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Developing an optimal plan to improve irrigation efficiency using a risk-based central force algorithm

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ABSTRACT

Losses in surface irrigation include deep percolation and runoff, which is one of the ways to increase the efficiency of furrow irrigation, using a closed-end mode in irrigation systems. This research was conducted to evaluate the effects of geometrical variables (slope and length of furrow) and flow control (inflow rate and cut-off time) on application efficiency (AE) and the uniformity of water distribution in a closed-end furrow irrigation system. The length, slope, inflow rate, and cut-off time are considered as the decision-making variables for developing the multi-objective genetic algorithm based on the non-dominated sorting. For this purpose, three irrigation furrows with the closed-end system were considered. The optimization algorithm for calculating the objective functions involves maximizing the minimum water depth and minimizing the infiltration depth in a modeling loop. The optimization algorithm was linked to the WinSRFR software to calculate the objective functions. The results showed that the best combination of inflow rate and the cut-off time for 75 mm of required water depth was 1.9 L/s/m and 150 min, respectively, which increased AE and distribution uniformity to 79 and 78%. Furthermore, the AE in the closed-end furrow irrigation system is higher (30–50%) than the open-end method in different scenarios.

Key words: central force algorithm, closed-end furrow irrigation system, infiltration equation parameters

HIGHLIGHTS

- The optimization model of the central force algorithm has been used to design the water distribution system in the farm.
- The application of optimal design could increase the efficiency of irrigation adequacy and the uniformity of distribution.
- The proposed modeling is a suitable tool for increasing crop production and water efficiency in agriculture.

INTRODUCTION

Runoff and deep percolation (DP) are the main problems of surface irrigation, and various studies have been conducted to increase water use efficiency and distribution uniformity (DU) of this system (Ebrahimian & Liaghat 2011; Lalehzari & Boroomand-Nasab 2017). The optimal design of surface irrigation with the aim of determining and managing variables of flow rate, cut-off time, geometric parameters, etc., is necessary to reduce losses and increase irrigation efficiency (Bautista *et al.* 2009a, 2009b). Due to the large number of parameters affecting surface irrigation and their temporal and spatial variations, as well as the complexity of surface irrigation management to achieve high efficiency and uniformity, the use of tools that can be achieved with proper design to achieve the maximum water efficiency is inevitable (Lalehzari *et al.* 2015).

Design, management, and evaluation of surface irrigation can be achieved by modeling the surface and subsurface flows before the irrigation process. Various models of irrigation water flow such as hydrodynamics (Katopodes & Strelkoff 1977), zero inertia (Strelkoff & Katopodes 1977), and kinematic wave (Walker & Humpherys 1983) have been obtained based on the Saint-Venant equations (Chow 1959; Strelkoff 1969). Furthermore, volume balance has a wider range of applications due to its simplification, accuracy, instability, and divergence for simulating water flow at the soil surface (Ebrahimian & Liaghat 2011; Lalehzari & Boroomand-Nasab 2017). The use of modeling tools in designing irrigation parameters has been considered by many researchers (Eldeiry *et al.* 2005; Ampas & Baltas 2009; Lima *et al.* 2014).

Soil water infiltration is one of the most sensitive hydraulic parameters affecting surface irrigation, and infiltration equation coefficients are one of the most difficult parameters to estimate. Different methods have been used in previous studies to

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estimate the infiltration coefficients. Ebrahimian *et al.* (2010) evaluated the numerical and analytical methods in estimating permeability parameters in furrow and furrow irrigation. Sepaskhah & Afshar-Chamanabad (2002) used the advance, recession, and storage curves to determine the infiltration parameters of the Kostiakov–Lewis equation at various regiems of furrow irrigation.

Holzapfel *et al.* (2004) compared two-point, advance curve, and furrow infiltration methods to determine the coefficients of the Kostiakov equation. Khatri & Smith (2005) used the advance curve data and Gillies & Smith (2005) used the advance curve and runoff data to calculate the parameters of the modified Kostiakov infiltration equation in furrow irrigation. In another study, the two-point method and the INFILT and IPARM models in estimating the parameters of the modified Kostiakov infiltration model were compared (Ebrahimian 2014). The results of the study showed that the IPARM model had more accurate results than the other two methods in all three irrigation methods. Moravejalahkami *et al.* (2009) estimated the influence of Kostiakov–Lewis infiltration in furrow irrigation and showed that the multilevel calibration method performed better than the two-point method. The abilities of optimization tools can also be used to estimate the parameters of infiltration equations. Among the various intelligent methods, the optimization algorithm based on non-dominated sorting has been introduced as one of the meta-heuristic methods as a suitable tool to find the decision variables in multi-objective problems. Therefore, the present study aimed to use the central force algorithm (CFA) in estimating the parameters of the infiltration equation and the soil roughness coefficient in the surface irrigation simulation model to improve the modeling performance with the aim of designing and optimally managing furrow irrigation. In this regard, the concept of simulation–optimization has been used with the link of the WinSRFR surface irrigation simulation model to the CFA in the MATLAB software. Finally, the interaction curves of the irrigation system were used as a new and efficient management tool to provide the optimal design and management of furrow irrigation.

MATERIAL AND METHODS

Data source

The information used was conducted through a field experiment with a closed-end furrow irrigation system. Experiments were created in furrow with dimensions of 120 m by 8 m, and a uniform longitudinal slope of 0.001 was set. In this research, four irrigations (I1, I2, I3, and I4) were carried out with a flow rate of 15 L/s in a closed-end furrow irrigation in the rape field. In order to measure the progress and regression curves, the furrow irrigation was stationed at 20 m intervals.

Conceptual model

A conceptual framework has been defined to develop a simulation and optimization process to search for the optimal response from the feasible domain of geometric parameters (length, width, and slope) and flow (inflow rate and cut-off time) for a furrow irrigation system. Five decision variables are initially defined in the possible range within 50% of the test range and for the optimal values obtained at the end of modeling; sensitivity analysis, in the range of 10, 25 and 50%, is done. The parameters p and q are the two hypothetical members of the population in the optimization algorithm. The objective functions (OF1 and OF2) and the constraints considered in the optimization problem are:

$$\text{Max OF}_1 = D_{\min}/D_{\text{req}} \tag{1}$$

$$\text{Min OF}_2 = D_{\text{dp}}$$

Subject to:

$$D_{\min}/D_{\text{req}} \leq 1$$

$$D_{\text{dp}} < D_{\min}$$

$$0 < k < 10$$

$0 < a \leq 1$

$0 \leq b \leq 15$

$0 \leq c \leq 5$

$0.01 \leq n \leq 0.1$

In the above equation, D_{min}, D_{req}, and D_{dp} are the minimum infiltration depth, required water depth, and DP, respectively. The constraints of the problem include the limits of variation of the coefficients k, a, b, and c (modified Kostiakov infiltration equation (Equation (2)) as well as the Manning roughness coefficient, n, which the extreme points have been obtained based on soil texture and various model runs to estimate the best amplitude of each.

$$Z_n = kt^a + bt + c \tag{2}$$

where Z_n is the cumulative depth of water infiltration into the soil (mm), and t is the opportunity time (h).

Optimization and evaluation

As mentioned, for repetitive calculations between simulation and optimization models, two opposing objectives of maximizing the ratio of the minimum water depth to the required water depth (mm) and minimizing the depth of infiltration height (mm) were used. The process is as follows: first, the coefficients of the infiltration equation and the Manning roughness coefficient are calibrated by a genetic algorithm based on the advance and recession information in an experiment, and the best values are estimated based on the root mean square error (RMSE) index. These coefficients are placed as definite data in a matrix as an input file to WinSRFR.

The next step is to create a matrix of problem decision variables including input flow, cut-off time, length, width, and slope of the furrow in the feasible domain. The feasible domain is equal to a 50% increase for the upper limit and a 50% decrease to determine the lower limit of the decision variables. The matrix of problem decision variables is converted by the developed code into the input structure of WinSRFR software and stored in its input folder. The software simulation window in the multiple execution section reads the information generated by the optimization algorithm, the furrow irrigation simulation is performed in turn for each stored dataset, and the output parameters are recorded in the same folder.

After the simulation runs (initial population = 1,000 runs), the evaluation parameters are imported by MATLAB. In this step, the objective functions are sent for ranking, and all members of the population are assigned a rank and front number. The selection operator from the genetic algorithm selects two members from the weaker fronts and sends them to the mutation and crossover operators. With the changes applied to the original population members and the generation of new members, the non-dominated sorting and crowding distance applications classify all members and select the best members according to the number of the initial population.

Other evaluation criteria (application efficiency (AE), DU, etc.) are coded for the members in the first front of the set of solutions to be used in the process of analysis and the selection of the optimal solution from the Pareto front. The termination criterion in this mechanism is based on the convergence of the responses located at extreme points of the Pareto front.

Central force algorithm

In multi-objective optimization problems, the model constitutes a n-dimensional space (n is the number of objectives) of the optimal solutions that for every X response in the feasible domain, there is a corresponding point in the objective function range (Deb *et al.* 2002). In a demographic algorithm with n objectives in the minimization process, if the following two conditions are met at the same time, the solution p dominates q:

$$p \leq q \quad \rightarrow \quad \begin{cases} f_n(p) \leq f_n(q) & \forall \quad n = 1,\ 2,\ \ldots,\ N \\ f_n(p) < f_n(q) & \exists \quad n = 1,\ 2,\ \ldots,\ N \end{cases}$$

The solution p in all objective functions should not be worse than the solution q, and p should be better than q in at least one objective function. Accordingly, all solutions that are not dominated by other points are considered non-dominated. In a two-objective function, the set of solutions is placed in a two-dimensional space, in which the form of the Pareto front depends on maximizing or minimizing each of the objectives. The solutions located in the feasible domain are possible but not optimal, and if the improvement of any objective function is directed toward increasing or decreasing, one of the boundaries is introduced as the optimal solution or the Pareto front. In the present study, the minimization of functions has been used for a more appropriate description due to the formation of a recognizable front.

To find the optimum values for objective functions in each iteration, the CFA was used. The CFA was introduced by Formato by adapting the phenomenon of gravitational force on objects. Gravity is a vector force that is applied to objects that are placed at different distances relative to each other (Formato 2007). The amount of this force is directly proportional to the product of the mass in the object and inversely proportional to the square of the distance between the centers in the object. For this reason, the name of this algorithm is central force optimization. More details are in Formato (2007).

Error analysis

After calibrating the mentioned parameters, correlation and error relationships between the observed and estimated values were used to evaluate the accuracy of the WinSRFR model in predicting advance and recession times. For this purpose, four indicators including RMSE coefficient of determination (R^2), coefficient of residual mass (CRM), and model efficiency (ME) have been used.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (x_s - x_o)_i^2}{n}}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n} (x_o - \overline{x_o})(x_s - \overline{x_s})}{\sum_{i=1}^{n} (x_o - \overline{x_o})^2 \sum_{i=1}^{n} (x_s - \overline{x_s})^2} \right)^2$$

$$\mathrm{CRM} = \frac{\sum_{i=1}^{n} x_o - \sum_{i=1}^{n} x_s}{\sum_{i=1}^{n} x_o}$$

$$\mathrm{ME} = \frac{\sum_{i=1}^{n} (x_o - \overline{x_o})^2 - \sum_{i=1}^{n} (x_s - x_o)^2}{\sum_{i=1}^{n} (x_o - \overline{x_o})_i^2}$$

where x_o and x_s are the measured and predicted values at each point, respectively, $\overline{x_o}$ and $\overline{x_s}$ are the average of the measured and predicted values, respectively, and n is the number of observations. The coefficient of determination is between zero and one variable, and the values close to one show better results. The CRM, which indicates the overestimation and underestimation of the model relative to the actual values, is calculated with positive and negative signs, respectively. The efficiency of the model varies from one for the best case to $-\infty$ for the worst case.

Design of inflow rate and cut-off time

In this study, in order to investigate the performance of combining different values of input flow rate (Q) and the cut-off time (T_{co}) and the optimization of these decision variables, the analysis of efficiency cores was used. This analysis shows the changes in irrigation performance parameters as a function of decision variables and is based on the maximum yield. The analysis may provide an operational recommendation for the medium estimated ground conditions (infiltration, roughness, and depth of use) or may suggest the need for an alternative design. These curves are created by interpolating the model simulation results into rectangular grids of points and generating efficiency-level lines in a possible space of flow values and cut-off times. Efficiency parity curves in this study include AE, DU, and percentage of DP.

In this process, as decision variables, 10 flow rates based on the minimum and maximum allowable flow inlets and the optimal efficiency of irrigation efficiency in the range of 5–20 L/s and 10 cut-off times in the range of 90–240 min (per the basis of considerations related to water reaching the end of the furrow and the optimal limit of irrigation efficiency) were considered, and with the implementation of the model, performance parameters were determined.

RESULTS AND DISCUSSION

Calibration

The parameters of the modified Kostiakov infiltration equation and the Manning roughness coefficient estimated by calibration are summarized in Table 1. The Manning roughness coefficient has increased from the first to the fourth irrigation due to the growth of rape crop and the increase of plant cover. The accuracy of predicting the time of advance and reversal by these coefficients is shown in Table 2. According to the table, the accuracy of the coefficients estimated by the CFA optimization model was acceptable.

Sensitivity analysis

Each calibration model with the aim of finding decision variables in order to adapt the observational and computational information requires the sensitivity analysis of the developed model to changes in the estimated uncertain values. Figure 1 shows the results of the model sensitivity analysis to changes in the coefficients of infiltration and the roughness equation. Based on the results obtained from this figure, increasing the coefficient k at the level of 10% has a greater error than decreasing it, and therefore, further estimation will lead to the underestimation of computational data. The sensitivity of the simulation model to changes in the coefficient a is less than the coefficient k. The maximum squared value of the mean squares error for this parameter is 3.87 min, which is obtained by a 50% increase. The highest sensitivity of the infiltration equation goes back to the exact calculation of the coefficient b in the calibration process. Because the opportunity time of infiltration is multiplied in the parameter b and becomes more important during the advance and recession phases with increasing time. A 50% decrease in the coefficient b causes an error of 11.07. The underestimation or overestimation of b causes flooding or a rapid decrease of flow in the recession phase, especially at the end of the furrow, and its effects in the advance phase are relatively the same with other parameters.

The parameter c in the modified Kostiakov infiltration equation, the value of which is zero in the first and second irrigations and 0.8 and 0.9 in the third and fourth irrigations, respectively, does not have much effect on the model sensitivity. Because the range of error changes is small and negligible. In bands with a shorter flow or cut-off time and in the advance phase, to

Table 1 | Calibrated parameters using the CFA

	Infiltration coefficients				**Manning's roughness coefficient**
Irrigation	***k*** **mm/h^a**	***a*** **–**	***b*** **mm/h**	***c*** **mm**	***n*** **m$^{1/6}$**
I1	2.67	0.63	5.67	0	0.0415
I2	3.36	0.54	6.65	0	0.0421
I3	4.13	0.48	7.46	0.78	0.0425
I4	3.96	0.47	7.82	0.87	0.0432

Table 2 | Accuracy of the calibrated experiments

	RMSE (min)		***R*^{2}**		**CRM**		**ME**	
Irrigation	**Advance**	**Recession**	**Advance**	**Recession**	**Advance**	**Recession**	**Advance**	**Recession**
I1	3.6	6.8	0.99	0.992	−0.01	−0.005	0.99	0.97
I2	4.3	9.6	0.98	0.980	−0.048	0.009	0.99	0.96
I3	3.8	9.7	0.98	0.982	−0.018	−0.004	0.99	0.97
I4	4.4	11.2	0.98	0.971	0.037	0.03	0.98	0.97

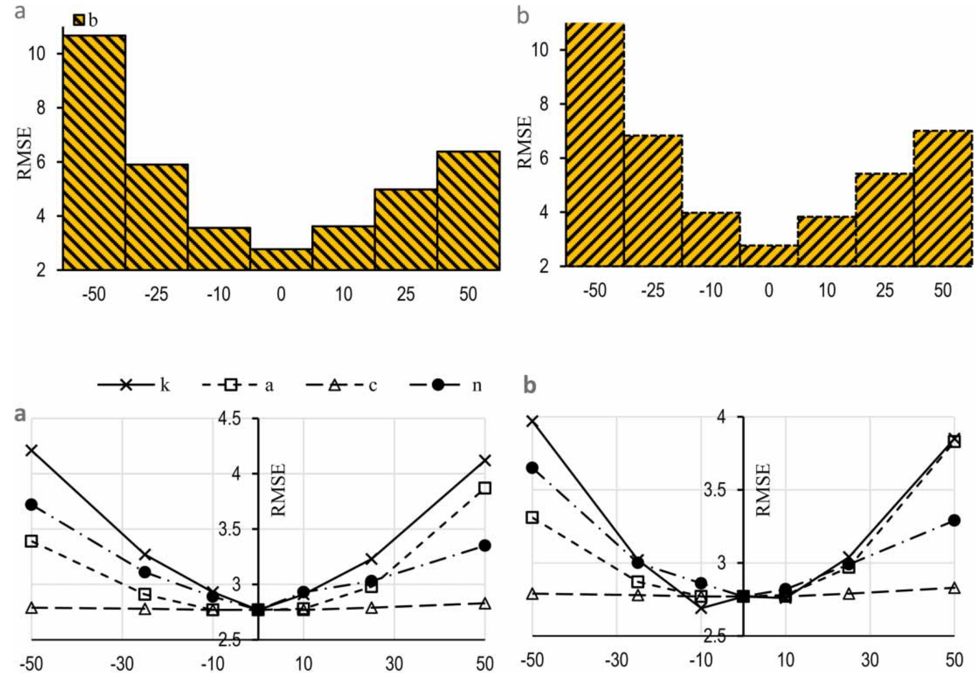

Figure 1 | Sensitivity analysis of the closed-end furrow irrigation simulation model depending on calibration coefficients (a) advance phase and (b) recession phase).

achieve the best time near the measured values, the coefficient *c* in the range of positive numbers close to zero is searched by the optimization model. The study was obtained for the coefficient *a* less than 0.5 equal to zero. The effect of this parameter in the advance phase is greater than the recession phase. Sensitivity analysis of the simulation model to the Manning roughness coefficient shows that the overestimation or underestimation of this parameter will have the same effect on the accuracy of the results. The results showed that the roughness coefficient had a different effect on the advance and recession phases. The flow velocity on the soil surface is affected by increasing the roughness coefficient and increasing the volume of water infiltrated in the advance phase. While in the evaluated system, the infiltration process in the recession phase was influenced by the texture and structure of the soil.

Efficiency curve

Figure 2 shows the AE, DU, and DP curves in selecting the optimal flow rates and water cut-off times in closed-end furrow irrigation. In this figure, the dotted line shows the position of the set of points equal to the depth required for irrigation ($D_{\mathrm{req}} = 75$ mm) and the minimum depth of infiltrated water ($D_{\min}$). In fact, this line indicates the location of points of Q and T_{co} where the required depth of irrigation is provided at the beginning of the furrow. The Q–T_{co} compounds to the left of the dotted line show $D_{\min} < D_{\mathrm{req}}$, whereas on the right is $D_{\mathrm{req}} < D_{\min}$.

The AE in conditions of water shortage (to the left of the dotted line) gradually increases and will have its maximum value and decreases on the right side of the graph with an increasing flow rate and the cut-off time. Therefore, although in the left part of the dotted line, different combinations of the inflow rate and the cut-off time achieve high AE, irrigation adequacy is less than 100% due to not providing the minimum required water depth at the beginning of the furrow.

The existing conditions, which are shown with a dark circle on the left side of the diagram, are one of these situations that with 98% AE cannot provide the water needed by the plant. To meet the required irrigation depth at the beginning of the furrow, the inflow rate and the cut-off time should be selected along the $D_{\mathrm{req}} = D_{\min}$ line. According to Figure 2, the inflow rate of 1.9 L/s per unit width of the furrow and the cut-off time of 150 min can provide the required depth of irrigation with an AE of about 80%.

In the open-end furrow irrigation system, runoff has a greater role in reducing water use efficiency than DP (Ebrahimian & Liaghat 2011). But in closed-end conditions, the only effective factor in controlling the efficiency of irrigation water application is DP. Therefore, the pattern of changes in the equilibrium curves of DP corresponds to the AE and in the

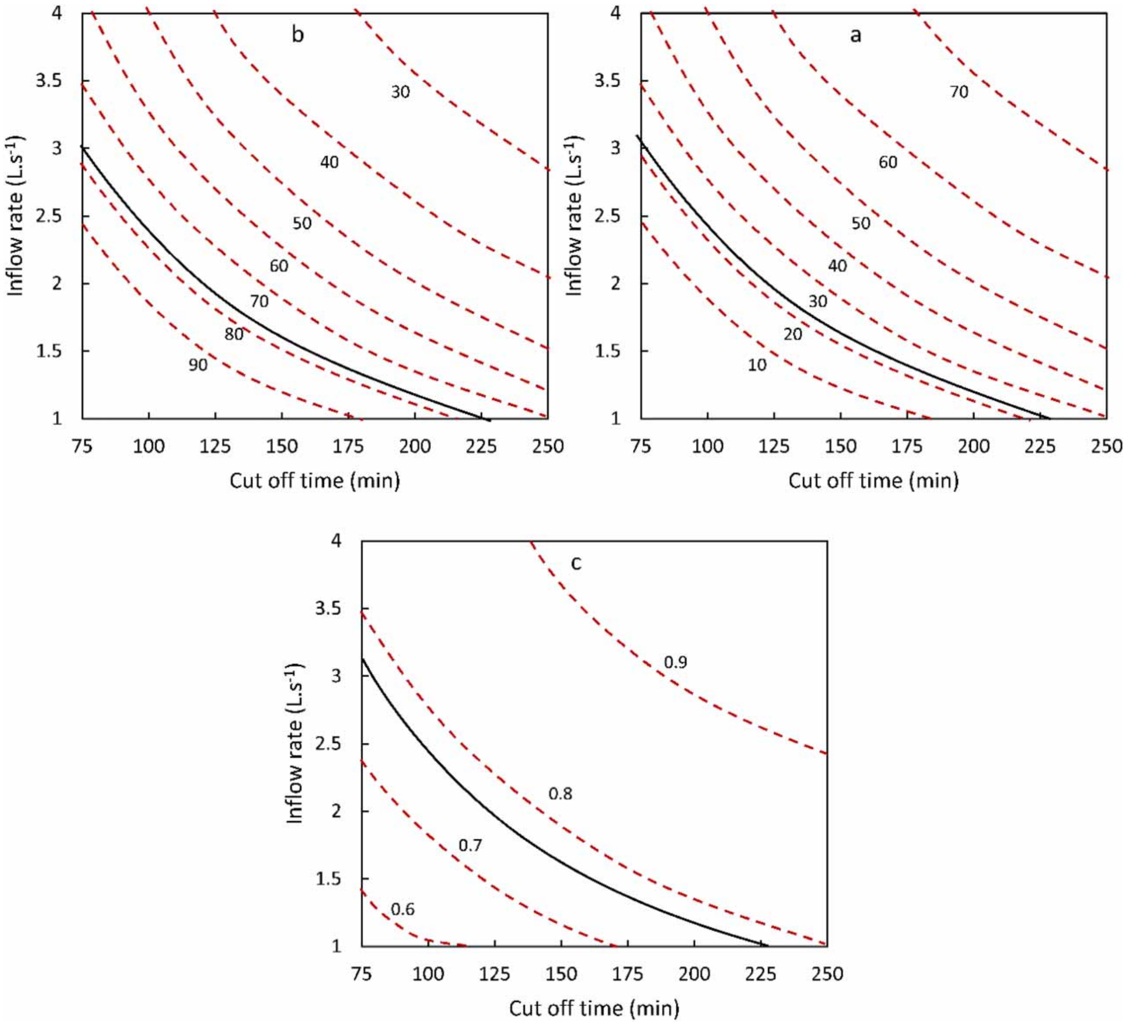

Figure 2 | Curves of the inflow rate and the cut-off time in closed-end furrow irrigation for (a) DU, (b) deep percolation, and (c) AE.

recommended optimal conditions (the inflow rate of 1.9 L/s during the irrigation time of 150 min) about 20% of the volume of deep irrigation water from the root area. The plant comes out. Due to the uniformity curves of the uniformity of the distribution, both the parameters of the input flow rate and the cut-off time had the same effect on the rate of increase of the uniformity of the distribution along the furrow.

In general, a desirable Q–T_{co} compound is a compound that maximizes the efficiency and DU. In this case, the adequacy of irrigation will be 100%. By moving on the line $D_{\mathrm{req}} = D_{\mathrm{min}}$ and aiming to provide the required depth of irrigation in this study, by selecting a flow rate of 1.9 L/s and a cut-off time of 150 min, the AE and DU will be about 80%, and irrigation adequacy will have its maximum value of 100%.

Optimal design

The optimization results of the four irrigations (I1–I4) are shown in Table 3. The inflow cannot change suddenly because the volume of water delivered to the farms is not subject to the decision of the operator and can be changed in a limited period by applying water distribution management. Therefore, to calculate the optimal response to supply the minimum water required by the plant at the beginning of the furrow, its applicability should be provided according to the available facilities.

As shown in Table 3, the inflow rate of about 12 L/s in 150 min of irrigation time can meet the required irrigation adequacy with an AE of between 82 and 84% and a DU of about 84%. It should be noted that the maximum cut-off time and the minimum inflow rate provide adequate irrigation or the minimum required water depth by completing the advance phase without flooding at the end of the furrow and have the maximum values of AE and DU.

Table 3 | Optimal parameters of the irrigation experiments

Parameter	Unit	I1	I2	I3	I4
Inflow rate	L/s	11.4	11.2	10.8	11.1
Cut-off time	min	148	150	156	151
Irrigation depth	mm	89	85	81	86
Minimum water demand	mm	60	60	60	60
AE	%	84	83	87	82
Deep percolation	%	16	17	15	16
DU	%	85	84	86	82

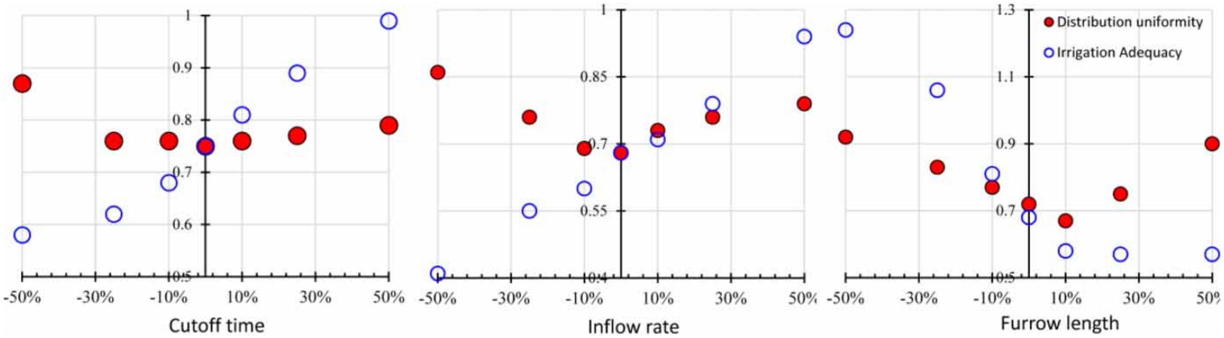

Figure 3 | Design sensitivity on the variations in input parameters.

Sensitivity on the variations in input parameters

The reliability of the calibrated model was evaluated using the analysis of evaluation criteria relative to the change of input parameters. With this concept, by making 10, 25, and 50% changes in the values of cut-off time, inflow rate, and the length of the furrows in positive and negative directions, the responses of the evaluation factors have been investigated. Figure 3 shows the comparison of the furrow irrigation evaluation parameters studied against the four main parameters of changes in cut-off time, inflow rate, and length of the furrows.

According to this figure, it can be seen that irrigation adequacy has increased with increasing time, and its slope has been relatively milder with decreasing time. In addition, with decreasing time, the uniformity of the minimum and low quarter distribution has increased due to the reduction of flooding at the end of the furrow. Under these conditions, 20 mm of the total 23 mm of water added to the optimal water depth as a DP is out of reach of the plant and reduces the AE by 26%. The uniformity of the minimum distribution is not significantly sensitive to changes in the input flow, and the range of its changes in the lower quarter reaches 6%. Furthermore, irrigation water depth, DP, and irrigation adequacy are directly related to the inflow rate when the cut-off time has a constant value. The responses of the closed-end furrow irrigation to the evaluation parameters have a different process depending on the length and inflow rate.

CONCLUSION

Minimizing the DP and maximizing the minimum infiltration depth were the two evaluation criteria considered for this purpose, which constitute the objective functions of the problem. The results showed that the best cut-off time to provide the required 75 mm water depth against the minimum DP in the closed-end system was 168 min and in the open-end system was 429 min. Difference between open-end and closed-end systems was more than 150 m^3 of water and more than 4 h of time for each irrigation. On the other hand, when the cut-off is 90 min, it is not possible to reach 100% irrigation adequacy in the open-end system, and the inflow rate obtained for the closed-end system is estimated at about 20 L/s with a DU of 83%. Changes in the evaluation parameters of the closed-end furrow irrigation on the change in furrow length showed that if the furrow length is reduced to 50%, it can increase irrigation adequacy to about three times, but the equivalent increase will be reduced water adequacy by 20%. The results showed that the management of water distribution in furrow irrigation depended to regulate the cut-off time and the length of the field. Reducing furrow length has a significant effect on increasing DU and thus reducing DP.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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