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Determination of effective design parameters affecting furrow irrigation system performance using clemmens algorithm

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ABSTRACT

Aim: Main aim of the study was to evaluate the operational impacts and sensitivity of key design variables on these performance parameters.

Materials and Methods: The study used a mathematical simulation model based on the Clemmens algorithm to evaluate the hydraulic performance of a furrowirrigation system. A factorial design was developed using different furrow lengths, inflow rates, irrigation depths, field slopes, and soil-infiltration parameters. Water advance, recession, infiltration, application efficiency, distribution uniformity, surface runoff and deep percolation were calculated using the Manning and modified Kostiakov–Lewis equations. The results were analyzed using factorial ANOVA, the Least Significant Difference test and sensitivity analysis in Statistix 8 at a 5% significance level.

Results: Furrow length, inflow rate and required depth exerted statistically significant effects on performance, whereas field slope had a negligible influence within the tested range. The highest application efficiency (60.3%) was recorded for a furrow length of 500 m combined with an inflow rate of 0.6 L/s. In contrast, the maximum distribution uniformity (99.61%) was achieved with a furrow length of 160 m and an inflow rate of 1.5 L/s.

Conclusion: It was concluded that furrow length emerged as a dominant factor; while longer furrows enhanced Ea and curtailed runoff, they concurrently diminished DU. Inflow rate presented a mirror image trade off, wherein greater inflows elevated DU but compromised Ea and exacerbated runoff.

Keywords: Furrow irrigation; irrigation performance; clemmens algorithm; furrow length; inflow rate.

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Introduction

Increasing population, climate variability, growing competition for water resources, and increasing demand for food production have intensified the need to improve the efficiency of agricultural water use. This need is particularly important in arid and semi-arid regions, where irrigation is the major consumer of available water resources. Surface irrigation remains one of the most widely used irrigation methods because of its relatively simple infrastructure and low operational requirements. However, its performance is often limited by inappropriate system design and management, resulting in excessive runoff, deep percolation, non-uniform water application, and low application efficiency (Holzapfel et al., 2010; Zerihun et al., 1997).

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Furrow irrigation is a widely used form of surface irrigation in which water is conveyed through small channels formed between crop rows. Water infiltrates vertically and laterally from the furrow into the soil, while the advancing water front progressively wets the furrow. The spatial and temporal distribution of infiltrated water depends on the hydraulic characteristics of the furrow and soil, as well as on the inflow rate, furrow length, field slope, infiltration characteristics, required depth, and irrigation time. Consequently, inappropriate selection of these variables can produce substantial differences in opportunity time and infiltrated depth between the upstream and downstream sections of a furrow.

The selection of an appropriate furrow length is particularly important because it affects both the hydraulic advance of water and the time available for infiltration. Long furrows may reduce the proportion of water lost through

runoff by allowing a greater proportion of the inflow to infiltrate before reaching the downstream end. However, excessive furrow length may increase the difference in opportunity time between the upper and lower portions of the field and consequently reduce uniformity. Conversely, short furrows may improve uniformity but may increase the proportion of water leaving the field as runoff. Similar trade-offs exist for inflow rate: a high inflow rate can accelerate advance and reduce the advance-time difference along the furrow, but may also increase runoff if the inflow exceeds the infiltration and storage capacity of the system.

Previous studies have demonstrated the importance of furrow length, inflow rate, slope, and irrigation time in determining surface-irrigation performance. Konukcu and Delibas (2006), for example, investigated the combined effects of furrow slope, inflow rate, and furrow length and identified combinations that produced high application efficiency. The FAO irrigation manual also recognizes the importance of soil texture, land slope, stream size, required irrigation depth, cultivation practices, and field dimensions in determining appropriate furrow dimensions and operating conditions (Savva and Frenken, 2002). Similarly, studies of furrow irrigation performance have demonstrated that irrigation efficiency and uniformity are strongly related to system variables and their interactions (Feyen and Zerihun, 1999; Holzapfel et al., 2010). Although these studies provide useful design criteria, identifying the relative importance of individual variables remains difficult because several design and management variables operate simultaneously. Furthermore, irrigation performance cannot adequately be described using a single indicator. Application efficiency (Ea), for example, reflects the proportion of applied water that is effectively stored in the target soil layer, whereas distribution uniformity (DU) describes the spatial uniformity of infiltrated water. Surface runoff and deep percolation provide additional information concerning the principal pathways of irrigation water loss. The simultaneous consideration of several performance indicators was therefore necessary to understand the trade-offs associated with alternative furrow designs.

Mathematical and simulation models provide an effective means of evaluating these relationships because they allow several combinations of design and operating variables to be investigated under controlled conditions. The Clemmens approach provides a relatively simple framework for surface-irrigation design and simulation based on water-volume balance, geometric relationships, and hydraulic flow calculations. It can therefore be used as a simulation engine to evaluate the effects of alternative furrow configurations without requiring a separate field experiment for every combination of design variables (Clemmens, 2007).

The present study applies the Clemmens algorithm to investigate the effects of four principal furrow-irrigation variables: furrow length, inflow rate, furrow slope, and required depth. The study considers application efficiency, distribution uniformity, surface runoff, and deep percolation as performance indicators. The specific objectives were to: (i) evaluate the effects of furrow length, inflow rate, slope, and required depth on furrow-irrigation performance; (ii) identify the variables and combinations of variables that have the greatest influence on application efficiency and distribution uniformity; and (iii) identify combinations of design and management variables that improve irrigation performance while reducing unnecessary runoff and deep percolation.

The study was intended to provide a quantitative basis for distinguishing between variables that can be effectively controlled through design and management and variables whose influence is relatively small within the range investigated. This approach can support more systematic selection of furrow design and operating conditions and provide a basis for subsequent development of decision-support procedures for surface-irrigation design.

Materials and Methods

Study Framework and Engineering Design Configuration

A factorial simulation framework was developed to evaluate the hydraulic performance of a furrow-irrigation system under different design and operating conditions. The investigated treatments included furrow length at five levels (160, 240, 320, 400, and 500 m), inflow rate at four levels (0.6, 0.9, 1.2, and 1.5 L/s), field slope at four levels (0.0005, 0.001, 0.002, and 0.003 m/m), and required irrigation depth at four levels (50, 75, 100, and 125 mm). A furrow spacing of 75 cm

was used and three soil-infiltration parameter sets were included as statistical replicates. The simulated furrow was represented as an open-channel hydraulic system with a defined cross-sectional geometry and longitudinal profile. The engineering configuration included the furrow bottom width, water depth, side-slope ratio, Manning roughness coefficient, soil-infiltration parameters, and cutoff time. These variables were incorporated into the Clemmens volume-balance algorithm to calculate flow area, hydraulic radius, water advance and recession, infiltration opportunity time, and irrigation-performance indicators.

Mathematical Structure of the Clemmens Algorithm

The model evaluates physical flow behavior (Figure1) based on continuous open-channel volume balance. Furrow cross-sectional flow area (A_o) is computed from water depth (y), bottom width (wb), and side slope ratio (Z):

$$A_o = y(Wb + Z \times y) = yWb + y^2Z \quad (1)$$

Inflow rate (Q_f) is determined using Manning's equation:

$$Q_f = \frac{1}{n} AR^{2/3} S_o{}^{1/2} \quad (2)$$

Where R: is the hydraulic radius (m) S_o: is the bed slope (m/m); n: is the Manning roughness coefficient.

Cumulative soil intake depth (d) over infiltration opportunity time (τ) follows the modified Kostiakov-Lewis equation:

$$d(\tau) = c + k\tau^a + b\tau \quad (3)$$

Where d: is the infiltration depth (mm); i: is the infiltration rate (mm/hr); τ: is the opportunity time for infiltration, (hr) and a,b,c,k are empirical constants (with b mm/hr. c mm, and k mm/hr^a).

The opportunity time at any field point (x) is defined by recession time (t_R) and advance time (t_A)

$$\tau_{opp}(x) = t_R(x) - t_A(x) \quad (4)$$

The required opportunity time (τ_{req}) to fulfill at the downstream end (x=L) is given by:

$$\tau_{req} = \left(\frac{D_{req}}{k}\right)^{(1/a)} \times 60 \quad (5)$$

The continuous volume balance integrates surface water storage (Vy) and cumulative infiltrated volume (Vz) against net inflow over time (t):

$$V_{in}(t) = V_y(t) + V_z(t) \quad (6)$$

$$V_z = w_f x \left(c + \sigma_z k t_x^a + \frac{h}{1+h} b t_x\right) \quad (7)$$

Where σ_y is the surface storage shape factor (typically 0.70–0.80 for furrows), σz the subsurface shape factor, $w_f$the furrow spacing, and Z(t) the infiltrated depth, and advance time follows a power function $t_x=sx^h$.

The algorithm iteratively computes the target cutoff time (tco) and spatial recession parameters to evaluate net water distribution profiles.

$$t_{co} = t_A + \tau_{req} \quad (8)$$

Evaluation Criteria

Performance indicators were defined as follows:

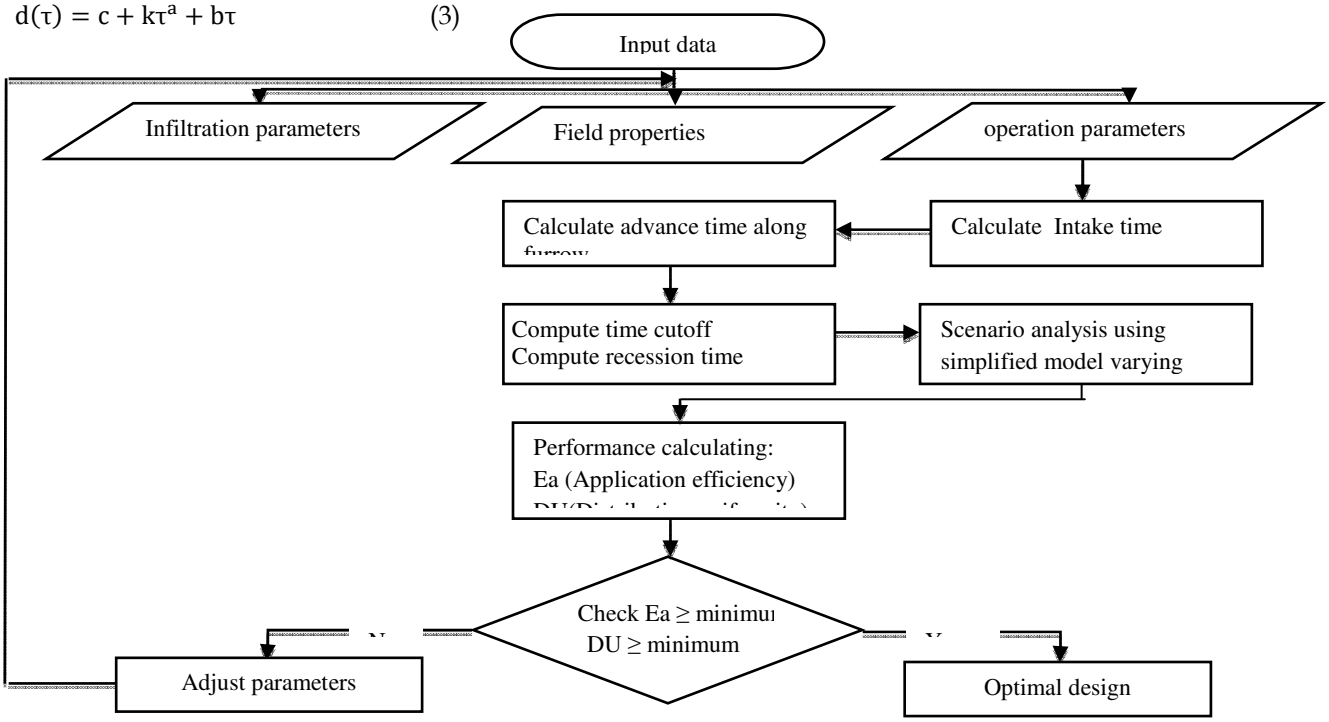


Fig.1. Conceptual flow chart of the Clemmens approach for furrow-irrigation design and performance simulation

Application efficiency

$$E_a = \frac{D_{req} \cdot w_f \cdot L}{V_{in}} \times 100 = \frac{D_{req} \cdot w_f \cdot L}{t_{co} \cdot Q_o} \times 100 \quad (9)$$

Surface runoff ratio

$$SRR = \frac{V_{in} - V_{inf}}{V_{in}} x100 \quad (10)$$

Deep percolation ratio

$$DPR = \frac{V_{dp}}{V_{in}} \times 100 \quad (11)$$

Distribution uniformity

$$DU = \left(1 - \frac{Y}{d^-}\right) \times 100 \quad (12)$$

Statistical analyses

Factorial ANOVA was conducted via Statistix 8 software, with mean comparisons isolated through the Least Significant Difference (LSD) test at a 5% significance threshold (α = 0.05). Sensitivity indices were derived to measure output vulnerability to variable input changes.2.6 Evaluation of variable influence

Results and Discussion

Application efficiency

The effects of furrow length, inflow rate, required depth, and furrow slope on application efficiency (Ea).Furrow length had a significant impact on Ea, with mean efficiency increasing from 21.7% at 160 m to 47.3% at 500 m. The data showed clear statistical differences among each furrow length, confirming that longer furrows lead to improved application efficiency. Additionally, longer furrows reduced surface runoff, suggesting that more water infiltrated rather than flowing downstream, consistent with previous research.Inflow rate also significantly affected Ea, with efficiency decreasing from 47.6% at 0.6 L/s to 25.9% at 1.5 L/s. The results indicate that higher inflow rates lead to increased runoff, thus reducing application efficiency. While higher rates can speed up water movement, they also exceed the infiltration requirements, causing a decrease in the stored water fraction.A notable interaction between furrow length and inflow rate was observed. The highest observed Ea of 60.3% occurred at a furrow length of 500 m and an inflow rate of 0.6 L/s, while the lowest, 14.5%, was at 160 m and 1.5 L/s, emphasizing that Ea is influenced by both variables (Holzapfel et al., 2010; Tesfaye et al., 2016). Required depth had a strong inverse effect on Ea, decreasing from 60.4% at 50 mm to 17.7% at 125 mm, with clear significant differences across the depths. This suggests that deeper irrigation requires more water, leading to greater runoff losses. Conversely, furrow slope had a minimal effect on Ea, with mean efficiencies ranging slightly around 35.1% to 35.5% across the slopes investigated. The lack of significant differences indicates that slope has a lesser influence on Ea compared to furrow length, inflow rate, and required depth.In summary, the study concludes that application efficiency is primarily influenced by furrow length, inflow rate, and required depth, while furrow slope plays a negligible role within the examined parameters.

Table 1. Effects of inflow rate and furrow length on application efficiency (%)

Furrow Length (m)	Inflow rate (L/s)				Means
	0.6	0.9	1.2	1.5	
160	31.6H	22.8J	17.7L	14.5M	21.7E
240	41.8E	31.5H	25.1I	20.8K	29.8D
320	49.3C	38.5F	31.3H	26.3I	36.4C
400	55.0B	44.3D	36.7G	31.2H	41.8B
500	60.3A	50.1C	42.4E	36.6G	47.3A
Means	47.6A	37.4B	30.7C	25.9D	

Table 2. Effects of required depth and furrow slope on application efficiency (%)

Required depth (mm)	Furrow slope (m/m)				Means
	0.0005	0.001	0.002	0.003	
50	59.7A	60.3A	60.7A	61.0A	60.4A
75	38.0B	38.1B	38.3B	38.4B	38.2B
100	25.1C	25.2C	25.2C	25.3C	25.2C
125	17.7D	17.7D	17.8D	17.8D	17.7D
Means	35.1A	35.3A	35.5A	35.6A	

Table 3. Effects of inflow rate and furrow length on surface runoff ratio (%)

Furrow Length (m)	Inflow rate (L/s)				Means
	0.6	0.9	1.2	1.5	
160	68.4F	77.2D	82.3B	85.5A	78.3A
240	58.2I	68.5F	74.9E	79.2C	70.2B
320	50.7K	61.5H	68.7F	73.7E	63.6C
400	44.9L	55.7J	63.3G	68.8F	58.2D
500	39.1M	49.9K	57.6I	63.4G	52.5E
Means	52.2A	62.6B	69.4C	74.1D	

Table 4. Effects of required depth and furrow slope on surface runoff ratio (%)

Required depth (mm)	Furrow slope (m/m)				Means
	0.0005	0.001	0.002	0.003	
50	40.1D	39.6D	39.1D	38.9D	39.4D
75	62.0C	61.9C	61.7C	61.6C	61.8C
100	74.9B	74.8B	74.8B	74.7B	74.8B
125	82.3A	82.3A	82.2A	82.2A	82.3A
Means	64.8A	64.6A	64.5A	64.4A	

Surface runoff ratio

The study analyzed the influence of furrow length, inflow rate, required depth, and furrow slope on the surface runoff ratio (SRR)are presented in Tables 3 and 4. Furrow length significantly affected SRR, with mean runoff decreasing from 78.3% at 160 m to 52.5% at 500 m. This decrease in runoff aligns with increased application efficiency, as longer furrows allow more time for infiltration, resulting in less runoff. Conversely, inflow rate significantly increased SRR, with means rising from 52.2% at 0.6 L/s to 74.1% at 1.5 L/s, indicating that greater inflow leads to higher runoff values. The combination of furrow length and inflow rate produced runoff variations from 39.1 to 85.5%, with maximum runoff at 160 m and 1.5 L/s. Required depth also significantly affected SRR, with mean runoff increasing from 39.4% at 50 mm to 82.3% at 125 mm. However, furrow slope did not exhibit a statistically significant effect on SRR, as mean runoff ratios were consistent across different slopes. Additionally, the interaction between slope and required depth was not statistically significant, despite some numerical variation. Overall, the study found significant correlations between furrow length, inflow rate, and application depth with SRR, while determining that slope did not play a significant role.

Deep percolation ratio

Deep percolation (DP) ratios were minimal across all simulated treatments, with no DP observed for furrow lengths of 160, 240, or 320 m. Only furrow lengths of 400 and 500 m exhibited DP, at 0.12% and 0.68%, respectively, and exclusively at an inflow rate of 0.6 L/s. This indicates that longer furrows at low inflowrates allowed infiltration to extend beyond the target soil depth. While small in magnitude compared to surface runoff, the occurrence of DP at longer furrow lengths highlights the balance between managing runoff and preventing water loss below the effective root zone. Additionally, Table 6 demonstrates DP correlation with the lowest application depths, with no DP at depths of 75, 100, and 125 mm. At 50 mm, small DP values were recorded at varying slopes. Overall, surface runoff was the predominant water-loss component, suggesting a greater focus on reducing it to enhance application efficiency.

Distribution uniformity

The effects of furrow length, inflow rate, required depth, and furrow slope on distribution uniformity (DU) are analyzed, showing clear numerical trends. Furrow length significantly impacts DU, decreasing from 99.280% at 160 m to 97.041% at 500 m, with mean-separation letters indicating statistical significance. This trend suggested that longer furrows reduce spatial uniformity due to varying opportunity times upstream and downstream.

Inflow rate also significantly affects DU, increasing from 97.063% at 0.6 L/s to 98.972% at 1.5 L/s. Each inflow rate corresponds to different statistical groups, confirming improved uniformity with higher rates, although increased runoff and decreased application efficiency must be considered. The interaction between furrow length and inflow rate resulted in DU values from 95.317 to 99.617%, with the highest value achieved at the 160-m furrow and 1.5 L/s inflow, demonstrating significant differences among various combinations.

Required depth notably influences DU as well, with mean DU rising from 95.792% at 50 mm to 99.536% at 125 mm, reflecting significant differences among depths. Conversely, furrow slope shows no statistically significant effect, with mean DU values remaining within the same statistical group across varying slopes, indicating minor numerical trends without significance. Additionally, the slope-depth interaction was also not significant, as all slopes within each depth level presented the same statistical group. The maximum observed DU of 99.547% occurred at a slope of 0.003 m/m with a required depth of 125 mm. Overall, while several factors significantly affect DU, furrow slope does not contribute meaningfully to variations in distribution uniformity.

Table 5. Effects of inflow rate and furrow length on deep percolation ratio (%)

Furrow Length (m)	Inflow rate (L/s)				Means
	0.6	0.9	1.2	1.5	
160	0	0	0	0	0
240	0	0	0	0	0
320	0	0	0	0	0
400	0.12	0	0	0	0.03
500	0.68	0	0	0	0.17
Means	0.16	0	0	0	

Performance Parameters as a Function of Design Variables

The performance parameters application efficiency (Ea), distribution uniformity (DU),

deep percolation ratio (DPR), and surface runoff ratio (SRR) were analyzed as functions of furrow length (L), inflow rate (Q_o), required irrigation depth (D_{req}), and field slope (So), as shown (Fig 2–4 and Tables 1–8).

Table 6. Effects of required depth and furrow slope on deep percolation ratio (%)

Required depth(mm)	Furrow slope (m/m)				Means
	0.0005	0.001	0.002	0.003	
50	0.17	0.16	0.16	0.15	0.16
75	0.00	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00	0.00
125	0.00	0.00	0.00	0.00	0.00
Means	0.042	0.040	0.039	0.038	

Table 7. Effects of inflow rate and furrow length on distribution uniformity (%)

Furrow Length (m)	Inflow rate (L/s)				Means
	0.6	0.9	1.2	1.5	
160	98.754EF	99.259BCD	99.489AB	99.617A	99.280A
240	97.912HI	98.722EF	99.108CD	99.327ABC	98.767B
320	97.071K	98.156GH	98.695F	99.008DE	98.233C
400	96.263L	97.585J	98.266G	98.671F	97.696D
500	95.317M	96.884K	97.725IJ	98.238G	97.041E
Means	97.063D	98.121C	98.657B	98.972A	

Table 8. Effects of required depth and furrow slope on distribution uniformity (%)

Required depth (mm)	Furrow slope (m/m)				Means
	0.0005	0.001	0.002	0.003	
50	95.680D	95.769D	95.841D	95.877D	95.792D
75	98.261C	98.302C	98.334C	98.350C	98.312C
100	99.148B	99.169B	99.186B	99.194B	99.174B
125	99.521A	99.533A	99.543A	99.547A	99.536A
Means	98.153A	98.193A	98.226A	98.242A	

Increasing furrow length from 160 to 500 m increased mean (Ea) from 21.7% to 47.3% (an increase of approximately 118%), while reducing (SRR) from 78.3% to 52.5% (a reduction of approximately 33%). Conversely, (DU) decreased slightly from 99.28% to 97.04%, whereas (DPR) increased from 0% to 0.17% because of the greater infiltration opportunity time in longer furrows. Increasing the inflow rate from 0.6 to 1.5 L/s improved (DU) from 97.06% to 98.97%, but reduced (Ea) from 47.6% to 25.9% and increased (SRR\) from 52.2% to 74.1%; meanwhile, (DPR) decreased from 0.16% to 0%.

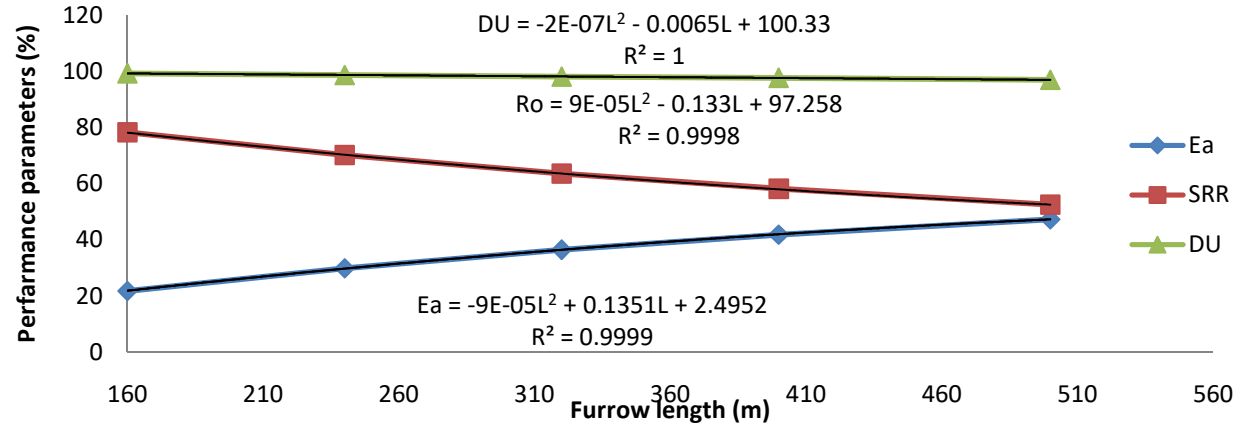


Fig. 2.Relationship between furrow length and irrigation-performance parameters

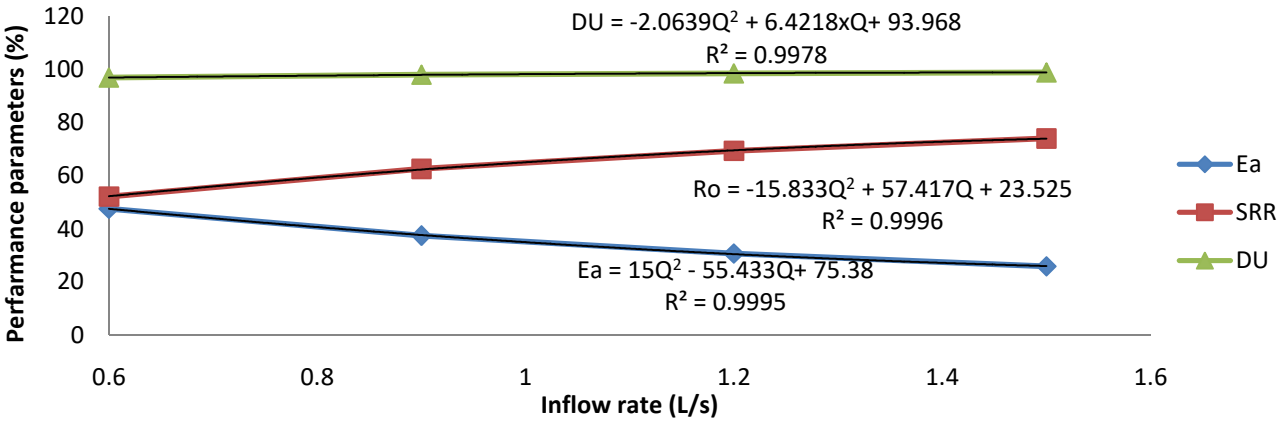


Fig. 3. Relationship between inflow rate and irrigation-performance parameters.

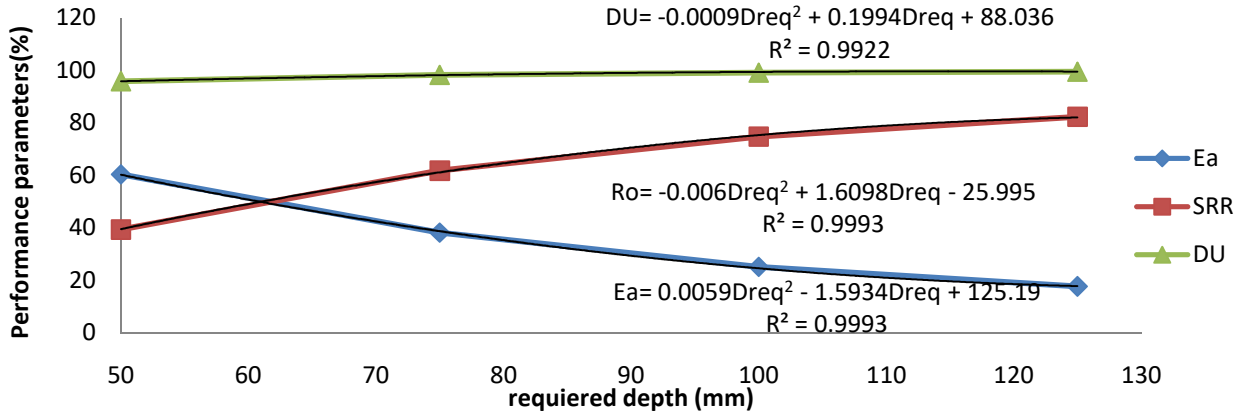


Fig. 4. Relationship between required depth and irrigation-performance parameters.

Similarly, increasing the required irrigation depth from 50 to 125 mm increased (DU) from 95.79% to 99.54% and (SRR) from 39.4% to 82.3%, while reducing (Ea) from 60.4% to 17.7% and (DPR) from 0.16% to 0%. Field slope had no statistically significant effect on any of the evaluated performance parameters within the tested range of 0.0005–0.003 m/m. The observed relationships between the design variables and irrigation-performance parameters were describedsatisfactorily by quadratic polynomial models, with coefficients ofdetermination exceeding (R^2=0.99)

Conclusions

The Clemmens algorithm is influential in defining design variables for enhancing furrow irrigation systems, as it facilitates improved comparability between design parameters and performance indicators namely application efficiency (Ea) and distribution uniformity (DU). By employing volume balance modeling, the algorithm allows for effective parameter adjustments across various configurations. These performance indicators correlate strongly with management variables such as inflow rate, furrow length, and required depth: Ea assesses deep percolation and surface runoff, while DU indicates water deficit or over application.

Applying this framework confirms that the four variables investigated do not influence furrow-irrigation performance equally. Furrow length emerged as a dominant factor; while longer furrows enhanced Ea and curtailed runoff, they concurrently diminished DU. Inflow rate presented a mirror image trade off, wherein greater inflows elevated DU but compromised Ea and exacerbated runoff. Required depth also substantially affected performance, positively correlating with both runoff and DU while negatively correlating with Ea. Conversely, furrow slope proved negligible across the tested range (0.0005–0.003 m/m), showing no statistically significant impact on any performance metric a finding reinforced by the near-identical slope means. This supports the broader observation that irrigation efficiency is largely stable across the tested slope range but remains highly sensitive to management variables.

A key practical implication is that no single performance indicator can guide optimization. The optimal Ea occurred with a 500m furrow and 0.6 L/s inflow, whereas the optimal DU occurred with a 160m furrow and 1.5 L/s inflow. These divergent outcomes underscore the inherent trade-off between efficiency and uniformity. Accordingly, sound design decisions must simultaneously balance Ea, DU, runoff, and deep percolation, rather than pursuing the maximization of an individual metric.

Ultimately, the utility of the Clemmens algorithm lies not in pinpointing a unique optimal design, but in offering a robust comparative platform to evaluate numerous design–management scenarios and systematically quantify their multi-dimensional performance outcomes. By doing so, it provides the essential insights needed for optimizing furrow irrigation systems under site specific constraints.

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