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Optimization of furrow irrigation systems with continuous flow using the software applied to surface irrigation simulations - SASI

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Surface irrigation systems still remain the most used irrigation system worldwide mainly due to its energy savings capacity and ease of operation. However, they show low performance level as a consequence to the general design and inadequate management. Therefore, the aim of this study was to develop a tool capable of optimizing the performance level of furrow irrigation systems with the continuous flow from successive simulations of the advance phase and predictions of performance parameters in irrigation systems. The proposed model, written in DELPHI 5.0 programming language and called Software Applied to Surface Irrigation Simulations (SASIS) had its validation tested for different field conditions. The results showed that the applied flow rate plays a decisive role on the performance parameters of irrigation systems with the best performances flow rates close to the minimum allowable levels. The field parameter that most impairs the optimization of the irrigation performance is infiltration, while the length and slope did not decisively interfere in optimization, which can be achieved for a wide range of values for these parameters, and also in soils with high infiltration rates. The great difficulty in optimization is to minimize percolation losses, but in soils with low infiltration rates, both percolation and runoff losses can be easily minimized. The SASIS model has been an effective mechanism in performing numerous simulations within a flow range between minimum and maximum, aiming to determine the relationship between flow rate and water application efficiency, percolation and runoff rates and hence optimize the performance of furrow irrigation systems with continuous flow.

Key words: Furrow irrigation, flow rate, performance.

INTRODUCTION

Although, surface irrigation is the most widely used it is considered as low water application efficiency, particularly in furrow irrigation systems, in which the furrow is responsible for lower efficiency levels. Surface irrigation is an irrigation method where water drains by gravity, using the agricultural soil surface as part of the water distribution system. The flow rate decreases as the water advances towards the irrigated portion due to infiltration. For the infiltrated water to be distributed as uniformly as possible along the area, irrigation should be designed and managed so that there is a balance between advance and water infiltration processes (López, 2006). Furrow irrigation is one of the most widely used irrigation system due to its low cost in materials and energy. The low efficiency of surface irrigation systems is due to the large part of the absence of careful designing and improper irrigation practices. According to Rezende et al. (1988), reduced levels of performance in furrow irrigation systems can be attributed to incorrect dimensioning. The use of assessment tests would be recommended, despite the high cost and time required for the performance of field works and analysis of results. Furthermore, it is virtually impossible to assess the combined results of numerous parameters involved in the designing and operation of systems.

To improve the efficiency of water application and distribution, some designs have used the maximum non-erosive flow rate, reducing the flow when the advance front reaches the end of the furrow. The efficiency of furrow irrigation systems can often be improved by reducing the inflow rate after water has advanced to the end of the field, a common practice is to cut back to 50% of the inflow (Clemmens, 2007). Another alternative is the use of intermittent flow to distribute water in the furrows. Both methods, despite showing improvement in the performance of furrow irrigation systems, have the disadvantage of requiring more labor and more investment in equipment. In practice, it is observed that the use of constant flow is predominant in furrow irrigation designs, which is probably due to the farmer's tradition of using only one flow in the water application during irrigation and to ease operation in the distribution of water in the furrows.

Rodríguez et al. (2004), comparing surge irrigation and conventional furrow irrigation for covered black tobacco cultivation in a Ferralsol soil, found that surge flow furrow irrigation with variable time cycles increased the application efficiency by more than six fold, and the water volume was reduced by more than 80% compared to continuous irrigation. The largest rises in distribution uniformity and reductions in percolation losses were obtained with a furrow length of 200 m and a discharge of 1 L s^{-1}, respectively.

Valipour (2012), researching the management strategies to increase the efficiency of furrow irrigation obtained from simulations using the software SIRMOD, found that the cutback and surge irrigation methods were able to increase irrigation efficiency in 11.66 and 28.37%, respectively. According to farmers the choice of limiting regime inflow can identify the best input flow to achieve maximum irrigation efficiency. The furrow irrigation system presents different variables with regard to operating system and with respect to field data, which influence its performance. The operating system variables are flow rate and time of application of water, while the field variables are slope, size, roughness of the surface, the furrow geometry and characteristic of water infiltration into the soil. Infiltration depends primarily on physical, chemical and biological soil properties, affecting the advance and recession processes, and it is important to estimate the optimal flow rate derived in an irrigated soil (Walker et al., 2006). For a good furrow irrigation design, one should consider these variables and their interactions (Wu and Liang, 1970; Reddy and Clyma, 1981).

Valipour and Montazar (2012b), studying the optimization of all effective infiltration parameters in furrow irrigation, worked to achieve full irrigation status. They used Genetic Algorithm Programming and MS Visual Basic (VB) programming. The best equation of distribution of curve water in the soil was determined by using the MS Visual Basic (VB) programming. While for the Genetic Algorithm (GA) coding in MATLAB software environment, all effective infiltration parameters in furrow irrigation were obtained for the best equation of distribution curve of water in the soil. The found results showed that by using VB and GA programming, water delivery and farm size could be optimized.

The SWDC and WinSRFR models were evaluated by Valipour and Montazar (2012a) to optimize the parameters of furrow irrigation. They found that because of the differences between the two models it was not possible to say which one is better. However, in SWDC model, input discharge becomes optimized, other infiltration parameters could be optimized in furrow irrigation using WinSRFR model and combining it with SWDC model.

The mathematical simulation of surface irrigation is a complex process of hydraulics and surface flow. These processes have been simulated by computer models with a large degree of complexity and accuracy (Strelkoff and Katopodes, 1977; Elliott et al., 1982; Walker and Humpherys, 1983; Strelkoff and Souza, 1984; Rayej and Wallender, 1985), and such models simulate the advance and recession of water over the soil surface and the volume of infiltrated and percolated water.

The different models that simulate surface irrigation have been developed to simulate an isolated irrigation event, assuming that there is no spatial variation in field parameters (infiltration, roughness, slope and cross section). In practice, the validity of this hypothesis has been found, considering that simulations have been very

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close to measurement made in field along the crop season. The objective of this study was to develop a freely accessible mathematical computer model to simulate and optimize furrow irrigation with continuous flow in both languages Portuguese and English. The model predicts through simulations of the advance phase, the performance of an irrigation event and selects the optimal flow rate in furrow irrigation systems with continuous flow, that is, one that maximizes the water application efficiency, balancing runoff and percolation losses.

MATERIALS AND METHODS

This study uses the kinematic wave model which represents a simplified form for the Hydrodynamic model. It assumes that there is no height variation of flux with distance, the force due to the weight component in the direction of flow is in balance with friction forces, that is, $\partial y/\partial x = 0$, completely neglecting the momentum equation, leaving the continuity equation (Equation 1) undetermined in term $\partial A/\partial t$. To solve this problem, assuming that there is a unique relationship that describes flow as a function of the flow area, then the momentum equation is replaced by the Manning equation (Equation 2). Therefore, the equations that constitute the kinematic wave model become continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + \frac{\partial Z}{\partial \tau} = 0 \qquad (1)$$

Manning Equation:

$$A = \sqrt{\frac{Q^2 n^2}{S_o\, R^{4/3}}} \qquad (2)$$

Where A = flow cross-sectional area (m^2), t = time (s), x = distance of water advance in the field (m), τ = infiltration opportunity time (s), Z = infiltrated volume per furrow length unit (m^3 m^{-1}), Q = discharge rate (m^3 s^{-1}), n = Manning roughness coefficient (m$^{-1/3}$ s), S_o = field slope (m m^{-1}), R = hydraulic radius (m), cross-sectional area divided by the wetted perimeter.

The Manning equation was used in this analysis to generate unique relationship between flow and hydraulic section. Elliott et al. (1982), proposed an empirical relationship for the hydraulic section, given by:

$$y = \sigma_1\ A^{\sigma_2} \qquad (3)$$

and

$$A^2 R^{1,33} = \rho_1 A^{\rho_2} \qquad (4)$$

Where y = flow height in the furrow (m), σ_1, σ_2, ρ_1 and ρ_2 = empirical parameters that depend on the furrow shape.

The hypothesis described ensures that the potential functions adequately describe relationships between flow height, cross-sectional area, width of the free-water surface, hydraulic radius etc. Through the Manning equation and according to Equation 4:

$$S_0 = \frac{Q^2 n^2}{A^2 R^{4/3}} = \frac{Q^2 n^2}{\rho_1 A^{\rho_2}} \qquad (5)$$

Thus, obtaining Q, whose derivative, together with the infiltration equation is used in equation 1, to yield a continuity equation of one unknown dependent parameter, A. It is assumed that the spatial and temporal dependence of Z are defined (Walker and Humpherys, 1983).

According to Equations 2 and 5, this type of model does not apply to furrows when the slope is very small or tends to zero. According to FAO (1989), the maximum and minimal recommended furrow slopes are 0.5 and 0.05%, respectively. In fact, their accuracy will decrease when S_0 approaches zero. Strelkoff and Katopodes. (1977), found that the higher the longitudinal slope, model simulates the flow conditions. Walker and Skogerboe (1987), do not recommend this type of model to simulate the recession phase.

Using Equation 4, the Manning equation becomes:

$$Q = \alpha A^m \qquad (6)$$

where:

$$\alpha = \frac{\sqrt{\rho_1 S_0}}{n} \qquad (7)$$

$$m = \frac{\rho_2}{2} \qquad (8)$$

Where α and m = empirical constants.

Depletion and recession phases

Generally, it is said that when the flow is suspended, the cross-section area at the head end of the furrow immediately drops to zero, favoring the statement that the depletion and recession phases could be neglected; this is a reasonable assumption for slope furrows, since the volume of water stored into the furrow is very small at the flow cutoff time making the duration of the depletion and recession phases very short, and therefore has a small effect on the water infiltration profile. The behavior of the recession phase is similar to the advance phase, but in the opposite direction. In this work, the depletion and recession phases were neglected, considering that the irrigation ends when water flow is stopped, that is, it was assumed that the recession time is equal to the flow cutoff time (Bernardo et al., 2009).

Over the years, infiltration has received much theoretical attention. Today, there are many equations that describe infiltration such as Kostiakov, Kostiakov-Lewis, Horton, Philip and Green-Ampt. In this study, the Kostiakov-Lewis equation was used (Equation 9), as one of the most widely used empirical expressions for furrow irrigation modeling.

$$Z = k\tau^a + f_o\tau \qquad (9)$$

where τ = infiltration opportunity time (s), k = empirical coefficient of Kostiakov-Lewis infiltration equation (m² s^{-a}), a = empirical exponent of the Kostiakov-Lewis infiltration equation, dimensionless, f_o = infiltration rate (m^3 m^{-1} s^{-1}).

To calculate the maximum non-erosive flow rate, the SASIS software was based on the method recommended by Walker and Skogerboe (1987). The authors studied the maximum non-erosive flow rate as a function of parameters obtained from the furrow dimensions and proposed the following equation:

$$Q_{máx} = \left[\left(\frac{V_{máx}^{\ \rho_2}\ n^2}{3600\ S_0\ \rho_1}\right)\right]^{\frac{1}{\rho_2 - 2}} \quad (10)$$

Where Q_{max} = maximum non-erosive flow (m^3 min^{-1}), V_{max} = maximum non-erosive speed (m min^{-1}), estimated by Walker and Skogerboe (1987) 8-10 m min^{-1} in erosive soils and 13-15 in less erosive soils.

Optimal flow

In the determination of the relationship between flow rate and water application efficiency, percolation and runoff losses, numerous simulations were performed by the SASIS model. The simulations occurred in a flow rate ranging between the minimum and maximum allowable, initiating at the minimum flow rate and increasing in the rate of 2% until it gets to the maximum allowable flow rate. The minimum flow rate is the one that guarantee the water will get to the end of the field. The optimal flow rate considered by the SASIS model through the successive simulations is the one that provides the best irrigation performance and balance between runoff and percolation losses.

Procedure for assessing the surface irrigation system

Assessing a surface irrigation system will identify various management practices that can be implemented to improve the efficiency of the irrigation system. These practices can be a reduction in the flow rate and its time of application, changes in the field length or maybe a combination of various strategies is required. The main goal of the SASIS software is to help search for surface irrigation management strategies, resulting in satisfactory efficiency levels.

The assessment procedure of furrow irrigation proposed by Walker and Skogerboe (1987) used in this analysis initially involves the trapezoidal rule to integrate the subsurface flow profile, thus determining the total infiltrated volume:

$$V_z = \frac{L}{2n}\left[Z_o + \left(2Z_1 + 2Z_2 + \ldots + 2Z_{n-1}\right) + Z_n\right] \quad (11)$$

Where V_z = infiltrated volume (m³), L = furrow length (m), Z_i = accumulated infiltration for point I (m^3 m^{-1}), n = number of segments in which the furrow is subdivided.

The infiltration accumulated in each furrow segment is given by:

$$Z_i = k\left[t_r - \left(t_a\right)_i\right]^a + f_o\left[t_r - \left(t_a\right)_i\right] \quad (12a)$$

Where k, a and f_o = as defined previously, t_r = recession time (min), $(t_a)_i$ = advance time for the i-th station (min).

For the purpose of project the flow cutoff time, t_{cutoff}, replaces t_r in Equation 12a, according to Equation 12b.

$$Z_i = k\left[t_{cutoff} - \left(t_a\right)_i\right]^a + f_o\left[t_{cutoff} - \left(t_a\right)_i\right] \quad (12b)$$

Measures to evaluate performance

Among the factors considered in evaluating the performance of an irrigation system or its management, the most common are efficiency and uniformity. The evaluation parameters are defined in various ways. There is no single parameter that adequately defines irrigation performance. Conceptually, achieving adequate irrigation depends on the amount of water stored in the crop root zone, percolation losses (below the root zone), runoff losses, uniformity of the water applied and on the remaining deficit in the root zone. After all, performance means knowing whether irrigation optimizes or not.

When a field has uniform slope, the soil receives uniform flow at its upper end and a wetting front will slowly advance at a decreasing rate until it reaches the end of the field. If not blocked, runoff will occur up to the end of recession. Figure 1 shows the water distribution along the furrow length, arising from the assumptions given above. The differences along the area in the infiltration opportunity time produce water depths that are not uniformly distributed - with a characteristic inclination to the end of the field.

The water that can be stored in the root zone can be found by the expression V_{rz} = $(L * Z_{req}) - V_{di}$, where Z_{req} is the required root zone depth calculated on the project. But as shown, some region of the root zone may not receive enough water due to the spatial variation in infiltration distribution. The water depth that would supply the root zone is Z_{req}, and the water that percolates below this zone is lost[1] to drainage or groundwater system. Calculating each of these components requires numerical integration of water infiltrated along the field length, and according to the aim of this discussion, it is convenient to define the components as follows:

V_{rz} = Water volume per width unit (1 m), which is actually stored in the root zone;
V_{di} = Water volume per width unit (1 m), corresponding to the portion of the root zone that is not irrigated;
V_{dp} = Water volume per width unit or furrow spacing that percolates under the root zone;
V_{ro} = Water volume per width unit or furrow spacing that flows out of the irrigated area;
Z_{min} = Minimum infiltrated water depth that generally occurs at the end of the furrow; and
Z_{lq} = Average water depth infiltrated in the 25% of the least irrigated area.

Distribution uniformity refers to the water distribution in the soil profile. Merriam and Keller (1978) proposed that the distribution uniformity is defined as the average water depth infiltrated in the 25% of the least irrigated area (Z_{lq}) divided by the average water depth infiltrated in the entire area ($\overline{Z}$). This term can be represented by the symbol *DU*. The same authors also suggest an absolute uniform distribution DU_a, which is the minimum water depth (Z_{min}) divided by the average water depth of the entire area.

The water application efficiency was accessed (E_a). For the no deficit irrigation condition, the following equations were used:

$$E_a = \frac{Z_{req}\ L}{Q\ .\ t_{cutoff}} 100\ \% \quad (13)$$

$$PL = \frac{V_z - Z_{req}\ L}{Q\ .\ t_{ccutoff}} 100\ \% \quad (14)$$

[1] Generally, these flows return to the reservoir and can be reused in another place or in the same area. Thus, they are lost in terms of the irrigated area in question, but perhaps not for the regional condition or basin. The negative connotations of loss should be maintained to the area being irrigated, although this water can be recovered and reused. The quality of these flows is almost always not good and the reuse time should not be computed (Walker, 2001).

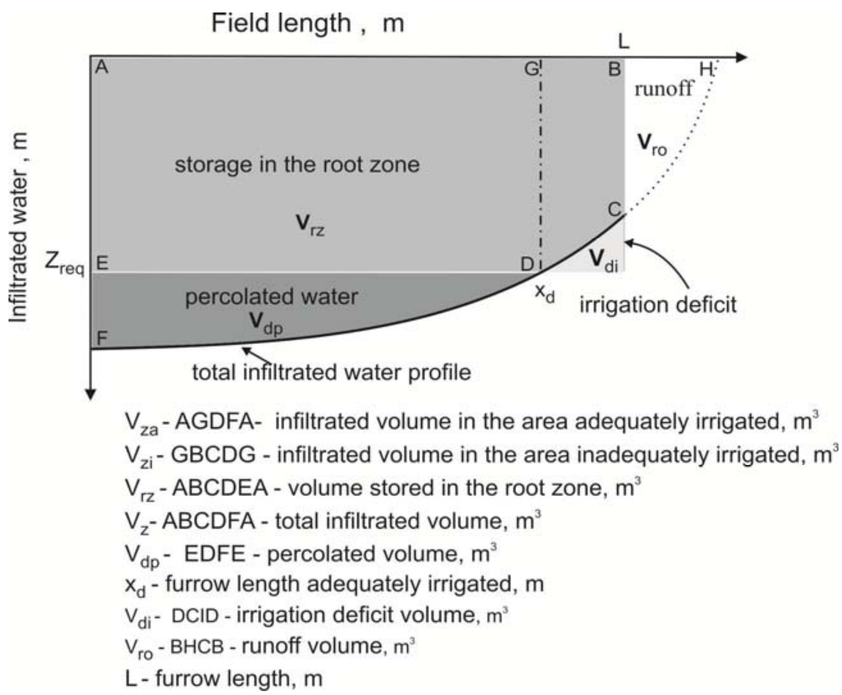

Figure 1. Components of the infiltration water profile in surface irrigation.

$$RL = 100 - E_a - PL \tag{15}$$

Where: E_a = water application efficiency, PL = percolation loss, RL = runoff loss.

For the no deficit irrigation condition it was assumed on the project that the efficiency of water requirement (E_r), also called storage efficiency, was 100%, with no deficit in the root zone. In the case of deficit irrigation, the following equations were used:

$$E_a = \frac{Z_{req}\, x_d + V_{zi}}{Q\,.\,t_{cutoff}} 100 \tag{16}$$

$$PL = \frac{V_{za} - Z_{req}\, x_d}{Q\,.\,t_{cutoff}} 100\% \tag{17}$$

$$RL = 100 - E_a - PL \tag{18}$$

$$E_r = \frac{Z_{req}\, x_d + V_{zi}}{Z_{req}\, L} 100 \tag{19}$$

$$DU = \left(\frac{Z_{lq}}{\overline{\overline{Z}}}\right)100 \quad \text{or} \quad DU = \left(\frac{L\,.\,Z_{lq}}{V_{rz} + V_{dp}}\right)100 \tag{20}$$

$$DU_a = \left(\frac{Z_{\min}}{\overline{\overline{Z}}}\right)100 \quad \text{or} \quad DU_a = \left(\frac{L\,.\,Z_{\min}}{V_{rz} + V_{dp}}\right)100 \tag{21}$$

The definition of water application efficiency E_a, was standardized as:

$$E_a = \frac{V_{rz}}{\mathrm{Q} * \mathrm{t}_{\mathrm{cutoff}}} 100\ \% \tag{22}$$

The water requirement efficiency, E_r, which is also called storage efficiency, was defined as:

$$E_r = \frac{V_{rz}}{\mathrm{Z}_{\mathrm{req}} * \mathrm{L}} * 100\% \tag{23}$$

If the furrow shows infiltrated water depth smaller than required, the infiltrated volume should be evaluated separately for the areas of excessive and deficient irrigation. After identifying the furrow section, x_d, from which the infiltrated water depth is less than required, the infiltrated volume will be calculated for the appropriately irrigated area V_{za}, by equation 11 and for the inadequately irrigated area, V_{zi}, as follows:

$$V_{zi} = V_z - V_{za} \tag{24}$$

The volume of runoff loss per unit width is given by:

$$V_{ro} = Q\, t_{cutoff} - V_z \tag{25}$$

The runoff loss (RL) is determined by equation:

$$RL = \left(\frac{V_{ro}}{Q\, t_{cutoff}}\right) 100\% \tag{26}$$

Table 1. Field data used in the validation of the SASIS model.

Field data	PISG1	PISG2	PISG3	PISG4	KWF	AMALGACQ	GUFCQ
Parameter	Soil type						
	Clay-sandy loam	Clay-sandy loam	Sandy loam	Clay-sandy loam	Silty-clay loam	Silty-clay	Silty-sandy
Flow (L s^{-1})	1.33[1]	1.47[1]	1.54[1]	1.13[1]	1.50[2]	1.80[2]	1.30[2]
Furrow length (m)	67	100	70	115	360	403	217
Slope (m m^{-1})	0.0030	0.0016	0.0043	0.0024	0.0104	0.0066	0.0173
Cutoff time (min)	90	115	41.7	86	450	500	300
Manning Coefficient, n ($m^{-1/3}s$)	0.020	0.020	0.025	0.020	0.013	0.013	0.013
Parameter of section, ρ_1	0.291	0.185	0.532	0.339	0.730	0.730	0.730
Parameter of section, ρ_2	2.847	2.766	2.840	2.806	2.980	2.980	2.980
k (m^3 m^{-a} m^{-1})	0.03781	0.02931	0.01024	0.0054	0.0088	0.00182	0.00896
a	0.165	0.302	0.326	0.412	0.533	0.234	0.0
f_o (m^3 min^{-1} m^{-1})	0.000186	0.000186	0.000264	0.000186	0.00017	0.00019	0.000022
Z_{req} (m)	0.090	0.060	0.020	0.020	0.090	0.090	0.050

[1] Flow rate adopted by the farmer in the field; [2] Flow determined in the design, used by the authors in the demonstration of the SIRMOD and SIRTOM models.

Table 2. Water advance data measured in the field and used in the validation of the SASIS model.

PISG1		PISG2		PISG3		PISG4		KWF		AMALGACQ		GUFCQ	
XA[1]	TA[2]	XA	TA	XA	TA	XA	TA	XA	TA	XA	TA	XA	TA
0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.70	2	9.09	1.05	7	1	11.50	3	40	5	31	12	31	4
13.40	4	18.18	2.35	14	2	23.00	5	80	14	62	22	62	8
20.10	6	27.27	3.60	21	3	34.50	7	100	20	93	30	93	12
26.80	9	36.36	5.00	28	5	46.00	10	120	30	124	46	124	16
33.50	13	45.45	6.50	35	7	57.50	14	140	37	155	53	155	20
40.20	16	54.54	8.50	42	10	69.00	17	160	48	186	68	186	24
46.90	20	63.64	9.65	49	13	80.50	27	200	75	217	85	217	28
53.60	23	72.73	11.55	56	16	92.00	40	220	89	248	98		
60.30	27	81.82	13.60	63	19	103.50	48	240	102	279	120		
67.00	32	90.91	15.65	70	24	115.00	66	275	130	310	140		
		100.00	17.95					300	150	341	155		
								320	170	372	191		
								350	200	403	232		
								360	208				

[1] XA = advance distance (m); [2] TA = advance time (min).

The SASIS model simulates the infiltrated water and the runoff conditions in the field. Regarding the water that infiltrates the field surface, the software determines depth of infiltrated water in the root zone and how much percolates below this zone. Considering that this information is determined for each point simulated in the field, the data can be used for the calculation of various efficiencies and uniformities.

The field data used in the validation of the SASIS model corresponded to four data sets (PISG1, PISG2, PISG3 and PISG4) collected in this research, relating to field assessments of furrow irrigation events in the irrigated region of São Gonçalo, Brazil, two data sets (AMALGACQ, private property and GUFCQ, Utah State University farm in Logan, USA) published by Azevedo (1992) used in the demonstration of the SIRTOM model, and one data set (KWF-Kimberly Wheel Furrow) published by Walker and Skogerboe (1987). The data for advance time measured in field, which was used to validate the SASIS model is shown in the Table 2. The SASIS model validation used both the measured flow practiced by the farmers and that suggested by the authors Walker (1989) and Azevedo (1992) in the demonstration of the SIRMOD and SIRTOM models.

RESULTS AND DISCUSSION

The curves generated by the model proposed for the irrigation performance as a function of the flow rate are shown in Figure 2. It was observed that in all studied cases, when the flow rate increases, the water application efficiency decreases, showing that this parameter is much more affected by runoff losses than by percolation losses. For the maximum non-erosive flow rate runoff losses are maximal and percolation losses minimal, whereas for minimum flow, that is, the one that ensures that the water will get to the end of the area, the opposite occurs. In addition, runoff losses are much more sensitive to flow variations in relation to percolation losses, a fact observed by the slopes of the curves. For the studied cases, there were dominance runoff losses over percolation losses, which occurred in the largest flow range. This leads to a greater effect of runoff losses in the water application efficiency value, making the water application efficiency curve to present almost the same behavior as the curve of percolation losses.

Figure 2a to f show the curves representing the runoff and percolation losses intersect for a given flow, indicating a change in the higher or lower effect of these losses on the water application efficiency from this value, as described in Table 3. It appears that, when there is a balance between runoff and percolation losses, that is, when they are balanced to the point that there is no predominance of one over the other. High levels of water application efficiency in furrow irrigation are achieved, according to field data PISG1 (Figure 2a), KWF (Figure 2b) and GUFCQ (Figure 2c). However, for field data PISG2 (Figure 2d), PISG3 (Figure 2e) and PISG4 (Figure 2f), runoff and percolation losses were high, consequently, low maximum water application efficiencies were obtained, respectively, 50.57, 34.28 and 48.51%.

Based on the maximum water application efficiency simulated for all studied field conditions, the optimal flow rate was found, as described in Table 3. In general, for all the field conditions the optimal flow rate corresponded to a value close to the minimum flow rate that was better accepted by the SASIS model, starting from 0.6 L s^{-1}. This tendency can be explained by the direct relation existent between the water application efficiency and water losses. The selection of the highest balance among the water application efficiency and water losses leads to values different from the highest flow rate, when the water losses are maximum.

For PISG1 (Figure 2a), the optimum flow rate was predicted by the SASIS model to be 1.05 L s^{-1}, which is close to the minimum (0.9 L s^{-1}). Values of runoff and percolation losses presented minimal discrepancy between them for the optimal flow, only 2.88%, and large discrepancy for maximum flow rate of 47.27%. This resulted in a predicted water application efficiency of 82.42% using the optimal flow rate and 43.7% using the maximum flow rate. It appears that the runoff loss was largely affected by the flow, which does not occur with percolation loss, a fact that can be justified by the type of soil for this data, which was clay-sandy loam, characterized by low infiltration rate (k = 0.03781 and f_o = 0.000186). For the flow rate adopted by the farmer in the field, the values for water application efficiency and for runoff and percolation losses were, respectively, 77.74, 16.20 and 6.06%, showing that percolation and runoff losses presented values well balanced, with difference of 10.14% between them. The results demonstrate that the smaller the difference between these losses, the better the performance of the irrigation system. For the optimal flow rate, the difference between percolation and runoff losses was 2.88%, resulting in a water application efficiency of 82.42%. The flow rate adopted by the farmer approached the optimal value predicted by the SASIS model.

For example KWF (Figure 2b), appears that for optimal flow rate, the values of runoff and percolation losses showed variation of only 9.91% between them, thus reaching high performance level in this irrigation system. Certainly, the low water infiltration rate (k = 0.0088 and f_o = 0.00017) in this clay-sandy loam soil greatly contributes in obtaining small values for these losses. For the flow rate adopted by the farmer, the values predicted for water application efficiency, for runoff and percolation losses were, respectively, 75.14, 14.47 and 10.39%, indicating values close to those predicted for the optimal flow rate, showing that this flow rate was a good option.

For field data GUFCQ (Figure 2c), it appears that the curve that refers to the runoff losses presents high slope, showing a large variation of the performance with the flow rate, since the curve that indicates the percolation losses has small slope, demonstrating that under these field conditions, it was slightly affected by the flow rate. The curve related to the water application efficiency shows the same slope as that of the runoff losses, but in the opposite direction. In this example, the difference between these losses for the optimal flow rate was only 1.78%, showing that the smaller these losses and the smaller the difference between them, the greater the water application efficiency in furrow irrigation. Furthermore, when optimal flow rate was applied, both runoff and percolation losses were low, resulting in high water application efficiency and when maximum flow rate was applied, the percolation losses remained low, while the runoff losses were very high, reaching 53.04%. It could be concluded that the low percolation losses, either for maximum or optimal flow rate, and the high runoff losses for maximum flow rate, can be explained by the low water infiltration rate in this type of soil (k = 0.00896 and f_o = 0.00022) and also by the presence of steep slopes in this area (0.0173 m m^{-1}). For the design flow rate (1.30 L s^{-1}), the values predicted for the water application efficiency, runoff and percolation losses were 44.65, 34.12 and 21.23% respectively, indicating that the flow rate selected by the SASIS model was absolutely inadequate.

For PISG2 (Figure 2d), the curves representing the water application efficiency and the percolation losses

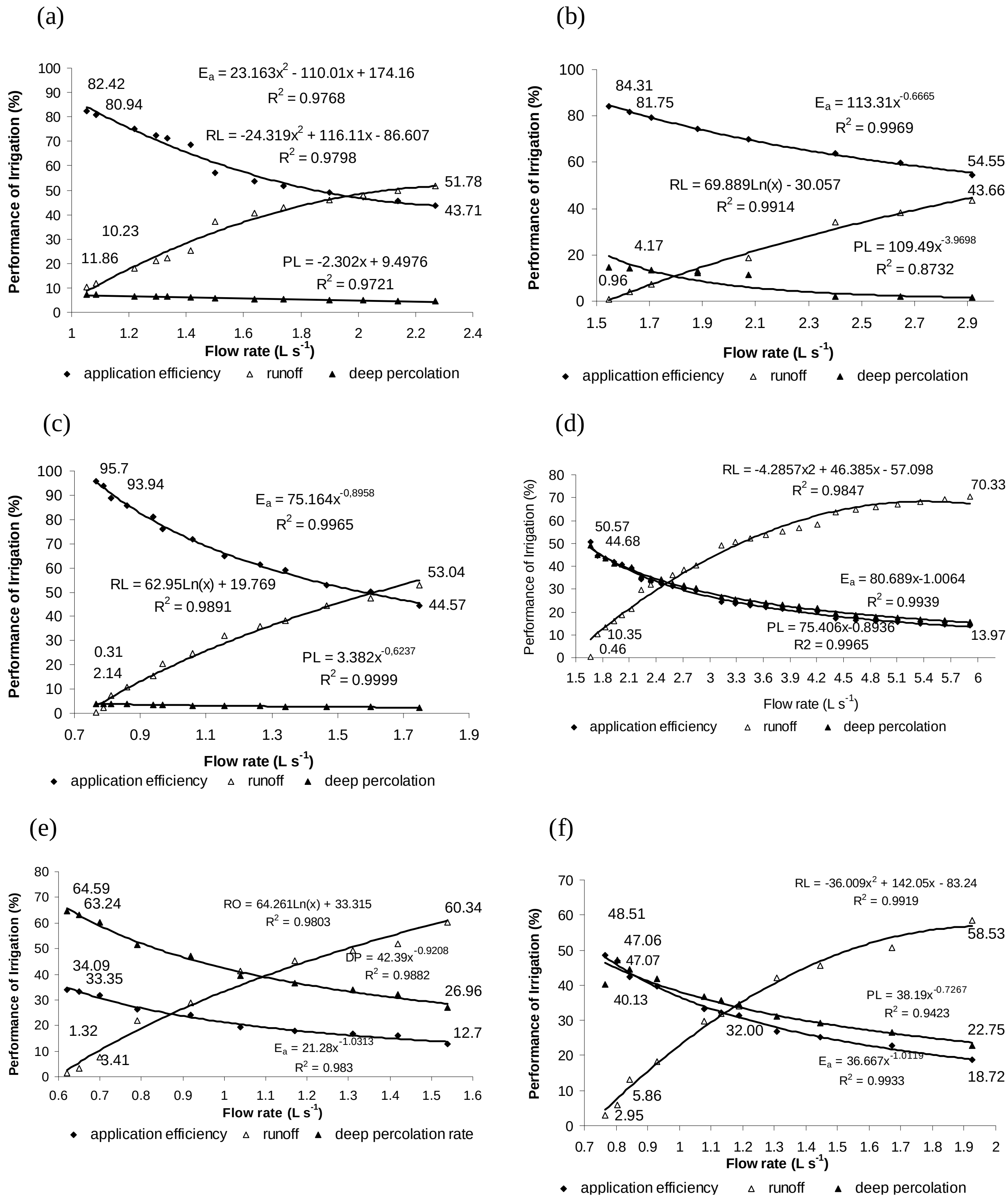

Figure 2. Irrigation performance as a function of flow rate and optimal flow rate: (a) PISG1 data and 1.05 L s^{-1}; (b) KWF data and 1.62 L s^{-1}; (c) GUFCQ data and 0.79 L s^{-1}; (d) PISG2 data and 1.66 L s^{-1}; (e) PISG3 data and 0.64 L s^{-1}; (f) PISG4 data and 0.77 L s^{-1}. E_a – water application efficiency, RL - runoff loss and PL - percolation values.

Table 3. Simulated data for minimum, maximum and optimal flow rate and performance parameters based on field data.

Field data	Minimum flow rate (L s^{-1})	Maximum flow rate (L s^{-1})	Optimal flow rate (L s^{-1})	Flow rate practiced by the farmer (L s^{-1})	Minimum [1]E_a (%)	Optimal [1]E_a (%)	Runoff (%)		Percolation (%)	
							MFR[2]	OFR[3]	MFR	OFR
PISG1	0.90	2.33	1.05	1.33	43.71	82.42	51.78	10.23	4.51	7.35
KWF	1.60	3.01	1.62	1.50	54.55	81.75	43.66	4.17	14.08	1.79
GUFCQ	0.60	1.79	0.79	1.30	44.57	93.94	53.04	2.14	2.38	3.92
PISG2	1.50	5.92	1.66	1.47	13.97	50.37	70.33	0.46	15.70	48.96
PISG3	0.76	1.56	0.64	1.54	12.66	34.28	60.45	0.78	26.88	64.94
PISG4	0.81	2.02	0.77	1.13	18.72	48.51	53.53	2.95	22.75	48.54

[1]E_a – water application efficiency; [2] Maximum flow rate; [3] Optimal flow rate.

is very similar to the point of practically overlap, with values very close to the same input flow. This example shows a large difference between runoff and percolation losses, since the difference between them was 48.5% for optimum flow rate and 54.63% for maximum flow rate, resulting in low water application efficiency. The flow rate also showed greater effect on runoff losses, with difference of 69.88% between values predicted for optimal and maximum flow rates, compared to percolation losses, for which the difference was 33.26%. For the design flow rate (1.47 L s^{-1}), the values predicted for the water application efficiency and for runoff and percolation losses were 47.62, 0 and 53.16%, respectively. Thus, showing values close to those predicted for the optimal flow rate, demonstrating that the farmer made the right choice for these field conditions.

For field data PISG3 (Figure 2e), the value predicted by the SASIS model for the optimal flow rate was 0.64 L s^{-1}, close to the minimum flow rate and for the maximum flow rate, it was 1.56 L s^{-1}, whose runoff losses were 0.78 and 60.45%, respectively, while percolation losses were 64.94 and 26.88%, resulting in water application efficiencies of 34.28 and 12.66%. That is also a critical field condition for the irrigation system management, whose percolation and runoff losses show large difference for both optimal flow rates as for the maximum flow rate. The difference between them for the optimal flow rate is 64.16%, and for the maximum flow rate is 37.57%. It was observed in this example that the curve for the percolation losses has basically the same behavior as the water application efficiency curve that is, similar slopes in certain flow rates, however, always with different values. For the design flow rate (1.54 L s^{-1}), the values predicted for the water application efficiency, runoff and percolation losses were 12.7, 60.3 and 27%, respectively, showing quite different predicted losses, demonstrating that the flow choice will cause large runoff losses, which indicates the need for flow management to reduce difference between these losses.

In the example of PSG4 (Figure 2f), the optimal flow rate predicted by the SASIS model, the difference between runoff and percolation losses was 45.59%, and for the maximum flow rate the difference was 35.78%. However, the results demonstrated that the flow rate has a much greater potential to affect the irrigation performance by runoff losses than the infiltration rate by percolation losses, considering that for the same water infiltration conditions the water application efficiency was 48.51% for the optimal flow rate, while for the maximum flow rate, it was 18.72%. Figure 2f shows that the curves that represent the water application efficiency and the percolation losses presented the same tendency, that is, the same slope with values quite close, while the curve related to the runoff losses shows high slope and values distinct from runoff losses predicted for optimal and maximum flow rates. When the flow rate practiced by the farmer (1.13 L s^{-1}) was used as input data to calculate water application efficiency and runoff and percolation losses, they were 38.25, 30.40 and 31.35%, respectively. Both runoff and percolation losses show very high values, which makes the water application efficiency low, even below the value for the optimal flow rate. Thus, in this example, the choice of the flow rate was not adequate. The fact that the values for water application efficiency, runoff and percolation losses were very close to each other is because the flow rate selected by the SASIS model is close to the intersection points of these curves.

The results of this research show the need for optimization in furrow irrigation systems with continuous flow and also identify that in some field conditions, one can achieve high performance levels. According to the studied examples, it was found that the best furrow irrigation performances with continuous flow are achieved for flow rates near the minimum allowable. When runoff and percolation losses are minimal, with little difference between them, that is, with no predominance of one over the other (total maximum losses around 20%), the best water application efficiency is achieved. In some field conditions, such losses cannot be controlled, that is water application efficiency cannot be optimized, and another flow rate which results in improved irrigation performance must be selected. The analyses of the obtained results show that high water application efficiencies were achieved for the low infiltration soils: PISG1, KWF and GUFCQ. While lower performances were achieved for high infiltration soils: PISG2, PISG3 and PISG4.

In field conditions in which runoff and percolation losses were controlled, soils have low infiltration rates; for these infiltration conditions, it was possible to obtain greater control of these losses for a furrow length range from 67 to 360 m and slope from 0.030 to 0.0173 m m^{-1}, showing that the optimization of the furrow irrigation system can be obtained in a wide range of length and steepness. In field conditions in which this control is not achieved, soils have high infiltration rates and the length and slope ranges were 70 to 115 m and 0.0016 to 0.0043 m m^{-1} respectively, showing once again that length and slope do not interfere in optimization.

Valipour (2012a), used the SIRMOD software to compare the hydrodynamic models, zero inertia and kinematic wave in surface irrigation. It was found that the hydrodynamic models and zero inertia were very accurate in the simulation process. However, when the gradient field was increased up to 0.01, the zero inertia and hydrodynamic models showed no difference, but for values greater than 0.01, due to the water velocity increasing, the zero inertia model failed. According to the author, for the Manning roughness coefficient up to 0.15 the error increases, after this value the error remains constant, and n = 0.15 is determined as critical flow. For the author, the accuracy of the kinematic wave model is reduced for heavy clay soils, high flow rates, elevated Manning roughness coefficient and basin irrigation.

Runoff losses affect the performance of furrow irrigation systems with continuous flow, since the low performance levels of furrow irrigation systems used in this study occurred due to the use of flow rates near maximum allowable values, and it is believed that this fact occurs in most areas where furrow irrigation with continuous flow is practiced, explaining the low performance levels recorded in literature.

According to Eldeiry et al. (2004), the high efficiency in furrows with length from 25 to 50 m can be achieved with small discharge. The authors affirm that furrows with a length of 100 m had an efficiency of 80% with discharge ranging from 0.05 to 0.10 m^3 min^{-1}. For small furrows, the efficiency is high for low flow rates with minor variations, while for long furrows, greater efficiency is obtained with less dependence on the flow rate, being the most widely used.

Thus, this study demonstrated well the importance of the SASIS model in forecasting the performance of furrow irrigation systems with continuous flow, selecting input flow in open furrow at the end of the area, allowing better water application efficiency and avoiding waste of water during irrigation.

Conclusions

The results showed that the flow rate plays a decisive role on the performance parameters of irrigation systems, with the best performances on flow rates. The analyses of the obtained results show that high water application efficiencies were achieved for the low infiltration soils, while lower performances were achieved for high infiltration soils. In soils with high infiltration rates, the immense difficulty in optimization is to minimize percolation losses, but in soils with low infiltration rates, both percolation and runoff losses can be easily minimized.

The SASIS model has effective mechanisms in performing numerous simulations within a flow rate range between minimum and maximum, aiming to determine the relationship between flow rate and water application efficiency, percolation and runoff losses and hence optimize the performance of furrow irrigation systems with continuous flow.

Conflict of Interest

The authors have not declared any conflict of interest.

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