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Optimal design of drip irrigation submains: presure-compensating emitters

Diseño óptimo de sectores de riego por goteo: emisores autocompensados

Carlos E. Schilardi Sícoli [1 *], Ricardo Aliod [2], Fernando Zorilla [2], José Antonio Morábito [1, 3]

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ABSTRACT

For a drip irrigation system to be successful, it must be well designed, properly installed, managed and maintained. In plots with steep slopes and irregular topography that have little land leveling capacity and/or that require very efficient agricultural machinery, drip irrigation designs generally use pressure-compensating emitters. This work develops a methodology and implements it in a computer tool that makes it possible to optimally determine in drip-irrigated plots with pressure-compensating emitters: a) telescopic sizing of the submain manifold pipe, b) supply valve pressure and c) subunit's intake valve location, when considering all hydraulic-economic aspects in the design phase. Techniques of optimal sizing of pipe networks and simulation of hydraulic networks under pressure are linked to economic analyzes of total annualized costs. Finally, the practical usefulness of the proposed methodology is shown with three examples of complex real cases where pipe design costs are reduced by 16-34% and energy costs by 37-51%.

Keywords
drip irrigation • design • submain • pressure-compensating emitters

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1 Universidad Nacional de Cuyo. Facultad de Ciencias Agrarias. Almirante Brown 500. Luján. C. P. M5528AHB. Mendoza. Argentina. * cschilardi@fca.uncu.edu.ar
2 Universidad de Zaragoza. Escuela Politécnica Superior de Huesca (EPSH). Carreterra de Cuarte S/N. C. P. 22071. Huesca. España.
3 Centro Regional Andino. Instituto Nacional del Agua. Belgrano 210 Oeste (M55500FIF). Mendoza. Argentina.

RESUMEN

Para que un sistema de riego por goteo tenga éxito, debe estar bien diseñado, adecuadamente instalado, apropiadamente manejado y mantenido. En parcelas con grandes pendientes, topografía irregular, con poca capacidad de nivelación y/o en situaciones donde se pretende tener una alta eficiencia de la maquinaria agrícola, los diseños de riego por goteo generalmente recurren a la utilización de emisores autocompensantes. El presente trabajo desarrolla una metodología y realiza su implementación en una herramienta informática que permite en sectores de riego por goteo con emisores autocompensantes determinar de manera óptima: a) el dimensionado telescópico de la tubería secundaria (porta-laterales), b) la presión en válvula de alimentación del sector y c) el punto de alimentación del sector (ubicación de dicha válvula); considerando todos los aspectos hidráulicos-económicos involucrados en la fase de diseño. Para ello, se vinculan técnicas de dimensionado óptimo de conducciones y simulación hidráulica de redes a presión con análisis económicos de costos totales anualizados. Finalmente, se demuestra la utilidad práctica de la metodología desarrollada mediante ejemplos reales de aplicación, donde los costos de diseño se reducen entre 16-34% y los costos de energía entre 37-51%.

Palabras clave
riego por goteo • diseño • subunidades • emisores autocompensantes

INTRODUCTION

The success of a drip irrigation system depends essentially on proper design, selection and installation (25) and correct management and maintenance (12). In order to ensure its financial sustainability, the benefit of the irrigated crop must cover the high capital costs which this method entails (17). Optimal design of drip irrigation is important to increase the investments in and benefits derived from irrigation (16). Such design should aim at minimizing total annualized piping and energy costs (32, 33) and ensuring water distribution uniformity (4, 6, 17, 19)

In steep slope plots (20) with irregular topography and little land leveling capacity and/or that require highly efficient agricultural machinery, drip irrigation systems generally use pressure-compensating emitters. They deliver a practically constant discharge over a wide range of pressures (20, 21, 35), called effective pressure compensation range, between 5 and 35 m, and can lower the limits by ± 2 or raise them by ± 5 m (3), depending on each manufacturer. Pressure regulation is achieved by means of an elastic membrane that covers the flow path (36). A pressure-compensating emitter can be described by the following pressure-discharge function (26):

$$q = \begin{cases} kh^{x}, 0 \langle h \leq h_0 \\ q_0, h_0 \langle h \langle h_{max} \end{cases} \tag{1}$$

where:

q = flow of the emitter [L] ^{3} [T] $^{-1}$

K = characteristic discharge coefficient of the emitter [L] $^{3-x}$ [T] $^{-1}$

h = emitter pressure [L]

x = emitter discharge exponent

q_0 = constant discharge for the compensation range [L] ^{3} [T] $^{-1}$

h_0 = minimum pressure of the compensation range [L]; this is defined as:

$$h_0 = \left(\frac{q_0}{K}\right)^{1/x} \qquad (2)$$

For a good pressure compensating emitter, most designers will try to keep the pressures throughout the field in a range between 7-24.5 m (5). Montalvo (2005) recommends for safety reasons a minimum pressure value for the emitter that is at least 2 m higher than the lower limit of the compensation range and a maximum pressure of 25 m. It is necessary to keep pressures within that range to avoid: a) disconnection of the drip laterals of the manifold, b) breakage of the drip irrigation lateral or exhaustion of their service life, and c) high energy consumption.

Several authors address the hydraulic-economic optimization to design irrigation subunits. Saad and Mariño (2002) developed a linear optimization model for rectangular subunits, with telescopic pipes placed in the direction of the slope gradient which minimizes the annualized equivalent irrigation and pumping costs and maximizes distribution uniformity. Valiantzas (2003) and Valiantzas *et al.* (2007) derived a simple equation to calculate the length and available diameters of pipes within a subunit that minimizes total annualized pipe and energy costs. Dercas and Valiantzas (2012) presented two simple analytical methods to calculate the adequate diameters of the main pipes based on hydraulic-economic analyzes.

In Irricad software (2013), the pipe sizing is carried out using a Linear Programming optimization (LP) in conjunction with hydraulic grade lines analysis method. Pipe sizes are optimized based on the annualized cost of pipes and energy (18). Intake valve position and pressure are defined by the user without optimization criteria.

Carrión *et al.* (2013) and Carrión *et al.* (2014) devised a methodology and computer tool (PRESUD-Presurized Submain Design) applied to turbulent drippers for the optimal design of submains. The criterion used to optimize the design was to reduce the total annualized costs of water per irrigated unit area (C_T). They adopted a double iterative process for the design of the submain manifold pipe and the intake valve pressure similar to the ones introduced in the present article. Their approach is valid only for rectangular plots, does not incorporate the telescopic design of submain manifold pipes and does not identify the optimum intake valve location.

Moreno *et al.* (2016) expands the PRESUD tool as PRESUD-IR to optimize the design of triangular or trapezoidal plots. It incorporates an extension of the algorithm above mentioned by Carrión *et al.* (2013 and 2014); at a third iteration intake valve location is determined by considering the location of each emitter as a possible feeding point for the submain. The optimum intake valve location is the one that maximizes distribution uniformity and minimizes the C_T. This update does not incorporate the telescopic design of submain manifold pipe and is not suitable for irregularly shaped subunits.

For determining the optimum intake valve location in the submain, previous works (20) stated that the location must be aligned to the slope and pressure loss in manifold pipes of a single diameter so as to balance the minimum pressures on both sides of the valve. For telescopic manifold pipes, this depends on the selected diameters and lengths. Finally, in order to optimize the feeding point of an irrigation subumain it is necessary to improve irrigation uniformity and considerably reduce the cost of pipes.

Rodrigo López *et al.* (1992) said that when the average slope of the land in the direction of manifold pipes is less than 3%, it is usually more economical to feed the subunit through an intermediate point so as to ensure that pressure variation is almost the same in the manifold pipe of the upstream and downstream feeding point.

Although there are some general recommendations and criteria for the optimal design of irrigation submains with pressure-compensating emitters, there is no methodology to define, both in topographies and/or arbitrary geometries, the pressure and the valve's intake point and the telescopic sizing of the submain manifold pipe that will lead to the best possible hydraulic-economic design.

Objective

To develop a methodology for subunits with pressure-compensating emitters to optimize: a) telescopic sizing of the submain manifold pipe; b) the intake valve's input pressure to the subunit; c) the intake valve location, by considering all hydraulic-economic aspects involved in the design phase so as to minimize total annualized costs per irrigated unit area. The resulting methodology is applied within the design module in drip irrigation plots in the GESTAR computer package (2), thus providing a new advanced functionality.

MATERIALS AND METHODS

For irrigation submains with pressure-compensating emitters, the methodology uses as initial design condition an admissible range of design pressures based on the criteria proposed by Burt and Styles (2007) and Montalvo (2005). However, the user will be able to modify the minimum and maximum valve's pressure for the design (admissible range of design pressures) according to the characteristics and knowledge of the submain.

The Darcy-Weisbach formula is used to calculate pressure losses in pipes and laterals where: 1) the friction factor (f) is determined by approximation to the Basius equation (in the case of laterals) and to the Colebrook's equation for manifold pipes; and 2) the Christiansen reduction coefficient is used to calculate pressure losses in pipes or lateral according to the number of outlets as pressure-compensating drippers conform to this model.

For optimal sizing of telescopic submain manifold pipe, the method developed by González and Aliod (2003), and González (2006) is applied. It is an optimization algorithm (LMM/KPH -LM) that uses an improved Lagrange Multipliers Method (LMM) (27) in conditions of Know Pressure Head (KPH), in combination of a Labye-type Method (LM) (22) for standardization of the continous diameters obtained in LMM. At each connection point of every lateral to the submain manifold pipe, the optimization algorithm must supply a minimum required pressure so that the most unfavorable pressure-compensating dripper of the respective lateral reaches its minimum operating pressure.

The Nodal Analysis method (1, 9, 10, 11) is used for hydraulic simulation of the irrigation submain, once it is already designed, which includes a set of matrix analysis techniques, extended to consider the specifities of pressure irrigation systems, that incorporates the integral-differential hydraulic modeling for drip laterals where the emitters discharge flow can depend on the local pressure (10, 15, 34). It makes it possible to perform a detailed quasi-stationary hydraulic-energy simulation either for turbulent or self compensating drippers.

The baseline data to be selected includes: a) for the hydraulic calculation of the subunit, the inner diameter (DI; mm), length (L_l; m), slope (S_o; m/m), separation (distance between rows; S_l; m) and laterals per crop row (N°lat/row); flow (q_o; L h^{-1}) and emitter spacing (S_e; m), maximum (PVmax; m) and minimum design pressure (PVmin; m) of the subunit, as well as the design pressure step range (PV Step; m); b) for the economic calculation of the subunit, gross crop water requirements (Nb; m^3 ha^{-1} $year^{-1}$) per year, pumping equipment efficiency (Ep; %/100), transmission ratio (Tr, this represents the additional amount of water that must be applied during the highest demand period taking into account the inevitable deep percolation, with values ranging between 1.0 and 1.1 (20)), cost of energy (C_e; € kwh^{-1}); water price (C_w; € m^{-3}); interest rate (i; %/100), service life (N); maintenance cost as a percentage of the irrigation system purchase cost (C_m; %/100). Figure 1 (page 159), shows the flow diagram of the design optimization process.

The proposed algorithm first determines if the lateral should be fed from one end or through an intermediate point by checking if Pmin = minimum design pressure of the submain is higher than Pminobj = minimum target design pressure. It also evaluates the intermediate feeding point of the lateral using the methodology defined by Keller and Bliesner (1990) according to the procedures mentioned in Schilardi *et al.* (2017).

Figure 1 (page 159), shows a nested iteration process to optimally determine the valve pressure (Pvop) and optimal intake valve location (Nop). The calculation sequence begins at the first possible intake point (N1) with an outer iterative process (position iteration), where optimal telescopic sizing of the submain manifold pipe is carried out at different intakes pressures which are stablished in a second inner iterative process (pressure iteration). Thus, for each possible intake position and for each possible valve pressure head, from the minimum (Pvmin) to the maximum design pressure (Pvmax) in an incremental range defined by the user (PV Step - Ex: 1 m), the optimal sizing of the submain manifold pipe is carried out with the above mentioned process (LMM-LM/KPH).

A variant of the LMM method for unknown pressure head (LMM /UPH) was not used to find in a single sequence pipe sizing and optimal valve pressure, avoiding the pressure iteration cycle, since it depends on the *a priori* identification of the most unfavorable point of the network, which is subject to uncertainty.

As additional conditions for the design of the irrigation submain, the speed in manifold pipes is restricted to a range of maximum and minimum admissible values, which are determined by the user, usually between 2.5 and 0.5 m s^{-1}.

For each pressure and position iteration (figure 1, page 159) an optimal design of the submain manifold pipe is obtained and its annualized total costs per unit of irrigated area (C_T; € ha^{-1} $year^{-1}$), life-cycle, total investment cost (C_a, € ha^{-1} $year^{-1}$), maintenance costs (C_m - 5% of Ca; € ha^{-1} $year^{-1}$), energy costs; if pumping is required (C_e; € ha^{-1} $year^{-1}$) and water cost (C_w; € ha^{-1} $year^{-1}$) associated to the subunit are calculated as shown in the following equation (Carrión *et al.* 2013) which states:

$$CT = 1.05C_a + C_e + C_w \qquad (3)$$

$$CT = \frac{\frac{i(1+i)^N}{i(1+i)^N - 1}}{S} + 1.05\frac{\frac{i(1+i)^N}{i(1+i)^N - 1}}{S} + \frac{\frac{9.81Q_{OS}H_O R_n}{Ep3600Q_{OS}eA}En_c}{S} + \frac{R_n Tr}{EU}P_w \qquad (4)$$

where:
C_i = total investment cost (€)
S = irrigated area (ha)
i = interest rate
N = service life (years)
Q_{os}= design flow ($m^3\ s^{-1}$)
Ho = subunit intake pressure (m)
Ep = pumping efficiency (0.65 on average)
Rn = annual net crop water requirement ($m^3\ ha^{-1}\ year^{-1}$)
Enc = average cost of energy consumed, (€ kwh^{-1})
Ea = general application efficiency for the irrigation system (%/100)
Tr = transmission ratio for maximum demand period (20)
Pw = price of water, excluding energy costs for pressure supply (€ m^{-3}).

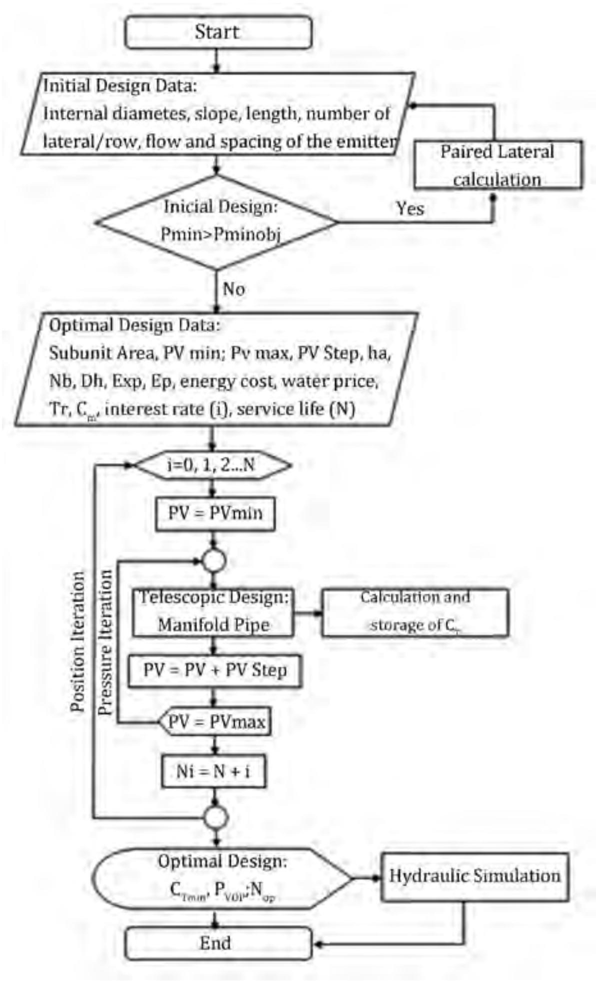


Figure 1. Subunit optimization process with pressure-compensating emitters (GESTAR).

Figura 1. Diagrama de flujo del proceso de optimización de sectores con emisores autocompensantes (GESTAR).

Though in the case of pressure-compensating emitters the values of C_w and C_m are constant, they are incorporated into the calculation process to be compared with designs made with other software and/or with designs that include turbulent emitters. The aforementioned cost approach does not consider explicitelly the extended length of the main pipe necessary to conect the optimum intake point to plot network. Nevertheless, this cost and all storage and infrastructure inevestments required to make the subunit operational can be included in Cw and, if it is appropriate, also the energy costs asociated to head losses in the plot network and collective network that drive water to the subunit.

Once the double nested iterative process is completed, the optimal joint design (telescopic sizing of the submain manifold pipe, pressure and valve intake location) is determined as the alternative that minimizes the total annualized cost per unit of irrigated area. A soon as the optimal design has been completed, its hydraulic simulation can be performed to predict the detailed pressure distribution and verify the proper hydraulic operation of the submain. The described methodology was implemented within the drip irrigation design module, in the GESTAR software package, using the Visual Basic 6.0 programming language, providing a new advanced functionality.

RESULTS

The methodology is applied to three examples of irrigation submains with pressure-compensating emitters for their optimal design, where the geometrical and topographic configuration is heterogeneous. The results obtained are compared with previous designs developed with another commercial computer tool (Irricad Pro) as a feasibility test.

The submains irrigate vineyards that share the following characteristics: a) distance between rows: 2 m, b) distance between plants: 1 m, c) emitter flow: 1.60 L h^{-1}, d) emitter spacing: 0.60 m, e) emitter range of compensation: 4-40 m, f) external diameters of the lateral: 16 mm, g) internal diameter of the lateral: 15.5 mm, h) number of laterals per row: 1 lateral, i) emitter manufacturing variation coefficient: 4%. For each example, the layout of the main pipe runs parallel to every manifold pipe; this gives the possibility of connecting the valve at any point along the submain manifold pipes.

Based on the external diameters (mm), table 1 shows the costs per linear meter of the possible pipes that are used in the LMM/KPH-LM algorithm for the submain manifold pipe optimization.

For the hydraulic-economic optimization of the submains, the following variables have been considered: a) energy price: 0.06 € kwh^{-1}, b) water price: 0.10 € m^{-3}, c) cost of the lateral: 0.33 € m^{-1}, d) interest rate: 7%, e) service life: 25 years, f) pump efficiency: 65%, g) annual net irrigation requirements: 6,000 m^3 ha^{-1}, h) transmission ratio: 1.05, and i) maintenance cost: 5% of annualized material acquisition cost (C_a).

Table 1. External diameters of pipes and their corresponding cost per linear meter.

Tabla 1. Diámetros externos de tuberías y su correspondiente costo por metro lineal.

DE (mm)	50	63	75	90	110	125	140	160	200
€/m	1.33	1.39	2.62	2.71	3.12	3.89	4.97	3.36	10.4

Figure 2 and table 2 show the geometrical and topographic characteristics and the results of the previous hydraulic design of the three submains, where the valve's pressure (Pv), submain flow, length, diameter and total cost of secondary pipes are shown.

Figure 3 (page 162), shows the new form created with the GESTAR tool to introduce the necessary data for the optimal hydraulic-economic design of the submains. Table 3 (page 162), summarizes the results of the hydraulic design optimization of the submains and shows: the number of hydraulic designs (Designs No.), the optimized design valve pressure (Pv); the length, diameter and total cost of the manifolds optimized pipes.

While the cost of the lateral for each design alternative (initial and optimized) is the same, significant cost savings are achieved by placing the valve at an intermediate point of the submain manifold pipe where the flows are divided and design is optimized using the proposed algortihm LMM/KPH-LM (13). Thus, in Example 1 a 22% manifold pipe cost reduction is achieved, while in Example 2 cost reduction is in the order of 34% (because the pipe throughout its entire length is on an ascending slope) and in Example 3 it is 16%.

Table 4 (page 162), summarizes the main results of the hydraulic-economic optimization of the irrigation submains and shows: the intake point of the subunit (X/Lp), where X is the distance downstream of the submain manifold pipe with respect to the connection of the valve and Lp is the total length of the submain manifold pipe (20).

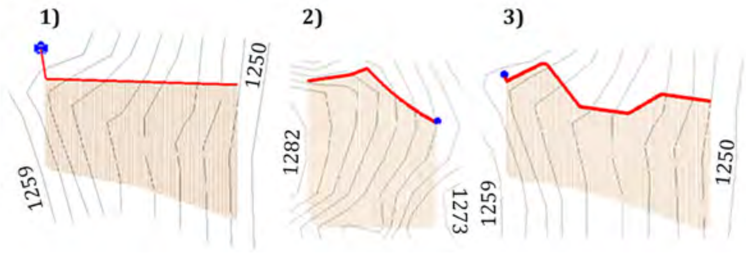


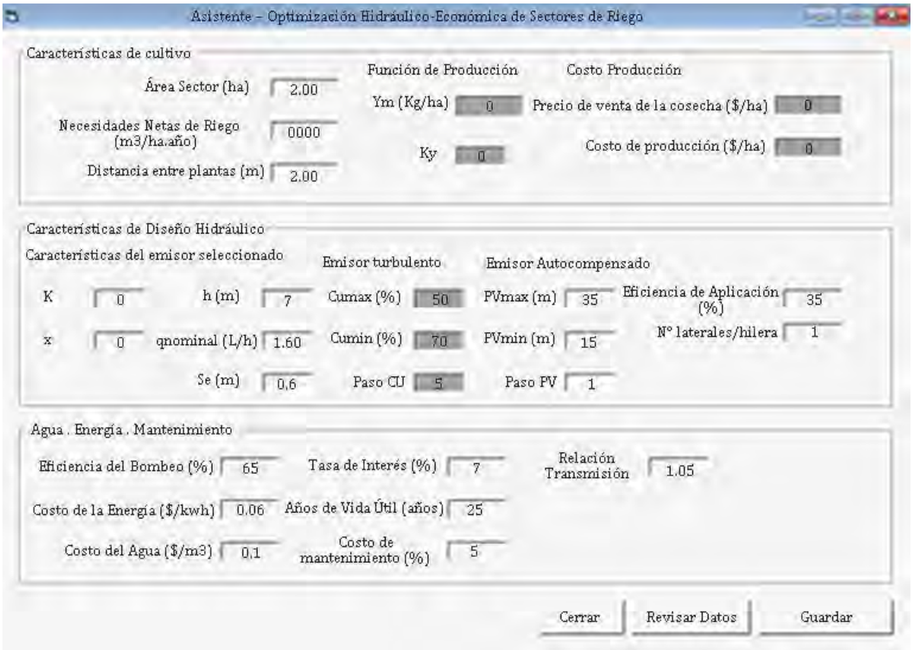
Figure 2. Geometric and topographic form of submains (contour lines every 1 m).

Figura 2. Forma geométrica y topográfica de sectores de riego (curvas de nivel cada 1 m).

Table 2. Hydraulic design characteristics of the irrigation sector according to Irricad Pro.

Tabla 2. Características hidráulicas de diseño de los sectores de riego ejemplo según Irricad Pro.

Ej.	S	Flow	Pv	Diameter (mm) and length (m) of pipes				Total length	Total Cost
	ha	m^3h^{-1}	m	90	75	63	50	m	€
1	2.30	30.67	28		66	56	78	200	354.5
2	1.94	25.87	24	49	70	38		157	369.8
3	2.09	27.87	24		50	65	118	232	376.6



Área Sector (ha) 2.00
Necesidades Netas de Riego (m3/ha.año) 0000
Distancia entre plantas (m) 2.00
Ym (Kg/ha) 0
Ky 0
Precio de venta de la cosecha ($/ha) 0
Costo de producción ($/ha) 0
K 0
x 0
h (m) 7
qnominal (L/h) 1.60
Se (m) 0,6
Cumax (%) 50
Cumin (%) 70
Paso CU 5
PVmax (m) 35
PVmin (m) 15
Paso PV 1
Eficiencia de Aplicación (%) 35
N° laterales/hilera 1
Eficiencia del Bombeo (%) 65
Costo de la Energía ($/kwh) 0.06
Costo del Agua ($/m3) 0,1
Tasa de Interés (%) 7
Años de Vida Útil (años) 25
Costo de mantenimiento (%) 5
Relación Transmisión 1.05

Figure 3. GESTAR form for data entry for economic hydraulic optimization of submains with pressure-compensating emitters.

Figura 3. Formulario GESTAR de ingreso de datos para la optimización hidráulica y económica de sectores con emisores autocompensados.

Table 3. Optimized hydraulic design features of the irrigation submains (Gestar).

Tabla 3. Características de diseño hidráulicas optimizadas de los sectores de riego (Gestar).

Ej.	Area	Designs	P_{Vop}	Diameter (mm) and Length (m) of pipes					Total	Total Cost
	ha	N°	m	110	90	75	63	50	m	€
1	2.30	1648	15			2	68	122	202	276.2
2	1.94	924	15	2		22.25	43.13	87.51	157	240.9
3	2.09	1648	15			2	72.31	157.59	232	315.4

Table 4. Main hydraulic operation characteristics of the optimized Gestar design for the irrigation submains (Gestar).

Tabla 4. Principales características de funcionamiento hidráulico del diseño optimizado de los sectores de riego (Gestar).

Ej.	X/Lp	Pv (m)	Pmax (m)	Pmin (m)	Vmax (m/s)	Vmin (m/s)	C_e	CeOpt.
1	77	15	14.46	7.48	2.47	0.041	49.30	23.77
2	72	15	14.90	6.62	2.50	0.102	42.26	26.41
3	92	15	15.24	7.49	2.50	0.041	49.30	26.41

The optimized valve pressure is also presented: P_{Vop} (m), the maximum and minimum dripper simulated pressures: Pmax, Pmin; the maximum and minimum secondary pipe simulated speeds: Vmax, Vmin (m/s); the annualized energy cost per unit of irrigated area (C_e; € kwh^{-1}) of the initial design; and the annualized energy cost of the optimized design.

Figure 4 graphically details the results of the hydraulic simulation of the optimal design for each irrigation submain. It shows the real hydraulic operation of the submain and the optimal design pressure in all the emitters (7-24 m). The high distribution uniformity is only dependent on the manufacturing variation coefficient of the emitter because it is a pressure-compensating emitter.

In terms of energy optimization of optimized designs, a 51% saving is achieved in Example 1 with respect to the annualized energy cost per unit area; a 37% saving is achieved in Example 2 and a 46% saving in Example 3 by reducing the valve pressure value to almost half of the initial Irricad design. Tarjuelo *et al.* (2010) stated that energy costs per unit area can reach approximately 40-50% of the total annualized cost when considering all the submains of a drip irrigation system. However, this depends on the characteristics of each irrigation design.

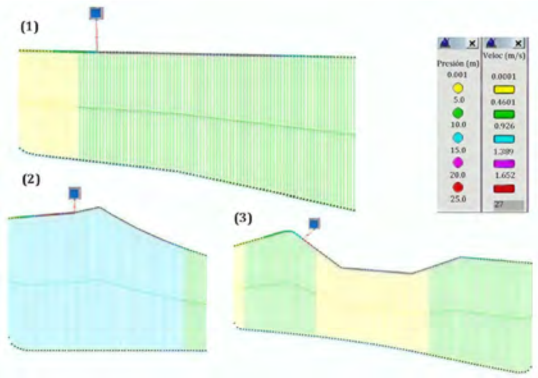


Figure 4. Hydraulic optimal design simulation in irrigation subunits (the color ramp is related to the speed of the water at the inlet of the lateral - Gestar).

Figura 4. Simulación hidráulica del diseño óptimo en sectores de riego (la escala de colores está relacionada con la presión y velocidad del agua al ingreso del lateral - Gestar).

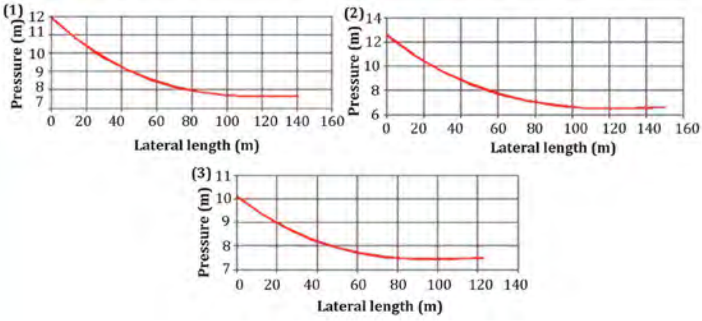


Figure 5. Pressure distribution for the critical lateral of each example (Gestar).

Figure 5. Distribución de presiones para el lateral crítico en cada ejemplo (Gestar).

CONCLUSIONS

A computational methodology was developed for the optimal hydraulic-economic design of irrigation submains using pressure-compensating emitters which makes it possible to optimize in each specific topographic and geometric sector: a) the telescopic sizing of the manifold pipe; b) the intake valve pressure and c) the submain's intake valve location, by minimizing the total annualized cost per unit of irrigated area. To this end, the optimal sizing algorithms of the pipes (13, 14) were used and generalized in a double nested iterative process.

The methodology was implemented in the design module of a drip irrigation plot, in the GESTAR computer package, using the Visual Basic 6.0 programming language which provided a new advanced functionality.

The hydraulic simulation techniques of pressure networks in the software (1, 2, 9, 10, 11, 15, 34) make it possible. If deemed appropriate, is posible to perform a final interactive verification and modification of the resulting design.

The practical usefulness of the methodology is shown with three examples of complex real cases where pipe design costs are reduced by 16-34% and energy costs by 37-51%. Results show that it is feasible to optimize the feeding point for any design condition and that the methodology is a useful decision-making tool for the design and management of drip irrigation systems with pressure-compensating emitters. Optimal design solution calls for deep knowledge of the design area as well as of agronomic management of the irrigated crop.

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