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A MODEL FOR HYDRAULIC DESIGN OF IRRIGATION LATERAL LINES

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Keywords:
pressure loss
energy conservation
mass conservation

ABSTRACT

There are several models for hydraulic designs and optimization of lateral lines depending on the existing pressure head profile and flow which allows designing longer lateral lines, therefore decreasing the cost of the system implementation. A model has been developed to calculate the pressure head and required flow rate at the inlet of lateral line using the back step method. A set of equations was implemented in an algorithm in the R language. For the calculations, the following variables must be provided: pressure head at the end of the lateral line (H_{end}), coefficients K and x of the characteristic equation (flow-pressure) of the emitter, pipe diameter (D), emitter spacing (Se) and number of emitters (Ne). For the evaluation of the model, the pressure head at the end of the lateral line, the pipe diameter and the number of emitters were varied within the established limits. Relationships between these variables were established by regression analysis using the least-squares method. The model shown in the study was suitable for the calculation of the pressure head and flow rate profile along the lateral line. The power, plateau, exponential and linear equations were adjusted to describe these relationships. These equations can help in the design of irrigation systems by simplifying the procedures in order to meet the design criteria. Also, the proposed equations allow evaluation of the systems still in the design phase.

Palavras-chave:
perda de carga
conservação da energia
conservação da massa

MODELO PARA DIMENSIONAMENTO HIDRÁULICO DA LINHA LATERAL DE SISTEMAS DE IRRIGAÇÃO

RESUMO

Existem inúmeros modelos hidráulicos para dimensionamento e otimização de linhas laterais em função do perfil de pressão e vazão existente, que permitem dimensionar sistemas de linhas laterais mais longas, diminuindo o custo da implantação do projeto. Um modelo foi desenvolvido para calcular a pressão e a vazão na entrada e ao longo de uma linha lateral sem declividade utilizando o método backstep. Um conjunto de equações foi implementada em um algoritmo na linguagem R. Para o cálculo do modelo as seguintes variáveis são necessárias: pressão no final da linha lateral (H_{end}), coeficientes K e x da equação característica (vazão-pressão) do emissor, diâmetro do tubo (D), espaçamento entre emissores (Se) e número de emissores (Ne). Para avaliação do modelo, a pressão no final da linha lateral, o diâmetro da tubulação e o número de emissores foram variados dentro de limites estabelecidos. As relações entre variáveis importantes ao dimensionamento foram ajustadas por análise de regressão utilizando o método dos mínimos quadrados. O modelo apresentado foi adequado para o cálculo do perfil de pressão de vazão ao longo da linha lateral. Equações do tipo potência, platô, exponencial e linear foram ajustadas para descrever as relações entre as variáveis de dimensionamento. Estas equações podem ajudar no dimensionamento de sistemas de irrigação, simplificando o procedimento de modo a atender os critérios de dimensionamento. Adicionalmente, as equações propostas permitem avaliar o sistema ainda na fase de dimensionamento.

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INTRODUCTION

Irrigated agriculture has been increasing in Brazil. However, with the high availability of water resources in the country, there is no concern with the rational use of water, leading to low efficiency of irrigation systems. Such fact can be attributed to inadequate management and erroneous hydraulic design (AYARS, 2007). According to IICA (2008), in Brazil, the design of the irrigation hydraulic system is constantly neglected, causing 36% of water to be lost in the system. These losses are attributed to poor distribution in hydraulic structures.

The good development of a crop is associated with adequate water availability through rainfall or irrigation. Irrigation water is distributed to plants through the lateral lines spaced along the derivation lines (Bernardo et al., 2011). The laterals must be designed to meet the water distribution uniformity criteria (Wu, 1997), defined as the ability of an irrigation system to deliver the same amount of water over an irrigated area. (Sokol et al., 2019).

The main tasks of the hydraulic design of a drip irrigation system are to determine the geometric characteristics (diameter and length) of the lateral lines; the pressure at the beginning of the lines; head losses along the lateral lines and the flow of the emitters (YILDIRIM, 2015). The performance of irrigation systems depends greatly on proper hydraulic design (CLARK et al., 2007). According to Wu (1997), determining the correct pressure is of great importance so not to compromise the system, as high pressures can result in failures in water application or result in injury to irrigation pipes. Thus, the use of software is important for the hydraulic design of an irrigation system, whose benefit is to reduce the time to perform the calculations and quickly analyze different situations (CASTIBLANCO, 2013).

To improve the design of lateral irrigation lines, hydraulic models can be used to obtain the flow and pressure along the lateral line based on iterative calculations. Many authors have described mathematical models to describe the pressure and flow along a lateral line (Kang & Nishiyama, 1996; Vallesquino & Luque-Escamilla, 2001; Mizyed, 2002; Zella et al., 2006; Yildirim, 2009, 2010, 2015; Sadeghi et al., 2012, 2015; Perea et al., 2013; Pandey, 2016)

The aim of this work was to develop a model to calculate the pressure and the required flow at the inlet of the lateral line and the pressure and flow profile along the lateral line using the back step method. Also, to fit the relationships between the design variables that are necessary to establish the laterals with greater efficiency.

MATERIAL AND METHODS

The pressure and flow profile along the lateral line was calculated through the back step method. In this method, the pressure head is set at the end of the lateral line and the pressure head and the flow rate profile is calculated iteratively up to the beginning of the lateral line (Jain et al., 2002). The backstep methods are a combination of mass conservation and energy conservation equations.

For the last emitter in lateral line (nth emitter) the pressure head was initially set (Equation 1). The flow rate of the last emitter was calculated through the characteristic equation of the emitter using the coefficients K and x (Equation 2). The flow rate of the last element of the lateral was considered equal to zero (no flow) (Equation 3).

$$H_n = H_e \tag{1}$$

$$q_n = K \cdot H_n^x \tag{2}$$

$$Q_n = 0 \tag{3}$$

Where,

H_n = pressure head in the last emitter, m;
H_e = pressure head in the end of lateral, m;
q_n = flow rate in the last emitter, $m^3.s^{-1}$;
K = emission coefficient;
x = emission exponent; and
Q_n = flow rate in the last lateral section, m^3 s^{-1}.

The iterative calculation begins in the penultimate emitter (i-1) and continues up to the first emitter of the lateral. The flow rate of the i-1 element of the lateral and the pressure head and flow rate of the i-1 emitter were calculated using equations 4-6.

$$Q_{i-1} = Q_i + q_i \tag{4}$$

$$H_{i-1} = H_i + hf(Q_{i-1}) \tag{5}$$

$$q_{i-1} = K \cdot H_{i-1}^{x} \tag{6}$$

Where,

Q_{i-1} = flow rate in the lateral section i-1, m³ s⁻¹;
Q_i = flow rate in the lateral section i, m³ s⁻¹;
q_i = flow rate in the emitter i, m³.s⁻¹;
H_{i-1} = pressure head in the emitter i-1, m;
H_i = pressure head in the emitter i, m;
hf (Q_{i-1}) = head loss in the lateral section i-1, m; and
q_{i-1} = flow rate in the emitter i-1, m³.s⁻¹.

The inlet flow rate and inlet pressure head of the lateral line was calculated through Equations 7 and 8.

$$Q_{in} = Q_1 + q_1 \tag{7}$$

$$H_{in} = H_1 + hf(Q_{in}) \tag{8}$$

Where,

Q_{in} = flow rate at inlet of the lateral, m³ s⁻¹;
Q_1 = flow rate in the first lateral section, m³.s⁻¹;
q_1 = flow rate in the first emitter, m³.s⁻¹;
H_{in} = pressure head at inlet of lateral, m;
H_1 = pressure head in the first emitter, m; and
hf (Q_{in}) = head loss at the inlet section of the lateral, m.

The head loss caused by friction was calculated through the Darcy-Weisbach (equation 9).

$$\mathrm{hf} = f\frac{L}{\mathrm{D}}\frac{\mathrm{V}^2}{2g} \tag{9}$$

Where,

hf = head loss, m;
f = friction factor;
L = length of the pipe, m;
V = velocity, m s⁻¹;
D = diameter, m; and
g = gravitational acceleration, m s⁻².

For turbulent flow, the friction factor was calculated through the Colebrook-White equation iteratively solved by the method of Newton-Raphson (equation 10).

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7\,D} + \frac{2.51}{Re\sqrt{f}}\right) \tag{10}$$

For laminar flow, the friction factor was calculated by the equation 11.

$$f = \frac{64}{Re} \tag{11}$$

Where,

$$Re = \frac{V \cdot D}{\nu} \tag{12}$$

ε = Roughness coefficient
Re = Reynolds number, dimensionless; and
ν = kinematic viscosity of fluid, m².s⁻¹.

The described equations were implemented in an algorithm in R language (Ihaka & Gentleman, 1996). In addition, the following variables must be provided: pressure head at the end of the lateral line (H_{end}), coefficients K and x of the characteristic equation (flow-pressure) of the emitter, pipe diameter (D), emitter spacing (Se) and number of emitters (Ne).

The model shown in here was calculated with the following variables:

H_{end} = 17 m;
K = 1.05e-6;

x = 0.5;
D = 0.016 m;
Se = 1 m; and
Ne = 100.

For the evaluation of the model, the pressure head at the end of the lateral, the pipe diameter and the number of emitters were varied at the intervals shown below.

Pressure at the end of the lateral line ranging from 1 to 100 m, with an increment of 0.1.

Lateral line diameter ranging from 0.01 to 0.1 m, with an increment of 0.001.

Number of emitters ranging from 50 to 300 units, with an increment of 1.

These ranges allowed to calculate the pressure head at the inlet of the lateral line, the flow at the inlet of the lateral line and the coefficient of variation of the flow emitters. Relationships between these variables were established by regression analysis using the least-squares method.

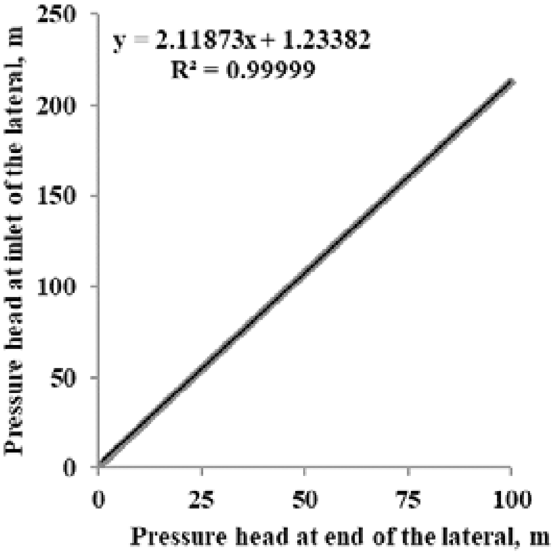

Figure 1. Relationship between the pressure head at the inlet and pressure head at the end of the lateral line.

The relationship between flow at the inlet of lateral line and pressure at the inlet and at the end of the lateral line were equations of power type whose coefficient of determination were quite high ($R^2 \approx 1$) (Figures 2 and 3).

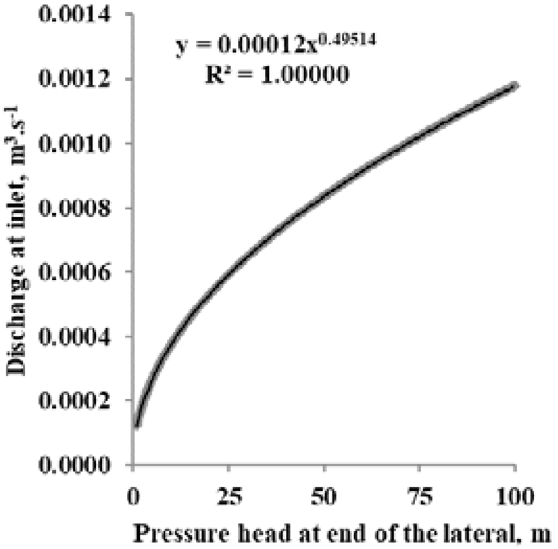

Figure 2. Relationship between inlet flow rate and pressure head at end of the lateral line.

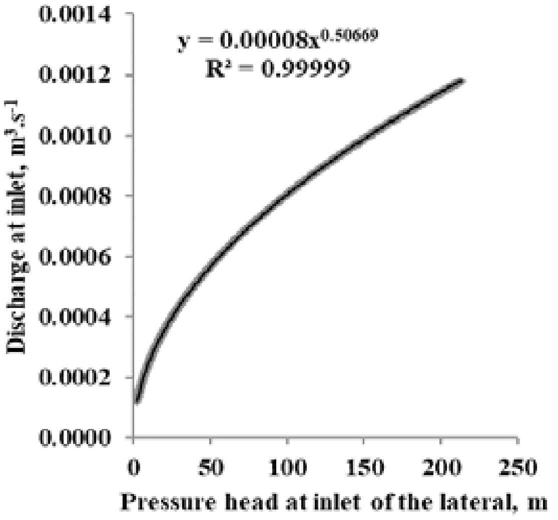

Figure 3. Relationship between the inlet flow rate and the inlet pressure head of the lateral.

Kang & Nishiyama (1996) used an equation of the polynomial type to express the relationship between inlet flow and inlet pressure head of the laterals.

Jain et al. (2002) described the use of a simple power equation to describe this relationship between the inlet pressure head and inlet flow rate of the lateral line because of the similarity in the hydraulics of laterals and emitters. The authors also demonstrated the advantages of the power equation type against the polynomial equation type.

Also, there was a good relation between the coefficient of variation of discharge the emitters and the inlet pressure head and inlet flow rate of the lateral (Figures 4 and 5). The best fit was obtained with the power equation type whose determination coefficients were high ($R^2 > 0.93$).

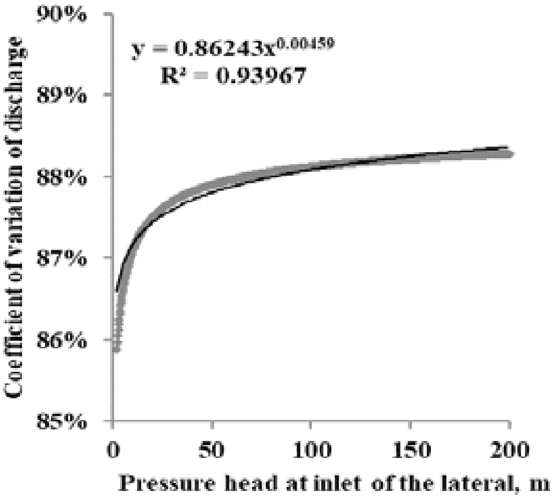

Figure 4. Relationship between coefficient of variation of discharge and inlet pressure head of the lateral line.

The coefficient of variation (CV) is used to classify the emission uniformity. Coefficients of variation greater than 90% are classified as excellent, between 80% and 90% are very good, 70% and 80% are regular, 60% to 70% are very bad and less than 60% are unacceptable. In general, low uniformity of irrigation means excess water at certain points and deficit in other points of the field (Bralts et al., 1987). The proposed equations allow the evaluation of the systems still in the design phase.

For the diameter variation, a good fit was found with the plateau equation type. For this equation type, from a determined diameter value, there is no change in the response. In the example studied, the inlet pressure head of the lateral to maintain a given flow rate remains constant for diameters above 0.0124 m (Figure 6). The inlet flow rate of the lateral for a given pressure head at the end of the line remains constant for diameters above 0.0151 m (Figure 7). The coefficient of variation of discharge remained unchanged for diameters above 0.018 m (Figure 8).

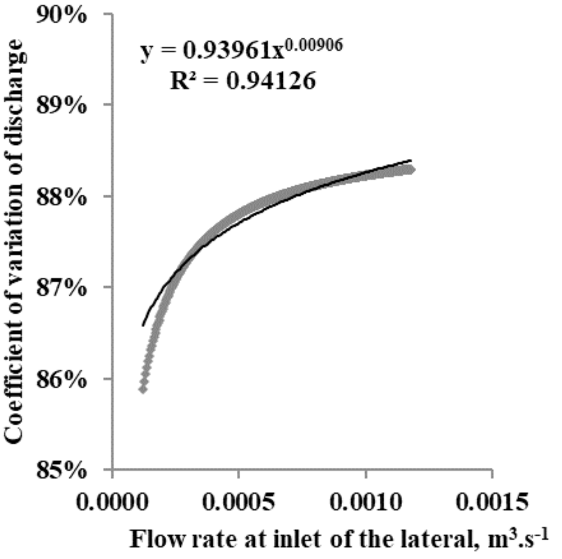

Figure 5. Relationship between coefficient of variation of discharge and inlet flow rate of the lateral line.

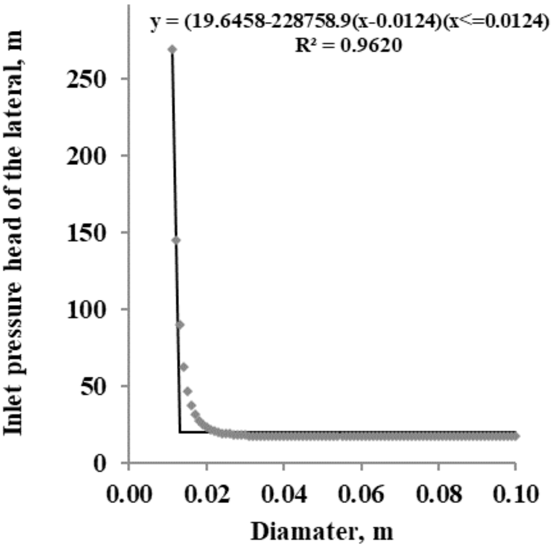

Figure 6. Relationship between pressure head at inlet and diameter of the lateral line.

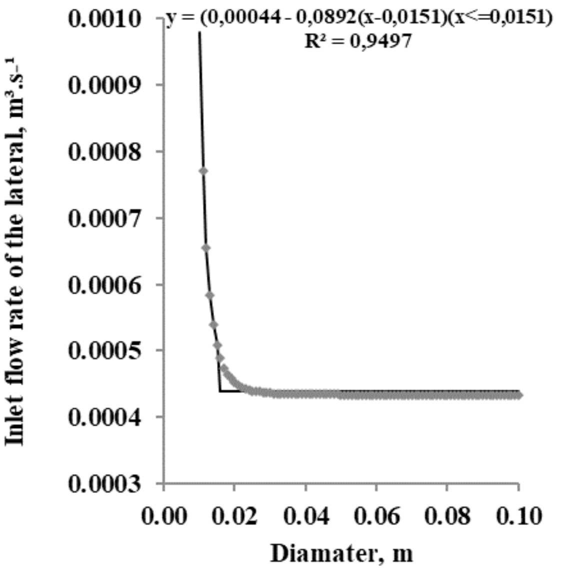

Figure 7. Relationship of discharge at inlet and diameter of the lateral line.

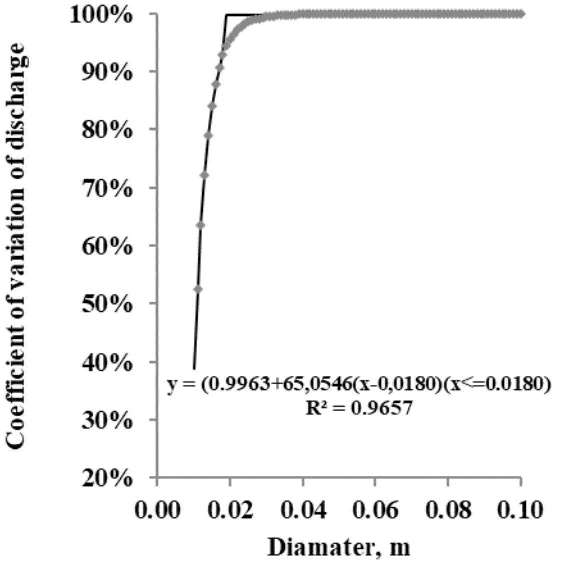

Figure 8. Relationship between coefficient of variation of discharge and diameter of the lateral line.

In relation to the change in the number of emitters, which is directly related to the length of the lateral line, exponential equations were adjusted for the relationship between the inlet pressure head and the number of emitters (Figure 9) and for the relationship between inlet flow rate and the number of transmitters (Figure 10). For the relationship between the coefficient of variation of discharge and number of emitters, the best fit was obtained by an equation of the linear type (Figure 11).

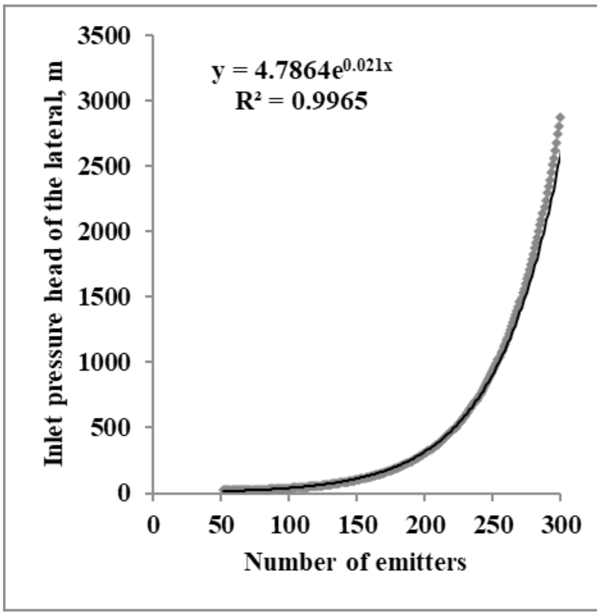

Figure 9. Relationship between inlet pressure head and number of emitters on the lateral.

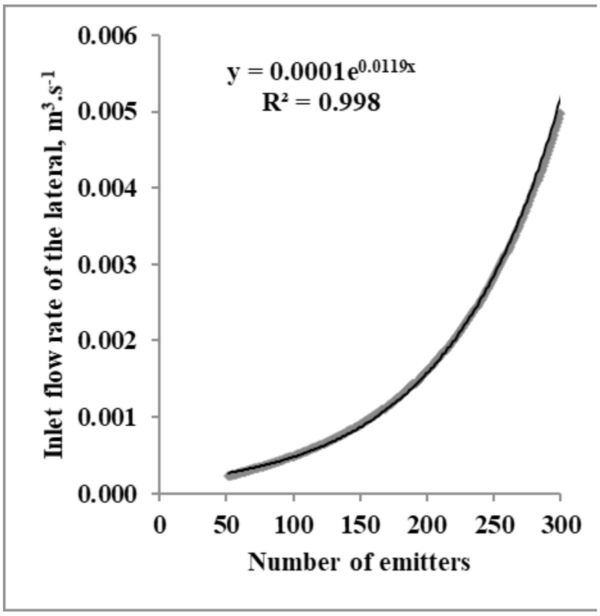

Figure 10. Relationship between inlet flow rate and number of emitters on the lateral line.

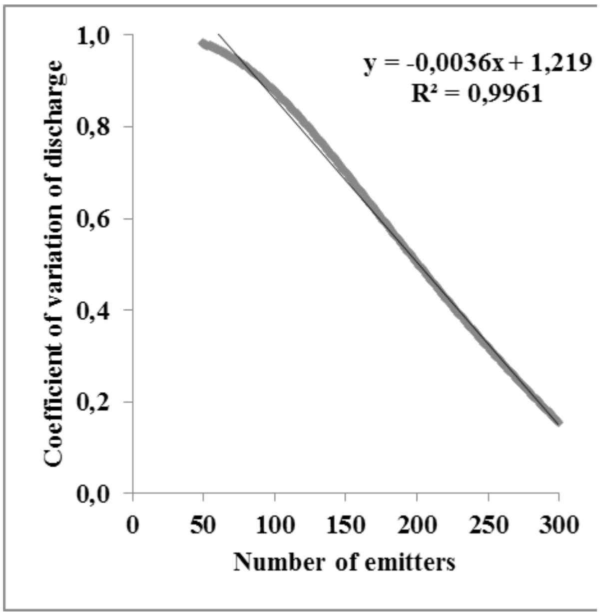

Figure 11. Relationship between coefficient of variation of discharge and number of emitters on the lateral line.

CONCLUSIONS

- The back step method was suitable for the calculation of the pressure head and flow rate at the beginning and along a lateral line.
- Several regression equations were presented relating the most important variables in the irrigation design. The power, plateau, exponential and linear equation were considered adequate to describe these relationships.
- These equations can help in the design of irrigation systems, simplifying the procedures in order to meet the design criteria. Also, the proposed equations allow evaluation of the systems still in the design phase.

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