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Valín M.I., Pereira L.S.

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DEPIVOT, A SOFTWARE TOOL FOR IMPROVED WATER USE WITH CENTER-PIVOT SPRINKLER SYSTEMS

M. I. Valín and L. S. Pereira
Agricultural Engineering Research Center, Institute of Agronomy, Technical University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal (email: isabelvalin@esa.ipvc.pt; lspereira@isa.utl.pt).

SUMMARY - Improving both the efficiency of water uses and water productivity in irrigation require appropriate solutions for design, management and maintenance of irrigation systems. Various software tools proved useful for designing new systems and to improve functioning and management of systems under operation. In this line, the model DEPIVOT is a new software tool aimed at the design and performance analysis of center-pivot systems. It allows considering performance criteria for design and when searching better solutions for systems operation. The model computes crop irrigation requirements with the ISAREG irrigation scheduling model and then computes the flow-rate to be supplied to the center-pivot system. The emitter chart selection is done automatically or user defined. A hydraulic simulation is then performed for calculation of the head losses, the pressure head at each nozzle, and the respective actual discharges. This allows to compute the system performance and to consider the need for pressure regulators. Evaporation and wind drift losses are estimated as a function of evapotranspiration, wind speed and drop sizes. The application rates are described by an elliptical function and the infiltration rate curve is described by the Kostiakov infiltration equation; both curves are compared for estimating the potential runoff. The paper illustrates the use of the model for a case study performance improvement of systems under operation comparing respective actual and improved system performances. This shows how using the model could be useful for farmers when they select a new system or they want to improve management and operation of existing systems.

Keywords: Sprinkler systems design, Sprinkler systems performance, Water use and productivity, Sprinkler wind losses, Infiltration and runoff, Sprinkler selection

RESUME – *L'amélioration des rendements et productivité de l'eau en irrigation requière des solutions adéquates pour le projet, gestion et maintenance des systèmes d'arrosage. L'utilité de plusieurs logiciels est bien prouvée tant pur la conception que pour l'amélioration de leur fonctionnement. Le logiciel DEPIVOT se situe dans cette perspective vu qu'il est conçu pour le projet et l'analyse de performance des rampes pivotantes et considère des critères de performance pour le projet et la recherche de solutions améliorées pour des systèmes en fonctionnement. DEPIVOT calcule les besoins en eau avec le modèle ISAREG et, par la suite, calcule le débit nécessaire à la rampe. La carte des asperseurs est sélectionnée en mode soit automatique soit manuel. La simulation hydraulique permet le calcul des pertes de charge, des pressions disponibles à chaque asperseur et donc des respectives débits. Par la suite, est estimée la performance du système et le besoin de régulateurs de pression. Les pertes par évaporation et le vent sont estimées en fonction de l'évapotranspiration, de la vitesse du vent et du diamètre des gouttes. Les taux d'application sont décrits par une fonction elliptique et les taux d'infiltration sont décrits par l'équation de Kostiakov ; l'estimation du ruissellement potentiel se fait en comparant les deux courbes. Cet article montre une application du model à une étude de cas tout en comparant les performances mesurées au terrain avec celles relatives à l'amélioration des rampes proposée par le modèle. Ceci permet de montrer l'utilité de DEPIVOT comme support aux irrigants lors qu'ils achètent un système ou qu'ils prétendent améliorer les systèmes déjà en fonctionnement.*

Mots-clés*: Projet de systèmes en aspersion, Performance des systèmes d'aspersion, Utilisation et productivité de l'eau, Pertes par le vent, Infiltration et ruissellement, Sélection des asperseurs*

INTRODUCTION

Center-pivot systems have experienced a wide diffusion since their first appearance due primarily to two factors: (i) automation is built into the center-pivot allowing for irrigation of many types of soils, terrains, and crops with minimal labor input; and (ii) center-pivot systems can be one of the most efficient and uniform methods of applying irrigation water if the system is properly designed and managed. Main disadvantages include high energy demand and very large application rates at the end of the spans, often above the soil infiltration rate causing high water operational losses. These problems may be solved or minimized when adopting appropriate solutions for design, management and maintenance, particularly using design models because they help a better consideration of the complexity of systems, which require that numerous factors and equipment solutions be taken into account.

Montero *et al.* (2001) consider that using a simulation model enables to reduce water and energy consumption and lead to increase the efficiency of utilization of these resources. Using simulation models for pressurized systems design and evaluation has proved useful in practice, such as AVASPER for set sprinkler systems (Jorge and Pereira, 2003) and MIRRIG for microirrigation systems (Pedras and Pereira, 2006). Considering the increased complexity of center-pivot design (Allen *et al*., 2000) such modeling approaches are required to support improved use of center-pivot systems (Wilmes *et al.,* 1993; Molle and Legat, 2000), including to consider the impacts of different kind of sprinkler and spray nozzles that may be selected as briefly analysed below. The model DEPIVOT (Valín and Pereira, 2006) was developed to respond to this complex decision process.

In the attempt of reducing pressure and energy requirements and improve systems performance, new emitters have been developed in the last few years that often replaced impact sprinklers. The first ones to appear were the *Fixed Spray Plate Sprinklers* (FSPS), where a vertical water jet formed by the sprinkler nozzle hits a fixed horizontal grooved plane. In a subsequent phase, appeared the *Rotating Spray Plate Sprinklers* (RSPS) where a vertical jet hits a deflector groove plane which rotates under the effect of the jet. Numerous works were produced to determine their characteristics such as the application rate curve (Faci *et al.,* 2001), the drop size distribution in the application rate profile (Kincaid *et al.,* 1996), the importance of velocity on rotating-plate diffusers (DeBoer, 2002), or their impact on the performance of center-pivot systems (Montero *et al.,* 2002; Clark *et al.,* 2003; Playán *et al.,* 2004).

One potential problem of center-pivot irrigation is the high application rate at the lateral end. The present trend is to place FSPS and RSPS emitters hanged and closer to the canopy to decrease wind drift and evaporation losses (Playán *et al.,* 2005) but this increases the application rates by reducing the wetted radius. It is therefore important to define the application rate profile of the system in order to compare it with the infiltration rate curve and estimate the potential runoff (Wilmes *et al.,* 1993). For many authors, the application rate profile which better adapts to center-pivot systems is the elliptical profile (Kincaid *et al*., 1969; Dillon *et al*., 1972; Gilley, 1984; Von Bernuth and Gilley, 1985; Allen, 1990); however, others consider that the parabolic profile (Luz and Heermann, 2005) or trapezoid pattern (DeBoer, 2001) are more adequate. The latter verified that for impact sprinkler each rising and falling segments ranged from 10% to 20 % of the total application time, with the remainder 80 to 60% time having a relatively constant application rate; he also find the values 40/20/40 for the FSPS and 25/50/25 for RSPS, both on drops, which clear indicates the superiority of RSPS over the FSPS. DeBoer (2001) alerts for a possible overestimation of the potential runoff, which may prevent the use of sprinkler technology, that in fact could be used without causing runoff problems, while underestimating the runoff potential can be the source of serious field operational problems.

This short discussion calls attention for the need to evaluate the center-pivot systems in the field operational conditions as referred by many authors (e.g. Von Bernuth and Gilley, 1985; Ortiz *et al.,* 2004). The study herein presented bases on field evaluations of systems under operation, which have shown quite poor performances (Valín *et al*., 2003). Investigating the causes for problems encountered, it was considered appropriate to develop a model that could support selection, design and evaluation of center-pivot systems, which led to the model DEPIVOT. This paper presents the model focusing its use for improving systems under operation; therefore a comparison between field observed performance indicators and model computed indicators relative to improved solutions for the same systems is shown to demonstrate the potential usefulness of this software tool.

THE MODEL

The software DEPIVOT (Valín and Pereira, 2006) is written in Visual Basic 6.0 and includes a database in Access 2003. Figure 1 shows the conceptual structure of the model, which is constituted of five main components relative to:

i) the calculation of gross irrigation requirements in relation to the crop, the soil and the climate. Computations may be done using a simplified soil water balance or interactively with the water balance simulation model ISAREG (Teixeira and Pereira 1992);
ii) the hydraulic simulation, where the diameter and length of the span pipes are selected from the database, including the spacing between outlets; using the selected values, the model computes the friction losses along the lateral and the pressure variation at the emitters following the approaches proposed by Keller and Bliesner (1990) and Allen *et al*., (2000);
iii) the selection of the emitter chart, including the calculation of the pressure and discharge for each nozzle, which allows to select the emitter characteristics and nozzle diameter required; after the emitter chart is elaborated, the model computes the water depths produced along the lateral (Tabuada *et al*.,2004) and the performance indicators (Pereira and Trout, 1999);
iv) the calculation of the application rate at several points along the lateral adopting an elliptical profile, and the infiltration rate using the Kostiakov infiltration equation (Silva and Serralheiro, 2005); then, comparing for the selected points the application and infiltration curves, the model estimates the runoff potential (Allen, 1990; Allen *et al*., 2000); and
v) e) when the model is used for evaluation of operating systems if a record the water depths is made along two radios of can catch and computed the system performance using several indicators such as the distribution uniformity DU and the coefficient of uniformity CU (Pereira and Trout, 1999).

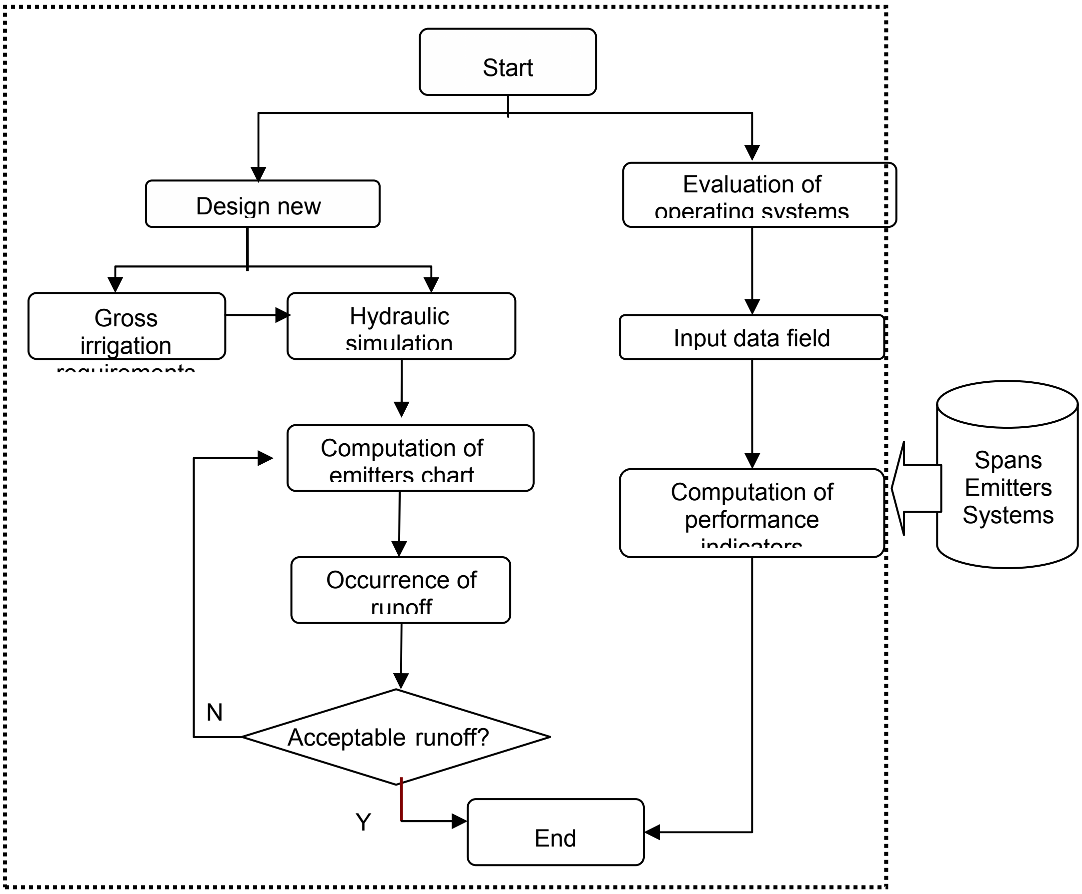

Fig. 1 Conceptual structure of the model DEPIVOT with indication of input data from a database

The hydraulic simulation (Fig. 2) starts introducing several input data:

vi) flow rate, introduced by the user or calculated with the help of the model;
vii) pressure at the upstream end of the system;
viii) radius of the field where the system will be installed; and
ix) ground elevation for different points.

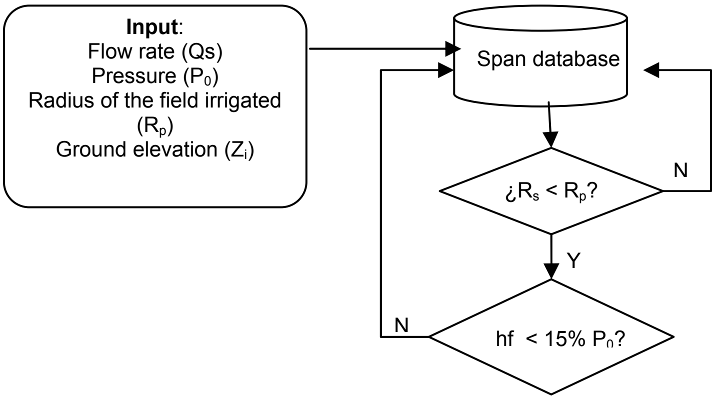

Fig. 2. Schematic representation of hydraulic simulation model.

The user chooses the lengths of spans and stores them in a database relative to the lateral being designed. The radius of the system (Rs) should be smaller than the field radius (Rp). The span database stores data on length, diameter and spacing between emitters. The model calculates the friction losses along the lateral and the pressure variation at the emitters. The Hazen – Williams equation is used to compute the friction losses (Allen *et al.,* 2000). The friction losses must be inferior to 15 % of the working pressure. Figure 3 shows the window used for selection from the database of diameters and lengths of the span pipes, including the spacing between outlets; for computation of friction losses, and for choosing or not an end-gun and respective booster pump; and to input the ground elevation at given locations.

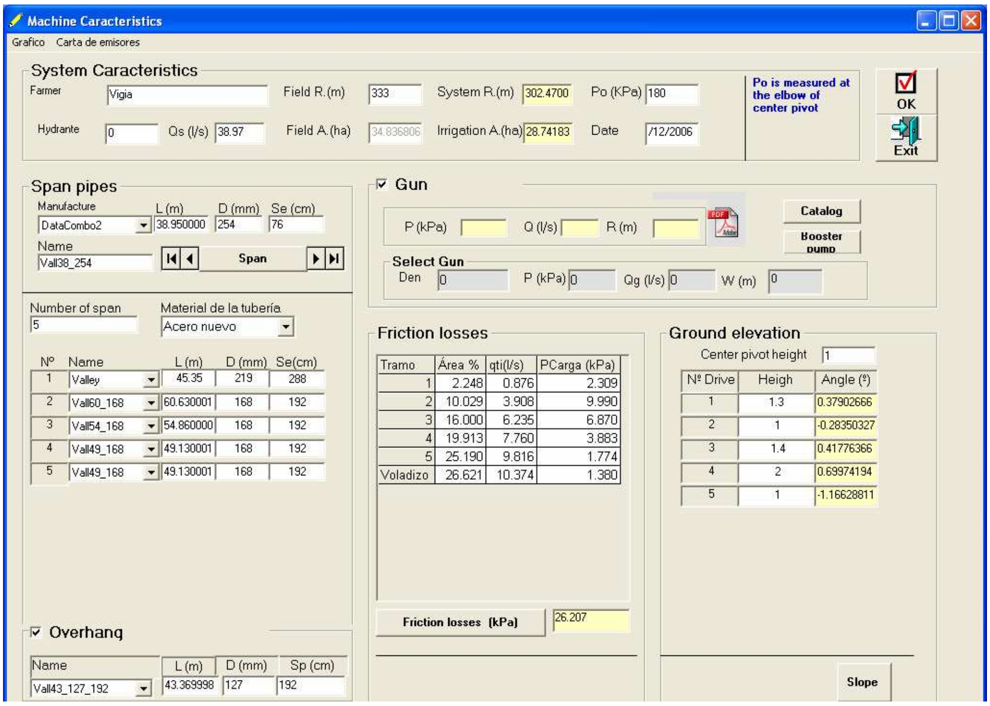

Fig. 3. Window for selection and sizing of the spans and end-gun, computation of friction losses along the lateral and pressure available at the outlets, and input of ground elevation.

After calculating the friction losses for all spans of the center-pivot lateral, the emitters configuration is simulated (Fig. 4): the first step is to calculate discharge required at each emitter (q_{ai}), the second is to compute the friction losses ($h_{f\ i,i+1}$ (Q-Σq_{ai})) and pressures (P_{i+1}=P_{ai} - $h_{f\ i,i+1}$) along lateral, section by section (outlet by outlet) and, finally, the discharge at each outlet ($q_{ai+1} = k_d\ (P_{i+1})^x$). The process is iterative until the desired discharge is met. The model then selects from the data base the emitter which discharge is closer to the required discharge (q_{ai}).

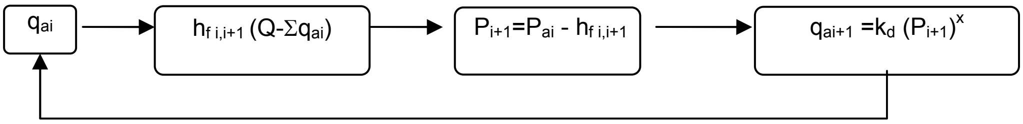

Fig.4. Iterative computation of pressure and emitters discharges.

Two internal validations are then performed: i) for each span, it is verified if the differences between required discharges and actual discharges relative to the selected emitters is < 10% of the required discharge; and ii) if the distribution uniformity (DU) and coefficient of uniformity (CU) computed with the selected emitters satisfies the values set for design. If any of these conditions is not verified the calculation is reinitiated. If variations in discharge and pressure are high, it is considered the use of pressure regulators at each sprinkler. Figure 5 shows the window relative to the discharge variation along the system for each of the spans and the computed DU and CU. Further details on the model calculations are presented by Valín and Pereira (2006).

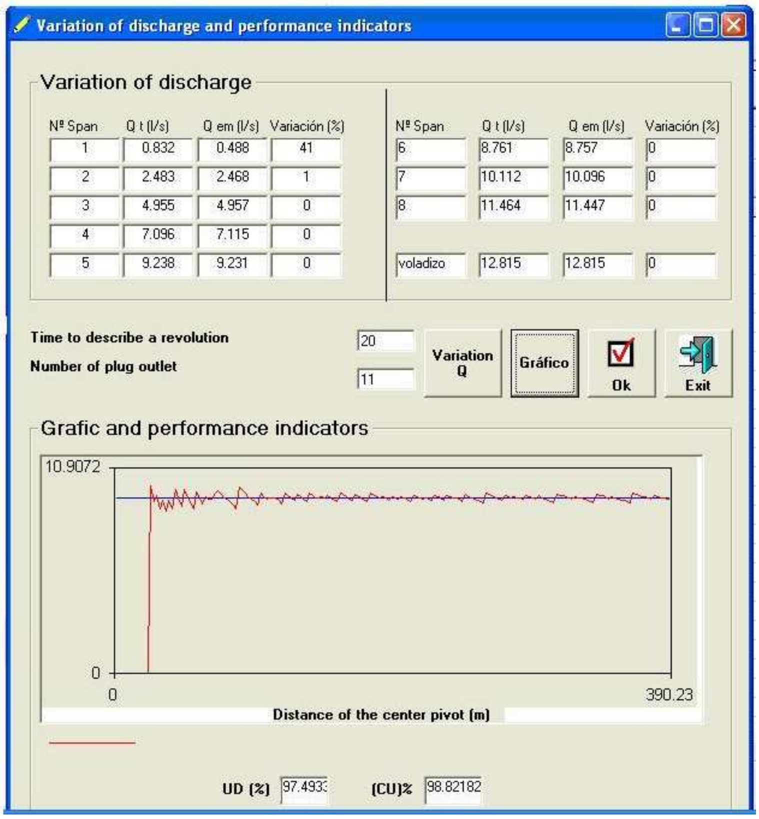

Fig. 5. Window showing results on discharge variation for each span and along the lateral, including the DU and CU indicators of uniformity.

MODEL APPLICATION

The results analyzed herein refer to field evaluations of center-pivot systems in operation in Alentejo (Valín *et al.*, 2003), which were performed following the methodology proposed by Merriam and Keller (1978). Table1 summarizes the performance indicators relative to 3 systems evaluated two or three times.

Table 1 Performance indicators obtained in field evaluations

	Lucefécit						**Lucefécit**				**Vigia**	
Hidrante	H233/234/235						H-116					
L (m)	445						168				310	
Fecha	13-Jun-00		14-Jun-00		16-Jun-00		28-Jun-00		13-Jul-00		28-Jun-00	
U (m/s)							3,14		0.72		3,5	
P_p (kPa)	476		518		497				555			
Q_h (m^3h^{-1})	273,8		281,1		272,9		50,6		50,8		130.9	
Resultados	**R A**	**R B**	**R A**	**R B**	**R A**	**R B**	**R A**			**R B**	**R A**	**R B**
Z_{av} (mm)	9,4	8,8	10	7,5	8,5	8.8	6,4	5,7	7.9	6,2	11,7	11,8
Z_{lq} (mm)	7,5	7,7	8,1	5,8	6,5	7,7	5,1	4,3	6,2	4,9	9,8	10,3
y (mm)	10,7		11		10,6		8,9		9,5		9,5	
UD (%)	79,4	87,7	80,4	76,8	77,6	80,4	79,3	74,6	78,2	78,8	83,8	87,2
CU (%)	88	91,4	83,7	85,6	85,6	88,8	81,3	79,1	85,7	85,5	88,4	88,15
PELQ (%)	71,2						52,8		58,8		58,8	

U: wind speed ($m.s^{-1}$); P_p: pressure at the top (kPa); Q_s: system discharge ($m^3.h^{-1}$); v_l: lineal velocity ($m.min^{-1}$); $v_{\%}$: perceptual velocity (%); T_r: time for one revolution (h); Z_{avg}: the average weighted applied depth (mm); Z_{lq}: the average weighted low quarter catch (mm); y: the average of water applied (mm); UD: Distribution Uniformity (%); CU: Coefficient of uniformity (%); PELQ: Potential efficiency of the low quarter (%). The abbreviations RA and RB refer respectively to evaluations performed along the radius A and B.

DU values ranged from 74,6% to 87,7% and CU from 79,3% to 91,4%. The resulting PELQ varied between 52,8% and 77,4%. Main problems were: i) high working pressure, ranging from 476 kPa to 555 kPa, much above recommended pressure for systems with FSPS emitters; ii) high wind drift and evaporation losses due to small diameter of droplets as a result of high functioning pressure of emitters; and iii) application rates excessive relative to soil infiltration rates. These problems result of poor design, mainly relative to the selection of spray heads which were not in agreement with the existing characteristics of the pressurized distribution network and the characteristics of the soils and relief in the area.

The model DEPIVOT was used to simulate alternatives to the existing systems. Simulations were performed selecting the optimized emitter chart option, maintaining the lengths of the spans and systems, and searching for systems that work at a low pressure without provoking high levels of runoff. Results from such simulations are presented in *Table 2*.

The system Lucefecit H233/4/5 has been designed to work at P_p = 325 kPa which means a reduction of 37,2 % relative to the observed working pressure. Wind velocity was assumed to be 2,5 $m.s^{-1}$, representing an averaged value observed in the area, which was used to estimate the wind drift and evaporation losses; these were considered to estimate the application efficiency and then to compute the system discharge Q_s (m^3/h^{-1}). The computed value is Q_s = 248 $m^3.h^{-1}$ inferior by about 10% to the observed ones (*Table 1*). The system has 8 spans with diameter values decreasing from the upstream to the downstream end. The friction losses totalise 44.04 kPa, thus less than 15% of P_p. the new emitter chart refers to RSPS sprayers to replace the existing FSPS ones, which allows to achieve good performance indicators (DU = 92,31% and CU = 97,08%) and no runoff as estimated by comparing the application rate and the infiltration rate curves. The potential application efficiency is estimated to be above 80%. Since the system operates in a flat land, no pressure regulators and soil runoff control measures were proposed.

Table 2. Performance indicators obtained in DEPIVOT.

	Lucefecit H233/4/5	Lucefecit H116	Vigia
L (m)	440	168	333
U (m/s)	2.5	3.14	3.5
P_p (kPa)	325	200	180
Q_s (m^3/h^{-1})	248.5	42.6	140.0
hf (kPa)	44.0	4.6	38.7
Y (mm)	9.0		8.9
UD (%)	92.3	94.8	95.3
CU (%)	97.1	96.8	97.2

U: wind speed ($m.s^{-1}$); P_p: pressure at the top (kPa); Q_s: system discharge ($m^3.h^{-1}$);
hf: friction losses (kPa); y: average depth (mm); UD: Distribution Uniformity (%);
CU: Coefficient of uniformity (%)

The system Lucefecit H-116 was designed to work 18 h day^{-1}, assuming an average wind speed of 3,14 m s^{-1} and for system discharge of 42,58 m^3 h^{-1}. The system is formed by 3 spans, the first with a diameter of 168 mm and the other two with 127 mm, and overhang (127 mm). The emitters are FSPS, and are not modified. The friction losses are 4,56 kPa. Because land is sloping, with 10 m difference between the pivot point and the lower position of the downstream end, and droplet sizes of FSPS are sensitive to pressure, the installation of pressure regulators (140 kPa) in each sprayer was proposed. The resulting performance indicators are UD = 94,84% and CU = 96,81%. The potential application efficiency is estimated to be close to 80%. From comparing the infiltration rate and the application rate for a point located at 146 m from the pivot point, the potential runoff estimated is 2,48 mm, which makes necessary that the farmer adopts reservoir tillage to control runoff.

The system installed in Vigia was designed assuming a wind speed of 3.5 m s^{-1}, which causes relative high that the design is made with an application efficiency of 77.06% project. The system is 333 m long, the discharge is 140 m^3h^{-1}, higher than at present, and the water depth applied is 9.1 mm when the system works at 100% velocity. The system comprises 5 spans, with varying internal diameter: 219 mm for the first, 168 mm for the three following ones, and 127 mm for the last one. Due to high wind speed, the selected FSPS emitters shall be installed on drops. The friction losses amounts for 38.67 kPa, that is inferior to the present one. The resulting uniformity indicators are high (UD = 95.27% and CU = 97.21 %). At 270 m from the pivot point, the emitter has a wetted diameter of 9.3 m. The estimated potential runoff is 1.81 mm. Despite the low slope, it is recommended to adopt reservoir tillage to avoid runoff.

CONCLUSIONS

Field evaluations of center-pivot systems have shown that these systems are often poorly designed and the selection of emitters is often inappropriate. In addition, when systems are installed in pressurized distribution networks, the operation pressure is excessive, out of the pressure range recommended by the manufacturers, thus causing much small drops that easily evaporate or are drawn by the wind. Friction losses observed were often greater than 20% of the operation pressure. Runoff was also often produced due to high application rates. Along with these problems, farmers often ignore the characteristics of their systems and ways to improve their performances. The model DEPIVOT was conceived to support farmers in selecting new systems and improving the existing ones. The comparison among characteristics and performances of systems in operation and respective alternative solutions proposed by using DEPIVOT shows that it is possible to achieve much better performances, reduce the operating pressure and save energy, control wind drift and evaporation losses, and control runoff, so improving the beneficial water use. Solutions refer to improved selection of emitters, use them on drops when wind speed is high, use pressure regulators when variation in pressure is high, namely for sloping land, and adopting reservoir tillage when estimated potential runoff is relatively important. Further studies are required as oriented to analyse the requirements to use the model in the practice of farmer advisers and irrigation projects managers.

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