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Comparison between surge irrigation and conventional furrow irrigation for covered black tobacco cultivation in a Ferralsol soil

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Abstract

Over 51,000 ha of low yield tobacco were harvested in the year 2000/2001 in Cuba. Since the Union of Tobacco Enterprises plans to increase this area to 72,000 ha of tobacco in 2005, where most of these new areas will be irrigated with surface irrigation, then the introduction of new irrigation technologies is an important premise to achieve high yield productions. Because of this, some field evaluations of furrow irrigation with continuous and intermittent flow applications were carried out on a plot belonging to the «Cítricos Ciego de Avila» enterprise, in the Ceballos municipality of the Ciego de Avila province, Cuba. The objective of these field evaluations was to compare the hydraulic behavior of different water management strategies of furrow irrigation for the cultivation of black tobacco in a Ferralsol soil, using a surface irrigation simulation model. The intermittent application of water considerably reduced the infiltration capacity of the soil. Likewise, the influence of soil water content and furrow wetted perimeter on infiltration parameters was corroborated. The 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.

Key words: infiltration, water management, performance indices.

Resumen

Comparación entre el riego por pulsos y el riego por surcos convencional para el cultivo del tabaco negro tapado en un suelo Ferralsol

En la campaña 2000/2001 se cosecharon en Cuba alrededor de 51.000 ha de tabaco con un rendimiento medio relativamente bajo. Si se considera que para el año 2005 la Unión de Empresas del Tabaco prevé crecer hasta 72.600 ha, en donde la mayor parte de esta superficie será regada con métodos superficiales, entonces la introducción de nuevas tecnologías de riego por superficie es una premisa necesaria para lograr los incrementos previstos en los volúmenes de producción del tabaco. Teniendo en cuenta lo anterior, se realizaron evaluaciones de campo de riego por surcos con flujo continuo e intermitente en áreas de la empresa «Cítricos de Ciego de Avila», ubicada en el municipio Ceballos de la provincia de Ciego de Ávila, Cuba. El objetivo de las evaluaciones fue comparar el comportamiento hidráulico de diferentes estrategias de manejo del riego por surcos para el cultivo del tabaco negro tapado en un suelo Ferralsol. Se ejecutaron experimentos numéricos con un modelo matemático de simulación a fin de determinar las estrategias óptimas de manejo del riego por pulsos y comparar sus índices de idoneidad con los del riego por surcos convencional. La aplicación intermitente del agua en el riego por surcos redujo considerablemente la capacidad de infiltración del suelo. Asimismo, se constató la influencia que ejerce el contenido de agua en el suelo y el perímetro mojado del surco sobre los parámetros de infiltración. El riego por pulsos con ciclos variables incrementó la eficiencia de aplicación en más de seis veces y redujo el volumen de agua aplicada en más del 80% respecto al riego con flujo continuo. Los mayores incrementos de la uniformidad de distribución y reducciones de las pérdidas por percolación se obtuvieron con una longitud de surcos de 200 m y un caudal de 1 L s^{-1} respectivamente.

Palabras clave: infiltración, manejo del agua, índices de idoneidad.

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Introduction

The cultivation of Cuban tobacco, almost all black tobacco (77 %), is a delicate and complex process and only gives favorable results if it is done in carefully managed soils. Tobacco is not a docile diffuse crop that can be grown using extensive and uniform cultivation practices, but is highly sensitive both to a deficit and excess of soil water content. Tobacco cultivation is even stricter when the quality of the tobacco crop is important. Black tobacco for cigar skins (covered black tobacco) is grown in crops covered with canopies of white material to reduce the effects of sun on the leaves, increasing their elasticity, texture, color and combustibility.

In the 2000/2001 growing season, around 51,000 ha of tobacco in Cuba were dedicated to different kinds of tobacco crops, with a relatively low mean yield (721 kg ha^{-1}) (TABACUBA, 2001). Since, for the year 2005, the aim of the Tobacco Companies Union is to increase production up to 72,600 ha, the majority of which will be irrigated by surface techniques, the introduction of new surface irrigation technologies that increase the efficiency of water use and crop yield is a necessary premise to achieve the proposed increase in volume of tobacco production.

Surge irrigation, also known as intermittent irrigation or surge flow (Stringham and Keller, 1979), has emerged over the last 20 years as one of the most efficient strategies for use of irrigation water and fertilizers. This water management strategy has considerably revolutionized gravity systems, drastically changing and improving all the parameters involved in this ancient irrigation technique.

The intermittent application of irrigation water in furrows permits a more uniform distribution of infiltrated depth, a considerable reduction of the volumes of water required, the possibility of using lighter irrigations, less water loss from deep percolation and reduced leaching of fertilizers (Walker and Skogerboe, 1987; USU, 1988). All these benefits are associated with a clear reduction in the infiltration rate of the soil.

This phenomenon occurs because, between one cycle and the next, the clods break up, particles are reoriented and there is migration of the sediments that seal the base of the furrow. Also, while the water supply in each cycle is interrupted, air is trapped in the soil pores (Walker and Skogerboe, 1987; Jalali-Farahni *et al.*, 1993b). Both effects facilitate the rapid advance of the water, solving the old problem of excess losses by deep percolation at the beginning of the furrow.

In surge irrigation, two phases are clearly identified: (1) the advance phase and (2) the post-advance phase (USU, 1988). During the advance phase, the water moves from the beginning to the end of the furrows. Advance cycles can be constant or variable. In the latter case, the cycles are progressively longer in time but advance approximately the same distance (Belt, 1993; Moody, 1993). The post-advance phase starts immediately after finishing the advance phase, i.e. when the water front reaches the far end of the furrows. This phase permits the required depth of water to be applied at the far end of the field, reducing or eliminating water losses from surface runoff.

In this work, mathematical modeling of surface irrigation was used to determine optimum surge irrigation water management strategies in the cultivation of covered black tobacco in a Ferralsol soil and to compare their performance indices with conventional furrow irrigation.

Material and Methods

In the months of November and December of 1997, field experiments were carried out with continuous and surge irrigation in fields belonging to the company «Cítricos de Ciego de Avila», located in the Ceballos municipality of the Ciego de Ávila province in Cuba. The plot where the experiments were conducted had a surface area of 4.21 ha, a mean slope of 0.45% and was prepared for sowing black tobacco (Habana 92 variety).

The soil of the experimental area is classified, according to the genetic classification system for Cuban soils (Hernández *et al.*, 1994), as typical Red Ferrilitic, which corresponds to a rodic Ferralsol according to the FAO-UNESCO (1988) classification.

Field experiments

A furrow irrigation system was set up with low density polyethylene piping of 200 mm diameter with 32, 34, 36 and 38 mm diameter discharge gates. A prototype of an automatic surge irrigation valve 150 mm in diameter made by the *Instituto Mexicano de Tecnología del Agua* (IMTA) was used. The plot was

Table 1. Data from field evaluations

Date	**24/11/97**	**27/11/97**	**6/12/97**	**6/12/97**
Management strategy	10 min constant cycle surge irrigation	7 min constant cycle surge irrigation	Variable cycle surge irrigation Cycle #1 of 6 min	Continuous irrigation
Number of cycles	4	3	4	—
Furrow spacing (m)	0.90	0.90	0.90	0.90
Furrow length (m)	97.20	92.60	91.80	86.40
p1	0.411	0.4201	0.497	0.497
p2	1.3251	1.3206	1.3594	1.3594
Manning's *n*	0.04	0.04	0.04	0.04
Inflow (L s^{-1})	0.90	0.94	1.00	1.25

p1 and *p2* are coefficients that depend on the furrow geometry (Walker, 1989).

leveled with laser technology before sowing the tobacco.

Four evaluations of furrow irrigation were made in three conditions of soil water content and four water management strategies. Considering the numerous tilling practices that cultivation of covered black tobacco requires (weeding, earthing up, etc.), all evaluations were carried out on recently prepared soils. Table 1 shows the general data for the evaluations.

The flow applied to the furrows was measured with a portable RBC flume situated at the head of the field. The slope of the field was determined by linear regression of the soil elevations measured with a laser level. The advance times of the water front were measured in stations located every 5.40 m, coinciding with the posts installed to support the canopy. The sections of furrows evaluated were measured with a profilometer (Walker, 1989) at three sites located at the start, the centre and the end of the field. Mean values were estimated for the geometric data corresponding to the furrow sections. Manning's rugosity coefficient *n* was estimated according to the value proposed by Walker and Skogerboe (1987) for the condition of freshly prepared soil.

Before starting each irrigation event, the soil water content at 60 cm depth was estimated at three stations located at the start, center and end of the field. These were done by the gravimetric technique. Mean values of soil water content and net irrigation depth are shown in Table 2. Net irrigation depths were estimated considering a root depth of 40 cm (typical for black tobacco), a field capacity of 0.324 g g^{-1} and a bulk density of 1.13 g cm^{-3}.

Determination of infiltration parameters

To characterize the infiltration process in irrigation measurements, a modified version of the Kostiakov infiltration equation was used (Lewis, 1937). This is the one used in the surface irrigation simulation model SIRMOD (USU, 2001). This mathematical model was used in this work to conduct numerical experiments to determine optimum irrigation management strategies. The modified Kostiakov infiltration equation is:

$$Z = K \cdot t^a + fo \cdot t \qquad [1]$$

where Z corresponds to cumulative infiltration ($m^3\ m^{-1}$), t is opportunity time (min), fo is the basic

Table 2. Soil water content at the beginning of each evaluation and corresponding net irrigation depth

Evaluation	**24/11/97**	**27/11/97**	**6/12/97**	**6/12/97**
	Surge irrigation	**Surge irrigation**	**Surge irrigation**	**Continuous irrigation**
Soil water content 0-20 cm (g g^{-1})	0.278	0.293	0.259	0.254
Soil water content 20-40 cm (g g^{-1})	0.281	0.296	0.271	0.276
Soil water content 40-60 cm (g g^{-1})	0.282	0.297	0.275	0.281
Net irrigation depth (mm)	20.0	13.3	26.6	26.6

infiltration rate (m^3 m^{-1} min^{-1}), while K and a are empirical coefficients.

SIRMOD characterizes infiltration in surge irrigation by applying the model proposed by Walker and Humpherys (1983), which requires estimation of the modified Kostiakov parameters for the first and third advance cycle. The first step to estimate these parameters by the volume balance method is to determine the basic infiltration rate.

Basic infiltration rate

Since the measurements required to estimate the basic infiltration rate according to the classical input-output method (Walker, 1989) were not made during the field evaluations, an alternative method had to be used.

Renault and Wallender (1992) identified two linear phases in the advance velocity diagram. The first phase, which characterizes the initial advance stage, is brief and the advance velocity rapidly decreases in response to the high infiltration rate of the soil. In the second phase (stabilized), the advance velocity slowly decreases with the distance. These authors identified four parameters in the advance velocity diagram that define asymptotic lines and the velocity fronts. Of these parameters, the maximum advance length during the stabilized phase, L_m, is directly related with the basic infiltration rate with equation [2]:

$$fo = \frac{Q}{L_m} \qquad [2]$$

where Q is the flow applied to the furrow (m^3 min^{-1}), and L_m is expressed in meters.

To estimate fo, advance velocity diagrams were constructed for the first, third and fourth cycle of each surge irrigation evaluation, calculating the velocity from the mean value between two consecutive points of advance. Then, the two linear phases of each diagram were identified, which permitted L_m to be obtained from the intercept of the stabilized phases with the abscissa axis. Finally, the value of fo corresponding to each advance cycle and field evaluation was calculated from equation [2].

Volume balance method

After obtaining the basic infiltration rate, the volume balance method with non linear regression analysis (Rodríguez, 1996) can be applied to estimate the remaining parameters of the modified Kostiakov model. This method is similar to that proposed by Walker (1989), except that, instead of using two points, all the advance data measured in the experiments are used. According to the volume balance equation, during an irrigation event, the volume of water applied, V_i, is equal to the sum of the volume accumulated in the soil surface, V_y, and the infiltrated volume, V_z. Therefore, V_z can be determined as:

$$V_z = V_i - V_y \qquad [3]$$

The advance curves measured in the field were adjusted to a power equation to estimate parameters p and r of equation [4]:

$$t = p \cdot x^r \qquad [4]$$

where t is the advance time (min), x is the advance distance (m), while p and r are empirical coefficients. Introducing the surface factor ($r_y = 0.77$) and subsurface factor, r_z, equation [3] can be expressed as:

$$V_z = r_z \cdot K \cdot t^a \cdot x + fo \cdot t \cdot x \cdot \frac{r}{(r+1)} = Q \cdot t - 0.77 \cdot A_0 \cdot x$$

$$V_z = \left[\frac{r}{r+1} + \frac{1-a}{(r+1)(a+1)}\right] K \cdot t^a \cdot x +$$

$$+ fo \cdot t \cdot x \cdot \frac{r}{(r+1)} = Q \cdot t - 0.77 \cdot A_0 \cdot x \qquad [5]$$

The right side of equation [5] was estimated for each advance time measured in the field. The area of surface flow, A_o, was estimated from Manning's equation (Walker, 1989):

$$A_o = \left(\frac{Q \cdot n}{60 \cdot p1\sqrt{S_o}}\right)^{\frac{1}{p2}} \qquad [6]$$

where S_o is the longitudinal slope of the furrow (m m^{-1}) (equivalent to 0.0045); while A_o and Q are expressed in (m^2) and (m^3 min^{-1}), respectively.

The infiltration parameters K and a were determined by non linear regression analysis between measured values of t and V_z, using the left side of the equation [5] as the regression function.

Infiltration parameters for untested discharges in the field experiments

With the purpose of using mathematical modeling as a tool to obtain optimum parameters for the design and management of surge irrigation in the study conditions, it was necessary to study a wider range of inflows and furrow lengths than those evaluated in the field experiments. A range of inflows was analyzed from 0.5 L s^{-1} to 2.5 L s^{-1} at intervals of 0.5 L s^{-1}, corresponding to the upper limit with the non erosive discharge according to Hamad and Stringham (1978).

To estimate infiltration parameters corresponding to untested inflows in the field experiments, the procedure proposed by Rodríguez (2003) was used, taking the evaluation done on the 24/11/97 as a reference, which corresponds to the one with the soil water content nearest to the recommended deficit for adequate development of covered black tobacco crops in red ferralitic soils (Juan *et al.*, 1986). To apply the procedure proposed by Rodríguez (2003), it was first necessary to determine equivalent infiltration parameters from the Kostiakov (1932) equation using the method developed by Valiantzas (2001). The equivalent Kostiakov equation is:

$$Z_{eq} = K_{eq} \cdot t^{a_{eq}} \quad [7]$$

After obtaining K_{eq} and a_{eq} for the inflow evaluated in the experiment conducted on the 24/11/97 (0.9 L s^{-1}), the parameters K_{eq} and *fo* corresponding to inflows not evaluated in the field evaluations were estimated from equations [8] and [9], respectively (Rodríguez, 2003).

$$K_{eq_{ne}} = K_{eq_e} \left(\frac{Q_{ne}}{Q_e} \right)^{\frac{1-a_{eq}}{p2} + a_{eq}} \quad [8]$$

$$fo_{ne} = fo_e \left(\frac{Q_{ne}}{Q_e} \right)^{\frac{2.5}{p2} - 1.5} \quad [9]$$

In equations [8] and [9] variables with subindex *ne* correspond to inflows not evaluated in the field experiments Q_{ne} (0.5, 1.5, 2.0 and 2.5 L s^{-1}), while the variables with subindex *e* refer to the inflow evaluated Q_e (0.9 L s^{-1}).

Finally, estimated infiltration parameters were reconverted into equivalent ones in the modified Kostiakov model, by applying the Valiantzas procedure in an inverse manner.

Validation of the SIRMOD model

To verify the predictive capacity and the precision of the SIRMOD model (complete hydrodynamic variant), advance curves measured in the field were compared with those obtained by the model. The model was validated using the same field experiments used to calibrate it (by estimating the infiltration parameters). Nonetheless, the data corresponding to the second and fourth advance cycles of these experiments are, in fact, independent and so were not used in the calibration. Evaluation of the quality of the results obtained by simulation was done using the following statistical indices:

1. Regression between measured and simulated advance times.
2. Root mean square error (*RMSE*):

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} d_i^2} \quad [10]$$

3. Mean absolute error (*MAE*):

$$MAE = \frac{1}{N} \sum_{i=1}^{N} d_i \quad [11]$$

where N is the number of observations to compare, d_i is the difference between the advance times obtained by the model and the experimental measurements.

RMSE provides information about the suitability of the model since the real differences between measured and simulated values can be compared term by term. On the other hand, with the *MAE* it can be estimated whether the model over or underestimates measured values. The positive value of *MAE* represents the average degree of overestimation.

Numerical experiments

With the infiltration equations corresponding to inflows ranging from 0.5 to 2.5 L s^{-1}, and making the furrow length vary from 80 m to 300 m, SIRMOD was used to simulate the irrigation events with continuous and surge flow. For each case of surge irrigation, constant and variable time cycles were simulated, using infiltration equations from the first and third advance cycles; while for simulating continuous flow irrigation, infiltration equations corresponding to the first advance cycles were used. The other data used in the simulations were obtained from the experiment carried out on the 24/11/97.

For each combination of inflow and furrow length studied, the optimum number and duration of the advance cycles were estimated, taking optimum management parameters as those that permit maximum application efficiency, *AE*. Similarly, the volume of water applied, *WV*, the distribution uniformity, *DU,* and the deep percolation losses, *DP*, for each optimum variant were also estimated.

Finally, the performance indices of surge and continuous irrigation management strategies were compared and the results were expressed as percentage increases or reductions in *AE*, *DU*, *WV* and *DP*.

Results

Infiltration parameters

Figure 1 shows advance velocity diagrams for each of the field evaluations carried out. Only cycles 1, 3 and 4 have been incorporated in this figure, since they are the ones that provide the information required to characterize the intermittent infiltration process.

Table 3 contains basic infiltration rates obtained for the velocity advance diagrams. Given the minimal differences found between the cycles 3 and 4 advance velocity curves (Fig. 1), it was considered that the basic infiltration rates suitable to characterize the intermittent infiltration process in the experiments on 24/11/97 and the 6/12/97, correspond to cycle 4.

Table 4 shows the infiltration parameters of the modified Kostiakov equation obtained by the volume balance method. The high determination coefficients,

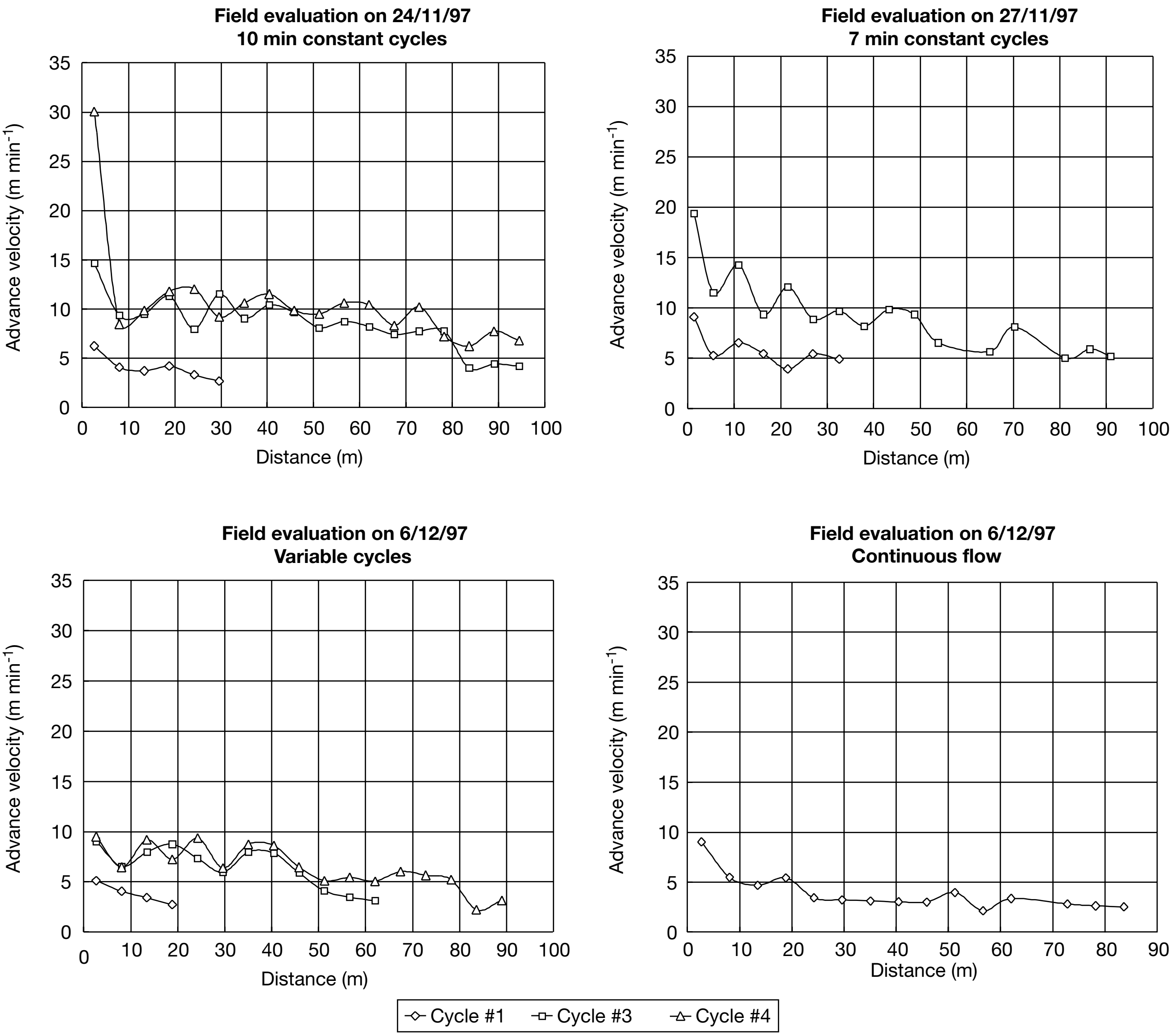


Figure 1. Advance velocity diagrams for the field evaluations performed.

Table 3. Basic infiltration rates (m^3 m^{-1} min^{-1}) obtained in the velocity advance diagrams

Evaluation	First cycle	3rd and 4th cycle	Continuous flow
24/11/97	0.00030	0.00020	0.00030
27/11/97	0.00031	0.00021	0.00031
6/12/97 Intermittent	0.00032	0.00025	0.00032
6/12/97 Continuous	—	—	0.00040

R^2, and the low standard errors obtained (*SE*), reflect the good fit of the experimental data to the infiltration model used and the efficacy of the method used to estimate its parameters.

On the other hand, Figure 2 represents the temporal evolution of infiltrated volumes per unit of furrow length for each of the surge irrigation evaluations. There are pronounced reductions in the volumes of infiltrated water when the cumulative infiltration of first advance cycle (equivalent to continuous flow irrigation) is compared with those obtained in the third and fourth cycle. Finally, Table 5 shows the parameters of the modified Kostiakov model corresponding to inflows not measured in the field evaluations.

Validation of the SIRMOD model

The advance curves measured in the field and simulated with the SIRMOD model are shown in Figure 3. An excellent correlation can be found between simulated and measured advance times both for continuous and surge irrigation, reflected in the statistical indices recorded in Table 6.

Regression between the measured and simulated advance data almost perfectly fit a line with an intercept close to zero, a slope close to one and a very high determination coefficient. Also, the errors obtained were very small, revealing a slight overestimation of simulated advance times (positive value of *MAE*), but in any case were shorter than half a minute (Table 6). These results confirm the validity of the procedures used to estimate infiltration parameters and the appropriate predictive potential of the simulation model used.

Optimum number of advance cycles

For the study conditions, an acceptable linear regression was obtained between furrow length and the optimum number of advance cycles (Fig. 4), independently of the other parameters such as applied inflow, the plot slope and the management of constant or variable time cycles.

Constant *vs.* variable cycles surge irrigation

Figures 5 and 6 show the contour lines for application efficiency and distribution uniformity obtained from numerical experiments carried out with SIRMOD. These figures contain the results obtained for optimum management strategies of surge irrigation with constant and variable cycles. The volumes of water applied presented a similar trend to application efficiencies.

Continuous *vs.* surge flow furrow irrigation

Finally, in Figures 7 and 8 the performance indices of continuous flow irrigation are compared with those

Table 4. Parameters of the modified Kostiakov model obtained by the volume balance method with non linear regression analysis

Evaluation	*K* (m^3 m^{-1} min^{-1})	*a*	*fo* (m^3 m^{-1} min^{-1})	R^2	*SE* (m^3 m^{-1})
24/11/97 First cycle	0.005065	0.3002	0.00030	0.9901	0.00035
24/11/97 Third cycle	0.001821	0.06616	0.00020	0.9927	0.000071
24/11/97 Fourth cycle	0.001349	0.05013	0.00020	0.9887	0.00006
27/11/97 First cycle	0.004110	0.27405	0.00031	0.9983	0.000111
27/11/97 Third cycle	0.001561	0.09806	0.00021	0.9955	0.000056
6/12/97 First cycle	0.007306	0.29545	0.00032	0.9910	0.000242
6/12/97 Third cycle	0.003987	0.05609	0.00025	0.9877	0.000198
6/12/97 Fourth cycle	0.003787	0.05608	0.00025	0.9942	0.000133
6/12/97 Continuous flow	0.008569	0.15573	0.00040	0.9921	0.000470

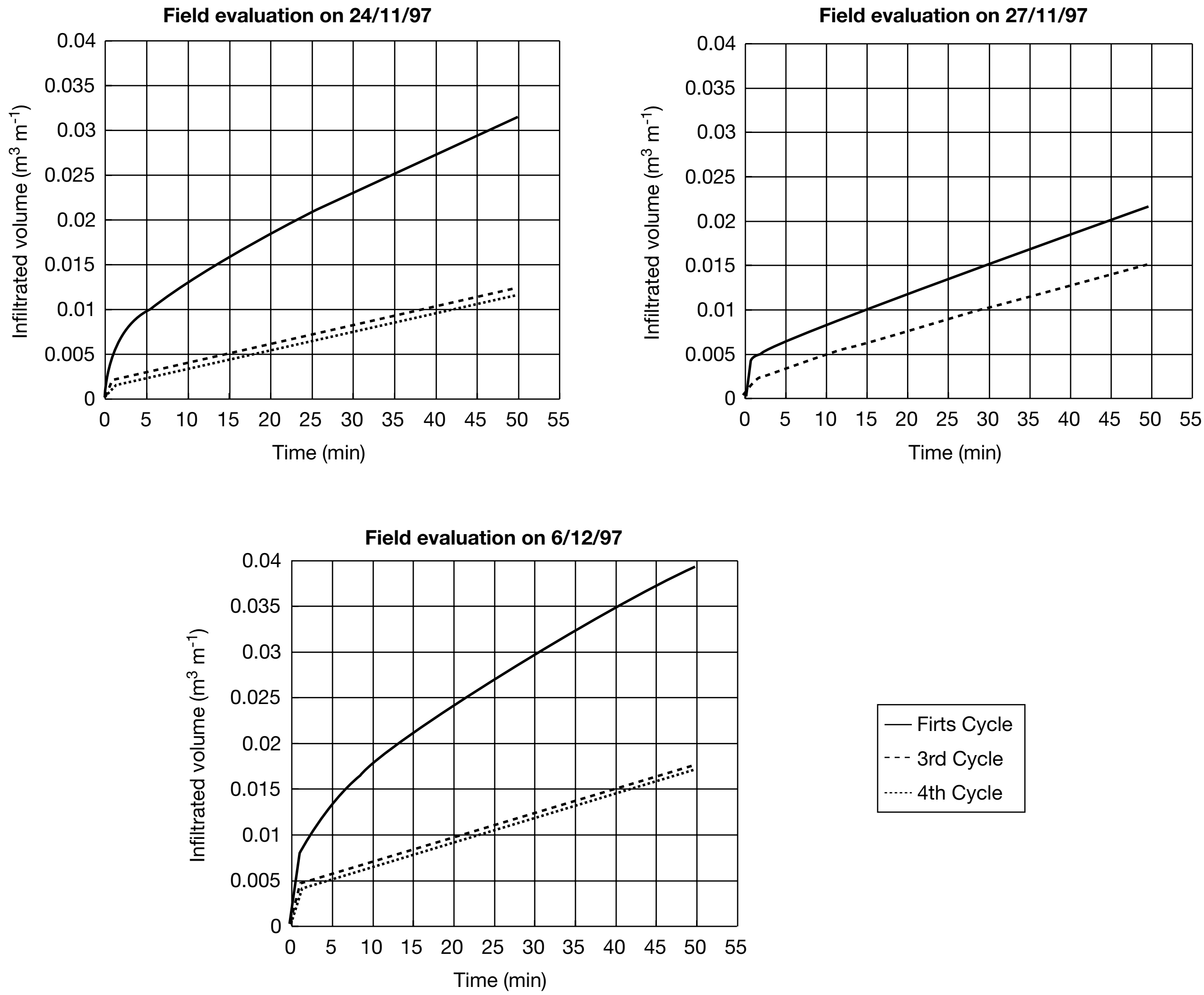


Figure 2. Volumes of infiltrated water for cycles 1, 3 and 4 obtained in surge irrigation evaluations.

Table 5. Parameters of the modified Kostiakov model for different inflows not evaluated in field experiments

Inflow ($L\ s^{-1}$)	*K* ($m^3\ m^{-1}\ min^{-1}$)	*a*	*fo* ($m^3\ m^{-1}\ min^{-1}$)
First cycle			
0.5	0.002991	0.2843	0.000239
1.5	0.007973	0.3124	0.000366
2.0	0.010280	0.3184	0.000408
2.5	0.012514	0.3227	0.000445
Third cycle			
0.5	0.001100	0.04848	0.000159
1.5	0.002804	0.08022	0.000244
2.0	0.003569	0.08682	0.000272
2.5	0.004301	0.09158	0.000297

of surge irrigation with variable time cycles. These results can be used to estimate the optimum parameters to design surge irrigation for the study conditions.

Discussion

Infiltration process

Regardless of soil water content on which each surge irrigation measurement was made (Table 2), the basic infiltration rates obtained were similar in each advance cycle (Table 3). Since the basic infiltration rate is equivalent to the saturated hydraulic conductivity (Skaggs *et al.*, 1980), which is independent of the initial water content of the soil, the results obtained were to be expected.

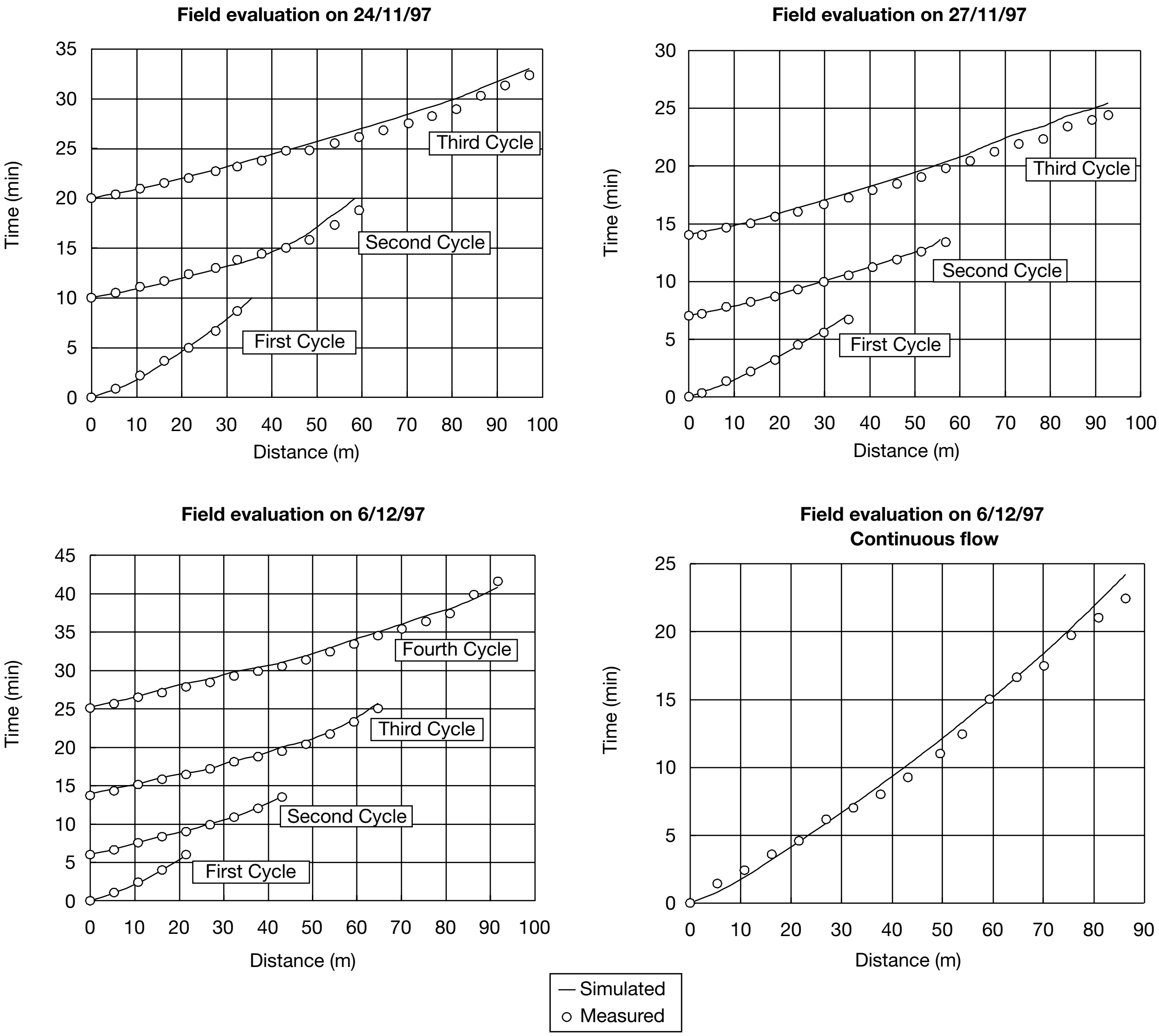


Figure 3. Comparison between measured advance curves and those obtained with the SIRMOD model.

On the other hand, it can also be observed in Table 3 that the *fo* values for the third and fourth cycles are lower than those corresponding to the first cycle, revealing the reduction in infiltration rate induced by consolidation processes, surface crust formation and trapping of air that take place with the surge flow regime (Walker and Skogerboe, 1987; Jalali-Farahni *et al*., 1993a, b).

Table 6. Statistical indices to assess the predictive capacity of the SIRMOD model

Statistical index	Value
Determination coefficient R^2	0.998
Intercept of regression line (min)	0.08
Slope of regression line	0.97
Number of observations	113
RMSE (min)	0.6941
MAE (min)	0.4091

Figure 2 shows the very small difference in the cumulative infiltration from the third and fourth cycles. This, therefore, means that the surge infiltration model proposed by Walker and Humpherys (1983) can be applied for the mathematical simulation of surge irrigation events, since one hypothesis on which this model is based is that significant reductions in infiltrations do not occur after the third advance cycle.

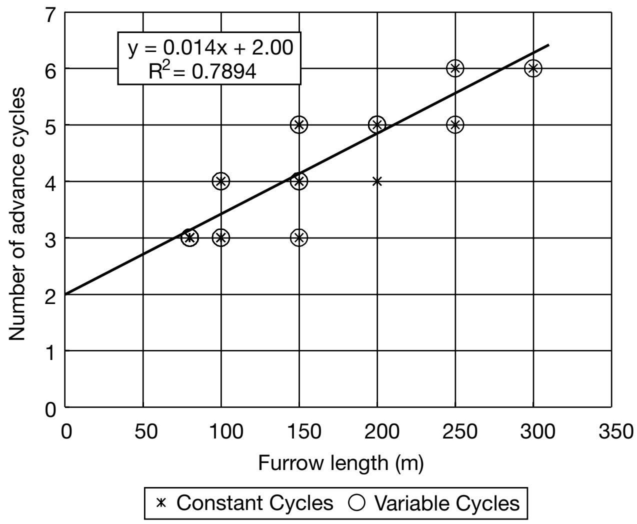


Figure 4. Regression between furrow length and optimum number of advance cycles.

Figure 2 also shows the influence of the initial soil water content on the infiltration process. Observe how, during the first cycle, the infiltrated volumes decrease as the soil water content increases. In the evaluation done on 27/11/97, which corresponded to the one with the largest soil water content (Table 2), a smaller volume of water infiltrated than in the other evaluations. This influence is also shown on the reduced infiltration rate under the surge flow regime.

In the third advance cycle of evaluation done on 27/11/97, a smaller reduction in cumulative infiltration was obtained than in the rest of the evaluations (Fig. 2). If one considers that the texture of soil analyzed is loam clay, in which the consolidation process is the main mechanism for reducing the intermittent infiltration rate (Jalali-Farahni *et al.*, 1993a, b), this behavior seems only logical. The consolidation process, which results from the increased surface tension of the soil as each advance cycle is used up, is highly dependent on the initial soil water content. As the soil becomes increasingly wet, the tensions generated after the wetting in each cycle are lower, therefore the compaction of its surface (the main cause of reduced infiltration) also decreases.

Table 5 shows the significant oscillations in infiltration parameters obtained with different inflows, reflecting the influence of the furrow wetted perimeter on the infiltration process (Izadi and Wallender, 1985; Trout, 1992). Surface irrigation simulation models are highly sensitive to infiltration parameters (Zerihun *et al.*, 1996; Schwankl *et al.*, 2000), and if these models are used to analyze optimum design and management strategies, they can generate significant errors if the variations in infiltration with furrow wetted perimeter (or the inflow used) are not taken into account.

Management parameters of surge irrigation

Owing to the small net irrigation depths that the covered black tobacco crop requires (from 20 to 25 mm; Juan *et al.*, 1986) and the high infiltration capacity of the soil studied, management of the

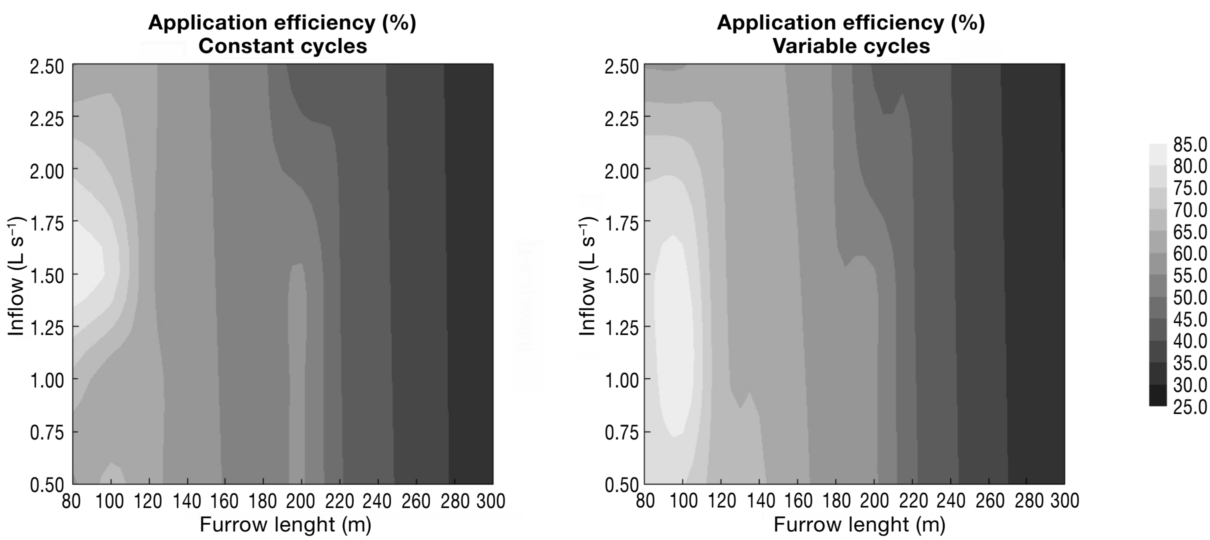


Figure 5. Contour lines of application efficiency obtained for constant cycle surge irrigation management strategies (left) and variable cycles (right).

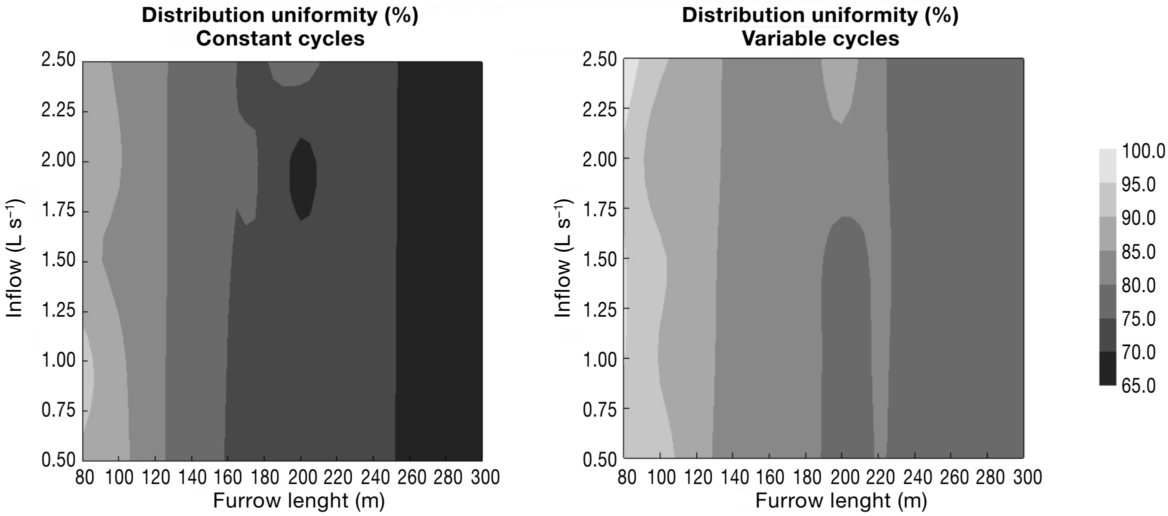


Figure 6. Contour lines of distribution uniformity obtained for constant cycle surge irrigation management strategies (left) and variable cycles (right).

post-advance phase in surge irrigation is no longer important in these conditions. The net irrigation depth is almost satisfied with the runoff from the final advance cycle or, possibly, it may be necessary to apply one or two additional post-advance cycles. Consequently, the main surge irrigation management parameters for the study conditions are the number and duration of the cycles required to complete the advance phase.

In this work, optimum surge irrigation management parameters are those which permit maximum application efficiency. Although optimum solutions for surface irrigation do not necessarily coincide with those that achieve the best application efficiencies (Ito *et al.*, 1999; Montesinos *et al.*, 2001); from a practical perspective it is accepted as a good selection criteria to choose designs that achieve the best efficiencies (Walker and Skogerboe, 1987; Walker, 1989).

The optimum number of advance cycles obtained varies between three and six for all the variants studied. This result coincides with recommendations given in specialized literature (USU, 1988). The number of cycles must be such that the advance phase finishes as soon as possible to achieve greater distribution uniformity of the infiltrated water. Each advance cycle should last long enough to reach the previously wetted

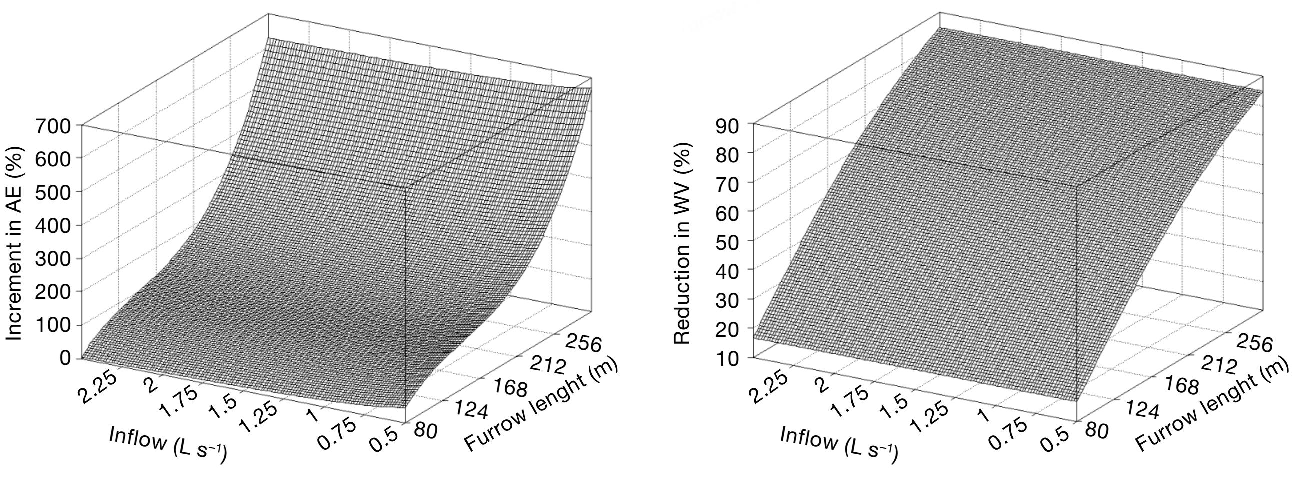
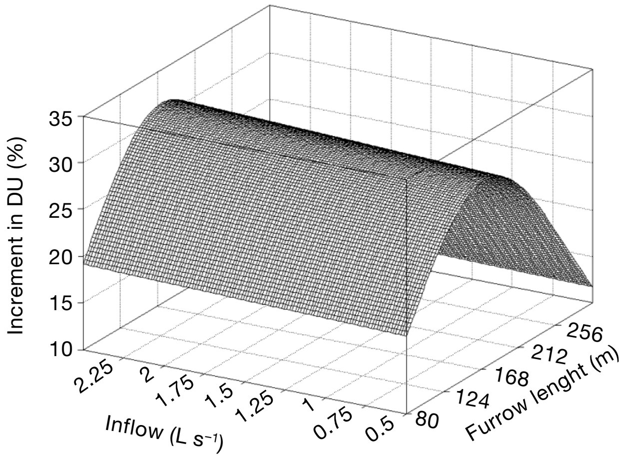


Figure 7. Increased application efficiency (left) and reduction in volume of water applied (right) obtained when comparing continuous flow irrigation with surge irrigation.



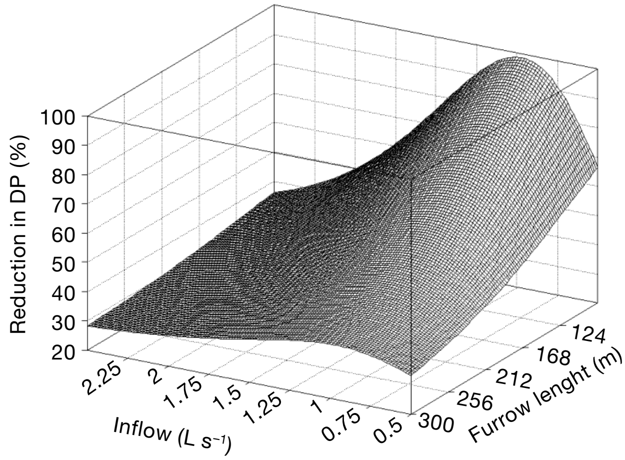


Figure 8. Increased distribution uniformity (left) and reduction in deep percolation losses (right) obtained when continuous flow irrigation is compared with surge irrigation.

part of the furrow and to continue on to the dry part. Advance cycles that are too short will overlap and will impede processes that reduce the soil's infiltration capacity. On the other hand, very long cycles will cause excess water losses by deep percolation near to the head of the field.

Figure 5 shows that the largest *AE* are achieved in the management with variable time cycles for furrow lengths less than approximately 200 m. However, for lengths over 200 m, the *AE* values are similar for both management strategies. The volumes of water applied present similar trends to the application efficiencies. Smaller *WV* were obtained in management with variable cycles for the whole range of inflows studied and furrow lengths smaller than 200 m.

Similarly, Figure 6 clearly shows great distribution uniformities in the management strategy with variable cycles for the whole range of variables studied. The *DU* revealed little sensitivity to inflow applied to the furrow, in contrast with the continuous flow irrigation, in which the *DU* increased significantly with the inflow (Walker, 1989; Feyen and Zerihun, 1999).

These results contradict the practice recommended by other authors to use constant time cycles for furrow lengths shorter than 400 m and variable time cycles for longer lengths (USU, 1988). These recommendations were obtained for arid and semiarid conditions in the United States, for furrow lengths and irrigation depths much higher than those used in covered black tobacco crops grown in Cuba. Nonetheless, research has shown that the greater application efficiencies and distribution uniformities in surge irrigation are obtained with variable time cycles (Walker and Skogerboe, 1987; USU, 1988; Latif and Ittaq, 1998). Therefore, most programmable surge irrigation controllers actually incorporate this management strategy (Yonts *et al.*, 1996).

Taking into account aspects studied previously, it can be deduced that, for the study conditions, the optimum surge irrigation management strategy is achieved with variable time cycles for any combination of inflow and furrow length included within the range studied. Although both the *AE* and the *WV* presented a similar behavior for furrow lengths over 200 m, the *DU* obtained were always larger in the management strategies with variable cycles; favoring crop growth and the uniform application of fertilizers and other chemical products with minimum pollution risks (Moody, 1993).

Design parameters for surge irrigation

Comparison of the performance indices of continuous furrow irrigation and variable cycle surge irrigation, one can see in Figure 7, left, that after furrow lengths of approximately 200 m, the difference between the *AE* of both management strategies increases importantly, showing that after this distance continuous flow irrigation presents much lower *AE* than variable cycle surge irrigation. The previous observation is related with the significant reductions in the volumes of water applied when continuous flow irrigation is compared with surge irrigation (Fig. 7, right).

For the distribution uniformity, a sustained maximum value can be observed in the response surface of

Figure 8, left, for a furrow length of approximately 200 m, oscillating between 25 and 30% increase in the *DU*. Similarly, a sharp drop in the gradient of the response surface can be observed for furrow lengths over 200 m, with only an improvement of around 10% compared to continuous flow irrigation of 300 m furrow length.

On the other hand, the surface response for reduced deep percolation losses (Fig. 8, right) reaches peak values (from 40 to 95%) with an inflow of 1 L s^{-1} and furrow lengths shorter than 200 m. However, reductions in *DP* are only between 30% and 40% for lengths over 200 m in the whole range of inflows studied. This unusual behavior can be explained if one considers that as the inflow applied is increased the advance time of the front is reduced, but at the same time the furrow wetted perimeter increases, increasing in turn the infiltration rate (Rodríguez, 2003). The increment of inflow in surge irrigation does not proportionally reduce deep percolation losses as usually occurs in basin irrigation (Playán and Martínez-Cob, 1999). If the influence of the furrow wetted perimeter on the infiltration process is ignored, a completely different result is obtained (larger inflows result in larger reductions in *DP*), leading to inaccurate conclusions.

If we finally consider the global behavior of the performance indices analyzed, it could be proposed that the variable cycles surge flow irrigation can increase the *AE* by more than 6 fold and reduce the *WV* by more than 80% compared to continuous flow irrigation. Moreover, the benefits of surge irrigation management compared to conventional irrigation strategies become more evident with the longer furrow lengths. Nonetheless, the better results related with the *DU* and the *DP* are obtained with a furrow length of 200 m and an inflow of 1 L s^{-1} respectively. With these design parameters, variable cycles surge irrigation not only permits a considerable saving of water compared to conventional irrigation, but is also a sustainable alternative to reduce the pollution by fertilizers or other chemical compounds required for the development of modern conventional agriculture.

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