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Influence of sprinkler operational parameters on the cost of conventional sprinkler irrigation systems[1]

Influência dos parâmetros operacionais de aspersores no custo de sistemas de irrigação por aspersão convencional

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ABSTRACT - The criterion used to select sprinklers in a conventional sprinkler irrigation system is based, in a first instance, on the water application intensity, which must be lower than or equal to the soil's basic infiltration velocity. However, other operating factors must be considered in the selection of sprinklers because these factors can influence the total annual cost of the irrigation system. Therefore, this paper aimed to evaluate the influence of the operation parameters of different commercial models of sprinklers on the cost of a conventional semifixed sprinkler irrigation system. The simulated variables were the operating pressure, the spacing between sprinklers, and the water application intensity of different sprinkler models available in the Brazilian market. We found that the operating pressure and flow variables most influenced the total annual cost of a conventional sprinkler irrigation system and must be considered in the project cost analysis so that the sprinklers that best suit the project can be selected.

Key words: Energy efficiency. Economic analysis. Design parameters.

RESUMO - Os critérios para a seleção de aspersores na irrigação por aspersão convencional baseiam-se, em primeira instância, na intensidade de aplicação do aspersor, que deve ser menor ou igual à velocidade de infiltração básica do solo. Porém, outros fatores relacionados às características de operação do aspersor devem ser considerados na seleção do aspersor, pois suas definições podem influenciar no custo total anual do sistema de irrigação. Sendo assim, este trabalho teve por objetivo avaliar a influência dos parâmetros operacionais de diferentes modelos comerciais de aspersores nos custos de um projeto de sistema de irrigação por aspersão convencional semifixo. As variáveis simuladas foram a pressão de serviço, o espaçamento entre aspersores, e a intensidade de aplicação de diferentes modelos de aspersores disponíveis no mercado brasileiro. Observou-se que a pressão de serviço e a vazão são as variáveis que mais influenciaram no custo total anual do sistema de irrigação por aspersão convencional, devendo-se levar em consideração na análise de custos do projeto para selecionar o aspersor que melhor se adeque ao projeto.

Palavras-chave: Eficiência energética. Análise econômica. Parâmetros do projeto.

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INTRODUCTION

Irrigation is a key practice in agriculture because it ensures production regardless of rainfall. However, irrigation technology is associated with the intensive use of inputs and requires expensive investments, which makes the economic analysis of the components of irrigation systems important (PEREIRA *et al.*, 2015). Oliveira *et al.* (2010) and Vieira *et al.* (2011), state that the choice of irrigation method should consider both the technical aspects and the economic aspects. In this sense, Bertossi *et al.* (2013), state that such analysis is essential for the economic success of an irrigation system.

Almeida *et al*. (2016), emphasize that the cost of implementing an irrigation system can be predicted through the analysis of the costs of its components. Frigo *et al.* (2013), stated that sprinklers are one of the main components of a conventional sprinkler system, especially because an irrigation system is designed around the operating characteristics of the sprinklers, which determine the head loss, the diameter of the tubing, and the choice of the pump, impacting the fixed and variable costs of the project.

The technical criterion for choosing sprinklers in conventional sprinkler irrigation projects is based on application intensities less than or equal to the soil's basic infiltration rate to reduce the possibility of losses from surface runoff (CALHEIROS *et al.*, 2009; MANTOVANI; BERNARDO; PALARETTI, 2009). However, according to Carvalho *et al.* (2005) and Perroni *et al.* (2015), an irrigation system, despite being hydraulically well designed, may not be economically viable because factors such as energy cost can act as a limiting factor in irrigated agriculture, highlighting the importance of more in-depth economic studies on the selection of its components. Perroni, Carvalho and Faria (2011) noted that the components of an irrigation system can contribute to the costs of an irrigation project.

Holzapfel *et al.* (2007), state that the economic aspects should receive as much weight in the selection of sprinklers as the technical aspects. In this sense, this study aimed to evaluate the influence of the operation parameters of different commercial models of sprinklers on the costs of conventional semifixed sprinkler irrigation systems.

MATERIAL AND METHODS

This study consisted of the application of a methodology to evaluate the effects of the operational characteristics of sprinklers on the costs of a conventional semifixed sprinkler irrigation system. Simulations were performed using the operational characteristics of several models of sprinklers available in the Brazilian market, namely, the operating pressure (OP), spacing between sprinklers (S_{spr}), and water application intensity (AI). The costs and the correlation matrices were plotted using Pearson's correlation coefficients (r) at 5% probability to determine the variable that most affects the costs. Agropolo NY-30 2849-BV, Fabrimar MID, and ECO A232; NaanDanJain 5022SD, 234B, and 6025SD; and RainBird 35A-TNT and 65PJADJ-TNT sprinklers were used.

The following characteristics were kept constant: bean crop: effective root depth of 400 mm - z, 0.5 availability factor - f, and maximum crop coefficient - kc equal to 1.1 (FAO, 56); soil: moisture contents of 0.34 cm^3 cm^{-3} (θ_{FC}) and 0.17 cm^3 cm^{-3} (θ_{PWP}) at field capacity and permanent wilting point, respectively, and 10.5 mm h^{-1} basic infiltration rate (BIR); climate: reference evapotranspiration of 4.6 mm h^{-1}; and project area: total area of 13.08 ha, 150 m wide and 436 m long, with a 2% slope in the length direction. Additionally, the following parameters were defined for the irrigation system: sprinklers at a height of one meter and a maximum working day (J) of 14 hours per day and a change and assembly time (T_m) of 45 minutes for changing the position of the lateral lines.

To evaluate the effect of the OP of the sprinkler on the cost of the irrigation system, 2 OP scenarios were used. In each case, the sprinkler flow rate and spacing were fixed; however, the OP differed. In scenario 1, sprinklers were grouped with a 3.2 m^3 h^{-1} flow rate and 18 x 18 m spacing. In scenario 2, sprinklers were grouped with a 4.38 m^3 h^{-1} flow rate and 24 x 24 m spacing.

To evaluate the effect of S_{spr} on the project cost, the emitters were grouped into 4 scenarios, in which the OP and AI were fixed with varying spacing. In scenario 1, OP of 20 mca of and AI of 7.4 mm h^{-1} were considered. In scenario 2, OP of 25 mca and AI of 8.4 mm h^{-1} were considered, while in scenario 3, OP of 30 mca and AI of 7.4 mm h^{-1} were used. Finally, in scenario 4, OP of 30 mca and AI of 7.8 mm h^{-1} were adopted.

To evaluate the effect of the change in rainfall intensity on the project costs, the sprinklers were grouped into 2 scenarios, keeping the S_{spr} and the OP fixed and varying the AI. In scenario 1, sprinklers with OP of 30 mca and 18 x 18 m spacing were used, and in scenario 2, sprinklers with OP of 40 mca and 24 x 24 m spacing were used.

In all the sprinklers selected in the evaluation, the water AI was lower than the soil's BIR. Additionally, in the design of the projects, the highest S_{spr} recommended by the manufacturer was adopted, aligned in the direction of the main line, which was installed in the direction of the slope of the terrain, keeping the lateral lines level.

The actual available water in the soil was calculated using Equation 1, and the irrigation frequency was calculated using Equation 2.

$$AAW = (\theta_{FC} - \theta_{PWP}) \,.\, z \,.\, f \tag{1}$$

where AAW is the actual available water (mm); θ_{FC} is the moisture at field capacity (cm^3 cm^{-3}); θ_{PWP} is the moisture at the permanent wilting point (cm^3 cm^{-3}); z is the root depth (mm); and f is the soil water availability factor (decimal).

$$IF = \frac{AAW}{ETc} \tag{2}$$

where IF is the irrigation frequency (days) and ETc is the evapotranspiration of the crop (mm.day^{-1}).

The net irrigation depth (NID) was calculated using Equation 3, and the gross irrigation depth was calculated using Equation 4. An 85% efficiency rate of the irrigation system was considered (MANTOVANI; BERNARDO; PALARETTI, 2009).

$$NID = ETc \,.\, IF \tag{3}$$

$$GID = \frac{NID}{Ef} \tag{4}$$

where GID is the gross irrigation depth (mm) and Ef is the efficiency of the irrigation system (decimal).

The time of an irrigation event was calculated using Equation 5, and the monthly irrigation time was estimated using Equation 6. The number of monthly irrigations was estimated using Equation 7.

$$T_i = \frac{GID}{AI} \tag{5}$$

$$T = \frac{GID}{AI}.N_i \tag{6}$$

$$N_i = \frac{30}{IF} \tag{7}$$

where T_i is the irrigation time of an event (h); AI is the sprinkler application intensity (mm.h^{-1}); T is the monthly irrigation time (h); and Ni is the number of monthly irrigations (dimensionless).

To estimate the total number of sprinklers for the irrigation project, the number of sprinklers was multiplied for each lateral line (Equation 8) and the number of lateral lines, obtaining Equation 9.

$$NS_{lx} = \frac{L_L}{S_{spr}} \tag{8}$$

where L is the length of the lateral line (m) and S_{spr} is the spacing between sprinklers (m).

$$N_{spr} = NL_{lat} \,.\, NS_{lat} \tag{9}$$

where N_{spr} is the total number of sprinklers (dimensionless); NS_{lat} is the number of sprinklers in the lateral line (dimensionless); and NL_{lat} is the number of lateral lines (dimensionless), which was calculated using Equation 10.

$$NL_{lat} = \frac{NIPLD}{NIPD} \tag{10}$$

where NIPLD is the number of irrigated positions per lateral line, per day (dimensionless), calculated by Equation 11, and NIPD is the total number of positions to be irrigated per day (dimensionless), calculated by Equation 12.

$$NIPLD = \frac{j}{T_i + T_m} \tag{11}$$

where J is the working hours (h) and T_m is the time of change in the lateral line positions (h).

$$NIPD = \frac{TNP}{IF - 1} \tag{12}$$

where TNP is the total number of positions in the main line (dimensionless) and IF is the irrigation frequency (days).

The TNP was estimated using Equation 13. To calculate the flow rate of the lateral line, Equation 14 was used.

$$TNP = \frac{L_p}{S_{lat}} \tag{13}$$

where L_p is the length of the area (m) and S_{lat} is the spacing between lateral lines (m).

$$Q_L = q \,.\, NS_{lat} \tag{14}$$

where Q_L is the flow rate of the lateral line (m^3 h^{-1}) and q is the flow rate of the sprinkler (m^3 h^{-1}).

The flow rate of the irrigation system was determined using Equations 15 and 16. Equation 16 was obtained by replacing NS_{lat} and NL_{lat} with Equations 8 and 10, respectively.

$$Q_p = q \,.\, NS_{lat} \,.\, NL_{lat} \tag{15}$$

$$Q_p = \frac{q.J.L_L.L_p}{IP.S_{spr}.S_{lat}.(\frac{GID}{AI} + T_m)} \tag{16}$$

where Q_p is the flow rate of the system (m^3 h^{-1}); IP is the irrigation period (days); and L_p is the length of the main line (m).

For the calculation of the maximum allowable head loss, the criterion adopted was that it should not exceed 20% of the OP of the sprinkler (Equation 17), as shown by Bernardo, Soares, and Mantovani (2008).

$$hf_{mca} = 0.2 \,.\, OP \pm \Delta Z \tag{17}$$

where OP is the operating pressure of the sprinkler (mca) and ΔZ is the terrain slope in the direction of the lateral line (m), which was assumed to be 0.

PVC tubes were adopted in the estimation of the diameter of the lateral line; Equation 18 was initially used, and Equation 19 was obtained by substitution.

$$D_L = \left[\frac{10.64.L_L.\left(\frac{Q_L}{3600}\right)^{1.852}}{C^{1.852}.(0.2.OP \pm \Delta Z)}.Fa \right]^{1/4.87} \tag{18}$$

$$DL = \left[\frac{10.64.L_L \left(\frac{q.L_L}{3600.S_{spr}} \right)^{1.852}}{C^{1.852}.(0.2.OP \pm \Delta Z)} ..Fa \right]^{1/4.87} \quad (19)$$

where D_L is the diameter of the lateral line (m); hf_{max} is the maximum head loss allowed in the lateral line (mca); Fa is Christiansen's correction factor for head loss modified by Scaloppi (decimal); and C is the Hazen-Williams coefficient of the material (dimensionless).

Christiansen's correction factor modified by Scaloppi was calculated using Equation 20 (FRIZZONE *et al.*, 2012).

$$Fa = \frac{(NS_{lat}.F) + X - 1}{NS_{lat} + X - 1} \quad (20)$$

where NS_{lat} is the number of sprinklers in the lateral line (dimensionless); X is the ratio between the distance of the first sprinkler and the regular spacing between the sprinklers (decimal); and F is Christiansen's correction factor for head loss (decimal), which was calculated by Equation 21 (MIRANDA; ROSAL; LIMA, 2018).

$$F = \frac{1}{m+1} + \frac{1}{2.NS_{lat}} + \frac{\sqrt{m-1}}{6.(NS_{lat})^2} \quad (21)$$

where m is the flow rate exponent in the head loss equation (dimensionless).

Equation 22 was used for the actual head loss of the lateral line. Equation 14 was substituted into Equation 22 so that the head loss was presented as a function of the characteristics of the sprinkler, resulting in Equation 23.

$$hf_{lat} = \frac{10.64.L_L \left(\frac{QL}{3600} \right)^{1.852}}{C^{1.852}.D_L^{4.87}}.Fa \quad (22)$$

$$hf_{lat} = \frac{10.64.L_L \left(\frac{q.L_L}{3600.S_{spr}} \right)^{1.852}}{C^{1.852}.D_L^{4.87}}.Fa \quad (23)$$

where hf_{lat} is the head loss in the lateral line (mca) and D_L is the diameter of the lateral line.

To calculate the pressure, at the beginning of the lateral line, Equation 24 was first used, followed by substitution into Equation 23, yielding Equation 25.

$$Pin = op + Aa + 0.75.\ hf_{lat} \pm 0.5\ \Delta Z \quad (24)$$

$$Pin = OP + Aa + 0.75. \left[\frac{10.64.L_L \left(\frac{q.L_L}{3600.S_{spr}} \right)^{1.852}}{C^{1.852}.D_L^{4.87}}.Fa \right] \pm 0.5.\Delta Z \quad (25)$$

where Pin is the pressure at the beginning of the lateral line (mca); hf_{lat} is the head loss in the lateral line (mca); Aa is the height of the sprinkler (m); and ΔZ is the slope of the lateral line (m).

The diameter of the main line was calculated, establishing a maximum flow velocity of 1.5 ms^{-1}, which, according to Perroni *et al.* (2015), is within the economic flow velocity range. Equations 26 and 27 were used for head loss in the main line.

$$hf_{LP} = \frac{10.64.L_p.(Q_p/3600)^{1.852}}{C^{1.852}.D_p^{4.87}} \quad (26)$$

$$hf_{LP} = \frac{10.64.L_p. \left[\frac{q.J.L_L.L_p}{3600.IP.S_{spr}.S_{lat}.\left(\frac{GID}{AI} + T_m \right)} \right]^{1.852}}{C^{1.852}.D_p^{4.87}} \quad (27)$$

Where L_p is the length of the main line (m) and D_p is the diameter of the main line (m).

Equation 26 was used to calculate the head loss in the main line and suction line, but the length and diameter were replaced with their respective values. The localized head losses were considered to be 5% of the sum of all head losses that occurred in the irrigation system (MANTOVANI; BERNARDO; PALARETTI, 2009). The system head was calculated using Equations 28 and 29.

$$Hman = pin + hf_{total} + Hg_T + hf_{loc} \quad (28)$$

$$hman = OP + Aa + 0.75. \left[\frac{10.64.L_L \left(\frac{q.L_L}{3600.S_{spr}} \right)^{1.852}}{C^{1.852}.D_L^{4.87}}.Fa \right] \pm 0.5.\Delta Z + hf_{total} + Hg_T + hf_{loc} \quad (29)$$

where Hg_T is the local head loss (mca); hf_{total} is total head loss (suction line, main line, and pressurized line) (mca); and hf_{loc} is the localized head loss (mca).

To calculate the absorbed power, the motor and pump efficiencies were considered to be 90 and 70%, respectively, and Equations 30 and 31 were used, respectively.

$$P_{abs} = \frac{Q_p.Hman}{270.n_B.n_M} \quad (30)$$

$$P_{abs} = \frac{q.J.L_L.L_p}{270.n_p.PI.S_{spr}.S_{lat}.\left(\frac{GID}{AI} + T_m \right)}.Hman \quad (31)$$

where P_{abs} is the absorbed power (cv) and n_p is the pump efficiency (dimensionless) (decimal).

In the calculation of costs, 10 years of amortization were considered, according to Holzapfel *et al.* (2007). In addition, a 12% interest rate was used, which is close to the values adopted by Oliveira *et al.* (2010) and Zocoler *et al.* (2011). Equation 32 was used to calculate the annual fixed cost.

$$AFC = I\ .\ CRF \quad (32)$$

where AFC is the annual fixed cost (R$); I is the investment (R$); and CRF is the capital recovery factor (R$), which was calculated using Equation 33 (ZOCOLER *et al.*, 2011).

$$CRF = \frac{(i+1)^T.i}{(i+1)^T - 1} \quad (33)$$

where i is the annual interest rate (decimal) and n is the amortization period (years).

The investment (I) was determined by the sum of the costs with the pumping system, tubing, sprinklers, and pump. Equation 34, recommended by Carvalho (2014), was used to calculate the cost of the pressurized system. The cost with tubing was obtained using Equation 35.

$$C_{ps} = 3.5 \cdot e^{[3.75 + \ln Qp + 0.083 \cdot (\ln Hman)2]} \quad (34)$$

where C_{ps} is the cost of the pumping system (R$).

$$C_{tub} = \frac{L}{6} . P_{tub} \quad (35)$$

where C_{tub} is the cost of tubing (R$); L is the length of the tube (m); and P_{tub} is the tube price (R$ tube^{-1}).

The calculation of the annual cost of electricity considered a tax of 0.26811 R$ kWh^{-1} for electric power consumption and R$ 11.05 per kW for electric power demand, which are the taxes used by the Companhia Energética de Minas Gerais (Minas Gerais Power Company - CEMIG) as the green tax flag. According to CEMIG, these are the taxes used for medium-sized consumers (with demand less than 500 kW). To calculate the cost of electricity, Equation 36, presented by Carvalho (2014), was used, and Equation 37 was obtained through substitutions.

$$EC = 12 \cdot (P_{ist} \cdot DT + P_{abs} \cdot T \cdot ET) \quad (36)$$

$$EC = 12 \left[Pist.DT + \frac{q.J.L_L.L_p}{270.n_p.IP.S_{spr}.S_{lat}\left(\frac{GID}{AI} + T_m\right)} .Hman.T.ET \right] \quad (37)$$

where EC is the electricity cost (R$ year^{-1}); P_{ist} is the power to be installed (kW); DT is the power demand tax (R$); P_{abs} is the power absorbed by the electric motor of the electric grid (kW); T is the system operating time per month (hour); and ET is the electricity tax (R$).

Finally, the total annual cost (TAC) was determined using Equation 38, and Equation 43 was obtained and through substitutions.

$$TAC = AFC + EC \quad (38)$$

$$TAC = AFC + 12 \left[P_{ist}.DT + \frac{q.J.L_L.L_p}{270.n_p.IP.S_{spr}.S_{lat}\left(\frac{GID}{AI} + T_m\right)} .Hman.T.ET \right] \quad (39)$$

RESULTS AND DISCUSSION

The results for AAW, GID, NID, and IF were 34 mm, 40 mm, 34 mm, and 7 days, respectively, and these values remained constant because the soil, climate, and crop data did not vary for any sprinklers analyzed.

Influence of the rainfall intensity

Table 1 shows that the TAC varied when AI varied and the S_{spr} and OP were fixed. This variation in cost occurs because sprinklers with low AI take longer to reach the desired GID, which leads to greater consumption of electricity. In scenario 1 (Table 1), the first and second sprinklers showed a 36% increase in AI, resulting in a 27% reduction in AFC; this reduction was due to the sprinkler flow rate not changing significantly during the increase in AI. In contrast, in scenario 2 (Table 1), a 36% increase in AI resulted in a 20% cost increase, which was influenced by the increase in the sprinkler flow rate. Holzapfel *et al.* (2007) also found that the cost of the irrigation system increased with increasing AI, noting that the flow rate of the sprinklers was the factor with the greatest effect. In addition, Rodrigues *et al.* (2019) found that sprinklers with higher AI have lower costs and greater benefits than those with lower AI.

Table 2 shows that the correlation coefficients between the AI and the other variables were almost all negative. This means that with constant OP and S_{spr}, as

Table 1 - Effect of sprinkler application intensity on the total annual cost of the conventional sprinkler irrigation system

Scenario	OP (mca)	q (m^3 h^{-1})	S_{spr} (m)	AI (mm h$_{-1}$)	NS_{lat}	NL_{lat}	EC (R$ year$_{-1}$)	AFC (R$)	TAC (R$)
1	30	1.24	18x18	3.8	8	4	2,166.97	9,608.57	11,775.54
	30	1.67	18x18	5.16	8	2	1,251.44	6,978.41	8,229.85
	30	2.2	18x18	6.8	8	2	1,497.76	7,765.55	9,263.31
	30	2.25	18x18	6.97	8	2	1,520.36	7,840.81	9,361.17
	30	2.44	18x18	7.5	8	2	1,616.10	8,403.78	10,019.88
	30	2.62	18x18	7	8	2	1,787.56	8,128.53	9,916.09
	30	2.95	18x18	9.1	8	1	909.9	5,991.66	6,901.56
2	40	2.90	24x24	5.00	6	1	1,010.92	5,641.17	6,652.09
	40	4.10	24x24	7.10	6	1	1,261.35	6,400.59	7,661.94
	40	3.90	24x24	6.80	6	1	1,215.48	6,272.65	7,488.13

AI increases, the costs decrease. To increase the AI to complete the irrigation within the desired time, the sprinkler flow rate must be increased because there is a positive correlation of 0.52 between the sprinkler flow rate and its AI. The correlation between AI and EC was negative, with a value of -0.48 (Table 2), which shows that when OP and S_{spr} are kept constant, as AI increases, the EC decreases; this reduction in EC is influenced by the irrigation time. According to Rodrigues *et al.* (2019), sprinklers with high AI generally take less time to complete irrigation. The correlation between AI and NL_{lat} was -0.59; therefore, an increase in AI results in a slight decrease in NL_{lat}. The correlation with NS_{lat} was 0.1, which means that a change in AI has no significant effects on NS_{lat}.

Influence of the operating pressure of the sprinkler

Table 3 shows that an increase in OP led to a slight increase in the investment and in the EC, AFC, and TAC. Miranda, Rosal and Lima (2018) showed that emitters with higher OP show greater head loss, which increases the pump head and power. In addition, Perroni *et al.* (2015) found that head loss has a strong influence on the EC, and as OP increases, the diameter of the tubes increases, which affects the AFC because larger diameter tubes are usually more expensive. In scenario 1 (Table 3), an increase of 10% in the OP resulted in increases of 13% in the EC, 3% in the AFC, 3% in the investment, and 4% in the TAC, which demonstrates that EC is the main variable that contributes to the increase in the cost of the irrigation system with variation in OP. Similar results were found by Holzapfel *et al.* (2007), who observed that a 50% increase in OP led to a 50% increase in variable costs, demonstrating that OP is a relevant parameter in variable costs. In addition, Mantovani, Bernardo and Palaretti (2009) stated that the calculation of the maximum head loss of the lateral line depends mainly on the OP, which justifies the effect of the OP on the increase in cost.

Table 2 - Correlation matrix between sprinkler application intensity and other variables

	OP	q	Sspr	AI	NS_{lat}	NL_{lat}	EC	AFC	TAC
OP	1								
q	0.778	1							
S_{spr}	n	0.778	1						
AI	-0.103	0.519	-0.103*	1					
NS_{lat}	n	-0.778	-1	0.103*	1				
NL_{lat}	-0.601	-0.829	-0.601	-0.595	0.601	1			
EC	-0.480	-0.582	-0.480*	-0.437*	0.480*	0.896	1		
AFC	-0.659	-0.696	-0.659	-0.335*	0.659	0.917	0.964	1	
TAC	-0.622	-0.674	-0.622	-0.361*	0.622	0.918	0.978	0.998	1

n: no correlation; *: nonsignificant correlation

Table 3 - Effect of the operating pressure of the sprinkler on the total annual cost of the conventional sprinkler irrigation system

Scenario	OP (mca)	q (m^3 h^{-1})	Sspr (m)	AI (mm h^{-1})	NS_{lat}	NL_{lat}	EC (R$ $year^{-1}$)	AFC (R$)	TAC (R$)
	20	3.2	18x18	9.9	8	1	753.78	5,846.05	6,599.83
	25	3.2	18x18	9.9	8	1	861.20	6,014.02	6,875.22
	30	3.2	18x18	9.9	8	1	968.62	6,179.65	7,148.27
1	35	3.2	18x18	9.9	8	1	1,076.04	6,343.43	7,419.47
	40	3.2	18x18	9.9	8	1	1,183.46	6,505.74	7,689.20
	45	3.2	18x18	9.9	8	1	1,290.88	6,666.88	7,957.76
	50	3.2	18x18	9.9	8	1	1,398.30	6,827.06	8,225.37
	40	4.38	24x24	7.6	6	1	1,320.75	6,580.73	7,901.48
2	45	4.38	24x24	7.6	6	1	1,440.32	6,746.11	8,186.44
	50	4.38	24x24	7.6	6	1	1,559.90	6,910.53	8,470.42

Table 4 shows that there is a very strong correlation of 0.97 between OP and EC, which suggests that when OP increases, EC increases by almost the same proportion. This was previously shown by Mantovani, Bernardo and Palaretti (2009), who reported that the calculation of the maximum head loss of the lateral line depends on the OP. In addition, Perroni *et al.* (2015), found that the head loss has a strong effect on the EC. The OP and AFC correlation was 0.99, so as OP increased, the AFC increased by the same proportion. Additionally, Table 4 shows a correlation of 0.55 between the flow rate of the sprinkler and EC, which means that the flow rate of the sprinkler also affects the increase in the TAC.

Influence of spacing between sprinklers

An increase in S_{spr} resulted in an increase in the TAC for scenarios 1, 2, and 3 (Table 5); for scenario 4, the opposite occurred. This is due to the AFC and EC, because to keep the AI fixed, the emitter flow rate had to be increased to reach the GID within the desired time. A 50% increase in S_{spr} resulted in decreases of approximately 10, 12, and 33% in AFC in scenarios 1, 2, and 3, respectively, which shows that the AFC is influenced by S_{spr}. The results corroborate the conclusions of Perroni, Carvalho and Faria (2011), who also observed that the cost of material varies as a function of the length of the tubing; however, this variation does not have much effect on the TAC.

In scenario 4 (Table 5), there was an increase in the TAC, but this was due to the increase in the flow rate of the sprinkler. To maintain the AI, it was necessary to select sprinklers with a higher flow rate, contributing to the increase in the EC. The results obtained are explained by Faria *et al.* (2012) and Campelo *et al*. (2014), who stated that the AI behaves in different ways with different spacings, affecting the operational costs.

There is a strong negative correlation between spacing and NS_{lat} or NL_{lat} (Table 7); thus, increasing the spacing between the sprinklers and between lateral lines results in a decrease in NS_{lat} and NL_{lat}, which affects the AFC. The correlation between NL_{lat} and AFC is 0.94 (Table 7); therefore, a small increase in NL_{lat} contributes to the decrease in AFC. Conversely, the correlation between NS_{lat} and AFC is 0.62, which is moderate, suggesting that the change in NS_{lat}, influenced by spacing, contributes to the increase in AFC; this also increases the TAC, but the increase is small. The correlation between the EC and the S_{spr} is -0.22; therefore, with constant OP and AI, a change in spacing does not have significant effects on the EC.

Table 4 - Correlation matrix between the operating pressure of the sprinkler and other

	OP	q	Sspr	AI	NS_{lat}	NL_{lat}	EC	AFC	TAC
OP	1								
q	0.331*	1							
S_{spr}	0.331*	n	1						
AI	-0.331*	n	n	1					
NS_{lat}	-0.331*	n	n	n	1				
NL_{lat}	n	n	n	n	n	1			
EC	0.970	0.551	0.551	-0.551	-0.551	n	1		
AFC	0.995	0.419*	0.419*	-0.419*	-0.419*	n	0.988	1	
TAC	0.987	0.476*	0.476*	-0.476*	-0.476*	n	0.996	0.998	1

n: no correlation; *: nonsignificant correlation

Table 6 - Effect of sprinkler spacing on the total annual cost of the conventional sprinkler irrigation system

Scenario	OP (mca)	q ($m^3 h^{-1}$)	S_{spr} (m)	AI (mm h^{-1})	NS_{lat}	NL_{lat}	EC (R$ $year^{-1}$)	AFC (R$)	TAC (R$)
1	20	1.06	12x12	7.4	12	3	1,221.55	8,552.30	9,773.85
	20	1.59	12x18	7.4	12	2	1,232.63	7,546.16	8,778.79
2	25	1.21	12x12	8.4	12	2	1,010.26	7,003.03	8,013.29
	25	2.72	18x18	8.4	8	1	760.3	5,679.20	6,439.49
3	30	1.56	12x18	7.4	12	2	1,551.22	7,975.18	9,526.41
	30	3.2	18x24	7.4	8	1	1,060.10	6,179.65	7,239.73
4	30	1.69	12x18	7.8	12	1	813.92	5,682.09	6,496.01
	30	3.36	18x24	7.8	8	1	1,097.15	6,300.85	7,398.00

Table 7 - Correlation matrix between spacing and other variables

	OP	q	S_{spr}	AI	NS_{lat}	NL_{lat}	EC	AFC	TAC
OP	1								
q	0.544	1							
S_{spr}	0.558	0.992	1						
AI	0.037*	0.077*	-0.045*	1					
NS_{lat}	-0.389*	-0.954	-0.924	-0.221*	1				
NL_{lat}	-0.704	-0.797	-0.761	-0.329*	0.696	1			
EC	-0.076*	-0.314*	-0.222*	-0.684	0.398*	0.588	1		
AFC	-0.551	-0.663	-0.599	-0.528	0.623	0.944	0.818	1	
TAC	-0.475*	-0.614	-0.543	-0.574	0.597	0.902	0.877	0.994	1

*: nonsignificant correlation

CONCLUSIONS

1. The higher the water AI is, the lower the electricity cost;
2. The greater the S_{spr} is, the lower the fixed cost and, therefore, the lower the total cost of the irrigation system;
3. Among all the variables related to sprinklers, the OP is the variable that most affects the cost of an irrigation system, especially the operating cost.

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