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TECHNICAL PAPER

THE DESIGN AND EVALUATION OF TRAVELLING GUN IRRIGATION SYSTEMS: ENROLADOR SOFTWARE

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ABSTRACT: Travelling gun irrigation systems offer great mobility and operation flexibility with a low investment cost per unit of irrigated area. However, the drawbacks include high operating pressure, low application efficiency, and high rainfall, runoff and erosion. Many of these problems can be minimized if the design and operation of travelling gun irrigation systems are carried out carefully, taking into account several design criteria that will ensure the quality of the irrigation performed by the system. The Enrolador software was developed to meet this goal. The software designs the travelling gun irrigation system, performs its simulation and its performance evaluation. This software was experimentally applied in the Alentejo region, Portugal. The design flow rates were computed for maize and sunflower crops with the soil water balance model IrrigRotation, considering a probability of non-exceedance of 75%. Meteorological data from the Évora weather station for the years 1961 to 1990 were used. Five plots with 3, 6, 9, 12 and 15 ha were chosen for the design of the irrigation systems using the software. The Enrolador software was used to select the equipment (gun, hose and reel) and the appropriate operating parameters for each plot. This software allows for the selection of the equipment that best meets the design criteria.

KEYWORDS: irrigation, travelling gun, irrigation design, software.

INTRODUCTION

Travelling gun irrigation systems allow for the irrigation of a diversity of crops, but they are most suitable for tall or very dense crops that provide a good ground cover (TARJUELO, 2005). The mobility and flexibility of these systems make them suitable for small farms that have dispersed plots with irregular shapes.

Travelling guns are often criticized for having high working pressures (400 to 1000 kPa), low application efficiency, low distribution uniformity, high operating costs, large droplets size (which can damage the soil structure and the crop) and high rainfall, runoff and erosion. The systems' performance is also greatly affected by the wind, which causes an uneven water distribution. However, the disadvantages are offset by the low investment cost per unit of irrigated area (ha) and by the limited need for hand labour (GRANIER et al. 2003; TARJUELO, 2005; OLIVEIRA et al., 2012; GRANIER & DEUMIER, 2013). The systems' problems can be minimized if the design and the operation of the travelling gun systems are performed carefully through the proper selection of the operating pressure, the nozzle type and diameter, and the towpath spacing (overlap). Therefore, in the design process, it is necessary to take into account the design criteria aimed at ensuring the quality of the irrigation performed by the travelling gun.

The design of irrigation systems is commonly executed using software tools to perform the hydraulic calculations and select the equipment that best meets the design criteria. One of the major advantages of using simulation models is the ability to simulate different design alternatives (PEDRAS et al., 2009; GONÇALVES et al., 2011; DAROUICH et al., 2014). In fact, the development of computational tools for irrigation has been an important area of research, with several models being developed to support irrigation management (ROLIM, 2013; STEDUTO et al., 2012;

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ROSA et al., 2012) and the design and management of irrigation systems (PEDRAS et al., 2009; GONÇALVES et al., 2011; VALÍN et al. 2012). A large number of studies have been performed based on the use of these models (ANDARZIAN et al., 2011; ROLIM et al., 2011; DAROUICH et al., 2012; FARIA et al., 2012; VALIPOUR, 2012; RODRIGUES et al., 2013; PAREDES et al., 2015; PEREIRA et al., 2015; MIAO et al., 2016).

Some examples of software applications that allow for the design and simulation of pressurized irrigation systems should be mentioned. The ISADIM model (ABREU & PEREIRA, 2002) allows for the design and simulation of solid set irrigation systems. For the design and evaluation of centre pivot irrigation systems, VALÍN et al. (2012) developed the DEPIVOT simulation model. Additionally, the MIRRIG software (PEDRAS et al., 2009; DAROUICH et al., 2014) is a DSS (Decision Support System) that performs the design and evaluation of micro-irrigation systems and comprises the simulation models, a multi-criteria analysis module and a database. Software applications for travelling gun irrigation systems include the IRRIPARC (GRANIER et al., 2003), TRAVGUN (SMITH et al., 2008) and SIA (OLIVEIRA et al., 2013) models, which simulate several regulations performed in the equipment, allowing for estimates of their performance to improve the system efficiency. The SIMULASOFT software, described in PRADO & COLOMBO (2010), simulates the precipitation depths applied by a gun moving along its path based on the gun discharge, radius, wetted sector angle, travel speed and radial application depth profile.

The Enrolador software was developed to design and evaluate the performance of travelling gun irrigation systems. This program selects the equipment that best meets the design criteria, performs a simulation of the operation of the designed equipment, simulating the gun precipitation profile, and provides a performance evaluation. When the travelling guns are poorly designed and managed, they often present low distribution uniformity and low irrigation efficiencies (GRANIER et al. 2003; TARJUELO, 2005). Therefore, a design software that minimizes these negative aspects is an important tool. In addition to introducing the Enrolador software, the purpose of this paper is to present the results of an experimental application of the Enrolador software to evaluate its ability to properly design travelling gun irrigation systems.

The following sections describe the theoretical basis of the Enrolador software, the software architecture, and the experimental application performed. The results related to the equipment selected for each simulation are presented and discussed, and the main conclusions are presented.

ENROLADOR SOFTWARE

The Enrolador software was developed in Visual Basic 2005 and consists of a graphical user interface (GUI) (Figure 1) and three calculation modules: hydraulic design, precipitation simulation and performance evaluation. The conceptual structure of the program is shown in Figure 2.

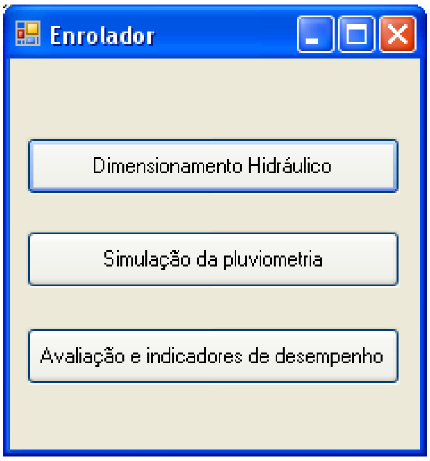

FIGURE 1. Enrolador software graphical user interface.

The software interface is quite simple, consisting of command buttons that run each of the program modules. The input data are supplied to the model through text files..

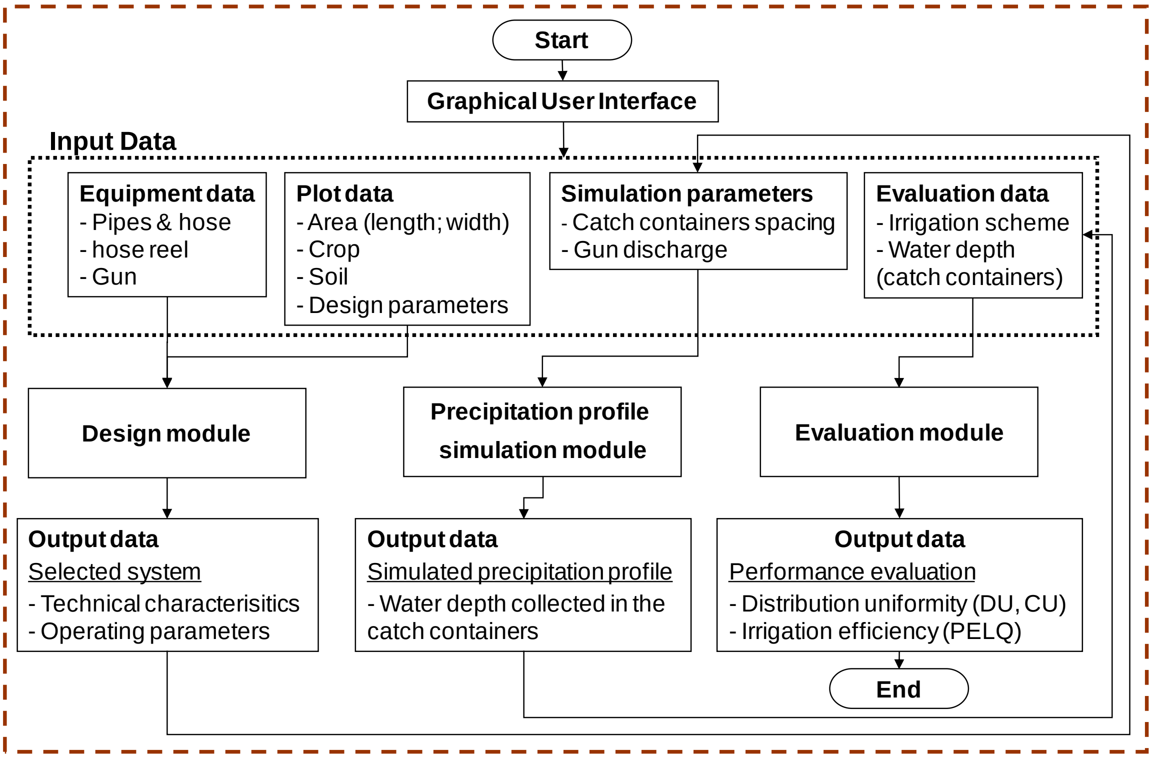

FIGURE 2. Conceptual framework of the Enrolador software (ROLIM, 2013).

To perform the design of the irrigation system, the software uses the peak irrigation requirements calculated by a soil water balance simulation model as the input data. The software also considers the soil, crop and plot characteristics. Based on the input data, the irrigation system design is performed by selecting the equipment from the database (gun, hose and reel, and optionally the main line) that best meets the design criteria. As outputs, the program produces a text file containing the equipment selected, the design flow rate, the pipe diameters, and the required pressure in the hydrant. These data can be used as input to the gun precipitation profile simulation module. The text file structure of this program is presented in Figure 3.

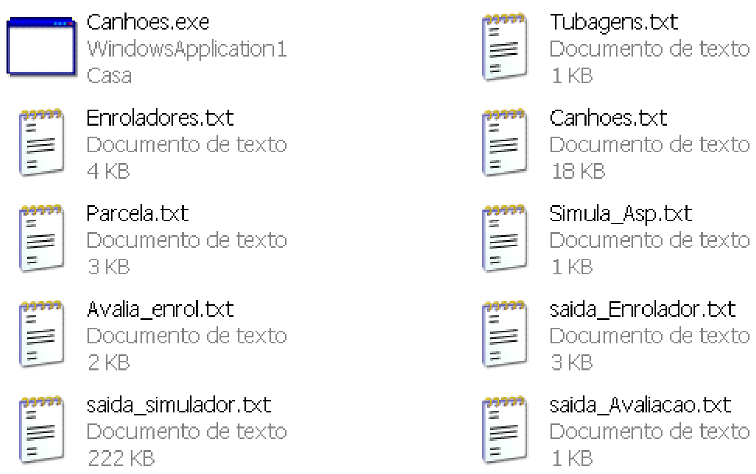

FIGURE 3. Text file structure of the Enrolador software (ROLIM, 2013).

CALCULATION PROCEDURE IMPLEMENTED IN THE ENROLADOR SOFTWARE DESIGN MODULE

The calculation procedure implemented by this software (ROLIM, 2013) for the design of travelling gun systems is based on the methodology proposed by TARJUELO (2005), which consists of the following main steps:

1- **Irrigation parameters**:

The design process starts with the computation of the gross irrigation depth (Dg):

$$Dg = \frac{Dn}{E_a} \quad (1)$$

where,

Dn is the net peak irrigation depth [mm] and E_a is the application efficiency [fraction].

2- **Design flow rate**:

The design flow rate is computed according to the following expression (TARJUELO, 2005):

$$Q = \frac{10 \times Dg \times A}{Td \times I} \quad (2)$$

where,

Q is the design flow rate [m^3/h];

Td is the daily irrigation time [h/day];

A is the irrigated area [ha], and

I is the time interval between irrigations [days].

3- **Gun selection:**

The gun selection is made based on the design flow rate (Q) and the recommended working pressures range according to the values recommended by CEMAGREF (1992). After selecting the gun, it is necessary to verify that the average application rate is smaller than the soil infiltration rate (CEMAGREF 1992; TARJUELO 2005).

$$I_t = 1000 \frac{Q}{\pi(0.9R)^2} \frac{360}{\alpha_{sr}} \quad (3)$$

where,

I_t is the average application rate [mm/h];

R is the gun wetted radius [m], and

α_{sr} is the wetted sector angle [º].

4- **Towpath spacing**:

The towpath spacing (T_S) is defined as the function of the recommended spacing (as a percentage of the wetted diameter) under various wind conditions.

5- **Travel speed**:

The travel speed is computed by the following expression:

$$V = \frac{Q}{Dg \times T_S} \quad (4)$$

where,

V is the travel speed [m/h] and T_s is the towpath spacing [m].

6- **Pressure required in the hydrant**:

The pressure required in the hydrant is computed by the following expression (CEMAGREF, 1992; TARJUELO, 2005):

$$P_{hidr} = P_g + 9.81 \times \left(H_h + H_{rs} + H_z + H_{ml} + \Delta H_{sl}\right) \quad (5)$$

where,

P_{hidr} is the pressure required in the hydrant [kPa];

P_g is the pressure required in the gun [kPa];

H_h is the head loss in the hose [m];

H_{rs} is the head loss in the reel, propulsion, control mechanisms and other singularities [m];

H_z is the head loss due to the height of the gun relative to the ground [m];

H_{ml} is the head loss in the main line [m], and

ΔH_{sl} is the head loss due to the slope between the hydrant and the initial position of the gun [m].

The flowchart of the design module of the Enrolador software is shown in Figure 4.

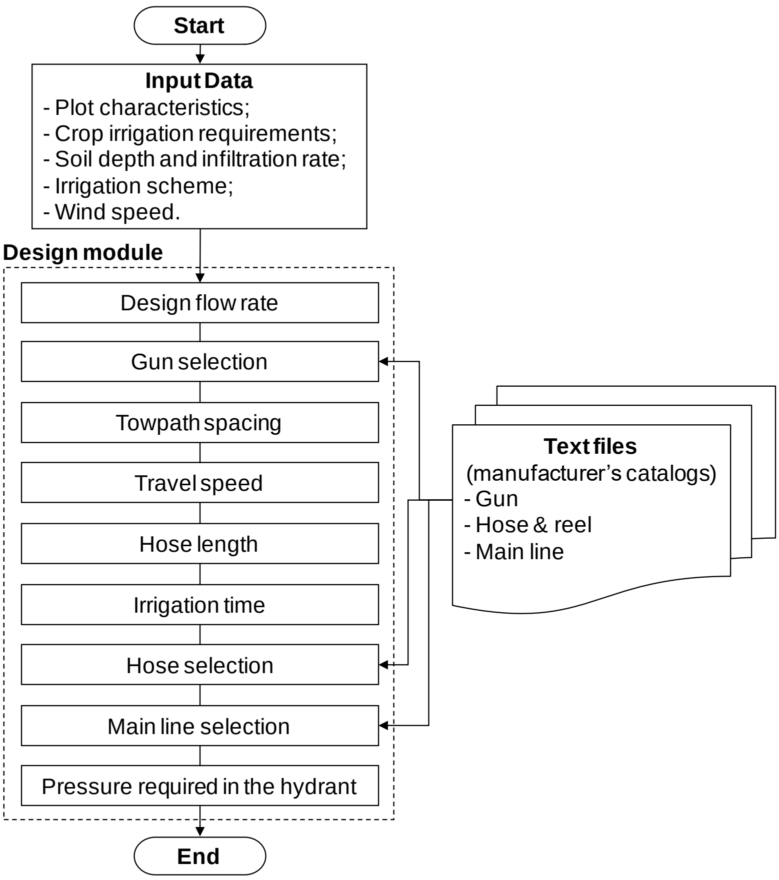

FIGURE 4. Flowchart of the calculation procedure used to design the travelling gun irrigation systems (ROLIM, 2013).

APPLICATION DEPTH PROFILE SIMULATION MODULE

This module performs the simulation of one gun working along its trajectory. It simulates the spatial distribution of water over the ground by the gun under the assumption that there is no wind. The module enables the estimation of water height applied to a set of points (fictitious rain gauges) perpendicular to the moving direction of the travelling gun, thus imitating the placement of rain gauges on the ground during a field evaluation. This module produces the precipitation heights that will be used by the evaluation module to calculate the performance indicators of the designed irrigation system. The gun radial precipitation profile is approximated by a function, triangular or elliptical, which is defined according to the gun discharge, radius and wetted sector angle. The input data for the simulation of the application depth profile consist of the gun radius [m], gun discharge [m^3/h], wetted sector angle [°], travel speed [m/h], radial precipitation profile function, and fictitious rain gauge spacing [m] (ROLIM, 2013).

EVALUATION MODULE

This module evaluates the performance for the travelling gun irrigation system according to the methodology proposed by KELLER & BLIESNER (1990) and TARJUELO (2005). From the various indicators available to characterize the irrigation quality, the following were chosen: distribution uniformity (DU), coefficient of uniformity (CU), application efficiency (E_a) and the potential application efficiency of low quarter (PELQ) (KELLER & BLIESNER, 1990; TARJUELO, 2005).

This module estimates the performance indicators of the irrigation system based on field data collected in the assessment of existing systems, or in water heights data produced by the precipitation profile simulation module, for the irrigation systems being designed.

EXPERIMENTAL APPLICATION

The experimental application of the Enrolador software was performed in Évora, in the Alentejo region, Portugal, to test it's ability to perform the design of the travelling gun systems. The base data used in the design of the travelling gun systems comprised data relative to the characteristics of the plot, crop, wind speed, irrigation, and equipment data.

Meteorological data from the Évora weather station (lat.: 38º 34' N, long.: 07º 54' W and alt.: 309 m) for the years 1961 to 1990, with a daily time step, were considered. Two crops produced in this region were selected for study: maize and sunflower. To compute the peak irrigation requirements (IRp), the soil water balance simulation with the IrrigRotation model (ROLIM, 2013) was performed. Based on the IRp values, the design flow rates were computed and the travelling guns were designed for each simulation considered using the Enrolador software.

PLOT DATA

Five hypothetical plots with different sizes were considered: 3 ha, 6 ha, 9 ha, 12 ha, and 15 ha, as described in the Table 1. The slope of the plots was null.

TABLE 1. Characteristics of the plots considered in the simulations.

Simulation	Crop	Area (ha)	Length (m)	Width (m)
M3 **S3**	Maize Sunflower	3	200	150
M6 **S6**	Maize Sunflower	6	300	200
M9 **S9**	Maize Sunflower	9	300	300
M12 **S12**	Maize Sunflower	12	400	300
M15 **S15**	Maize Sunflower	15	400	375

SOIL DATA

The soil considered was the Luvisol (LV) soil group, whose parameters are presented in Table 2.

TABLE 2. Soil parameters of the Luvisol (LV) soil.

Site	Soil water capacity (mm/cm)	Infiltration rate (mm/h)	Texture
Évora	1.7	Bare soil: 18 Soil covered: 36	Sandy loam

PEAK IRRIGATION REQUIREMENTS DATA

The design of the irrigation systems is based on the seasonal irrigation requirements (IR) and peak irrigation requirements (IRp). It is based on the IRp that is defined the design flow rate used in the design of the irrigation systems. The seasonal and peak irrigation requirement values change from year to year depending on the climate variability. Thus, it is necessary to perform an frequential analysis of a series of years, and a minimum of 30 years is generally recommended (ROLIM, 2013; ROLIM et al., 2016). To perform the design of the travel gun irrigation systems, a non-exceedance probability of 75% for the IRp values was considered (Table 3).

TABLE 3. Seasonal irrigation requirements (IR) and peak irrigation requirements (IRp), for the non-exceedance probability of 75%.

Crop	IRp (mm/d) non-exceedance prob. 75%	IR (mm) non-exceedance prob. 75%
Maize	8.6	687
Sunflower	8.2	685

OTHER PARAMETERS

Other base data used in the definition of the simulations include the average wind speed in Évora (2.9 m/s), application efficiency (Ea = 75%) and daily irrigation time (Td = 22 h).

RESULTS AND DISCUSSION

TRAVELLING GUN SYSTEMS DESIGN

For each one of the simulations, the design module of the Enrolador software produced a list of the equipment, the operating parameters and the regulations to be performed on the equipment. The gun selected for each simulation considered is presented in Table 4.

TABLE 4. Gun selected by the Enrolador software for each simulation.

Simulation	Crop	Area (ha)	Gun model	Discharge (m^3/h)	Pressure (kPa)	Radius (m)	Nozzle (mm)
M3	Maize	3	Komet - TwinMax	17.3	400	35	15
S3	Sunflower		Komet - TwinMax	16.2	350	33.3	15
M6	Maize	6	Komet - Twin160	31.98	450	46	20
S6	Sunflower		Komet - Twin160	31.98	450	46	20
M9	Maize	9	Komet - TwinMax	49.5	500	49.2	24
S9	Sunflower		Komet - TwinMax	49.5	500	49.2	24
M12	Maize	12	Komet - Twin160	66.73	550	58.5	27.5
S12	Sunflower		Komet - Twin140	60.9	550	53.3	26
M15	Maize	15	Komet - Twin160	82.9	600	62.5	30
S15	Sunflower		Komet - Twin160	82.9	600	62.5	30

In Table 5, the hoses selected for each simulation are presented. The hose diameters ranged from 63 mm (3 ha) to 110 mm (15 ha). The main line diameters and the pressures required at the traveller and the hydrant are also presented. For the main line the Enrolador software selected aluminium pipes with diameters ranging from 76.2 mm (3 ha) to 152.4 mm (15 ha). The pressure required in the hydrant tends to increase with the plot area.

The main operating parameters and equipment settings are listed in Table 6. From the analysis of Tables 4, 5 and 6, the selected equipment (gun, traveller and main line) as well as the operating parameters and settings tend to be equal for the same plot areas because the peak irrigation requirements of maize and sunflower crops are very similar. When comparing the different plot areas, larger equipment is selected as the area to be irrigated increases.

TABLE 5. Hose and main line selection by the Enrolador software for each simulation.

Simulation	Crop	Area (ha)	Hose diam. (mm) [a]	Hose length (m) [a]	Pressure traveller (kPa)	Main line diam. (mm) [a]	Main line length. (m)	Hydrant pressure (kPa)
M3	Maize	3	63	200	678	76.2	180	714
S3	Sunflower		50	240	1050	76.2	180	1082
M6	Maize	6	75	300	856	101.6	270	897
S6	Sunflower		75	300	856	101.6	270	897
M9	Maize	9	90	220	822	101.6	270	915
S9	Sunflower		90	220	822	101.6	270	915
M12	Maize	12	100	210	859	127	360	932
S12	Sunflower		100	210	831	127	367	893
M15	Maize	15	110	200	883	152.4	360	928
S15	Sunflower		110	200	883	152.4	360	928

[a] commercial sizes.

TABLE 6. Operation parameters and regulations of the designed travelling gun systems.

Simulation	Crop	Area (ha)	Dg (mm)	Dn (mm)	Towpath Nº	Towpath spacing (m)	Towpath irrigation time (h)	Travel speed (m/h)	Application rate (mm/h)
M3	Maize		57.3	43	5	40	20	7.5	9.1
S3	Sunflower	3	54.7	41	5	40	20.3	7.4	9.4
M6	Maize		57.3	43	5	60	21.5	9.3	9.7
S6	Sunflower	6	54.7	41	5	60	20.6	9.7	9.7
M9	Maize		57.3	43	5	60	10.4	14.4	13.1
S9	Sunflower	9	54.7	41	5	60	9.93	15.1	13.1
M12	Maize		57.3	43	5	80	10.3	14.5	12.5
S12	Sunflower	12	65.6	49.2	6	66.7	10.8	13.9	13.8
M15	Maize		57.3	43	5	80	10.4	18.1	13.6
S15	Sunflower	15	54.7	41	5	80	9.87	19	13.6

Dg - gross irrigation depth; Dn – net irrigation depth.

EVALUATION OF THE POTENTIAL PERFORMANCE OF THE DESIGNED SYSTEMS

The results of the performance evaluation relative to the distribution uniformity, the coefficient of uniformity and the potential efficiency of low quarter are presented in Table 7. Considering the PELQ values, all the selected equipment presents a good irrigation performance with a minimum of 70.5% and a maximum of 86.7%. These values are overestimations because the simulation conditions assume no wind and perfect equipment management.

TABLE 7. Potential performance indicators of the travel gun systems designed with the Enrolador software, assuming no wind and well-managed and maintained equipment.

Crop	Plot	DU (%)	CU (%)	PELQ (%)
Maize	3 ha	70.5	81.6	72
	6 ha	82.2	82.8	82.2
	9 ha	77.2	81.2	77.2
	12 ha	85.5	85	86.7
	15 ha	80.4	82	81.5
Sunflower	3 ha	74.7	80.9	76.5
	6 ha	82.2	82.8	82.2
	9 ha	77.2	81.2	77.2
	12 ha	77.9	81.3	79.8
	15 ha	80.4	82	81.5

DU - distribution uniformity; CU - coefficient of uniformity; PELQ - potential efficiency of low quarter.

CONCLUSIONS

The Enrolador software performs the hydraulic design of travelling gun irrigation systems, automatically selecting the equipment that best meets the design criteria. It performs the gun precipitation profile simulation that is used to assess the potential performance of the selected equipment. This software includes a module that calculates the performance indicators based on data collected from field assessments or on data obtained by simulating the precipitation profile. Thus, this program can be used both for the design of new irrigation systems or to evaluate the performance of existing irrigation systems to improve irrigation management.

The experimental application of the Enrolador software allowed for the design of travelling gun systems in a simple and quick way, which demonstrates the usefulness of having software available to compute an optimized design solution for a given plot layout.

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REFERENCES

ABREU, V.M.; PEREIRA, L.S. Sprinkler irrigation systems design using ISADim. In: **ASAE ANNUAL INTERNATIONAL MEETING / CIGR WORLD CONGRESS**, 2002, Chicago.

ANDARZIAN, B.; BANNAYAN, M.; STEDUTO, P.; MAZRAEH, H.; BARATI, M.E.; BARATI, M.A.; RAHNAMA, A. Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. **Agricultural Water Management,** 100, p.1–8, 2011.

CEMAGREF. **Irrigation – Guide pratique**. 2nd éd. Paris: CEMAGREF et Editions France Agricole, 1992. 294 p.

DAROUICH, H.; GONÇALVES, J.M.; MUGA, A.; PEREIRA, L.S. Water saving vs. farm economics in cotton surface irrigation: An application of multicriteria analysis. **Agricultural Water Management**, v. 115, p. 223-231, 2012.

DAROUICH, H.; PEDRAS, C.M.G.; GONÇALVES J.M.; PEREIRA, L.S. Drip vs. surface irrigation: A comparison focusing on water saving and economic returns using multicriteria analysis applied to cotton. **Biosystems Engineering**, London, v. 122, p. 74-90, 2014.

FARIA, L.C.; COLOMBO, A.; OLIVEIRA, H.F.E.; BESKOW, S.; PRADO, G. Distorção do vento na área molhada por canhões hidráulicos: Extensão da modelagem para aspersores médios. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 16, n. 7, p. 699–705, 2012.

GRANIER, J.; MOLLE, B.; DEUMIER, J.M.; LACROIX, B. **Optimisation des réglages et de l'utilisation des systèmes d'irrigation par canon-enrouleur**. Ingénieres-EAT, Technologies pour les agrosystèmes durables, 2003. 125-140 p. Numéro spécial.

GRANIER, J.; DEUMIER, J.M. Efficience hydraulique et énergétique : les nouveaux critères de performances pour les systèmes d'irrigation du futur. **Sciences Eaux & Territoires**, Antony, v. 11, p. 30-34, 2013.

GONÇALVES, J.M.; HORST, M.G.; PEREIRA, L.S. Furrow irrigation design with multicriteria analysis. **Biosystems Engineering**, London, v. 109, p. 266–275, 2011.

KELLER, J.; BLIESNER, R.D. **Sprinkler and trickle irrigation**. New York: Van Nostrand Reinhold, New York, 1990. 652 p.

MIAO, Q.; ROSA, R.D.; SHI, H.; PAREDES, P.; ZHU, L.; DAI, J.; GONÇALVES, J.M.; PEREIRA, L.S. Modeling water use, transpiration and soil evaporation of spring wheat–maize and spring wheat–sunflower relay intercropping using the dual crop coefficient approach. **Agricultural Water Management**, Amsterdam, v. 165, p. 211–229, 2016.

OLIVEIRA, H.F.E.; COLOMBO, A.; FARIA, L.C.; PRADO, G. Efeitos da velocidade e da direcção do vento na uniformidade de aplicação de água de sistemas autopropelidos. **Engenharia Agrícola**, Jaboticabal, v.32, n.4, p.669-678, jul./ago. 2012.

OLIVEIRA, H.F.E.; COLOMBO, A.; FARIA, L.C.; BESKOW, S., PRADO, G. SIA: Modelo para simulação da irrigação por aspersão - Calibração e validação. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v.17, n.3, p.253–260, 2013.

PAREDES, P.; WEI, Z.; LIU, Y.; XU, D.; XIN, Y.; ZHANG, B.; PEREIRA, L.S. Performance assessment of the FAO AquaCrop model for soil water, soil evaporation, biomass and yield of soybeans in North China Plain. **Agricultural Water Management**, Amsterdam, v. 152, p. 57–71, 2015.

PEDRAS, C.M.G.; PEREIRA, L.S.; GONÇALVES, J.M. MIRRIG: A decision support system for design and evaluation of microirrigation systems. **Agricultural water management**, Amsterdam, v. 96, p. 691 – 701, 2009.

PEREIRA, L.S.; PAREDES, P.; RODRIGUES, G.C.; NEVES, M. Modeling malt barley water use and evapotranspiration partitioning in two contrasting rainfall years. Assessing AquaCrop and SIMDualKc models. **Agricultural Water Management**, Amsterdam, v. 159, p. 239–254, 2015.

PRADO, G.; COLOMBO A. Determinação do perfil radial de aspersores a partir de ensaios de distribuição de água em sistemas autopropelidos de irrigação. **Engenharia Agrícola**, Jaboticabal, v.30, n.2, p.232-243, mar./abr. 2010.

RODRIGUES, G.C.; MARTINS, J.D.; SILVA, F.G.; CARLESSO, R.; PEREIRA, L.S. Modelling economic impacts of deficit irrigated maize in Brazil with consideration of different rainfall regimes. **Biosystems Engineering**, London, v. 116, p. 97-110, 2013.

ROLIM, J.; CATALÃO, J.; TEIXEIRA, J.L. The influence of different methods of interpolating spatial meteorological data on calculated irrigation requirements. **Applied Engineering in Agriculture**, St. Joseph, v. 27, n. 6, p. 979-989, 2011.

ROLIM, J. **Metodologias para a avaliação dos impactes das mudanças climáticas na agricultura de regadio e nos sistemas de rega.** 2013. 322 f. Thesis (PhD) - Instituto Superior de Agronomia, Technical University of Lisbon, Lisbon, 2013.

ROLIM, J.; TEIXEIRA, J.L.; CATALÃO J.; SHAHIDIAN, S. The Impacts of Climate Change on Irrigated Agriculture in Southern Portugal l. **Irrigation and Drainage**, Chichester, v. 53, p. 135-143, 2016. doi: 10.1002/ird.1996

ROSA, R.D.; PAREDES, P.; RODRIGUES, G.C.; ALVES, I.; FERNANDO, R.M.; PEREIRA, L.S.; ALLEN, R.G. Implementing the dual crop coefficient approach in interactive software: 1. Background and computational strategy. **Agricultural Water Management**, Amsterdam, v. 103, p. 8–24, 2012.

SMITH, R.J.; GILLIES, M.H.; NEWELL, G.; FOLEY, J.P. A decision support model for travelling gun irrigation machines. **Biosystems Engineering**, London, v. 100, p. 126 – 136, 2008.

STEDUTO, P.; HSIAO, T.C.; FERERES, E.; RAES, D. **Crop yield response to water**. Rome: FAO Irrigation and Drainage, 2012. 500 p. (Paper, 66).

TARJUELO, J.M. **El Riego por Aspersion y su Tecnología**. 3rd ed. Mundi-Prensa: Madrid, 2005. 581 p.

VALÍN, M.I.; CAMEIRA, M.R.; TEODORO, P.R.; PEREIRA, L.S. DEPIVOT: A model for center-pivot design and evaluation. **Computers and Electronics in Agriculture,** New York, v. 87, p. 159-70, 2012.

VALIPOUR, M. Sprinkle and Trickle Irrigation System Design Using Tapered Pipes for Pressure Loss Adjusting. **Journal of Agricultural Science**, Toronto, v. 4, n. 12, p. 125-133, 2012.