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IRRIGATION UNIFORMITY OPTIMISATION OF A MINI-CENTRE PIVOT SYSTEM

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KEYWORDS

genetic algorithm, mini-centre pivot, nozzle design, uniformity coefficient.

ABSTRACT

In El Oued, southern Algeria, the traditional Mini-Centre Pivot System (MCPS) is widely used for the irrigation of agricultural crops, and its use has been growing continuously. However, these systems have a constant nozzle diameter along the lateral pipe, which affects productivity directly, besides decreasing both the quantity and quality of agricultural products by irrigation heterogeneity. Therefore, optimising the design of the MCPS nozzles is linked strongly to the desired uniform irrigation. This study aims to determine the optimal configuration of nozzles for high irrigation uniformity. To achieve this goal, a genetic algorithm was used for maximising the uniformity of MCPS-mediated irrigation. The optimisation is carried out according to water distribution modelling, calculation of the Heermann and Hein uniformity coefficient (CUH), and existing nozzle diameters. To verify the accuracy of the proposed model, three existing MCPS (60 m, 50 m, and 46 m in length) are investigated experimentally. The developed code findings in terms of CUH are in agreement with those obtained by experimental tests. The analysis indicated that the nozzle diameter should vary from 5 to 15 mm along the lateral pipe. In these optimal conditions, the CUH was improved by 29.77%, 33.99%, and 19.36%, respectively, for the existing 60, 50, and 46 m irrigation systems. The most obvious findings to emerge from this study is that using a genetic algorithm to optimise the design based on the nozzle size improves water application uniformity by more than 19% in terms of the CUH.

INTRODUCTION

In a centre pivot irrigation system, the heterogeneity of water distribution or water delivery over the entire irrigated area is a challenge for improving the design of the system based on optimisation modelling. This optimisation is also necessary for many applications in precision agriculture. Furthermore, because irrigated agriculture is so important to the economy, there are long-term benefits to optimising irrigation uniformity and conserving water (Rogers et al., 2019). In recent studies, many researchers have used optimisation techniques for irrigation systems to investigate the hydraulic efficiency of these systems, as these models can consider the interaction between several parameters affecting an irrigation system, such as the atmospheric characteristics, the pump unit, the crop, and the geometry of the system.

The most commonly used irrigation method in El Oued, southern Algeria, is the traditional Mini-Centre Pivot System with more than 35,000 implementations, which represented approximately 40% of Algeria's national production of potatoes in 2015 (Rebai et al., 2017). Ben Charfi et al. (2021) created a mathematical model based on the ballistic principle on a daily and hourly basis. This model accurately estimates the water distribution pattern for one or more centre-pivot irrigation systems. The mode of spray application has a significant impact on the efficiency of sprinkler irrigation systems. Rajan et al. (2015) evaluated the features of spray application of 14 centre pivot irrigation systems located in the Texas High Plains, in the southern United States of America. These authors concluded that the centre pivots in the application of the low energy precision application (LEPA) type showed superior efficiency of

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application compared with mid-elevation spray application (MESA) and low elevation spray application (LESA) systems. However, if the crop allows, water savings could be realised by switching from MESA or LESA to the LEPA system.

One of the problems influencing the uniformity under a centre pivot and a linear movement irrigation system in the field are the variable-rate technologies. Under specific soil conditions, two-system movement speeds and three variable-rate settings that change in the field using variable-rate control systems indicate that centre pivot and linear systems are uniform when functioning in non-variable-rate mode (Dukes & Perry, 2006).

Li et al. (2020) showed that the importance of the system's water application uniformity, the travel speed selection, the collector diameter, and the sitting height should be ameliorated for the centre pivot equipped with FSPS and RSPS fixed, and rotating sprinklers. Considering the Heermann and Hein uniformity coefficient (CUH), the CUH of an RSPS was 12.7% greater than the CUH of an FSPS and decreased as the travel speed increased. Furthermore, while the collector had a wide opening cross-section compared with the smaller opening cross-section, and whenever the collector had a low setting height compared with when the FSPS had an increased setting height, the CUH was greater.

Varlev (1988) presented a significant analysis and discussion on a particular form of the sprinkler head to define the optimal sprinkler spacing for various wind speeds and two different types of crops under Bulgaria's specific economic conditions. Almeida et al. (2017) proposed a design measurement technique to compare a new system named localised mobile drip irrigation (IRGMO). This system was created to combine the practicality and rusticity of the centre pivot irrigation system with the reliability and water conservation of dripping irrigation systems with the traditional centre pivot system commonly used in Brazil. Compared with the traditional system of fixed drip irrigation lines in the field, this technique enables a 99% reduction in the number of drip tubes.

Valín et al. (2012) developed a simulation model called 'DEPIVOT' to pick a sprinkler package and to evaluate the respective runoff capacity during the crop season of the existing irrigation systems. This model supports all the needed operational parameters to adjust the configuration for a better distribution of the water uniformity of the device (e.g. pivot point pressure, change of ground elevation pressure, and the position of aboveground sprinklers positions), yet adjusting the span size and configuration is also supported by the model. The authors described the model and offered examples of the implementation. Salah et al. (2019) conducted a survey and proposed a theoretical method for analytically evaluating the spaces of the nozzles under particular operating conditions, including the inlet flow rate, wind velocity, and the total radius of the centre pivot irrigation system, without taking into account the effect of friction loss over the pivot.

A genetic algorithm (GA) is a useful technique in engineering to solve the problems of multi-variable optimisation. In the irrigation field, several researchers (Ferdyn-Grygierek & Grygierek, 2017; Leyva et al., 2021; Zhang et al., 2020) has applied a GA successfully to optimise designs. Valipour & Montazar (2012) proposed a new methodology using MS Visual Basic and the GA of the MATLAB software and concluded that it could optimise water distribution and farm size to achieve maximum irrigation status.

The irrigation uniformity of centre pivot spray sprinklers is also affected by climatic conditions. Delirhasannia et al. (2010) investigated an improved model of water application by centre pivot spray sprinklers, using MATLAB software to show the impact of wind on irrigation uniformity. The authors developed and tested a prototype and then used if for the simulation of a case study. They found that for the CUH and the average water depth applied, the resulting simulation errors were 0.02% and 0.08 mm, respectively.

The present study aims to develop a methodology for design optimisation of a Mini-Centre Pivot System, based on sizing nozzles of traditional pivots and comparisons with the actual (original) size of nozzles of the same pivot irrigation system type.

MATERIAL AND METHODS

Characterisation of the area

The study was carried out in a Mini-Centre Pivot System located at the Debila (78 km^2 of the area), 507 km from Alger, in El Oued, southern Algeria. The boundary of the area is: 6.952533°E along the longitude and 33.514810°N along the latitude, at an elevation of 57 m.

System characteristics

The applied method of this study is for irrigating small- and medium-sized farms that are widely used and less costly because their manufacturing cost is low. For an artisanal Mini-Centre Pivot System, the mechanism is lower than the medium operating pressure between 1.0×10^5 and 1.7×10^5 Pa. In southern Algeria, particularly in the El Oued region, a device made by local artisans has been built mostly to irrigate potatoes. Because the improvements in this study only varied based on the nozzle size, the nozzle is an important part of the system. The fixed spray nozzle is the most common kind of nozzle used for the Mini-Centre Pivot System in El Oued. In many existing systems, these nozzles are installed without the use of a pressure regulator. This nozzle is highlighted in Figure 1. It was designed by local artisans to offer the most sprayed water possible. However, the nozzle's wetted diameter is 4.6 mm, and the droplet size of this nozzle can be minimised and maximised by using a flat head screw. Therefore, a large diameter range is available – between 3 and 15 mm. Figure 1 shows the form of nozzles that are used in the Mini-Centre Pivot System.

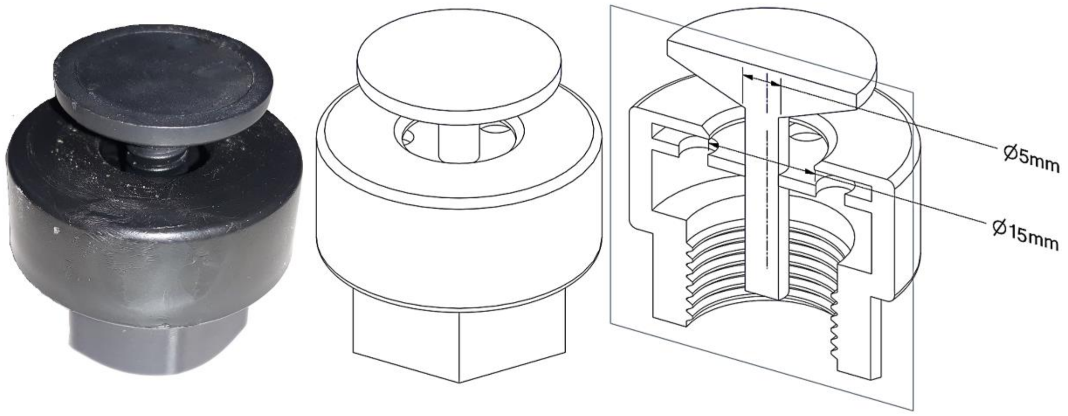

FIGURE 1. The type of nozzle used in the studied Mini-Centre Pivot Systems.

All the studied systems are generated with a rate of 23 m^3 h^{-1} of a water inlet flow, and the variable distance between the nozzles begins with less than 4.6 m near the pivot point and decreases to approximately 1 m at the outer or moving end of the lateral pipe. The system consists of one span including the main water pipeline, nozzles, a supporting trussing structure, a pivot point anchoring the machine to a permanent field spot, and a drive unit usually located at the end of the second third of the lateral pipe far from the pivot point (the system presented in Figure 2).

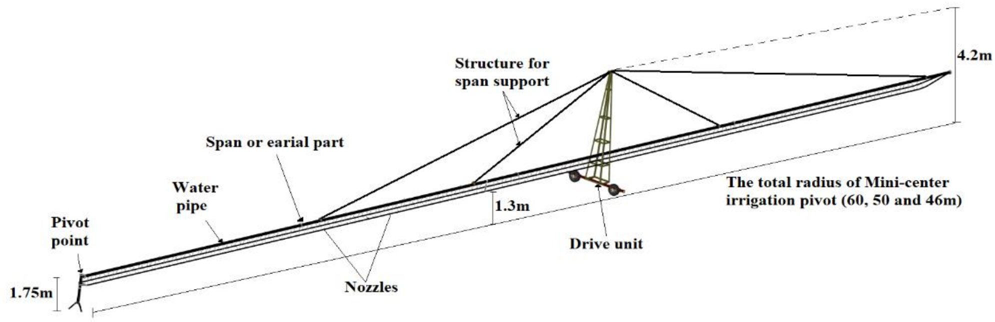

FIGURE 2. The conventional Mini-Centre Pivot Systems used in the study.

In the proposed methodology to optimise the design of a Mini-Centre Pivot System, the nozzle size (diameter) is the only variables. Nevertheless, it is necessary to input parameters for the procedure calculations. The parameters that will be used in the following equations are described in Table 1.

TABLE 1. The properties of the studied Mini-Centre Pivot Systems.

Property and symbol	**Value**
Inlet flow rate (Q_{in}), m^3 h^{-1}	23
Total length (L), m	60; 50; 46
Pipe diameter (D), m	0.06
Pivot pressure (P_0), Pa	1.25×10^5
Nozzle diameter (Φ), mm	13
Regulator's pressure (P_i), Pa	1.034×10^5
Elevation difference (h_0), m	1.3
Kinematic viscosity at 25 °C (ϑ), m² s^{-1}	0.884×10^{-6}
The density of the fluid (ρ), kg m^{-3}	10^3

The international standards stipulate that the normalisation factor of the CUH should be > 80% to provide uniform water (Bliesner & Keller, 1990). Centre pivots cannot operate properly if the nozzle's discharge along the system is not appropriate. In these systems, the circular irrigated area determined by the distance x from the pivot point is directly proportional to the square of this distance of the circle's area (if the circle's distance is increased x times, its area will be raised to x^2 times the original area). However, most of the areas of the circles are located on the outer end of the lateral pipe. Figure 3 shows the heterogeneity of water distribution along the lateral pipe of the 46-m-long Mini-Centre Pivot System considering the actual (original) nozzle sizes, using 808 collectors that are uniformly spaced 3 m in all directions over the whole field.

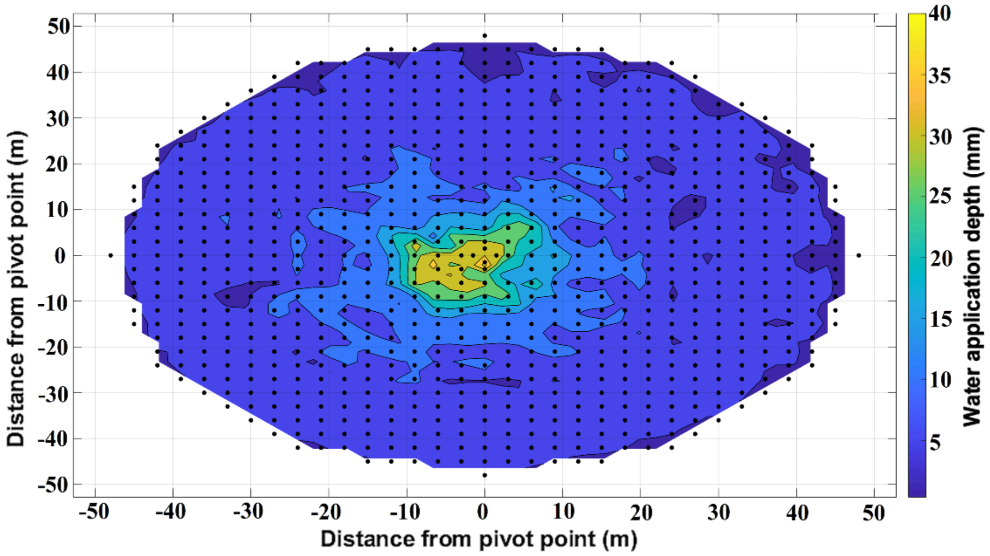

FIGURE 3. The increase in the circular wet areas over the mini-centre pivot system (46 m).

In this traditional system, all the nozzles have the same size (diameter), although the nozzles farthest from the pivot point cover more area (a larger portion of the field). However, as it moves away from the pivot point, the water application depth decreases, a phenomenon that decreases the uniformity of water distribution greatly. Consequently, great efforts should be made to allow an adequate flow rate and a maximum distribution of irrigation uniformity. Therefore, determining the nozzle size of the traditional Mini-Centre Pivot System is a crucial factor for the application and popularisation of this methodology.

Test procedure

The catch can test is a common method for determining the irrigation uniformity of centre pivot systems. The catch cans have a diameter of 8.5 cm in the catchment area, a height of 15 cm, and were positioned in a radial line with a 3-m separation. They were installed on the crop without supports, and the volumes were measured as required with graduated test tubes. The catch can test was performed on the Mini-Centre Pivot Systems as a whole. The radial line along which the catch cans were positioned was far from the pipeline to enable the machine to achieve working conditions before arriving at the test site. By dividing the volume caught by the open area of the catch can, the water depth collected was determined.

Meanwhile, the average wind speed was set at < 3 m s^{-1}, which is considered acceptable according to Robles Rovelo et al. (2019). The CUH was calculated experimentally for the pivots 60, 50, and 46 m in length for both the actual (original) nozzle configuration (i.e. before optimisation) and the optimised configuration by applying the proposed model, where the formulation conditions and equipment are based on ISO 11545:2009 (2009). Before choosing the model for all possible Mini-Centre Pivots Systems, the comparison between the experimental and analytical calculations should be implemented.

Mathematical formulation

Whenever the water is in motion, it should travel in a real way of mass conservation in the central pivot irrigation system. If the flow at the entry and exit points is one-dimensional and does not change with time, as shown in [eq. (1)], the velocity V is constant over area A.

$$Q_{in} = \sum_i^n Q_{out} \tag{1}$$

in which:

Q_{in} - inlet flow rate,

Q_{out} - outlet flow rate.

The Bernoulli equation can be considered a suitable energy conservation theory for moving fluids, and for an incompressible fluid, the simple form of the Bernoulli principle is appropriate. The level of attitude representation for the nozzles is the attitude reference frame $h_i = 0$. Despite the complexity of the process, in a simplified form, the Bernoulli principle can be represented by [eq. (2)]:

$$v_i = \sqrt{\frac{2(P_0 - P_i - \Delta P_{i(l+s)})}{\rho} + v_0^2 + 2gh_0} \tag{2}$$

in which:

v_i - outlet velocity of the nozzle (m s^{-1});

ρ - density of the fluid (kg m^{-3});

g - acceleration of gravity (m s^{-2});

h_0 - elevation difference between the pivot point and the position of the last nozzle (m), which can be positive or negative;

P_0 - pivot pressure (Pa);

v_0 - water inlet velocity at the pivot point (m s^{-1});

P_i - outlet pressure of the nozzle (Pa),

$\Delta P_{i(l+s)}$ - total head loss pressure (Pa).

To allow a wider flow rate range for optimal efficiency, the research needs a universal pressure regulator before each nozzle. To avoid nozzle damage, this pressure also needs to be held within a range of 15 PSI (or 1.034 bar) based on the Nelson sprinkler data. Consequently:

$$P_1 = P_2 = P_3 = \dots P_n \tag{3}$$

The total pressure loss in the system is given by the following equation:

$$\Delta P_{i(l+s)} = \Delta P_{i_l} + \Delta P_{i_s} \quad (4)$$

in which:

ΔP_{i_l} - linear pressure loss,

ΔP_{i_s} - pressure loss in the nozzle.

The pressure drop caused by the flow conditioner ΔP_{i_s} is presented in [eq. (5)].

$$\Delta P_{i_s} = k\rho \frac{v_i^2}{2} \quad (5)$$

in which:

k - pressure loss coefficient of a flow conditioner,

v_i - average velocity in the pipeline or the bulk velocity in the pipe, which is the volume flow divided by the cross-sectional area.

The extra losses due to entries and exits, orifices, and valves are historically referred to as minor losses in process piping. Further energy dissipation in the flow is reflected by these losses. In this research, orifice losses are considered negligible ($\Delta P_{i_s} << \Delta P_{i_l}$). In this case, [eq. (6)] becomes:

$$\Delta P_{i(l+s)} = \Delta P_{i_l} = \Delta P_i \quad (6)$$

The Darcy–Weisbach equation shows that ΔP_{i_l} is proportional to $L\, d^{-1}$ and V^2. The suggested correlation, still as effective today as in 1850, is:

$$\Delta P_{i_l} = f\left(\frac{L}{D}\right)\left(\frac{\rho v_i^2}{2}\right) \quad (7)$$

in which:

f - dimensionless parameter called the Darcy friction factor;

L - length of the pipe;

v_i - mean velocity of the flow,

D - diameter of the pipe.

Using the Reynolds number – defined by Osborne Reynolds – laminar and turbulent flows can be characterised and quantified. Usually, the flow is laminar for Re < 2100 and turbulent for Re > 4000. For the studied Mini-Centre Pivot System, an equal type of steel pipes is used, and according to many experiences, the kind of flow is known.

For turbulent flow, the Colebrook–White equation should be used to solve almost any problem involving friction losses in long pipe flows. For rough pipes over the entire turbulent flow range, the Colebrook formula provides a reasonable approximation for the relation *f-Re-ε/D* as presented in [eq. (8)].

For turbulent friction, this is the accepted design formula. In 1944, Moody plotted it into what is now known as the Moody pipe friction chart, which is the most popular and useful figure in fluid mechanics. However, the use of a long straight pipe length will increase the loss of friction and will need different diameters of orifices for better flow discharge.

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right] \quad (8)$$

in which:

ε - degree of roughness, with *ε* = 0.0014 for seamless steel pipes. Except when a variable spray nozzle diameter is used instead of a constant nozzle diameter, the spray mist system is identical to the variable spacing system.

As shown in Figure 4, a uniform flow is produced by using a variable nozzle size until the end of the central pivot irrigation system.

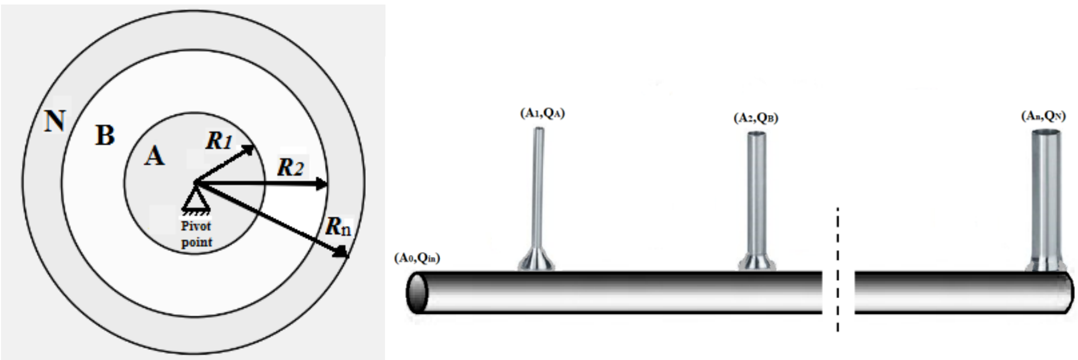

FIGURE 4. The uniform flow discharge for the variable nozzle size for a Mini-Centre Pivot System.

Section $A = \pi R_1^2$
Section $B = \pi R_2^2 - \pi R_1^2$
Section $N = \pi R_n^2 - \pi R_{n-1}^2 - \cdots - \pi R_2^2 - \pi R_1^2$
in which
section N > section N-1 > … > section B > section A, and section A+B+…N = section total S_{total}.

Equation 9 calculates the nozzle's discharge along with the Mini-Centre Pivot System.

$$Q_i = \frac{S_i}{S_{total}} Q_{in} \quad (9)$$

There is a growing body of literature suggesting that the flow is usually completely turbulent in an orifice emitter. Orifice flow rates are better defined as a function of operating pressure by empirically measuring the flow levels. This empirical characterisation is called the function of the orifice flow, which is presented in [eq. (10)]:

$$q_i = \mathrm{K} * (P_i)^x \quad (10)$$

in which:

q_i - flow rate of the nozzle;

K - a factor that characterises the orifice dimensions,

x - orifice exponent, which characterises the flow regime.

The coefficients K and x are determined by plotting q versus P_{nozzle} on a log-log plot. The slope of the straight line is x, and the intercept at P_{nozzle} = 1.0 is K. The orifice discharge exponent is x = 1.0 for laminar flow, x = 0.5 for turbulent flow, and x = 0 for compensating flow.

Hermann and Hein uniformity coefficient

Centre pivot irrigation system efficiency can be estimated by using indicators adapted to the system (Barbosa et al., 2018). The CUH is used widely to describe the distribution of water uniformity, and the most common interval of water application efficiency with such systems is about 90% (Lecina et al., 2016). The CUH should be > 80%; any other type of system that has a CUH below this value should not be used (Bliesner & Keller, 1990). In this research, Hermann and Hein's modified formula was adopted to measure the water distribution uniformity. The equation given below (Equation 11) was proposed by ISO 11545:2009.

$$CUH = 100 * [1 - [\sum_{j=1}^{m}(S_j \mid h_j - h_{moy} \mid)/\sum(h_j * S_j)] \ [\%] \quad (11)$$

The weighted average volume of water collected h_{moy} is computed as shown in [eq. (12)]:

$$h_{moy} = \sum_{j=1}^{m}(S_j * h_j)/\sum_{j=1}^{m} S_j \quad (12)$$

in which:

m - number of collectors used;

j - a number assigned to classify a particular collector usually starting with the collector located nearest to the pivot point j = 1 and finishing with $j = m$ for the collector far from the pivot point;

h_j - volume or mass of water collected in the j^{th} collector;

h_{moy} - weighted average volume of water collected,

S_j - distance from the pivot point of the j^{th} collector.

Optimisation problem

This paper presents a procedure using the GA optimisation model to make design changes for a Mini-Centre Pivot System based on sizing nozzles. The MATLAB genetic algorithm toolbox (Saraswat, 2013) solves the optimisation problem of the continuous variables mentioned above. Based on the conceivable range variables of design, an initial random population variable of the design is generated. Before the conditions for the stoppage are completed, the iterative search process is conducted. During this cycle, the penalty function method will exclude them in the subsequent evolution method if there is an individual who fails to meet one of the conditions of limitation (see Figure 5). The maximum generative number is set at 100. The initial population consists of 100 individuals who adopt the method of rank scaling. Crossover distributed stochastic uniform selection and mutation of the default constraint is used.

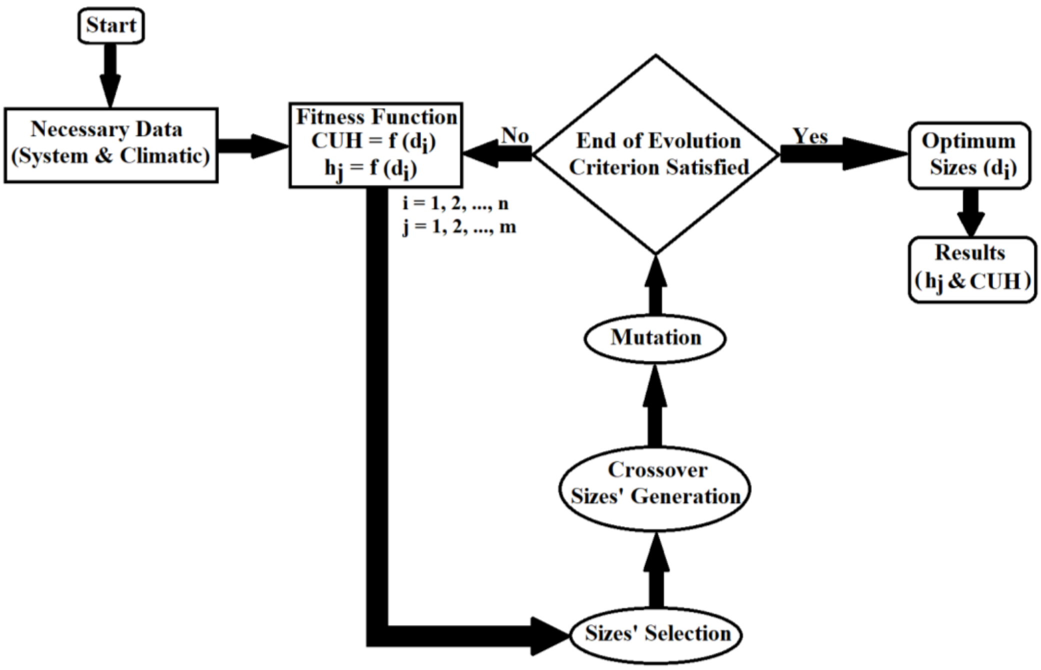

FIGURE 5. The main steps of the studied genetic algorithm optimisation method. CUH, Heermann and Hein uniformity coefficient.

After 100 generations, the objective function is constant and reaches the maximum value when the condition of termination is reached. The best individual is selected according to the value of the fitness function of each individual for each generation in the process of evolution. The optimisation aims to maximise the uniformity coefficient of a Mini-Centre Pivot System 60, 50, and 46 m in length with single upstream pressure and flow rate by finding the optimal nozzle size that satisfies all the stated nonlinear constraints. In this approach, the adjusted formula of Heermann and Hein is established as the objective function, the conditions of nonlinear constraint are often used, the nozzle size variables are assumed, and the GA is employed for solving the problems of optimisation that may result. The optimised mathematical model corresponding to the problem considered in this work is as follows:

Find $D = \{d_1, d_2, d_3, \dots, d_n\}$ (13)

in which:

d - nozzle diameter.

Maximising the uniformity of water distribution is the most effective criteria for optimisation in centre pivot irrigation systems. The hydraulics parameters are always optimised on this basis. The fitness function is defined as follows (Equations 14 and 15):

$$Minimize \ -p(x) \ such \ as \ x \in S \subset R^n \quad (14)$$

$$p(x) = CUH = 100\left[1 - \frac{\sum_{j=1}^{m} 3(j)\left|h_j^{(k)} - h_{moy}\right|}{\sum_{j=1}^{m} 3(j)\, h_j^{(k)}}\right], \text{ (j = 1, 2, 3…, m)} \quad (15)$$

in which:

m - the number of collectors.

Determining the nozzle diameter is one of the significant factors in the hydraulic design of centre pivots. For the optimal design, a GA method was applied to obtain a precise, optimised model for sizing sprinklers over the pivot. In this model, all the possible volume of the collected water is represented by specifying a nozzle mass (mm), a surface of the collector (m^2), and a difference between the increased circular area (m^2). Thus, a volume of the collected water in the *jth* collector is represented in [eq. (16)]:

$$h_j^{(k)} = \frac{S_{coll}}{\pi(l_i^2 - l_{i-1}^2)}\, h_i^{(k)}, \text{ (i = 1, 2, 3…, n)} \quad (16)$$

The volume of water collected is estimated by using [eq. (17)]:

$$h_i^{(k)} = \frac{\pi^2}{16\, K^2\, \rho g}\, {d_i^{(k)}}^4 \left[2\ 10^2 \left(P_0 - P_i - 0.074 l_i^{(k)}\right) + v_0^2 + 2gh\right] \quad (17)$$

Equation 18 describes how to compute the average weight volume of water collected by the nozzles:

$$h_{moy} = \frac{\sum_{j=1}^{m} 3(j)\, h_j^{(k)}}{\sum_{j=1}^{m} 3(j)} \quad (18)$$

in which:

l - nozzle distance from the pivot point;

S_{coll} - surface of the collector,

n - number of nozzles.

The conditions for the nonlinear constraints are that the size of any nozzle should be between 5 and 15 mm, and the size increases when the sprinkler is far from the pivot point.

$$\begin{cases} 5 \le d_i \le 15\ mm, \\ d_i > d_{i-1} \end{cases} \quad (19)$$

RESULTS AND DISCUSSION

Optimisation results

After 100 generations, the optimal solutions for each nozzle size of the Mini-Centre Pivot Systems 60, 50, and 46 m in length are presented in Figure 6. The optimisation results indicate that the adjusted CUH increases as the size of the nozzle increases starting with the nozzle next to the pivot point and terminating with the nozzle farthest from the pivot point. The findings obtained from the optimisations can be observed in Figures 6, 7, and 8. These results are in a summary form to provide an overview of the data obtained for each optimisation.

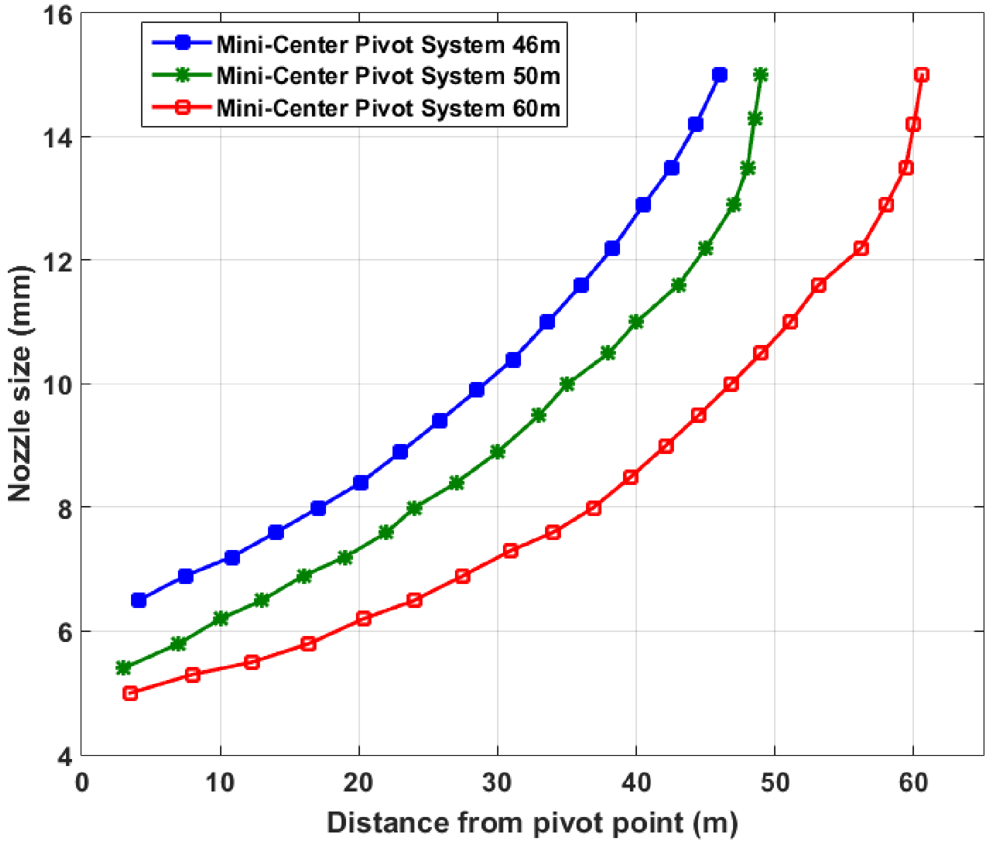

FIGURE 6. The optimal nozzle size of the studied Mini-Centre Pivot Systems.

If the values of these effective parameters are all well identified, an accurate model is obtained that will provide the optimal nozzle sizes. The right model will be used to optimise the overall efficiency of the centre pivots systems.

For each system examined, the measured catch can volumes are compared with the volumes given by the proposed model in Figure 7.

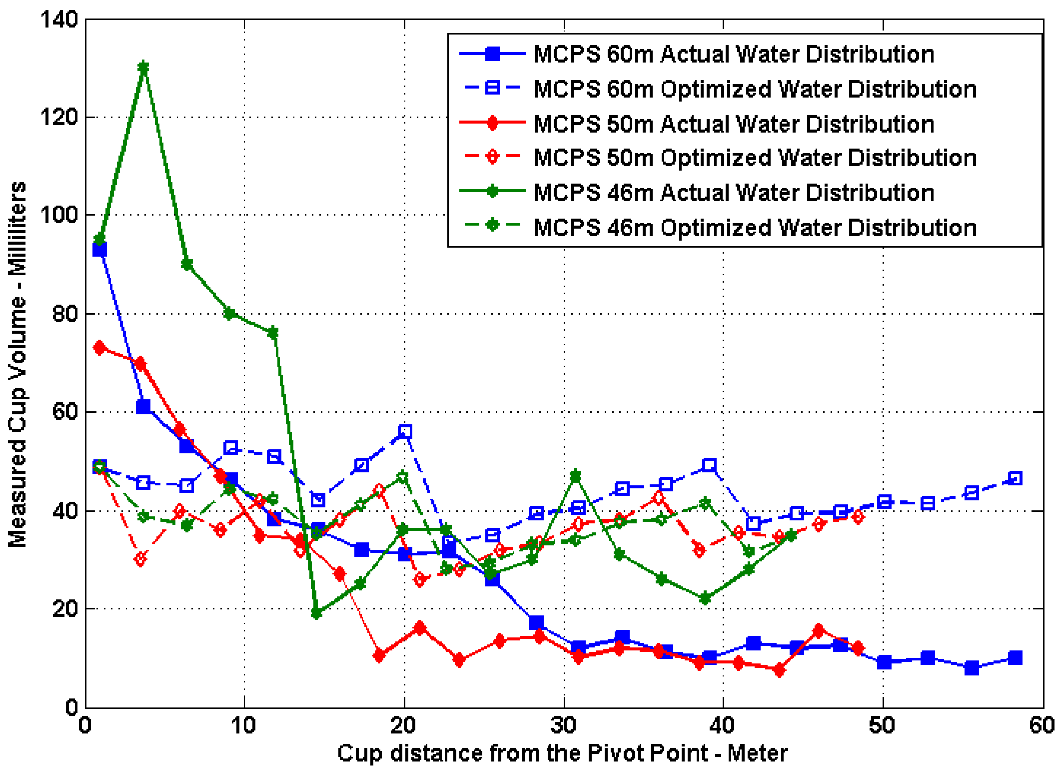

FIGURE 7. A comparison of the measured catch can volumes for the studied Mini-Centre Pivot Systems.

Figure 7 shows the actual water distributions of the Mini-Centre Pivot System. These distributions indicate the heterogeneity of water along the lateral pipe for each system and their respective inadequate flow discharge. The volume of water collected in catch cans decreases drastically near the pivot point to approximately 15 m from the pivot point. After that, there is a gradual decrease in inappropriate volumes of water collected until the end of the pivot. These reductions in catch can volumes along the lateral pipe reduce the water distribution uniformity; hence, the productivity of the crop decreases. The methodology for the nozzle sizing of the Mini-Centre Pivot System revealed a slight decrease in volumes of catch cans along the lateral pipe of the systems, which gives a suitable average volume of water collected in all catch cans. Therefore, an adequate flow delivery by each nozzle allows a uniform water distribution for every distance from the pivot point along with the system. Consequently, the water application uniformity along the studied Mini-Centre Pivot Systems is improved.

The experimental validation

For the actual nozzle distribution of the studied Mini-Centre Pivot Systems (before optimisation), the nozzle sizes were measured with computation of pressure at each outlet. These nozzles have approximately the same diameter, namely 13 mm. In addition, as the pressure regulator is not used in these traditional systems, the experimentally measured pressure at each outlet of the nozzle when the system is running is inserted into the model as a vector in place of pressure regulators. In this case, the experimentally measured CUH was 64.34%, 59.58%, and 69.92% for the 60 m, 50 m, and 46 m Mini-Centre Pivot Systems, respectively.

Then, the results of the experiments that analytically measured the CUH for the existing systems in the actual and optimised nozzles distribution by the research are compared with the CUH calculated experimentally before the optimisation. Figure 8 shows a comparison of these findings.

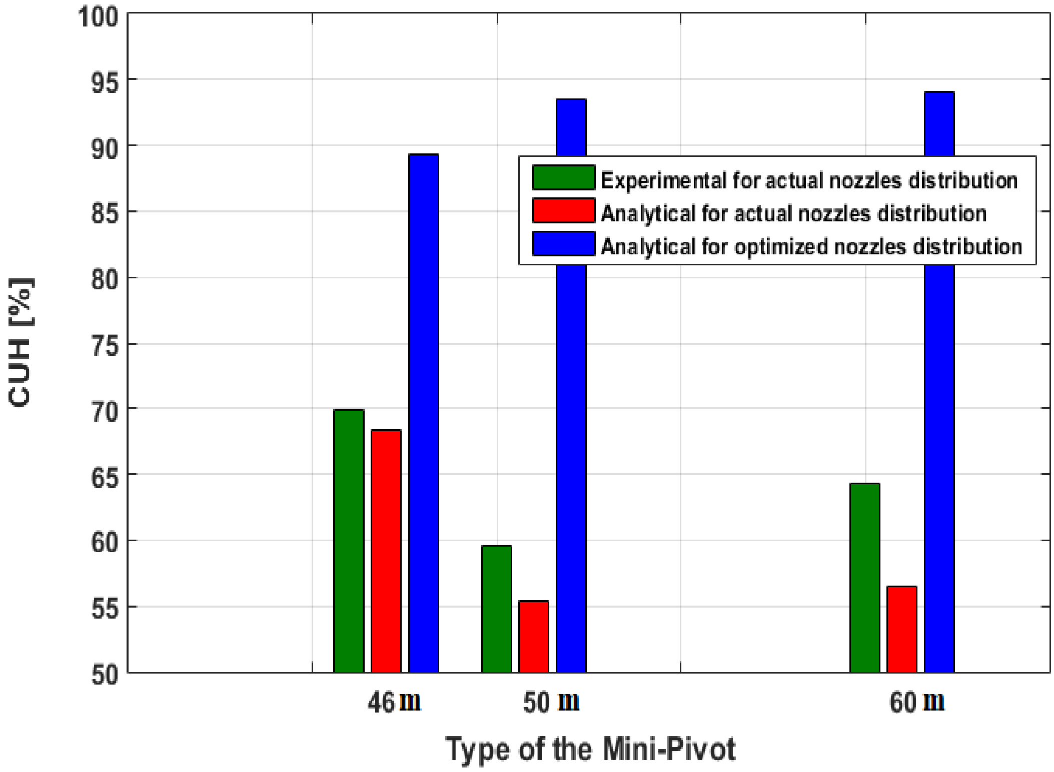

FIGURE 8. A comparison of the experimental and analytical Heermann and Hein uniformity coefficient (CUH).

The methodology using a GA for sizing nozzles of a Mini-Centre Pivot System revealed that if the operating conditions and system characteristics are well defined, the difference between the experimental and modelled CUH is acceptable (7.86%, 4.17%, and 1.62% difference for the 60, 50 and 46 m Mini-Centre Pivot Systems, respectively). As seen in Figure 8, there is no significant difference between the experimental and modelled CUH for the actual nozzle size of each studied system. This finding validates the outputs of the presented methodology when the parameters of the system are well defined, and the operating conditions are well determined.

There is a notable peculiarity of the methodology, namely the possibility of estimating the experimental uniformity of irrigation based on the calculation using the proposed methodology for a Mini-Centre Pivot System. This occurs due to rounding in the CUH calculation in the methodology.

For the studied Mini-Centre Pivot System, the CUH of the sized nozzles where the pressure regulator was used are much higher than in actual (original) nozzles in three optimised situations. On average, the uniformity of irrigation increases by more than 32% based on this new methodology. Therefore, using the presented methodology for sizing nozzles guarantees that this type of system obtains an adequate improvement in efficiency. Another advantage of the optimisation methodology is the possibility of estimating the CUH with or without pressure regulators, when the nozzle's pressure is measured experimentally and then inserted in the model as a vector. The CUH could be used in the future to improve the irrigation efficiency in a centre pivot equipped with fixed sprinklers (FSPS) by switching the FSPS to rotating sprinklers (RSPS), as found by Li et al. (2020).

CONCLUSIONS

The traditional Mini-Centre Pivot System is commonly used for irrigating crops in the El Oued region, southern Algeria, and its use has increased rapidly. The original design provides water with a CUH < 80% unless the configuration of the nozzles along the lateral pipe is altered. The proposed methodology enables design optimisation in new project deployments as well as modifications to existing systems in the field. In addition, even though this new technology requires well-defined operating conditions and characteristics of a Mini-Centre Pivot System, this optimised design provides nozzle sizes that improve the uniformity of irrigation, with a substantial increase in both yield and higher quality agricultural products compared with the actual (original) nozzle distribution of a Mini-Centre Pivot System.

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