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Design of microirrigation subunit of minimum cost with proper operation

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Abstract Matlab software named PRESUD (Pressurized Subunit Design) was developed to identify the optimum microirrigation subunit design using the annual water application cost per unit of irrigated area (C_T). This is defined as the cost per cubic meter of water applied to the soil for crop use, calculated as the sum of investment, maintenance, energy, and water (C_w) costs. In this study, only rectangular subunits are considered, using an iterative method for calculating the lateral and manifold pipelines. The infrastructure necessary for water delivery to the subunit inlet was taken into account in the price of water. The results indicate that C_w is the most important factor in C_T, which includes the investment and energy costs for moving water from the source to the subunit inlet. Other important factors, in order of importance, are the emission exponent (x), coefficient of variation of emitter manufacturer (CV_{qmf}), and emitter spacing (s_e). The minimum water application cost for a typical subunit to irrigate vegetable crops such as pepper is obtained with a subunit of 0.3–0.5 ha, with 80 m of paired lateral pipe length of 16 (13.6 mm) PE 0.25 MPa diameter, and 50 (44 mm) PE 0.4 MPa of manifold pipe diameter. The cost of a typical drip irrigation subunit design for a crop, such as grapevines on trellises, is equivalent to 25 % of the C_T of a typical subunit to irrigate vegetable crops, such as pepper.

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List of symbols

A	Investment annuity (€ T^{-1})
C_a	Investment annuity per unit of irrigated area (€ $L^{-2}T^{-1}$)
C_e	Energy cost 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 (dimensionless)
CV_q	Total coefficient of variation of flow rate (dimensionless)
CV_{qh}	$D_q\, q_{ah}^{-1}$ = coefficient of variation of emitter flow due to pressure variation (dimensionless)
CV_h	$\sigma_h\, h_a^{-1}$ = coefficient of variation of pressure (dimensionless)
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_q	Standard deviation of the emitter flow due to the pressure variation (dimensionless)
e	Number of emitters per plant
ee	Annual rate of escalation in energy costs
E_a	General application efficiency for the irrigation system (dimensionless)
E_p	Efficiency of pumping system (dimensionless)
En_c	Energy rates (€ kWh^{-1})

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EU	Emission uniformity (dimensionless)
F	The Christiansen's reduction factor for $s_0 = s$, with s_0 as the distance between the inlet point and the first emitter
F_G	The Christiansen's reduction general factor
h_e	Inlet 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_{fL}	Lateral pipe head loss (L)
h_{fS}	Manifold pipe head loss (L)
h_{mh}	Minimum pressure head in the subunit (L)
h_0	Lateral pipe inlet head (L)
H_0	Pressure head required at the inlet of the microirrigation subunit (L) and flow rate (Q_{0s}, in $m^3\ s^{-1}$)
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 emitters in the lateral
N	Useful life (T)
O_t	Annual operating time of the irrigation system ($T\ T^{-1}$)
P	Power consumed for irrigation water application (kW)
P_l	Lateral pipe price (€ L^{-1})
P_m	Manifold pipe price (€ L^{-1})
P_w	Water price (€ L^{-3})
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_0	Inflow rate to the pipe (L^3 T)
Q_{0s}	Inflow rate to the microirrigation subunit (L^3 T)
q_u	Emission rate by unit of length (L^3 T)
R	Reynolds number
R_g	Gross annual crop irrigation water requirement ($L^3\ L^{-2}\ T^{-1}$)
R_n	Net annual 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)
s_0	Distance between the inlet point and the first emitter
S_0	Slope ($L\ L^{-1}$)
Tr	Transpiration relationship
US	Uniformity index
x	Emission exponent

Greek symbols

σ_h	Standard deviation of the emitters pressure in the subunit (m)
ν	Water kinematic viscosity ($L^2\ T^{-1}$)
Δh	Difference in pressure head in the irrigation subunit (% of h_a)
Δq	Difference in emitter flow in the irrigation subunit (% of q_a)
ΔZ	Differences in elevation in the pipe (lateral or manifold)
$\Psi(r_L)$	Function of $r_L = L_a\ L^{-1}$

Introduction

The optimum hydraulic design of a microirrigation subunit is based on finding the sizes of lateral and manifold pipes that ensure optimal emission uniformity (EU) from the emitter flow and inlet pressure head in the emitters, from an economic point of view.

Solomon (1985) states that a lack of uniformity in microirrigation subunits is mainly affected by (a) emitter aging and clogging; (b) number of emitters per plant (e); (d) manufacture's coefficient of variation of the emitters (CV_{qmf}) (ISO 9261–2004); (e) emitter sensitivity to temperature; (f) stability of the emitter operation characteristics over time; (g) emission exponent (x). The general emitter equation is expressed as follows (Karmeli and Keller 1975):

$$q_h = K \cdot h_e^x \tag{1}$$

where q_h = emission rate; K = emission coefficient; x = emission exponent; h_e = inlet pressure head of the emitter.

Assuming that clogging problems are controlled, the characteristics of the emitter are stable over time, and the effects of temperature can be neglected when turbulent flow emitters are used (Peng et al. 1986), the causes of flow variation in the design are considered to be e, CV_{qmf}, and pressure head differences (Δh).

Laboratory testing (Provenzano and Pumo 2004; Juana et al. 2002; Palau-Salvador et al. 2006) supports the idea that emitter insertion produces local losses that should be considered in the hydraulic modelling of drip lateral pipes. Recently, numerical approaches have been adopted to estimate the emitter insertion local losses. Provenzano et al. (2007) used computational fluid dynamics to evaluate friction and emitter local losses in drip lateral pipes with inline coextruded emitters. Juana et al. (2002) determined values of the friction coefficient (K_e) and equivalent length

(l_e) for various emitter models using analytical and experimental procedures, studying the effects of the geometric variables (D, S_e, and r) and the inlet head (h_0) on minor head losses, where $D =$ inner pipe diameter; $s_e =$ emitter spacing (L); $r =$ obstruction ratio (ratio between the flow cross-sectional area where the emitter is located and the pipe section area). Palau-Salvador et al. (2006) obtained a general equation for directly calculating the local losses of online emitters as a function of the numbers of emitters, average emitter flow and the ratio between the protrusion area and the area of the pipe cross section.

The relative difference in flow in the irrigation subunit is frequently limited to a maximum emitter flow variation (Δq) over the average emitter flow in the subunit (q_a) (Zayani et al. 2001). This implies a limitation on the relative difference from the pressure head (Δh), defined as

$$\frac{\Delta h}{h_a} = \frac{1}{x}\frac{\Delta q}{q_a} \quad (2)$$

The difference in the pressure head between any two points in the irrigation subunit (Δh) is due to elevational differences and head losses (h_f) produced along the pipe between those points. Given these differences in elevation, the limitation of the pressure difference becomes a limitation to head losses divided between the lateral and manifold pipes. Thus, the length and diameter of each pipe could be selected from the expression of the head loss adopted.

The main objective in the hydraulic design of a drip irrigation subunit is to achieve optimal emission uniformity (EU) from an economic point of view. The factors that determine optimal EU are investment costs, the cost of water and energy, crop response to water application (yield decrease due to the heterogeneity of irrigation), or the unit value of yield, among others. The first three variables will be used to calculate the irrigation water application cost.

The unit cost of the system increases with the number of emitters per plant (e) (Keller and Bliesner 1990). Likewise, costs for reaching a certain EU increase with increasing elevational differences (undulating or slopes >2 %).

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

$$EU = \left(1 - \frac{1.27 CV_{qmf}}{\sqrt{e}}\right)\frac{q_{mh}}{q_{ah}} 100 \quad (3)$$

where $e =$ number of emitters per plant, $q_{mh} =$ minimum emitter flow in the subunit due to the pressure, $q_{ah} =$ mean of all emitter flow values due to variations in pressure.

Assuming its validity, the q_{mh} to achieve the desired EU could be determined, given CV_{qmf} (a datum supplied by the manufacturer), e and q_{ah}. With q_{mh} and Eq. (1), the value of h_{mh} at the emitter with the lowest pressure can be estimated. Similarly, the value of q_{ah} corresponds to h_a. Therefore, the inlet head (H_0) in the irrigation subunit can be obtained from these two pressure head values.

The total coefficient of variation of flow rate in the subunit (CV_q) was estimated by Bralts et al. (1987), who considered both causes of variation (head and manufacturer) to be independent

$$CV_q = \sqrt{CV_{qmf}^2 + CV_{qh}^2} \cong \sqrt{CV_{qmf}^2 + x^2\, CV_h^2} \quad (4)$$

where $CV_{qmf} =$ manufacturer coefficient of variation of the emitters, $CV_{qh} =$ coefficient of variation of emitter flow due to pressure variation ($CV_{qh} = D_q\, q_{ah}^{-1}$, $D_q =$ standard deviation of the emitter flow due to the variation in pressure, $q_{ah} =$ average emitter flow due to the variation in pressure), $CV_h =$ pressure coefficient of variation ($CV_h = \sigma_h\, h_a^{-1}$, $\sigma_h =$ standard deviation of the emitters pressure in the subunit, and $h_a =$ average emitter pressure in the subunit), and x is the emission exponent, considering the approximation $CV_{qh} \approx x\, CV_h$ (Bralts et al. 1987). The statistical uniformity index was used for drip irrigation design, defined as

$$US = 1 - CV \quad (5)$$

Equation (4) can also be used to analyze the results of a field evaluation of the irrigation subunit (Keller and Bliesner 1990; Rodriguez-Sinobas et al. 2009). Thus, if $CV_{qmf} > 0.2$, the emitter may be considered inadequate (high CV_{qmf}) or clogged, and if $CV_q > 0.2$ (low uniformity) and $CV_{qmf} < 0.2$, the lack of uniformity is due to hydraulic causes (inadequate hydraulic design, lack of pressure regulation) or inefficient management.

Warrick and Yitayew (1988) present several graphs for determining the length and diameter of lateral pipes and the inlet head assuming a given average emitter flow and water application uniformity. They used analytical relationships that improved the precision obtained with the methods proposed by Wu and Gitlin (1975) and Keller and Bliesner (1990). Kang et al. (1999) used the finite element method, and the golden section searches (Kang and Nishiyama 1996) to build contour maps that relate Christiansen's uniformity coefficient (CUC) to diameter and length of the microirrigation lateral pipe, and relate these latter two to the inlet head (h_0). The CUC and the h_0 are determined for each pair of length and diameter values, assuming an average emitter flow (q_a). Juana et al. (2004) developed analytical relationships suitable for designing rectangular drip irrigation units. To our knowledge, there are no studies that thoroughly analyze the effects of all main factors considered in the designing irrigation subunits.

The aim of this study is to develop a tool to perform the hydraulic design of a microirrigation 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 (x, CV_{qmf}, s_e, EU, l_e, D, slope, among others) are also analyzed using an iterative method for the calculation of lateral and manifold pipes. Two case studies will be analyzed to perform a sensitivity analysis of the results for pepper and grapevine crops in Spain (high and low water requirements, respectively).

Methodology

To identify the optimum microirrigation 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 cost of the infrastructure for water delivery to the subunit inlet were taken into account in the water costs.

Although an iterative method is used for the calculation of lateral and manifold pipes, the tool uses Christiansen's reduction factor method for presizing the subunit (Keller and Bliesner 1990), that is, determining the optimal location of the subunit inlet in paired laterals and estimating the pressure head required at the inlet of the microirrigation subunit. It will be the first step in the iterative process.

The lateral and manifold pipe head losses can be calculated with Eq. (6)

$$h_{fL} = h_f F_G \tag{6}$$

$$F_G = \frac{s_e}{L_l}(nF + r_s - 1) \tag{7}$$

where h_{fL} = lateral head loss (L), h_f = pipe head loss with constant flow rate (L), F_G = the Christiansen's reduction general factor, n = number of emitters in the lateral pipe, s_e = emitters spacing, L_l = length of lateral pipe (L), F = Christiansen's reduction factor for $s_0 = s_e$ (Eq. 8), with s_0 = distance between the inlet point and the first emitter, $r_s = s_0\, s_e^{-1}$.

$$F = \frac{1}{m+1} + \frac{1}{2n} + \frac{\sqrt{m-1}}{6n^2} \tag{8}$$

where m = flow exponent in the head loss equation (Eqs. 9, 10).

The same expressions are valid for head losses in the manifold pipe (h_{fS}).

The introduction of the Blasius friction factor $f = 0.316 \cdot R^{-0.25}$ into the Darcy–Weisbach equation provides an accurate estimate of the frictional losses produced by turbulent flow inside uniform pipes with low wall roughness and when the Reynolds number (R) falls within the range 3,000–100,000. Since the pipe material for lateral and manifold pipes is smooth [polyethylene (PE) or polyvinylchloride (PVC)] and the diameters are small, the Blasius ($R < 10^{-5}$) and Veronesse-Datei ($R < 10^{-6}$) head loss equations can be used to determine hydraulic calculations with PE and PVC, respectively.

The Blasius equation is (S.I. units)

$$h_f = 0.0246 v^{0.25}\, D^{-4.75}\, Q_0^{1.75} L\left(1 + \frac{l_e}{s}\right) \tag{9}$$

The Veronesse-Datei equation is (S.I. units)

$$h_f = 0.0099 v^{0.172}\, D^{-4.80}\, Q_0^{1.8} L\left(1 + \frac{l_e}{s}\right) \tag{10}$$

where v = water kinematic viscosity ($L^2\,T^{-1}$), D = inner pipe diameter (L), Q_0 = flow rate of the pipe ($L^3\,T^{-1}$), L = pipe length (L), and l_e = equivalent length due to a minor singularity (emitter insertion or lateral connection) (L) (Juana et al. 2002; Provenzano and Pumo 2004).

To identify the manifold pipe position in the case of paired lateral pipes on a uniformly sloping field (Fig. 1), Eq. (11) is used (Kang and Nishiyama 1996; Kang et al. 1996; Montalvo 2007). Although Eq. (12) was developed assuming a continuous and steady discharge, in practice it can be used as a good approximation when the lateral has many emitters as it is the case of drip irrigation systems (Table 1).

$$\Psi(r_l) = (1 - r_L)^{m+1} - r_L^{m+1} = \frac{0.5\, S_0(1+m)}{0.74 M q_u^m L^m} \tag{11}$$

with $r_L = \frac{L_a}{L}$ and $M = 0.0246 v^{0.25}\, D^{-4.75}$ for Blasius and $M = 0.0099 v^{0.172}\, D^{-4.80}$ for Veronese-Datei 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), and D = inner diameter of lateral pipe (L).

Microirrigation subunit design

Matlab software named PRESUD (Pressurized Subunit Design) was developed to analyze water distribution in a microirrigation subunit. After defining the initial length and diameter of lateral (L_l and D_l) and manifold pipes (L_m and D_m), the slope of lateral (S_{0l}) and manifold pipes (S_{0m}), the emitter characteristics [Eq. (1), q_a, h_a, k, and x, selected in the agronomic design of microirrigation subunit], the manufacturer coefficient of variation (CV_{qmf}), the number of emitters per plant (e), the equivalent length of the

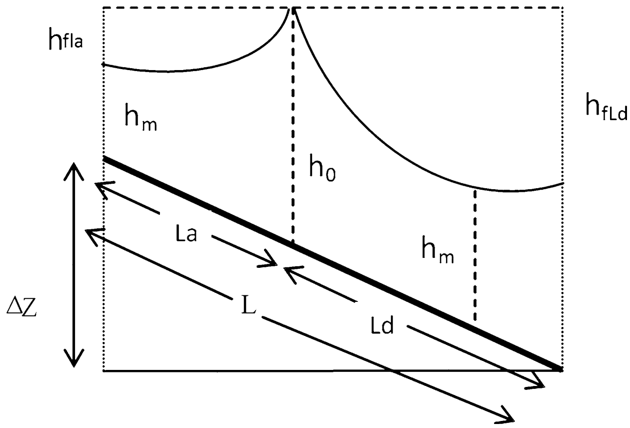

Fig. 1 Diagram of a paired lateral pipe

Table 1 Values of r_L for paired lateral and manifold pipes

r_L	$\Psi(r_L)$	r_L	$\Psi(r_L)$	r_L	$\Psi(r_L)$	r_L	$\Psi(r_L)$
0.01	0.973	0.14	0.656	0.27	0.394	0.40	0.165
0.02	0.946	0.15	0.634	0.28	0.375	0.41	0.148
0.03	0.920	0.16	0.613	0.29	0.357	0.42	0.132
0.04	0.894	0.17	0.591	0.30	0.339	0.43	0.115
0.05	0.868	0.18	0.570	0.31	0.321	0.44	0.098
0.06	0.843	0.19	0.550	0.32	0.303	0.45	0.082
0.07	0.818	0.20	0.529	0.33	0.285	0.46	0.065
0.08	0.794	0.21	0.509	0.34	0.267	0.47	0.049
0.09	0.770	0.22	0.489	0.35	0.250	0.48	0.033
0.10	0.747	0.23	0.470	0.36	0.233	0.49	0.016
0.11	0.723	0.24	0.450	0.37	0.216	0.50	0.000
0.12	0.701	0.25	0.431	0.38	0.199		
0.13	0.878	0.26	0.412	0.39	0.182		

$r_L = L_a\ L^{-1}$

$\Psi(r_L)$ = function of $r_L = L_a\ L^{-1}$

emitter connection (l_{ee}) and lateral connection (l_{el}), the emitter spacing (s_e), and the lateral spacing (s_l), the tool permits two possibilities. The first is that the location of the inlet point and the pressure head of the microirrigation subunit (H_0) are known, and the second is that both are unknown. In the latter, the tool performs a preliminary hydraulic design of the subunit, using the procedure of Christiansen's reducing factor. The proposed methodology can be summarized in the Fig. 2.

The procedure uses the following calculation stages:

1. Stage 1. Identification of the inlet point and first approximation of H_0. When the location of the inlet point and H_0 is not known, the procedure begins by identifying a point of supply with Eq. (11) for the previously selected diameter of lateral or manifold pipes. Next, it makes a first estimate of the pressure head in the inlet subunit (H_0), using the Christiansen's reduction factor method described above. For this, it calculates the pressure at the origin of the average lateral with Eq. (12).

$$h_0 = h_a + \beta h_{fL} + 0.5\Delta Z \tag{12}$$

where h_0 = lateral pipe inlet head (L), h_a = average pressure head in the emitters in the subunit (L), h_{fL} = lateral pipe head loss (L) (Eqs. 6–10), ΔZ = differences in elevation in the lateral pipe (positive for uphill and negative for downhill), β = a coefficient that depends on n and m values, with the most frequent values of 0.74 for $m = 1.75$ and n = 17–200 emitters. The same equations are valid for obtaining the pressure head required by the manifold pipe at the inlet of the microirrigation subunit (H_0).

2. Stage 2. Determination of emitter pressure (h_{ei}) and discharge (q_{ei}) of each emitter within the subunit. For the H_0 value determined in Stage 1, the pressure head is estimated at each emitter insertion point (h_{ei}) (or lateral insertion point in the manifold) by applying the energy equation

$$h_{ei} = h_{ei-1} - h_{f(i-1)-i} \pm S_0 s_e \tag{13}$$

where $h_{f(i-1)-i}$ = head losses between two consecutive emitters $i-1$ and i (Eqs. 9, 10), considering $q_{ei} = q_a$ in the first iteration, S_0 = slope (L L^{-1}) and s_e = emitter spacing (L).
Once the pressure of each emitter (h_{ei}) has been estimated, emitter flow (q_{hi}) is calculated with Eq. (1). Then, an iterative process begins calculating the discharge of each emitter (q_{hi}), 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 emitter discharge downstream of a specific point and satisfying the continuity principle. The process is repeated until the difference in emitter pressure between two consecutive iterations is lower than 0.0001 m.

3. Stage 3. Calculation of the H_0 value that matches the average flow of all emitters to the 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 emitters in the subunit and the desired average flow (q_a) is <0.001 L h^{-1}.

4. Stage 4. Calculation of the coefficients describing the suitability of water distribution in the subunit taking into account the emitter manufacturer coefficient of variation (CV_{qmf}): EU (Eq. 3), CV_q (Eq. 4), Δq = difference in emitter flow in the irrigation subunit, Δh = difference in pressure head in the irrigation subunit, and the total water application cost in the subunit (C_T) (Eq. 14), for a given water price (P_w), energy price (En_c), lateral and manifold pipe price

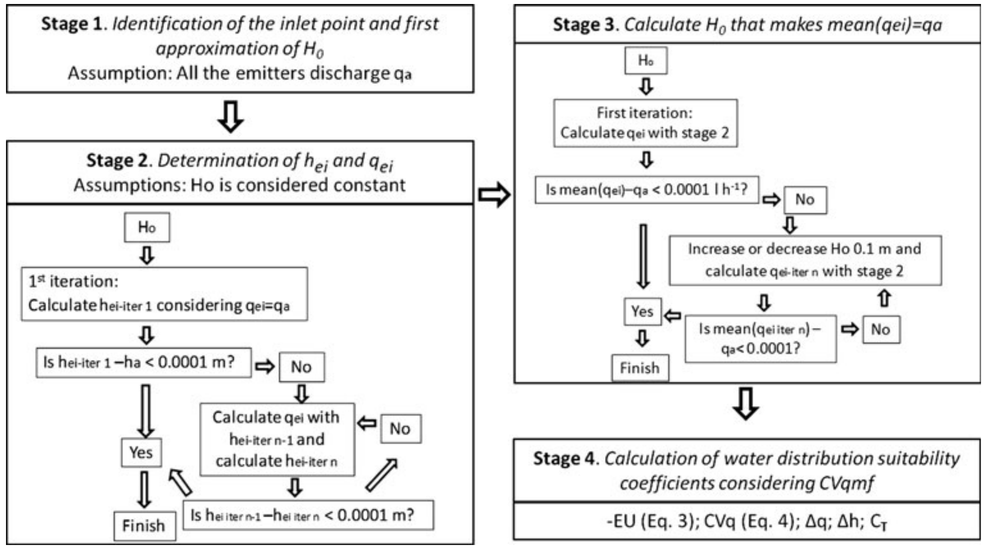

Fig. 2 Diagram of the calculus process of PRESUD tool

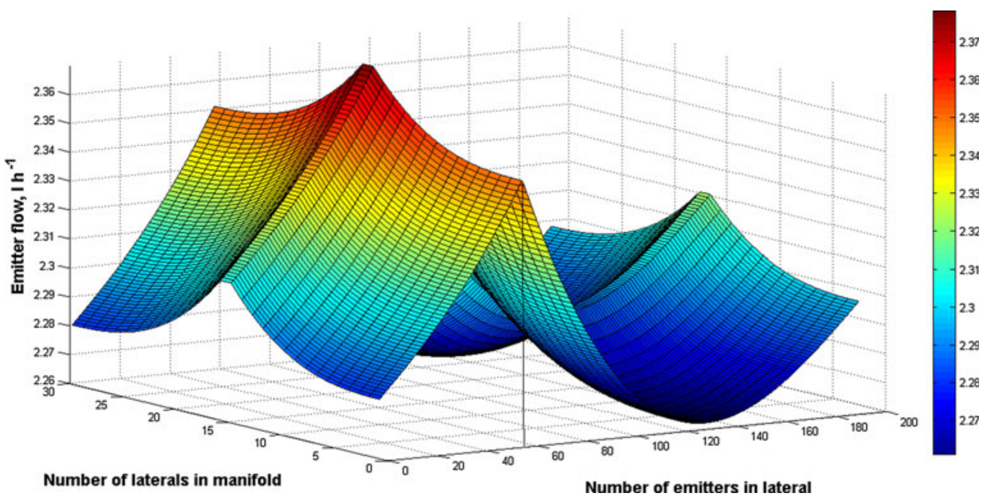

Fig. 3 Example of emitter flow distribution in the subunit for $S_{0l} = 1.5$ % and $S_{0m} = 0$ %

(P_l and P_m), 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 and diameter of lateral and manifold pipes (L_l, L_m, D_l, D_m), emission exponent (x), equivalent length due to a minor singularity (l_e), emitter manufacturer coefficient of variation (CV_{qmf}), slope in lateral and manifold pipes (S_{0l}, S_{0m}), emitter spacing (s_e), lateral spacing (s_l). For all cases, the coefficients that define the suitability of water application in the subunit (EU, CV_q, Δq, Δh, and C_T) are calculated. As an example, Fig. 3 shows the discharge distribution in a subunit, for $q_a = 2.3$ l h^{-1}, $s_e = 0.65$ m, $s_l = 1.1$ m, $x = 0.42$, $h_a = 10$ m, $S_{0l} = 1.5$ % and $S_{0m} = 0$ %, $L_l = 125$ m, $L_m = 33$ m.

Total cost

To identify the more appropriate design of a microirrigation subunit, the total annual cost of water application (C_T, in € ha^{-1} year^{-1}), computed as the sum of the investment (C_a), energy (C_e), water (C_w), and maintenance (C_m) annuity per unit of irrigated area, can be used.

$$C_T = C_a + C_e + C_w + C_m \quad (14)$$

Investment costs

For investment cost (C_i), only the pipes (lateral and manifold) and emitter costs have been included. The other costs (regulation and control valve in the inlet of microirrigation subunit) are considered similar for any conditions.

The annuity (A = CRF C_i, in € year^{-1}) for the total investment cost (C_i, in €) was computed considering a useful life (N) of 15 years and an interest rate (i) of 0.06. The capital recovery factor (CRF) and the investment annuity per unit of irrigated area (C_a, in € ha^{-1} year^{-1}) were calculated using Eqs. (15) and (16):

$$\mathrm{CRF} = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (15)$$

$$C_a = \frac{A}{S} = \frac{\mathrm{CRF} \cdot C_i}{S} \quad (16)$$

where S is the irrigated area by the microirrigation subunit (in ha).

To determine the total investment cost (C_i), the average prices of different manufacturers and distributors in Spain were considered (Table 2).

Energy cost

The annual energy cost per unit of irrigated area (C_e, in € year^{-1}ha^{-1}) was calculated using Eq. (17)

$$C_e = \frac{P \cdot O_t \cdot \mathrm{En}_c}{S} \quad (17)$$

where P = the power required [in kW, (Eq. 18)] for water application, O_t = annual operating time of the irrigation system [in h year^{-1}, (Eq. 19)] considering water requirement for pepper and grapevine crops in Spain as application example, En_c = energy rate (in € kWh^{-1}) and S = irrigated area (in ha).

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}) necessary at the inlet of the microirrigation subunit:

$$P = \frac{9.81 \cdot Q_{0s} \cdot H_0}{E_p} \quad (18)$$

where E_p = efficiency of pumping system (dimensionless).

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; Córcoles et al. 2011).

The number of operating hours per year (O_t) was calculated with Eq. (19):

$$O_t = \frac{R_n S}{3600 E_a Q_{0s}} \quad (19)$$

where R_n = net crop irrigation water requirement per year (m^3 ha^{-1} year^{-1}) (5,900 m^3 ha^{-1} year^{-1} for pepper and 1,500 m^3 ha^{-1} year^{-1} for grapevine in this study), E_a = general application efficiency for the irrigation system (dimensionless), Q_{0s} = inflow rate to the microirrigation subunit (m^3 s^{-1}) and S = irrigated area (ha).

Although application efficiency, E_a, is not explicitly related to emission uniformity (EU), E_a can be approximated for microirrigation by:

$$E_a = \mathrm{EU}/\mathrm{Tr} \quad (20)$$

where Tr = peak-use period transmission ratio (Keller and Bliesner 1990). This represents the extra water that must be applied even during the peak-use period to offset unavoidable percolation beyond the root zone, with values among 1.0 and 1.1 (Keller and Bliesner 1990).

Thus, the gross irrigation water requirement per year (R_g) in the subunit, as a function of net requirement (R_n), is

$$R_g = \frac{R_n Tr}{\mathrm{EU}} \quad (21)$$

To consider the possibility of changing energy prices to rates different from the general rate of inflation, Eq. (22) (Keller and Bliesner 1990) has been applied in the PRESUD software.

$$\mathrm{EAE} = \left[\frac{(1+\mathrm{ee})^N - (1+i)^N}{(1+\mathrm{ee}) - (1+i)}\right] \cdot \left[\frac{i}{(1+i)^N - 1}\right] \quad (22)$$

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.

Table 2 Average prices of different manufacturers and distributors in Spain

Material	Lateral pipe diameter (mm) PE 0.25 MPa	Lateral pipe price (€ m^{-1})					Manifold pipe PE 0.4 MPa	
		Emission exponent (x)	Emitter spacing (s) (m)				External (inner) diameter (mm)	Price (€ m^{-1})
PE			0.5	0.75	1.0	1.25	32 (28.0)	0.32
	16 (13.6)	0.1	0.20	0.18	0.16	0.14	40 (35.2)	0.48
		0.5	0.175	0.16	0.145	0.13	50 (44.0)	0.75
		0.9	0.125	0.12	0.115	0.11	63 (55.4)	1.20
	17.5 (15.6)	0.1	0.25	0.22	0.20	0.19	75 (66.0)	1.75
	20 (17.4)	0.1	0.29	0.26	0.25	0.24	90 (79.2)	2.60

Water costs

Irrigation water price (P_w) is the cost of obtaining the water from the source (investment in infrastructure and operational costs). The differences in water price depend mainly on water availability and the initial water energy (surface or groundwater).

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

$$C_w = \frac{R_g P_w}{S} \tag{23}$$

Three different water prices were considered in the sensitivity analysis: 0.05, 0.1, and 0.15 € m^{-3}. This P_w mainly depends on water availability and the initial water energy (surface or groundwater) and range widely, representing the real conditions over time in Spain and in many other regions of the world.

Maintenance costs

An additional 5 % of investment costs were considered for maintenance of the irrigation system (C_m) to reach a useful life of 15 years.

Influence of the main factors over the total cost

To analyze the influence of each factor on C_T, the following reference values have been considered (Table 3).

Results

As a first application of the model, the effect of slope and lateral pipe length on the EU was studied under standard conditions. Rectangular irrigation subunits with paired lateral pipes for a typical horticultural crop, such as pepper, and a woody crop, such as grapevine on trellises, were analyzed. Next, the effect on C_T of L_l, L_m, D_l, D_m, CV_{qmf}, x, l_e, q_a, s_e, S_{0l}, S_{0m}, P_w, and En_c was analyzed. In all cases, the coefficients that characterize the suitability of water application in the subunit were calculated: EU, CV_q, C_T, H_0, Δq, and Δh.

The D_l that minimizes the total cost is 16 (13.6) mm for all cases. Thus, in the following analyses, only this diameter will be considered. The results are shown for EU > 90 % and for the manifold pipe diameters (D_m) for minimum cost (40, 50, and 63 mm).

Effect of different variables on C_T

The most important cost influencing total cost (C_T) is water costs (C_w) (Fig. 4), followed by C_a, for both pepper and grapevine irrigation subunit design, considering the

Table 3 Summary of the reference parameter considered in the study

Parameter	Value in reference conditions	
	Pepper irrigation subunit	Grapevine irrigation subunit
Slope in lateral S_{0l}	1 %	
Slope in manifold S_{0m}	0 %	
Emission exponent x	0.5	
Coefficient of variation of emitter manufacturer CV_{qmf}	0.05	
Equivalent length due to emitter insertion on the lateral pipe l_{ee}	0.5 m	
Equivalent length due to lateral connection to the manifold pipe l_{el}	0.25 m	
Lateral diameter D_l	16 (13.6 mm, inner diameter) PE of 0.25 MPa	
Number of lateral pipes		
in the subunit	40	
Water price (P_w) (€ m^{-3})	0.10	
Energy price (En_c) (€ kWh^{-1})	0.10	
Plant spacing (m)	0.7	1.5
Net annual crop irrigation water requirement R_n (m^3 ha^{-1} year^{-1})	5,900[a]	1,500[a]
Emitter pressure h_a (m)	10	10
Emitter flow q_a (L h^{-1})	2	4
Emitter spacing s_e (m)	0.75	1.25
Lateral spacing on manifold pipes (m)	1.0	3.0
Peak-use period transmission ratio Tr	1.05	1.00

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

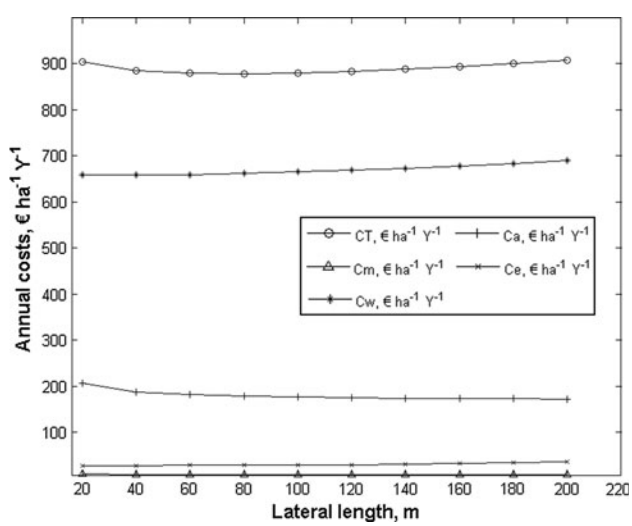

Fig. 4 Annual costs per unit area for a drip irrigation subunit, considering the reference values for a pepper crop

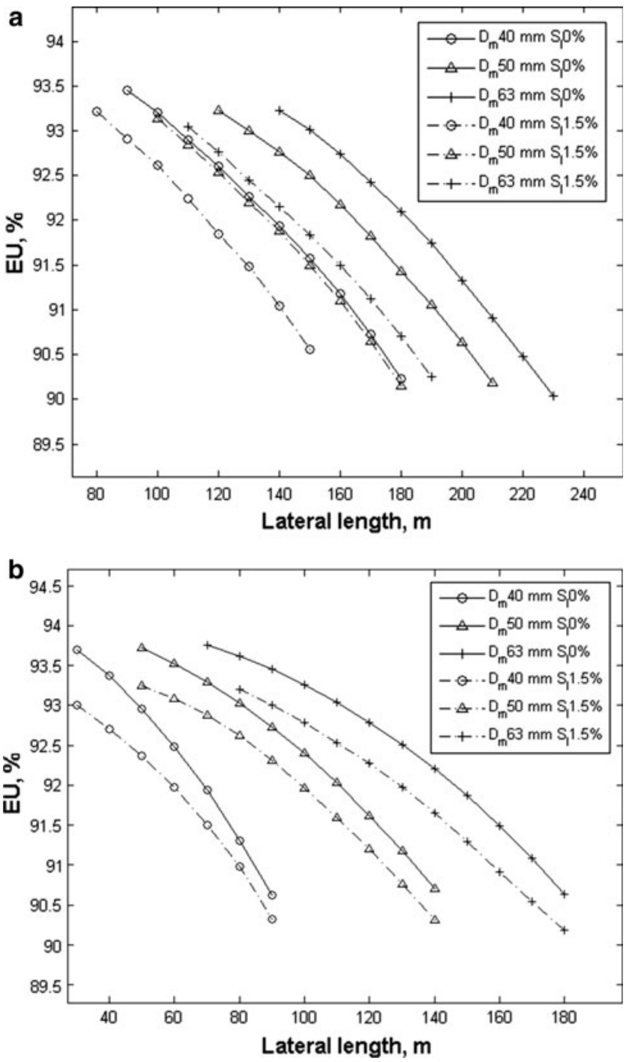

Fig. 5 Effect of S_{0l} on EU, for different L_l, with values of $S_{0l} = 0$ and 1.5 %, considering reference values for the other parameters, for the typical pepper (**a**) and grapevine (**b**) subunit design

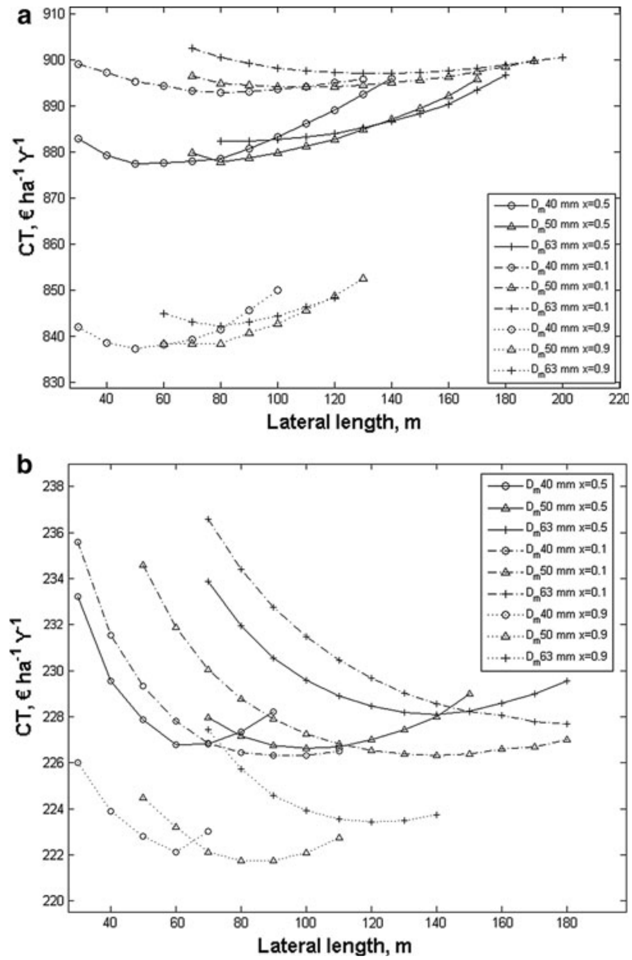

Fig. 6 Effect of x on C_T, for different L_l values, with $x = 0.1$, 0.5, and 0.9, considering reference values for the other parameters, for the typical pepper (**a**) and grapevine (**b**) subunit design

reference values. An increase in C_T from 60 % is obtained when the P_w increasing from 0.05 to 0.1 € m^{-3} (100 % increase) and a 38 % when increasing from 0.1 to 0.15 € m^{-3} (50 % increase) for pepper subunits. The irrigation subunits of grapevine show the same trends, with a 56 and 36 % increase in C_T, respectively. Nonetheless, the value of C_w accounts for the investment and energy costs to pump the water from the source to the subunit intake. Thus, when C_w is 0.1 € m^{-3}, over 40 % of the cost is from the energy cost (Tarjuelo et al. 2010). So, energy plays a very important role in C_T, accounting for 40–50 % of the C_T, including the energy required for water application in the subunit (approx. 3 % of C_T).

Other important factors, in the order of importance, are as follows: emission exponent (x), coefficient of variation of emitter manufacturer (CV_{qmf}), and emitter spacing (s_e). Minor factors, also listed in the order of importance, are as follows: manifold pipe length (L_m), average emitter flow (q_a), equivalent length due to a minor singularity (l_e), and lateral and manifold pipe slopes (S_{0l} and S_{0m}), for the values studied ($S_0 < 2$ %).

Figure 5 shows the effect of lateral slope (S_{0l}) on EU for different L_l, with S_{0l} values of 0 and 1.5 %. The reference values for the other parameters have been considered.

The results show as that EU significantly decreases when L_l increases, with higher influence of D_m in grapevine subunits (Fig. 5b).

Figure 6 shows the effect of x on C_T for different L_l, with $x = 0.1$, 0.5, and 0.9, for the typical subunit design of pepper and grapevine. The reference values for the other parameters have been considered.

A decrease in x value, typical of regulated emitters, increases C_T value (Fig. 6), due to higher emitter costs (Table 2). As expected, the variation of C_T with L_l is lower for low x values, due to higher EU values achieved. In grapevine irrigation subunits (Fig. 6b), the variation in

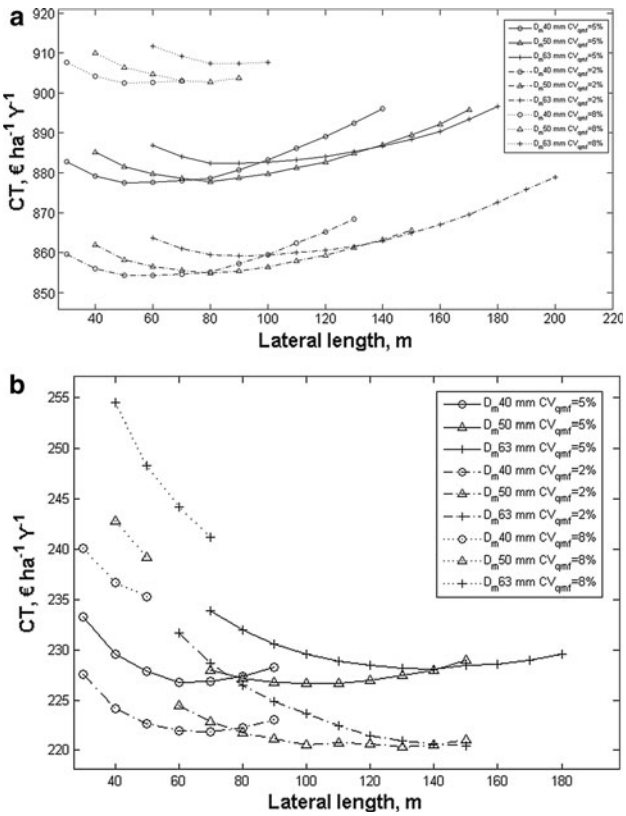

Fig. 7 Effect of CV_{qmf} on C_T for different L_l, with $CV_{qmf} = 0.02$, 0.05, and 0.08, considering reference values for the other parameters, for the typical pepper (**a**) and grapevine (**b**) subunit design

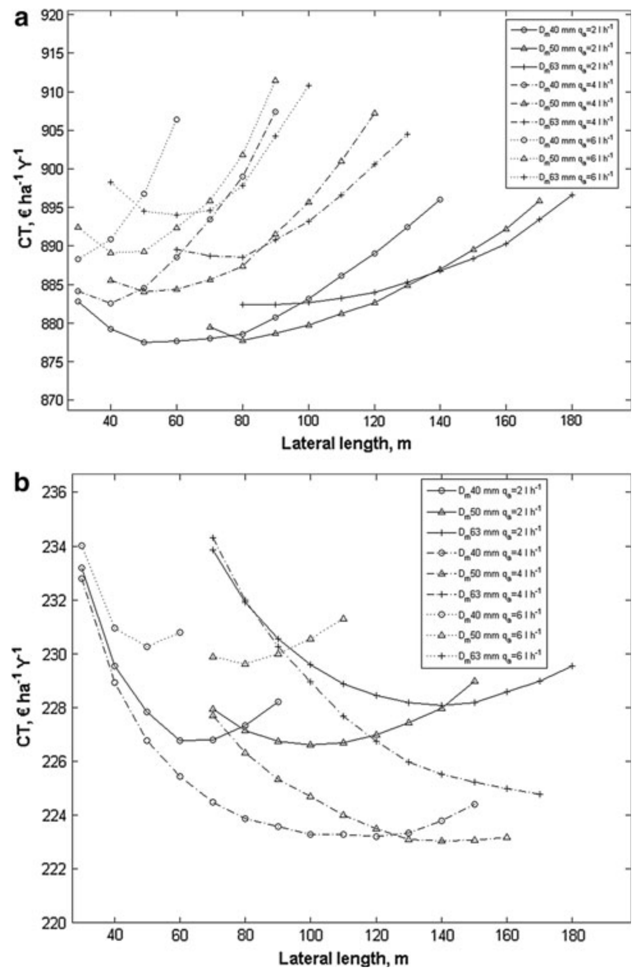

Fig. 8 Effect of q_a on C_T for different L_l values, with $q_a = 2$, 4, and 6 L h^{-1}, considering reference values for the other parameters, for the typical pepper (**a**) and grapevine (**b**) subunit design

C_T is almost negligible with the x and L_l values considered. As expected, when x decreases, EU increases and Δq and Δh decrease.

The increase in EU when reducing the x value is not enough advantage to select this type of emitter because it leads to an increase in C_T compared to that obtained with higher x values ($x = 0.9$). However, it should be noted that normally higher x values are often associated with higher CV_{qmf} values. When that is the case, C_T may be lower when regulated emitters are used ($x \approx 0.1$ and $CV_{qmf} \approx 0.02$).

Figure 7 shows the effect of CV_{qmf} on C_T for different L_l, with $CV_{qmf} = 0.02$, 0.05, and 0.08. The reference values for the other parameters have been considered.

The results show that C_T increases when CV_{qmf} increases. In addition, C_T increases when L_l is higher than 80 m in pepper and 150 m in grapevine. A reduction in EU and an increasing in C_T are obtained when CV_{qmf} increases, making it difficult to get an EU > 90 % with $CV_{qmf} \geq 0.08$.

Figure 8 shows the effect of q_a on C_T, for different L_l, with $q_a = 2$, 4, and 6 L h^{-1}. The reference values for the other parameters have been considered.

As expected, increasing C_T with L_l is greater at higher q_a values (Fig. 8). The results demonstrate that the most interesting design of subunits for vegetable crops is to use low-flow emitters and small subunits (0.3–0.4 ha). The greater the q_a values, the smaller the optimal size of the subunit. The design of subunits for grapevines with minimum C_T shows the same trends (Fig. 8), with lower variations in C_T with q_a and L_l, and larger subunits (over 2 ha with $q_a = 2$ L h^{-1}).

As expected, s_e is one of the most influential factors on C_T in a trickle irrigation subunit (Fig. 9), increasing C_T with decreasing s_e.

Effect of subunit size on C_T

The minimum C_T for a drip irrigation subunit, considering the reference values for a pepper crop, increases with the subunit size (Fig. 10a). Table 4 shows the diameter and length of lateral and manifold of minimum C_T as function of the subunit area and the pressure head required at the intake of the subunit (H_0), as well as the EU, Δq, and Δh values. Subunits bigger than 1.75 ha have not been considered since the necessary manifold diameter is bigger

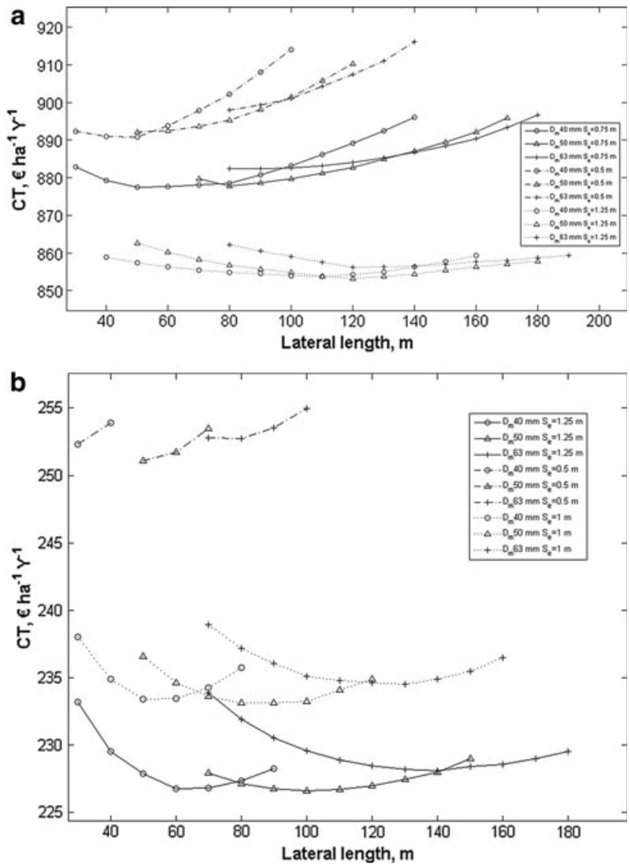

Fig. 9 Effect of s_e on C_T for different L_l values, with $s_e = 0.5$, 0.75, and 1.25 m, considering reference values for the other parameters, for the typical pepper (**a**) and grapevine (**b**) subunit design

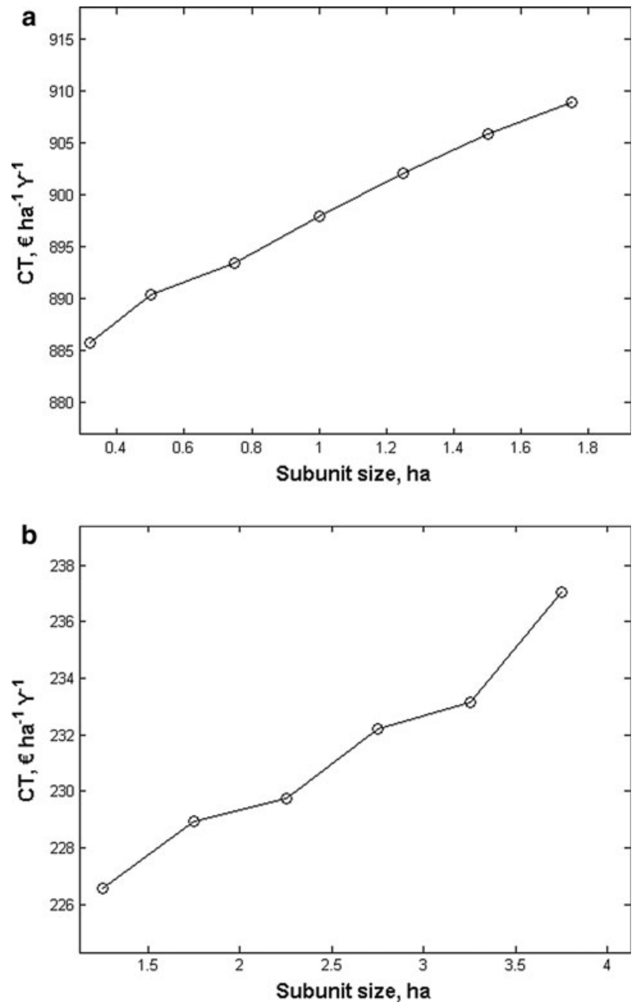

Fig. 10 Effect of subunit size on C_T, considering the reference values for the typical pepper (**a**) and grapevine (**b**) subunit design

than 90 mm, situation that is not very usual. The small variations in the slope of the trend line are due to change in manifold diameter (Table 4). The irrigation subunits of grapevine show the same trends (Fig. 10b), but now the variations in the slope of the trend line of CT due to change in manifold diameter (Table 5) are more marked, and the size of subunits is larger.

Conclusions

A useful tool for designing microirrigation subunits with minimum costs has been developed. It calculates different performance indexes of the irrigation systems that permit technicians to make decisions for proper irrigation system design.

Considering investment costs (C_a), energy (C_e), and the cost of the water (C_w) in typical designs for vegetable crops such as pepper, with emitter spacing of 0.75 m and lateral pipe spacing of 1 m, the drip irrigation subunit with the lowest total annual water application cost (C_T) is with a relatively small subunit size (0.3–0.5 ha), low-flow emitters (2 L h^{-1}), lateral pipe diameter of 16 (13.6 mm) PE 0.25 MPa and manifold pipe diameter of 50 (44 mm) PE 0.4 MPa. Under these conditions, emission uniformity (EU) is 92–93 %. The difference in emitter flow in the irrigation subunit Δq is <5 %, and the difference in pressure head in the irrigation subunit Δh is <15 %.

The cost of water (C_w) is the most important factor included in total cost (C_T) which includes the investment and energy costs for moving water from the source to the subunit intake. When C_w is 0.1 € m^{-3}, over 40 % of the cost is due to energy costs (Tarjuelo et al. 2010). Thus, energy plays a very important role in total cost (C_T), accounting for 40–50 % of C_T, including the energy required for water application in the subunit (approx. 3 % of C_T). This indicates a necessity for developing algorithms and tools to optimize the performance of water pumping facilities in irrigation systems.

A drip irrigation subunit typical for woody crops, such as grapevine on trellises, with emitters spaced at 1.25 m and manifold pipe spacing of 3 m, emitters of 4 L h^{-1},

Table 4 Diameter and length of lateral and manifold for minimum C_T as function of the subunit size, and H_0 and UE values, considering the reference values for the typical pepper crop subunit design

Subunit area (ha)	Lateral length (m)	Manifold length (m)				C_T (€ $ha^{-1}year^{-1}$)	H_0 (m)	EU (%)	Δq	Δh
	Lateral diameter (mm)	Manifold diameter (mm)								
	16	50	63	75	90					
0.32	80	40				885.7	10.4	92.6	2.9	5.9
0.50	91	55				890.4	10.5	92.4	5.3	10.7
0.75	94		80			893.4	10.8	91.9	5.4	10.8
1.00	110			90		897.9	10.8	91.7	5.6	11.4
1.25	139			90		902.1	11.2	90.9	8.4	17.0
1.50	136				110	905.8	11.1	91.2	7.3	14.8
1.75	146				120	908.9	11.3	90.7	9.0	18.4

Table 5 Diameter and length of lateral and manifold for minimum C_T as function of the subunit size, and the H_0 and EU values, considering the reference values for the typical grapevine subunit design

Subunit area (ha)	Lateral length (m)	Manifold length (m)					C_T (€ $ha^{-1}year^{-1}$)	H_0 (m)	EU (%)	Δq	Δh
	Lateral diameter (mm)	Manifold diameter (mm)									
	16	40	50	63	75	90					
0.5	111	45					223.8	10.7	92.7	4.3	8.7
1.25	104		120				226.6	11.2	92.0	7.7	15.6
1.75	130			135			229.0	11.2	91.8	8.0	16.1
2.25	150			150			229.8	11.9	90.9	11.9	24.4
2.75	158				174		232.2	11.7	91.2	10.9	22.2
3.25	175				186		233.2	12.3	90.3	14.6	30.0
3.75	187					201	237.0	12.2	90.4	13.8	28.3

lateral pipe diameter of 16 (13.6 mm) PE 0.25 MPa and manifold pipe diameter of 50 (44 mm) PE 0.4 MPa, has a C_T value equivalent to 25 % of the C_T for a subunit of vegetable crops such as pepper.

The criterion of limiting Δq to 10 %, considering EU = 90 %, widely used when designing a drip irrigation subunit, not always lead to solutions of minimum C_T, and the use of tools as PRESUD can help to obtain better solutions.

The total cost for water application in a drip irrigation subunit (C_T) increases with the subunit size, but for automation of irrigation on large parcels, it is necessary to find a balancing between the size and number of subunits to handle.

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