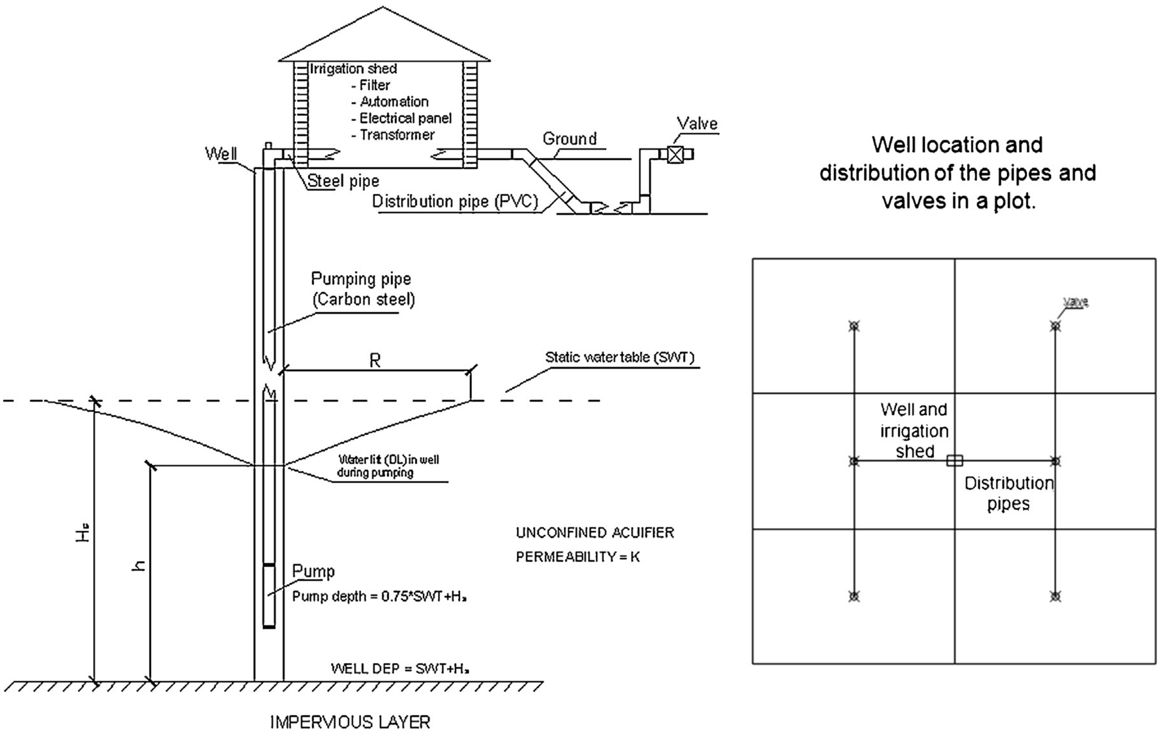

Fig. 1. Diagram of the microirrigation system infrastructure for six irrigation subunits.

parameters such the dynamic lift in the aquifer (DL), the number of subunits (NS), the irrigated area (S), crop irrigation water requirements (R_g), and others.

2. Materials and methods

MATLAB software, PRESUD (pressurized subunit design), was developed to determine the optimum microirrigation subunit design by minimizing annual water application costs, as described in Carrión et al. (2013). The approach has been extended in this paper for the full irrigation system design (from the water source to the emitter).

To identify the optimum microirrigation system design, the annual water application costs per irrigated area is calculated. This is defined as the cost of a cubic meter of water applied to the soil for crops, and is calculated as the sum of investment, maintenance and energy costs. This study considers rectangular plots, with the tube well located in the center. This layout leads to lower investment costs (Fig. 1). However, the PRESUD tool allows for optimizing the design of microirrigation systems with other topologies.

Since the pipes used for lateral, manifold, and distribution pipes are made of smooth material (polyethylene (PE) or polyvinylchloride (PVC)), and the diameters are small, the Blasius (Eq. (3), S.I. units) (Reynolds number, $R_e < 10^{-5}$) and Veronesse-Datei (Eq. (4), S.I. units) ($R_e < 10^{-6}$) head loss equations have been used for the hydraulic calculations with PE and PVC, respectively. For steel pipes, for pumping from the tube well, the Hazen-Williams equation (Eq. (5), S.I. units) is used.

$$h_f = 0.0246\,\nu^{0.25}\,D^{-4.75}Q_0^{1.75}L \tag{3}$$

$$h_f = 0.0099\,\nu^{0.172}\,D^{-4.80}Q_0^{1.8}L \tag{4}$$

$$h_f = 10.62\,C^{-1.85}D^{-4.87}Q_0^{1.85}L \tag{5}$$

where h_f is the pipe head loss (L); ν is the water kinematic viscosity($L^2\,T^{-1}$); D is the inner diameter of pipe (L); Q_0 is the inflow rate to the pipe (L^3 T); L is the pipe length (L); C is the friction coefficient ($C = 115$ for steel pipe in the case study).

Minor singular head losses (h_s) are considered to comprise 10% of h_f in the distribution pipe network and pumping pipe. The equivalent length method was used to calculate the microirrigation subunits (Carrión et al., 2013).

2.1. Objective function and optimization variables

Fig. 2 summarizes the optimization process implemented by the PRESUD tool. The optimization variables were head flow rate (Q), coefficient of the characteristic curve (c) (see next section), pumping pipe diameter (D_p), and the distribution pipe diameter (D_d). The optimization process was carried out using the Downhill Simplex Method (Nelder and Mead, 1965), which aims to minimize the total cost:

$$\mathrm{MIN}(C_a + C_m + C_e) \tag{6}$$

where C_a is the annual investment cost, C_m is the annual maintenance cost, and C_e is the annual energy cost. All costs are considered per unit area (€ha^{-1}).

2.1.1. Model design

To select the optimum pump for powering the irrigation system directly from the tube well, the software must consider the shape of the characteristic (Q–H) and efficiency (Q–E_p) curves, as well as the optimum sizing of the pump pipe and the distribution pipe. These variables will determine the energy efficiency of the whole system through the irrigation season and fit it to varying conditions of the aquifer.

The characteristic and efficiency curves of the pumps (H–Q and E_p–Q) can be approximated by Eqs. (7) and (8) (Moreno et al., 2010b):

$$H = a + cQ^2 \tag{7}$$

$$E_p = eQ + fQ^2 \tag{8}$$

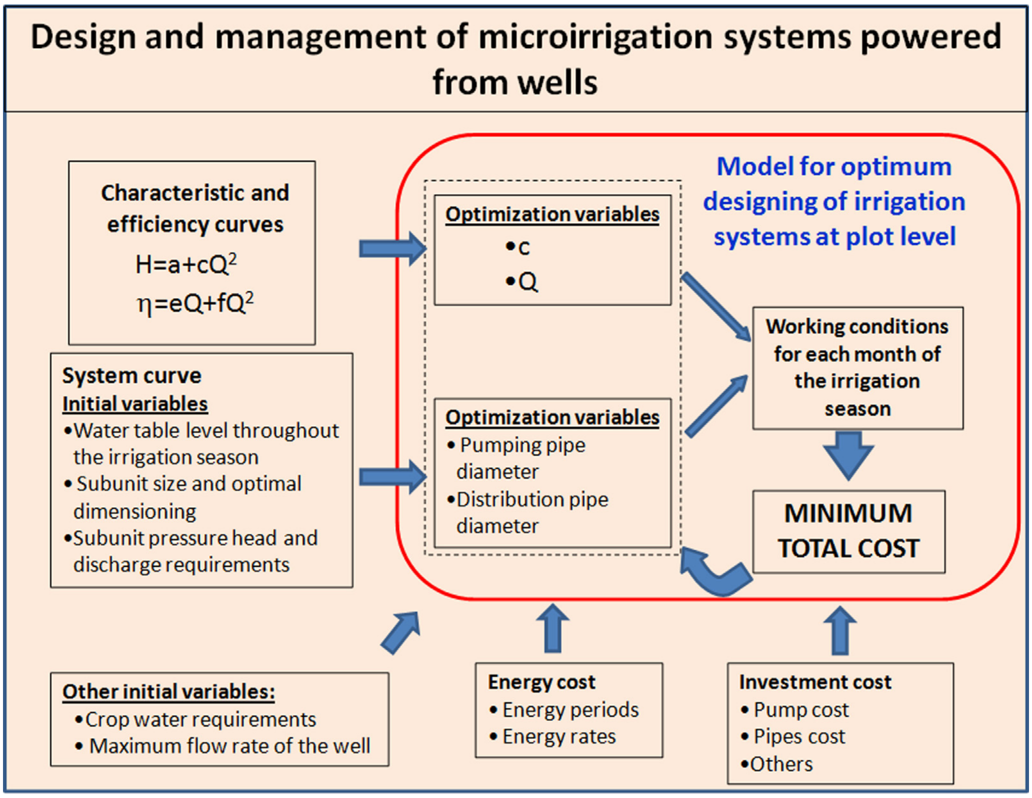

Fig. 2. Diagram of the optimization process.

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

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

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 $H = Hg + hQ^2$, where Hg is the elevation difference over which the system pumps water (dynamic lift (DL) in this case), and hQ^2 represents the head losses in the pipes. Thus, the system curve depends on the DL and the head losses of the pipe network.

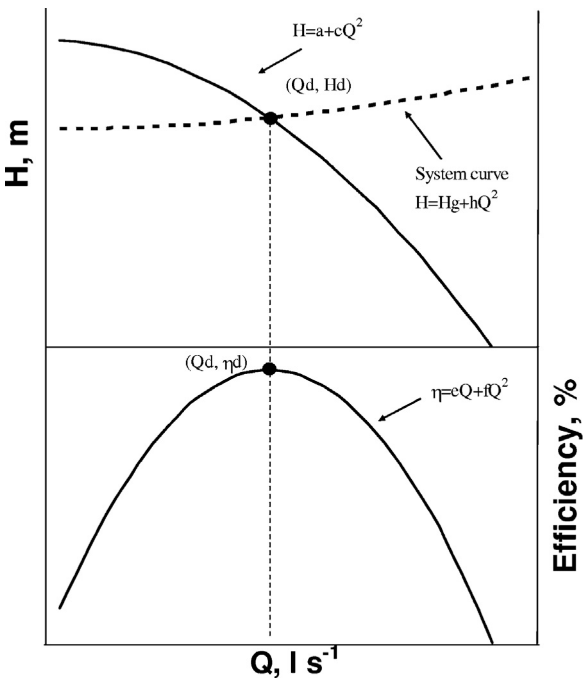

Fig. 3. Diagram of the characteristic and efficiency curves of the pumps.

When H and E_p equal zero (Fig. 3), and considering Eqs. (7) and (8):

$$H = 0 \Rightarrow a = -cQ_{\max}^2 \Rightarrow Q_{\max} = \left(\frac{-a}{c}\right)^{0.5} \quad (9)$$

$$E_p = 0 \Rightarrow eQ_{\max} = -fQ_{\max}^2 \quad (10)$$

Thus, coefficient e is defined in Eq. (11) as:

$$e = -f\left(-\frac{a}{c}\right)^{0.5} \quad (11)$$

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

$$E_{p\max} \Rightarrow \frac{dE_p}{dQ} = 2fQ + e = 0 \Rightarrow Q = -\frac{e}{2f} \quad (12)$$

With Eqs. (8) and (12) the following equation can be obtained:

$$E_{p\max} = f\left(-\frac{e}{2f}\right)^2 + e\left(-\frac{e}{2f}\right) = -\frac{e^2}{4f} \quad (13)$$

Considering Eqs. (11) and (13):

$$f = \frac{4 \cdot E_{p\max}}{(a/c)} \quad (14)$$

From Eq. (7), the following equation can be established:

$$a = H_d - c(Q_d)^2 \quad (15)$$

where H_d is the design pressure head; Q_d is the design flow rate.

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

Concept	Material	Cost (€unit^{-1})	R^2
Lateral	PE 0.25 MPa	0.16 and 0.13 (€m^{-1}) for 16 mm of diameter, with emitters spaced 0.75 and 1.25 m, respectively	
Manifold	PE 0.4 MPa	$y = 0.0003\,D^{2.0315}$	0.999
Distribution pipe	PVC 0.6 MPa	$C = 0.001253\,D^{1.632397}$	0.992
Pumping pipe	Steel	$C = 0.0009\,D^{1.8013}$ (€m^{-1})	0.999
Hydraulic valves	Cast iron	$C = 0.017385\,D^2 + 0.010499\,D - 26.648651$	0.997
Filter system and flow meter		$C = 0.011323\,Q^2 + 4.073859\,Q + 107.332258$	0.965
Pump		$C = 0.0016\,{P_p}^3 + 0.924\,{P_p}^2 + 268.28P_p$	0.943
Electrical wire	Cooper	$C = 0.0025318\,{P_p}^2 + 0.0823262\,P_p + 5.7296411$	0.99
Electrical panel		$C = 224.418612\,{P_p}^{0.329085}$	0.99
Electronic starter		$C = -0.023988\,{P_p}^2 + 25.423305\,P_p + 758.163174$	0.98
Controller and auxiliary		$C = 800$ (€)	
Voltage transformer		$C = 0.012140\,P^2 + 9.699422\,P + 4051.880598$	0.975
Diesel fuel electrical generator		$C = -0.199837\,P^2 + 92.277799\,P + 2460.159007$ 0.283 L kWh^{-1} and 0.8 €L^{-1} of fuel-oil	0.979

D, inner pipe diameter (mm); P, power of the transformer or generator (kVA); Q, flow rate (m^3 h^{-1}); P_p, power of the pump (kW).

The maximum efficiency (E_{pmax}) can be determined from manufacturer information. In this study, a theoretical maximum pump efficiency of 80% was considered.

2.1.2. Investment costs

The investment costs (C_i) considered were: pipe costs (laterals with drippers and manifold (both PE), distribution (PVC), and well pumping (steel) pipes), hydraulic valves with a pressure regulator and flow limiter for each irrigation subunit, the automation system with a PLC that controls the valves of the subunits, the filtering system, the low voltage accessories, the well drilling, the pump, the electrical line and voltage transformer for using conventional electrical energy, and the diesel fuel electrical generator as an alternative source of energy.

The investment annuity ($A = \mathrm{CRF}\,C_i$, in €Y^{-1}) for the total investment cost (C_i, in €) was computed considering a useful life (N) of 12 years for pump, fuel electrical generator, and filter; and 24 years for pipes, tube well, 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 (C_a, en €ha^{-1} yr^{-1}) were calculated using Eqs. (16) and (17):

$$\mathrm{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{16}$$

$$C_a = \frac{A}{S} = \frac{\mathrm{CRF}.C_i}{S} \tag{17}$$

where S is the area irrigated by the microirrigation 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 1). PRESUD software allows the user to change the coefficients of the equations for other price conditions.

For permanent operating conditions in unconfined aquifer, the saturated depth of drilled aquifer after pumping (h, in m, in Fig. 1) can be calculated with the simplified equation

$$h = \sqrt{H_s^2 - \left(\frac{86.4 \cdot Q}{\pi \cdot K} \cdot \ln\left(\frac{2 \cdot R}{D_{pp}}\right)\right)} \tag{18}$$

where Q is the system flow (in L s^{-1}); K is the permeability of the aquifer (m day^{-1}); D_{pp} is the well pipe diameter (m); R is the radius of the cone of influence (m); H_s is the saturated depth of drilled aquifer before pumping (with static water table (SWL) in Fig. 1) (m).

The dynamic lift, DL, is the depth to the SWT plus the drawdown (H_s–h).

In this study we assume:

Table 2
Cost of well drilling.

	Superficie parcela (ha)		
	<10 ha	10–20 ha	20–30 ha
Drilling type	Rotopercussion	Percussion	Percussion
Drilling diameter (D_{pp}) (mm)	225	350	500
Iron pipe			
Diameter (mm)	200	250	350
Thickness (mm)	6	6	8
Average cost (€m^{-1})	**60**	**216**	**307**

These costs also include the costs of transportation and installation of machinery, pipe-filter, gravel calibrated and project.

- An unconfined aquifer typical of “La Mancha” (Spain), with $R = 1500$ m and $K = 20$ m day^{-1}.
- if SWT < 30 m, then $H_s = 30$ m; if 30 m < SWT < 80 m, then H_s = SWT; if EWT > 80 m, then H_s = 0.75 SWT.
- The well depth is SWT depth plus H_s, and pump depth is = 0.75 SWT + H_s.
- The D_{pp} values included in Table 2 as a function of plot area.

The considered cost of well drilling is included in Table 2 and of electric line cost in Table 3. As electrical line length is considered 500 m plus half square side assigned to each parcel size, since the tube well and the pump are located in the center of the plot.

Carrión et al. (2013) report the typical microirrigation subunit design of minimum cost as function of the subunit size for pepper (Table 4) and grapevine (Table 5) crops.

For all case studies, a pressure head at the valve located in the origin of every irrigation subunit was set at H_o = 15 m to consider the head losses in the valves. In addition, a head loss of 10 m was considered in the irrigation shed, which includes the filtering system, the flow meter, valves, and other elements.

2.2. Energy costs

Two options were considered regarding the energy cost depending on the source of energy: (a) conventional electrical energy and (b) a diesel fuel electrical generator, For conventional electrical energy, the annual operation cost (C_{op}) charged by the electrical company is divided into two terms: (1) power access, which is

Table 3
Cost of electric line.

	Plot size (ha)		
	<10	10–20	21–30
Cost of electric line (€km^{-1})	4550	6500	7800

Table 4
Investment cost of a microirrigation subunit for minimum total cost C_T (Carrion et al., 2012) as a function of the subunit area, including the diameters and lengths of lateral and manifold pipes, H_0 and EU values, considering reference values for a typical pepper crop subunit design in Spain.

Subunit area (ha)	Lateral length (m) Lateral diameter (mm)	Manifold length (m) Manifold diameter (mm)				C_i (€ha^{-1} Y^{-1})	H_0 (m)	EU (%)
	16	50	63	75	90			
0.32	80	40				2141	10.40	92.6
0.50	91		55			2129	10.45	92.4
0.75	94		80			2189	10.80	91.9
1.00	110			90		2201	10.80	91.7
1.25	139			90		2183	11.20	91.2
1.50	136				110	2258	11.05	90.9
1.75	146				120	2250	11.30	90.7

Table 5
Investment cost (C_i) of a microirrigation subunit for minimum total cost C_T (Carrion et al., 2012) as function of the subunit area, including the diameter and length of lateral and manifold pipes, H_0 and EU values, considering the reference values for a typical grapevine subunit design in Spain.

Subunit area (ha)	Lateral diameter (m) Lateral length (mm)	Manifold diameter (m) Manifold length (mm)					C_i (€ha^{-1} Y^{-1})	H_0 (m)	EU (%)
	16	40	50	63	75	90			
0.5	111	45					60.2	10.7	92.7
1.25	104		120				63.8	11.2	92.0
1.75	130			135			66.6	11.2	91.8
2.25	150			150			64.9	11.9	91.3
2.75	158				174		68.7	11.7	91.2
3.25	175				186		67.5	12.3	90.6
3.75	187					201	72.5	12.2	90.4

a fixed cost for using power during each period, and (2) energy consumption, which is a cost that varies depending on the energy consumed by the system. Thus, operation costs can be calculated with Eqs. (19) and (20).

$$C_{op} = \text{Power access} + \text{Energy consumtion} \quad (19)$$

$$C_{op} = \sum_{i=1}^{12}\sum_{j=1}^{k}(N_p)_i Pa_{ij} + \sum_{i=1}^{12}\sum_{j=1}^{k}(N_p)_i T_{ij} P_{ij} \quad (20)$$

where N_p is the power absorbed for irrigation water application (kW); T is the monthly operation time of the pump (h); Pa is the power access price (€kW^{-1} month^{-1}); P is the 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 favorable microirrigation subunit:

$$N_p = \frac{9.81 Q_{0s} H}{E_p} \quad (21)$$

where E_p is the efficiency of pumping system.

The pressure head can be obtained with Eq. (22):

$$H = DL + hf + hs + H_o \quad (22)$$

where H_o is the required pressure at the intake of the subunit. In this case, considering the head losses in the valve, it is considered H_o = 15 m.

The number of operating hours per month was calculated from the monthly distribution of net crop irrigation water requirement (R_n) (Table 6) and the optimum flow rate obtained in the optimization process.

The gross crop irrigation water requirement (R_g) for the subunit can be calculated with Eq. (23):

$$R_g = \frac{R_n \; Tr}{\text{EU}} \quad (23)$$

where R_n is the net crop irrigation water requirement (m^3 ha^{-1}); EU is the emission uniformity of the miroirrigation system; Tr is the peak-use-period transmission ratio (Keller and Bliesner, 1990) (Tr = 1.05 and 1 for pepper and grapevine, respectively in this study).

From Tables 4 and 5 (Carrión et al., 2013), the relationships between EU and S for pepper crop (Eq. (24)) and vineyard (Eq. (25))

$$\text{EU} = -0.0137S + 0.9301 \quad (R^2 = 0.9887) \quad (24)$$

$$\text{EU} = -0.007S + 0.9298 \quad (R^2 = 0.9838) \quad (25)$$

In the case studies, located in Spain, the energy rates of this country are utilized. For these energy rates, the available hours in each period considered are described in Table 7. The distribution of high, medium, and low energy rate times is 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 (0:00–8:00 am). The energy rates for each period are detailed in Table 8.

When a diesel fuel electrical generator is utilized, only the price of the diesel fuel (0.9 €L^{-1}) and the efficiency in the generation of

Table 6
Monthly distribution of net crop irrigation water requirement for pepper and grapevine.

Crop	Monthly net crop irrigation water requirement (m^3 ha^{-1})						
	April	May	June	July	August	September	Annual total
Pepper	30.26	285.27	1834.84	2149.29	1600.35	0	5900
Grapevine		167.56	326.63	553.57	425.52	26.72	1500

Table 7
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

electrical energy from diesel fuel (0.283 kWh L^{-1}) are considered to determine the energy cost.

To consider the possibility that energy prices will change due to the general rate of inflation (i), Eq. (26) (Keller and Bliesner, 1990) has been implemented in PRESUD tool.

$$EAE = \left[\frac{(1+e)^n - (1+i)^n}{(1+e) - (1+i)}\right] \cdot \left[\frac{i}{(1+i)^n - 1}\right] \quad (26)$$

where e is the annual rate of escalation in energy costs (0.05 in this study).

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

All the data assumed for the case studies can be modified in the PRESUD tool to fit the requirements of any case study.

2.3. 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, fuel electrical generator, and filter; and 24 years for pipes, tube well, electrical line, valves, electrical line, voltage transformer.

2.4. Influence of the main factors over the total cost

To analyze the influence of the main factors on C_T, the reference values in Table 9 have been considered. Sensitivity analysis is then performed for the most influential factors among those described in Table 9.

3. Results

3.1. Effect of the number of subunits (SN) on total cost (C_T)

Fig. 4 shows the effect of the number of irrigation subunits on C_T in typical microirrigation systems for pepper and grapevine crops, with different plot sizes (6, 8, 10, 20, and 30 ha), a DL of 80 m, and all other parameters as described in Table 9.

For pepper crops (Fig. 4a), there are slight differences in C_T due to changes in the number of irrigation subunits. The minimum cost for plot sizes of <6 ha are obtained with 6 irrigation subunits. For plot sizes greater than 10 ha, the optimal SN is 8. However, in the latter case, increasing SN means using the system practically 24 h a day in the peak month (July) (Fig. 5), which implies a high risk of break-downs or maintenance needs.

For grapevine (Fig. 4b), there is a slight difference in C_T according to the number of irrigation subunits. For microirrigation subunits, the recommendation is to select the maximum number of irrigation subunits in energy periods P2 and P3 (medium and low energy prices, respectively), leaving P1 (high energy cost) for maintenance tasks or repairing break-downs. Decreasing to a minimum number of irrigation subunits would increase the flexibility in the irrigation process, but also increases the volume of water demanded (lower EU). This has implications in areas of environmental restrictions, especially where there is water scarcity.

Table 8
Energy rates of power access and energy consumption.

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

3.2. Effect of irrigated area (S) on total cost (C_T)

As expected, C_T decreases with an increase in plot size (Fig. 6), with high costs for plots <4–6 ha. This is due to the contribution of the tube well and electrical line costs on C_T. Although EU decreases slightly when increasing the irrigation subunit size (Tables 4 and 5), the increase in gross water requirements has a small effect on C_T. However, this factor should be considered in areas with problems of water scarcity.

Fig. 6 compares using conventional electrical energy or electrical generators (diesel fuel) as sources of energy. When DL < 60 m, generator use yields a lower C_T for small plots (up to 3–5 ha for pepper (Fig. 6a)). For grapevines (Fig. 6b), with DL = 20 m, generator use produces lower C_T values for plot sizes up to 30 ha, and up to 6 ha for DL = 100 m.

By increasing the length of the electrical wire (or the price per unit of length) from the standard parameters (Table 9), the plot size for lower C_T using the electrical generator is grater for the same DL (standard value of DL = 60 m). Thus, for pepper crops, the electrical generator contributes to a lower C_T for S < 6 ha for an electrical line length of 3 km. In the case of grapevine, electrical generator usage leads to a lower C_T for S < 12 ha with 0.5 km of electrical cables, and S < 30 ha for a length of 3 km.

Table 9
Summary of the reference parameters considered in the study.

Parameter	Value in reference conditions	
	Pepper subunit	Grapevine subunit
Land slope	0%	
Emission exponent (x)	0.5	
Emitter manufacturer coefficient of variation (CV_{qmf})	0.05	
D_I (nominal) PE 0.25 MPa	16	
Dynamic lift (DL)	60 m	
Surface of plot (S)	10 ha	
Use of electric energy from a network	658 m of wire length	
Plant spacing	0.7 m	1.5 m
Annual crop water requirement (R_n)	5900[a] (m^3 ha^{-1} Y^{-1})	1500[a] (m^3 ha^{-1} Y^{-1})
Emitter flow (q_a)	2 L h^{-1}	4 L h^{-1}
Emitter spacing	0.75 m	1.25 m
Lateral pipe spacing	1.0 m	3.0 m
Peak use period transmission ratio (Tr)	1.05	1.0

[a] Representative data for these crop in the Albacete area, Spain; Martín de Santa Olalla et al. (2003) and de Juan et al. (2009).

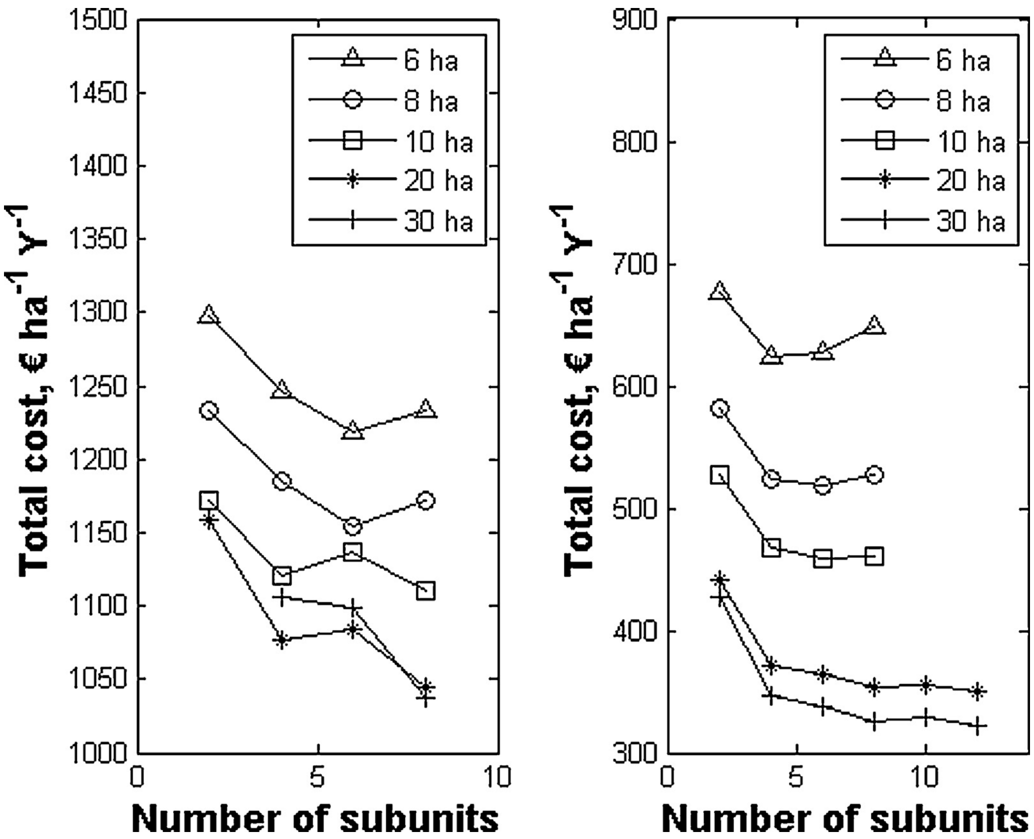

Fig. 4. Effect of SN on C_T in typical microirrigation systems for (a) pepper and (b) grapevine crops, with different plot sizes, DL = 80 m, and all other parameters as described in Table 9.

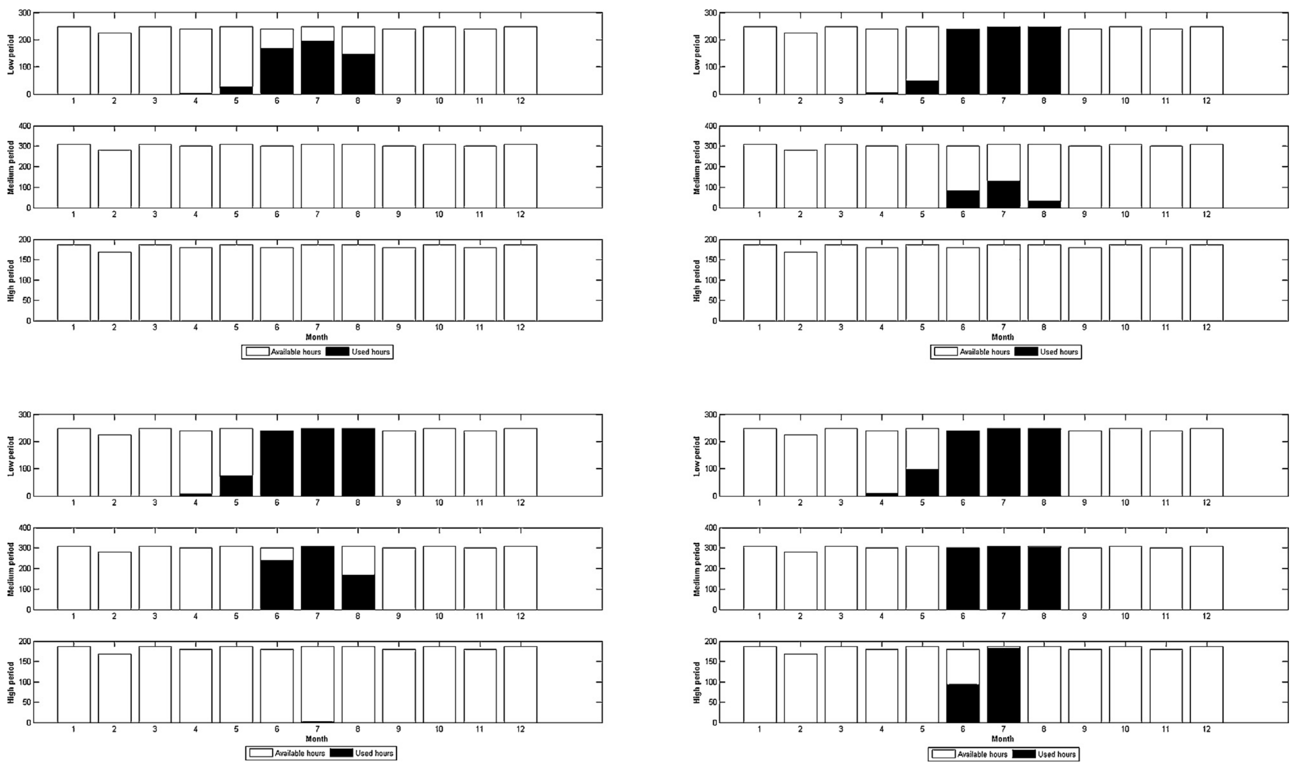

Fig. 5. Example of distribution of operating hours during the different energy periods for pepper crop under standard conditions (Table 9) for a plot size of 10 ha with (a) 2, (b) 4, (c) 6, and (d) 8 irrigation subunits.

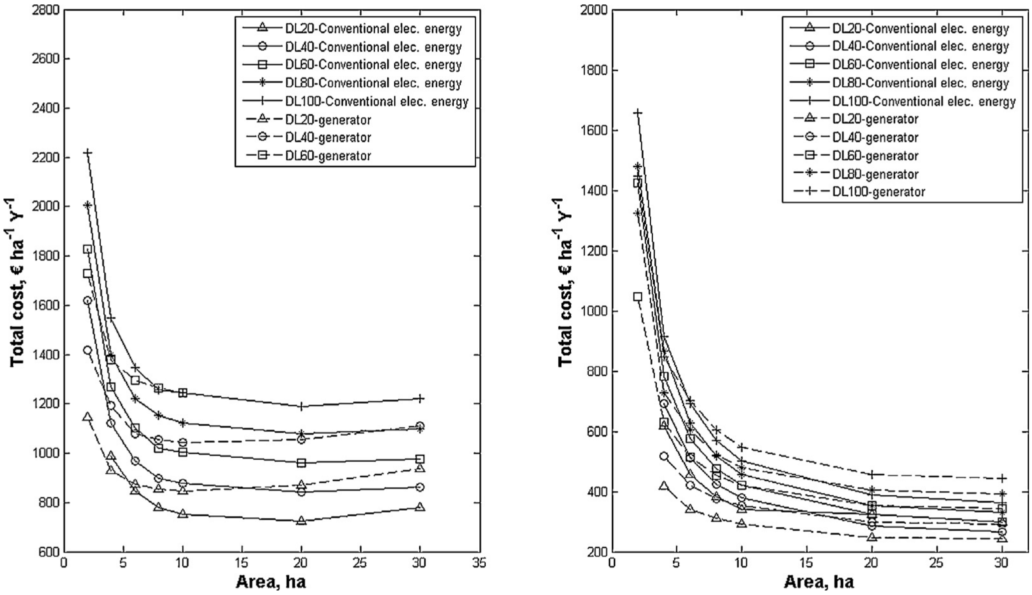

Fig. 6. Effect on C_T of using diesel fuel electrical generators or conventional electrical energy (1 km of electrical wire) in the sizing process of microirrigation systems for pepper (a) and grapevine (b), for different DL and plot sizes, considering standard parameters (Table 9).

3.3. Analysis of the components of total cost (C_T)

Fig. 7 shows the pattern of energy costs (C_e) and investment costs ($C_a + C_m$) for different numbers of irrigation subunits in 10 ha pepper (a) and grapevine (b) plots. This scenario shows costs associated with using conventional electrical energy for DL = 60 and 80 m, considering the standard values for all other parameters.

For pepper (Fig. 7a), C_e and $C_a + C_m$ values contribute to approximately 50% of C_T each, increasing the value and influence of C_e on C_T with a greater number of irrigation subunits. For grapevine (Fig. 7b), the same pattern can be seen regarding the number of irrigation subunits, with a lower influence of C_e on C_T (36%) and a lower rate of increase in C_e with more irrigation subunits. The high cost for grapevine is notable with 2 irrigation subunits. This is because the high irrigation subunit size (5 ha) demands a very high head flow. In the case of pepper, the increase in $C_a + C_m$ is compensated by a decrease in C_e.

As mentioned above, when plot size is 10 ha and an electrical generator is used, (Fig. 6a) the total cost is higher for pepper crop than using conventional electrical energy, but it is smaller for grapevine only for ≤60 m (Fig. 6b). For both crops, energy costs remain practically constant with electrical generators when the number of irrigation subunits is increased (Fig. 8). A slight decrease can be observed in C_e when NS increases due to an increase in EU. The investment cost ($C_a + C_m$) decreases with greater NS values. Therefore, C_T decreases with increasing NS. For grapevine (Fig. 8b),

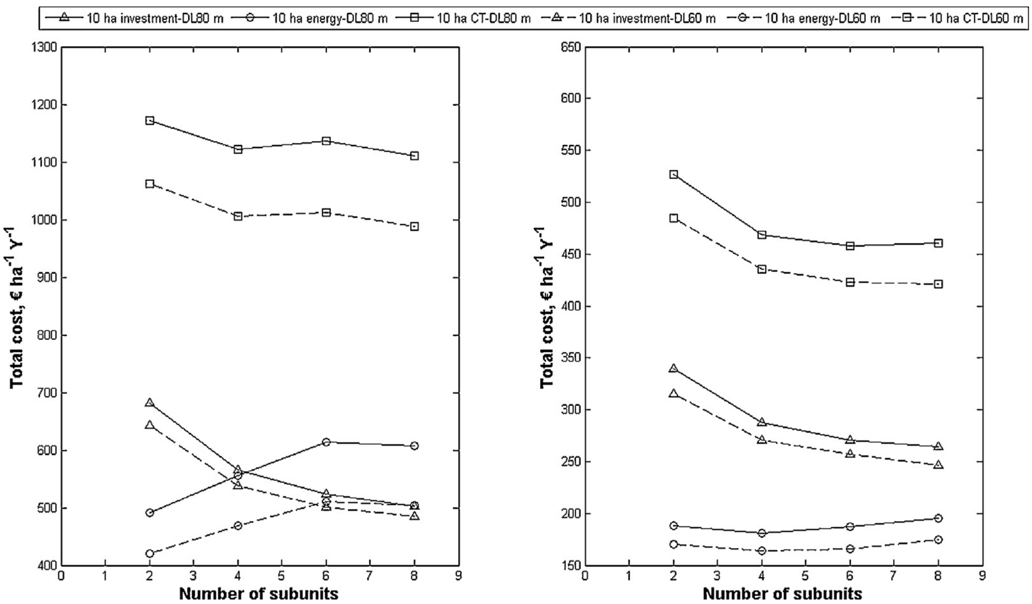

Fig. 7. Patterns of energy (C_e) and investment costs ($C_a + C_m$) for different numbers of irrigation subunits in 10 ha pepper (a) and grapevine (b) plots. These graphs show values for conventional electrical energy use for DL = 60 and 80 m, considering standard values for all other parameters.

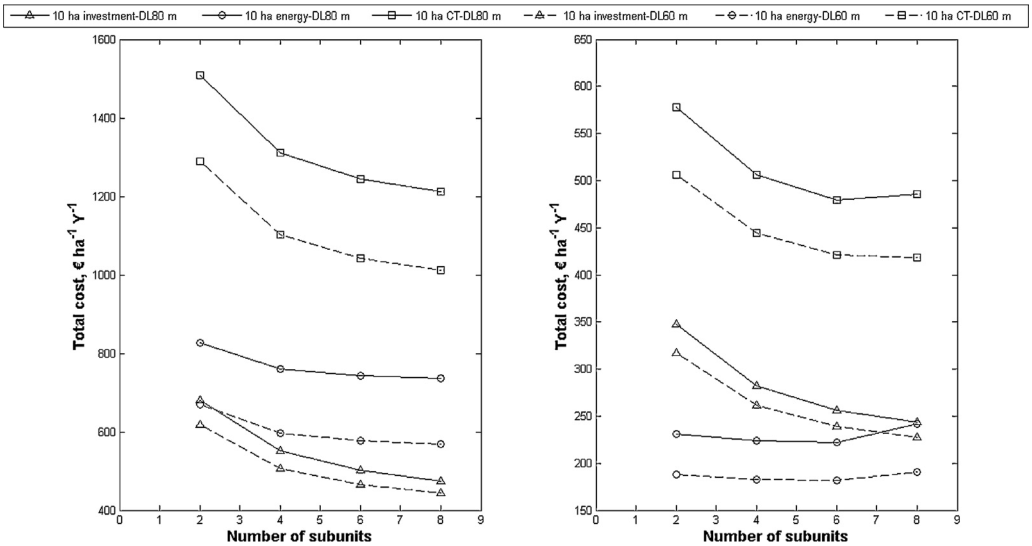

Fig. 8. Pattern of energy (C_e) and investment costs ($C_a + C_m$) for different numbers of irrigation subunits in 10 ha of pepper (a) and grapevine (b) plots, using an electrical generator. DL = 40 and 60 m for pepper and DL = 60 and 80 m for grapevine, with standard values for all other parameters.

when NS = 8, energy costs increase because of a change in the nominal diameter, as mentioned above.

For pepper crops, the number of irrigation subunits does not greatly affect C_T if conventional electrical energy is used (Fig. 7a). However, with an electrical generator, C_T clearly decreases with an increase in NS (Fig. 8a). This is mainly due to the effect of different energy rates for conventional electrical energy throughout the day, which is not applicable when using electrical generators.

As an example, Fig. 9 shows the percentage that C_e represents in C_T for different numbers of irrigation subunits and different values of DL in a typical microirrigation system in pepper and grapevine. These values apply to a plot size of 10 ha and conventional electrical energy. Results show that the weight of C_e on C_T increases at a higher rate with greater DL values than an increase in the number of irrigation subunits. This is more notable for pepper (Fig. 9a) than grapevine (Fig. 9b).

When electrical generators are used instead of conventional electrical energy (Fig. 10), the influence of C_e on C_T increases slightly for pepper crops (7–11% higher depending on DL and NS). This increase is greater for grapevine, with increasing differences when DL is greater (13–23%, higher for DL = 100 m).

Fig. 11 shows the results of the percentage that C_e contributes to C_T for different plot sizes and numbers of irrigation subunits, for DL = 60 m using conventional electrical energy. Results show an increase in the percentage C_e comprises of C_T when increasing plot size, both pepper (Fig. 11a) as grapevine (Fig. 11b) crops.

Using electrical generators instead of conventional electrical energy increases the contribution of C_e to C_T with an increase in

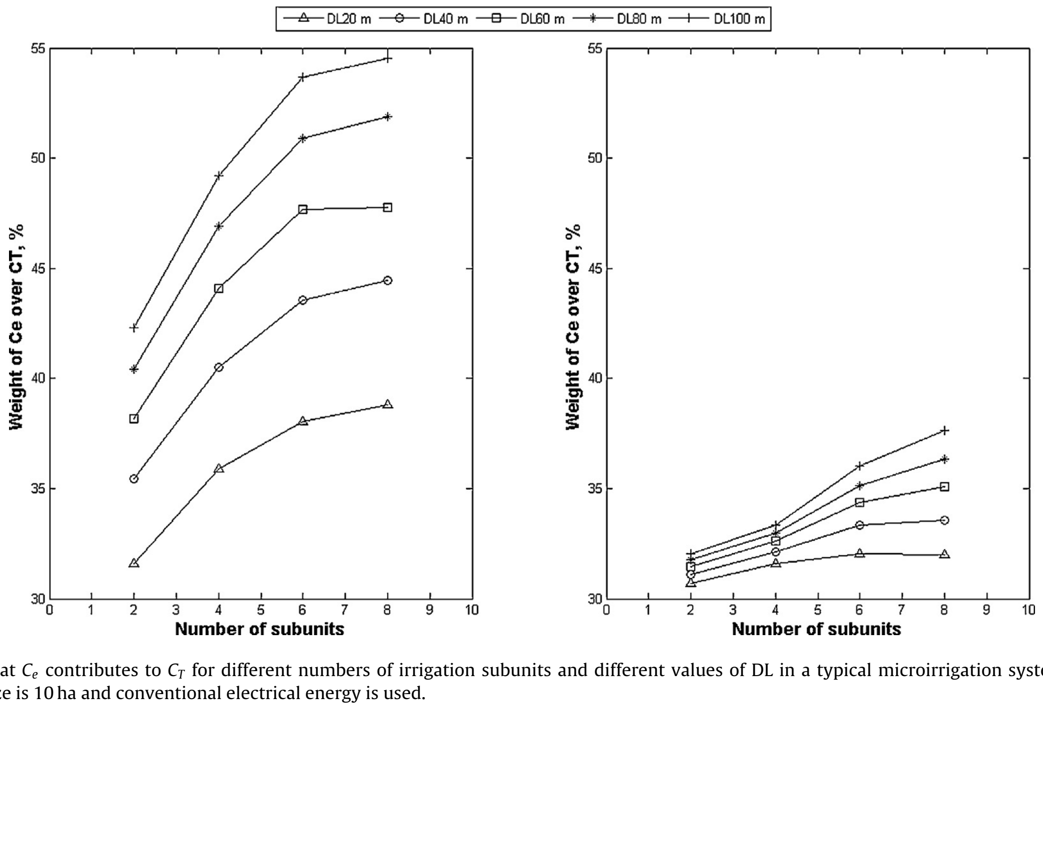

Fig. 9. Percentage that C_e contributes to C_T for different numbers of irrigation subunits and different values of DL in a typical microirrigation system in pepper (a) and grapevine (b). Plot size is 10 ha and conventional electrical energy is used.

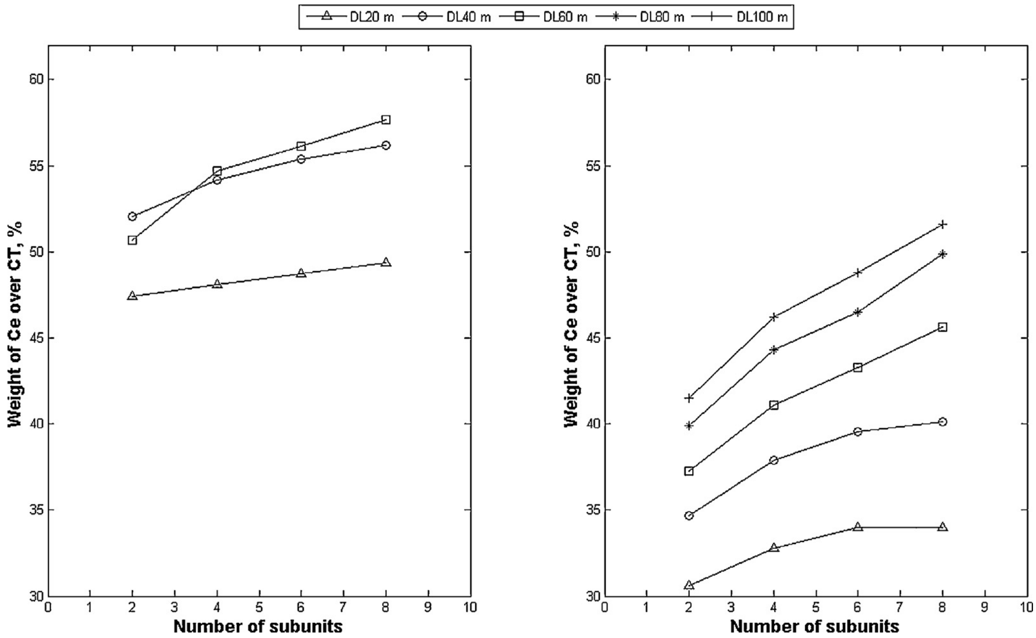

Fig. 10. Percentage of C_T contributed by C_e for different numbers of irrigation subunits and different DL values in a typical microirrigation system in pepper and grapevine for a plot size of 10 ha, using an electrical generator.

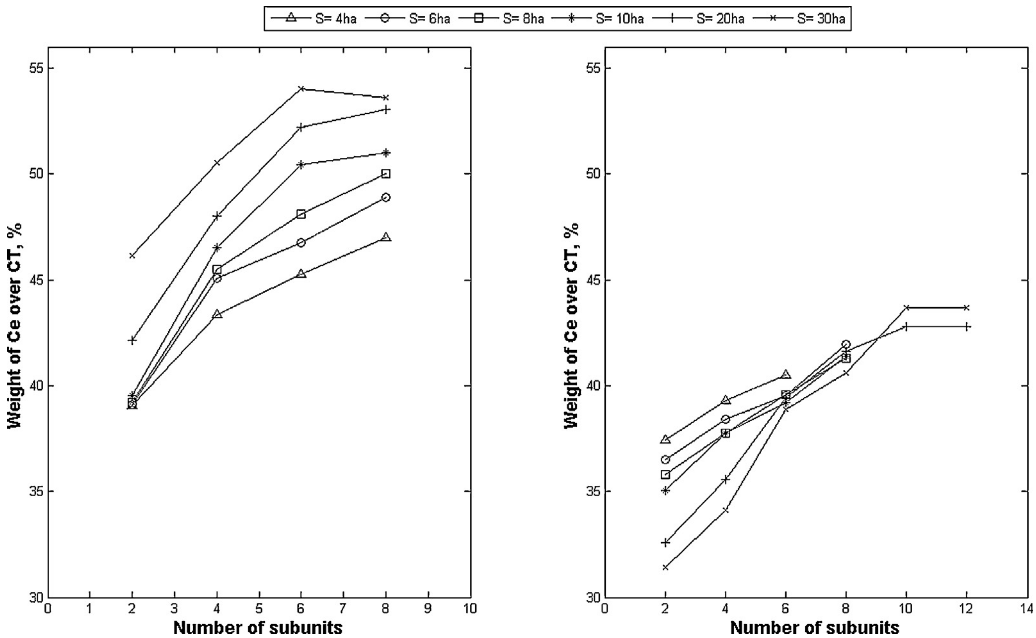

Fig. 11. Percentage that C_e comprises of C_T for different numbers of irrigation subunits and plot sizes in a typical microirrigation system in pepper and grapevine. DL = 60 m, and conventional electrical energy is used.

plot size for pepper and grapevine, similar to the change observed when increasing DL.

4. Conclusions

A useful tool named PRESUD has been developed to determine the optimal pump size as well as pumping pipe and distribution pipe diameters, together with the optimal irrigation subunit sizing under specific conditions of an irrigated plot. It is a valuable Decision Support System tool for irrigation advisory services in helping farmers and technicians in the design and sizing of their microirrigation systems.

The annual water application cost per unit of area with a microirrigation system (C_T) increases when crop water requirements (R_n) and the wetted area increase. However, the number of irrigation subunits into which the plot is divided has a very small effect on C_T. Thus, only practical parameters, such as saving certain times of day for maintenance and break-down events, should be factored into deciding on the optimal number of irrigation subunits. These activities can be performed during times of high energy rates in order to lower energy costs.

C_T decreases when plot size increases, with large increases in cost for plots smaller than 3–5 ha. This is due to the high contribution of the well and electrical line costs on total cost. As expected, C_T increases with DL. In these case studies, use of diesel fuel electrical generators is recommended for plots < 4 ha for pepper crops and up to 15 ha for grapevine considering a DL of 40 m. These limits vary for different DL values or changes in the cost and length of the electrical line.

The contribution of C_e on C_T increases with R_n, DL, and with plot size, and increases slightly with NS. Differences can also be seen if electrical generators are used, especially for crops with high water requirements.

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). They also wish to thank Mondragón Solutions for their support of this work by providing the data and products needed to carry out the work.

References

Carrión, F., Tarjuelo, J.M., Hernández, D., Moreno, M.A., 2013. Design of microirrigation subunit of minimum cost with proper operation. Irrigation Science, http://dx.doi.org/10.1007/s00271-013-0399-8.

de Juan, J.A., Picornell, M., Tarjuelo, J.M., Martínez, A., 2009. Riego y fertilización del viñedo. Tierras de Castilla y León 161, 70–75 (in Spanihs).

Juana, L., Losada, A., Rodríguez-Sinobas, L., Sánchez, R., 2004. Analytical relationships for designing rectangular drip irrigation units. Journal of Irrigation and Drainage Engineering, ASCE 130 (1), 47–59.

Kang, Y., Nishiyama, S., 1996. Analysis and design of microirrigation laterals. Journal of Irrigation and Drainage Engineering 122 (2), 75–82.

Kang, Y., Yuan, B., Nishiyama, S., 1999. Design of microirrigation laterals at minimum cost. Irrigation Science 18, 125–133.

Karmeli, D., Keller, J., 1975. Trickle Irrigation Design. Rain Bird Sprinkler Manufacturing Corp., Glendora, 133 pp.

Keller, J., Bliesner, R.D., 1990. Trickle Irrigation, Sprinkler and Trickle Irrigation. Van Nostrand Reinhold, New York, pp. 427–582.

Lamaddalena, N., Khila, S., 2012. Energy saving with variable speed pumps in on-demand irrigation systems. Irrigation Science 30 (2), 157–166.

Martín de Santa Olalla, F.J., Calera, A., Domínguez, A., 2003. Monitoring irrigation water use by combining Irrigation Advisory Service, and remotely sensed data with a geographic information system. Agricultural Water Management 61 (2), 111–124.

Moradi-Jalal, M., Mariño, M.A., Afshar, A., 2003. Optimal design and operation of irrigation pumping stations. Journal of Irrigation and Drainage Engineering 129 (3), 149–154.

Moradi-Jalal, M., Rodin, S.I., Mariño, M.A., 2004. Use of genetic algorithm in optimization of irrigation pumping stations. Journal of Irrigation and Drainage Engineering 130 (5), 336–357.

Moreno, M.A., Carrión, P.A., Planells, P., Ortega, J.F., Tarjuelo, J.M., 2007. Measurement and improvement of the efficiency at pumping stations. Biosystems Engineering 98, 479–486.

Moreno, M.A., Planells, P., Córcoles, J.I., Tarjuelo, J.M., Carrión, P.A., 2009. Development of a new methodology to obtain the characteristic pump curves that minimize the total cost at pumping stations. Biosystems Engineering 102, 95–105.

Moreno, M.A., Corcoles, J.I., Moraleda, D.A., Martinez, A., Tarjuelo, J.M., 2010a. Optimization of underground wáter pumping. Journal of Irrigation and Drainage Engineering 136, 414–420.

Moreno, M.A., Ortega, J.F., Córcoles, J.I., Martínez, A., Tarjuelo, J.M., 2010b. Energy analysis of irrigation delivery systems: monitoring and evaluation of proposed measures for improving energy efficiency. Irrigation Science 28, 445–460.

Moreno, M.A., Medina, D., Ortega, J.F., Tarjuelo, J.M., 2012. Optimal design of centre pivot systems with water supplied from wells. Agricultural Water Management 107, 112–121.

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

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

Planells, P., Carrioĭn, P.A., Ortega, J.F., Moreno, M.A., Tarjuelo, J.M., 2005. Pumping selection and regulation for water distribution networks. Journal of Irrigation and Drainage Engineering 131 (3), 273–281.

Rodríguez, J.A., Montesinos, P., Camacho, E., 2012. Detecting critical points in on-demand irrigation pressurized networks—a new methodology. Water Resources Management, http://dx.doi.org/10.1007/s11269-012-9981-8.

Scherer, T., Weigel, J., 1993. In Planning to Irrigate. A Checklistin. NDSU Extension Service. North Dakota State University http://www.ext.nodak.edu/extpubs/ageng/-irrigate/ae91w.htm (21.03.03).

Warrick, A.W., Yitayew, M., 1988. Trickle lateral hydraulics. I. Analytical solution. II. Design and examples. Journal of Irrigation and Drainage Engineering 114 (2), 281–288.