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Water distribution from medium-size sprinkler in solid set sprinkler systems

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Key words:
distribution curve
simulation
distribution uniformity

ABSTRACT

The study aimed to evaluate the water distribution from a medium-size sprinkler working in solid set sprinkler systems. Water distribution radial curves from the sprinkler operating under four nozzle diameter combinations (4.0 x 4.6; 5.0 x 4.6; 6.2 x 4.6 and; 7.1 x 4.6 mm) and four working pressures (196; 245; 294 and 343 kPa) were evaluated on the sprinkler test bench of the State University of Maringá, in Cidade Gaúcha, Paraná, Brazil. The sixteen water distribution curves were normalized and subjected to clustering analysis (K-Means algorithm), identifying the occurrence of normalized distribution curves with three different geometric shapes. A computer algorithm, in Visual Basic for Applications in Excel spreadsheet, was developed to simulate the water application uniformity (Christiansen's Coefficient - CU) from the sprinklers working with rectangular and triangular layouts in solid set sprinkler systems. For the three geometric shapes of the normalized water distribution curves, digital simulation results of water distribution uniformity for the sprinklers on mainline and lateral line spaced between 10 to 100% of wetted diameter indicated that sprinkler spacings around 50% of the wetted diameter provide acceptable CU values.

Palavras-chave:
perfil radial
simulação digital
uniformidade de distribuição

Distribuição de água de aspersor de tamanho médio em sistemas fixos de irrigação por aspersão

RESUMO

Objetivou-se avaliar, neste trabalho, a distribuição de água de um aspersor de tamanho médio operando em sistemas fixos de irrigação por aspersão. Perfis radiais de distribuição de água do aspersor, operando sob quatro condições de bocais (4,0 x 4,6; 5,0 x 4,6; 6,2 x 4,6 e 7,1 x 4,6 mm) e quatro de pressões serviço (196; 245; 294 e 343 kPa) foram determinados na bancada de ensaio de aspersores da Universidade Estadual de Maringá, em Cidade Gaúcha, Paraná. Os dezesseis perfis radiais de distribuição de água foram adimensionalizados e submetidos à análise de agrupamento (método "K-Means"), indicando a ocorrência de perfis radiais adimensionais com três formatos geométricos distintos. A uniformidade de aplicação de água (Coeficiente de Christiansen - CU) do aspersor operando em sistemas fixos de irrigação, distribuídos em um arranjo retangular e triangular, foi simulada em um programa desenvolvido em Visual Basic da planilha Excel. Simulações da uniformidade de aplicação de água para espaçamento entre 10 e 100% do diâmetro molhado do aspersor na linha principal e lateral indicaram, para as três formas geométricas do perfil radial adimensional do aspersor, que espaçamentos de aproximadamente 50% do diâmetro molhados, proporcionam valores apropriados de CU.

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INTRODUCTION

Agricultural production is a business activity, which has made farmers achieve high production rates, with maximum technical and economic efficiency. The irrigation techniques have been used for increasing agricultural productivity in dry regions, as well as where the water supply by rain is not enough for growing crops.

Sprinkler irrigation systems have been widely employed due to the operational simplicity that this irrigation method offers. Furthermore, this kind of irrigation provides good water distribution uniformity, precise controlling of irrigation depth applied, high water application efficiency and potential of use in different types of soil and topography conditions (Bernardo et al., 2006; Frizzone et al., 2011).

Nowadays, environmental protection and conservation of water resources have been emphasized and, in addition, water and energy costs are increasing, which leads to a concern by sprinklers' manufacturers, designers and irrigation users about irrigation management (Louie & Selker, 2000; Faria et al., 2013). Knowledges of water application uniformity is indispensable for sprinkler irrigation systems to provide the amount of water demanded by the crop (Mateos, 1998; Prado et al., 2008). Irregular water application produces areas that receive an excess of water, while the remaining area is under-irrigated. Therefore, to ensure that whole irrigated area receives the irrigation depth, avoiding the negative impact of under-irrigation on crop yield, irrigation users have applied an excess of water, producing a waste of water, energy and fertilizers (Clemmens, 1991).

Despite the importance of water application uniformity, sprinklers' manufactures have just presented data of flow rate, working pressure, nozzle diameter and application rate for different sprinkler spacings in their technical manuals. Martín-Benito et al. (1992) and Prado & Colombo (2007) pointed out the surprising lack of information about sprinklers available in the market, becoming complicated the precise selection of a sprinkler.

The solid set sprinkler irrigation systems include those in which sprinkler lines remain stationary during the irrigation (Prado et al. 2008; Keller & Bliesner, 1990; Faria et al., 2013). In such systems, water application uniformity is influenced by many factors, controlled or not by the operator. Among those factors that can be handled by the operator, there are: i) geometric shape of the radial leg, which depends on the kind of sprinkler, nozzle diameter, working pressure and trajectory angle; ii) sprinkler spacings; and iii) sprinklers layouts (rectangular and triangular) (Bernardo et al., 2006; Keller & Bliesner, 1990). However, wind (speed and direction) cannot be controlled by the operator (Seginer et al., 1992; Carrión et al., 2001; Faria et al., 2009; Beskow et al., 2011; Faria et al., 2012).

Typically, designers and irrigation users, in order to achieve high uniformity levels, have set up, without specific criteria, the sprinkler lines closer, which leads to increasing total costs (Holzapfel et al., 2007). There are suitable operational combinations that result in high water distribution uniformity (Playán et al., 2006; Zapata et al., 2007). According to Dechmi et al. (2003), these conditions can be found more precisely through digital simulations.

The radial leg obtained under no wind condition and a combination of working pressure and nozzle diameter is required by the simulation models to establish the water distribution uniformity values. These simulation models have been developed for different kinds of sprinkler irrigation systems, such as: stationary sprinkler (Carrión et al., 2001), travelling gun irrigation (Prado & Colombo, 2010) and center pivot (Omary & Summer, 2001).

Prado et al. (2008) and Zhang et al. (2013) to simulate water distribution uniformity for solid set sprinkler systems, under no wind condition and sprinklers working under different combinations of nozzle diameters, pressure and spacing, used sprinkler water distribution radial curves obtained on test benches. Spacing between sprinklers, recommended in these studies, can be generalized for different sprinkler models since the water distribution radial curves of these sprinklers have similarity in the geometric shape.

According to Prado & Colombo (2010), the simulations are a useful and precise tool to examine the several possible working sprinkler conditions, intending to maximize the water distribution uniformity. In addition, simulations have an important role in designing irrigation projects, assessment of irrigation equipment, development of new sprinkler models and evaluating the accuracy of usual irrigation procedures. Thus, the objectives of this study were: i) set out the water distribution radial curves of NY30 sprinkler; ii) identify the typical geometric shapes (K-cluster) assumed by the sprinkler water distribution radial curves; and iii) define the sprinkler working conditions that result in acceptable Christiansen Uniformity Coefficients.

MATERIAL AND METHODS

The study was carried out at the State University of Maringá (UEM), in Cidade Gaúcha, Paraná State, using a NY30 sprinkler, manufactured by Agropolo® Industry. This plastic sprinkler presents a trajectory angle of 30º, 1" female thread connection, full circle of water coverage, rotation provided by impact of the arm on the water stream and four different combinations of nozzle diameters (4.0 x 4.6; 5.0 x 4.6; 6.2 x 4.6; 7.1 x 4.6 mm).

Regarding the different working conditions of the NY30 sprinkler, given by four nozzle diameters and four different working pressures (196; 245; 294; 343 kPa), recommended by Agropolo®, sixteen trials were conducted to obtain the sprinkler water distribution radial curves.

The outdoor trials were performed at dawn or dusk, trying to avoid wind velocities greater than 0.9 m s^{-1}, as recommended by ISO 7749-2 (ISO, 1990). The wind speed data, measured with an anemometer installed at 10 m above the soil surface, were obtained at a weather station located 50 m far from the tests location. Tests performed in disagreement with wind speed limit were discarded and repeated.

For running the tests, the sprinkler was installed on a test bench assembled by a straight line of metallic catch cans, white painted, along 25 m from the sprinkler center. The catch cans with 0.168 m diameter and 0.190 m height were located 0.8 m below the main nozzle, at same level and equally spaced by 1 m.

After setting the working pressure, measured in a middle point at the riser pipe with pressure gauge placed on the same vertical plane of the main nozzle, the impact arm was released and the sprinkler began its rotation for one hour of water application. During the tests, the pressure values were examined at every 10 min intervals and at the end of each test, the volumes of water applied in each catch can were collected to determine the radius of throw and the water distribution radial curve (distance versus application rate).

Subsequent to each sprinkler evaluation, as Seginer et al. (1992) suggested, the amounts of water collected in the catch cans were used to estimate the sprinkler's flow rate. On the assumption that the water application pattern is radially symmetric, the flow rate could be calculated by:

$$Q_e = 2\pi \cdot \int_0^R \frac{a(r)}{1000} \cdot r \cdot dr \qquad (1)$$

where:

Q_e - flow rate estimated from water distribution radial curve, $m^3\ h^{-1}$;

a(r) - application rate collected in a catch can located at a radial distance (r) from the sprinkler, mm h^{-1};

R - radius of throw, m; and

r - radial distance from the sprinkler, m.

In cases where the difference between flow rate estimated by Eq. 1 and that informed in the sprinkler's catalog differed by 10%, the trials were replicated until reaching a difference smaller than 10% (Prado & Colombo, 2005). For the other cases (difference smaller than 10%), the application rates observed were adjusted by the ratio of these two flow rates.

According to Solomon & Bezdek (1980), the application rate values, observed along the radius of throw, were expressed by the fraction of the average application rate, respectively, the distance from sprinkler values were expressed by the fraction of radius of throw. Each dimensionless water distribution radial curve was represented by twenty values of dimensionless application rate with dimensionless distance from the sprinkler, regularly spaced at 5% (2.5, 7.5, ..., 92.5 and 97.5%).

The sixteen dimensionless water distribution radial curves were subjected to the cluster analysis, using "K-Means" algorithm (Tou & Gonzales, 1974). In order to apply this algorithm and identify the typical geometric shapes assumed by the dimensionless water distribution radial curves, a computer program was written in Visual Basic for Application of Excel spreadsheet, as described by Prado & Colombo (2005).

Typical geometric shapes of NY30 sprinkler type, represented by K-cluster center of dimensionless water distribution radial curves, as well as Christiansen's water distribution radial curves type B (triangular), were used to simulate water application uniformity for solid set sprinkler irrigation systems. The simulations were run for the main line and lateral line spaced from 10 to 100% of the wetted diameter (WD) and sprinklers located in rectangular and triangular layout.

A computer program, regarding the different possible working conditions of the NY30 sprinkler type and the geometric shapes of the water distribution radial curves, was written in Visual Basic for Application of Excel spreadsheet to simulate the water distribution uniformity (Figure 1). The simulation results of water distribution were expressed by Christiansen's coefficient of Uniformity (CU) and presented in contour map for the different geometric shapes of the water distribution radial curves.

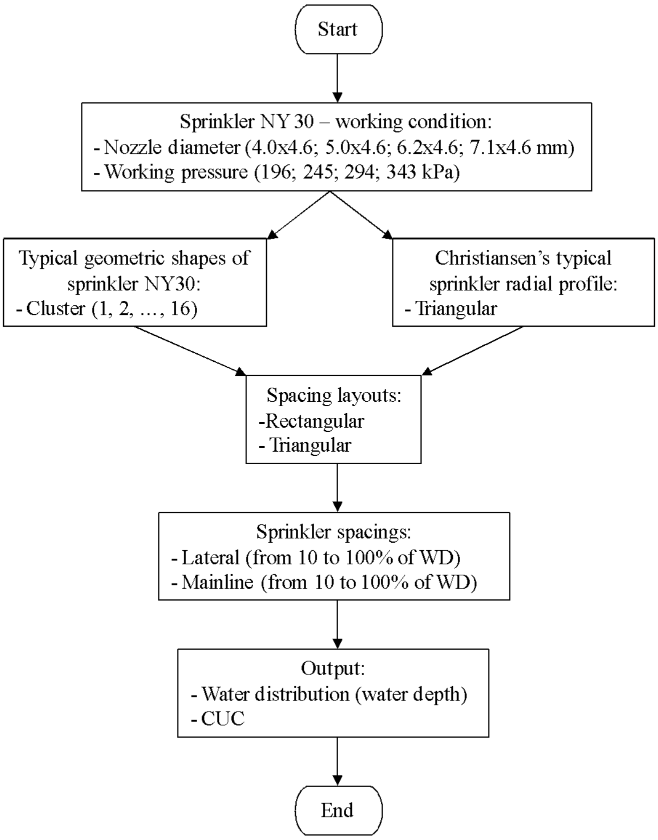

Figure 1. Flowchart representing the software sequence to simulate water distribution from solid set sprinkler irrigation working with NY30 sprinkler type

In all response surfaces of CU, a line was drawn, which defined the full water coverage zone for spacing between sprinklers (Chen & Wallender, 1984). The sprinkler spacing combinations, whose overlapping provides incomplete water coverage, for triangular and rectangular layouts, respectively, could be calculated by the following expressions:

$$\frac{Sl}{WD} = \sqrt{1 - \left(\frac{Sm}{WD}\right)^2} \qquad (2)$$

$$\frac{Sl}{WD} = \sqrt{1 - 4 \cdot \left(\frac{Sm}{WD} - 0.5\right)^2} \qquad (3)$$

where:

Sl - lateral spacing, m;

Sm - mainline spacing, m; and,

WD - wetted diameter of the sprinkler, m.

Results and Discussion

The sixteen water distribution radial curves obtained in the trials, under four different nozzle diameters and four working pressures, are presented in Figure 2. As Keller & Bliesner (1990) and Bernardo et al. (2006) pointed out that, increasing working pressure for a same combination of nozzle diameters, the water from the nozzles break up into fine drops and settle near the sprinkler. Concerning the two smaller nozzle diameters, 4.0 x 4.6 mm and 5.0 x 4.6 mm, stepping up working pressure from 294 to 343 kPa led to a reduction of the radius of throw (Table 1) due to a greater spraying of the jet into small drops. Decrease in radius of throw by virtue of increasing working pressure was also observed by Zhang et al. (2013).

Raising the K cluster number of dimensionless radial legs (Figure 3), there are two distinct reduction rates in the root mean square - RMS. As Solomon & Bezdek (1980) and Prado & Colombo (2005) indicated, the number of typical dimensionless radial curves is given at the K clusters' point where a sharp change is observed in the slopes of the RMS values. Therefore, clustering the sixteen water distribution radial curves into three typical geometric shapes (K = 3) (Figure 3), there is a RMS of 0.19, and from that point, the RMS decrease gradually until reaching zero (K = 16). Solomon & Bezdek (1980) and Prado & Colombo (2005), clustering dimensionless radial legs of gun sprinklers, found out, respectively, RMS of 0.12 and 0.15.

There is a tendency of the typical geometric shapes of the dimensionless water distribution curves in representing particular working conditions of the sprinkler. As indicated in Table 1, regardless of the working pressure, the typical geometric shapes I and II, respectively, represent the nozzles 4.0 x 4.6 mm and 5.0 x 4.6 mm, whereas the typical geometric shape III characterizes the largest nozzles (6.2 x 4.6 mm and 7.1 x 4.6 mm). In relation to gun sprinklers, Solomon & Bezdek (1980), Prado & Colombo (2005) and Prado & Colombo (2007) observed that the typical geometric shapes of water distribution radial curves had a better representation in terms of working pressure, instead of the only nozzle diameters; as a result, the low working pressure conditions had typical geometric shapes totally different from the high ones.

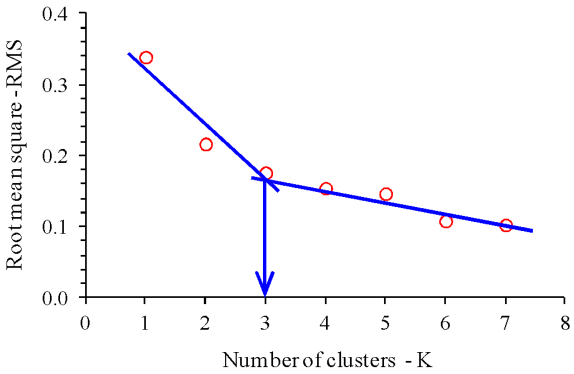

Figure 3. Root mean square for the number of cluster (K) settled

Table 1. Flow rates, radius of throws and normalized radial leg types of Agropolo NY30 sprinkler, working under no wind conditions and different combinations of working pressures and nozzle diameters

Pressure (kPa)	Technical data	Nozzle diameter (mm)			
		4.0 x 4.6	5.0 x 4.6	6.2 x 4.6	7.1 x 4.6
196	Flow rate (m^3 h^{-1})	1.79	2.17	2.88	3.27
	Radius of throw (m)	13.17	15.07	15.70	16.25
	Profile type	I	II	III	III
245	Flow rate (m^3 h^{-1})	2.00	2.43	3.22	3.66
	Radius of throw (m)	13.17	16.14	16.28	17.23
	Profile type	I	II	III	III
294	Flow rate (m^3 h^{-1})	2.19	2.66	3.53	4.01
	Radius of throw (m)	14.28	16.33	17.11	17.25
	Profile type	I	II	III	III
343	Flow rate (m^3 h^{-1})	2.34	2.87	3.81	4.33
	Radius of throw (m)	13.50	16.18	17.33	17.72
	Profile type	I	II	III	III

The three geometric shapes assumed by the dimensionless water distribution radial curves of NY30 sprinkler are represented in Figure 4. In accordance with the hypothetical water distribution radial curves classified by Christiansen (1942), the radial legs presented in Figure 4 have a tendency

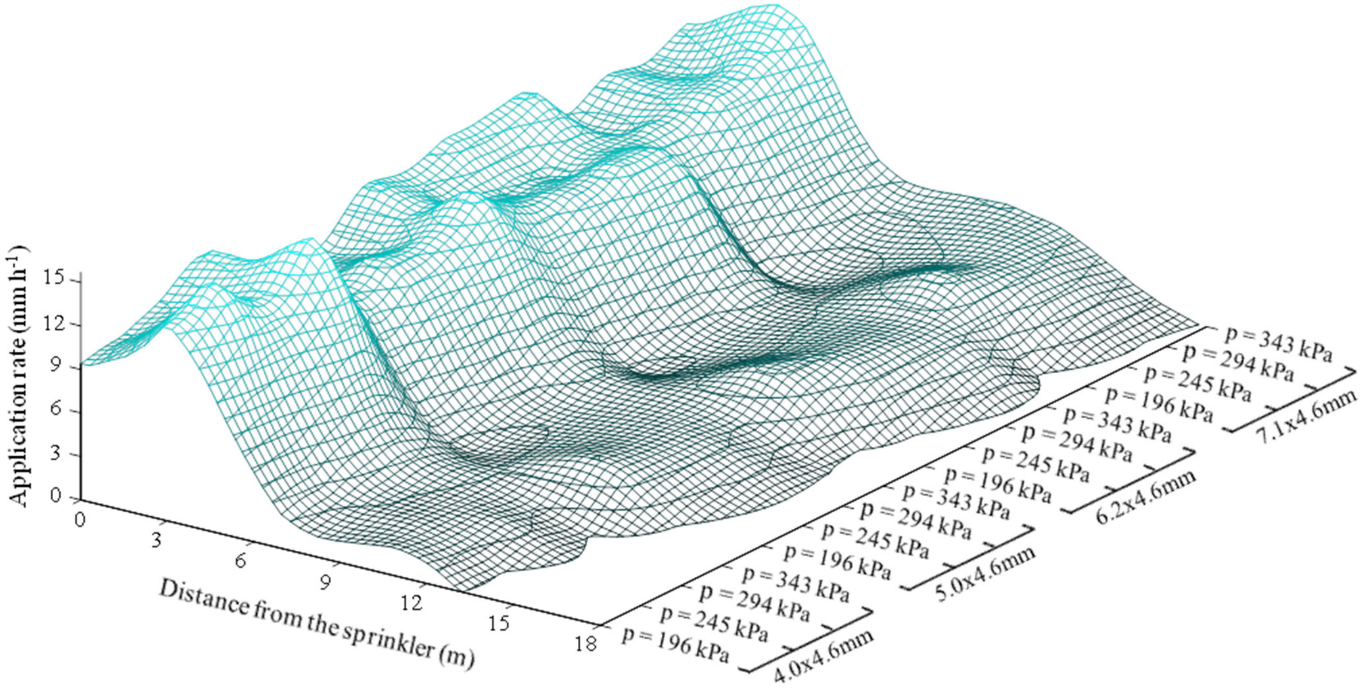

Figure 2. Representation of radial legs got in the trials for different working pressures and nozzle diameters

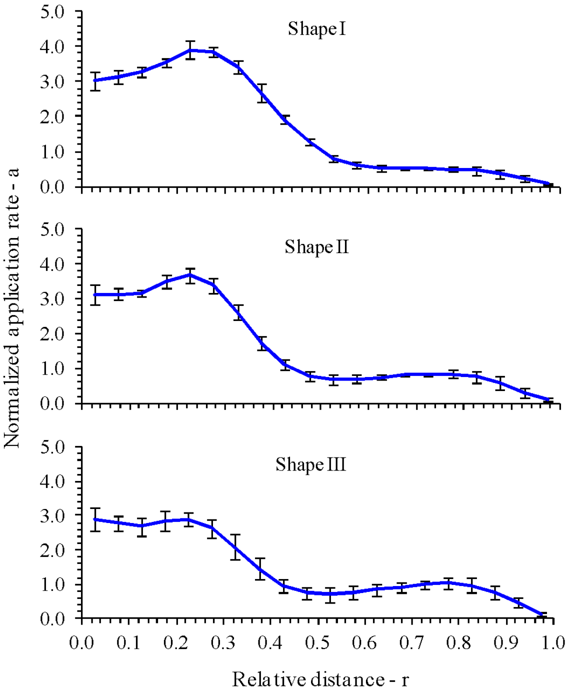

Figure 4. Typical normalized radial legs of Agropolo NY30 sprinkler. The vertical bars represent an equivalent variation of a ± 1 RMS

for triangular geometric shape (Christiansen's radial leg type B). This sort of water distribution radial curve is peculiar of small- and medium-size sprinklers working with two nozzles (Keller & Bliesner, 1990).

The typical geometric shapes of the NY30 sprinkler (Figure 4) and Christiansen's triangular radial profile, according to the sprinkler working conditions shown in Table 1, were used to simulate water distribution from solid set sprinkler systems. The outcomes of water distribution simulations were employed for drawing contour maps from Christiansen's coefficient of uniformity - CU (Figures 5 and 6) with spacing between sprinkler set out as a function of the wetted sprinkler diameter (WD). In the sprinkler uniformity response surfaces, the dotted lines, obtained using Eqs. 2 and 3, identify the boundary of full water coverage among sprinklers, above these lines, geometrically, a portion of wetted area remains uncovered.

The accuracy of Christiansen's coefficients of Uniformity for rectangular spacings (Figure 5), obtained by the developed computer program, is revealed by the symmetry around an imaginary 45° diagonal line through the origin, which set out the square spacings (Sl = Sm). The precision of CU data obtained by this software has also been validated from the response surfaces derived from Christiansen's radial profile

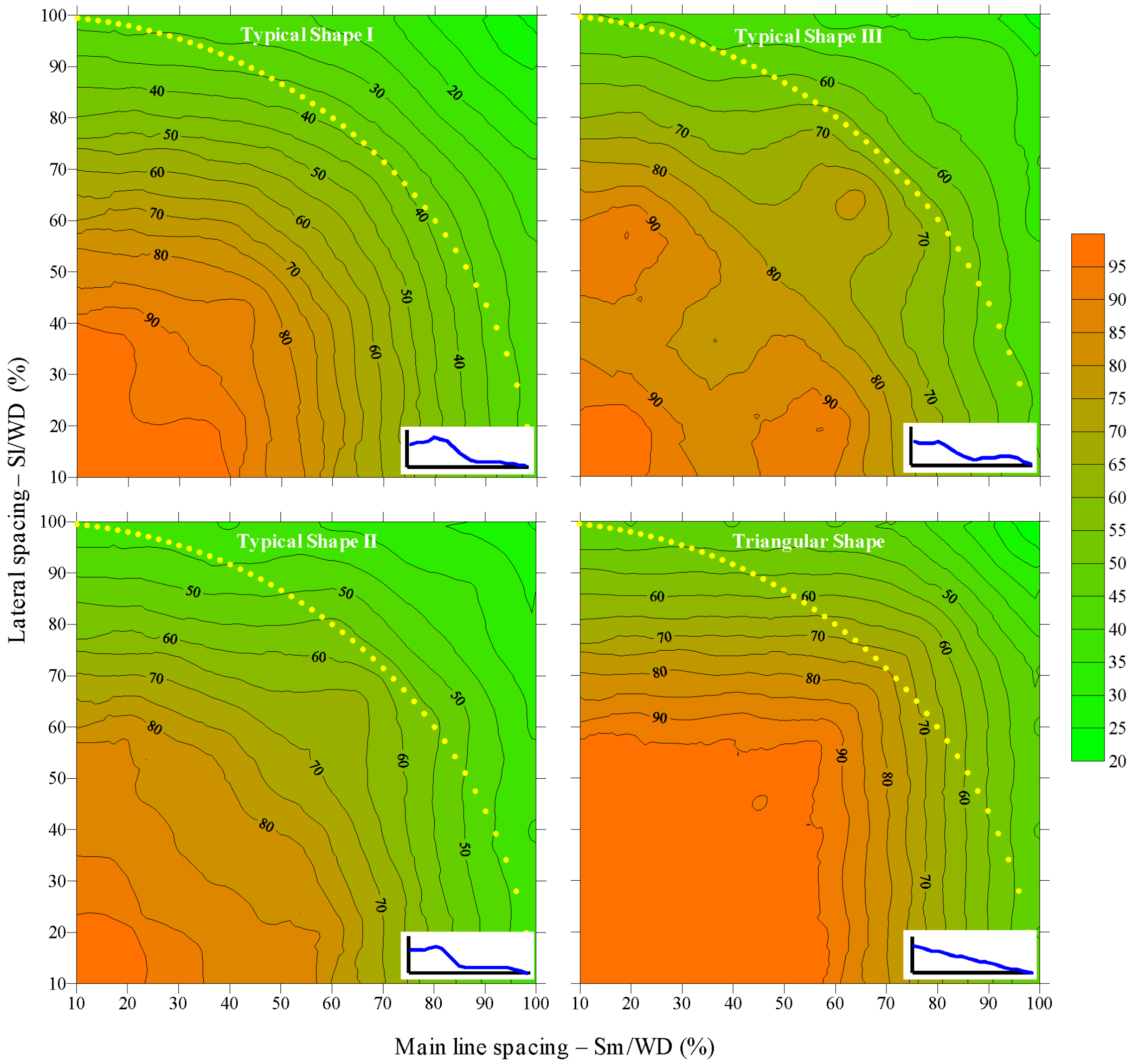

Figure 5. Christiansen's coefficients of Uniformity - CU (%) for rectangular spacings, simulated from the three typical geometric shapes of Agropolo NY30 sprinkler and the hypothetical Christiansen's radial leg B

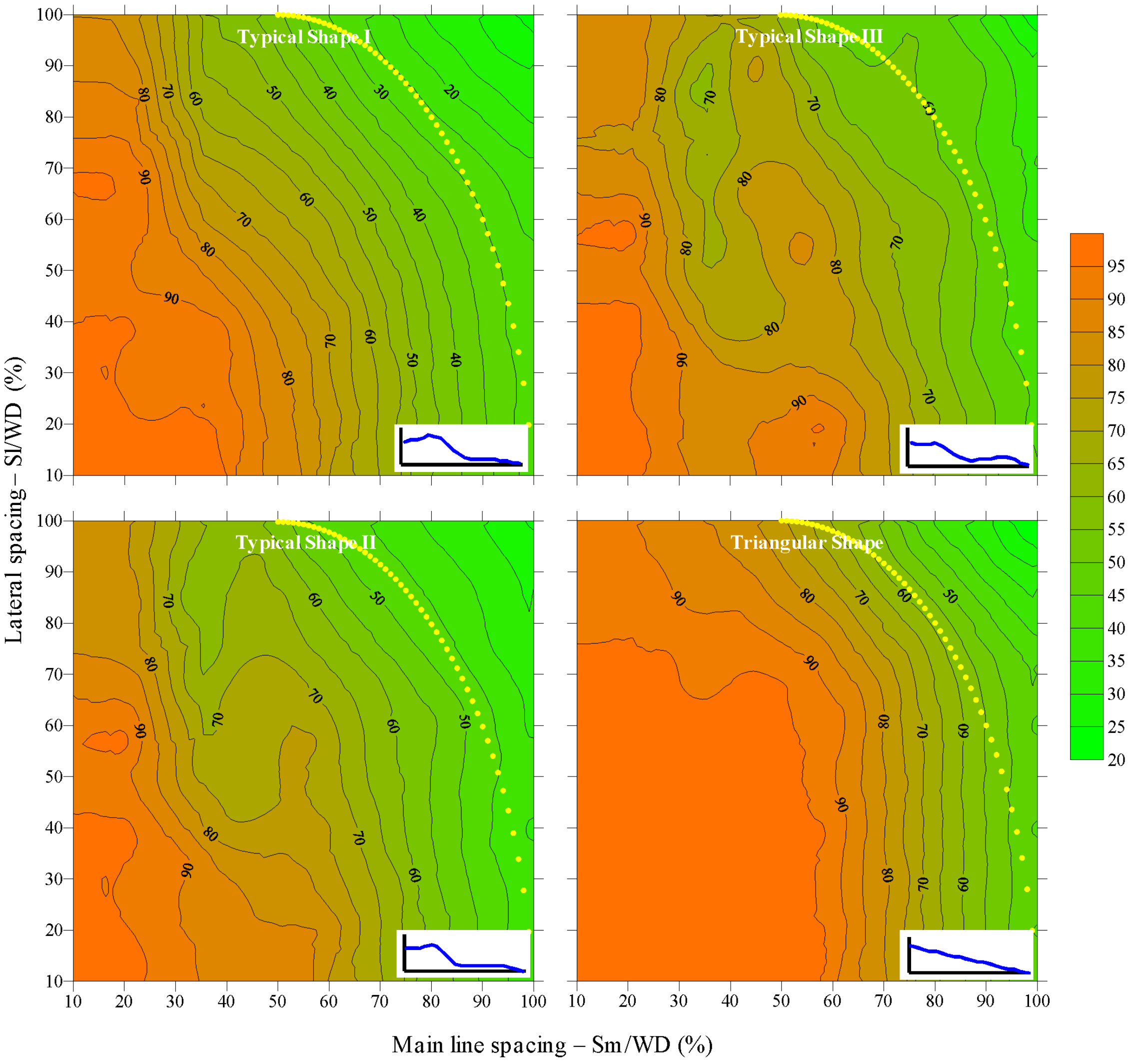

Figure 6. Christiansen's coefficients of Uniformity - CU (%) for triangular spacings, simulated from the three typical geometric shapes of Agropolo NY30 sprinkler and the hypothetical Christiansen's radial leg B (triangular)

type B (triangular) for rectangular (Figure 5) and triangular (Figure 6) layouts. In these two figures, the contour lines obtained from the hypothetical triangular radial profile have a close similarity to those obtained by Chen & Wallender (1984) for the same sort of radial profile. As pointed out by these authors, using sprinkler uniformity response surfaces to simplify the process of comparing spacing alternatives, even on irregular areas of the surface, it is relatively easy to pair uniformities and spacings.

Although the geometric shapes of the NY30 sprinkler dimensionless radial profiles (Figure 4) resemble a triangular geometric shape, it was observed that sprinkler spacings shorter than those recommended by Christiansen (Keller & Bliesner, 1990), for the typical radial profile B, resulted in CU values greater than 80% for rectangular (Figure 5) and triangular (Figure 6) layouts. Keller & Bliesner (1990) also mentioned that highest uniformities are obtained at spacings of 40% or less of the wetted diameter, but these close spacings increase both precipitation rate and costs.

Spacings between sprinklers (Figure 5), as function of wetted diameter, which result in suitable CU values (CU > 80%), are given by square spacings shorter than 45% of WD for radial profile I and II, 50% of WD for radial profile III and 65% of WD for Christiansen's triangular radial profile. However, for rectangular spacings, greater CU values were obtained by sprinkler spacings shorter than 40 x 50% of WD for radial profile I and II, 40 x 60% of WD for radial profile III and 40 to 60 x 65% of WD for Christiansen' triangular radial profile.

Spacing sprinklers in triangular layouts (Figure 6), equilateral spacings closer than 66% of WD, as indicated by Keller & Bliesner (1990) for Christiansen's radial profile type B, result in high CU values. For the geometric shape I of the NY30 sprinkler, this spacing is 45% of WD and 50% of WD for geometric shapes II and III; however, in the sprinkler uniformity response surfaces of these last two typical profiles, around the spacings pointed out, there are uniformity zones that could lead to high CU values, as well as to small ones.

Zhang et al. (2013) found that sprinkler spacing variations have larger influence on water distribution uniformity than the working pressure variations in the lateral lines. This outcome has been evidenced in this work, regarding to the same nozzle diameter combination, the geometric shape of the dimensionless radial profiles of the NY30 sprinkler had negligible differences, which could result in small variation in the CU values; however, varying spacings between sprinklers culminate in large variation (Figure 5 and 6).

Conclusions

1. Three normalized typical geometric shapes are sufficient for representing the water distribution radial curves of the NY30 sprinkler set out in the tests.

2. The superiority of triangular spacings was not noticeable in relation to rectangular spacings.

3. Sprinkler spacings around the radius of throw provide acceptable water distribution uniformities.

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