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Iterative calculation of local head loss coefficient of emitters in lateral lines[1]

Cálculo iterativo do coeficiente de perda de carga localizada de emissores em linhas laterais

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HIGHLIGHTS:

Local head loss data from emitters are scarce and iterative procedures can contribute to obtaining them.
The procedure proposed can be run from the input and output pressure of the lateral line.
Data obtained in the laboratory tests presented a slight difference from those estimated by the iterative procedure.

ABSTRACT: This study aimed to iteratively set the local head loss coefficient of the Naan® micro-sprinkler, model 7110 Hadar, installed in a lateral irrigation line. To evaluate the total head loss along the lateral line, tests were performed using a rigid PVC pipe with an inner diameter of 15.8 mm, 12 m in length, and 24 micro-sprinklers inserted along the pipe, regularly spaced 0.5 m. In the tests carried out for four micro-sprinkler nozzle diameters (0.9, 1.0, 1.1, and 1.2 mm) and six inlet pressure head values (5, 10, 15, 20, 25, and 30 m) in the line, the pressure head difference between inlet and outlet in the pipe and the discharge of each emitter along the pipe were measured. The head loss computation was performed by the step-by-step procedure, starting from the downstream end to the upstream end of the line; since varying the local head loss coefficient values iteratively, the total head loss measured in the tests was equal to the calculated. For the different working conditions of the inlet pressure head and the micro-sprinkler nozzle diameter, the local head loss coefficient had values from 0.051 to 0.169. Relating the discharge values measured and estimated along the lateral line, the confidence coefficient of 0.9991 was verified, and the calculation procedure was considered optimal.

Key words: pressure head, emitter discharge, nozzle diameter

RESUMO: Este estudo objetivou determinar iterativamente o coeficiente de perda de carga localizada do microaspersor Naan®, model 7110 Hadar, inserido em linha lateral de irrigação. Para avaliar a perda de carga total da linha lateral foram realizados ensaios empregando um tubo de PVC rígido com diâmetro interno de 15,8 mm, 12 m de comprimento e 24 microaspersores inseridos na linha, regularmente espaçados em 0,5 m. Nos ensaios, realizados para quatro diâmetros de bocais do microaspersor (0,9, 1,0, 1,1 e 1,2 mm) e seis pressões de entrada (5, 10, 15, 20, 25 e 30 m) na linha, foram determinados o diferencial de pressão entre o início e o final da tubulação e a vazão de cada emissor ao longo da tubulação. O cálculo da perda de carga foi realizado do último para o primeiro emissor, pelo método trecho a trecho, de modo que, variando iterativamente os valores de coeficiente de perda de carga localizada, a perda de carga total observada nos ensaios fosse igual à estimada. Para as diferentes condições operacionais de pressão de entrada e diâmetro de bocal do microaspersor, os coeficientes de perda de carga localizada apresentaram valores entre 0,051 a 0,169. Ao relacionar os valores de vazão mensurados e estimados ao longo da linha lateral verificou-se índice de confiança igual a 0,9991, classificando o procedimento de cálculo como ótimo.

Palavras-chave: pressão de entrada, vazão do emissor, diâmetro de bocal

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INTRODUCTION

The lower water and energy consumption obtained with micro-irrigation systems is associated with the point-source application of water through emitters, which works under low-pressures (Prado et al., 2014). However, to micro-irrigation systems achieve high efficiency, factors that affect water uniformity must be considered, such as emitter discharge variation due to head loss along the pipes.

Technical data of equipment and components used in irrigation and water supply systems are essential for sizing projects accurately (Gomes et al., 2010; Prado, 2015; Kotowski et al., 2011). Among this technical information, the head losses significantly influence the pressure head available and flow rate pumped through the pipes from an irrigation system (Bombardelli et al., 2019; Cardoso & Frizzone, 2014).

In irrigation systems, the decrease of pressure energy can be caused by friction losses along the pipe and local head losses (minor losses) due to the insertion of emitters or installing fittings or valves in the irrigation line (Zitterell et al., 2014). The magnitude of minor losses caused by an emitter depends on the area occupied by it and its geometric shape (Keller & Bliesner, 1990; Demir et al., 2019).

The lack of technical data regarding the local head loss by the emitter insertion in irrigation lines leads designers to neglect this quantification in irrigation projects. Hence, laboratory tests to obtain current local head loss data and the development of mathematical models to estimate pressure losses are essential for the precise design of irrigation systems (Provenzano & Pumo, 2004; Vilaça et al., 2017; Alves et al., 2012).

Thus, this study aimed to iteratively estimate the local head loss coefficient of emitters inserted in irrigation pipes from technical data of the emitter (discharge versus pressure head) and the input and output pressure of the lateral line.

MATERIAL AND METHODS

The study was carried out at the Hydraulics Laboratory from the Agricultural Engineering Department at the State University of Maringá, in Cidade Gaúcha, Paraná State, Brazil. The micro-sprinkler Naan®, model 7110 Hadar, was used to evaluate the head losses in a lateral irrigation line.

The micro-sprinkler performance characteristics (discharge versus pressure head) were determined according to ISO Standard 8026 (ISO, 2009). In these tests, to minimize the effect of pressure variation along the lateral line of emitters, a rigid PVC pipe with an inner diameter of 40.1 mm and 3 m in length was employed. Five connectors for coupling the micro-sprinkler nozzles, spaced at 0.265 m, were inserted in this pipe.

The five micro-sprinkler nozzles were set on the pipeline. For each emitter, the discharge was measured by the weight method (the mass/time ratio) considering the absolute water density of 1,000 kg m^{-3} and a minimum time to collect water of 180 s. These micro-sprinklers, in nozzle diameters of 0.9 (gray), 1.0 (purple), 1.1 (red), and 1.2 mm (orange), were submitted to increasing pressure heads of 5, 10, 15, 20, 25, and 30 m. The pressures were regulated with a gate valve; they were measured by a digital pressure gauge, on the scale of 0 to 5 kgf cm^{-2}, with pressure coupling located in the pipeline center.

The micro-sprinkler discharge of each nozzle, for a working pressure head, represented the mean discharge of the five emitters evaluated. Thus, the relation between standard deviation and the mean discharge expresses the coefficient of manufacturing variation, calculated by:

$$CV = \frac{s_d}{q_a} 100 \tag{1}$$

where:

CV - coefficient of manufacturing variation, %;
q_a - average emitter discharge, L h^{-1}; and,
s_q - standard deviation of the discharges, L h^{-1}.

Data of mean discharge measured versus working pressure head of each micro-sprinkler nozzle was used to fit a power function, given by:

$$q = a\ h^x \tag{2}$$

where:

q - emitter discharge, L h^{-1};
a - constant of proportionality that characterizes each emitter;
h - working pressure head of emitter, m; and,
x - emitter discharge exponent.

A rigid PVC pipe with an inner diameter of 15.8 mm and 12 m in length was used to evaluate the total head loss along the lateral line. In this pipe were inserted 24 connectors, regularly spaced in 0.5 m, for coupling the micro-sprinklers. The insertion of each connector caused a reduction in the cross-sectional pipe area of 18.88%.

For running the head loss tests, the lateral line was set up at the same horizontal level, and a digital manometer, on a scale of 0 to 5 kgf cm^{-2}, was used to measure the inlet pressure head (5, 10, 15, 20, 25, and 30 m). The pressure head difference between the ends of the lateral line, respectively, 0.25 m before and after the first and the last emitter was measured by a mercury differential manometer (U-tube) and, the head loss along the lateral line with emitters was calculated by:

$$\Delta h = 0.0126 h_m \tag{3}$$

where:

Δh - pressure head difference in the lateral line, m; and,
h_m - difference between the mercury levels, mmHg.

These head loss tests were performed for the four nozzle diameters of the micro-sprinkler and the six inlet pressure head of the pipe. Furthermore, the discharges of each micro-sprinkler were measured along the lateral line by the weight method (the ratio of mass to time) considering absolute water density of 1,000 kg m^{-3} and a minimum time to collect water of 180 s.

Measured data of inlet pressure head (h_{in}) and difference pressure head (Δh) along the lateral line were used to compute the pressure head ($h_{(n)}$) and the discharge ($q_{(n)}$) for the distal end emitter, which represents the flow rate (Q (n)) in a segment of the lateral line between the two distal end emitters. Thus, for emitters regularly spaced in 0.5 m and an inner pipe diameter of 15.8 mm, it is possible to calculate the pipe friction head loss through the Darcy-Weisbach equation (Eq. 4 and 5), given by:

$$hf_p = f\frac{V^2}{2g}\frac{L}{D} \tag{4}$$

$$V = \frac{0.000001111Q}{\pi D^2} \tag{5}$$

where:

hf_p - head loss due to pipe friction, m;
V - mean water velocity in the pipe, m s^{-1};
D - inner diameter of the pipe, m;
L - space between emitters, m;
g - acceleration due to gravity, 9.80665 m s^{-2};
f - Darcy-Weisbach pipe friction factor, decimal; and,
Q - flow rate in the pipe, L h^{-1}.

The friction factor was computed by the Swamee equation (Eq. 6), based on an absolute roughness (e) for PVC pipes of 0.00001 m (Carvalho & Oliveira, 2008). According to Rocha et al. (2017) and Minhoni et al. (2020), this equation can be applied to regimes laminar flow, hydraulically smooth turbulent flow, transitional flow, and rough turbulent flow. Furthermore, to quantify the Reynolds number (Eq. 7), a water kinematic viscosity of 1.01 x 10^{-6} m^2 s^{-1} (temperature of 20 °C) was used.

$$f = \left\{\left(\frac{64}{Re}\right)^8 + 9.5\left[\ln\left(\frac{e}{3.7D} + \frac{5.74}{Re^{0.9}}\right) - \left(\frac{2500}{Re}\right)^6\right]^{-16}\right\}^{0.125} \tag{6}$$

$$Re = \frac{VD}{\nu} \tag{7}$$

where:

e - absolute roughness of pipe, m;
Re - Reynolds number, decimal; and,
ν - water kinematic viscosity, m^2 s^{-1}.

As the local head loss coefficient (α) was unknown, an initial value was set to compute the minor losses (Eq. 8) caused by inserting the connector in the lateral line.

$$hf_{loc} = \alpha\frac{V^2}{2g} \tag{8}$$

where:

hf_{loc} - local head loss, m; and,
α - local head loss coefficient, decimal.

The total head loss (hf_T) in a pipe segment between two emitters represents the sum of the pipe friction loss and the minor loss caused by the emitter. This calculation procedure was done step-by-step, starting from the downstream end to the upstream end of the lateral line, accumulating the micro-sprinklers discharge along the pipe. As a result, the total head loss ($hf_{T(n)}$), the flow rate along the pipe (Q(n)), and the emitter pressure head (h(n)) vectors were set out, according to the algorithm:

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INPUT: n; $h_{in}$; $\Delta h$; constants "a" and "x" of the emitter equation.
Step 1:    Set: $h_{(n)} = h_{in} - \Delta h$
           $Q_{(n)} = q_{(n)} = a\,h_{(n)}^{x}$
           $hf_{T(n)} = hf_{p(n)} + hf_{loc(n)}$
Step 2:    For i = 0, 1, ..., n - 1
               Set: $h_{(n-i)} = h_{(n+1-i)} + hf_{T(n+1-i)}$
               $Q_{(n-i)} = Q_{(n+1-i)} + a\,h_{(n-i)}^{x}$
               $hf_{T(n-i)} = hf_{p(n-i)} + hf_{loc(n-i)}$
OUTPUT: $Q_{(n)}$, $h_{(n)}$ and $hf_{T(n)}$, for i = 0, 1, ..., n
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Summing the total head loss of each segment between micro-sprinklers (vector $hf_{T(n)}$) is set out the head loss along the pipe. In case this value is equal to the pressure head difference (Δh) measured in the test, the assigned local head loss coefficient (α) satisfies the problem condition. Still, if this value is different, new values of the local head loss coefficient (α) are set until solving the problem. This procedure was performed iteratively, using the Excel® spreadsheet solver tool.

Aiming to evaluate the model accuracy, the micro-sprinkler discharges measured (qobs) and estimated (qest) along the lateral line were compared by i) average of the absolute difference between measured and estimated values; ii) coefficient of determination (R^2) and; iii) confidence coefficient (c) proposed by Camargo & Sentelhas (1997), which is given by the product of correlation coefficient (r) and exactness coefficient (d) (Willmott et al., 1985).

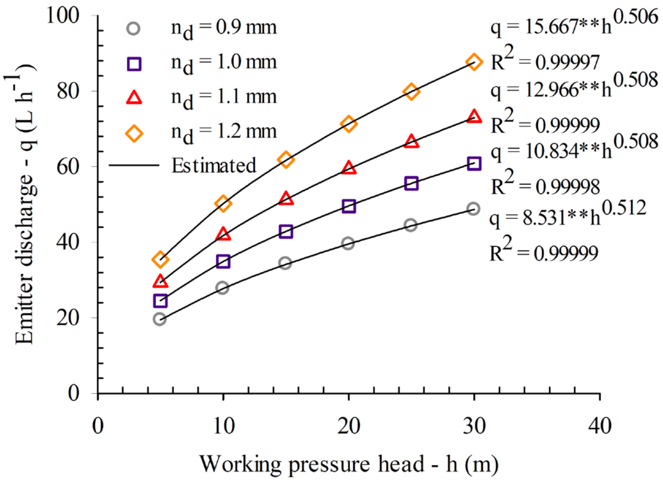
RESULTS AND DISCUSSION

Measured discharge data versus working pressure head for the four micro-sprinkler nozzle diameters are shown in Figure 1. This figure shows that increasing the nozzle diameter and working pressure head increases the micro-sprinkler discharge.

According to Figure 1, by fitting power equations for the discharge as a function of the working pressure head, the micro-sprinkler presented range discharge exponents from 0.506 to 0.512; consequently, this micro-sprinkler can be classified as a turbulent-flow emitter (Keller & Karmelli, 1974). In performing the equation adjustments (Figure 1), the coefficients of determination of these four equations were almost equal to one, which indicates that the data fitted closely to the power equation model.

The coefficient of manufacturing variation (CV) values for the different nozzle diameters and working pressures are shown in Table 1. The micro-sprinkler presented CV values lower than 1.5% for the different working conditions, ranging from 0.210 to 1.033%, leading to high values of emission uniformity. By ASAE Standard EP 405 (ASABE, 2003), the evaluated micro-sprinkler can be classified as good (CV < 10%).

Oliveira (2008) pointed out that in the manufacture of several emitters, however accurate, the production of two



** - Significant at $p \leq 0.0001$ by t-test; R^2 - Coefficient of determination

Figure 1. Emitter discharge according to the working pressure head for different nozzle diameters (n_d) of micro-sprinkler

equal pieces is unlikely. The difference between emitters, characterized by high values of coefficient of manufacturing variation, can cause significant variations of flow rate in the lateral lines, compromising the hydraulic sizing and the water application uniformity by the irrigation system.

Table 2 shows the total head loss values along the lateral line of micro-sprinklers, measured in the tests for different working conditions. These data were employed to compute the head loss due to the pipe friction and the local head loss caused by the micro-sprinkler insertion, expressed as a percentage of the total head loss. In this procedure, the local head loss coefficient (α) values were computed iteratively to the estimated total head loss along the pipe was equal to the total head loss measured.

Table 1. Mean values of coefficient of manufacturing variation CV (%) according to the pressure head for the micro-sprinkler of different nozzle diameters

Pressure head - h (m)	Nozzle diameter - n_d (mm)			
	0.9	1.0	1.1	1.2
5	0.833	0.719	0.274	0.830
10	0.968	0.706	0.365	0.788
15	0.906	0.879	0.256	1.033
20	0.912	0.867	0.313	0.838
25	0.933	0.876	0.210	0.874
30	0.887	0.937	0.386	0.944
Mean	0.907	0.831	0.301	0.884

Table 2. Total head loss measured (hf_T), percentage of pipe friction head loss (hf_p), and percentage of local head loss (hf_{loc}), as a function of inlet pressure head (h_{in}) and nozzle diameter (n_d) of the micro-sprinkler

h_{in} (m)	hf_T (m)	hf_p (%)	hf_{loc}	hf_T (m)	hf_p (%)	hf_{loc}
	n_d = 0.9 mm (gray)			n_d = 1.0 mm (purple)		
5	0.202	95.419	4.581	0.302	94.237	5.763
10	0.391	92.115	7.885	0.605	87.586	12.414
15	0.592	87.576	12.424	0.882	86.569	13.431
20	0.769	87.613	12.387	1.159	85.442	14.558
25	0.945	87.312	12.688	1.436	84.411	15.589
30	1.121	86.885	13.115	1.701	84.164	15.836
	n_d = 1.1 mm (red)			n_d = 1.2 mm (orange)		
5	0.428	89.439	10.561	0.605	85.472	14.528
10	0.794	85.986	14.986	1.134	85.482	14.518
15	1.235	83.553	16.447	1.676	83.560	16.440
20	1.625	82.455	17.545	2.180	83.636	16.364
25	1.991	82.602	17.398	2.696	82.955	17.045
30	2.344	82.984	17.016	3.188	83.020	16.980

On average, the pipe friction head losses and the minor losses, respectively, represented 86.270 and 13.730% of the total head losses in the pipe. Whereas the local head loss had a trend towards increasing with stepping up the inlet pressure head and the micro-sprinkler nozzle diameter, the pipe friction head loss decreased (Table 2), which can be caused directly by the increase in the flow rate in the lateral irrigation line.

Al-Amoud (1995), evaluating the total head loss of different emitters installed in a lateral line of the inner diameters from 13 to 25 mm, found that local head loss led to an increase in total head loss between 5 and 32%, depending on the area of the emitter barb protrusion. According to Yildirim (2007), neglecting the local head loss can lead to errors of the order of 25 and 7%, respectively, in the sizing of the pipe diameter and the length of the lateral line.

The local head loss coefficients, which ranged from 0.051 to 0.169, trended to increase with increasing the inlet pressure head and micro-sprinkler nozzle diameter (Table 3), as happened to the minor losses (Table 2). Provenzano & Pumo (2004) observed significant differences between the local head loss coefficient values (from 0.102 to 1.194) for different emitters (drippers) inserted in irrigation lateral lines. Based on this paper, Baiamonte (2018) employed a unique value of head loss coefficient (α = 0.8) due to emitter insertion to compute maximum lengths of lateral lines since values higher than this has rarely occurred in practice.

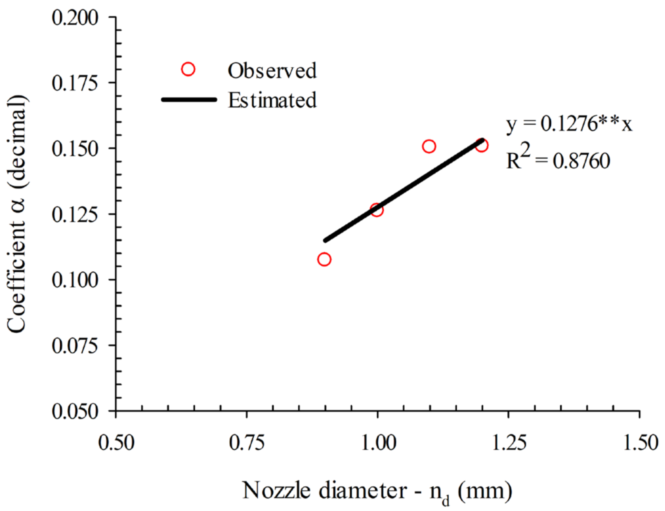
The mean values of the local head loss coefficient for each inlet pressure head according to the emitter nozzle diameter are shown in Figure 2. In this Figure, the fitting linear equation represents that for each 0.1 mm variation in the nozzle diameter, there is a variation in the local head loss coefficient value of 0.01276. According to Vilaça et al. (2017), the information on the parameters that influenced the hydraulic characteristics of the equipment has been vital for the accurate design of irrigation systems.

The measured discharges along the lateral line with the estimated discharges are shown in Figure 3. As presented in this figure, the fitted linear equation, with angular and linear coefficients, respectively, equal to 0.9865 and 0.8004, an average absolute difference of 0.4899 L h^{-1} and a coefficient of determination (R^2) of 0.9989, had a slight difference from the 1:1 line.

This coefficient of determination was higher than the value (R^2 > 0.85) proposed by Molle & Gat (2000) to accept

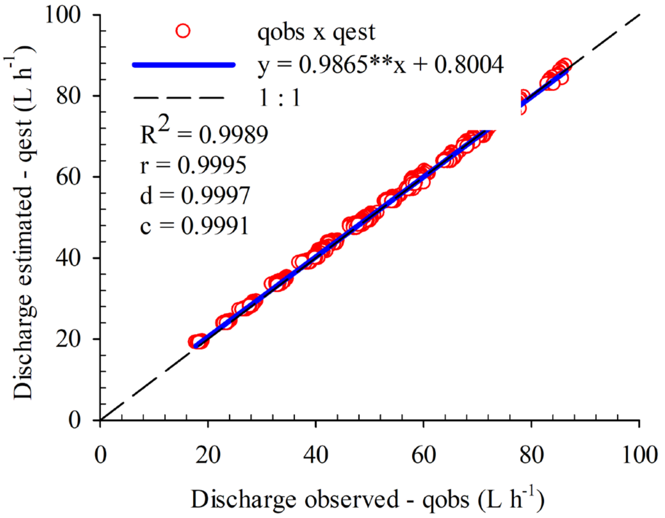
Table 3. Head local loss coefficient values (α) according to the inlet pressure head (h_{in}) and the micro-sprinkler nozzle diameter (n_d)

h_{in} (m)	n_d = 0.9	n_d = 1.0	n_d = 1.1	n_d = 1.2
	(mm)			
5	0.051	0.060	0.110	0.151
10	0.083	0.127	0.140	0.154
15	0.131	0.132	0.162	0.150
20	0.126	0.141	0.169	0.156
25	0.126	0.149	0.164	0.141
30	0.128	0.149	0.157	0.152



** - Significant at $p \leq 0.0001$ by t-test; R^2 - Coefficient of determination

Figure 2. Mean local head loss coefficient (α) according to the micro-sprinkler nozzle diameter



** - Significant at $p \leq 0.0001$ by t-test; R^2 - Coefficient of determination; r - Correlation coefficient; d - Exactness coefficient; c - Confidence coefficient

Figure 3. Relationship between estimated and observed discharges along the lateral line

a simulation model as valid. Furthermore, the confidence coefficient of Camargo & Sentelhas (1997) presented a value of 0.9991 (Figure 3), which classified the estimated discharges as optimal (c > 0.85) as well as the local head loss coefficient values set out by the model.

Bombardelli et al. (2019) and Vilaça et al. (2017) pointed out that local head loss computation has enormous relevance in the hydraulic design of irrigation systems. However, this is possible only with the availability of technical data of the hydraulic equipment employed, which is often scarce. Thus, finding the local head loss coefficient iteratively from the emitter characteristic curve and the inlet and outlet pressure head measured in the lateral line is a procedure that can be employed to provide this technical information.

Conclusions

1. The evaluated micro-sprinkler nozzle diameters presented a low coefficient of manufacturing variation.

2. The iterative procedure provided accurate data of local head loss coefficients.

3. Increasing the micro-sprinkler nozzle diameter and the inlet pressure head in the lateral line led to higher local head loss coefficient values.

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