Spatial and Temporal Variability of Infiltration Parameters in Furrow Irrigation

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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 evaluate in the field. The infiltration values of a certain point may affect opportunity time at all points downstream along the furrow. The present study focuses on infiltration variability along a furrow made during sugarcane growth season. A range of field experiments were carried out on furrow irrigation in a sugarcane field to estimate spatial and temporal infiltration variability. Seven irrigation scenarios were studied on two groups of furrows; the first group with the assumption of uniform characteristics, and the second group with the assumption of varying infiltration characteristics. Each group included three furrows 1.8 m wide and 140 m long. The results of the uniform furrow group showed that from the beginning to the end of growing season the final infiltration rate (f_0) and cumulative infiltration (Z) reduced 32 and 26%, respectively. In the variable furrow group, these parameters decreased 29 and 43% from inlet to the end of the furrow. The reductions were different for each irrigation event; however, the difference of cumulative infiltration between the first and second irrigations was higher as compared to other irrigation events.

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1. Introduction:

The soil conditions in a farm may change with time and space. The infiltration rate can be measured by different instruments such as by pass, single and double ring and blocked furrow infiltrometers. These instruments are effective for measuring infiltration in small areas but don't take into account the variability of infiltration across the entire field (Norum and Gray, 1970). Also, these kinds of measurements cannot take into account the effect of water movement. Ring infiltrometers and other instruments that use stagnant conditions tend to underestimate the cumulative infiltration while blocked or unblocked furrow tests give a better approximation because they take into account the effect of flowing water (Baustista and Wallender 1985, Camecho *et al.,* 1997). Trout (1992) reported that stagnant water conditions do not necessarily represent the dynamics of the flow. The inflow-outflow infiltration measurement technique uses the difference between inflow and outflow hydrographs to determine the infiltration. In addition, when run-off rate becomes steady, this technique is often used to calculate the final infiltration rate (f_o). The data collected for the entire furrow length gives one an average value for the infiltration function. This simplification of averaging infiltration dos not necessarily represent infiltration variability of the whole furrow, especially in long furrows, since spatial variation of soil infiltration properties in different parts of the furrow are not considered while the movement of water in the furrow will cause erosion and deposition that will impede the infiltration by surface sealing and particle settlement. Despite the known effects of soil variability on the distribution of the infiltrated depth, soil variability is rarely accounted for in irrigation evaluations, i.e., the evaluation procedures usually assume that a single infiltration equation can be validly applied to the entire furrow. (Mateos and Oyonarte 2005). Studies by Wallender and co-workers (Bautista and Wallender, 1985; Wallender, 1986; Bali and Wallender, 1987; Rayej and Wallender, 1988; Schwankl and Wallender, 1988) compared infiltration measurements along irrigation furrows with infiltration simulations assuming constant and varying soil infiltration characteristics. These studies demonstrated the importance of considering soil variability when determining irrigation uniformity. Soil hydraulic properties can also be affected by time, leveling, and agricultural practices (van Es *et al.*, 1999; Drohan *et al.*, 2003; Lin *et al.*, 1999). These temporal variations in the hydraulic properties of soil may be more important than spatial variations. Van Es *et al.*, 1999 found that spatial changes of infiltration between two different regions depends upon the soil texture; however, this is affected by temporal variability of infiltration. Therefore, since temporal variability significantly affects soil infiltration during the growth season, it should be considered in design and management of surface irrigation schemes (Elliott *et al*, 1983). Generally, infiltration is high in the initial irrigation while it is reduced in later irrigation events. After several irrigation events and when the soil becomes more stabilized, infiltration variability tends to decrease gradually. This normally occurs in the second half of the planting season. Also, the reduction in temporal infiltration variability is not necessarily linear (Elliott *et al*, 1983). In general, during the initial irrigation at the start of the growing season, the prediction of soil infiltration is not possible or it is very difficult due to its extensive temporal changes (Izadi *et al*, 1991). Since the highest infiltration variability occurs in initial irrigations, Walker *et al* (2006) suggested an irrigation condition factor (ICF) in order to predict infiltration parameters of modified Kostiakov-Lewis equation for later irrigations, using initial irrigation data. Some factors affecting temporal infiltration changes are as applying water with high SAR, and initial water content due to summer rainfalls (Emdad *et al*, 2004). Li *et al.*, 2001 found that soil compaction is one of the factors affecting soil infiltration during the growing season. This ultimately reduces final infiltration rate (f_0). Gish *et al.*, 1983 studied the effect of plant growth stages on soil infiltration; due to the low correlation of data obtained, they concluded that the effect of plant growth stages is less than spatial variability on infiltration characteristics. Oyonarte *et al*, 2002 suggested that the variability of the soil infiltration characteristics depends on the variability of the infiltration equation parameters (Oyonarte *et al*, 2002). Variability of infiltration parameters of modified Kostiakov equation during the growth season are negligible and difficult to determine as after reviewing k and a values of a growing season, Horst *et al.*, 2005 reported that k showed a small increase while a decreased marginally through the growing season. However, Hunsaker *et al.*, 1999 reported an increase of 33% for the k value and a constant a value during a farming season. The objective of this study was to evaluate spatial and temporal variability of soil infiltration characteristics in different places along a furrow during the sugarcane growing season.

2. 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):

$$Z = kt^{a} \tag{1}$$

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 the final infiltration rate (in m^3 min^{-1} m^{-2}), the Kostiakov–Lewis equation provides more realistic results:

$$Z = kt^{a} + f_0 t \tag{2}$$

where f_0 is the final infiltration rate. Research indicates 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:

$$I(t) = \frac{Q_i - Q_o}{LW_P} \tag{3}$$

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. As Holzapfel *et al.* (2004) argued, the parameters a and k in the equation (1) can be determined by direct integration of (2). It should be noted that the infiltration rate decreases as the soil gradually becomes saturated. The coefficient of variation represents the ratio of the standard deviation σ to the mean μ, and it is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other:

$$c_v = \frac{\sigma}{\mu} \tag{4}$$

Hence the coefficient of variation applied to explain infiltration variability.

3. Materials and Methods

This research was carried out in ARC2-7 farm from January 2010 to December 2011. The farm is one of the research fields of Sugarcane Research Center located in Amir Kabir Sugarcane Planting and by products comoany of Khuzestan, southwest Iran. The soil has a silty clay loam texture and a composition of 43% silt, 28% clay and 24% sand. The field work was conducted on two sets of furrows. 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 areas. 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 (0-30, 30-60 and 60-90 centimeters), the water content of soil was measured, using the weighing method, to determine infiltration depth, one day before and two days after each irrigation events. Type II fiberglass flumes (WSC) were used at the inlet and the end of each furrow in set 1 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 the 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. The inflows and outflows during each irrigation event and the flow in the flumes were measured by measuring the flow depths. The water application, surface runoff, average water infiltration for each furrow and the average water infiltration of the farm 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 (CVf_o) was obtained for the total length of the furrow for each individual irrigation event. The WSC flume type II was used to determine the discharge in the flume, the flow depth in each flume was measured using equation (5) which is as follow:

$$Q = c\,W\,H^{3/2} \qquad (5)$$

where:

Q: is the flow in cubic metres per second
W: is the width of opening in metres
H: is the depth of flow in meters
c: is a coefficient of discharge which depends on the geometry of the culvert. A typical value is 0.6

The water application, surface runoff, and 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.

4. Results and Discussion:

4.1 study The impacts of opportunity time on cumulative infiltration during growth season:

In order to study the impacts of opportunity time on cumulative infiltration depth during the growth season, coefficient of variation (CV) of different infiltration depths along the uniform furrow in different opportunity times, 0-100, 100-250 and 250-500 minutes, were calculated and presented in table 1. As seen from table 1, CV is high at the beginning of irrigation (0-100 min) and decreases as the opportunity time increases to the point where CV is almost three times less than its initial value at the end of each individual irrigation. Walker *et al*., 1990 reported that as the time increases, the infiltration variation tends to decrease. Also the data of table 1, show as the time passes, the infiltration variation decreases in each irrigation event.

Table (1): coefficient of variation of the cumulative infiltration depths (CV Z) in different opportunity times for each irrigation event

	0-100 (min)	100-250 (min)	250-500 (min)
Irrigation 1	0.309	0.124	0.096
Irrigation 2	0.274	0.109	0.084
Irrigation 3	0.254	0.100	0.077
Irrigation 4	0.232	0.090	0.070
Irrigation 5	0.238	0.093	0.072
Irrigation 6	0.245	0.096	0.074
Irrigation 7	0.254	0.100	0.077

4. 2. Temporal and spatial variation of Cumulative infiltration depth through growing season:

In order to study the cumulative infiltration variability of each section, the cumulative infiltration values were averaged after 500 min in each section. As table 2 shows, cumulative infiltration values begin to decrease with the number of irrigation events. Depending on the behaviour of each section, this trend continues into the midpoint of the growing season and then reverses. This reversal may be related to the vegetative cover of the furrow, which slows down water movement through advance trajectory, thus increasing opportunity time in the furrow and increasing the cumulative infiltration values. Angers and Mehuys 1989 and Rowel *et al*., 1969 suggested that the vegetative cover of the soil prevents the water drops from collision with the soil surface and clay dispersion, hence it preventing a decrease of soil infiltration. Miller *et al.*, 1992 studying sodium-calcium exchanges of soil, concluded that the vegetative cover increases opportunity time; since legume plants have low carbon and nitrogen, their decomposition rate is high, and therefore they stabilize the soil structure and reduce clay dispersion. Fig. 1, indicates that the difference of cumulative infiltration values between first and second irrigation is higher as compared to other irrigation events.

Table (2): average of cumulative infiltration depth in each section

	Section 1	Section 2	Section 3	Section 4	Uniform furrow
Irrigation 1	14.63	8.47	10.86	10.82	12.84
Irrigation 2	11.40	6.26	7.97	7.89	9.40
Irrigation 3	10.07	5.55	7.08	7.38	8.62
Irrigation 4	8.79	5.23	6.75	6.98	8.05
Irrigation 5	9.26	5.22	6.33	7.12	8.29
Irrigation 6	9.66	5.27	7.05	7.32	8.34
Irrigation 7	10.17	5.71	7.31	7.63	8.52

This can be related to soil degradation and down sizing of soil pores after the first irrigation. The results by Linderman and Stegman (1971) show the significant decrease from the first to the second irrigation. They related this to surface soil cracking and soil roughness. Sojka and Bjorneberg (2002) suggested that air entrapment and rapid wetting of dry soil in furrows were among factors eroding soil particles and decreasing soil infiltration after the first irrigation.

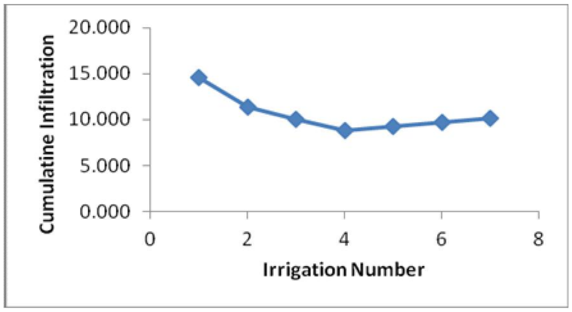

Fig. (1): cumulative infiltration results throughout the season for a nominal opportunity time of 500 min in the uniform furrow.

Table (2) shows the average cumulative infiltration depth in the uniform furrow and each section of the variable furrow through seven irrigation events. As table (2) shows, cumulative infiltration varies for different irrigation events. It should be noted that each of these areas displays different infiltration features to the number of irrigation. This can be related to variation in soil salinity, displacement of suspended solids in water and blockage of soil pores surface, soil water content, root development pattern, soil surface cracks, soil compaction, and the interactions of such parameters in each particular section. However, the cumulative infiltration shows an overall decreasing trend to the irrigation numbers. This trend continues depending upon the behaviour of each section through the midpoint of the growing season, after which the cumulative infiltration increases. According to Fig. 2, the average cumulative infiltration variability trend in the uniform furrow can be described well by an algorithmic model during a growing season. Shepard *et al.,* 1993 compared five methods for measuring soils with different texture types. The average infiltration by all methods showed a reduction in soil infiltration, the value of which, depending upon the method applied, ranged from 44 to 78%.

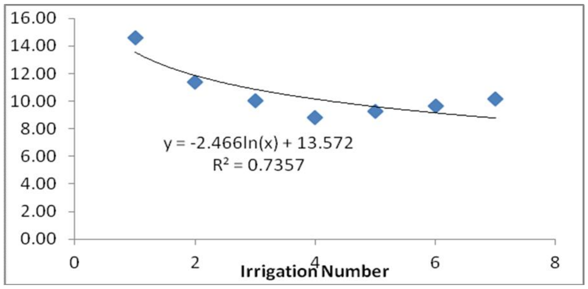

Fig (2): Cumulative infiltration trend with number of irrigations

The Analysis of variance test (ANOVA) was applied In order to assess significance of difference of cumulative infiltration in different sections and during the season. ANOVA can be used to determine if the variability in a sample can be explained by a factor or is caused by random variation. In this way the ANOVA - Two Factor without Replication test, table 3, can be used to assess the significance of the temporal and spatial variability of infiltration rates and cumulative infiltration. The F statistic in table 3, shows proportion of “between-group variation” compared to “within- group variation”. In general, the larger this value is, the more significant “between-group variation" would be. If the F-Statistic is larger than F-Critical, then the variation between the groups is statistically significant. As can be seen from table 3, F is greater than F-Critical and P is smaller than 0.05 which indicate that there is statistically significant difference between f_0 values both spatially or between sections, and temporally or between irrigation events.

Table 3. Analysis of variance test to determine spatial and temporal variability of f_0 and Z

	Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Z	temporal	48.31763	6	8.052938	117.6468	1.91E-13	2.661305
	spatial	36.19202	3	12.06401	176.2452	1.58E-13	3.159908
	Error	1.232103	18	0.06845			

4. 3. Spatial and temporal variability of final infiltration rate:

Values of f_o for all sections of the variable furrow are presented in table 4. In order to study the spatial variability of final infiltration rate, the coefficient of variation of f_o of all sections in each irrigation and their values were compared for different irrigation events. As may be seen from table 3 and table 4, there is statistically significant difference between f_0 values spatially and temporally. However temporal variability during growing season is lower than spatial variability. The result may be related to the development of sugarcane roots in the soil profile at the middle of the growth season which improves the final infiltration rate. Table 4, also shows that the largest reduction of the final infiltration rate occurs between the first and second irrigation events which becomes less in further irrigations. The behaviour of final infiltration variability was similar to the variations of the cumulative infiltration depth which shows that final infiltration rate has a noticeable impact on the cumulative infiltration depth. Oyonarte *et al*., 2002 reported that up to 90% of the variation in the infiltration depth can be explained by the final infiltration rate.

Table (4) Spatial and temporal variability of final infiltration rate (m^3/m/min) during a growth season

	Section 1 *10^-3	Section 2 *10^-3	Section 3 *10^-3	Section 4 *10^-3	CV f_0
Irrigation 1	0. 205	0. 170	0.120	0.116	0.28
Irrigation 2	0.155	0. 120	0.110	0.088	0.24
Irrigation 3	0.144	0. 121	0.110	0.079	0.24
Irrigation 4	0.140	0. 111	0.108	0. 080	0.22
Irrigation 5	0.133	0. 118	0.108	0.071	0.25
Irrigation 6	0.151	0. 141	0.110	0.101	0.19
Irrigation 7	0.151	0. 144	0.110	0.110	0.17

The final infiltration variability follows an algorithmic model (Fig. 3) through a growing season. These results agree with those obtained by Esfandiari and Mahshovari (1997). They also reported a 40% reduction in f_o during the growth season. In the present study, the f_o reductions between the first and the last irrigation events for uniform and the sections in variable furrow are given in table 5. During the growth season, some physical properties such as soil pores decrease due to soil erosion and reduction of soil particle stability because of water movement over the soil's surface. These two factors directly affect the hydraulic conductivity of soil saturation. If the variability in soil physical parameters follows a specific trend, f_o normally follows a specific trend as a dependent variable, as well. The results of this study confirm this variability.

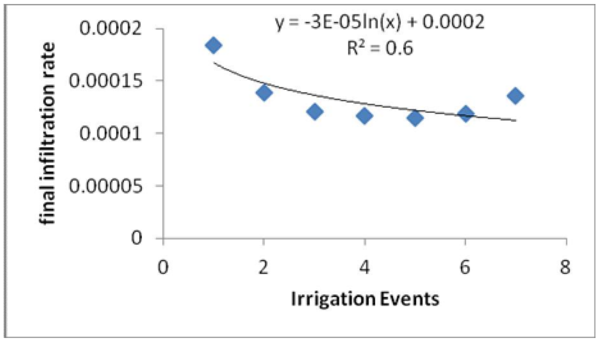

Fig 3. final infiltration rate through the season

At the beginning of the planting season, soil porosity and final infiltration rate are high due to plowing. After the first irrigation, soil porosity decreases and soil particles are damaged due to water flow over the soil's surface these two factors simultaneously decrease the final infiltration rate after the first irrigation onwards. Mateos and Gira´ldez (2005) also reported that sediment load was great in the first irrigation and declined in successive irrigations. Also, the development of sugarcane roots in the soil profile at the middle of the growth season noticeably improves the final infiltration rate by creating narrow channels in the soil profile. This leads to quicker passage of water as compared with soil movement through soil pores, which relatively increases final infiltration rate. However, as seen from table 4, the final infiltration rate from the beginning to the end of the variable furrow has a decreasing trend, which may be related to different factors such as accumulation of salinity at the ends of the furrow, non-maturity of fertilizers used, or displacement of eroded soil particles at the end of the furrow. These factors may cause less growth of roots in the ending parts of furrow and, correspondingly, the decrease of final infiltration rate. In furrow irrigation, the highest water velocity occurs at the beginning of the furrow and decreases gradually to the furrow's end. Hence, the erosion increases in the first quadrate of the furrow and decreases in the second half of the furrow (Trout, 1996). Ferna´ndez Go´mez *et al*., 2004 concluded that the soil erosion in upstream furrow is six times greater than the average erosion occurring along a furrow. Trout (1996) also concluded that the soil erosion upstream furrow is twenty times greater than the average soil erosion along a furrow. Some eroded particles in the water may be driven out of the furrow by surface runoff while much of the eroded particles displaced in the second half of the furrow before exiting. This may cause a non-uniform redistribution of soil particles along the furrow. This also affects the spatial variability of infiltration. Horst *et al*,. 2007 reported that a change of irrigation regime, such as surge irrigation, increases soil erosion as compared to continuous irrigation in furrow.

Table 5. Percentage of reduction between the first and the last irrigation events

Irrigation Events	Section 1	Section 2	Section 3	Section 4	Uniform Furrow	CV f_0
Irrigation 1	0.000205	0.00017	0.00012	0.000160	0.000184	0.28
Irrigation 7	0.000151	0.000144	0.000110	0.000110	0.000136	0.17
Percentage of reduction	26.4	15.2	8.3	5.7	26.1	43.7

4. 4. Variation of parameters *k* and *a* of Kostiakov-Lewis equation:

The variation of the parameters *a* and *k* in the Kostiakov-Lewis equation from the early to the late season period are shown in fig 4 and 5. Observation of trends in the *k* and *a* parameters of the modified Kostiakov equation are conflicting. As seen from the figures, *a* decreased by the number of irrigations while *k* slightly increased during the season. however the parameters do not follow a specific trend related to the variability of Z or f_0 in each individual irrigation or section during the season. Attempts in the literature to observe the parameters individually have not successful as the parameters such *a* and *k* are interdependent (Hopmans 1989). Horst *et al*. (2005) measured a slight increase in *k* and decrease in *a*. Similarly, Shafique and Skogerboe (1983) did not find any significant trend in the values of *a* with the majority of general decline in infiltration rates caused by a decrease in the parameter *k*. According to results by Hunsaker *et al*,. 1999 variations of parameter *a* in the Kostiakov-Lewis equation follow neither an algorithmic model nor a linear model through a growing season. It may appear obvious to describe the variability using the infiltration parameters, as they are simple numerical constants. However, since the parameters *k* and *a* are empirical this approach is not justified, therefore have no physical meaning. Jaynes and Hunsaker 1989 reported even where strong relationships exist between infiltrated depths there does no appear to be any correlation between the raw values of the parameters *k* and *a*. Hence, studies of the infiltration variability should consider the infiltration rates or cumulative depths rather than other parameters.

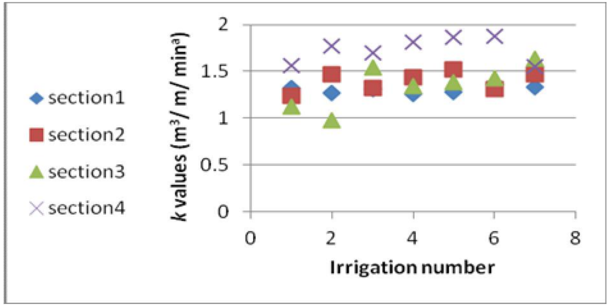

Fig 4. parameter *k* in different sections and irrigation events

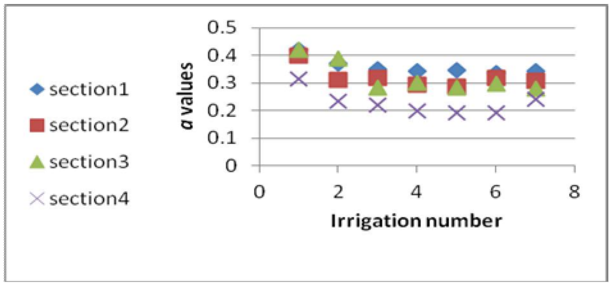

Fig 5. parameter *a* in different sections and irrigation events

5. Conclusion

It is traditionally believed that opportunity time is the only parameter which affects infiltrated depth variability. However, this study shows that there factors other than opportunity time which affect infiltration along a furrow and throughout the growing season which cannot be neglected. The Kostiakov-Lewis equation may be used for the estimation of soil infiltration parameters. The results of the study indicate that the cumulative infiltration and final infiltration rate display a decreasing trend throughout a growing season. This trend continues depending upon the behaviour of each section to the midpoint of the growing season. The results presented also show that the spatial variation of infiltration is greater than temporal infiltration. It may be related to the development of sugarcane roots in the soil profile at the middle of the growth season which improves the final infiltration rate.

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