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Effect of Surge Flow Irrigation on Water Use Efficiency and Maize Production

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IMPROVING water use efficiency is strategically significant in arid and semi-arid regions where water scarcity is an issue. This implies that surge flow irrigation (SF) could positively impact crop production in water-scarce areas by enhancing water use efficiency (WUE). This study aimed to evaluate the performance of SF compared to continuous flow irrigation (CF) by assessing the water advance time, soil moisture distribution pattern, application efficiency, and WUE for maize production. The experiment utilized 120m long furrows with 0.70m spacing and a 0.1% average slope on clay soil. The treatments comprised three inflow rates (Q1: 0.49 l s^{-1}, Q2: 0.74 l s^{-1}, and Q3: 0.90 l s^{-1}) and three SF treatments with four surges (SF4), five surges (SF5), and six surges (SF6), as well as three CF treatments (CF1, CF2, CF3) with the same inflow rates for comparison The results revealed that the SF treatments reduce the water advance time compared to the CF treatment. The SF6 treatment reduced the advance time by 15.23% compared to the CF treatment. Moreover, the SF63 treatment achieved the highest application efficiency of 91.93%, whereas the CF3 treatment achieved the lowest value of 55.51%. On the other hand, maize yield was significantly influenced, with the SF61 treatment producing the highest yield (3740 kg fed^{-1}) and the CF3 treatment yielding the lowest (2756 kg fed^{-1}). The SF63 treatment also showed the highest WUE value (1.91 kg m^{-3}) compared to the CF3 treatment, which had the lowest WUE value (0.94 kg m^{-3}). Additionally, surge flow-irrigated furrows achieved water savings ranging from 19.83% to 32.26% under different surges from the SF4 to SF6 treatments. These results indicate that the SF system is a promising technology for maize production in regions with limited water use.

Keywords: Irrigation water management, soil moisture distribution pattern, soil moisture content, water scarcity, water saving.

1. Introduction

The surface irrigation (SI) method is the oldest and most general for irrigating various crops. In this method, irrigation water is moved over the soil by gravity to wet it wholly or partially, where the irrigation water flows or collects on the soil surface, and then it gradually infiltrates over time into the desired soil depth (Savva and Frenken, 2002a; Koech et al., 2014). Surface irrigation involves introducing water at a specific point in a field and allowing it to flow across the soil surface to reach the crops. This method has been used in numerous parts of the world for thousands of years (Hoffman et al., 2007).

Furrow irrigation systems present better capabilities for managing on-farm irrigation water under most conditions of surface irrigation method (EL-Sayed et al., 2022). In furrow irrigation, the flow rates/unit width can be ultimately lowered (Helmy and El-Sherpiny, 2022). The evaporative losses for widely spaced crops can be reduced by reducing the wetted area.

Furrow irrigation is one of the oldest controlled methods (Ali, 2011). Furrow irrigation is the most effective surface irrigation method because it provides adequate aeration in the root zone (Wu et al., 2017). However, poor design and inadequate irrigation management can lead to low performance in surface irrigation systems, resulting in issues such as low efficiency, uneven water distribution, high

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runoff, and excessive deep percolation (Moravejalahkami et al. (2009); Ebrahimian and Liaghat (2011); Mazarei et al. (2021). In arid and semi-arid regions worldwide facing water scarcity due to climate change, it is crucial to efficiently manage and utilize existing water resources (Abbaspour et al., 2009). Many researchers have tried to improve SI performance and reduce water losses via different strategies (Walker and Skogerboe, 1987). Research in Ethiopia, Egypt, and Pakistan has shown that surge flow irrigation methods can improve overall irrigation performance and water use efficiency (Zaghloul (1988); Amer (1998); Mahmood et al. (2003); Ismail et al. (2004); Kifle et al. (2008); Amer and Attafy (2017); Okasha et al. (2022). However, these studies focus on surge flow irrigation with furrow lengths of 70 meters or more and are specific to furrow irrigation systems. Additionally, research on alternate irrigation has demonstrated that it uses less water while maintaining the exact grain yield and offers better water use efficiency than conventional furrow irrigation (Graterol et al., 1993; Kang et al., 2000).

Surge irrigation, also known as the intermittent or pulse water application to furrow or border inlets, was initially employed at Utah State University by Stringham and Keller (1979) to minimize irrigation runoff and facilitate the automation of cutback furrow irrigation. Subsequent research by Bishop et al. (1981) and El-Nady and Hadad (2016) revealed that surge flow irrigation led to shorter advance times and lower water consumption during the advance phase compared to continuous flow methods. The cyclic water movement over the soil's surface in surge flow irrigation modifies the soil's infiltration description by reducing intake. Surface irrigation efficiency could be enhanced by transitioning from continuous flow to surge flow irrigation. Surge irrigation offers the advantages of furrow irrigation without requiring costly kits (Horst et al., 2007). It is the most effective method for reducing runoff volume during irrigation by intermittently applying water into the furrow (Ojaghlou et al. (2020); Ahmadabad et al. (2021). Ismail and Depeweg (2005) reported that the critical element of surge irrigation is the regulation of on and off times, which denote the periods during which water is added to the furrow (on-time) and the periods when water is paused (off-time). James (1988), Allen and Schneider (1992), Ismail et al. (2004), and Horst et al. (2007) stated that surge flow irrigation involves applying water through a series of cycles, with each cycle comprising a specific set of on/off times. The cycle number is a critical factor in surge flow irrigation, as it dictates how many cycles are required to complete the advance process in the furrow. By introducing water in multiple cycles, surge irrigation (SI) improves the homogeny of advance time, which is the time needed to reach the field end or a designated point and enhances the consistency of water infiltration depth. When surge irrigation is optimized with appropriate inflow parameters like rate of inflow, time of cut-off, and length of furrow and practical parameters of surge such as cycle ratio and on-off time, it promotes crops uniform irrigation, reduces runoff and deep percolation and improves the efficiency of irrigation by maintaining a consistent rate of infiltration throughout the furrow (Kifle et al., 2017). Benham et al. (2000) mentioned that high infiltration rates can lead to reduced irrigation performance due to deep percolation and uneven distribution of irrigation water through the field. However, the surge flow irrigation technique decreases the volume of irrigation water that infiltrates and improves irrigation efficiency.

Several factors contribute to the reduced infiltration in surge flow irrigation compared to continuous flow irrigation, including the sealing caused by the clay particles expansion after hydration, the decrease in a hydraulic gradient of soil as the soil becomes wetter, the hysteretic behaviour of hydraulic properties of soil, entrapment between surges, the surface soil layer consolidation through the off-time, and entry of air and sealing due to sediment particle clogging. Therefore, an accurate design of surge flow irrigation is essential for improving irrigation performance and minimizing the losses of on-farm water. (Smerdon and Blair, 1985; Izadi et al., 1995). Surge irrigation was initially developed for large fields with long furrows. In small fields and short furrows (100m or less), which are common in developing countries, surge irrigation reduced advance time, improved uniformity and the efficiency of water application by minimizing deep percolation and lowered the amount of irrigation water used by 15–35% (Ismail et al., 2004; Ismail and Depeweg, 2005).

SF is a water-saving technique that builds on furrow irrigation. It saves water by applying irrigation in controlled intervals rather than a steady flow. The benefit of surge flow (SF) irrigation lies in its ability to reduce infiltration losses by decreasing soil permeability through cyclic irrigation. During the initial water application, soil permeability decreases, which accelerates water flow during subsequent applications. This reduction in infiltration is driven by four physical processes: consolidation due to the movement and reorientation of soil particles, air entrapment, water redistribution, and channel smoothing (Mitchell and Stevenson, 1994; Onishi et al., 2019). According to Mitchell and Stevenson (1994), SF has achieved around a 50% reduction in irrigation water use without significantly affecting peppermint yield compared to traditional irrigation methods. In Uzbekistan, Horst et al. (2005) conducted a study in a cotton field in the Central Fergana Valley and observed a 21% reduction in irrigation water usage with SF.

The SF method reduces infiltration losses by decreasing the permeability of the furrows through staged water application. The reduction in permeability by the SF method is caused by four physical processes: soil compaction due to soil movement and rearrangement, air entrapment in soil pores, reduction in infiltration rate due to water redistribution, and smoothing of the water flow surface (Mitchell and Stevenson, 1994). Additionally, by suppressing the permeability of the furrows during the first irrigation, it is expected that the flow rate of irrigation water applied in subsequent stages will increase, thereby shortening the time water passes through the furrows.

The maize plant (*Zea mays* L.) is Egypt's most significant crop, ranking as the second most strategic crop for human and animal consumption. Moreover, maize is highly valued for its nutritional content, including essential minerals such as nitrogen, phosphorus, potassium, and magnesium, and its grains are used to produce healthy oil (Abdelraof et al., 2023). It is cultivated on approximately 2.7 million feddans, following wheat and rice (Yaseen et al., 2020). This research trial focused on the maize plant's pronounced response to water alterations in the root zone (El-Sherpiny et al., 2020). Therefore, the specific objectives of this study were to evaluate the performance of surge flow (SF) and continuous flow irrigation (CF) under field conditions using changes in soil moisture content, measure the water advance time, evaluate application efficiency, and determine the effects of SF on yield and WUE.

2. Materials and methods

2.1. Experimental site

A field experiment was conducted during the summer season of 2023 at the El-Serw Agriculture Research Station, Agriculture Research Center (ARC), Damietta Governorate, Egypt (31°14'37.8" N 31°47'41.1" E). Before planting, some physical and chemical analysis was conducted of the soil samples taken from soil depths 0–60cm, according to Dane and Topp (2020) and Sparks et al. (2020), and the analysis results are shown in Table 1.

2.2. Agricultural practices

Maize grains (*Zea mays* L.) of variety SC-30k8 were obtained from the ARC, Giza, Egypt. Maize grains were sown on the 12th of May and harvested on the 30th of August. Two grains were sown per pit in the lower third of each furrow and 25 cm between plants within rows. The experimental plot area was 120m furrow length×0.70m furrow width. The maize plants were thinned to one plant/pit three weeks after planting. According to the Egyptian Ministry of Agriculture, recommended cultural practices for maize plants were followed. All plants received the recommended nitrogen (N), phosphorus (P), and potassium (K) fertilizers. Treatment settings and layout for the experiment are shown in Figures 1 and 2. There was a two-meter free space between blocks and along the borders. The average slope of the experimental plot was 0.1%. The experiment comprised twelve treatments, which were replicated five times. Each replicate had three furrows. The mid-furrow was employed for data collection. Meanwhile, the furrows in every aspect represent buffer zones.

2.3. Experimental design and Treatments

The experiment had a split-plot design with five replicates. The main plots were given an inflow rate, and different flow irrigation methods were given to the subplot. Three surge flow irrigation (SF) treatments, SF4 (4 pulses), SF5 (5 pulses), and SF6 (6 pulses), were tested with three different inflow rates (Q1: 0.49 l s^{-1}, Q2: 0.74 l s^{-1}, and Q3: 0.90 l s^{-1}). Additionally, three continuous flow (CF) treatments (CF1, CF2, and CF3) corresponding to the same inflow rates (Q1, Q2, and Q3) were tested. The SF treatments were designated by combining the inflow rate and the number of surges: SF41, SF42, SF43, SF51, SF52, SF53, SF61, SF62, and SF63. There were six irrigations during the growing season of maize, excluding the El-Mohaya irrigation (first after planting). A water amount of 445 m^3 fed^{-1} was added for all treatments during the El-Mohaya irrigation. Irrigation flow treatments were followed after El-Mohaya irrigation, i.e., 25 days after sowing. The water cut-off time was 10 minutes between each pulse in all the surge flow irrigation treatments. Thus, the total water cut-off time was 30, 40, and 50 minutes for treatments SF4, SF5, and SF6, respectively, and this time is deducted from the total irrigation time for the furrow in the treatment. Table 2 describes the treatments used and their codes.

2.4. Crop water requirements and irrigation scheduling

Crop water requirements for maize crops in the study area were determined based on reference evapotranspiration inputs and the appropriate crop coefficients for each growth stage of maize, as outlined by Savva and Frenken (2002b). Water requirements for maize were calculated for a growing period of 110 days. The growing period of maize was divided into four main stages: initial, development, mid, and late stages, which lasted 15, 35, 30, and 30 days, respectively. The crop coefficient (K_c) of the $K_{c\ ini}$, $K_{c\ mid}$, and $K_{c\ end}$ stages were 0.5, 1.15, and 0.4, respectively (Savva and Frenken, 2002b). Net irrigation requirements were calculated by subtracting adequate rainfall from the estimated crop water requirements. The study area had almost no rainfall during the experiment.

The maize crop's reference evapotranspiration (ET_o) during its different growth stages was determined using the FAO Penman-Monteith method (Savva and Frenken, 2002b). Crop evapotranspiration (ET_c) was calculated using the K_c according to Doorenbos and Pruitt (1977). The gross water application depth required for each treatment was computed based on an assumed application efficiency of 50% and 65%

for CF and SF, respectively, as outlined by Doorenbos and Pruitt (1977) and Ismail and Depewege (2005). Irrigation scheduling was then carried out using FAO CROPWAT version 8.

2.5. Field data measurements

On the upstream side of the experimental furrows, a temporary supply channel was constructed and lined with plastic sheets to prevent seepage. A 50 mm diameter gated PVC pipe was placed along the edges of the ditch, with a constant head maintained to ensure a steady inflow rate. Before starting the experiment, the maximum non-erosive inflow rate was measured to be one l s^{-1}, according to Cuenca (1989), considering the clay soil and a furrow slope of 0.1%. Furrow length was divided into four locations along the furrow: 0.25, 0.50, 0.75, and 1.00 of furrow length, that is, 30, 60, 90, and 120m along the furrow. The advance time at each location and the total irrigation water at the furrow's end were recorded.

The depth of water applied (D_{ap}, mm) for every treatment was calculated according to (Horst et al., 2007):

Table 1. Some physicochemical characteristics of soil under study.

Soil properties	Unit	Soil depths (cm)			
		0-15	15-30	30-45	45-60
Particle size distribution:					
Coarse sand	(%)	4.41	3.93	3.65	3.96
Fine sand		16.25	15.44	15.02	15.23
Silt		24.18	24.87	23.96	24.12
Clay		55.16	55.76	57.37	56.69
Texture class		Clay	Clay	Clay	Clay
Field capacity (FC)	(%)	40.45	40.11	39.99	39.84
Permanent wilting point (PWP)		19.15	18.89	18.94	18.69
Available water (AW)		21.30	21.22	21.05	21.15
Bulk density	(Mg m^{-3})	1.20	1.23	1.27	1.30
Total porosity	(%)	54.72	53.58	52.08	50.94
Void ratio		1.21	1.15	1.09	1.04
Hydraulic conductivity (HC)	(cm h^{-1})	0.19	0.18	0.15	0.16
pH (1:2.5 soil water suspension)		8.14	8.20	8.15	8.17
EC_e (soil paste extract)	(dS m^{-1})	6.65	6.63	6.52	6.45
Organic carbon	(g kg^{-1})	4.88	4.76	4.74	4.63
Organic matter		8.39	8.19	8.15	7.96

Table 2. Description of the used treatments and their codes.

Inflow rate (l s^{-1})	Flow irrigation methods	Code
Q1=0.49	Continuous (CF)	CF1
	Four surges (SF4)	SF41
	Five surges (SF5)	SF51
	Six surges (SF6)	SF61
Q2=0.74	Continuous (CF)	CF2
	Four surges (SF4)	SF42
	Five surges (SF5)	SF52
	Six surges (SF6)	SF62
Q3=0.90	Continuous (CF)	CF3
	Four surges (SF4)	SF43
	Five surges (SF5)	SF53
	Six surges (SF6)	SF63

Q: inflow rate; CF: continuous flow irrigation; SF4: four equal pulses of surge flow irrigation; SF5: five equal pulses of surge flow irrigation; and SF6: six equal pulses of surge flow irrigation.

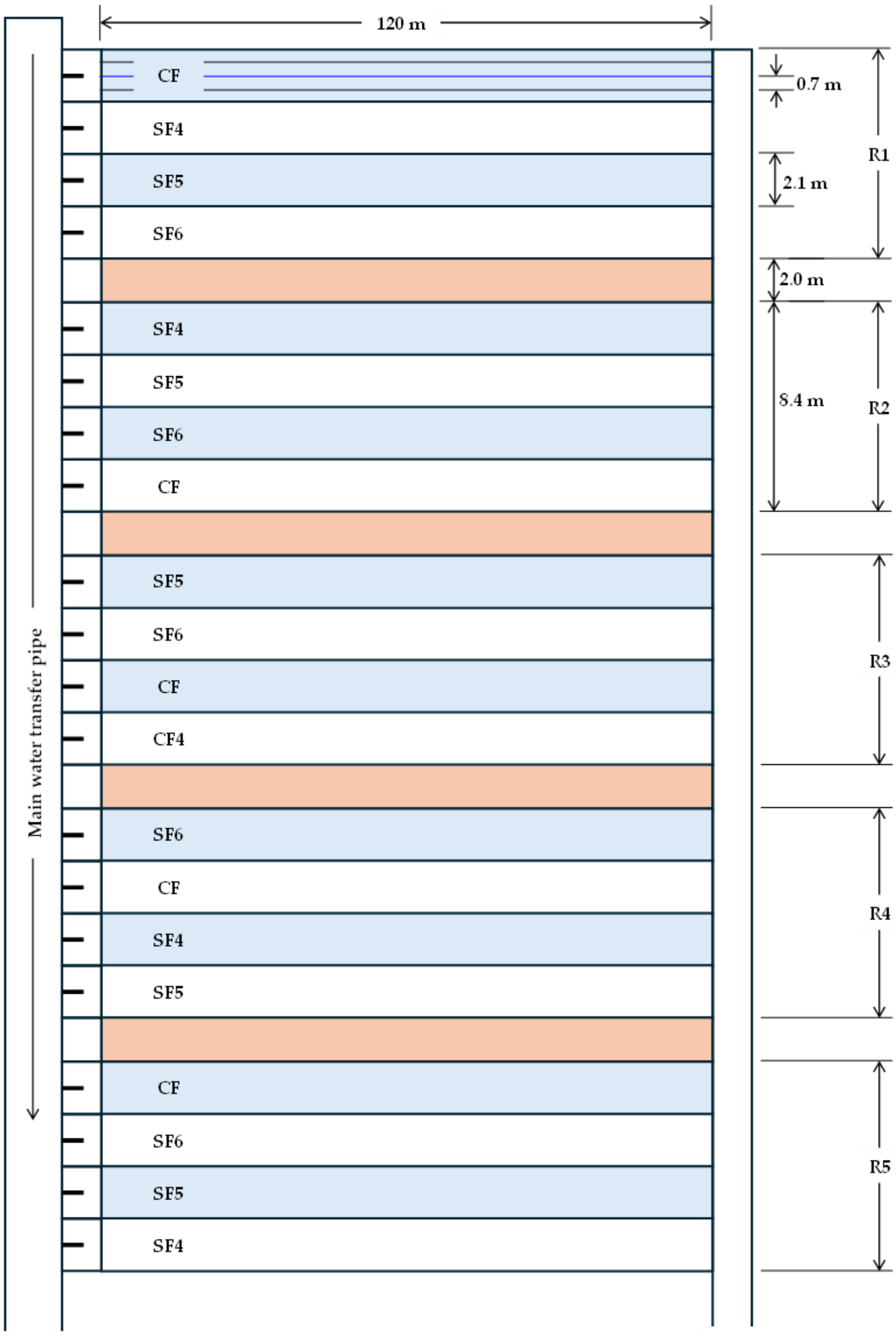

Fig. 1. Layout of the experimental plots for SF and CF. CF: continuous flow irrigation; SF4: four equal pulses of surge flow irrigation; SF5: five equal pulses of surge flow irrigation; and SF6: six equal pulses of surge flow irrigation.

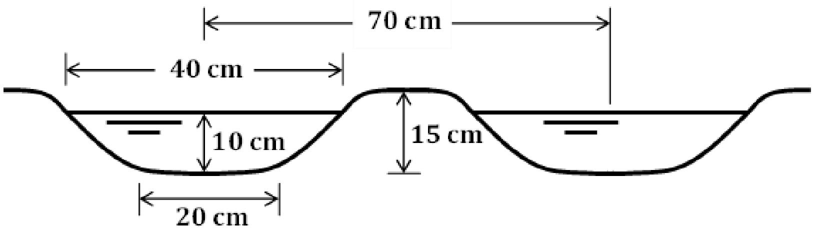

Fig. 2. Geometry of furrow irrigation.

$$D_{ap}=\frac{Q\times 60\times t_{co}}{L\times S}$$

Where:
D_{ap}: The gross water applied depth (mm),
Q: The inflow rate ($l\ s^{-1}$),
t_{co}: The time of water applied (min),
l: The length of furrow (m) and
S: The width of the furrow (m).

To determine the soil water content (θ_w), soil samples were collected using a soil auger from four soil depths 0–60cm based on the effective root length of maize plants before each instance of water was added. Soil samples were collected at four points along furrows (0, 40, 80, and 120m). After 48 h of irrigation, soil samples were collected from the same points in the horizontal and vertical directions. The θ_w was determined by weighing a mass of wet soil samples and then drying the soil for 24 hours at 105°C (up to constant weight) and reweighing the samples. The θ_w was calculated by the gravimetric method.
To demonstrate the distribution patterns of soil moisture at various depths and along multiple points of the furrow across all experimental treatments, contour maps were generated using the graphic software Surfer®23 (2023). The contour lines, created using the Kriging (Gridding Method), represent radial areas with uniform water content (%) within the wetted soil volume.
The moisture retention depth in the soil's root zone was determined by analyzing the water content of soil samples collected with an auger before irrigation and 48 hours afterward. Samples were taken from four locations along the furrow (30, 60, 90, and 120m) at 0–60cm depths. The retained water depth in the root zone was calculated according to (Kifle et al., 2008):

$$d=10\times\sum_{i}^{n}\frac{(d_f - d_i)}{100}\times A_{si}\times D_i$$

Where:
d: water retained depth into the soil root zone (mm),
d_f and d_i: The water content in the i^{th} soil layer after 48 hours of irrigation and before irrigation, respectively, (% weight),
A_{si}: The bulk density of the i^{th} soil layer,
D_i: The depth of the soil layer (m) and
n: The layers number.

The irrigation application efficiency (Ea) relates to the actual storage of water in the root zone to meet crop water needs compared to the water added to the field (Howell, 2003). So, it was used as a performance indicator to evaluate continuous flow and surge flow treatments and was calculated by (James, 1988):

$$E_a=\frac{W_s}{IWA}\times 100$$

Where:
E_a: Irrigation application efficiency (%),
W_s: Water stored amount in the root zone (mm), and
IWA: Irrigation water applied (mm).

2.6. Grain yield and WUE

Grain yield was calculated based on the harvested plot and converted to kg fed^{-1}. The WUE (Kg m^{-3}) was calculated using the equation as mentioned by Payero et al., 2008:

$$WUE=\frac{\text{Grain yield (kg fed}^{-1})}{\text{Irrigation water applied (m}^3\text{fed}^{-1})}$$

2.7. Statistical analyses

The experiment was conducted using a split-plot design. The data were subjected to variance analysis using the CoStat software. Significant differences between treatment means were made using Tukey's HSD test at $P \leq 0.05$ level, according to (Snedecor and Cochran, 1980).

3. Results

3.1. Advanced time

Fig. 3 presents the water advance time curves for different irrigation methods and inflow rates at 0.49, 0.74, and 0.90 $l\ s^{-1}$. The interaction detected the maximum values of advance time at the CF1 treatment (300 min). In contrast, the minimum advance time values were stated at the SF63 treatment (132 min). Moreover, increasing the surge number from four to six reduced the water advance time from 273, 182, and 140 min under SF41, SF42, and SF43 to 247, 172, and 132 min under SF61, SF62, and SF63, respectively. On the other hand, the findings indicate that the SF treatments reduced the water advance time. The mean values of advance time were 198.33, 188.33, and 183.67 min at SF4, SF5, and SF6, respectively, compared to the CF treatment (216.67 min). This demonstrates that the SF method reduces advance time by 8.46%, 13.08%, and 15.23% at the SF4, SF5, and SF6 treatments, respectively, compared to the CF treatment.

3.2. Soil moisture distribution pattern

Figures 4, 5, and 6 present contour maps illustrating soil moisture distribution affected by the different inflow rates, number of surges, and distance from the upper end of the furrow in comparison to CF. Generally, the soil moisture content showed higher levels at the upper end than at the tail end from along the furrow length.
Under SF, soil moisture distribution evolved from a gradual pattern before irrigation to a more uniform pattern 48 hours later. This improved uniformity is due to the SF system's effective water distribution,

which results in more even moisture in the root zone. Before irrigation, soil moisture was relatively uniform but a little, ranging from 27.0% to 36.0% at depths of 0 to 60 cm. After irrigation, moisture content increased to 32.5% and 45.0% at 60cm depth. The soil profile up to 60 cm depth was moister with the SF compared to the CF, which led to high moisture levels throughout the soil profile.

Additionally, the soil moisture content 48 hours after irrigation for all SF and CF treatments was within the field capacity of the soil. However, under SF treatments, the soil moisture content was distributed more evenly in the soil compared to CF treatments, ensuring better aeration for plant roots. This finding suggests that SF reduces infiltration rate, resulting in quicker water movement and more even distribution along the furrow than the CF treatment.

3.3. Irrigation water applied

Fig. 7 demonstrates the interaction between inflow rates and different flow irrigation systems. The lowest values of IWA were observed at the SF63 treatment (1903.00 m^3 fed^{-1}). In contrast, the highest IWA values were reported at the CF1 treatment (3091.00 m^3 fed^{-1}). As a result, water savings were achieved when using SF by an increase of 19.83, 27.58, and 32.26% at SF4, SF5, and SF6, respectively, compared with CF. Additionally, the SF6 treatment reduced IWA by approximately 976.98 m^3 fed^{-1} compared to the CF treatment.

3.4. Application efficiency (Ea)

The variance analysis revealed that the interaction between the inflow rates and different flow irrigation significantly impacted Ea (Fig. 7). The higher Ea values were detected at 81.93%. In comparison, the lowest values of Ea were 55.51% under the SF63 and CF3 treatments, respectively. These findings suggest that SF treatments outperform CF treatments in terms of their water application efficiency. On the other hand, Ea was consistently lower for CF than for SF, a difference inherent to the irrigation method and not due to increased water application.

3.5. Grain yield

The data in Fig. 8 showed that inflow rates and different irrigation flow treatments significantly influenced the maize yield. The maximum yield values were observed (3740 kg fed^{-1}) under the SF61 treatment. In contrast, the minimum yield values were observed (2756 kg fed^{-1}) under the CF3 treatment.

3.6. Water use efficiency

WUE was significantly affected by the interaction between inflow rates and irrigation flow treatments (Fig. 8). The maize plants showed higher WUE values with the inflow rate (Q3=0.90 l s^{-1}) with the SF6 treatment, where its value reached 1.91 kg m^{-3}. In contrast, the lowest values of WUE (0.94 kg m^{-3}) were obtained from the CF3 treatment. These findings indicate 40.27, 69.28, and 84.30% increases in water productivity with SF at SF4, SF5, and SF6, respectively, compared to the CF treatment.

4. Discussion

Overall, SF required less time to complete the advanced phase than CF due to infiltration rate reduction, which results from surface sealing and soil consolidation. On the other hand, the rate of water advance within furrows was faster when using the surge flow irrigation method than when using the continuous irrigation method. The data indicate that SF enables the soil to reach its introductory infiltration rate much faster for the same discharge and volume of water added to the furrows, which advances faster along the furrows with SF than CF. This results in quicker waterfront advancement and more uniform soil moisture storage and distribution from the head to the tail end of the field with minimal losses (Mathew and Senthilvel, 2007). Radmanesh et al. (2023) showed that SF reduces the volume of water infiltrated in advance and enhances the distribution uniformity along the furrow. Amer and Attafy (2017) suggested that SF forms a thin surface crust of fine clay and silt, decreasing infiltration. This reduction in vertical water penetration may lead to a faster lateral water movement. These findings were consistent with those reported by Kifle et al. (2017).

One of the main objectives of this study was to illustrate patterns of soil moisture distribution at different depths under SF compared to CF, which other researchers have not sufficiently studied. In surge irrigation, the longitudinal distribution of soil moisture post-irrigation was more consistent than in continuous flow (Mathew and Senthilvel, 2007). Surge irrigation shows significantly better distribution uniformity, achieving 84.1%, compared to the lower efficiencies observed in continuous irrigation systems (Shibeshi et al., 2023; El-Sayed et al., 2019).

This approach improves soil moisture retention, increasing crop yield potential (El-Sayed et al., 2019). Field studies by Radmanesh and Ahmadi (2024) verified that surge irrigation enhances infiltration and moisture distribution, particularly with optimized inflow rates and furrow lengths. According to Radmanesh et al. (2023), employing SF promotes more effective water penetration and minimizes deep percolation and runoff, which are crucial for sustaining soil moisture. These results agreed with the report by Mohammed et al. (2015) and Ismail (2004).

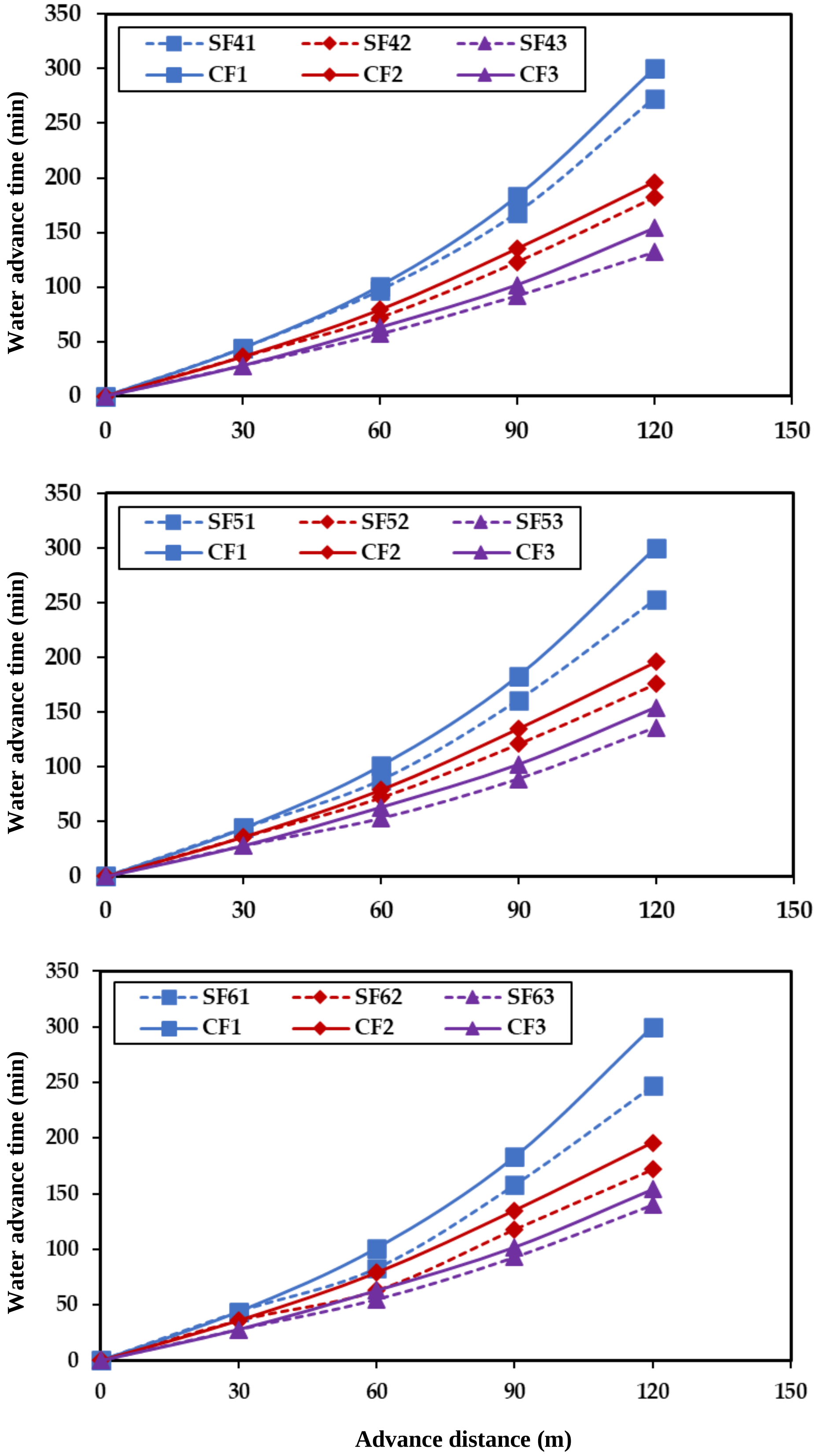

Fig. 3. Comparison of water advance time and distance along the furrow length at inflow rates of 0.49, 0.74, and 0.90 l s^{-1} for 4, 5, and 6 surges compared to the CF1, CF2, and CF3 treatments.

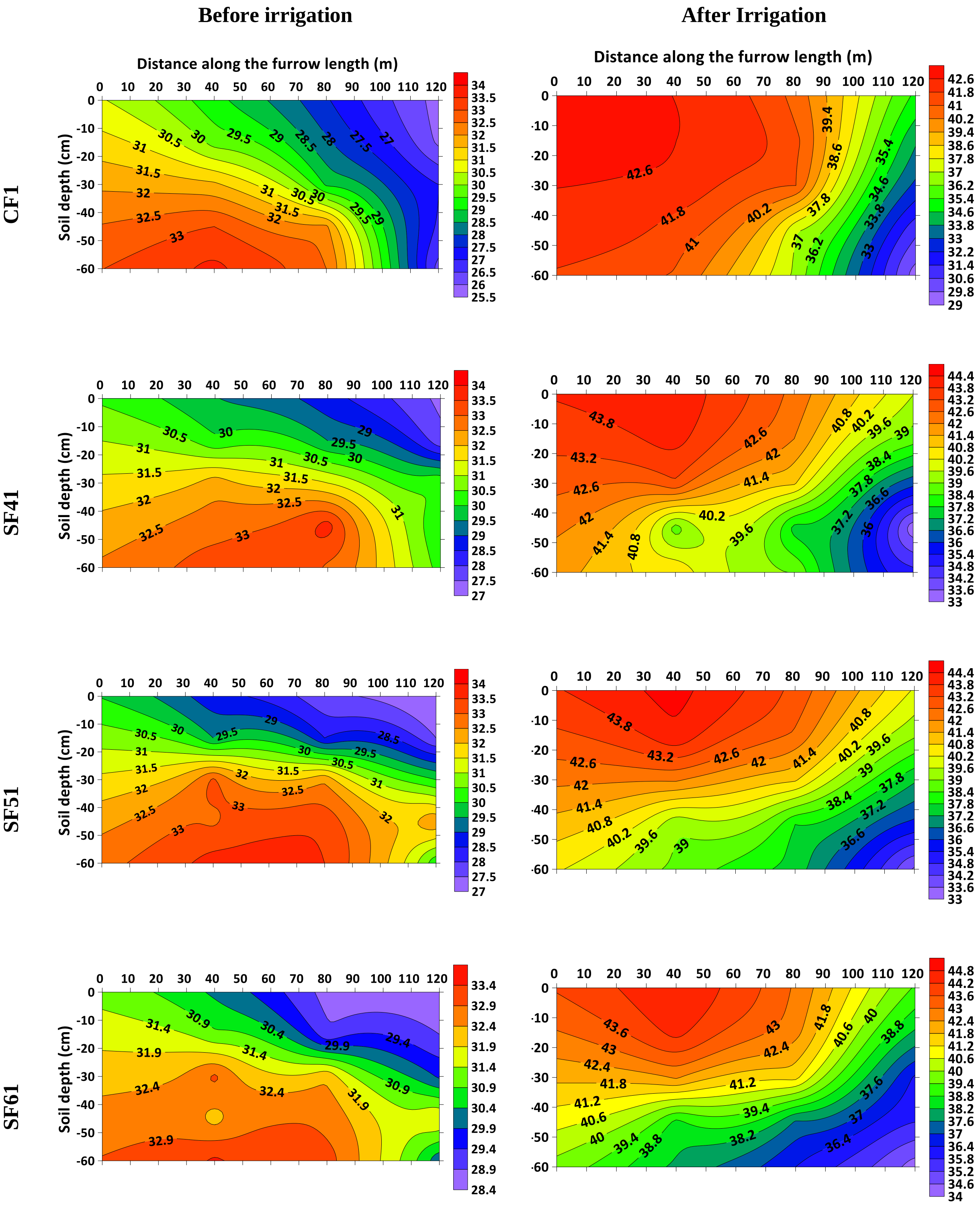

Fig. 4. Soil moisture distribution pattern before and after irrigation water for 4, 5, and 6 surges flow irrigation at an inflow rate of 0.49 l s^{-1} compared to the CF1 treatment. The values on the contour lines indicate the soil moisture content (%).

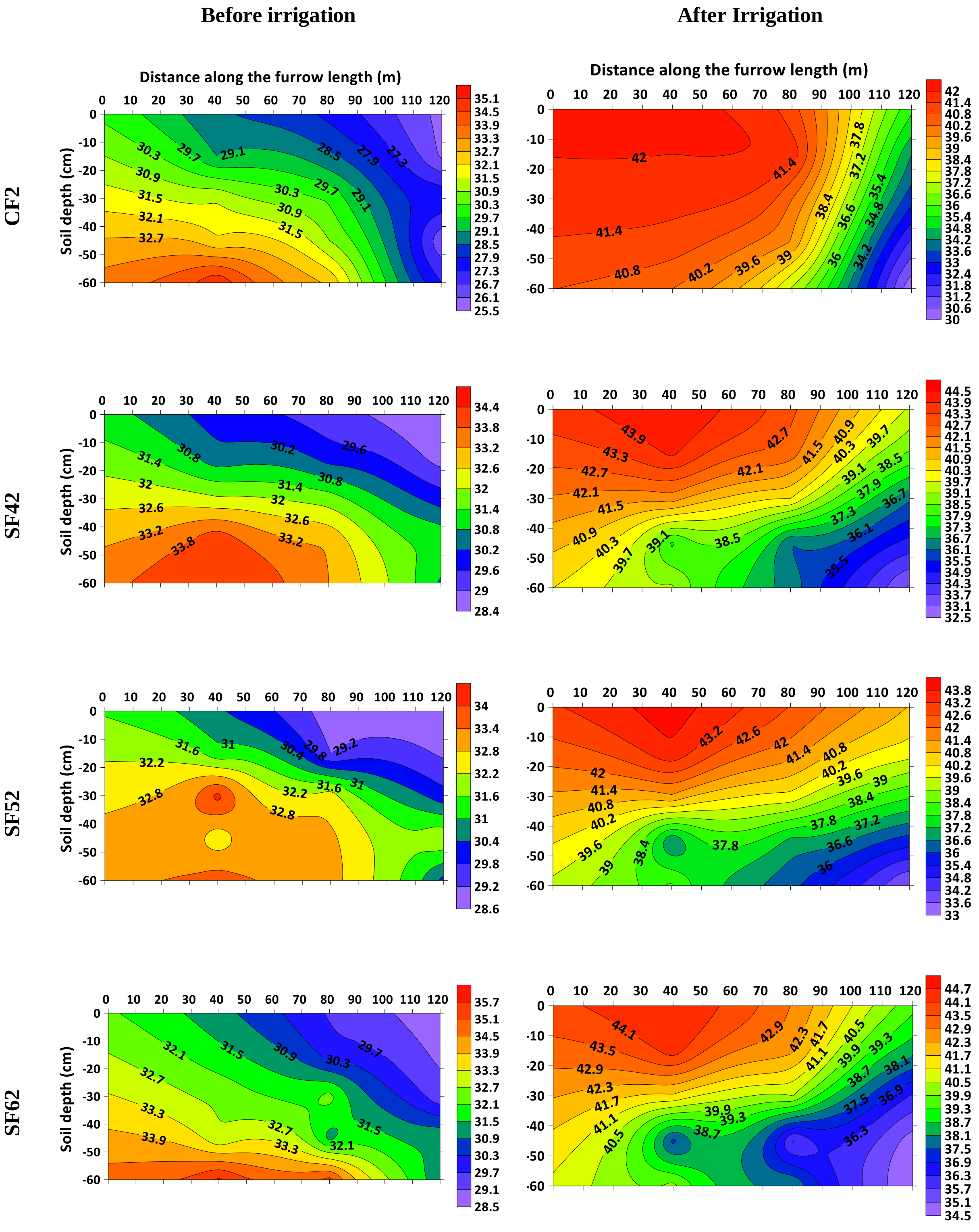

Fig. 5. Soil moisture distribution pattern before and after irrigation water for 4, 5, and 6 surges flow irrigation at an inflow rate of 0.74 l s^{-1} compared to the CF2 treatment. The values on the contour lines indicate the soil moisture content (%).

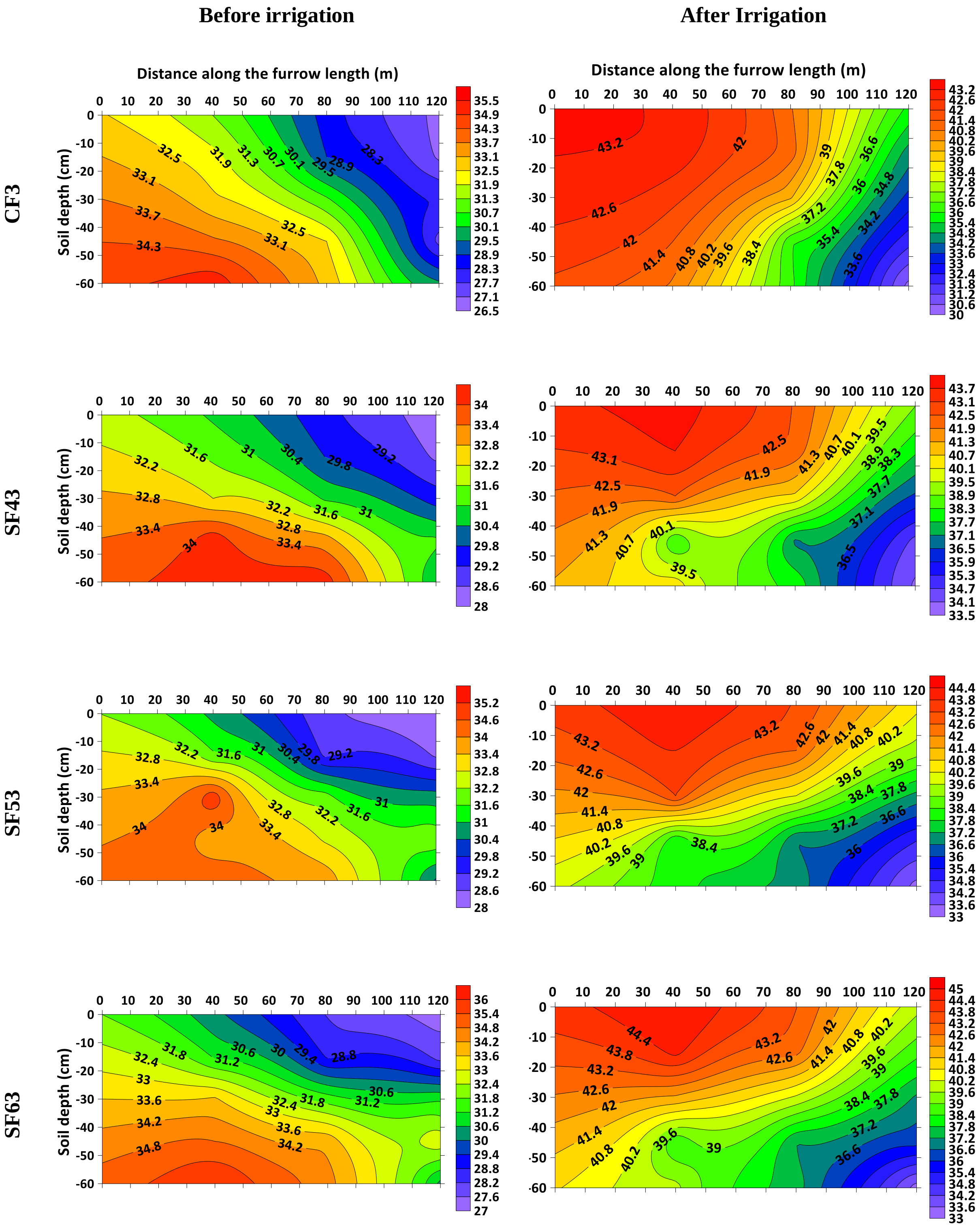

Fig. 6. Soil moisture distribution pattern before and after irrigation water for 4, 5, and 6 surges flow irrigation at an inflow rate of 0.90 l s^{-1} compared to the CF3 treatment. The values on the contour lines indicate the soil moisture content (%).

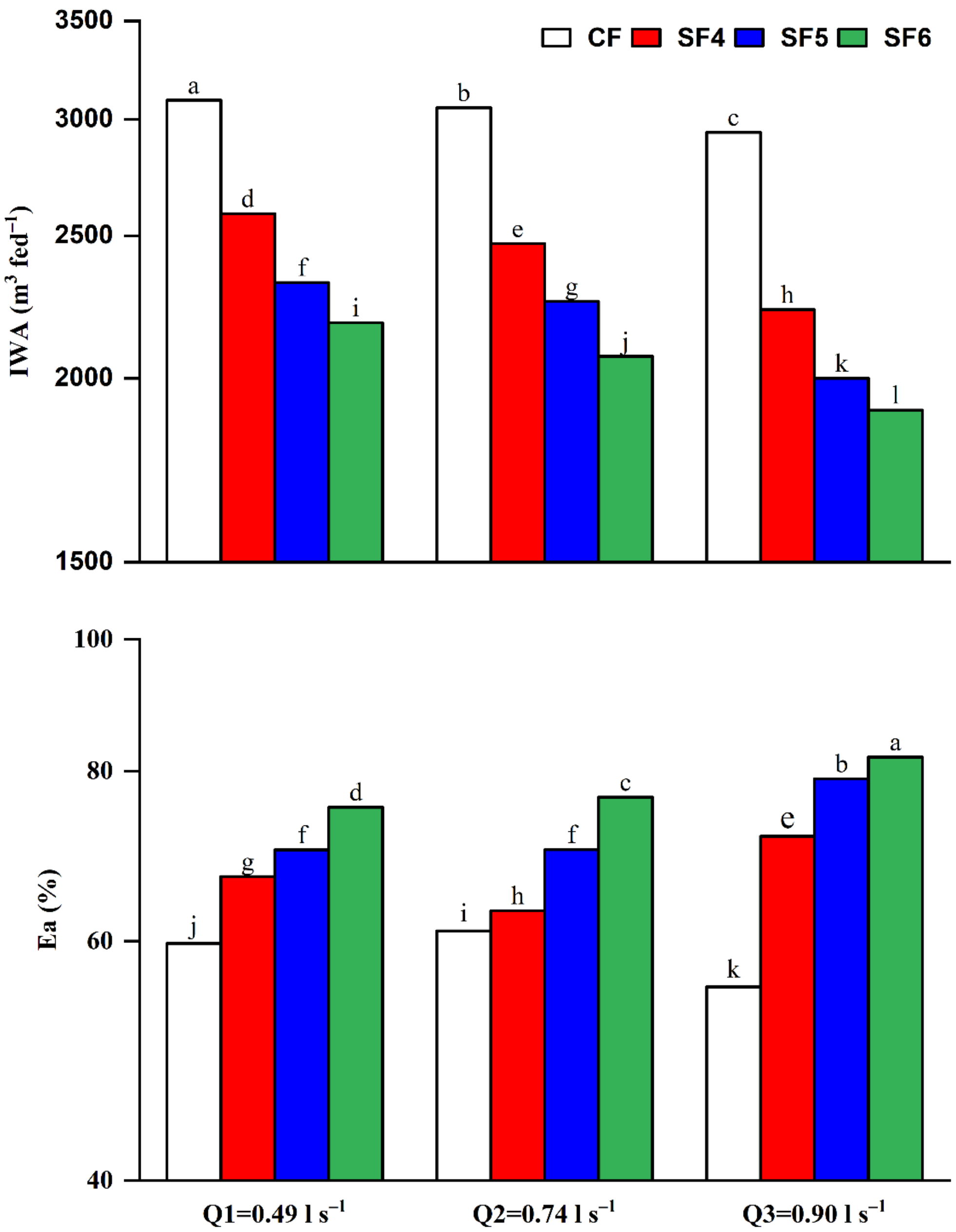

Fig. 7. Effect of inflow rates and different flow irrigation methods on irrigation water applied (IWA) and application efficiency (Ea). Columns with different letters are significantly different ($P \leq 0.05$ level).

Regarding the impact of SF on water applied, these results can be attributed to the SF technique, which delivers water intermittently and thus results in longer advance times for SF than CF. This intermittent application reduces water loss to deep percolation at the start of the furrow, allowing water to move down the furrow more rapidly. By minimizing deep percolation at the beginning and tailwater at the end, SF ensures uniform water distribution, lowers total water usage, and significantly reduces runoff. Since water must infiltrate through the soil surface, a longer surface time slows the infiltration rate, leading to less water infiltrating per unit of time towards the end of irrigation. These findings align with those reported by Onishi et al. (2019), Amer and Attafy (2017), Mattar et al. (2017), and Wood et al. (2017).

Application efficiency is an essential parameter for evaluating surface irrigation systems. With the SF technique, performance metrics, such as seasonal

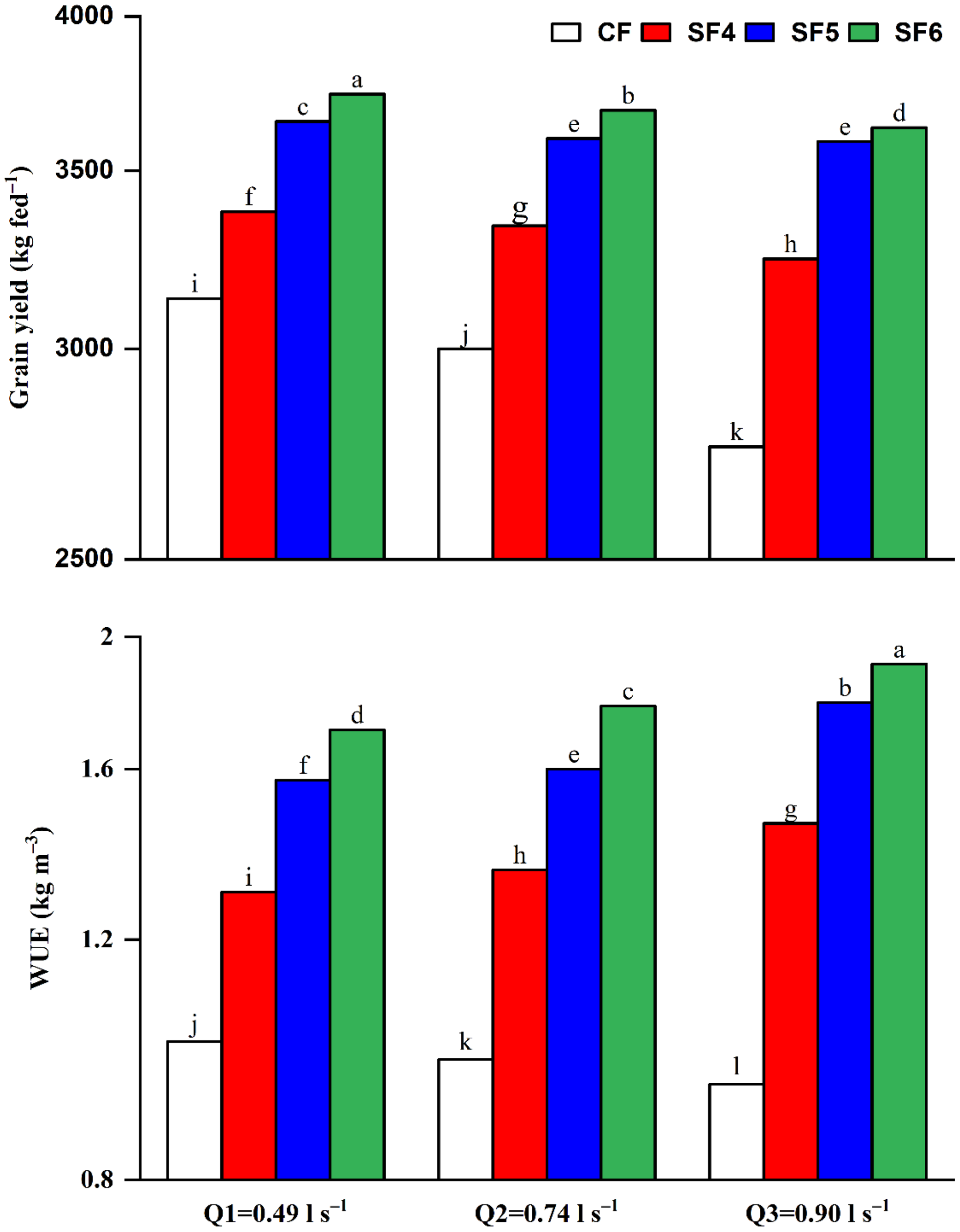

Fig. 8. Effect of inflow rates and different flow irrigation methods on grain yield and water use efficiency (WUE). Columns with the same letters are not significantly different (*P* ≤ 0.05 level).

irrigation water demands and application efficiency have shown improvements compared to continuous irrigation for maize (Romay et al., 2024). Abdelmonem (2005) demonstrated that SF enhances surface irrigation efficiency, reduces deep percolation, minimizes fertilizer waste, and improves the viability of the irrigation process. SF can attain application efficiencies greater than 80%, with some studies documenting efficiencies of up to 87% under certain conditions (Romay et al., 2024; Shibeshi et al., 2023). This approach reduces water loss due to deep percolation and runoff, reducing losses from 30% to 24.3% compared to traditional methods (Shibeshi et al., 2023). Additionally, surge flow irrigation reduces the deep percolation ratio to 14–19%, whereas continuous flow results in 23–24% (Shihab and Awjagh, 2016). Surge irrigation can conserve up to 40% more irrigation water than continuous irrigation methods (Ismail, 2004). Surge flow irrigation can conserve up to 28% of the water in extended furrows, particularly when paired with ideal surge cycles and discharge rates (El-Sayed et al., 2019). This versatile method permits modifications according to the field conditions, boosting its overall efficiency (Radmanesh and Ahmadi, 2024).

One of the critical factors in evaluating any plant-soil water relationship is crop yield. From the previously mentioned data, it can be concluded that the highest yield of maize crops was obtained under SF compared to CF. The highest yield of maize crops in SF may be attributed to increasing soil aeration with relatively low applied irrigation amounts. Conversely, the maize yield may decrease under CF due to nutrient leaching from the soil profile because of the high quantity of water drained. SF has been shown to significantly boost maize yields (Okasha et al., 2022). SF with scheduling resulted in a maize yield of 2.3 times that of CF, and WUE and income were 2.7 and 2.8 times higher, respectively (Mintesinot et al., 2007). Additionally, surge irrigation with different on-off timings influenced the plant height, root volume, and cob length of maize compared with continuous flow and traditional irrigation methods (Rajagopal and Dhanapal, 2000).

These findings are corroborated by Mahmood et al. (2003), who found that wheat yields were higher with SF than with CF. The study conducted by Mintesinot et al. (2007) in Ethiopia found that surge flow irrigation achieved the highest maize yields compared to alternate, complete, and conventional CF systems. In Egypt, Amer (1998) observed that SF increased cotton yield by 9% with high and 4% with low inflow rates. Also, in Egypt, Zaghloul (1988) noted that yields of wheat grain under SF were 27.4%, 27.4%, and 8.3% higher than those achieved with CF in the 1st, 2nd, and 3rd growing seasons, respectively.

Interestingly, compared to CF, SF positively influences water use efficiency by conserving water. This method effectively saves water and boosts crop yield, including maize, especially under water-scarce conditions (Okasha et al., 2022). According to Amer and Attafy (2017), this method can reduce water usage by 18-30% compared to CF. For maize, SF can achieve a peak WUE of 1.63 kg m^{-3}, a significant increase compared to the 1.05 kg m^{-3} efficiency observed with continuous irrigation (Kaur et al., 2021). The alternating surge treatment notably increased WUE by 94.74% and 73.68% over continuous irrigation (Xin et al., 2019). Similarly, Horst et al. (2007) found that SF was the most effective system for water conservation and increasing water productivity. Compared to traditional CF, which had a productivity of 0.38 kg m^{-3}, SF achieved a productivity of 0.61 kg m^{-3}. Additionally, Mintesinot et al. (2007) found that SF achieved higher WUE levels than the conventional CF method, establishing it as the most effective water management strategy. He noted that SF increased water productivity by approximately 62% over traditional practices. Although SF shows promising results, its effectiveness can be influenced by various factors, such as soil texture class, furrow length, and inflow rates. Nonetheless, moisture distribution and efficiency benefits make it a compelling choice in modern irrigation practices.

Conclusions

Based on this study's results, performance indices, e.g., Ea and patterns of soil moisture distribution, were enhanced under SF. SF performed better in reaching the tail end of the furrow with less water advance time than the CF treatment. On the other hand, SF performed better than CF in terms of saving water by an increase of 19.83, 27.58, and 32.26% under the SF4, SF5, and SF6 treatments, respectively, compared to the CF treatment. This suggests that SF improves water use efficiency for maize production by an increase of 40.27, 69.28, and 84.30% at the SF4, SF5, and SF6 treatments, respectively, compared to the CF treatment. Therefore, it can be applied to farmers in areas with limited irrigation water.

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5. References

Abbaspour KC, Faramarzi M, Ghasemi SS, Yang H (2009). Assessing the impact of climate change on water resources in Iran. Water Resour. res., 45(10).

Abdelmonem Y (2005). The use of surges to improve surface irrigation. Irri. Drain., 40:1–12.

Abdelraof E, Nassar IN, Gomaa I, Aboukila E (2023). Valorization of cheese whey as a fertilizer: effects on maize germination and growth in clay loam and calcareous soil. Egypt. J. Soil Sci., 63(4): 489–502.

Ahmadabad YH, Liaghat A, Sohrabi T, Rasoulzadeh A, Ebrahimian H (2021). Improving performance of furrow irrigation systems using simulation modelling in the Moghan plain of Iran. Irrig. Drain., 70(1): 131–149.

Ali H (2011). Practices of Irrigation & On-farm Water Management: Volume 2 (Vol. 2). Springer Science & Business Media.

Allen RR, Schneider AD (1992). Furrow water intake reduction with surge irrigation or traffic compaction. Appl. Eng. Agric., 8(4): 455–460

Amer M, Attafy T (2017). Effect of surge flow on some irrigation indices of furrow irrigation system. J. Soil Sci. Agric. Eng., 8(12): 703–708.

Amer MH (1998). Surge flow irrigation as a farm practice for cotton production. Zagazig J. Agric. Res, 25(4): 659–669.

Benham BL, Reddell DL, Marek TH (2000). Performance of three infiltration models under surge irrigation. Irrig. Sci., 20: 37-43.

Bishop AA, Poole GJ, Allen NL, Walker WR (1981).

Furrow advance rates under surge flow systems. J. Irrig. Drain. Div., 107(3): 257–264.

Cuenca RH (1989). Irrigation system design: an engineering approach. Prentice-Hall, New Jersey.

Dane JH, Topp CG (2020). Methods of soil analysis, Part 4: Physical methods (Vol. 20). John Wiley and Sons.

Doorenbos J, Pruitt WO (1977). Guidelines for predicting crop water requirements. Irrigation and drainage paper number 24. FAO, Rome.

Ebrahimian H, Liaghat A, (2011). Field evaluation of various mathematical models for furrow and border irrigation systems. Soil Water Res., 6 (2): 91–101.

El-Nady MA, Hadad WM (2016). Water use efficiency of soybean under different tillage and irrigation methods. Egypt. J. Soil Sci., 56(2): 295–312.

EL-Sayed MM, Gebreel M, Elglaly AM, Abdelhalem AK (2022). Potato productivity in response to furrow irrigation practices, rabbit manure rates, and potassium fertilizer levels. Egypt. J. Soil Sci., 62(4): 335–348.

El-Sayed MM, Khalafalla MY, Gebreel M, Abdel-Mawgoud ASA (2019). Surge flow performance for furrow irrigation under upper Egypt conditions. J. Soil Sci. Agric. Eng., 10(11): 685–691.

El-Sherpiny MA, Baddour AG, El-Kafrawy MM (2020). Effect of zeolite soil addition under different irrigation intervals on maize yield (*Zea mays* L.) and some soil properties. J. Soil Sci. Agric. Eng., 11(12): 793–799.

Graterol YE, Eisenhauer DE, Elmore RW (1993). Alternate-furrow irrigation for soybean production. Agric. Water Manag., 24(2): 133–145.

Helmy AA, El-Sherpiny MA (2022). Response of maize plant grown under water deficit stress to compost and melatonin under terraces and alternate furrow irrigation techniques. Egypt. J. Soil Sci., 62(4): 383–394.

Hoffman GJ, Evans RG, Jensen ME, Martin DL, Elliott RL (Eds.) (2007). Design and operation of farm irrigation systems (pp. 436p-437p). St. Joseph, MI: American Society of Agricultural and Biological Engineers.

Horst MG, Shamutalov SS, Goncalves JM, Pereira LS (2007). Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. Agric. Water Manag., 87(2): 115–127.

Horst MG, Shamutalov SS, Pereira LS, Gonçalves JM (2005). Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea basin. Agric. Water Manag., 77(1-3): 210–231.

Howell TA (2003). Irrigation Efficiency. In: Encyclopedia of water science. New York (USA): Marcel Dekker, Inc.

Ismail SM (2004). Effectiveness of surge flow irrigation in Egypt: water use efficiency in field crop production. IHE Delft Institute for Water Education.

Ismail SM, Depeweg H (2005). Simulation of continuous and surge flow irrigation under short field conditions. Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage, 54(2): 217–230.

Ismail SM, Depeweg H, Schultz B (2004). Surge flow irrigation under short field conditions in Egypt. Irrig. Drain., 53(4): 461–475.

Izadi B, Podmore TH, Seymour, RM (1995). Consideration of air entrapment in surface irrigation; A computer simulation study. Agric. Water Manag., 28(3): 245–252.

James LG, (1988). Principles of Farm Irrigation System Design. John Wiley and Sons, Inc., New York, pp. 342–344.

Kang S, Liang Z, Pan Y, Shi P, Zhang J (2000). Alternate furrow irrigation for maize production in an arid area. Agric. Water Manag., 45(3): 267–274.

Kaur S, Kaushal A, Shelke P (2021). Enhancement of water productivity with surge irrigation. Int. J. Agric. Sci., 17: 340–347.

Kifle M, Gebremicael TG, Girmay A, Gebremedihin T (2017). Effect of surge flow and alternate irrigation on the irrigation efficiency and water productivity of onion in the semiarid areas of North Ethiopia. Agric. water Manag., 187: 69–76.

Kifle M, Tilahun K, Yazew E (2008). Evaluation of surge flow furrow irrigation for onion production in a semiarid region of Ethiopia. Irrig. Sci., 26: 325–333.

Koech RK, Smith RJ, Gillies MH (2014). Evaluating the performance of a real-time optimisation system for furrow irrigation. Agric. Water Manag., 142: 77–87.

Mahmood S, Kahan MA, Latif M, Sial JK (2003). Application of surge irrigation on borders for water saving and wheat production: first year study result. Ital. J. Agron., 7(1): 49–55.

Mathew AC, Senthilvel S (2007). Performance evaluation of an automated surge irrigation in paired row furrows. Madras Agric. J., 94: 242–255.

Mattar MA, El-Saadawy MA, Helmy MA, Sorour HM (2017). Field assessment of surge and continuous furrow irrigation methods in relation to tillage systems. Int. Agrophys., 31(2): 219–230.

Mazarei R, Mohammadi AS, Ebrahimian H, Naseri AA (2021). Temporal variability of infiltration and roughness coefficients and furrow irrigation performance under different inflow rates. Agric. Water Manag., 245, 106465.

Mintesinot B, Verplancke H, Van Ranst E, Mitiku H (2007). Enhancing the productivity of irrigated Vertisols: a comparative study between a traditional method and surge/intermittent management. Soil Use Manag., 23 (1): 36–39.

Mitchell AR, Stevenson K (1994). Surge flow and alternating furrow irrigation of peppermint to conserve water. Central Oregon Agricultural Research Center Annual Reports, 1993, AES OSU, Special Report, 930: 79–87.

Mohammed A, Abdeen N, Hamid A (2015). Effect of irrigation technique on efficiency of furrow irrigation. Inter. Conf. on Chem, Env. Bio. Sci. (CEBS), Dubai (UAE): 168–170.

Moravejalahkami, B, Mostafazadeh-Fard B, Heidarpour M, Abbasi F (2009). Furrow infiltration and roughness prediction for different furrow inflow hydrographs using a zero-inertia model with a multilevel calibration approach. Biosyst. Eng., 103(3): 374–381.

Ojaghlou H, Sohrabi T, Abbasi F, Javani H (2020). Development and evaluation of a water flow and solute transport model for furrow fertigation with surge flow. Irrig. Drain., 69(4): 682–695.

Okasha AM, Khalifa EM, Moustafa MM, Khattab MS (2022). Effect of fertilization with surge flow technique on application efficiency, water productivity, yield and irrigation cost of maize crop (*Zea mays* L.). Misr J. Agric. Eng., 39(1): 71–92.

Onishi J, Ikeura H, Paluashova GK, Shirokova YI, Kitamura Y, Fujimaki H (2019). Suitable inflow rate and furrow length for simplified surge flow irrigation. Paddy Water Environ., 17: 185-193.

Payero JO, Tarkalson DD, Irmak S, Davison D, Petersen JL (2008). Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. Agric. Water Manag., 95: 895–908.

Radmanesh M, Ahmadi SH (2024). Surge irrigation modeling and scenario analyses for the best furrow irrigation management practices. J. Hydrol., 629: 130618.

Radmanesh M, Ahmadi SH, Sepaskhah AR (2023). Measurement and simulation of irrigation performance in continuous and surge furrow irrigation using WinSRFR and SIRMOD models. Sci. Rep., 13 (1): 5768.

Rajagopal A, Dhanapal R (2000). Surge irrigation studies in maize. (i) Crop response for geometry and on-off timings. Madras Agric. J., 87: 29–34.

Romay C, Ezquerra-Canalejo A, Botta GF (2024). Sensitivity analysis of performance indices of surge-flow irrigation with system variables using the SIRMOD model. Agronomy, 14(7):1509.

Savva AP, Frenken K (2002a). Irrigation manual planning, development monitoring and evaluation of irrigated agriculture with farmer Participation Volume II Module 7 (Surface irrigation systems planning, design, operation and maintenance). Food and Agriculture Organization of the United Nations (FAO) sub-regional office for East and Southern Africa, Harare.

Savva AP, Frenken K (2002b). Irrigation manual planning, development monitoring and evaluation of irrigated agriculture with farmer participation volume I module 4 (crop water requirements and irrigation scheduling). Food and Agriculture Organization of the United Nations (FAO) sub-regional office for East and Southern Africa, Harare.

Shibeshi FZ, Mogiso TM, Eniyew YZ (2023). Evaluation of irrigation water application techniques at Omo Kuraz Left Bank Canal, SNNPRE, Ethiopia. Indones. J. Earth Sci., 3(1): A515.

Shihab RM, Awjagh MSA (2016). Assessment of surge irrigation flow performance in short furrow under gypsiferous soil conditions. Tikrit J. Agric. Sci., 16(4): 117–129.

Smerdon ET, Blair AW (1985). Improving Surge Flow Irrigation Efficiency Based on Analysis of Infiltration and Hydrodynamic Effects. Texas Water Resources Institute. Texas A&M University, Technical Report No. 18.

Snedecor GW, Cochran WG (1980). Statistical Methods. 12th ed., Iowa State Univ. Press, Ames, Iowa, USA.

Sparks DL, Page AL, Helmke PA, Loeppert RH (Eds.). (2020). Methods of soil analysis, part 3: Chemical methods (Vol. 14). John Wiley and Sons.

Stringham GE, Keller J (1979) Surge flow automatic irrigation. In: Proceedings of the ASCE, irrigation and drainage division specialty conference, Albuquerque, NM: 132–142.

Walker WR, Skogerboe GV (1987). Surface Irrigation: 'Theory and Practice.' Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Wood CW, Krutz LJ, Falconer L, Pringle III HC, Henry B, Irby T, Orlowski JM, Bryant CJ, Boykin DL, Atwill RL, Pickelmann DM (2017). Surge irrigation reduces irrigation requirements for soybean on smectitic clay-textured soils. Crop, Forage & Turfgrass Manag., 3(1): 1-6.

Wu D, Xue J, Bo X, Meng W, Wu Y, Du T (2017). Simulation of irrigation uniformity and optimization of irrigation technical parameters based on the SIRMOD model under alternate furrow irrigation. Irrig. Drain., 66(4): 478-491.

Xin Q, Xu R, Li ZY, Lin SZ, Wang NN, Wang CT (2019). Experimental study on irrigation characteristics of wheat under surge irrigation. Int. J. Agric. Biol., 21 (2): 416-420.

Yaseen R, Hegab R, Kenawey M, Eissa D (2020). Effect of super absorbent polymer and bio fertilization on Maize productivity and soil fertility under drought stress conditions. Egypt. J. Soil Sci., 60(4): 377–395.

Zaghloul MA (1988). Wheat response to surge irrigation. Misr J. Agric. Eng., 5(2): 13–19.