Effects of Infiltration Variability on Furrow Irrigation Performances

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Abstract: Furrow infiltration is a complex process and depends on several parameters that are quite difficult (if possible at all) to be evaluated in the field. This research studied the effects of spatial and temporal variations of soil infiltration on furrow irrigation performances. A range of field experiments were carried out on furrow irrigation in a sugarcane field to estimate spatial and temporal infiltration variability as well as irrigation performances. Four criteria were considered to study irrigation performance including application efficiency, distribution uniformity, tail water ratio, and deep percolation ratio. Seven irrigation scenarios were studied on two groups of furrows. Each group included three furrows 1.8 m wide and 140 m long. The performances of the first group of furrows (with the assumption of uniform) and of the second group (with the assumption of varying infiltration) were determined. Field data and Mateos and Oyonarte (2005) model, were used to assess the performances. The simulated distribution uniformity for the first irrigation event was 94.36 % and 63.17 % for uniform and non uniform-infiltration-assumption scenarios, respectively. As well, distribution uniformity for the last irrigation events was 96.44 and 76.33 %, respectively. Moreover, the infiltration variations decreased by time and so did the effects of infiltration changes on distribution uniformity.

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1. Introduction

Performance assessment is a key task for effective design and management of irrigation systems; so performance indicators and standard evaluation procedures have been developed for surface-, sprinkler-, and drip/trickle-irrigation systems in agriculture (Merriam and Keller, 1978). The design, evaluation and management of furrow irrigation depend on infiltration characteristics. Furrow infiltration comprises both local and field-average infiltration, and affects the advance and recession times, runoff and infiltrated volume, and uniformity of water applied during an irrigation event (Jobling and Turner, 1973 and Fonteh and Podmore, 1993). Due to spatial and temporal variations of infiltration, it is extremely difficult (if not impossible) to achieve irrigation uniformity and high efficiency in practice (Austin and Prendergast, 1997). Such variations and simplifying assumptions inherent in modeling make the predicted irrigation efficiencies be unrealistic and mostly overestimated. Irrigation engineers have suggested various criteria to assess irrigation system's performance (Hart *et al.*, 1979). Willardson (1972) reported twenty definitions for irrigation efficiency. Application efficiency (EA), distribution uniformity (DU), tail water ratio (TWR), and deep percolation ratio (DPR) are the most common criteria to assess irrigation system's performance. Studying spatial variations of infiltration, Bali and Wallender (1987) suggested that using infiltration variations in studying DU causes the efficiency to be underestimated; however, as the average infiltration rate increased, the overestimated efficiency began to decrease. Researches showed that the effects of infiltration variations mainly depend upon a furrow's cross section and its wetted premier (Schwankl *et al.*, 2000; Oyonarte *et al.*, 2002; and Trout, 1997). Mateos and Oyonarte (2005) estimated DU for three irrigations in Cordoba, Spain. They reported a range of 95 to 98 percent for DU when infiltration assumed uniform along a furrow; however, DU was reduced to 73% when infiltration variation was considered. To compare variable and uniform infiltration assumption along a furrow, they also used coefficient of variation (CV) of the final infiltration rate (f_0) obtained from different Blocked Furrows. However, the assumption of uniform f_0 along the furrow made the model overestimate DU by almost 40% (Oyonarte *et al.*, 2002). Walker (1993) developed the Surface Irrigation Model (SIRMOD) to evaluate the surface irrigation systems that has been widely used in practice for assessing field designs and management practices (Raine and Bakker, 1996). The SIRMOD uses three approaches including the full hydrodynamic, zero-inertia, and kinematic-wave to simulate the hydraulics of surface irrigation (Walker, 1998). Maheshwari and McMahon (1993a and 1993b) argued that hydrodynamic and zero- inertia approaches in SIRMOD underestimated the advance trajectory time but provided an acceptable prediction of irrigation performance. However, where the performance of SIRMOD was assessed for furrow irrigation of sugarcane, it was found that the model consistently under predict the advance times by an average of 22% and the infiltrated volume by an average of 16.9% (McClymont *et al*., 1996). This was attributed to either uncertainties in the infiltration parameters (Maheshwari and McMahon, 1993b) or the systematic error within the model (McClymont *et al*., 1996), which can be removed by an appropriate calibration procedure. While the SIRMOD consider infiltration characteristics to be uniform along the furrow, the Spreadsheet takes infiltration variability into account for evaluating performances. Using a Spreadsheet simulation and considering soil infiltration variability along the furrow and stagnant water in blocked furrows, Oyonarte *et al*. (2002) reported that up to 90% of the variation in the infiltration depth can be explained by the final infiltration rate f_0. Later, Mateos and Oyonarte (2005) developed Spreadsheet model to evaluate furrow irrigation performances. The Spreadsheet model revealed the following CVf_0 for three types of infiltration characteristics: a) soil with uniform infiltration has low infiltration variations with CVf_0 equal or less than 0.2; b) soil with medium infiltration variability has CVf_0 in the range of 0.2 to 0.3; and c) soil with high infiltration variability has CVf_0 in the range of 0.3 to 0.4. However, Trout (1992) reported that stagnant water conditions do not represent dynamics of the flow.

Generally, models should provide simulations that are more similar to the range of field conditions when compared to the other mathematical models. Hence, the performance indicators calculated by widely field measured data from for the experimental furrows are compared to those obtained by the proposed model (Mateos and Oyonarte, 2005) to demonstrate the accuracy and validity of the new model. The objective of the present study was to estimate Kastiakov-Lewis equation parameters in different places along a furrow considering dynamic flow conditions. This study further compared irrigation performances obtained from Spreadsheet model for variable soil infiltration characteristics with those obtained using field measured data from the experimental furrow assuming uniform infiltration conditions along the furrow.

2. Materials and Methods

Sugarcane is an important crop of tropical areas such as Iran. Thus, the crop utilizes most of the moisture stored in the root-zone. The life cycle of sugarcane is divided into four distinct phases namely germination phase (from planting to 60th day); formative phase (from 60th to 130th day); grand growth phase (from 130th to 250th day) and maturity phase (250th to 365th day). The total requirement of water for sugarcane approximately has been estimated from 0.2-0.3 meters. The crop may need an average of 7 irrigations; however, this may increase in drier climate and light soil textures. This research was carried out in ARC2-7 farm from January 2010 to December 2011. As one of the research fields of Sugarcane Research Center in Amir Kabir Sugarcane Planting and by products company of Khuzestan, the farm is located southwest of Iran. The soil had clay loam texture with 44.95% sand, 23.73% silt and 31.32 % clay. The field work was conducted on two sets of furrow irrigation. Each set had three furrows 1.8 m wide and 140 m long. The middle furrow of each set was used to take measurements, while the side furrows were used as buffering area. By measuring inflow, outflow, and calculating surface water storage, the volume of infiltrated water was determined. The advance and recession times were recorded at 14 points at 10 m intervals along each furrow. Seven irrigation events were examined. Taking soil samples from the furrows at three depths (0-33, 33-66 and 66-100 centimeters), soil water content were measured, using weighing method, to determine infiltration depth and irrigation time and volume, before and after each irrigation events. Fiberglass flumes (WSC) type II was used at the beginning and the end of each furrow in the first set where inflow/outflow measurements were to be taken. In the first set, experiments were carried out in order to determine the final infiltration rate (f_0) with the assumption of uniform soil infiltration characteristics (uniform furrow). First, inflow and outflow of the furrow were measured at the beginning and the end of two Fiberglass WSC flumes. Then, when the flow reached a constant level, f_0 was measured. The second set was used to study the spatial and temporal infiltration variability along a furrow and during planting season. Thus, using five fiberglass flumes, a furrow was divided into four reaches each 35 m long (variable furrow). Five flow meters were installed at the beginning of each reach (0, 35, 70, 105 and 140 meters away from the inlet) of each furrow. The four reaches were in series; thus the inflow to one reach was the outflow from the previous one. For each irrigation event, the flow depth in each flume was measured in order to determine the discharge in the flume by:

$$Q= cW H^{3/2} \qquad (1)$$

where Q is the discharge (in m^3/s), W is the width of opening (in meter), H is the depth of flow (in meter) and c is a coefficient of discharge which depends on the geometry of the culvert. A typical value is

0.6.more precise can be taken from tables such as in USDA-ARS (1979).

The water application, surface runoff, average water infiltration for each furrow were taken from inflow and outflow hydrographs. Then, infiltration rate values were obtained for each reach and the coefficient of variation of final infiltration rate (CV f_o) was obtained for total length of furrow.

2.1 Infiltration Function

Soil infiltration characteristics are usually expressed in a time-dependant infiltration equation. The most common one is the Kostiakov equation (Furman *et al*., 2006):

$$Z = kt^{a} \qquad (2)$$

where Z is the cumulative infiltration depth (m^3 m^{-1}), t is infiltration opportunity time (min), k (m^3 m^{-1}min^{-a}) is a coefficient indicating initial infiltration, and a is an exponent indicating the shape of the accumulated infiltration curve. When the duration of the water application is relatively short, the infiltration rate ($I = \partial Z/\partial t$) derived from Equation (1) does not significantly underestimate infiltration at the end of irrigation. However, this is not an adequate assumption when the intake opportunity time exceeds 3–4 hours; a situation commonly encountered in furrow irrigation and irrigation of large borders or basins (Walker *et al.*, 2006). Considering final infiltration rate (in m^3 min^{-1} m^{-2}), the Kostiakov–Lewis equation provides more realistic results:

$$Z = kt^{a} + f_0 t \qquad (3)$$

where f_0 is the final infiltration rate. Researches indicated that the Kostiakov–Lewis equation can simulate the advance trajectory more accurately, while those obtained from inflow/outflow data are better at predicting the runoff volumes and cumulative infiltration (Gillies and Smith, 2005 and Ebrahimian *et al*., 2010).

2.2. Furrow infiltrometer

Criddle *et al.* (1956) suggested, infiltrometer for estimating the infiltration rate, which required measurements of inflow and outflow at the inlet and outlet of the furrow as well as the length and the wetted perimeter of the furrow. Infiltration rate is calculated as follows:

$$I(t) = \frac{Q_i - Q_o}{LW_P} \qquad (4)$$

where I is the infiltration rate at t time (m^3 min^{-1} m^{-2}), Q_i and Q_o are the inflow and outflow discharges and L and W_P are the length and wetted perimeter of the furrow's section, respectively. While the infiltrometer takes into account the length of a furrow, it provides only an average estimate of the infiltration rate. It should be noted that the infiltration rate decreases as the soil gradually becomes saturated. Ultimately, the supply rate exceeds the capability of the soil to absorb the water; for which, the infiltration rate approaches the final infiltration rate f_0. In order to assess the performances, seven data sets for furrows were used in this study. Data were derived from the experimental furrows through sugarcane planting season under the free draining conditions. Table 1 indicates field data and parameters of the kostiakov-Lewis equation through seven irrigation events during growth season.

Table 1. Field data and Kostiakove-Lewis parameters used for assessment of the performances for uniform infiltration conditions

Parameters	Irrig 1	Irrig 2	Irrig 3	Irrig 4	Irrig 5	Irrig 6	Irrig 7
Inflow rate, *Qo* (l/s)	1.55	1.55	1.55	1.55	1.55	1.55	1.55
Time of advance phase (min)	260	245	227	216	234	247	247
time of cut-off (min)	500	500	500	500	500	500	500
Field length, *L* (m)	140	140	140	140	140	140	140
Field slope, S_o(m/m)	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Manning's *n* (m1/6)	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Separation between furrows (m)	1.8	1.8	1.8	1.8	1.8	1.8	1.8

2.3. Performance Indicators

Mateos and Oyonarte (2005) defined commonly-used irrigation performances as follow: distribution uniformity (DU), deep percolation ratio (DPR), tail water ratio (TWR), application efficiency (EA), and deficit ratio (DR). DPR and TWR are defined as the fraction of applied water going to percolation and tail water runoff, respectively (Walker and Skogerboe, 1987). DR is defined as the fraction of the root zone not filled to field capacity with irrigation water. EA is defined as the fraction of applied water stored in the root zone. DU is defined as the ratio between the average depth infiltrated in the quarter of the field with the lowest infiltrated depths and the average infiltrated depth, and can be related to the mean $(\bar{Z})$ and variance of the infiltrated depth $\sigma(Z)$ by (Warrick, 1983):

$$DU = 1 - 1.3\frac{\sigma(Z)}{(\bar{Z})} \tag{5}$$

The performance indicators DPR, TWR, and EA can be determined from the areas A to C in Fig. 1 (Anyoji and Wu, 1994) and from a fourth hypothetical area (D) that represents the runoff volume as:

$$DPR = \frac{B}{A+B+D} \tag{6}$$

$$TWR = \frac{D}{A+B+D} \tag{7}$$

$$EA = \frac{A}{A+B+D} \tag{8}$$

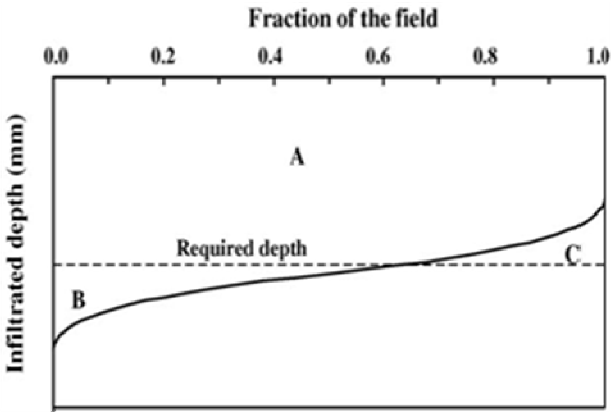

Fig. 1 - Cumulative frequency curve of normal distribution (Mateous and Oyonarte, 2005).

3. Results and Discussion

Table (2) compared the results for final infiltration rate (f_0) for uniform and (different reaches of) variable furrow as well as CV f_0 for each irrigation event. The Table clearly shows a considerable reduction of 29.7% in the variability of f_o by the irrigation events. This is in fact in agreement with Esfandiari and Mahshovari (1997) as they reported a 40% reduction for f_o in growth season. Walker *et al.* (1990) suggested that as irrigation time increases, the infiltration variation begin to decrease. The results of comparisons between the first and the second irrigation events (table 2) indicate that the reduction is large at the beginning of the growing season, it becomes less after. At the beginning of planting season, soil porosity and final infiltration rate are high due to its early furrowing of the farm. After the first irrigation, soil porosity decreases and because of the surface flow, the soil particles are eroded then it's structure is damaged. The combination of these factors ultimately decreases the final infiltration rate after the second irrigation onwards. Mateos and Giraldez (2005) also reported that sediment load was greatest in the first irrigation and declined in successive irrigations. Moreover, as sugarcane root is developing in the middle of the growth season, it creates narrow channels in the soil profile that eventually leads to quicker passage of water. This can increases the final infiltration rate. During the growth season, the soil pores decreased due to soil degradation and reduced soil particle stability because of surface flow. These two factors can affect the hydraulic conductivity of soil. However, as seen from table (2) the final infiltration rate from the beginning to the end of the variable furrow has spatially decreasing behavior, which may be related to different factors including accumulation of salinity at the ending parts of the furrow, non-maturity of fertilizers used, or displacement of eroded soil particles at the end of furrow. These factors may cause less growth of roots in the ending furrow and correspondingly, the decrease of final infiltration rate.

Table 2. Values of f_o and (CV f_0) for different reaches through growing season.

Irrigation Event	final infiltration rate (f_o)					CV f_0
	reach 1	reach 2	reach 3	reach 4	uniform	
Irrigation 1	0.000205	0.000170	0.000120	0.000116	0.000184	0.28
Irrigation 2	0.000155	0.000120	0.000110	0.000088	0.000139	0.24
Irrigation 3	0.000144	0.000121	0.000110	0.000079	0.000129	0.24
Irrigation 4	0.000140	0.000111	0.000108	0.000080	0.000117	0.22
Irrigation 5	0.000133	0.000118	0.000108	0.000077	0.000117	0.22
Irrigation 6	0.000151	0.000141	0.000110	0.000101	0.000121	0.19
Irrigation 7	0.000155	0.000144	0.000110	0.000110	0.000129	0.18
Reduction (%)	24.44	15.29	7.27	5.14	29.7	36.87

In furrow irrigation, the highest water velocity occurs at the beginning of furrow which decreased gradually to the end of furrow. Hence, the erosion increases in the first quadrate of the furrow while it decreases in the second half of the furrow (Trout, 1996). Fernandez Gomez *et al* (2004) indicated that the soil erosion in upstream of a furrow is six times the average erosion occurring along the furrow. To demonstrate the accuracy of the model, performance indicators were calculated from field data in uniform furrows (using equations suggested by Burt *et al.*, 1997) correlated with those simulated by Mateos and Oyonart (2005) model, with the assumption of uniform infiltration along a furrow and presented in Figs. 2 to 5. Simulated performances using Mateos and Oyonart (2005) model, with both uniform and variable infiltration characteristics assumption, given in table (3), to evaluate the differences between the two assumptions. In order to study the effects of spatial variations on irrigation performances, performances affected by CVf_0 in the variable furrow were simulated and compared with performances in the uniform furrow for each irrigation event.

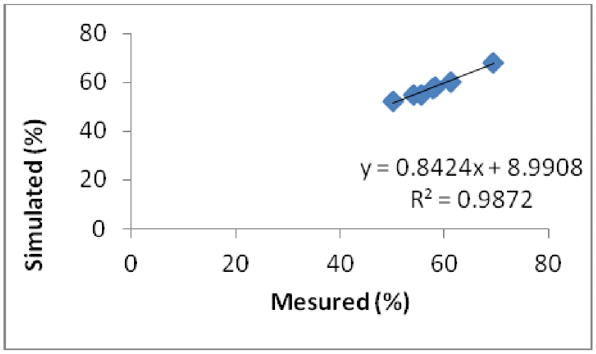

Fig. 2 - Water application efficiency obtained by measured and simulated data by Mateos and Oyonarte (2005) model.

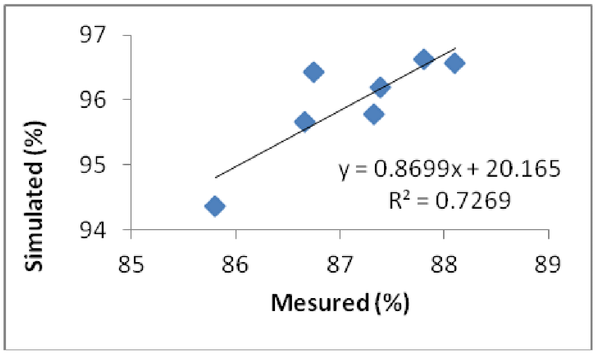

Fig. 3 - Distribution uniformity efficiency obtained by measured and simulated data by Mateos and Oyonarte (2005) model.

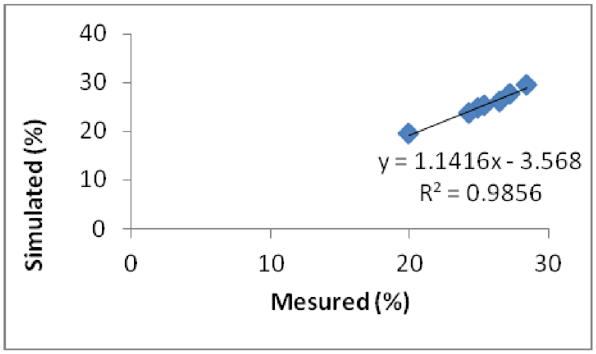

Fig. 4 - Surface Tail Water Ratio obtained by measured and simulated data by Mateos and Oyonarte (2005) model.

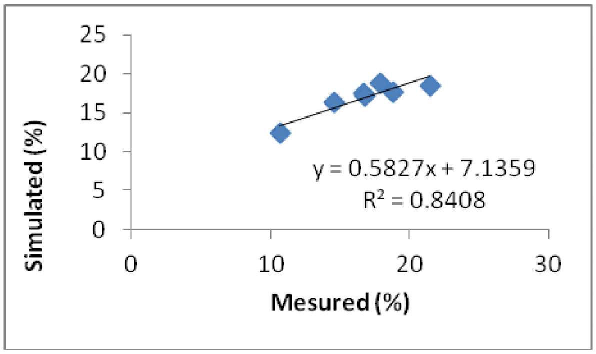

Fig. 5 - Deep Percolation Ratio obtained by measured and simulated data by Mateos and Oyonarte (2005) model.

Table 3 presents the two set of simulated performance indicators by mateos and oyonarte (2005) model, for seven irrigation events during sugarcane growing season for uniform and variable furrows. The table indicates that as the number of irrigation increases, tail water ratio increases to the forth irrigation event. This can be interpreted as a result of reduction in infiltration from the beginning to the forth irrigation event.

Table 3. simulated irrigation performances under variable and uniform soil infiltration characteristics.

Irrigation Scenario	Variable Infiltration characteristic				Uniform Infiltration characteristic			
	DU	EA	DPR	TWR	DU	EA	DPR	TWR
Irrigation 1	63.17	63.77	16.68	19.54	94.36	68.10	12.36	19.54
Irrigation 2	68.50	56.24	19.08	24.68	95.66	57.87	17.45	24.68
Irrigation 3	68.52	53.34	19.10	27.57	95.79	54.73	17.70	27.57
Irrigation 4	69.91	51.04	19.48	29.48	96.62	52.01	18.51	29.48
Irrigation 5	71.20	54.15	19.69	26.16	96.58	55.09	18.75	26.16
Irrigation 6	75.01	56.94	17.82	25.25	96.19	57.68	17.07	25.25
Irrigation 7	76.33	59.23	16.99	23.78	96.44	59.98	16.24	23.78

Comparing performances in both uniform and variable assumptions showed that infiltration variability decreases DU and Ea, and increases DPR. In which in variable assumption in the first irrigation, DU and Ea were % 33 and % 6.35 less and DPR was %25.9 more than uniform assumption. However, the differences of DU, Ea and DPR reduced to %20.84, % 1.25 and % 4.42 respectively at the end of the season. Assessing DU through growth season showed that DU increased from the beginning to the end of the season. Ea dwindled from the first to the forth irrigation then trend to increase until the end of the season. DPR and TWR were increased from the first to the forth irrigation then had decreasing trend until the end of growth season.

4. Conclusion

The infiltration characteristics of field soils may vary throughout the planting season and across the furrow, and can affect irrigation performances. While this could be achieved through the medium of individual design charts, it might well be better don through a much enhanced surface irrigation models. For more realistic evaluation of furrow irrigation performances, considering soil spatial and temporal variability is important especially for determining of water distribution uniformity.

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