Australian Journal of Crop Science AJCS
AJCS 6(5):884-890 (2012) ISSN:1835-2707

Solute distribution uniformity and fertilizer losses under meandering and standard furrow irrigation methods

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Abstract

Surface fertigation is a cost-effective and simple method of applying fertilizer if well-managed and designed. Surface irrigation in sloping fields has some difficulties, especially when soil is not deep enough for adequate leveling. In these fields, fertigation may result in contamination of surface waters due to runoff. The purpose of this study was to examine the effects of meandering furrow irrigation and field slope on the hydraulic parameters (advance time, recession time, water depth and runoff), distribution uniformities and application efficiency of water and fertilizer. A field experiment was conducted to evaluate the effect of field slope (1.1 and 2.9%) and furrow type (meandering furrow (MF) and standard furrow (SF) irrigation on hydraulic performance and efficiencies of irrigation and fertigation. Results indicated that application efficiency and advance time in MF irrigation were significantly more than SF irrigation ($P<0.05$) for both irrigation events. The average tail water runoff loss and consequently mass of fertilizer loss in MFs (718 L, 206 gr) were significantly (P< 0.05) less than SFs (1304 L, 399 gr), which could result in less surface water contamination. The average low quarter distribution uniformity (DU_{LQ}) and low half distribution uniformity (DU_{LH}) of water and fertilizer were high (almost 90%) for both irrigation methods. In general, the use of MF irrigation in sloping fields is recommended as a good management option for both irrigation and fertigation.

Keywords: Distribution uniformity; fertigation; furrow irrigation; meandering furrow.
Abbreviations: d_{15}-water depth at 15 m station from inlet; DU_{LH}-low half distribution uniformity; DU_{LQ}-low quarter distribution uniformity; E_a-application efficiency; F_R- fertilizer mass due to runoff; MF-meandering furrow; SF-standard furrow; t_a-advance time; t_r-recession time; V_{out}-tail water runoff volume.

Introduction

Furrow irrigation is the most commonly used irrigation method in the world. Simplicity of design and low capital investment has contributed to its popularity (Walker and Skogerboe, 1987). Selection of irrigation method depends on factors such as water availability, crop type, soil characteristics, land topography, and associated costs. Since land leveling is costly and not technically feasible in sloping lands, farmers in Iran use MF (snake-type) irrigation system in a traditional fashion in the direction of field slope (Sepaskhah and Shaabani, 2007). This type of furrow irrigation, which is locally called Gholam-gardeshi irrigation, is a modified form of furrow irrigation, and has being used for some farmlands and orchards traditionally for a long time. In this method of irrigation, the hydraulic behavior is different as compared to the SF irrigation because water moves in snake-shaped furrows with lower velocity of advance in the direction of field slope (Mostafazadeh-Fard et al., 2010). The linear distance between two end points of MF is much less than its length; so, the mean bed slope of MF is less than the field slope. In addition, channel sinuosity, which is defined as the ratio of total meandering channel length to linear distance between its endpoints in furrow, is severe, because this type of furrow has almost 90 degree bends.

Increasing channel sinuosity lowers flow velocity and increases flow depth, and accordingly, increases the wetted perimeter of the channel. Increasing flow depth will decrease flow resistance (*n*). But according to Chow (1959), meandering that happens in rivers can increase the *n* values by as much as 30%. The roughness coefficient in channels is affected by flow depth and sinuosity factor. Therefore, making MFs in sloping land increases application efficiency of irrigation as compared to SFs due to decreasing runoff losses, lower velocity of flow and higher infiltration volume (Mostafazadeh-Fard and Moravejalahkami, 2006). To develop the infiltration equation, field measured data of advance, recession, inflow and outflow rates are usually used. Sepaskhah and Shaabani, (2007) conducted an experiment to determine the parameters of Kostiakov-Lewis infiltration equation, flow hydraulic and geometric parameters for MF irrigation as compared to SF irrigation. For years, soil erosion has been a concern with furrow irrigation in sloping lands. The erosion rates on a field vary widely. Erosion and sediment transport capacity increases with the shear or velocity of the flow, which increases with the flow rate and furrow slope (Trout and Neibling, 1993). The mean bed slope of MF is less than the SF irrigation; therefore, tail water runoff and erosion are significantly lower for MF as

Table 1. Effect of field slope and irrigation method on efficiency and distribution uniformity parameters for the first irrigation.

Treatment	Runoff, V_{out} (L)	Advance time, t_a (min)	Recession time, t_r (min)	E_a (%)	Water	
					DU_{LH} (%)	DU_{LQ} (%)
Field slope (%)						
2.9	1531 ± 370^{a1}	11.1 ± 3.3^{b}	82.1 ± 2.2^{b}	58.1 ± 10.4^{b}	98.0 ± 1.6^{a}	96.6 ± 3.2^{a}
1.1	1030 ± 246^{b}	14.1 ± 3.9^{a}	86.6 ± 2.7^{a}	75.8 ± 12.1^{a}	98.5 ± 0.8^{a}	97.0 ± 1.8^{a}
Furrow type						
MF	822 ± 181^{b}	17.9 ± 2.1^{a}	84.5 ± 3.6^{a}	76.7 ± 8.9^{a}	97.5 ± 1.3^{a}	95.6 ± 2.8^{a}
SF	1739 ± 344^{a}	7.3 ± 1.9^{b}	84.1 ± 3.2^{a}	52.5 ± 9.9^{b}	98.9 ± 0.6^{a}	98.5 ± 0.9^{a}

[1] $\bar{x} \pm SD$. Means within a column that are followed by the same letter are not significantly different at the 5% level. V_{out}-tail water runoff volume; t_a-advance time; tr-recession time; E_a-application efficiency; DU_{LH}- low half distribution uniformity; DU_{LQ}-low quarter distribution uniformity; MF-meandering furrow; SF-standard furrow.

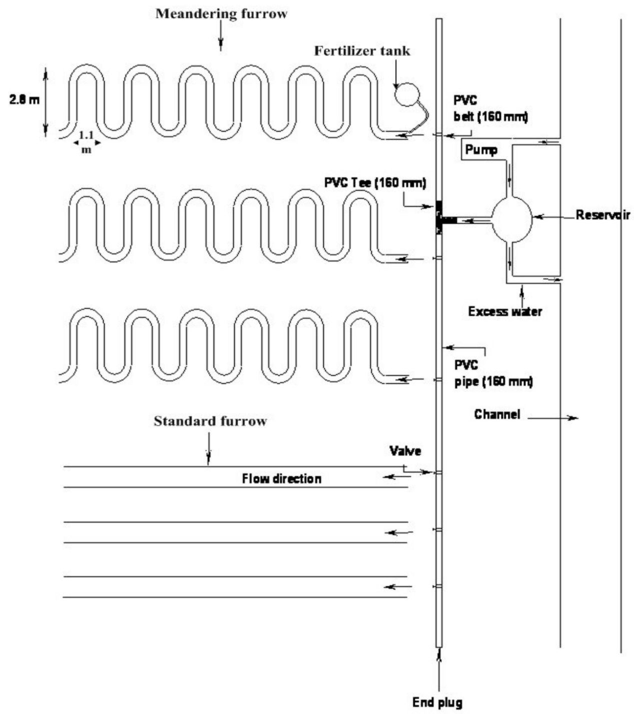

Fig 1. Schematic of constant-head water delivery system to the furrows (subplot).

compared to SF (Mostafazadeh-Fard et al., 2009). For soils with higher potential for erosion, and higher furrow inflow rate, the MF irrigation has the capability to reduce furrow erosion (Mostafazadeh-Fard et al., 2010). Fertigation is the application of water-soluble fertilizers through an irrigation system. Fertigation in general, when well-managed, can provide relatively uniform and timely applications of agricultural chemicals (Sabillon and Merkley, 2004). Despite the above advantages, there has been relatively little use of fertigation in surface irrigation. Likely reasons for the limited use of surface fertigation are typically low uniformity of surface irrigation systems and fertilizer losses due to runoff (Playán and Faci, 1997; Abbasi et al., 2003b). Previous researches on surface fertigation emphasize on some management strategies to control fertilizer losses due to runoff and deep percolation. Bouwer et al. (1990) suggested that the fertilizer should be added during the end of irrigation event to avoid deep percolation of chemicals to groundwater. Another suggestion was to inject the fertilizer at a constant rate during the entire irrigation event. This recommendation assumes that the tail water runoff will be mixed with other waters and reused in another field (Burt et al., 1998). The modeling studies have showed that the timing and duration of fertigation applications during the surface irrigation event plays a critical role in determining the distribution of fertilizer in the field and potential movement of nitrate to groundwater (Playán and Faci, 1997; Sabillón and Merkley, 2004). Nitrogen is the nutrient that is most commonly applied by fertigation (Burt et al., 1998). These days, one of the environmental concerns is contamination of surface water and groundwater by deep percolation and runoff of nitrogen in irrigated districts (Zerihun et al., 2003). So, surface irrigation systems should be well-designed and managed to minimize contamination of water resources by surface fertigation. The management strategies are evaluated by nitrogen distribution uniformity and runoff efficiency of surface fertigation systems (Playan and Faci, 1997; Abbasi et al., 2003b; Zerihun et al., 2003; Adamsen et al., 2005). MF irrigation is inexpensive and can be used as an alternative choice for more expensive methods of irrigation such as sprinkle or trickle systems, especially for fields with

Table 2. Effect of field slope and irrigation method on efficiency and distribution uniformity parameters for water and fertilizer for the second irrigation

Treatment	Runoff, V_{out} (L)	F_R (gr)	D_{15} (cm)	t_a (min)	t_r (min)	E_a (%)	Water DU_{LH} (%)	Water DU_{LQ} (%)	Fertilizer DU_{LH} (%)	Fertilizer DU_{LQ} (%)
Field slope (%)										
2.9	1235 ± 320[a1]	350 ± 74[a]	2.5 ± 0.5[a]	10.9 ± 1.8[b]	68.6 ± 1.7[b]	50.5 ± 7.4[b]	97 ± 2[a]	94 ± 4[a]	92 ± 3[a]	89 ± 5[a]
1.1	787 ± 242[b]	251± 56[b]	2.9 ± 0.4[a]	14.6 ± 2.7[a]	73.1 ± 1.7[a]	68.4 ± 8.7[a]	95 ± 3[a]	93 ± 4[a]	93 ± 3[a]	91 ± 4[a]
Furrow type										
MF	718 ± 140[b]	206 ± 50[b]	3.2 ± 0.4[a]	15.1 ± 2.2[a]	71.5 ± 2.3[a]	70.1 ± 10.2[a]	95 ± 3[a]	92 ± 4[a]	91 ± 3[a]	87 ± 5[a]
SF	1304 ± 228[a]	399 ± 70[a]	2.2 ± 0.3[b]	9.4 ± 1.3[b]	70.1 ± 3.3[a]	47.2 ± 8.3[b]	96 ± 3[a]	95 ± 3[a]	94 ± 2[a]	92 ± 2[a]

1 $\bar{x} \pm SD$. Means within a column that are followed by the same letter are not significantly different at the 5% level. V_{out}-tail water runoff volume; F_R-fertilizer mass due to runoff; d_{15}-water depth at 15 m station from inlet; t_a-advance time; t_r-recession time; E_a-application efficiency; DU_{LH}- low half distribution uniformity; DU_{LQ}-low quarter distribution uniformity; MF-meandering furrow; SF-standard furrow.

Table 3. Soil moisture at upstream end, middle and downstream end of the furrow three days after the second irrigation

	Sampling location: Upstream end of furrow	Middle	Lower end of furrow
Field slope (%)			
2.9	7.9 ± 1.5[a1]	8.1 ± 1.9[a]	7.0 ± 1.8[a]
1.1	10.5 ± 1.8[a]	8.0 ± 1.4[a]	7.7 ± 1.5[a]
Furrow type			
MF	9.1 ± 2.0[a]	8.1 ± 2.0[a]	7.4 ± 1.7[a]
SF	9.3 ± 2.2[a]	7.9 ± 1.2[a]	7.4 ± 1.7[a]
Sampling depth			
0-15 cm	10.2 ± 2.5[a]	8.7 ± 1.8[a]	8.8 ± 1.3[a]
15-30 cm	8.5 ± 1.9[b]	8.3 ± 1.4[a]	7.2 ± 1.4[b]
30-45 cm	8.8 ±1.5 [b]	7.1 ± 1.2[b]	6.2 ± 1.2[c]

1 $\bar{x} \pm SD$. Means within a column that are followed by the same letter are not significantly different at the 5% level.
MF-meandering furrow; SF-standard furrow.

larger slopes, where SF irrigation has low efficiency and high fertilizer losses. To date, there is no study on fertigation in MF irrigation. The main objective of this study was to compare the MF irrigation and SF irrigation on fertigation efficiencies, water losses and hydraulic performance.

Results and discussion

Water advance and recession times

The time of water advance in MF and SF irrigation was 17.89 and 7.26 min for the first irrigation (Table 1). Similarly, water arrived to the end of MF and SF irrigation at 15.12 and 9.36 min, respectively, for the second irrigation (Table 2). Therefore, advance time in MF irrigation was significantly ($P<0.05$) more than SF irrigation. These results are consistent with the results reported by Mostafazadeh-Fard and Moravejalahkami (2006), Sepaskhah and Shaabani, (2007) and Mostafazadeh-Fard et al. (2009) which reported lower velocity of water advance in MF irrigation as compared to SF irrigation. As shown in Tables 1 and 2, the velocity of advance for SF irrigation for the second irrigation event is slightly less than the first irrigation event. The velocity of advance of MF irrigation for the second irrigation is more than the first irrigation. For a constant field slope, the variables influencing the advance time are inflow rate and the Manning roughness coefficient (n). The average value of inflow rate for the first irrigation was more than the second irrigation. For both irrigation methods, the change of flow rate from the first irrigation to the second irrigation was the same. Therefore, the reason that the difference in advance time between the first and second irrigations for MF is higher than the SF is because the roughness coefficient was reduced faster from the first irrigation to the second irrigation for MF as compared to SF. The inflow discharge to furrows was chosen by considering real bed slope of MFs. So, there was not any difficulty in advancing of water in MFs. Overall results of the experimental plots showed that for both irrigation methods, as field slope increased, velocity of advance and recession increased for the first and second irrigations (Tables 1 and 2). The recession time for MFs was higher than SFs for both irrigation events, but the differences were not statistically significant. These results are consistent with the results reported by Sepaskhah and Shaabani, (2007) which have reported higher recession time for MFs as compared to SFs.

Runoff volume and fertilizer losses

The runoff volume in MF irrigation was significantly ($P<0.05$) less than SF irrigation for the first and second irrigations (Tables 1 and 2). As shown in Table 1, the volume of runoff for MF irrigation is 822 L, while for SF irrigation, for the same irrigation event, is 1739 L. These results are consistent with the results obtained by Mostafazadeh-Fard and Moravejalahkami (2006) and Mostafazadeh-Fard et al. (2009). Consequently, as shown in Table 2, the mass of

Table 4. Overland solute concentrations at different sampling times.

Treatment	Elapsed time (min)						
	Advance time	20 min	30 min	40 min	50 min	60 min	Recession time
Field slope (%)							
2.9	474 ± 79[a1]	379 ± 55[a]	411 ± 60[a]	427 ± 56 [a]	418 ± 45[a]	411 ±47[a]	365 ± 38[a]
1.1	486 ± 85[a]	406 ± 69[a]	405 ± 59[a]	376 ± 50[a]	390 ± 50[a]	385 ±55[a]	355 ± 31[a]
Furrow type							
MF	477 ± 80[a]	396 ±60 [a]	433 ±51[a]	413 ±62 [a]	387 ± 41[a]	397 ± 53[a]	342 ± 26[a]
SF	483 ± 84[a]	388 ±49 [a]	383 ± 58[a]	390 ± 50[a]	392 ± 48[a]	398 ± 57[a]	341 ± 39[a]
Sampling location							
15 m from inlet	521 ± 62[a]	402 ± 47[a]	406 ± 60[a]	405 ± 34[a]	391 ± 45[a]	399 ± 42[a]	334 ± 25[a]
30 m from inlet	478 ± 63[b]	396 ± 52[a]	412 ± 58[a]	396 ± 55[a]	403 ± 41[a]	405 ± 35[a]	352 ± 39[a]
45 m from inlet	441 ± 65[b]	378 ± 61[a]	407 ± 49[a]	403 ± 61[a]	375 ± 46[a]	389 ± 50[a]	338 ±42 [a]

[1] $\bar{x} \pm SD$. Means within a column that are followed by the same letter are not significantly different at the 5% level. MF-meandering furrow; SF-standard furrow.

Table 5. Soil solute concentration along the length of furrows.

	Sampling location		
	Upper end of furrow	Middle	Lower end of furrow
Field bed slope (%)			
2.9	255 ± 40[a1]	255 ± 25[a]	302 ± 77[a]
1.1	305 ± 61[a]	280 ± 50[a]	262 ± 29[a]
Furrow type			
MF	261 ± 46[a]	256 ± 23[a]	251 ± 29[b]
SF	299 ± 65[a]	279 + 52[a]	311 ± 75[a]
Sampling depth			
0-15 cm	308 ± 26[a]	266 ± 20[ab]	269 ± 24[a]
15-30 cm	275 ± 20 [a]	285 ± 60[a]	267 ± 33[a]
30-45 cm	257 ± 20 [a]	251 ± 32[b]	280 ± 57[a]

[1] $\bar{x} \pm SD$. Means within a column that are followed by the same letter are not significantly different at the 5% level. MF-meandering furrow; SF-standard furrow.

Table 6. Soil physical and chemical properties for the trial site.

Depth (cm)	Soil texture	Soil particles (%)			EC (dS/m)	pH
		Clay	Silt	Sand		
0-15	Sandy clay loam	20.8	26.4	52.8	0.42	7.9
15-30	Sandy clay loam	21.6	23.2	55.2	0.93	7.9
30-45	Sandy clay loam	24.8	21.6	53.6	1.38	7.7

nitrate losses due to runoff in MF irrigation was significantly less than SF irrigation. As shown in Table 2, the mass of fertilizer losses for MF irrigation is 206.1 gr, while for SF irrigation is 399.9 gr. These results show that the use of MFs instead of SFs can reduce the volume of runoff and consequently the mass of fertilizer losses to almost half for the same irrigation event. As shown in Tables 1 and 2, as field slope increased, the volume of runoff and consequently the mass of nitrate losses increased for both MF and SF irrigations.

Application efficiency and uniformities

The application efficiency of MF irrigation was significantly (*P<0.05*) higher than SF irrigation in both irrigation events (Tables 1 and 2). As shown in Table 1, the application efficiency of MF irrigation is 76.7%, while for SF irrigation, for the first irrigation event, is 52.5%. Also, for the second irrigation, the application efficiency of MF irrigation is 71%, while for SF irrigation is 47% (Table 2). This is because less runoff occurred in MF irrigation as compared to SF irrigation as reported by Mostafazadeh-Fard and Moravejalahkami (2006). As shown in Tables 1 and 2, for both irrigation methods, as field slope increased, the application efficiency of water decreased. The irrigation method and field slope did not show any significant effect on water distribution uniformities for both irrigation events (Tables 1 and 2). The values of water distribution uniformities were high for both irrigation methods as a result of low water advance time in furrows. The distribution uniformities of water and fertilizer for MF irrigation were less than SF irrigation, but the differences were not significant. Differences in nitrate DU_{LH}, DU_{LQ} were not significant between two field slopes (Table 2). The nitrate distribution uniformities (ranged from 87.3 to 93.8%) were less than water uniformities (ranged from 92.1 to 98.9%); but the differences were not significant (Table 2). Jaynes et al. (1992), Playán and Faci

(1997) and Adamsen et al. (2005) reported lower uniformity values for fertilizer distribution as compared to water distribution. The application efficiency of MF irrigation was significantly ($P<0.05$) more than SF irrigation. Distribution uniformities were high in all irrigation events, which means that there were not significant fertilizer losses in MFs due to less deep percolation. With high water uniformity and efficiency of the irrigation event, the best fertilizer management can be obtained (Playán and Faci, 1997).

Soil moisture

The field slope and irrigation method did not have significant effect on soil moisture at the upstream end, middle and downstream end of the furrows. But, moisture distribution in soil profile was not uniform (Table 3). Soil moisture at the upstream end in surface layer was the highest. As expected, soil moisture in the top 15 cm was significantly more than the other two soil layers at upstream and downstream ends of the furrows.

The gradient of soil moisture profile at the downstream end of furrows was more than the upstream end. Moisture content in the third soil layer was significantly less than the second layer. In the middle of furrows, the first two soil layers had almost the same moisture content, but the moisture content in the third layer was significantly less than the upper layers (Table 3).

Flow depth

As shown in Table 2, as the field slope increased from 1.1% to 2.9%, flow depth decreased, but the differences were not significant. The water depth in MF irrigation was significantly higher than SF irrigation (Table 2). Abbasi et al. (2003a) found that infiltrated water/solute increased with increasing water level, and higher water levels required less time for prescribed amounts of water/chemicals to infiltrate. So, infiltrated solute in MF irrigation was more than SF irrigation.

Surface water nitrate concentration

Field slope and furrow irrigation method did not have significant effect on overland nitrate concentrations at different sampling times (Table 4). During the advance phase, the overland solute concentration in 15 m station from the injection point was significantly more than 30 and 45 m stations. But there was no significant difference in overland solute concentration at different locations along the furrows at other sampling times (Table 4). Therefore, nitrate concentration in irrigation water was fairly constant both through time and along the length of the furrows. Similar results were reported by Adamsen et al. (2005). In advance time, there was some deviation due to undesired flow rate changes as reported by Abbasi et al. (2003b).

Soil nitrate concentration

Field slope did not have significant effect on soil nitrate concentration along the furrow length. There were no significant differences between soil nitrate concentrations of different soil layers at different locations along the furrows (Table 5). Soil nitrate concentration was uniform along the soil depth and along the entire furrow length. Similar results have been reported by Adamsen et al. (2005). Furrow irrigation method did not have significant effect on soil nitrate concentrations at the upstream end and middle of the furrows. But for the MF irrigation, soil nitrate concentration at the downstream end was significantly less than SF irrigation (Table 5). The time for water to reach downstream end of furrow for MF irrigation was higher than SF irrigation (Table 2). This will result in less infiltrated fertilizer at the downstream end for the MF irrigation.

Materials and methods

Site description

The experiment was conducted at Agricultural Research Field (32.32 N., 51.23 E.) of Isfahan University of Technology, Isfahan, Iran. The experimental field has a sandy clay loam soil with no vegetation. Physical and chemical properties of the soil are shown in Table 6.

Experimental design and statistical analysis

The experiment was laid out in Randomized Complete Blocks (RCB) design with split plot arrangement using three replications. To examine the effect of field slope and furrow type on irrigation performance factors (advance and recession time, runoff volume, water depth, fertilizer loss due to runoff, application efficiency and distribution uniformity), two field slopes (2.9 and 1.1%) were kept in main plots while two furrow types (SF and MF) were assigned to the subplots. The response from each subplot was taken as the mean of three furrows. Fig. 1 represents a schematic of a subplot. The effect of soil sampling depth on soil moisture and soil solute concentration was analyzed by RCB design with a split-split ANOVA. The main plots and subplots were as mentioned before. Each subplot was split into three soil layers (0-15, 15-30 and 30-45 cm) as the sub-subplot factor. Also, the effect of water sampling location on overland solute concentrations was analyzed by RCB design with a split-split ANOVA. The main plots and subplots were as mentioned before. Each subplot was split into three sampling location (15, 30 and 45 m from the inlet) as the sub-subplot factor.

The collected data were subjected to analysis of variance using general linear models (GLM) procedure (SAS, 1987). The means for different traits were tested using a least significant difference (LSD) test at probability level of 0.05.

Experimental set-up and data measurements

A constant-head water delivery system to the furrows was installed at the upstream end of each experimental field to irrigate the subplots. The schematic of constant-head water delivery system and experimental furrows is shown in Fig. 1. The experiments were conducted under free draining conditions. The MFs and SFs were 45 m long and spaced 0.75 m apart. For MF irrigation method, the distance between two turning points of water was 1.1 m. The furrow cross-sectional geometry was measured at three locations of the upstream end, middle, and downstream end of each furrow. Soil surface elevation at the bottom of furrows was surveyed for each furrow with an automatic level.

The furrows were staked every 5 m for the 45 m length of furrows. All stations were used to monitor the advance and recession phases. The experiments were run for two successive irrigation events with 15 days apart. The first irrigation lasted 75 min and the second 60 min. The average inflow rates to each furrow were 0.9 and 0.7 L/s for the first and second irrigations, respectively. A trapezoidal WSC flume was used at the upstream and downstream ends of each furrow for measuring inflow and outflow for both irrigation methods. The first irrigation was conducted without injecting fertilizer. In the second irrigation, nitrate (KNO_3) fertilizer was injected at a constant rate of 6.2 $g\ NO_3.\ L^{-1}$ during the entire irrigation event. Moreover, water flow depth readings were recorded at each 15 m (15, 30 and 45 m) using staff gauges placed at the bottom of each furrow. Water samples were taken manually from surface water of each furrow for nitrate concentration at different stations along the furrows. Water samples were taken each 10 minutes as soon as water reached the stations. Nitrate samples were taken to laboratory, frozen and preserved in high-density polyethylene (HDPE) bottles. Clough et al. (2001) reported that this procedure prevents sample transformation and maintains the initial concentration, as well as being a simple, easy and rapid method.

Soil samples were collected three days after each irrigation event at inlet, middle, and outlet stations for analyzing average nitrate concentrations and soil water content. At each station, the samples were taken from bottom of the furrow at different depths down to 45 cm. Soil and water samples were analyzed for nitrate concentration using steam distillation method described by Bremner and Keeney (1965).

Irrigation and fertigation evaluation

The collected data from furrows were used to determine the Kostiakov-Lewis infiltration equation using volume balance method (Walker and Skogerboe, 1987):

$$Z = k\,\tau^{a} + f_0 t \tag{1}$$

where, Z = infiltrated volume per unit furrow length, f_0 = basic infiltration rate and k , a = empirical constants. The irrigation and fertigation events were evaluated using the distribution uniformity of the low quarter (DU_{LQ}) and distribution uniformity of low half (DU_{LH}) indices for infiltrated depths along the furrow (Merriam and Keller, 1978):

$$DU_{LQ} = \frac{\overline{\varphi_{LQ}}}{\varphi}. \tag{2}$$

$$DU_{LH} = \frac{\overline{\varphi_{LH}}}{\overline{\varphi}} \tag{3}$$

where, $\overline{\varphi}$ = either the average infiltrated depth or the average infiltrated nitrate in furrow, $\overline{\varphi_{LQ}}$ and $\overline{\varphi_{HQ}}$ = average of low quarter and low half of infiltrated depth or infiltrated nitrate, respectively. Infiltrated water was estimated by the Kostiakov-Lewis infiltration equation. The mass of solute infiltrated between two consecutive water sampling was estimated as the difference between the corresponding infiltrated depths multiply by the average concentration of the overland water. The mass of fertilizer losses due to runoff at the downstream end was estimated using outflow rates and overland water concentrations as follows:

$$F_R = \frac{\left(Q_R^{t+\Delta t} + Q_R^{t}\right)}{2} \times \frac{\left(C^{t+\Delta t} + C^{t}\right)}{2} \times \Delta t \tag{4}$$

where, F_R = fertilizer mass due to runoff, Q_R outflow rate at the end of furrow and C = solute concentration.

Conclusions

The MF irrigation significantly affected the advance time, runoff volume, mass of fertilizer losses and flow depth due to a significant decrease in actual furrow slope. The application efficiency, advance time and flow depth in MF irrigation were significantly higher than SF irrigation. The results showed that use of MF irrigation instead of SF irrigation can significantly reduce the volume of runoff and consequently the mass of fertilizer losses.

The field slope and furrow irrigation method did not have any significant effect on overland nitrate concentrations. For both irrigation methods, as field slope increased, the velocity of advance and recession, volume of runoff and consequently the mass of nitrate losses increased. Field slope had opposite effect on application efficiency. The use of MF irrigation in sloping fields is recommended as a good management option for both irrigation and fertigation.

Acknowledgements

This research was funded by Isfahan University of Technology. This assistance is gratefully acknowledged.

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