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ORIGINAL ARTICLE

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Experimental Theoretical Model for Improving the Management of Electrical Center Pivot Machines

Modelo teórico experimental para el mejoramiento del manejo de máquinas de pivote central eléctricas

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ABSTRACT: Polynomial regression is a useful tool for modeling problems related to the prediction of pressures along a pipeline with multiple outlets in pressurized irrigation systems. The fundamental characteristic of this model is its simplicity to forecast pressure data in an irrigation pipe and extend the number of observations. In the investigation, models were developed in which the pressure along the pipeline was related to different independent variables such as the flow at each outlet and the sum of the spacing between outlets from the beginning of the pipeline. The validation of the model was carried out from data used for estimation and forecasting, using the coefficient of determination (R^2) which is a recommended indicator to measure the reliability of the model and the mean percentage error widely used to measure the performance of the model. As a case study, an electric central pivot irrigation system was used in the cultivation of sugarcane, where the most appropriate model was the second-order and decreasing polynomial type, which achieved an excellent approximation to the real behavior of the data, with an R2 of 0.9972 and an average percentage error of less than 12%.

Keywords: Polynomial Regression, Multiple Outlet Pipes, Pressurized Irrigation Systems.

RESUMEN: La regresión polinómica es una herramienta útil para la modelación de problemas relacionados con la predicción de presiones a lo largo de una tubería con salidas múltiples en sistemas de riego presurizado. La característica fundamental de este modelo es su simplicidad para pronosticar datos de presión en una tubería de riego y extender el número de observaciones. En la investigación se desarrollaron modelos en los que se relacionó la presión a lo largo de la tubería con diferentes variables independientes como el caudal en cada salida y la sumatoria de los espaciamientos entre salidas desde el inicio de la tubería. La validación del modelo se realizó a partir de datos utilizados para la estimación y el pronóstico, mediante el coeficiente de determinación (R^2) que es un indicador recomendado para medir la fiabilidad del modelo y el error porcentual medio ampliamente utilizado para medir el desempeño del modelo. Como caso de estudio se utilizó un sistema de riego de pivote central eléctrico en el cultivo de la caña de azúcar, donde el modelo más apropiado fue del tipo polinómico de segundo orden y decreciente, el cual logró una excelente aproximación al comportamiento real de los datos, con un R^2 de 0,9972 y un error porcentual medio inferior al 12%.

Palabras clave: regresión polinómica, tuberías de múltiples salidas, sistemas de riego presurizados.

INTRODUCTION

The increasing levels of competitiveness in the current agricultural market have motivated the urgent need to optimize the resources used in the productive systems, as is the case of the water used in agriculture according to Pérez-Armas *et al.* (2020), which is the user that consumes 85 % of the water on the planet. As a means to mitigate this problem, different systems have been developed for its saving, based on its best use and the use of more efficient technologies; since the scarcity of water and the inadequate use of irrigation systems generate higher production costs for farmers (Guijarro-Rodríguez *et al.*, 2018; Barrezueta-Unda *et al.*, 2020).

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The pressurized irrigation technique has a great impact on the rational use of water, due to the inputs used and its proper functioning, which allows reducing the amount of water used as a contributionrrr to the optimization of water consumption without causing water stress in crops (Meneses-Rojas & Sulca-Castilla, 2020).

In pressurized irrigation systems, the water is conducted through pipes with a certain pressure so that it can reach the plants through emitters that can be drippers, sprinklers, micro sprinklers, etc. These devices also allow the application of fertilizers with the irrigation water with a high efficiency of water application depending on the type of emitter (Calejo *et al.*, 2008; Attia *et al.*, 2019).

Among the most widely used pressurized irrigation systems in the world are electric central pivot machines, which allow notable water and energy savings when compared to other irrigation techniques such as traditional sprinklers and hydraulically operated pivots (Pérez-Armas *et al.*, 2020).

The proper design of pressurized irrigation systems is closely related to the correct operation and high efficiency in the use of water (Del Río-San José *et al.*, 2019). The laterals of these systems are frequently made up of pipes with multiple outlets, which makes the hydraulic design of said pipes more complex (González-Quirino *et al.*, 2021).

The hydraulics of the pipes that distribute the flow of pressurized irrigation systems is a matter that has not yet been sufficiently resolved because it is a complex problem due to it deals with highly non-linear processes and involves various parameters and physical principles such as conservation of matter and energy in moving fluids (Riveras & Mujica-Cervantes, 2012; Alegret & Martínez, 2019).

For the experimental obtaining of variables of design and management of irrigation systems, regression models can be used, which have become an essential tool for the integral management of water resources and the environment, the spatial prediction of precipitation in hydrographic basins and the design and management of agricultural irrigation systems. Once calibrated in the specific conditions in which they were developed, they become a valuable alternative applicable to pressurized and gravity irrigation systems (Álvarez-Sevilla *et al.*, 2021). These models are applicable in the modeling of problems related to the forecast of parameters in irrigation systems due to their simplicity and ability to forecast the variables involved.

Taking into account the aspects expressed above, the objective of the work is to develop an experimental theoretical mathematical model that allows the improvement of the management of electric central pivot machines which have a distribution pipe equipped with multiple outlets.

MATERIALS AND METHODS

The research was carried out at the "Ethiopian Revolution" Agricultural Production Cooperative located at coordinates 21°50´20"N and 78°39´06"W, Morón Highway, two kilometers from Santana Town. In this cooperative, there are currently seven electric central pivot machines that irrigate an area of $5,65.10^6$ m^2 (Figure 1).

FIGURE 1. Location of the electric center pivot machine.

The electrical central pivot machine evaluated is of the BAYATUSA-WESTERN brand installed for the irrigation of sugar cane and presents the following characteristics: nine towers of 55 m, working pressure of 250 kPa, galvanized zinc irrigation pipe, total length of the lateral is 502 m, diameter of the lateral is 168.3 mm and diameter of the pivot is 200 mm. Each section has 19 sprinklers except the first one that has 14 sprinklers. The machine has 166 *Spray* type sprinklers of different diameters placed at intervals of 3 m (Table 1 and Figure 2).

TABLE 1. Technical characteristics of the electric central pivot machine

Brand	BAYATUSA-WESTERN
Work pressure	250 kPa
Irrigation pipe	Galvanized Zinc
Full length of the side	502 m
Side diameter	168,3 mm
Pivot diameter	200 mm
Number of towers	9
Total number of sprinklers	166

The experiment began with the transfer of the irrigation machine towards the road that separates the cultivated fields with a speed of 2,57 m min^{-1} in the last tower. The average working pressure during the

FIGURE 2. BAYATUSA-WESTERN electrical center pivot machine.

FIGURE 3. Volumetric capacity of the sprinklers.

test was 250 kPa. The experimental process was based on the measurement of the wind speed with a calibrated integral-cup anemometer of the brand ГОСТ 7193-74 M/C and precision of ±0,10 m s^{-1}. The pressure was measured in the metallic Bourdon manometer of the DeWit brand with a pressure of 60.0 psi (413,7 kPa) and a precision of 0.90 psi (20 kPa) placed in the pivot. The flow rate was measured in all the sprinklers using the volumetric gauging method to optimize the resources used in the productive systems, as is the case of the water used in agriculture according to Cisneros-Zayas *et al.* (2019); Catalán-López (2022) from which the volume discharged in a 10 L container was captured in a determined time. The measurement instruments used were a 500 mL graduated cylinder with a precision of one milliliter and a Timer & Counter digital chronometer with precision to seconds (Figure 3).

As results of the experiment, different mathematical statistical models were developed to relate the pressure along the pipeline with different independent variables such as the flow at each outlet and the sum of the spacing between outlets from the beginning of the pipeline. The validation of the model was carried out from data used for estimation and forecasting, using the coefficient of determination (R^2), which is a recommended indicator to measure the reliability of the model, and the mean percentage error (E_{pm}) widely used to measure the performance of the model. This was estimated using the following equation: The model is accepted when the $E_{pm} \leq 20\%$

RESULT AND DISCUSSION

Development of the Experimental Theoretical Model to Estimate the Pressure at the Lateral Outlets

The procedure to develop the experimental theoretical model was aimed at estimating the pressure at each outlet of the irrigation pipe in the electric central pivot machine and it was implemented progressively, segment by segment from the manometer at the beginning of the system to the end of the lateral. In this new procedure, the physical principles of conservation of mass and conservation of energy were taken into account.

The principle of conservation of mass was applied in this investigation to quantify the flow at the entrance of the lateral and its variation along the irrigation line, taking into account that the flow that enters through one end of the pipe has to be equal to the flow that comes out according to Riaño-Valle (2021). That constitutes the starting point of the model proposed to improve the management of electric central pivot machines and is expressed by the continuity equation.

The principle of conservation of energy was used through the energy balance applied firstly between the height of the manometer placed on the pivot and the rotating elbow; subsequently between this point and all outlets along the irrigation pipe. This principle materialized through the Bernoulli Equation, which establishes an inverse relationship between the energy that circulates through the duct and the velocity (Vega-Calderón *et al.*, 2017).

The flow at the inlet of the lateral of the pivot machine was determined by the sum of the flows discharged by each sprinkler from the following equation:

$$Q_0 = \sum_{i=1}^{i=N} q_i \quad (1)$$

Where Q_0 is the total flow of the lateral (L s^{-1}); q_i the flow that comes out of each sprinkler (L s^{-1}); N the total number of outlets of the lateral; i the index that expresses the number of sprinkles evaluated (i = 1, 2, …, 166).

The total flow of the lateral as it circulates through each section of the pipe decreases due to the combined effect of the loss of energy and the diversion of the flow q_i at each outlet; as expressed in the following equation:

$$Q_i = Q_{i-1} - q_i \quad (2)$$

where Q_i is the circulation flow for each section (L s^{-1}); Q_{i-1} is the circulation flow in the previous section (L s^{-1}); q_i the flow that comes out of each sprinkler (L s^{-1}); *i* the index that expresses the number of sprinklers evaluated ($i = 1, 2, \ldots, 166$).

For calculating the pressure in the first section between the point located on the pivot manometer (M) and the point placed on the rotating elbow (C), where the beginning of the lateral of the pivot machine begins, the Equation of Bernoulli is exposed, which is given by:

$$\frac{P_M}{\gamma} + \frac{v_M{}^2}{2g} + Z_M = \frac{P_C}{\gamma} + \frac{v_C^2}{2g} + Z_C + \sum h_{M-C} \quad (3)$$

Where P_M is the value of the pressure registered in the manometer placed on the pivot (kg m^{-1} s^{-2}); v_M the speed in the first stretch (m s^{-1}); Z_M the height of the manometer considered zero because it is the point where the reference level for the energy balance is drawn (m). Σh is the sum of the head losses due to friction and located (m); γ the specific weight of water (kg m^{-2} s^{-2}); *g* the acceleration due to gravity (m s^{-2}).

To calculate the pressure head at point *C*, this term was solved in equation (5), considering it is a pipe without branches; therefore, the flow is constant throughout the length of the section analyzed. In this first section, the velocities are simplified; so the following equation is obtained:

$$\frac{P_M}{\gamma} + \frac{v_M{}^2}{2g} + Z_M = \frac{P_C}{\gamma} + \frac{v_C^2}{2g} + Z_C + \sum h_{M-C} \quad (4)$$

From the first outlet on the lateral, the diameter remains constant; but the flow varies because it is a pipe with multiple outlets; therefore, velocity must be taken into account in the analysis of each section. In all cases, the velocity of the fluid was calculated by the economic velocity method through the following equation:

$$v = \frac{4 \cdot Q}{\pi \cdot D^2} \quad (5)$$

where *v* is the velocity of the flow; *Q* the total flow of the lateral (m^3 s^{-1}); *D* the diameter of the lateral (m).

To calculate the pressure head in each outlet, the following equation is used:

$$\frac{P_i}{\gamma} = \frac{P_{i-1}}{\gamma} + \frac{v_{i-1}{}^2}{2g} + Z_{i-1} - \frac{v_i^2}{2g} - Z_i - \sum h_{(i-1)-\mathrm{i}} \quad (6)$$

where P_i is the pressure value at each lateral outlet (kg m^{-1} s^{-2}); v_{i-1} the velocity of the flow in the previous section (m s^{-1}); Z_{i-1} the height of the pipe at the previous outlet above the reference level (m); v_i the velocity of the flow in the current section (m s-1). Z_i is the height of the pipe in the current outlet above the reference level (m); $\Sigma h_{(i-1)-i}$ the sum of the head losses due to friction and located (m) between the two outlets analyzed; *γ* the specific weight of water (kg m^{-2} s^{-2}); *g* the acceleration due to gravity (m s^{-2}).

Substituting equation (7) in (8) it is achieved that the equation is only a function of the flow.

$$\frac{P_i}{\gamma} = \frac{P_{i-1}}{\gamma} + \frac{\left(\frac{4 \cdot Q_{i-1}}{\pi \cdot D_{i-1}^2}\right)^2}{2g} + Z_{i-1} - \frac{\left(\frac{4 \cdot Q_i}{\pi \cdot D_i^2}\right)^2}{2g} - Z_i - \sum h_{(\mathrm{i}-1)-\mathrm{i}} \quad (7)$$

Simplifying the above equation, it is obtained:

$$\frac{P_i}{\gamma} = \frac{P_{i-1}}{\gamma} + \frac{8Q_{i-1}^2}{\pi^2 . D_{i-1}^4 \cdot g} + Z_{i-1} - \frac{8Q_i^2}{\pi^2 . D_i^4 . g} - Z_i - \sum h_{(\mathrm{i}-1)-\mathrm{i}} \quad (8)$$

Taking out a common factor, the following expression is obtained:

$$\frac{P_i}{\gamma} = \frac{P_{i-1}}{\gamma} + \frac{8}{\pi^2 . g}\left(\frac{Q_{i-1}^2}{D_{i-1}^4} - \frac{Q_i^2}{D_i^4}\right) + Z_{i-1} - Z_i - \sum h_{(\mathrm{i}-1)-\mathrm{i}} \quad (9)$$

The above expression is the general equation for estimating pressures at all lateral pipe outlets of an electric center pivot machine. This analytical formulation was developed section by section from the beginning of the pipeline to the end. To apply this equation, it is necessary to know the head losses for each section between outlets, which are determined by the Darcy- Weisbach Equation.

The friction factor was calculated using the Swamee-Jain Equation according to Caparicona-Marca (2020) in case the flow was turbulent. When the flow was laminar, the Poiseuille Equation was used (Ladino-Moreno *et al.*, 2019).

$$f = \frac{0.25}{\left[\log\left(\frac{\varepsilon/D}{3.7} + \frac{5.74}{NR_i^{0.9}}\right)\right]^2} \quad (10)$$

$$f_i = \frac{64}{NR_i} \quad (11)$$

Where *ε* is the absolute roughness (m); *D* the diameter of the lateral pipe (m); NR_i the Reynolds number in each stretch (dimensionless).

Development of the Statistical Regression Model

The general equation for the estimation of the pressures in all the outlets of the lateral pipe, was applied in the electric central pivot machine of the BAYATUSA-WESTERN brand installed for the irrigation of sugar cane, obtaining different models of exponential and polynomials shown below.

Figure 4 shows the curve that relates the pressures at each outlet of the lateral pipe with the flow of each outlet, which satisfactorily adjusts to the exponential model with a high coefficient of determination (R^2) of 0.9526 and a mean percentage error of (E_{pm}) of 1.30%, which indicates its high reliability to be used for forecasting purposes. The equation found was:

$$P_i = 25.395e^{-1{,}361q_i} \quad (12)$$

Figure 5 shows the curve that relates the pressures at each outlet of the lateral pipe with the sum of the spacing between outlets, which satisfactorily adjusts to the polynomial model of degree two, with a high coefficient of determination (R^2) of 0.9982 and a mean percentage error of (E_{pm}) of 0.50%. That indicates its high reliability to be used for forecasting purposes. The equation found was:

$$P_i = 0.00003\left(\Sigma E^2\right) - 0.,0249(\Sigma E) + 23.458 \quad (13)$$

Figure 6 shows the curve that relates the pressures at each outlet of the lateral pipe with the circulation flow of each section, which satisfactorily adjusts to the polynomial model of degree two, with a high coefficient of determination (R^2) of 0.9524 and a mean percentage error of (E_{pm}) of 1.04 %. That indicates its high reliability to be used for forecasting purposes. The equation found was:

$$P_i = 0.0091Q_i^2 - 0.1767Q_i + 19.136 \quad (14)$$

CONCLUSIONS

- It is possible to develop a mathematical model based on field measurements, for the hydraulic design of multi-outlet pipes of an electric central pivot irrigation system for sugarcane cultivation. It allowed estimating the behavior of the pressure as a function of the outlet flow $P_i = f(q_i)$, the sum of the spacing between outlets $P_i = f(\Sigma E_i)$ and the circulation flow in each section $P_i = f(Q_i)$.
- The model developed to estimate the pressure as a function of the sum of the spacing between outlets, of the circulation and outlet flows, has a high reliability due to the fact that the coefficient of determination (R^2) is greater than 0.95 in all the cases analyzed.
- The mean percentage errors obtained by the three curves are within the range established to be acceptable, the values being 1.30%; 0.50% and 1.04% less than 20%, respectively.

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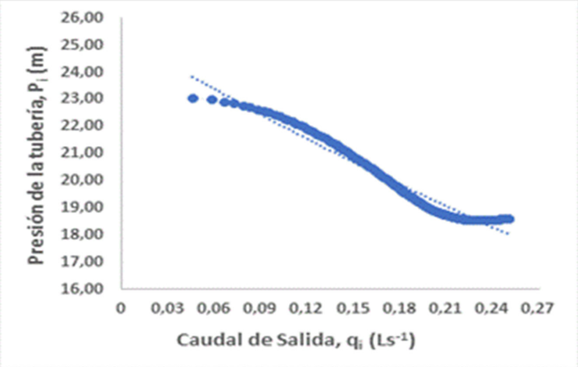

FIGURE 4. Behavior of the pressure as a function of the output flow

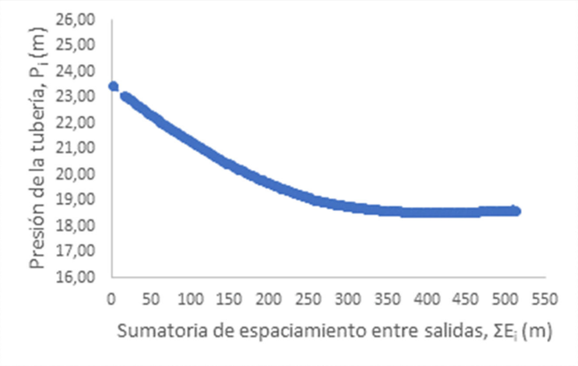

FIGURE 5. Behavior of the pressure as a function of the sum of spacing between outlets

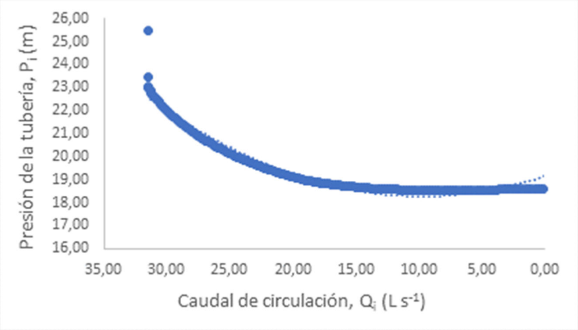

FIGURE 6. Behavior of the pressure as a function of the circulation flow in each section.

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